RIKEN Accelerator Progress Report 2014
vol. 48

RIKEN Nishina Center for Accelerator-Based Science
Wako, Saitama, 351-0198 JAPAN
RIKEN Accelerator Progress Report 2014 vol.48

This is an unabridged version of the 48th volume of RIKEN Accelerator Progress Report (hereinafter referred to as APR), the official annual report of the Nishina Center for Accelerator-Based Science.

A PDF version of APR can be downloaded from our website. http://www.nishina.riken.jp/researcher/APR/index_e.html
The readers of RIKEN Accelerator Progress Report (APR) must have realized that we have stopped sending you a thick volume of papers. Instead, you now receive a compilation of the gravure and the highlights of the year with information of a web page where you can download a full set of the articles. While such change has been made to adapt to the changing times, it may make the readers of the older generation miss the good old times.

Nevertheless, when you pick up a thin booklet of the latest APR, please look into one of the highlights, “RI beam production at BigRIPS in 2014” written by N. Fukuda and his coauthors. From the impressive nuclear chart showing the history of RI beam production, you will learn that from March 2007 to December 2014, 140 new isotopes were discovered at BigRIPS, and that the production yields were measured for more than 1,000 isotopes. A total of 89 experiments have been performed so far. The Nishina Center is proud of these accomplishments and all the members who have contributed to this remarkable achievement must be applauded.

According to the BigRIPS compilation, the most popular primary beam is without a doubt uranium-238, and the close second is calcium-48. Containing 20 protons and 28 neutrons, calcium-48 is the so-called doubly magic nucleus. It is very neutron rich but its life time is 43 quintillion (10^{18}) years, much longer than the life of the universe (14 billion years). This is why there still exists natural calcium-48, but since its quantity totals only 0.18% of all the calcium, it is very expensive. Calcium-48 is our key tool to study the nuclear region called “island of inversion” and to find out where a neutron drip line for fluorine (F), neon (Ne), sodium (Na) etc. is. In 2014, our Ion Source Team succeeded in the calcium-48 ion production which is highly budget-friendly. As highlighted in this volume of APR as “Supply of 48Ca beam from 18-GHz ECRIS using the micro-oven” by K. Ozeki and his coauthors, the consumption of calcium-48 has been reduced by nearly a factor of 10 and the stability of the ion source has much improved. One should acknowledge that such behind the scene effort is essential for our beam performance.

Other important subject which became quite visible at the RIKEN RI Beam Factory in 2014 is nuclear chemistry. With the third event of element 113 observed in the summer of 2012, the search for 113th element was concluded which propelled us to take the next step forward, i.e. to begin search for element 119 and 120. With this shift, a long-waited research for nuclear chemistry of super-heavy elements came into full swing. There are two outstanding reports in this APR, “First chemical synthesis and investigation of Sg(CO)₆” by J. Even et al. and “Results of first online tests of small ion-surfing RF carpet gas cell at GARIS-II” by P. Schury et al.. The former determined that seaborgium belongs to the 6th family chemically, and the latter revealed the powerful potential of GARIS-II in its application to super heavy element chemistry when combined with the RF carpet technology developed to slow RIs down for high precision measurements. I believe super heavy chemistry has moved into an unexplored new stage of research.

The year 2014 was the landmark year for the Nishina Center in that it made a shift toward a new direction in response to the needs of today’s society. We have started two governmental projects, ImPACT (Impulsing Paradigm Change through Disruptive Technologies) program titled “Reduction and Resource Recycle of High Level Radioactive Wastes with Nuclear Transmutation” and SIP (Strategic Innovation Promotion) program titled “Technology for creating next-generation forestry, agriculture and fisheries”, both of which are based on our long time bottom-up efforts and activities. By initiating these governmental projects, we have declared to the society that we will give back to the community our research results.

In spite of such impressive progress made in the Nishina Center however, it was truly unfortunate that the entire JFY2014 had to be spent on complying with RIKEN’s countermeasures against the STAP incident, a serious scientific misconduct that occurred at the RIKEN Center for Developmental Biology. I apologize for any inconveniences you have had to deal with. I must, however, repeat once again what I had wrote in the preface of APR2013. If any similar incident ever occurred at the Nishina Center, the Center would cease to exist. We thus declare that we will never let such an incident happen in our field.

Hideto En'yo

Director,
RIKEN Nishina Center for Accelerator-Based Science
EURICA: A state-of-the-art decay spectrometer

The RIBF in Japan, one of the world’s most powerful radioactive beam facilities, has been providing intense beams of exotic nuclei since 2007. Following the success of the first decay spectroscopy experiments in 2009, which focused on the study of neutron-rich nuclei with masses of around $A = 100-117$, a world-class decay project called EURICA (Euroball-RIKEN Cluster Array)† was launched owing to the efforts of 190 international collaborators. This state-of-the-art spectrometer, which consists of twelve Euroball HPGe cluster detectors (formerly GSI RISING) and the highly-segmented RIKEN β-ray detector WAS3ABi, markedly improves the performance of high-resolution decay spectroscopy of exotic nuclei with fast radioactive beams. EURICA has been in operation since 2012, and has harvested the decay properties of several hundred exotic nuclei. The lifetimes and level schemes of isotopes produced in BigRIPS can be deduced by measuring the times of flight, trajectories, and energies of the isotopes, and their subsequent β and γ rays emitted in the β-γ decay.
**β-decay half-lives and nuclear astrophysics**

~ How and where were the heavy elements produced in the universe? ~

The β-decay half-lives of isotopes with production rates as low as several events per day were measured using the EURICA spectrometer. In the fall of 2012, the half-lives of neutron-rich nuclei in the vicinity of \(^{78}\text{Ni}\) (Z=28, N=50) were investigated using WAS3ABi, a device that consists of 8 layers of double-sided silicon-strip detectors (shown in the image on the right). The results are summarized in Figure 1. The systematics of the half-lives indicate a sudden decrease beyond N=50 (\(^{79,80}\text{Ni}\)) and below Z=28 (\(^{77}\text{Co}\)), thus providing robust evidence for a doubly magic \(^{79}\text{Ni}\).

The decay properties of exotic nuclei are also key to uncovering some of the long-standing mysteries of the astrophysical rapid-neutron capture process (r-process), namely, the main astronomical site(s) and its mechanism. The r-process is a sequence of neutron-capture and β-decay processes that is known to be responsible for the synthesis of approximately half of the elements heavier than iron. Nuclear physics inputs, for example, nuclear masses (\(Q_β\)), neutron-capture rates, β-decay half-lives, and β-delayed neutron emission probabilities of very neutron-rich nuclei, are expected to play a significant role in the understanding of the mechanism and site(s) of the r-process. Figure 2 summarizes the nuclei surveyed with EURICA at the RIBF. A first attempt to study the universality of the astrophysical r-process was performed by measuring the β-decay half-lives of 110 neutron-rich nuclei around mass A=100-140, where 40 half-lives were measured for the first time. As shown in Figure 3, the reaction-network calculations of supernova nucleosynthesis with the new half-lives indicate that the \((n,γ)^*(γ,n)\) equilibrium is still valid, and reproduces the universality of the elements with Z > 56.
Figure 2: Summary of the nuclei surveyed with EURICA, where known half-lives are presented in color. The open circles indicate the data collected prior to the Kr beam campaign in 2015. The results are presented in S. Nishimura et al. PRL 106, 052502 (2011), Z.Y. Xu et al. PRL 113, 032505 (2014), and G. Lorusso et al. PRL 114, 192501 (2015).

Figure 3: Abundances of r-process elements compared with estimations of reaction-network calculations of supernova nucleosynthesis.
Magicity and deformation

~ The magic numbers 28, 50, and 82, and regions far from the valley of stability ~

Understanding nuclear shell structure and its evolution toward the drip-lines is one of the major topics in nuclear structure research as well as nuclear astrophysics. One of the main goals of EURICA is to study the shell gaps around the doubly magic nuclei $^{78}\text{Ni}$ ($Z=28$, $N=50$), $^{132}\text{Sn}$ ($Z=50$, $N=82$), and $^{100}\text{Sn}$ ($Z=50$, $N=50$), where a possible weakening of the magicity and shell quenching effects have been discussed. Figure 4 provides a compilation of the energies of the first excited states in even-even nuclei obtained via $\gamma$ rays from isomers and $\beta$-delayed $\gamma$ rays from daughter nuclei. In addition, detailed level schemes were deduced for $^{116,118}\text{Ru}$, $^{129}\text{In}$, and $^{131}\text{In}$ via the $\beta$-delayed $\gamma$ rays of $^{116,118}\text{Tc}$, $^{129}\text{Cd}$, and $^{131,132}\text{Cd}$, respectively, and long-lived isomers in $^{126}\text{Pd}$ and $^{131}\text{Cd}$ were identified via internal conversion. Some of the EURICA results from 2012 are related to low-lying states in neutron-rich nuclei that contribute to the formation of the r-process peak around mass $A\sim130$. Further systematic studies on shell evolution of both neutron- and proton-rich nuclei have been conducted using $\beta$-$\gamma$ spectroscopy with EURICA at the RIBF and will be reported in the future.

![Figure 4: Overview of first excited state energies in even-even nuclei obtained via $\gamma$ rays from isomers and $\beta$-delayed $\gamma$ rays from daughter nuclei.](image)

† EURICA was supported by the EUROBALL Owners Committee for the loan of the germanium detectors, and the PreSpec collaboration for the use of the readout electronics. WAS3ABi was partly funded by the Priority Centers Research Program in Korea (2009-0093817). Ten international Ph.D. students participating in the EURICA collaboration were supported by RIKEN IPA (International Program Associates).
addition, detailed level schemes were deduced for 116,118Ru, 129In, and 131In via the 
effects have been discussed. Figure 4 provides a compilation of the energies of the first excited states 
A of 116,118Tc, 129Cd, and 131,132Cd, respectively, and long- lived isomers in 126Pd and 131Cd were 
funded by the Priority Centers Research Program in Korea (2009- 0093817). Ten i nternational Ph.D. 
detectors, and the PreSpec collaboration for the use of the readout electronics. WAS3ABi was partly 
Program Associates). 
EURICA was supported by the EUROBALL Owners Committee for the loan of the germanium 
-130. Further systematic studies on shell evolution of both neutron- and proton-rich nuclei have 
~ The magic numbers 28, 50, and regions far from the valley of stability ~ 
Magicity and deformation 
Understanding nuclear shell structure and its evolution toward the drip- lines is one of the major 
~130. Further systematic studies on shell evolution of both neutron- and proton-rich nuclei have 
\[\text{PLB 704, 270 (2011)}\] 
H. Watanabe et al. 
~130. Further systematic studies on shell evolution of both neutron- and proton-rich nuclei have 
\[\text{PRL 113, 042502 (2014)}\] 
P.-A. Söderström et al. 
\[\text{88}, 024301 (2013)}\] 
H. Watanabe et al. 
\[\text{PRL 113, 132502 (2014)}\] 
G. Simpson et al. 
\[\text{Proton-Hole State in }^{132}\text{Sn and Shell Structure Along N=82} \] 
J. Even et al. 
\[\text{contained within a high-yield supernova explosion, for example, the galaxy SN1987A.} \] 
J. Hillebrandt et al. 
\[\text{I.1 HIGHLIGHTS OF THE YEAR} \] 
1p\textsubscript{1/2} Proton-Hole State in \(1^{12}\text{Sn} \) and Shell Structure Along N=82 
J. Taprogge et al. 
Isomer decay spectroscopy of \(^{160}\text{Sm} \) and \(^{166}\text{Gd} \): mid-shell collectivity around N=100 
Z. Patel et al. 
\(\beta\) -Decay half-lives of \(^{77}\text{Co}, \(^{78}\text{Ni} \) and \(^{64}\text{Cu} \): experimental indication of doubly magic \(^{78}\text{Ni} \) 
Z. Y. Xu et al. 
Intermediate-energy Coulomb excitation of \(^{108}\text{Sn} \): Moderate E2 strength decrease approaching \(^{130}\text{Sn} \) 
P. Doorenbal et al. 
First campaign of the SEASTAR project 
P. Doornenbal et al. 
Fragmentation of \(^{117}\text{Cs} \) and \(^{86}\text{Sr} \) on proton and deuterium 
H. Wang et al. 
Missing-mass spectroscopy of tetra-neutron system via exothermic double-charge exchange reaction 
\( ^{4}\text{He}(^{4}\text{He},^{4}\text{He})4n \) 
K. Kisamori et al. 
Laser-RF double resonance spectroscopy of \(^{183,187}\text{Rb} \) isotopes trapped in superfluid helium 
X.F. Yang et al. 
RI beam production at BigRIPS in 2014 
N. Fukuda et al. 
Neutron drip-line search using 48Ca beam 
N. Inabe et al. 
High-resolution hadronic-atom X-ray spectroscopy with superconducting transition-edge-sensor microcalorimeters 
S. Okada et al. 
Measurement of high-\(\mu\) neutral mesons with a high-energy photon trigger in ALICE 
S. Yano and K. Shigaki 
Transverse single-spin asymmetries in prompt photon production from proton-proton collisions 
D. Pityonyak et al. 
Entanglement entropy of de Sitter space \(\alpha\)-vacua 
N. Izuka, T. Noumi, N. Ogawa 
Current Reflection and Transmission at Conformal Defects: Applying BCFT to Transport Process 
T. Kimura and M. Murata 
Magnetic field of the slowest rotating neutron star in the symbiotic X-ray binary \(4U 1954+319\) 
T. Enoto et al. 
Short-term spectral softening of black-hole binary Swift J1753.5-0127 
A. Yoshikawa et al. 
Installation of return BT line from IRC 
Y. Watanabe et al. 
Supply of \(^{40}\text{Ca} \) beam from 18-GHz ECRIS using the micro-oven 
K. Ozeki et al. 
Particle identification for Sn region with SAMURAI 
J. Yasuda et al. 
Results of first online tests of small ion-surfinRF carpet gas cell at GARIS-II 
P. Schury et al. 
Electron scattering spectrometer for the SCRIT project 
K. Tsuchida et al. 
Measurement of isochronism using \(\alpha\)-source for the Rare RI Ring 
Y. Abe et al. 
Time-stamping system for nuclear physics experiments at RIKEN RIBF 
H. Baba et al. 
First chemical synthesis and investigation of \(\text{Sg(CO)}_{2}\) 
J. Even et al. 

\[\text{CONTENTS RIKEN Accel. Prog. Rep. 48 (2015)}\]
II. RESEARCH ACTIVITIES I (Nuclear, Particle and Astro-Physics)

1. Nuclear Physics

- Long-lived isomer in $^{126}$Pd
  H. Watanabe
  27

- Yrast 6’ Seniority Isomers of $^{136,138}$Sn
  G. Simpson et al.
  28

- Gamma-Spectroscopy around $^{106}$Sn
  J. Park and D. Lubos
  29

- Identification of a millisecond isomeric state $^{129}$Cd via the detection of internal conversion and Compton electrons
  J. Taprogge et al.
  30

- Study of shape evolution in neutron-rich Cs isotopes using $\beta$-decay spectroscopy
  J. Vagi et al.
  31

- Shell evolution in neutron-rich Te isotopes beyond doubly magic $^{132}$Sn
  P. Lee et al.
  32

- Decay spectroscopy of neutron-rich Z > 60 isotopes
  E. Ideguchi et al.
  33

- Investigation of octupole correlations of neutron-rich Z > 56 isotopes through $\beta$-$\gamma$ spectroscopy
  R. Yokoyama et al.
  34

- Decay spectroscopy of neutron-rich rare-earth isotopes
  P-A Söderström et al.
  35

- Rotational level structure of sodium isotopes inside the “Island of Inversion”
  P. Doornenbal et al.
  36

- In-beam $\gamma$-ray spectroscopy of $^{37}$Ar
  D. Steppenbeck et al.
  37

- Experimental study of isoscalar and isovector dipole resonances in neutron-rich oxygen isotopes
  N. Nakatsuka et al.
  38

- Study of the pygmy-dipole resonances of $^{132}$Sn and $^{130}$Sn in inelastic $\alpha$-scattering
  J. Tscheuschner, T. Aumann et al.
  39

- Coulomb excitation of $^{120}$Cd
  H. Wang, N. Aoi et al.
  40

- Search of E1 strength around threshold in $^{70}$Ni
  R. Avigo, O. Wieland et al.
  41

- Structure at and beyond the dripline in the vicinity of the N=14 and 16 sub-shell closures
  S. Leblond et al.
  42

- Study of neutron-unbound states of $^{19}$C at SAMURAI
  J. Hwang et al.
  43

- Measurement of unbound states in $^{17}$C at SAMURAI
  S. Kim et al.
  44

- Detailed analysis of tracking detectors for SAMURAI08 experiment
  S. Koyama et al.
  45

- Fission Barrier Studies of Neutron-Rich Nuclei via the (p,2p) Reaction: Status of NP1306-SAMURAI-14 Experiment
  S. Reichert et al.
  46

- Identification of fission fragments from tracks measured by the FDC1
  M. Sako et al.
  47

- Study of Neutron-Proton Correlations & 3N Forces in $^{12}$C
  H. N. Liu et al.
  48

- Simulation for experimental studies of breakup reactions on neutron-deficient isotopes relevant to the astrophysical $\tau p$-process
  V. Panin et al.
  49

- Future plan to study light nuclei near the neutron dripline via charge-exchange (p,n) reactions in inverse kinematics
  L. Stuhl et al.
  50

- Spin-dipole response of $^4$He by using ($^8$He, $^8$Li(1$^+$))
  H. Miya et al.
  51
Spectroscopy of Single-Particle States in Oxygen Isotopes via $^4\text{O}(\bar{p}, 2p)$ Reaction with Polarized Protons

S. Kawase et al.

Status on residual analysis of SHARAQ04 experiment

T.L. Tang et al.

Parity-transfer reaction for study of spin-dipole $0^-$ mode

M. Dozono et al.

Direct mass measurements of neutron-rich Ca isotopes beyond $N = 34$

M. Kobayashi et al.

Gamma-ray detector array for isomer tagging at SHARAQ

Y. Kiyokawa et al.

Study of nuclear structure in proton-rich carbon isotopes

T. Miyazaki et al.

Triton contamination in the $^{10}\text{C}$ secondary beam produced by RIPS

T. Miyazaki et al.

$\beta$-NMR measurement of $^{41}\text{S}$

Y. Ichikawa, Y. Ohtomo et al.

$\beta$-NMR measurement in coincidence with $\beta$-delayed $\gamma$ rays of $^{41}\text{S}$

Y. Ichikawa et al.

Interaction of $^8\text{B}$, unstable and loosely bound, with $^{208}\text{Pb}$: scattering and breakup

C. Signorini, M. Mazzocco et al.

First production of $^{15}\text{Be}$ beam at CRIB and $^{15}\text{Be} + \alpha$ resonant elastic scattering

H. Yamaguchi et al.

Investigation of the waiting point $^{27}\text{Mg}$ in the rp-process

N.N. Duy et al.

Production of Lv isotope in the hot fusion reaction of $^{248}\text{Cm} + ^{48}\text{Ca}$ at $E^* = 38.4$ MeV

D. Kaji et al.

Production of $^{215}\text{U}$ and $^{216}\text{U}$ and attempt to produce $^{217}\text{Np}$ and $^{218}\text{Pu}$

Y. Wakabayashi et al.

Search for new isotopes in the region around $Z = 33$ using the in-flight fission of a $^{238}\text{U}$ beam at 345 MeV/nucleon

Y. Shimizu et al.

Search for new neutron-rich isotopes with $Z \sim 55-70$ using a 345 MeV/nucleon $^{238}\text{U}$ beam

N. Inabe et al.

Study of particle identification and RI beam separation for the $Z \sim 80$ region using projectile fragmentation of $^{238}\text{U}$

N. Inabe et al.

Production cross section measurements of radioactive isotopes produced from a $^{124}\text{Xe}$ beam at 345 MeV/u by the BigRIPS separator

H. Suzuki et al.

Production cross section measurements for fragments of $^{70}\text{Zn}$ beam

D.S. Ahn et al.

On-line test of rotating magnetic field system for $\beta$-NMR method

Y. Ishihashi et al.

Probing the critical behavior in the evolution of GDR width at very low temperatures in $A \sim 100$ mass region

B. Dey et al.

2. Nuclear Physics (Theory)

Hoyle band and $\alpha$ condensation in $^{12}\text{C}$

Y. Funaki

Energy and mass-number dependence of hadron-nucleus total reaction cross sections

A. Kohama et al.

Systematic calculation of $T = 1$ triplets with proton–neutron mixed energy density functionals

K. Sato et al.

Correlated two-neutron emission in decay of unbound nucleus $^{20}\text{O}$

K. Hagino and H. Sagawa

Three-body model calculation of the $2^+$ state in $^{20}\text{O}$

K. Hagino and H. Sagawa

Proton-neutron pairing vibrations in $^{40}\text{Ca}$: Precursory soft mode of the isoscalar spin-triplet pairing condensation

K. Yoshida

Study of low-frequency negative-parity vibrational excitations of superdeformed rotational band in $^{40}\text{Ca}$ using cranked Skyrme-RPA calculations

M. Yamagami and K. Matsuyanagi
Self-consistent Hartree-Fock and RPA Green’s function method for monopole response of neutron-rich Ni isotopes ........................................ 86
I. Hamamoto and H. Sagawa

Origin of fusion hindrance in heavy systems ...................................... 87
K. Washiyama

Pairing effect in thermal shape fluctuation model on the width of giant dipole resonance ......................................................... 88
A.K. Rhine Kumar et al.

Shell-model study of Gamow-Teller transition from $^{100}$Sn ................ 89
M. Honma et al.

Reentrance phenomenon of superfluid pairing in hot rotating nuclei .... 90
N. Quang Hung et al.

Giant dipole resonance in highly excited nuclei ................................... 91
N. Dinh Dang

Theoretical analysis of $^{132}$Xe by generator coordinate method ............ 92
N. Yoshinaga et al.

Tops-on-top model applied to TSD bands in $^{164}$Lu ............................. 93
K. Sugawara-Tanabe et al.

Recent progress and open issues on pseudospin and spin symmetries .... 94
H. Z. Liang et al.

Nuclear moment of inertia in super-normal phase transition region ...... 95
K. Tanabe et al.

Joint project for large-scale nuclear structure calculations in 2014 ......... 96
N. Shimizu et al.

3. Nuclear Data

Development of a new EXFOR editor system ................................... 97
A. Sarsembayeva et al.

Thick-target yields derived from inverse kinematics toward transmutation 98
S. Imai et al.

Compilation of nuclear reaction data from the RIBF .......................... 99
D. Ichinkhorloo et al.

4. Hadron Physics

Performance improvement of PHENIX MUID .................................. 101
S. Han et al.

PHENIX Run13 Local Polarimetry .................................................... 102
M. Kim et al.

Hadronic backgrounds pattern study for $W^+ \rightarrow \mu^+$ analysis in PHENIX 103
C. Kim et al.

$W \rightarrow \mu$ parity violating asymmetries from the 2013 running period in the PHENIX experiment ................................. 104
R. Seidl

Neutral pion double helicity asymmetry ............................................ 105
K. Boyle

Preliminary results of $A_{LL}$ measurement at $\sqrt{s} = 510$ GeV at mid-rapidity through a PHENIX experiment ....................... 106
I. Yoon

Cross section and asymmetry measurement of very forward neutral particle production at RHIC ................................................... 107
Y. Goto

Fragmentation function measurements in Belle .................................. 108
R. Seidl et al.

Measurement of direct photon azimuthal anisotropy in $\sqrt{s_{NN}} = 200$GeV Au+Au collisions in RHIC-PHENIX experiment ............. 109
S. Mizuno for the PHENIX

Charged hadron elliptic and triangular flow in Cu+Au at $\sqrt{s_{NN}} = 200$GeV ................................................................. 110
H. Nakagomi et al.

Commissioning and operation of silicon vertex detector for PHENIX experiment in RHIC Run-14 .............................. 111
M. Kurosawa

Alignment of the PHENIX Silicon Vertex Tracker (VTX) in the 2014 RUN 112
T. Moon et al.

Distance of closest approach analysis with VTX at RHIC-PHENIX ........ 113
H. Asano et al.

Current status of bottom and charm measurements using VTX at RHIC-PHENIX ....................................................... 114
T. Hachiya et al.
Development of the FVTX high multiplicity trigger system for the PHENIX experiment ................................................................. 115
T. Nagashima et al.

Study of direct photon polarization to shed on strong magnetic field in heavy ion collisions at PHENIX ................................................................. 116
T. Hoshino

Measurement of dielectron production in $\sqrt{s_{NN}} = 5.02$ TeV p-Pb collisions by using the ALICE detector ................................................................. 117
S. Hayashi et al.

Measurement of neutral pion $\pi^0$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE experiment ................................................................. 118
T. Tsuji et al.

Long-range correlation in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector ................................................................. 119
Y. Sekiguchi et al.

Azimuthal distributions of jets with respect to high-$p_T$ neutral pion triggers in $pp$ collisions at $\sqrt{s} = 7$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE ................................................................. 120
D. Watanabe

Study of ion backflow with 2GEMs + MICROMEGAS for the ALICE-TPC upgrade ................................................................. 121
K. Terasaki et al.

Search for dark photons from neutral meson decays in $p + p$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV ................................................................. 122
Y. Akiba and Y. Yamaguchi

Progress in probing flavor asymmetry of antiquarks in protons in the E906/SeaQuest experiment at Fermilab ................................................................. 123
K. Nagai et al.

Results of the $K^+ - pp$ bound-state search in J-PARC E15 $^{14}$ ................................................................. 124
T. Hashimoto et al.

Measurement of the proton Zemach radius from the hyperfine splitting energy in ground-state muonic hydrogen ................................................................. 125
M. Sato et al.

5. Hadron Physics (Theory)

Strong enhancement of jet-medium coupling in the quark-gluon plasma near transition temperature ................................................................. 127
J. Liao

Magnetic moments of light nuclei from lattice QCD ................................................................. 128
S. Beane et al.

Nucleon structure in lattice QCD near physical mass ................................................................. 129
S. Ohta

Holographic heavy-quark symmetry ................................................................. 130
K. Hashimoto et al.

Possibility of ferromagnetic neutron matter ................................................................. 131
K. Hashimoto

Pion and Kaon form factors in the NJL model ................................................................. 132
Y. Ninomiya et al.

Chiral Magnetic and Vortical Effects at Weak Coupling ................................................................. 133
H.-U. Yee

Collinear parton splitting for early thermalization and chemical equilibration in heavy-ion collisions ................................................................. 134
A. Momma and B. Mueller

Chemical equilibration of QCD medium for photon $v_2$ puzzle ................................................................. 135
A. Momma

Refraction of light in the quark-gluon plasma ................................................................. 136
A. Momma

Transverse single-spin asymmetries in proton-proton collisions and the role of twist-3 fragmentation ................................................................. 137
D. Pironyak et al.

Left-right spin asymmetries in lepton-nucleon collisions ................................................................. 138
D. Pironyak et al.

Twist-3 double-spin asymmetries in lepton-nucleon collisions ................................................................. 139
D. Pironyak et al.

Strong binding and shrinkage of single and double $K$ nuclear systems ($K^+ pp$, $K^- ppp$, $K^- K^+ p$ and $K^- K^+ pp$) predicted by Faddeev-Yukubovskiy calculations ................................................................. 140
T. Yamazaki et al.

New way to produce dense double-antikaonic dibaryon system, $K^+ K^- pp$, through $\Lambda(1405) -$ doorway sticking in $p + p$ collisions ................................................................. 141
T. Yamazaki et al.

Theoretical analysis of $\Lambda(1405) \rightarrow (\Sigma n)^0$ mass spectra produced in $p + p \rightarrow \Lambda(1405) + K^0$ reactions ................................................................. 142
M. Hassanvand, S.Z. Kalantari

### 6. Particle Physics

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^0 \rightarrow c\bar{c}$ as a test case for quark flavor violation in the MSSM</td>
<td>143</td>
</tr>
<tr>
<td>A. Bartl et al.</td>
<td></td>
</tr>
<tr>
<td>Update on lattice QCD calculation of neutral $B$ meson mixing in static limit of $b$-quark</td>
<td>144</td>
</tr>
<tr>
<td>T. Ishikawa et al.</td>
<td></td>
</tr>
<tr>
<td>Progress toward an $ab$-initio, Standard Model calculation of direct CP-violation in K-decays</td>
<td>145</td>
</tr>
<tr>
<td>C. Kelly</td>
<td></td>
</tr>
<tr>
<td>Collisional Energy Loss in Semi-Quark Gluon Plasma</td>
<td>146</td>
</tr>
<tr>
<td>S. Lin et al.</td>
<td></td>
</tr>
<tr>
<td>Entropic destruction of heavy quarkonium in non-Abelian plasma from the holographic correspondence</td>
<td>147</td>
</tr>
<tr>
<td>K. Hashimoto and D. Kharzeev</td>
<td></td>
</tr>
<tr>
<td>Magnetic instability in AdS/CFT: Schwinger effect and Euler-Heisenberg Lagrangian of Supersymmetric QCD</td>
<td>148</td>
</tr>
<tr>
<td>K. Hashimoto, T. Oka et al.</td>
<td></td>
</tr>
<tr>
<td>Turbulent meson condensation in quark deconfinement</td>
<td>149</td>
</tr>
<tr>
<td>K. Hashimoto et al.</td>
<td></td>
</tr>
<tr>
<td>Meson turbulence at quark deconfinement from AdS/CFT</td>
<td>150</td>
</tr>
<tr>
<td>K. Hashimoto et al.</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic instability in holographic QCD</td>
<td>151</td>
</tr>
<tr>
<td>K. Hashimoto et al.</td>
<td></td>
</tr>
<tr>
<td>Electric Field Quench in AdS/CFT</td>
<td>152</td>
</tr>
<tr>
<td>K. Hashimoto et al.</td>
<td></td>
</tr>
<tr>
<td>Holographic entanglement and causal shadow in the time-dependent Janus black hole</td>
<td>153</td>
</tr>
<tr>
<td>Y. Nakaguchi, N. Ogawa, T. Ugajin</td>
<td></td>
</tr>
<tr>
<td>Radion stabilization in the presence of Wilson line phase</td>
<td>154</td>
</tr>
<tr>
<td>Y. Abe et al.</td>
<td></td>
</tr>
<tr>
<td>Is cosmological constant screened in Liouville gravity with matter?</td>
<td>155</td>
</tr>
<tr>
<td>T. Inami et al.</td>
<td></td>
</tr>
<tr>
<td>Effective Higgs interactions of composite dark matter</td>
<td>156</td>
</tr>
<tr>
<td>E. T. Neil</td>
<td></td>
</tr>
<tr>
<td>Effective field theory for spacetime symmetry breaking</td>
<td>157</td>
</tr>
<tr>
<td>Y. Hidaka, T. Nouni, G. Shiu</td>
<td></td>
</tr>
<tr>
<td>Dynamical breaking of shift-symmetry in supergravity-based inflation</td>
<td>158</td>
</tr>
<tr>
<td>A. Mazumdar, T. Nouni et al.</td>
<td></td>
</tr>
<tr>
<td>Non-Gaussianities of primordial perturbations and tensor sound speed</td>
<td>159</td>
</tr>
<tr>
<td>T. Nouni and M. Yamaguchi</td>
<td></td>
</tr>
<tr>
<td>Spin operator and entanglement in quantum field theory</td>
<td>160</td>
</tr>
<tr>
<td>K. Fujikawa et al.</td>
<td></td>
</tr>
<tr>
<td>Linearity of quantum probability measure and Hardy’s model</td>
<td>161</td>
</tr>
<tr>
<td>K. Fujikawa et al.</td>
<td></td>
</tr>
<tr>
<td>SSD and the infinite circumference limit of CFT</td>
<td>162</td>
</tr>
<tr>
<td>T. Tada</td>
<td></td>
</tr>
<tr>
<td>Towards U($N</td>
<td>M$) knot invariant from ABJM theory</td>
</tr>
<tr>
<td>B. Eynard and T. Kimura</td>
<td></td>
</tr>
<tr>
<td>Duality and integrability of supermatrix model with external source</td>
<td>164</td>
</tr>
<tr>
<td>T. Kimura</td>
<td></td>
</tr>
<tr>
<td>Bulk angular momentum and Hall viscosity in chiral superconductors</td>
<td>165</td>
</tr>
<tr>
<td>A. Shitade and T. Kimura</td>
<td></td>
</tr>
</tbody>
</table>

### 7. Astrophysics and Astro-Glaciology

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insights from Antarctica on volcanic forcing during the Common Era</td>
<td>167</td>
</tr>
<tr>
<td>M. Sigl et al.</td>
<td></td>
</tr>
<tr>
<td>Variation in chemical composition induced by solar energetic particle events in the middle atmosphere</td>
<td>168</td>
</tr>
<tr>
<td>Y. Nakai et al.</td>
<td></td>
</tr>
<tr>
<td>Measurements of nitrogen isotope ratios in samples with very low nitrate concentrations from the Dome Fuji ice core (Antarctica) drilled in 2010</td>
<td>169</td>
</tr>
<tr>
<td>Y. Motizuki et al.</td>
<td></td>
</tr>
<tr>
<td>X-ray and Optical/UV Correlation Studies of Active Galactic Nuclei</td>
<td>170</td>
</tr>
<tr>
<td>H. Noda</td>
<td></td>
</tr>
<tr>
<td>Time-variable Fe K emission lines from accreting white dwarf binaries</td>
<td>171</td>
</tr>
<tr>
<td>T. Yuasa</td>
<td></td>
</tr>
</tbody>
</table>
Spectral and Temporal Approach to Physics of Neutron Stars
T. Enoto, T. Tamagawa et al. ................................................................. 172

Timing analysis of solar flares in hard X-ray and soft $\gamma$-ray bands measured by the Suzaku Wide-band All-sky Monitor
W. Iwakiri et al. .................................................................................. 173

Spurious shear from tree-rings on LSST CCD
Y. Okura et al. .................................................................................. 174

Performance test of TPC Polarimeter for cosmic X-ray sources at BNL NSLS-I
W. Iwakiri et al. .................................................................................. 175

Fabrication of a TPC X-ray Polarimeter and Preliminary Testing with the Synchrotron Radiation Light Source at Spring-8
A. Hayato et al. .................................................................................. 176

Measurement of X-ray beam polarization of BL32B2 at SPring-8 using a Compton polarimeter
M. Kubota et al. .................................................................................. 177

Performance test of Modulated X-ray Source using UV-LED and Channel Electron Multiplier
W. Iwakiri et al. .................................................................................. 178

Property of LCP-GEM in pure dimethyl ether at low pressures
Y. Takeuchi et al. .................................................................................. 179

Measurement of the electron drift velocity in DME gas
M. Kubota et al. .................................................................................. 180

Measures for Micro Meteoroids and Orbital Debris in Cooler Driver Harnesses of the Soft X-ray Spectrometer onboard ASTRO-H
H. Noda et al. .................................................................................. 181

8. Accelerator

Emittance measurements for RIKEN 28 GHZ SC-ECRIS
Y. Higashits et al. .................................................................................. 183

Supply of $^{40}$Zn beam from 18-GHz ECRIS using the micro-oven
K. Ozeki et al. .................................................................................. 184

Current status of the RIKEN 18-GHz superconducting ECR ion source
T. Nagatomo et al. .................................................................................. 185

Acceleration test of $^{235}$U
K. Ozeki et al. .................................................................................. 186

Modification of septum electrode for RRC-EDC
K. Yamada et al. .................................................................................. 187

Construction of new amplifiers for RILAC
K. Suda et al. .................................................................................. 188

Magnet system for a new beam transport line from IRC to E5 experimental room
K. Kumagai et al. .................................................................................. 189

Improved-flatness beryllium disk stripper for uranium acceleration at RIKEN RIBF
H. Hasebe et al. .................................................................................. 190

Thinning effect of gas strippers for high-intensity very heavy ion beams
H. Imao et al. .................................................................................. 191

Control and monitoring system of gas strippers
R. Koyama and H. Imao .................................................................................. 192

Beam Energy and Longitudinal Beam Profile Measurement System at the RIBF
T. Watanabe et al. .................................................................................. 193

Maintenance and development of the RIBF control system
M. Komiyama et al. .................................................................................. 194

Development of new operational log system for RIBF operation
A. Uchiyama et al. .................................................................................. 195

Commissioning of the Laser Ion Source for RHIC EBIS
M. Okamura and T. Kanesue .................................................................................. 196

NISHINA RIBF water-cooling system 2014
T. Maie et al. .................................................................................. 197

Charge State Selective Ion Beam Acceleration Using the RFQ Linac
Y. Fuwa et al. .................................................................................. 198

Investigation of the effect of solenoidal magnetic field on Fe plasma flux for application to laser ion source
S. Ikeda et al. .................................................................................. 199

9. Instrumentation

Operational status of the superconducting SAMURAI magnet
H. Sato et al. .................................................................................. 201
| S. Reichert and M. Sako et al. | Preparation status of the \((p, 2p)\) fission experiment with the SAMURAI spectrometer | 202 |
| J. Yasuda et al. | Slow neutron detector WINDS for \((p, n)\) reaction in inverse kinematics with SAMURAI | 203 |
| T. Isobe et al. | Integration of GET system for SnRIT-TPC | 204 |
| G. Jhang, T. Isobe et al. | Performance evaluation of GET readout electronics for heavy ion collision experiments at RIBF | 205 |
| M. Kurata-Nishimura et al. | Status of SnRIT-TPC | 206 |
| Y. Togano et al. | Test of prototype crystals of the \(\gamma\)-ray detector CATANA | 207 |
| H. Takeda et al. | Isotope separation with new ion-optics mode | 208 |
| S. Takeuchi et al. | A NaI (Tl) detector array for measurements of \(\gamma\) rays from fast radioactive isotope beams | 209 |
| R. Tanishia et al. | Development of a total-kinetic-energy counter for high-rate experiments at ZeroDegree spectrometer | 210 |
| Y. Matsuda et al. | Low-pressure MWDC system for ESPRI experiment | 211 |
| H. Matsuzawa et al. | Proposal of novel delayed-neutron branching ratio measurements using MKTOF | 212 |
| M. Wada | Advanced development of GARIS-II using He-H\(_2\) mixture as a filled gas toward the study of superheavy element | 213 |
| D. Kaji et al. | Pulse shape analysis for short-lived decay of superheavy elements | 214 |
| S. Yamaki et al. | Performance of ion surfing rf-carpet for high-energy RI beam gas catcher | 215 |
| F. Arai et al. | Evaluation of effects of a large energy deposition on Deuterium gaseous active target for a high-intensity ion beam injection | 216 |
| C. S. Lee, S. Ota et al. | Design of a thin-film polarized proton target system for low-energy RI beam experiments | 217 |
| K. Tateishi et al. | Kinetic parameters of photo-excited triplet state of pentacene determined by dynamic nuclear polarization | 218 |
| Y. Sato et al. | Development of single-crystal CVD diamond detector for time-of-flight measurements | 219 |
| K. Tateishi et al. | Efficient excitation of photo-excited triplet electrons of pentacene for dynamic nuclear polarization | 220 |
| M. Hayasaka et al. | Realization of \(^1\)H spin polarization of 40\% at room temperature | 221 |
| M. Hayasaka et al. | Production of spin polarization of atoms in superfluid helium using a pulsed Ti: sapphire laser | 222 |
| S. Chebotaryov et al. | Microwave system development of enlarged spin-polarized proton target for RI beam experiments | 223 |
| T. Ohnishi et al. | The off-line adjustment of the parasitic production of low-energy RI-beam system for installation in BigRIPS | 224 |
| T. Sonoda et al. | Current status of the gas cell ion beam cooler-buncher at SLOWRI | 225 |
| Y. Ito et al. | SCRIT luminosity monitor | 226 |
| S. Yoneyama et al. | Study of the performance of the SCRIT rear drift chamber | 227 |
| S. Matsuo et al. | Current status of RI beam production at electron-beam-driven RI separator for SCRIT (ERIS) | 228 |
| T. Ohnishi et al. | Development of the readout system for SCRIT WiSES | 229 |
| A. Enokizono et al. | New fast-kicker system for Rare RI Ring | 230 |
| Y. Yamaguchi et al. | Realization of \(^1\)H spin polarization of 40\% at room temperature | 231 |
Status of the resonant Schottky pick-up for the Rare RI Ring project .................................................. 232
F. Suzaki et al.

Extraction of multi-nucleon transfer reaction products in $^{136}$Xe and $^{198}$Pt systems .......................... 233
Y. Hirayama et al.

Detector system for the KEK isotope separation system ................................................................. 234
S. Kimura et al.

Q-value resolution improvements in the spectroscopy of deeply bound pionic atoms using BigRIPS ...... 235
T. Nishi et al.

Development of D$_2$ gas-filled drift chamber for spectroscopy measurements of pionic atoms in inverse kinematics ................................................................. 236
Y. N. Watanabe et al.

Radiation monitoring in the RIBF using ionization chamber .......................................................... 237
M. Nakamura et al.

Measurement of activation around the He gas stripper at RIBF ..................................................... 238
A. Akashio et al.

Beam preparation for fee-based utilization of a 70-MeV/\(\alpha\) Kr-beam .............................................. 239
A. Yoshida and T. Kambara

Implantation of $^7$Be and $^{22}$Na beams for wear diagnostics application ........................................... 240
A. Yoshida et al.

Development of a GEM tracker for the J-PARC E16 experiment .................................................... 241
W. Nakai

Preparation status of the J-PARC E16 experiment: measurement of spectral change of vector mesons in nuclei ................................................................. 242
S. Yokkaichi et al.

Simulation of HBD response in the J-PARC E16 experiment based on test results .......................... 243
K. Kanno et al.

Resistive Plate Chamber (RPC) for BGOegg Experiment .............................................................. 244
T. Nam, N. Tomida

Quality assurance test of pixel detector ladders for VTX ................................................................. 245
T. Surumita et al.

Fast clear technique for NEBULA data acquisition for SAMURAI17 experiment ......................... 246
Y. Togano et al.

Test of the advanced implantation detector array (AIDA) at RIBF ............................................. 247
C. Griffin et al.

CCJ operations in 2014 ....................................................................................................................... 248
S. Yokkaichi et al.

Computing and network environment at the RIKEN Nishina Center ........................................... 249
T. Ichihara, Y. Watanabe, H. Baba

III. RESEARCH ACTIVITIES II (Material Science and Biology)

1. Atomic and Solid State Physics (Ion)

Hyperfine structure measurement of $^{133}$Cs atoms in superfluid helium ........................................ 251
K. Imamura et al.

Lattice location and density distribution of hydrogen in $\beta$-\(V\),\(H\) .................................................. 252
E. Yagi et al.

Observation of the FFLO-like nodal planes in the Au layer of Nb/Au/Fe trilayers by neutron reflectivity measurements .......................................................... 253
H. Yamazaki et al.

Response of polyimide films to U ion beams as etched-track detectors ........................................ 254
T. Yamauchi et al.

High-density \(n\)-type doping of diamond by nitrogen beam implantation ......................................... 255
H. Ueno et al.

2. Atomic and Solid State Physics (Muon)

$\mu$SR study of the magnetism and superconductivity in the multi-layered Bi-2223 high-$T_c$ superconductor ......................................................................................... 257
T. Adachi et al.

$\mu$SR study of the Al-induced magnetic order in La$_{1-x}$Sr$_x$Cu$_{0.4}$AlO$_4$ ......................................... 258
K. M. Suzuki et al.

$\mu$SR study of cluster-glass state in Sr$_{1-x}$La$_x$RuO$_3$ ..................................................................... 259
I. Kawasaki et al.

Investigation of magnetic ground states in mixed kagome systems (Rb$_{1-x}$Cs$_x$)$_2$Cu$_3$SnF$_{12}$ by $\mu$SR ............................................................................................... 260
T. Suzuki et al.

High pressure $\mu$SR study of quantum phase transition in CeNiAsO ............................................... 261
H. Guo et al.
Investigation of hydrogen dynamics in hydroxyl salts Co₂(OD)₃Cl
X.G. Zheng et al. ................................................................. 262

Partial magnetic order in the quantum spin system NH₄CuCl₃
T. Goto et al. ................................................................. 263

Zn-substitution effects on distorted tetrahedral spin-chain system Cu₃Mo₂O₉
H. Kuroe et al. ................................................................. 264

Magnetic ground state of Cu₃O₄MCI (M = Y, Pb) with a caged structure
K. Kawashima et al. ................................................................. 265

μSR studies on antiferromagnet RRu₂Al₁₀ (R = Sm, Gd)
H. Tanida, H. Guo et al. ................................................................. 266

Determination of muon sites on metal-organic hybrids of (C₆H₅CH₂CH₂NH₃)₂CuCl₄ and (C₂H₅NH₃)₂CuCl₄
E. Suprayoga et al. ................................................................. 267

Investigation of muon sites in YBa₂Cu₃O₆ using density functional theory
S.S. Mohd-Tajudin ................................................................. 268

Muon sites in Ce(Ru, Rh)₂Al₁₀ investigated using Density Functional Theory from the perspective of electronic potential
N. Adam et al. ................................................................. 269

μSR study of the density wave state in α-(BEDT-TTF)₂MHg(SCN)₄ (M=K, Rb)
K. Ichimura et al. ................................................................. 270

Study on coupling between electron conduction and spin fluctuation in novel organic charge transfer complexes with TANC
M. Enomoto et al. ................................................................. 271

Study of charge carrier transport in active layer P3HT:ZnO:PCBM hybrid solar cells measured by muon spin relaxation
L. Safriani et al. ................................................................. 272

μSR study on antiferromagnetism in K-Rb alloy and Rb clusters in sodalite
T. Nakano et al. ................................................................. 273

Li-ion diffusion in LiₓFePO₄ with x = 0, 0.25 and 0.5
I. Umegaki et al. ................................................................. 274

Investigations of defects in TiO₂ rutile crystal by muon and muonium
K. Asakura, H. Ariga et al. ................................................................. 275

Response of muonium to oxygen contents in hemoglobin and other biological aqueous solutions for cancer research
K. Nagamine ................................................................. 276

Development of gas system for MuSEUM experiment
K. S. Tanaka et al. ................................................................. 277

Development of online muon beam profile monitor for the MuSEUM experiment
S. Kanda ................................................................. 278

3. Radiochemistry and Nuclear Chemistry

Reversed-phase extraction behavior of the 105th element, Db, with tributyl phosphate
M. Murakami et al. ................................................................. 279

Solid-liquid extraction of 266Rf from hydrochloric acid with Aliquat 336 resin
T. Yokokita et al. ................................................................. 280

Extraction behavior of rutherfordium as a cationic fluoride complex with a 2-thenoyltrifluoroacetone chelate extractant from HF/HNO₃ acidic solutions
Y. Kitayama et al. ................................................................. 281

Thermal stability of the group 6 hexacarbonyl complexes
I. Usoltsev et al. ................................................................. 282

Extraction behavior of Mo and W from H₂SO₄ using amine-extractant (Aliquat336) as homolog of seaborgium
A. Toyoshima et al. ................................................................. 283

Solvent extraction of short-lived isotopes of Mo and W from oxalic acid solution with Aliquat 336 for chemical studies of seaborgium (Sg)
N. Goto et al. ................................................................. 284

Reversed-phase chromatography of Nb and Ta with TBP for conducting a chemical experiment on the 105th element, Db
M. Murakami et al. ................................................................. 285

Liquid-liquid extraction of Nb and Ta with Aliquat 336 from 0.27 M HF solution
D. Sato et al. ................................................................. 286

Coprecipitation Behaviors of Zr, Hf, and Th with Sm Hydroxide for Chemical Study of Element 104, Rf
Y. Kasamatsu, et al. ................................................................. 287

Liquid-liquid extraction of zirconium and hafnium with 2-thenoyltrifluoroacetone for chemical studies of element 104, rutherfordium
A. Tanaka et al. ................................................................. 288

Production of platinum radiotracer for Gamma-Ray Emission Imaging
S. Komoto et al. ................................................................. 289

Production of 88Y for gamma-ray emission imaging
K. Higashikawa et al. ................................................................. 290
Ru Mössbauer spectroscopy of Na-ion batteries of Na₂RuO₃ (I) .......................................................... 291
Y. Kobayashi et al.

Production of ²⁶²,²⁶³Db in the ²⁴⁸Cm(²⁹F, xn)²⁶⁷⁻xDb reactions at E₉₀ = 96 MeV ........................................... 292
M. Murakami et al.

Production of ¹⁷⁴Re in the natGd(²³Na, xn) reactions for future studies on Bh chemistry using GARIS ............... 293
H. Haba et al.

Excitation function of the ²⁴⁴Hf(α, x)¹⁸²gTa reaction: Cyclotron production of a long-lived γ-ray emitter ¹⁸²gTa ........................................................ 294
M. Murakami et al.

Production cross sections of (d, x) reactions on natural ytterbium ................................................................. 295
M. U. Khandaker and H. Haba

Measurement of production cross sections of α-induced cross sections for ⁹⁰Cr and ⁹⁴Cr up to 50 MeV ...................... 297
H. Kikunaga et al.

Improvement in the chemical yield of purified ¹⁰⁹Cd for fee-based distribution at the RIKEN AVF cyclotron ....... 298
Y. Wakitani et al.

Preparation of no-carrier-added ⁸⁵Sr using the natRb(d, x)⁸⁵Sr reaction .............................................................. 299
S. Yano et al.

4. Radiation Chemistry and Biology

Localization of Rad51 and phosphorylated DNA-PKcs after heavy-ion irradiation in mammalian cells ....... 301
M. Izumi et al.

Low-dose high-LET heavy ion-induced bystander signaling ................................................................. 302
M. Tomita et al.

Effect of days after irradiation on lethal rate of F3 progeny in the fruit fly mutation isolation system .......... 303
K. Tomoezumi and T. Abe

Extra-early-flowering wheat mutants produced by heavy-ion-beam mutagenesis ........................................ 304
A. Nishiura et al.

Heredity analysis of radiation induced semidwarf mutants in Tartary buckwheat (Fagopyrum tataricum Gaertn.) .... 305
T. Morishita et al.

Effects of Ar-ion beam irradiation on inducing mutations in chrysanthemum and sweetpotato ................. 306
Y. Tanokashira et al.

Rapid screening of heavy-ion-induced large deletion mutants by using quantitative real-time PCR in Arabidopsis thaliana ................................................... 307
Y. Kazama et al.

LET-dependent effect on mutation induction DNA repair-deficient background in Arabidopsis thaliana .... 308
K. Ishii et al.

Characterization of isolates derived from heavy-ion-beam irradiated cells in the unicellular green alga Parachlorella kessleri .............................................................. 309
T. Yamazaki et al.

Effects of Ar-ion beam irradiation on survival rate of Aurantiochytrium sp. ...................................................... 310
K. Ikeda et al.

Analysis of DNA breakpoint detected from rice exome sequencing data ...................................................... 311
R. Morita et al.

Establishment of rice transformation systems to study gene functions .......................................................... 312
R. Morita et al.

Functional analysis of a new virescent mutant in rice induced by heavy-ion beam irradiation ..................... 313
H. Abe et al.

Tracking alleles linked with Fusarium head blight resistance QTLs in wheat (Triticum aestivum) released in Kyushu region .............................................................. 314
S. Niwa et al.

Ion track observation in cell nucleus irradiated by 3 MeV He ion microbeams produced with glass capillaries ...... 315
T. Ikeda et al.

Estimation method of microbeam divergence from glass capillaries for biological use .............................. 316
R.J. Bereczky et al.

Fricke nanocomposite gel dosimeter for heavy ion beam irradiation ....................................................... 317
T. Maeyama et al.

IV. OPERATION RECORDS

Program Advisory Committee meetings for nuclear physics and for material and life science ....................... 319
K. Yoneda et al.

Beam-time statistics of RIBF experiments ......................................................................................................... 320
K. Yoneda et al.
<table>
<thead>
<tr>
<th>Operation report of the industrial cooperation team</th>
<th>A. Yoshida et al.</th>
<th>321</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power condition of Wako campus in 2014</td>
<td>E. Ikezawa et al.</td>
<td>322</td>
</tr>
<tr>
<td>Radiation safety management at RIBF</td>
<td>K. Tanaka et al.</td>
<td>323</td>
</tr>
<tr>
<td>RILAC operation</td>
<td>E. Ikezawa et al.</td>
<td>326</td>
</tr>
<tr>
<td>AVF operations in 2014</td>
<td>N. Tsukiori et al.</td>
<td>327</td>
</tr>
<tr>
<td>Present status of the liquid-helium supply and recovery system</td>
<td>T. Dantsuka et al.</td>
<td>328</td>
</tr>
<tr>
<td>Operation of the superconducting ring cyclotron cryogenic system</td>
<td>H. Okuno et al.</td>
<td>329</td>
</tr>
<tr>
<td>Present status of the BigRIPS cryogenic plant</td>
<td>K. Kusaka et al.</td>
<td>330</td>
</tr>
<tr>
<td>Operation report on the ring-cyclotrons in the RIBF accelerator complex</td>
<td>S. Fukuzawa et al.</td>
<td>331</td>
</tr>
</tbody>
</table>

### V. EVENTS

### VI. ORGANIZATION AND ACTIVITIES OF RIKEN NISHINA CENTER (Activities and Members)

#### Organization

- Finances
- Staffing
- Research publication
- Management
- International Collaboration
- Awards
- Brief overview of the RI Beam Factory

#### Theoretical Research Division

- Quantum Hadron Physics Laboratory
- Theoretical Nuclear Physics Laboratory
- Strangeness Nuclear Physics Laboratory
- Mathematical Physics Laboratory

#### Sub Nuclear System Research Division

- Radiation Laboratory
- Advanced Meson Science Laboratory
- RIKEN-BNL Research Center
  - Theory Group
  - Computing Group
  - Experimental Group

#### RIBF Research Division

- Radioactive Isotope Physics Laboratory
- Spin isospin Laboratory
- Nuclear Spectroscopy Laboratory
- High Energy Astrophysics Laboratory
- Astro-Glaciology Research Unit
- Research Group for Superheavy Element
  - Superheavy Element Production Team
  - Superheavy Element Research Device Development Team
- Nuclear Transmutation Data Research Group
- Fast RI Data Team
I. HIGHLIGHTS OF THE YEAR

<< Selection process of highlights >>

Highlights are selected by a two-step process. In the first step, a referee who reviews a manuscript decides whether she/he would recommend it as one of the highlights. Members of the editorial board then make additional recommendations if they think an important contribution has not been recommended by the referee.

The second step involves the editor-in-chief proposing a list of highlights based on the recommendation given above to the editorial board. After discussing the scientific merits and uniqueness of the manuscripts from viewpoints of experts/non-experts, the editorial board makes the final decision.
1p$_{3/2}$ Proton-Hole State in $^{132}$Sn and Shell Structure Along N=82†

J. Taprogge,*1,2,3 A. Jungclaus,*1 H. Grawe,*4 S. Nishimura,*2 P. Doornenbal,*2 G. Lorusso,*2 G.S. Simpson,*5 P.-A. Söderström,*1 T. Sumikama,*6 Z.Y. Xu,*7 H. Sakurai,*2,*7 H.Watanabe,*2 on behalf of the RIBF-85 and RIBF-60&62R1 collaborations

The nucleus $^{132}$Sn is of particular interest for nuclear structure investigations since it is the only heavy neutron-rich doubly-magic nucleus far away from the valley of stability which is accessible for experimental studies. While $^{132}$Sn as well as the neighboring Sn ($Z=50$) and Sb ($Z=51$) isotopes have been studied in detail in the past, the experimental information for nuclei in the region below $^{132}$Sn is scarce. Important knowledge, e.g. with respect to the energies of the proton single-hole states in $^{132}$Sn, is still missing.

In an experiment performed in December 2012 as part of the EURICA campaign at the Radioactive-Isotope Beam Factory (RIBF), the neutron-rich nuclei $^{131,132}$Cd were produced by the in-flight fission of a $^{238}$U beam and implanted into the active stopper WAS3AB. The γ rays emitted following the β decay of $^{131}$Cd and after β-delayed neutron emission of $^{132}$Cd were detected with the EURICA array comprising 84 germanium crystals. A single γ ray with an energy of 988 keV was observed in the decays of both $^{131}$Cd and $^{132}$Cd. It was placed to populate the known (1/2−) β-decaying isomer in $^{131}$In at an excitation energy of $E_X = 365(8)$ keV thus defining a second excited state at 1353 keV. This newly identified state is preliminary assigned to have spin and parity of 3/2− and to correspond to the previously unknown 1p$_{3/2}$ proton single-hole state with respect to the $^{132}$Sn core. A full account of the arguments which lead to this assignment is presented in Ref. 2).

Using the newly established 1p$_{3/2}$ proton single-hole energy, shell-model calculations have been performed to calculate the energies of the first excited 2+ states and the proton gaps $\Delta_{2p}$ [defined here as $\Delta_{2p} = M(Z+2,N) + M(Z−2,N) − 2M(Z,N)$, with $M(Z,N)$ the mass of a nucleus with Z protons and N neutrons] for the N=82 isotones below $^{132}$Sn as shown in Fig. 1. For comparison, Fig. 1 also shows the results of similar SM calculations performed for the N=50 isotones below $^{108}$Sn, in that case in comparison with available experimental information. While for the N=50 isotonic chain typical signatures of sub-shell closures are observed at Z=38 and 40,$^{1,4}$ they disappear for the N=82 isotones below $^{132}$Sn. The disappearance of the proton sub-shell closures has its origin in the small energy gap between the 1p$_{1/2}$ and the next single-particle orbital (SPO), independent of the character of the latter. Figs. 1 c) and d) show the reappearance of the sub-shell gap when increasing the energy separation between the 1p$_{1/2}$ orbit and the next SPO.

Without the existence of pronounced proton sub-shell closures the N=82 isotones $^{126}$Sr and $^{122}$Zr should behave as mid-shell nuclei and consequently enhanced cross-shell excitations are expected to lead to a reduction of the N=82 shell gap in that region. Such a reduction would have a significant impact on r-process calculations and it is therefore concluded that preference should be given to mass models which indeed predict a reduction of the N=82 gap, such as the HFB24*5 approach.

References
Isomer decay spectroscopy of $^{164}$Sm and $^{166}$Gd: mid-shell collectivity around $N=100$†

Z. Patel,*1,*2 P.-A. Söderström,*1 Zs. Podolyák,*2 P. H. Regan,*2,*3 P. M. Walker*2 H. Watanabe*1,*4 E. Ideguchi*5 G. S. Simpson*6 H. L. Liu*7 S. Nishimura,*1 Q. Wu,*8 F. R. Xu,*8 H. Sakurai,*1

The RIBF-86 Collaboration and the EURICA Collaboration

The deformation of nuclei around $A = 160$ may influence the elemental abundances in the rare earth element peak. Macroscopic-microscopic calculations show a deformation maximum close to $N = 104$ and $Z = 66$ ($^{170}$Dy)1). However, these calculations seem to be contradicted by recent experimental data2,3). We utilise the existence of K isomers in this deformed region, to reveal the low-lying excited states in $A \approx 160$ nuclei that can provide insight into their deformation.

Neutron-rich $Z = 62, 64$ isotopes were produced by in-flight fission of a 345 A-MeV $^{238}$U beam with an average beam intensity of 10 pnA incident on a $^9$Be target at the RIBF. The secondary RI beam containing the nuclei of interest is passed through BigRIPS and the ZeroDegree spectrometers that separate and identify the beam species on an ion basis, using TOF, $B_\beta$ and $\Delta $E. The ions of interest were implanted in a stopper and the $\gamma$ rays emitted following isomeric decay were detected using EURICA (Euroball-RIKEN Cluster Array): 84 HPGe crystals arranged in a 4π configuration around the stopper.

The decay from isomeric states in $^{166}$Gd and $^{164}$Sm ($N = 102$) has been detected for the first time. The half-lives of the isomeric states have been measured to be 950(60) ns and 600(140) ns for $^{166}$Gd and $^{164}$Sm respectively. Their level schemes, seen in Figs. 1 and 2, were deduced from $\gamma-\gamma$ coincidence analysis. Potential energy surface calculations4) with total energy minimised in ($\beta_2, \beta_4, \beta_6$) deformation space and $\gamma = 0$ suggest a 6+ state with a 2-neutron $\nu \frac{2}{2}^+[512] \otimes \nu \frac{2}{2}^+[633]$ configuration is isomeric in both $^{166}$Gd and $^{164}$Sm.

A key feature of our results are the first $2^+$ and $4^+$ energies. The systematics of $E(2^+)$ and $E(4^+ \rightarrow 2^+)$ are shown in Fig. 3. The observed $2^+$ and $4^+$ energies of $^{166}$Gd and $^{164}$Sm are the lowest in their isotopic chains and of the $N = 102$ isotones, suggesting they are the most deformed $N = 102$ nuclei observed in this region to date. Our new points in the systematics also highlight the increase of $E(2^+)$ and $E(4^+ \rightarrow 2^+)$ at $N = 100$. This behaviour supports the appearance of a recently predicted deformed shell gap at $N = 100$5) that will influence $\beta$-process abundance calculations.

Fig. 1. Level scheme of $^{166}$Gd obtained in this work.

Fig. 2. Level scheme of $^{164}$Sm obtained in this work.

Fig. 3. Systematics of $E(2^+)$ and $E(4^+ \rightarrow 2^+)$ for Sm, Gd, Dy, Er and Yb isotopes. All data points from ENDSDF and this work.

References
1) P. Moller et al., Atomic and Nuclear Data Tables 59, 185 (1995).

*1 RIKEN Nishina Center
*2 Department of Physics, University of Surrey
*3 Radioactivity Group, National Physics Laboratory
*4 Department of Physics, Beihang University
*5 RCNP, Osaka University
*6 LPSC, UJF, CHRS, INPG, Grenoble
*7 Department of Applied Physics, Xi'an Jiaotong University
*8 School of Physics, Peking University

† Unequal number of authors indicates equal contribution.
In order to study the nuclear shell evolution around $^{78,77}\text{Ni}$, the $\beta$-decay half-lives of neutron-rich nuclei, i.e., $^{76,77}\text{Co}$, $^{79,80}\text{Ni}$ and $^{81}\text{Cu}$ were measured for the first time. The experiment was performed as part of an EURICA campaign at the RIBF facility, RIKEN in 2012. A high-intensity $^{238}\text{U}$ beam was accelerated up to an energy of 345 $\text{MeV}$ by the RIKEN cyclotron accelerator complex before hitting a 3-mm-thick beryllium target to produce secondary beams via in-flight fission. The $^{238}\text{U}$ beam was delivered at an average current of 5 $\text{pA}$ to the production target position. During the 13 days of the experiment, about $1.2 \times 10^4$ $^{78}\text{Ni}$ nuclei were identified and delivered to the experimental decay station at the end of the ZeroDegree spectrometer.

Figure 1 shows the experimental results (solid symbols) and the values in the literature (open symbols) as a function of the neutron number. Due to the fifth power relation between the half-life and its $Q_\beta$ value, a linear relationship between $\log_{10} T_{1/2}$ and the neutron number of the parent nucleus is expected phenomenologically when $Q_\beta$ evolves smoothly in an isotopic chain. In Fig. 1 this linearity is clearly visible below $N = 50$. Beyond that, a sudden reduction is seen in the $Z = 28$ isotopic chain due to the shorter half-lives of $^{79,80}\text{Ni}$ with reference to the systematics at $N \leq 50$. The fast $\beta$-decay processes in $^{79,80}\text{Ni}$ could be attributed to the neutrons outside the $N = 50$ shell, which result in higher $Q_\beta$ values and $\beta$-decay rates of $^{79,80}\text{Ni}$ compared to that of $^{78}\text{Ni}$.

In addition, a large gap can be noticed in Fig. 1 between the half-lives of the Co and Ni isotopes from $N = 44$ to $N = 50$. According to shell model calculations, this can be explained by the filled proton $f_{7/2}$ single particle orbit (SPO) in Ni isotopes. In this case, the proton produced in the $\beta$ decay of Ni isotopes fills the $\pi f_{5/2}$ SPO above $\pi f_{7/2}$, leading to a reduction of the $Q_\beta$ value and longer half-lives of Ni isotopes than those of Co isotopes. The newly measured half-lives of $^{76,77}\text{Co}$ follow the decreasing trend with considerable gaps relative to those of the corresponding Ni isotones, indicating an almost constant $Z = 28$ shell gap without significant quenching up to $N = 50$.

**References**


2. Department of Physics, University of Tokyo

3. RIKEN Nishina Center

4. University of Brighton

5. LFSC, Université Grenoble-Alpes, CNRS/IN2P3

6. ILL, Grenoble

7. Department of Physics, University of Notre Dame

8. Department of Physics, Peking University

9. Department of Physics, Tohoku University

10. Universidad Autónoma de Madrid

11. Instituto de Estructura de la Materia, CSIC

12. Atomki, Debrecen

13. IRCCNPC, Beihang University

14. Department of Physics, Osaka University

15. Department of Physics, Tokyo University of Science

16. Institut de Physique Nucléaire d’Orsay, IN2P3-CNRS

17. Università di Padova and INFN Sezione di Padova

18. GSI

19. Istituto Nazionale di Fisica Nucleare

20. Wright Nuclear Structure Laboratory, Yale University

---

Intermediate-energy Coulomb excitation of $^{104}$Sn: Moderate $E2$ strength decrease approaching $^{100}$Sn$^\dagger$

P. Doornenbal,1,2 S. Takeuchi,3 N. Aoi,2 M. Matsushita,2,4,5 A. Obertelli,5 H. Wang,5,6 L. Audirac,4 H. Baba,4 P. Bednarczyk,7 S. Boissinot,5 M. Ciernia,7 A. Corsi,4,5 T. Furumoto,8 T. Ise,1 A. Jungclaus,9 V. Lapoux,9 J. Lee,1 K. Matsui,10 T. Motobayashi,1,11 D. Nishimura,12 S. Ota,3 E.C. Pollacco,5 H. Sakurai,12 Y. Shiga,12 D. Sohler,12 and R. Tanifuuchi10

In recent years, several experimental findings generated a large interest regarding the $E2$ strength pattern in the tin isotopes. While the neutron-rich isotopes with $A = 126, 128, 130$ follow the anticipated trend of smoothly decreasing $B(E2)$ values towards the major shell closure well described by large-scale shell-model (LSSM) calculations1–3, the proton-rich nuclei take a different path. Commencing with the stable $A = 114$ isotope a steadily growing deviation from the shell-model expectations was observed with almost constant $B(E2)$ values for the $A = 106 – 112$ isotopes4,5. A first attempt for $^{104}$Sn with limited statistics has recently been made6. The result of $0.10(4)$ $e^2b^2$ indicates a steep decrease of excitation strength in agreement with LSSM calculations. In a second measurement, a considerably larger value of $0.180(37)$ $e^2b^2$ was obtained5. Here, we report on the first $B(E2)↑$ extraction of $^{104}$Sn from absolute Coulomb excitation cross-sections at intermediate energies.

A $^{124}$Xe primary beam was accelerated up to an energy of 345 MeV/nucleon and impinged on a 3 mm thick Be production target at the F0 focus of the BigRIPS fragment separator6. The $Bp – ΔE – Bρ$ method was applied to select and purify secondary beams of $^{104}$Sn and $^{112}$Sn in two subsequent measurements. The secondary beams were transported to the focal point F8, where a 557 mg/cm² thick Pb target was inserted to induce Coulomb excitation reactions. To detect γ-rays from the $2^+ → 0^+_1$ transitions, the reaction target was surrounded by the DALI2 array7. Reaction products were identified behind the reaction target by the ZeroDegree spectrometer11.

A $B(E2)↑$ value of $0.173(28)$ $e^2b^2$ was deduced for $^{104}$Sn. The run with $^{112}$Sn, which has a known $B(E2)↑$ value, was used for feeding estimations. Our result is in agreement with the $0.180(37)$ $e^2b^2$ obtained in Ref.5 with largely overlapping error bars, but deviates significantly from the value of $0.10(4)$ $e^2b^2$ obtained in Ref.4. The drop in excitation strength is much smoother than suggested in Ref.4 and cannot be reproduced by present LSSM calculations using standard effective charges as well as proton and neutron excitation across the $N = Z = 50$ shell.

References
First campaign of the SEASTAR project


The SEASTAR (Shell Evolution And Search for Two-plus energies At the RIBF) project aims to measure systematically $2\gamma$ energies of neutron-rich nuclei via in-beam $\gamma$-ray spectroscopy. Its setup combines the DALI2 $\gamma$-ray spectrometer$^1$ with the MINOS setup including a liquid hydrogen target system$^2$, as shown in Fig. 1, while exotic nuclei are produced with BigRIPS$^3$. In the first campaign $2\gamma$ energies of $^{66}$Cr, $^{70,72}$Fe, and $^{78}$Ni were measured with three different secondary beam settings.

A $^{238}$U primary beam was accelerated to 345 MeV/nucleon and impinging on a 3-mm thick Be target at the entrance of BigRIPS. The beam intensity varied between 13 to 15 particle-n.a. The spectrometer was tuned for $^{67}$Mn, $^{71,73}$Co, and $^{79}$Cu ions to enable $(p,2p)$ reactions and to populate $2\gamma$ states in the above mentioned nuclei. Particle identification was performed with the $B\rho$-ΔE-TOF method, employing standard BigRIPS detectors. Beam energies in front of the MINOS target were around 250 MeV/nucleon, beam purities in the order of 0.1–0.3 %, and total intensities of 4 to 6 kHz.

The MINOS and DALI2 setups were installed at the F8 focus. A reaction target thickness of 102 mm was employed for all three settings. A key feature of the MINOS system was its time projection chamber, which enabled to reconstruct vertex positions of $(p,2p)$ (and also $(p,3p)$) reactions with an accuracy of a few mm$^2$. DALI2 was employed in its standard configuration of 186 large-volume NaI(Tl) detectors. However, MINOS was installed further upstream than reaction targets are usually employed, resulting in an azimuthal angular coverage of DALI2 between 10° and 100°.

Reaction products were identified with the spectrometer ZeroDegree$^4$, providing again particle identification via the $B\rho$ – ΔE – TOF method with standard detectors. ZeroDegree was tuned for the $(p,2p)$ reaction channel in MINOS, resulting in total rates between 450 and 1200 Hz.

Data were collected for 7.5 days during the three settings in total, while secondary beam production with BigRIPS took 1.5 days and 1 day was used for user tuning. The $2\gamma$ energies were observed on-line for the $^{66}$Cr, $^{70,72}$Fe, and $^{78}$Ni isotopes. Currently, these data as well as many by-products are under analysis by several groups belonging to the SEASTAR collaboration.

References
Fragmentation of $^{137}$Cs and $^{90}$Sr on proton and deuterium


Properties of long-lived fission products (LLFP) have been studied for decades. LLFP nuclei are highly radioactive, although they are close to the line of $\beta$ stability. These fission products are also of great interest for nuclear engineering as they carry a large weight fraction in the nuclear waste from nuclear reactor systems. Transmutation of the fission products into stable or short-lived isotopes has been suggested. Aiming at investigating the LLFP transmutation, we report on the fragmentation of $^{137}$Cs and $^{90}$Sr on proton and deuterium in inverse kinematics.

A primary beam U was accelerated to 345 MeV/nucleon, and it bombarded a 1-mm thick Be target located at the object point of the BigRIPS fragment separator. The average beam intensity was about 12 particle nA. Two secondary beam settings were applied and optimized for the $^{137}$Cs and $^{90}$Sr isotopes. The energies were about 185 MeV/nucleon in front of the secondary targets for both beams. The intensities of the $^{137}$Cs and $^{90}$Sr beams were $1.2 \times 10^3$ and $7.1 \times 10^3$ Hz, with purities of 14% and 28%, respectively.

Three targets, 179.2 mg/cm$^2$ CH$_2$, 217.8 mg/cm$^2$ CD$_2$, and 226.0 mg/cm$^2$ $^{12}$C were used to induce the secondary reactions. Data were also collected using an empty target to obtain the contribution from the beam-line materials. Reaction products were identified by the ZeroDegree spectrometer using the TOF-$B\rho$-$\Delta E$ method. A total kinetic energy measurement was performed for identification of the charge states. In order to cover the fragments over a wide range, several settings in ZeroDegree were applied.

The isotopic distributions of the fragmentation cross sections for the $^{137}$Cs and $^{90}$Sr beams on proton and deuterium are shown in Figs. 1 and 2, respectively. The proton- and deuterium-induced cross sections were deduced from the CH$_2$ and CD$_2$ targets, respectively, after subtraction of the carbon contributions by the C target as well as the background contributions by the empty target run. The validation of the cross section values was around 1 mb, as determined by statistics. The results are generally reproduced by PHITS$^2$, while EPAX$^3$ shows some discrepancies for the multi-nucleon removal channels.

Fig. 1. Measured cross sections presented as isotope distributions for the fragments produced by $^{137}$Cs on proton and deuterium. EPAX and PHITS calculations are displayed for comparison.

Fig. 2. Same as Fig. 1 but for $^{90}$Sr

References
Missing-mass spectroscopy of tetra-neutron system via exothermic double-charge exchange reaction $^4$He($^8$He,$^8$Be)$4n$

K. Kisamori,$^1$ S. Shimoura,$^2$ H. Miya,$^1$ M. Assie,$^3$ H. Baba,$^1$ T. Baba,$^4$ D. Beaumel,$^1$ M. Dozono,$^1$ T. Fujii,$^1$ N. Fukuda,$^4$ S. Go,$^1$ F. Hammache,$^3$ E. Ideguchi,$^5$ N. Inabe,$^1$ M. Itoh,$^6$ D. Kameda,$^1$ S. Kawase,$^2$ T. Kawabata,$^4$ M. Kobayashi,$^2$ Y. Kondo,$^1$ T. Kubo,$^1$ Y. Kubota,$^1$ M. Kurata-Nishimura,$^1$ C. S. Lee,$^1$ Y. Maeda,$^8$ H. Matsubara,$^4$ S. Michimasa,$^2$ K. Miki,$^5$ T. Nishi,$^1$ S. Noji,$^1$ S. Ota,$^2$ S. Sakaguchi,$^1$ H. Sakai,$^1$ Y. Sasamoto,$^2$ M. Sasano,$^1$ H. Sato,$^1$ Y. Shimizu,$^1$ A. Stolz,$^9$ H. Suzuki,$^1$ M. Takaki,$^2$ H. Takeda,$^1$ S. Takeuchi,$^1$ A. Tamii,$^9$ L. Tang,$^8$ H. Tokieda,$^2$ M. Tsumura,$^4$ T. Uesaka,$^1$ K. Yako,$^2$ Y. Yanagisawa,$^1$ and R. Yokoyama$^2$

Since the report on candidates of a bound tetra-neutron system$^1$, multi-neutron systems in nuclei have attracted considerable attention on both the experimental and theoretical fronts. On the other hand, later theoretical studies using ab-initio calculations$^2$ have suggested that the tetra-neutron cannot exist as a bound system but possibly as a resonance system. We performed missing-mass spectroscopy of the $4n$ system via the exothermic double-charge exchange reaction $^4$He($^8$He,$^8$Be)$4n$.$^3$. The primary goal of the experiment was to determine the energy level and its width of the $4n$ system. In order to produce the $4n$ system with a small momentum transfer of less than 20 MeV/c, a secondary beam of $^8$He with a large internal energy was used.

The experiment was performed at the RIKEN RI Beam Factory (RIBF) using the SHARAQ spectrometer and a liquid He target system.$^5$ We measured the momentum of the $^8$He beam at BigRIPS-F6 with the High-Resolution Beamline and the momenta of two alpha particles, which were the decay products of the $^8$Be ejectile, with the SHARAQ spectrometer. The incident beam energy of $^8$He was 186 MeV/u.

Events resulting from the $^4$He($^8$He,$^8$Be)$4n$ reaction were selected. Two $\alpha$ particles from the $^8$Be ejectile were detected simultaneously at the final focal plane of the SHARAQ spectrometer. Furthermore, a method to reconstruct trajectories for more than two particles under a high-intensity beam ($\sim$2 MHz) was developed.$^5$ In order to obtain good signal-to-noise ratio, it was important to identify multi-particles in one bunch, which have the possibility to create the background events. These events were rejected using the Multi-Wire Drift Chamber (MWDC) at F6.

We obtained the missing-mass spectrum of a tetra-neutron system, as shown in Fig. 1. The spectrum contains 28 events including background events. The background events were estimated from the number of events that was not identified as multi-particle in one bunch in the MWDC at F6. There were only 2.2 ± 1.0 events in the whole spectrum region, which is almost negligible compared to the selected 28 events. The excitation energy ($E_{\text{exc}}$) of the spectrum was calibrated using the peak position of the $^6$Li($^1$H) state and the scale of magnetic rigidity of the SHARAQ spectrometer. $^6$Li was produced by the inverse kinematics of the (p,n) reaction of $^8$He. The uncertainty of the energy determination accuracy was 1.25 MeV at the one sigma level. The resolution of the spectrum was 1.16 MeV at the one sigma level.

The events were concentrated in the low-excitation-energy region of $0 < E_{\text{in}} < 2$ MeV and a continuum were observed at a region of $E_{\text{in}} > 2$ MeV. The mean of the four events at $0 < E_{\text{in}} < 2$ MeV was $0.83 \pm 0.25$ MeV. The possibility of the resonance state at the low-energy region and the shape of the continuum will be discussed in comparison with results of a theoretical calculation assuming the correlation of di-neutron clusters.

---

*$^1$ RIKEN Nishina Center
*$^2$ Center for Nuclear Study, the University of Tokyo
*$^3$ IPN, Orsay
*$^4$ Department of Physics, Kyoto University
*$^5$ Research Center Nuclear Physics, Osaka University
*$^6$ Cyclotron and Radioisotope Center, Tohoku University
*$^7$ Department of Physics, Tokyo Institute of Technology
*$^8$ Faculty of Engineering, University of Miyazaki
*$^9$ Department of Physics, the University of Tokyo
*$^{10}$ National Superconducting Cyclotron Laboratory, Michigan State University
*$^{11}$ Faculty of Science, Kyushu University

**References**


4) M. Kurata-Nishimura et. al.: Accelerator Progress Rep. 46 (2013)

Laser-RF double resonance spectroscopy of $^{84-87}$Rb isotopes trapped in superfluid helium†

X.F. Yang,*1,2 T. Furukawa,*1,3 T. Wakui,*1,4 K. Imamura,*1,5 T. Fujita,*1,6 Y. Mitsuya,*1,5 M. Hayasaka,*1,7 Y. Ichikawa,*1 Y. Ishibashi,*1,9 H. Shirai,*1,8 T. Suzuki,*1,8 Y. Ebara,*3 A. Hatakeyama,*10 M. Wada,*1 T. Sonoda,*1 Y. Ito,*1 T. Kobayashi,*1 S. Nishimura,*1 M. Kurata-Nishimura,*1 Y. Kondo,*1,8 K. Yoneda,*1 H. Ueno,*1 T. Shimozuka,*3 T. Shimoda,*6 K. Asahi,*1,8 and Y. Matsuo*1,12

Laser spectroscopy measurements of various isotopes have provided a number of valuable results, such as nuclear spins, moments, and charge radii. However, to further study exotic atoms that are far from stability, higher efficiency and higher resolution are strongly required to overcome certain experimental limitations (low yield, limited beam time, large contaminations, and so on). Therefore, a new method called OROCHI was developed for laser spectroscopy measurements of radioactive isotopes (RIs) in superfluid helium (He II) using a small and controllable number of atoms.1) In this method, using He II as the trapping medium for the energetic ion beam and matrix for trapped atoms, we aim to systematically determine the nuclear spins and moments of RIs with a low yield. This measurement is based on the observation of Zeeman and hyperfine structures by optical pumping and the double resonance method. Recently, we have succeeded in trapping, polarization, and laser spectroscopy measurements of $^{84-87}$Rb isotopes in He II.

A general introduction to the experimental principle and method has been presented elsewhere.2) In this experiment, both stable $^{85,87}$Rb and unstable $^{84,86}$Rb energetic ions produced from the RIPS were counted accurately and implanted into He II. The number of atoms injected into He II was on the order of $10^4$ pp/s for the current setup. Using the trapping position control system, we confirmed the precision of the trapping site (around 1 mm) of atoms in He II by detecting laser-induced fluorescence (LIF).3) On the basis of the trapping volume ($\pi \times 5 \times 5 \times 1$ mm$^3$) of atoms in He II (ion beam spot size: $\phi \approx 10$ mm), and the observation range ($5 \times 2 \times 2$ mm$^3$) of the LIF detection system, we estimated that more than 20% of the trapped atoms were used for laser spectroscopy measurements. From the number of injected ions and detected LIF photons, the number of detectable LIF photons from one injected atom was estimated to be approximately $10^4$.

† Condensed from the article in Phys. Rev. A 90, 052516 (2014)

0.2 - 0.3.

After the precise trapping of $^{84-87}$Rb in He II, the atoms were optically pumped and polarized with a polarized laser light. In addition, laser-RF double resonance spectra of the $^{84-87}$Rb atoms were measured by monitoring the LIF signal as a function of the scanned external magnetic field with a fixed-frequency transverse RF field applied to the atoms, as shown in Fig. 1. Relatively high spin polarization (above 40%) was achieved for the $^{84-85}$Rb isotopes,4) which was estimated from the difference in the LIF intensity between the linearly and circularly polarized laser. The resonance peaks provide information regarding the Zeeman splitting of atoms in a magnetic field. From these Zeeman resonance peaks, nuclear spin values for $^{84,86}$Rb isotopes were determined with reasonable accuracy, after eliminating the effect of the background magnetic field.

In conclusion, we performed the effective trapping and laser spectroscopy measurements of $^{84-87}$Rb isotopes with a controllable number of atoms in He II using the newly developed method. The achievement of high trapping efficiency and high spin polarization and the determination of the nuclear spins of RIs in He II suggest the potential application of this method to the study of various exotic particles in He II.

References

RI beam production at BigRIPS in 2014

N. Fukuda,*1 Y. Shimizu,*1 H. Takeda,*1 H. Suzuki,*1 D.S. Ahn,*1 N. Inabe,*1 D. Murai,*1 K. Yoshida,*1 H. Sato,*1 Y. Sato,*1 K. Kusaka,*1 Y. Yanagisawa,*1 M. Ohtake,*1 D. Kameda,*1 and T. Kubo,*1

RI beam production at the BigRIPS fragment separator1 in 2014 is presented. Table 1 lists the experimental programs carried out at BigRIPS in this period and the RI beams produced for each experiment.

The beam time at the RIBF started in March with the Uranium beam campaign, in which 6 experiments were performed. The long-lived fission products, 157Cs and 90Sr, were produced by the in-flight fission of the 238U beam to investigate their nuclear-transmutation reaction2. Owing to their proximity to the β-stability line, we experienced difficulties in improving the purities of the isotopes of interest.

The 51Ca and 56Ca beams were produced by projectile fragmentation of a 70Zn beam for a direct mass measurement at the SHARAQ spectrometer. A spectroscopy of deeply-bound pionic atoms was performed using the BigRIPS separator as a high-resolution spectrometer. The spring beam time ended with the 16O beam experiment at the SHARAQ spectrometer.

The autumn beam time began in October with the second Uranium beam campaign, which consisted of 6 experiments. First, a machine study was conducted to study particle identification and isotope separation when producing heavier beams with an atomic number (Z) of around 803). It was the first attempt at the RIBF. The 172Dy and 170Dy beams were delivered to the EURICA experiment. The RI-beam production around Z = 65 at BigRIPS has been pioneered in recent new-isotope-search experiments4,5).

The 48Ca primary beam was provided with a high intensity of approximately 500 nA. Such a high-intensity beam made it possible to search for the neutron drip line for the F, Ne, and Na isotopes.

The experiments to search for new neutron-rich isotopes were performed using the in-flight fission of a 238U beam5,7), as shown in Table 1. A total of 28 new isotopes were identified in the preliminary analysis.

Table 1. List of the experimental programs and RI beams produced at the BigRIPS in 2014 (in chronological order).

<table>
<thead>
<tr>
<th>Primary beam</th>
<th>Proposal No.</th>
<th>Course</th>
<th>RI beam (Primary beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1306-SAMURAI17</td>
<td>SAMURAI</td>
<td>132Sn</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1306-SAMURAI14</td>
<td>SAMURAI</td>
<td>(239)U</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>DA14-01</td>
<td>ZeroDegree</td>
<td>130Cd</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>DA14-02-01</td>
<td>BigRIPS</td>
<td>137Cs, 40Sr</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1312-RIB118</td>
<td>ZeroDegree</td>
<td>New isotope search (Z ~ 55—70 region)</td>
</tr>
<tr>
<td>70Zn 345 MeV/u</td>
<td>NP1312-SHARAQ3R</td>
<td>SHARAQ</td>
<td>56Ca, 55Ca, 54Sc</td>
</tr>
<tr>
<td>48Ca 250 MeV/u</td>
<td>NP1312-RIBF54R1</td>
<td>BigRIPS</td>
<td>1H, 3He *(d, 3He) reaction for pionic atom</td>
</tr>
<tr>
<td>48Ca 250 MeV/u</td>
<td>NP1112-SHARAQ08</td>
<td>SHARAQ</td>
<td>1H, (16O)</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1012-RIBF63</td>
<td>BigRIPS</td>
<td>RI-beam production in the region of Z ~ 80</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1012-RIBF61</td>
<td>ZeroDegree</td>
<td>132Sn, 128Sn</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>DA14-02-02</td>
<td>BigRIPS</td>
<td>76Ni</td>
</tr>
<tr>
<td>238U 345 MeV/u</td>
<td>NP1112-RIBF88R1</td>
<td>EURICA</td>
<td>New isotope search (Z ~ 33 region)</td>
</tr>
<tr>
<td>48Ca 345 MeV/u</td>
<td>NP1312-RIBF56R1</td>
<td>ZeroDegree</td>
<td>172Dy, 170Dy</td>
</tr>
<tr>
<td>48Ca 345 MeV/u</td>
<td>NP1312-SAMURAI18R1</td>
<td>SAMURAI</td>
<td>19B, 11B, 44Be, 11Li</td>
</tr>
<tr>
<td>48Ca 345 MeV/u</td>
<td>DA14-02-03</td>
<td>BigRIPS</td>
<td>Drip line search for F, Ne, Na</td>
</tr>
</tbody>
</table>

*1 RIKEN Nishina Center
*2 Department of Physics, Rikkyo University
Fig. 1 shows the nuclear chart, in which all the isotopes produced at the BigRIPS from the commissioning in March 2007 to December 2014 are indicated along with the new isotopes observed at BigRIPS. The number of RI-beams produced amounted to approximately 350, and the number of new isotopes reached approximately 140. Production yields for more than 1,000 isotopes were obtained.

The number of experiments using RI beams at BigRIPS is tallied in Table 2, for various primary beams in each year. A total of 89 experiments have been performed so far.

Table 2. Number of experiments using RI beams at the BigRIPS.

<table>
<thead>
<tr>
<th>Year</th>
<th>$^{238}$U</th>
<th>$^{124}$Xe</th>
<th>$^{86}$Kr</th>
<th>$^{70}$Zn</th>
<th>$^{48}$Ca</th>
<th>$^{18}$O</th>
<th>$^{16}$O</th>
<th>$^{14}$N</th>
<th>$^{4}$He</th>
<th>$^{2}$H</th>
<th>Yearly total</th>
</tr>
</thead>
<tbody>
<tr>
<td>'07</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>'08</td>
<td>2</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>'09</td>
<td>3</td>
<td></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>'10</td>
<td></td>
<td></td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>'11</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>'12</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>'13</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>'14</td>
<td>11</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>24</td>
<td>12</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>89</td>
</tr>
</tbody>
</table>
Neutron drip-line search using 48Ca beam

K. Kusaka,1* Y. Yanagisawa,1* M. Ohtake,1* K. Yoshida,4* H. Otsu,6* N. Iwasa,*3 T. Nakamura,*4
O. Tarasov,5* B. Sherrill,5* D. Morrissey,5* H. Geissel,*6 and T. Kubo1*

A neutron drip-line has been determined till O1) of which mass number(A) is 24, three times the atomic number(Z). However for F, Ne and Na isotopes with A=3Z+4 were found. The sudden increase in neutron numbers suggests that there might be a change in the nuclear structure of F. The drip-line search is important to investigate how many neutron number increases and determination of the drip line gives some constraints to nuclear models.

The drip-line search was performed by using the BigRIPS with a 345 MeV/u 48Ca beam of high intensity (> 400 particle na). In the search, we used two settings of the BigRIPS for 33F and 36Ne&39Na. In the two settings, magnetic rigidities before a degrader located at F1 were the same (9.385 Tm) but those after it were different. The magnetic rigidities were determined so that 1H for the former and center of 32Ne and 36Na for the latter became a central orbit. Radioactive isotopes were produced by the 20 mm Be target. The thickness of the degrader at F1 was 15 mm. A rather thick target and degrader were used so as not to be over the maximum magnetic rigidities of both the first and second stage in the BigRIPS. Another degrader at F5 (7 mm) was used to remove light particles such as triton. Widths of momentum slits at both F1 and F5 were ±120 mm and those of both F2 and F7 slits were ±20 mm. A collimator made using iron was located upstream of F2 to remove triton, 4He of long stopping ranges that could not be removed by the F2 slit. The length of the collimator for beam direction was 450 mm and the opening widths were ±35 mm at the entrance and ±20 mm at the exit. In order to study yield systematics, we measured the yields of 23~31F, 34Ne, and 37Na using the same settings of the target, degraders, and slits as the drip-line search. We also studied the secondary reaction effect in the target wherein isotope A is produced in 2 steps via a different isotope B (Here A is produced by 48Ca→B→A). In this study we measured target thickness dependence (Be 5 mm, 10 mm and 20 mm) of the production yields using 37Na.

Particle identification (PID) was performed by determination of Z and A/Z event by event using the ΔE-TOF-Bp method. The ΔE was measured using four 300 μm Si stacks, the MUSIC, and plastic scintillators at F7 redundantly. TOF was measured using 2 plastic scintillators at F5 and F7. Bp was determined by track reconstruction using positions and angles measured by PPACs located at F5 and F7. Because around Z=10, efficiency of the PPAC was not 100 %, we also measured the positions using the plastic scintillators. In the drip-line search, A/Z was determined for only the second half (from F5 to F7) in the second stage due to large contaminants at F3 (> 1 MHz), which is mainly triton.

Figure 1 shows a PID plot for the setting of the drip-line search of 33F with a running time of 14.3 hours. In this measurement live time of data acquisition was 74.5 % and the intensity of 48Ca beam was 415 particle na on average. As shown in Fig. 1, 31F was clearly seen but there is no event in the 33F area although an expected value of 33F are 20.7 counts if we assume a production cross section of 33F predicted by EPAX 2.15.

Figure 2 shows the yield systematics of F isotopes with prediction of EPAX 2.15 (solid line). The measured yields are in good agreement with those of EPAX2.15.

We estimated probability that 33F is 0 count in the measurement by applying the expected value (20.7 counts) to the Poisson distribution. The estimated probability is 0.00000103 % and this implies that the probability that 33F is unbound is 99.999999897% in this assumption. In the study of the secondary reaction effect, we did not observe a large enhancement at the thick target as expected. Detailed analysis including the 36Ne&39Na setting is in progress.

References
High-resolution hadronic-atom X-ray spectroscopy with superconducting transition-edge-sensor microcalorimeters


Hadronic atoms provide a unique laboratory to study the strong interaction between the hadron and atomic nucleus at the low-energy limit. Effects of the strong interaction are experimentally extracted by performing characteristic X-ray-emission spectroscopy of the most tightly bound energy levels, which are most perturbed by strong forces. As for kaonic atoms, many experiments have collected data on a variety of targets; however, the energy resolution of conventional semiconductor X-ray spectrometers employed in the past measurements has been insufficient to detect small spectral effects attributed to the strong interaction. As a result, the depth of the $K^-$-nucleus potential at zero energy remains still unknown. This is closely related to the recent investigations of bound states of the kaon in the nucleus and is one of the greatest concerns in the recent strangeness nuclear physics.

With the aim of providing a breakthrough to the current situation, we are preparing an ultra-high resolution X-ray measurement of kaonic atoms using a novel cryogenic X-ray detector, i.e., an array of superconducting transition-edge-sensor (TES) microcalorimeters which has recently been developed at NIST. The energy resolution is about two orders of magnitude better than that of conventional silicon drift detectors (SDDs).

To demonstrate the feasibility of the X-ray spectroscopy with TES in a hadron beam environment, we recently performed a pioneering experiment by measuring pionic carbon X rays with a 240-pixel TES array using 173 MeV/c $\pi^-$ beam at the $\pi$M1 beamline of Paul Scherrer Institute. Figure 1 shows the preliminary results of (a) a correlation plot of the measured X-ray time versus energy distributions for $\pi^-$ triggered events, and (b) and (c) show the projections. A sharp peak from the pionic carbon 4-3 X-ray transition was successfully observed at 6.43 keV with a clear timing correlation with the beam. The characteristic X rays of Fe Kα1 (6.404 keV) and Fe Kα2 (6.391 keV) that are uncorrelated with beam timing originate from surrounded materials that are excited using an X-ray tube. The achieved average energy resolution is 5 eV (FWHM) at 6 keV in “beam-off” condition, and 8 eV in “beam-on” condition, while the energy resolution of a SDD used as a reference in this experiment is ~165 eV as shown in Fig. 1 (d).

This demonstration is the world’s first application of a TES spectrometer to the hadronic-atom X-ray spectroscopy and a key milestone toward more general use of high-resolution microcalorimeter spectrometers at charged-particle beam lines.

Fig. 1. Preliminary results of the measured X-ray time and energy distributions for $\pi^-$ triggered events. (a) A correlation plot of the time difference between pion arrival and X-ray detection vs the X-ray energy measured by the TES array. (b) The projections on the time axis. (c) The projection on the energy axis. The energy spectra with two time gates, pions (“π”) and background (“BG”) indicated in (b), are shown. (d) An X-ray energy spectrum measured by the reference SDD.

References
Measurement of high-$p_T$ neutral mesons with a high-energy photon trigger in ALICE

S. Yano\textsuperscript{*1,*2} and K. Shigaki\textsuperscript{*1}

ALICE, one of the experiments at the Large Hadron Collider (LHC) at CERN, is aimed at studying heavy-ion collisions and the properties of a deconfined state of matter, the quark-gluon plasma (QGP)\textsuperscript{1). High-$p_T$ particle production is a powerful tool for characterizing the QGP because the interaction between its fast partons depends on the QGP transport properties. The hadron yields in heavy-ion collisions can be quantified by the nuclear modification factor ($R_{AA}$), which is the ratio of the particle yield in heavy-ion collisions normalized by the number of inelastic nucleon–nucleon collisions to the yield in $pp$ collisions. Previous experiments have shown that $R_{AA}$ at high $p_T$ is significantly smaller than 1, which can be explained by the energy loss of fast partons traversing in QGP.

The ALICE experiment includes a high-resolution and high-granularity electromagnetic calorimeter called PHOS\textsuperscript{1). One of the main physics goals achievable by PHOS is the study of energy loss through the measurement of high-$p_T$ neutral mesons ($\pi^0$ and $\eta$). Three PHOS modules are installed in the ALICE experiment, which covers azimuthal angles in the range $260^\circ < \phi < 320^\circ$ and pseudorapidity $|\eta| < 0.125$. PHOS provides a photon trigger (PHOS trigger) by requiring the measured energy to be above a threshold. The threshold was set to be 2 and 4 GeV in $pp$ collisions at $\sqrt{s} = 8$ TeV. By using the PHOS trigger, high-$p_T$ neutral mesons can be efficiently measured in the ALICE experiment. This paper discloses the analysis status of neutral-pion production measured with the PHOS trigger and minimum-bias (MB) trigger data in $pp$ collisions.

Further, neutral-pion production in $pp$ collisions at $\sqrt{s} = 8$ TeV are compared with results for other LHC energies (0.9, 2.76 and 7 TeV)\textsuperscript{2,3). In this analysis, 0.3 nb\textsuperscript{-1} and 70 nb\textsuperscript{-1} MB-trigger and PHOS-trigger data respectively, in $pp$ collisions at $\sqrt{s} = 8$ TeV are used.

The invariant cross-section can be calculated as

$$d^3\sigma_{pp\to \pi^0X}/ dp^3 = 1/2\pi p_T N_{\text{ext}} \varepsilon \times \text{Acc} \Delta \eta \Delta p_T$$

Here $\sigma_{MB}$ is the cross-section of minimum-bias (MB), $N^\pi$ is the number of reconstructed neutral pions, and $\Delta \eta \Delta p_T$ is the PHOS acceptance correction. $N_{\text{ext}}$ is the number of analyzed events in the minimum-bias trigger data analysis. In case of the PHOS trigger data analysis, it is the number of analyzed PHOS trigger events times the rejection factor. In the minimum-bias trigger data analysis, $\varepsilon$ indicates the reconstruction efficiency, whereas in the PHOS trigger data analysis, it indicates the reconstruction efficiency times the trigger efficiency for a neutral-pion meson.

The invariant cross-section of a neutral pion in $pp$ collisions at LHC energies are shown in Fig. 1. As shown in Fig. 1, the 0.9, 2.76 and 7 TeV analyses used only minimum-bias (MB) trigger data, but the 8 TeV analysis (this analysis) used not only minimum-bias but also PHOS trigger data. The very-low $p_T$ ($\sim 1$ GeV/c) region cross-section was measured by the Photon Conversion Method (PCM)\textsuperscript{3} with the tracking detectors of the central barrel\textsuperscript{1). For the 8 TeV result, the minimum-bias and PHOS trigger data were combined to measure the very wide $p_T$ range neutral-pion meson. The dashed line denotes the result fitted to Tsallis functions.

![Fig. 1. Neutral-pion cross section in $pp$ collisions at LHC energies.](image)

By comparing the results for different LHC energies, pertubative Quantum Chromodynamics (pQCD) can be tested at LHC energies and the fragmentation function (FF) of gluon to the neutral-pion model can be restricted. Further, this comparison can help predict a neutral-pion production cross-section in $pp$ collisions at other energies. This has not been measured yet and more precise references to study phenomena induced by AA collisions can be estimated for QGP study.

References

\textsuperscript{*1} Department of Physics Science, Hiroshima University
\textsuperscript{*2} RIKEN Nishina Center
Transverse single-spin asymmetries in prompt photon production from proton-proton collisions†

D. Pitonyak,*1 K. Kanazawa,*2 Y. Koike,*3 and A. Metz†2

Collinear twist-3 factorization has been used since the 1980s in order to describe transverse single-spin asymmetries \( A_N \). For a general process \( AIB \rightarrow CX \), the cross section can be written as the sum of three terms depending on which non-perturbative function is kept at twist-3. For hadron production, which has been intensely studied for close to 40 years, the distribution and fragmentation contributions to the cross section cannot be disentangled, i.e., all of them are summed together in the cross section. For many years it was often assumed that the piece involving the so-called Quin-Sterman (QS) function \( G_F(x, x) \) was the main cause of \( A_N \). However, this led to a so-called “sign mismatch” between the QS function and the transverse momentum dependent (TMD) Sivers function extracted from semi-inclusive deep-inelastic scattering (SIDIS)11. Recently we showed in 2) for the first time that the fragmentation contribution in collinear twist-3 factorization actually can describe \( A_N \) very well. By using a Sivers function fully consistent with SIDIS, we demonstrated that this mechanism could also resolve the sign-mismatch puzzle. Nevertheless, an independent extraction of \( G_F(x, x) \), through observables like \( A_N^{\text{cut}} \) and \( A_N \), is crucial to confirm this assertion. However, one must keep in mind that for \( A_N^{\text{cut}} \) and \( A_N \) other twist-3 distribution effects can enter besides the QS function. Thus, in order to have a “clean” extraction of \( G_F(x, x) \), it would be ideal if these other terms were small.

Therefore, we return to the SSA in \( p^+p \rightarrow \gamma X \) to see if this reaction could provide such an observable. In twist-3 collinear factorization, \( A_N^{\text{cut}} \) has contributions from multiparton correlators inside either the transversely polarized proton or the unpolarized proton. For this process the former has been widely discussed in the literature for both (twist-3) quark-gluon-quark3-10 and tri-gluon11 non-perturbative functions, which are chiral-even objects evaluated at either soft-gluon or soft-fermion poles (SGPs/SFPs). The full result for twist-3 effects on the side of the unpolarized proton is a new piece from this work and, although we refrain from showing the explicit formula for brevity, will be included in our numerical analysis. This term involves a chiral-odd quark-gluon-quark correlator \( E_F(x, x) \), which is related to the TMD Boer-Mulders function.

We now focus on the phenomenology. For the SGP correlators \( E_F(x, x) \) and \( G_F(x, x) \) we make use of identities that relate the first to the Boer-Mulders function and the second to the Sivers function. Since at this point no information on the SFP functions is available, we assume the relation \( G_F(0, x) + G_F(0, x) = G_F(x, x) \). Model calculations of quark-gluon-quark correlators show that chiral-even SFP functions are much smaller as compared to the SGP one and might even vanish. Therefore, we believe that this ansatz is reasonable.

In Fig.1 we show an estimate of \( A_N^{\text{cut}} \) (along with an uncertainty band) from all these pole contributions for a set of kinematics relevant for the measurement of this observable at PHENIX and STAR. One sees that the entire effect is due to the “Sivers-type” QS mechanism. Using the Sivers function extracted from SIDIS, our results show that \( A_N^{\text{cut}} \) could be on the order of several (negative) percent in the forward region, providing a “clean” observable to extract of the QS function \( G_F(x, x) \). In light of the “sign-mismatch” crisis involving \( G_F(x, x) \) and the Sivers function11, and the recently proposed solution to this issue that relies on the twist-3 fragmentation mechanism21, such an extraction is of vital importance. In addition, one can obtain important information on the process dependence of the Sivers function as well as help discriminate between the Generalized Parton Model and twist-3 formalisms since the former predicts a positive asymmetry. Thus, measurements of this process by PHENIX and STAR are crucial.

References

---

† Condensed from the article in PRD 91, 014013 (2015)
*1 RIKEN Nishina Center
*2 Department of Physics, Temple University
*3 Department of Physics, Niigata University
Entanglement entropy of de Sitter space $\alpha$-vacua†

N. Izuka,*1 T. Nouni,*2 and N. Ogawa*2

The de Sitter space is a very interesting space-time. It is a solution of Einstein equation when cosmological constant dominates, and it is related to the inflationary stage of our universe, as well as to the current stage of accelerating universe. A peculiar property of the de Sitter space is that the de Sitter invariant vacuum is not unique; it has a one-parameter family of invariant vacuum states $|\alpha\rangle$, called $\alpha$-vacua1(2).

The $\alpha$-vacua give very peculiar behavior for the two point functions in the de Sitter space; the two-point functions on $\alpha$-vacua between points $x$ and $y$ contain not only the usual short distance singularity $\delta(|x-y|)$, where $|x-y|$ is the de Sitter invariant distance between $x$ and $y$, but also contain very strange singularity such as $\delta(|x-\bar{y}|)$ and $\delta(|\bar{x}-y|)$, where $\bar{x}$ and $\bar{y}$ represent the antipodal points of $x$ and $y$, respectively. Since antipodal points in the de Sitter space are not physically accessible due to the separation by a horizon, one cannot have an immediate reason to discard two-point functions containing such an antipodal singularity. It is therefore unclear which vacuum should be realized in our universe. As a result, a number of studies have been done on phenomenological aspects of the $\alpha$-vacua (e.g. primordial perturbations generated during inflation).

Since which vacuum one should choose is always a very important question, one is motivated to calculate physical quantities not only in a particular vacuum but also in others, and see if there is a big reason to choose or discard a particular vacuum.

In this work, we computed the entanglement entropy in de Sitter $\alpha$-vacua. By generalizing the recent calculation by Maldacena and Pimentel3 in the Euclidean (or Bunch-Davies) vacuum for free scalar fields, we derived how entanglement entropy depends on $\alpha$. The results are shown in Fig. 1 and Fig. 2.

As is seen in Fig. 2, the entanglement entropy increases significantly as we take $\alpha$ very large for generic values of $\nu$. However only for $\nu = 1/2$ and $3/2$, this tendency disappears. Note that $\nu = 1/2$ is the conformal mass and $\nu = 3/2$ is massless. It is interesting to understand more physically why such a mass dependence occurs.

Our calculation is done for the free scalar field. Therefore direct comparison with the holographic calculation for the Euclidean vacuum4 is difficult. It must be interesting to ask how the calculation of entanglement entropy on the $\alpha$-vacua can be done in the strong coupling limit via holography, a la Ryu-Takayanagi formula5. Understanding these will hopefully shed more light on the question of which vacuum one should choose in the de Sitter space. We hope to come back to this question in near future.

References

---

† Condensed from the article arXiv:1404.7487 [hep-th].
*1 Department of Physics, Osaka University
*2 RIKEN Nishina Center

Fig. 1. Plot of $S_{EE}/V$ against $\nu$, for $\alpha = 0$ (red), 0.1 (orange), 0.25 (yellow), 1 (green) and 2 (blue). Notice the periodicity and reflection symmetries.

Fig. 2. Plot of $S_{EE}/V$ against $\alpha$, for $\nu = 0$ (red), 0.25 (orange), $\nu_c = 0.4062\ldots$ (green), 0.43 (blue) and 0.5 (purple).
Current Reflection and Transmission at Conformal Defects:
Applying BCFT to Transport Process

T. Kimura*1,∗2 and M. Murata*3

A powerful method for studying critical phenomena with conformal defects is boundary conformal field theory (BCFT). However, it has not been completely understood how BCFT describes the reflection/transmission at conformal defects. In this report, we define the reflection/transmission coefficient for conserved currents, as a natural generalization of that based on the energy-momentum tensor.1

We consider two one-dimensional quantum systems connected by a junction, which can be considered as an impurity interacting with the bulk. Let us assume that the first system is in the positive domain \( x > 0 \), the second is in the negative \( x < 0 \), and they are connected at the origin as depicted in Fig. 1(a). Now we shall describe the above system in terms of BCFT. Corresponding to the two quantum systems, the BCFT picture involves two CFTs: CFT1 and CFT2. These CFTs are defined in the upper and lower half planes respectively as depicted in Fig. 1(b). The real axis, which divides the two CFTs, stands for the world line of the impurity, or the defect. We can reformulate this system to obtain CFT1 \( \times \) CFT2 in the upper half plane thanks to the folding trick,2 as shown in Fig. 2. In this way, the junction of the one-dimensional quantum systems can be mapped into a CFT boundary condition.

![Fig. 1. From the impurity to the defect. (a) Two one-dimensional systems are connected through the impurity at \( x = 0 \). (b) Adding the time direction and taking the continuum limit, that system is mapped into the two-dimensional system with the defect along the line \( x = 0 \).](image)

We assume that CFT1,2 have the same symmetry subalgebra \( \mathcal{C} \), which is preserved at the conformal defect. For such a defect, we choose the following current gluing condition \( \left( j^\text{tot.} + \tilde{j}^\text{tot.} \right) |B\rangle = 0 \), where \( j^\text{tot.} \) takes values in the Kac–Moody algebra \( \hat{\mathcal{C}} \), and \( \tilde{j} \) is the anti-holomorphic part. We then introduce the R-matrix based on this boundary state \( |B\rangle \),

\[
R[\mathcal{C}]_{ij}^{ab} = -\frac{\langle 0|j^a|1\rangle \langle 1|j^b|B\rangle}{\langle 0|B\rangle}.
\] (1)

Since we have three constraints for this matrix, it has only one degree of freedom. Letting \( \omega_B[\mathcal{C}] \) be

\[
d^{ab}_{ij}\omega_B[\mathcal{C}] = -\frac{1}{k_1 k_2 (k_1 + k_2)} \left( \frac{1}{k_1} \right) + \frac{1}{k_1} \left( \frac{1}{k_1} \right)\right),
\] (2)

the R-matrix is given by

\[
R[\mathcal{C}] = \frac{k_1 k_2}{k_1 + k_2} \left( \frac{k_1}{k_2} \right) + \omega_B[\mathcal{C}] \left( \frac{1}{k_1} \right),
\] (3)

where \( d^{ab} \) is the Cartan–Killing form, \( k_i \) is the level of the Kac–Moody algebra, and \( K_n^a = k_{2j}j_{1,a} - k_{2j}j_{2,a} \).

We can introduce the reflection and transmission coefficients based on this matrix:

\[
\mathcal{R}[\mathcal{C}] = \frac{R_1 + R_2}{k_1 + k_2}, \quad \mathcal{T}[\mathcal{C}] = \frac{R_1^2 + R_2^2}{k_1 + k_2},
\] (4)

which satisfy the current conservation \( \mathcal{R} + \mathcal{T} = 1 \). Applying this formula to the coset-type boundary state with \( \mathcal{C} = su(2) \),3 we obtain

\[
\mathcal{T}[su(2)] = \frac{2k_1 k_2}{(k_1 + k_2)^2} \left( 1 - \frac{S_{\mu\nu}^{(k_1 + k_2)}}{\rho_{\mu\nu}^{(k_1 + k_2)}} \right),
\] (5)

with the modular \( S \)-matrix of \( SU(2)_k \) labeled by two integers, \( S_{\mu\nu}^{(k)} = \sqrt{\frac{2\pi}{k+2}} \sin \left( \frac{\pi}{k+2}(2\mu + 1)(2\nu + 1) \right) \).

References
1) T. Quella et al., JHEP 0704 (2007) 095.
Magnetic field of the slowest rotating neutron star in the symbiotic X-ray binary 4U 1954+319†

T. Enoto,*1,2,3 M. Sasano,*4 S. Yamada,*5 T. Tamagawa,*1 K. Makishima,*4,6 and Suzaku 4U 1954+319 Analysis Team

Neutron stars (NSs) are not boring degenerate compact objects with a uniform face, but exhibit a large variety of observational diversities mainly due to a wide range of magnetic field (B-field, ∼10^4–10^{12} T), rotation spin period (P ∼ 10^{-3–4}s), and (in some cases) mass accretion from a companion star. Binary systems with NSs are conventionally classified into high-mass X-ray binaries (HMXBs, an optical counterpart mass M_2 > 10M_{⊙}) or low-mass X-ray binaries (LMXBs, M_2 < 1–2M_{⊙}). The former and latter are thought to host NSs with higher and lower B-field of 10^7–8 T and 10^4–6 T, respectively. However, the symbiotic X-ray binary (SyXB) 4U 1954+319 was recently recognized as a rare system hosting a peculiar NS and M-type companion, and found to be the slowest rotator among known X-ray pulsars with P ∼ 5.4 h.

We performed two observations of 4U 1954+319 with the X-ray satellite Suzaku in 2011 (quiescent) and 2012 (flare phase), and investigated the spectral and temporal nature of this peculiar system. Although the optical counterpart is classified as a “low mass” star, its X-ray features are quite similar to a wind-fed type HMXB system; e.g., 1) high pulsed fraction, ∼60–80%, 2) shot-like mass accretion, characterized by the log-normal distribution of the count rate (Fig.1), 3) broadband spectral similarity to low-luminosity slowly rotating NSs in HMXBs (Fig. 2), and 4) a narrow 6.4 keV Fe-Kα line. Combined with a sign of the spin-equilibrium over a long time scale, we proposed a quasi-spherical accretion regime from a slow stellar wind from the M-type companion (Fig. 3). Even though we do not need an extremely strong B-field like magnetars, which were expected from the canonical disk-type accretion, we still need a higher B-field in the range of 10^{8–9} T as the HMXB-NSs rather than the LMXB-NSs. Our study indicates a new interesting subclass of X-ray pulsars, i.e., SyXBs, and casts a question on its evolutionary path to make such a peculiar system.

References

Fig. 1. The 1–10 keV X-ray count rates of 4U 1954+319 observed with X-ray CCD instruments (X-ray Imaging Spectrometer) on board the Suzaku satellite†, during a quiescent state (panel a and b) and an outburst (c and d) in 2011 and 2012, respectively.

Fig. 2. Spectral comparison of 4U 1954+319 with other long period pulsars in HMXBs (modified from Enoto et al., 20141).

Fig. 3. Schematic view of the quasi-spherical accretion from stellar wind in the X-ray binary 4U 1954+3191.
Short-term spectral softening of black-hole binary
Swift J1753.5–0127†

A. Yoshikawa,**†2 S. Yamada,**3 S. Nakahira,**4 M. Matsuoka,**5 H. Negoro,**6 T. Mihara,**5 and T. Tamagawa,**1

The X-ray emission from black-hole binaries (BHBs) is driven by the release of gravitational energy from accreting matter falling into a black hole (BH). The X-ray intensities are known to fluctuate for approximately weeks or months (outburst). There are two states: the low-luminosity hard (low/hard) and the high-luminosity soft (high/soft) states. The X-ray spectra of the low/hard state can be well reproduced by a power law with a photon index of 1.4–2.1.† The spectra of the high/soft state can be explained by optically thick thermal disk emission (accretion disk).†‡

Transitions between the low/hard and high/soft states during the outburst have been observed in many BHBs. The Swift J1753.5–0127 outburst was occurred on May 30 2005.†‡ After the outburst, the source flux peaked on July 9 2005, and then gradually decreased for more than 9 years. Dips were observed in the 15–50 keV energy range that lasted for approximately 25 days (short-term variation). The dips are interpreted as a possible eclipse by the warped disk.† Our observations with MAX† revealed the increase of the intensity in the 2–4 keV energy range during the variation in 2009.‡ The increase can not be explained by the eclipse. To investigate the cause of the short-term variation, we have studied the X-ray spectrum.

For another short-term variation of the source on April 23 2012, we succeeded in tracing its spectral time evolution, as shown in Fig. 1. We overlaid the light curves for the various energy ranges normalized by the mean count rates, which were calculated by averaging over approximately 40 days. The light curves below and above 10 keV were observed using MAX† and Swift, respectively. The hump in the 0.7–4 keV band and the dip in the 15–50 keV band correspond to the growth and decay of the accretion disk, respectively (Fig. 1a). The X-ray spectrum observed by using the Swift-XRT† changed during the short-term variation (Fig. 1b). The spectrum can be fitted by the emission model of the accretion disk. The disk temperatures \( T_{\text{in}} \) and energy fluxes \( F_{\text{disk}} \) changed from 0.48 to 0.2 keV and from \( 4.8 \times 10^{-9} \) to \( 2.2 \times 10^{-9} \) erg s\(^{-1}\) cm\(^{-2}\), respectively. The best-fit parameters show the variation of the accretion disk and the state transitions from the low/hard to high/soft state (softening) during the short-term variation. The \( F_{\text{disk}} \) and \( T_{\text{in}} \) did not obey the relationship \( F_{\text{disk}} \propto T_{\text{in}}^{-4} \), suggesting that the structure of the accretion disk changed during the softening.

References
Installation of return BT line from IRC

Y. Watanabe,*1 N. Fukunishi,*1 M. Fujimaki,*1 M. Komiyama,*1 K. Kumagai,*1 T. Maie,*1 H. Yamasawa,*1 S. Fukazawa,*2 M. Hamanaka,*2 S. Ishikawa,*2 K. Kobayashi,*2 Y. Kotaka,*2 R. Koyama,*2 T. Nakamura,*2 M. Nishida,*2 M. Nishimura,*2 J. Shibata,*2 N. Tsukiori,*2 and K. Yadomi*2

The return beam transport (BT) line from IRC to the E5 room was installed from FY2012 to FY2014 because of the biology experiments requiring a higher energy beam by a relatively heavy ion such as an Ar beam. In particular, the installed return BT line was from dipole magnet DMKR to dipole magnet DMA1, as shown in Fig. 1. The installation of the return BT line was supported by the ‘Formation of Tohoku Marine Science Center’ of the Ministry of Education, culture, Sports, Science and Technology, Japan. Table 1 shows the installation schedule of the return BT line. The return BT line was primarily installed in the maintenance period during every summer and winter.

As preparatory works, all necessary components and works were first listed and the installation schedule was planned in FY2012. We arranged some existing components that we could use, and listed some new components that had to be produced and work that had to be done. Some quadrupole magnets, all profile monitor (PF), chambers, turbo molecular pumps (TMP) were produced in FY2012 because these components were already designed and the models chosen. A part of IRC bypass BT line and the infrastructure were modified and constructed in FY2013 before the installation of the return BT line. After temporary removal of a part of IRC bypass BT line from dipole magnet DMH6 to double quadrupole magnet QDH71, a tefler was constructed in the area from dipole magnet DMR6 to double quadrupole magnet QDR64, and some openings (holes) were made in the wall and floor in order to lay some cables in the summer of 2013. Because the old

Table 1 Installation schedule of the return BT line.

<table>
<thead>
<tr>
<th>Period</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY2012</td>
<td>Preparatory works and production of some quadrupole magnets, all PF, chambers, and TMP</td>
</tr>
<tr>
<td>Summer of 2013</td>
<td>Removal of part of the IRC bypass BT line, modification of old DMH6, construction of telpher, and boring of the wall and floor</td>
</tr>
<tr>
<td>Winter of 2013/2014</td>
<td>Production of new DMH6 and power supply, carrying in of some magnets and stands, laying of some cooling water piping, and installation of removed IRC bypass BT line</td>
</tr>
<tr>
<td>Summer of 2014</td>
<td>Installation of return BT line, except the IRC bypass BT line, laying of all cooling water piping and cables for magnets, modification of DMA1, and production of FC, N-DIM, RP, GV, and stands</td>
</tr>
<tr>
<td>Winter of 2014/2015</td>
<td>Set up of all PF, FC, N-DIM, vacuum pumps, laying of all cables for monitors, and finally operation check</td>
</tr>
<tr>
<td>Jan. 2015</td>
<td>Acceleration test with Ar beam</td>
</tr>
</tbody>
</table>

DMH6 was used as a new DMR6, the chamber and outer yokes of the old DMH6 were reversed to change the direction of flange after the dismantlement of the old DMH6, a new DMR6 was assembled, and a new DMH6 was produced. In addition, a power supply of DMKR, some stands, and ducts were produced in FY2013. Three double quadrupole magnets that were used in the old RILAC line were transferred from the E21 room to IRC room. After all magnets, stands, and chambers were carried in the area from DMR6 to QDR64, the removed IRC bypass BT line, including the new DMH6 and new DMR6, was again installed according a new line design in the winter of 2013/2014. All of the return BT line expect the IRC bypass BT line was installed in FY2014. Some quadrupole and steering magnets that were used in the old line were transferred from the E2 and E4 room to the E1 and RRC-A room, and all chambers and stands were also carried in each area. While almost all of the return BT line was installed in the summer of 2014, all cooling water piping and cables for magnets were laid, and the outer yokes of DMA1 were replaced with new ones that were fabricated such that a beam duct could be installed from the chamber R80. All faraday cups (FC), network device interface modules (N-DIM), rotary pumps (RP), gate valves (GV), stands, ducts and cables for monitors were produced by the summer of 2014, and these components were set up gradually. Finally, the operation check was smoothly done without any problem, and the first acceleration test with the Ar beam in the AVF-RRC-IRC mode using the return BT line was successfully completed in the end of January 2015.

Fig. 1. Layout of the return BT line.

*1 RIKEN Nishina Center
*2 SHI Accelerator Service Ltd.
Supply of $^{48}$Ca beam from 18-GHz ECRIS using the micro-oven

K. Ozeki,*1 Y. Higurashi,*1 M. Kidera,*1 and T. Nakagawa*1

In order to enhance the intensity and stability of the $^{48}$Ca beam supplied from the RIKEN 18-GHz Electron Cyclotron Resonance Ion Source (ECRIS),1) we have been conducting operational tests on a micro-oven using $^{40}$Ca.2) Owing to the cost of the material in which the $^{48}$Ca isotope is highly enriched (70-80%), it is very important to reduce its consumption rate. For this purpose, we adopted the so-called “hot liner”3-5) and studied its effect on the reduction of the consumption rate. In this study, wherein a tantalum cylinder and disk of 0.1-mm thick were installed into the ECRIS, we observed an apparent reduction of the material consumption rate by using the hot liner. Details of the results are described in Ref. 6.

The $^{48}$Ca beams for a series of experiments using the micro-oven have been supplied three times until now. Each series of experiments is summarized in Table 1. The statuses of the beam supply for experiments-1, such as beam intensity and material consumption rate, are reported in Ref. 6.

Table 1. Supply of the $^{48}$Ca beam using a micro-oven.

<table>
<thead>
<tr>
<th>Days</th>
<th>Charge</th>
<th>Beam course</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nov. to Dec. 2013</td>
<td>11+</td>
<td>GARIS, RIPS</td>
</tr>
<tr>
<td>2 Sep. to Oct. 2014</td>
<td>11+</td>
<td>GARIS, RIPS</td>
</tr>
<tr>
<td>3 Nov. to Dec. 2014</td>
<td>10+</td>
<td>BigRIPS</td>
</tr>
</tbody>
</table>

In the series of experiments-3, the $^{48}$Ca beam produced by the present method was first supplied to the new RIBF accelerator complex. Figure 1 shows the charge distribution of the $^{48}$Ca ions. The RF power fed to the ECRIS was 370 W.

The beam intensity at the exit of ECRIS and the oven current are shown in Fig. 2. The beam intensity was adjusted according to the requirements of the experiment, by changing the aperture of the slit at the exit of ECRIS. A beam intensity of ~35 electric μA with maximum slit aperture was maintained throughout the experimental duration.

Fig. 1. Charge distribution of the $^{48}$Ca ions.

The amounts of $^{48}$Ca placed into the crucible and subsequently consumed were 299 mg and 98 mg, respectively. The consumption rate of $^{48}$Ca was 0.13 mg/h. We succeeded in supplying stable and highly intense (twice as high compared to before, at the exit of ECRIS) beam with low material consumption rate (nearly one-tenth as low compared to before).

Previously, the peak intensity of the $^{48}$Ca beam extracted from Superconducting Ring Cyclotron was 415 particle nA, but it was impractical to maintain the beam intensity at this level because of insufficient stability and high material consumption rate. The practical application of the micro-oven system realized long-term stable supply of the $^{48}$Ca beam with an intensity of more than 400 particle nA to users.7)

References
7) http://www.nishina.riken.jp/RIBF/accelerator/tecinfo.html

*1 RIKEN Nishina Center
Particle identification for Sn region with SAMURAI


We performed the SAMURAI17 experiment1 at RIKEN RIBF to study Gamow-Teller transition in 132Sn by (p, n) reaction with the WINDS2 and the SAMURAI spectrometer3. The SAMURAI spectrometer was used for tagging (p, n)-reaction events with the particle identification (PID) of the beam heavy fragments. The PID was performed with the TOF-$B_{\rho}$-$\Delta E$ method. Here we report the preliminarily results on the PID.

Here, we used the 132Sn beam run with empty-target cell at F13 and selected the non-reacted trigger events in order to estimate the resolution of TOF, $B_{\rho}$ and $\Delta E$. The beam rigidity was measured by the BigRIPS with a typical momentum resolution of $R/\sigma_R \sim 3000$.

The TOF was measured by using the plastic scintillators SBT1,2 and the HODS with flight path length $L \sim 12.5$ m. The HODS consists of 6 plastic scintillation counters with size of 450 mm $\times$ 100 mm $\times$ 5 mm. The obtained TOF resolution is $\sigma_t = 62.1 \pm 2.7$(stat.) ps, where the statistical uncertainty is indicated. It should be noted that the non-uniformity of SBT1 thickness is as large as about 20% which corresponds to 1 MeV/nucleon energy loss difference for 200 MeV/nucleon 132Sn beam. In this analysis we gated the central position of SBT1 to estimate the TOF resolution, by using tracking information from BDC1.2 drift chamber which were placed between SBT1,2 and the target. In the following the resolution was estimated with the same manners.

The energy loss $\Delta E$ was measured by HODS. The $\Delta E$ is sensitive to the HODS thickness. In this experiment the non-uniformity of HODS thickness is about 10–20% for 6 counters. In order to correct the thickness dependence, we used the tracking information from FDC2 drift chamber which was placed after the SAMURAI spectrometer. The obtained $\Delta E$ resolution is $\sigma_{\Delta E}/\Delta E = 0.43 \pm 0.03$(stat.) %.

The rigidity was analyzed by using four drift chambers BDC1,2, FDC1 and FDC2. The obtained rigidity resolution is $R/\sigma_R = 1318 \pm 27$(stat.).

Figure 1(a) shows the PID spectrum with respect to atomic number $Z$ and mass to charge ratio $A/Q$. The $Z$ resolution is $\sigma_Z = 0.22$ corresponding to 4.6$\sigma$ separation for $Z=50$ and 51. The $A/Q$ resolution is $\sigma_{A/Q} = 0.14$ % for 132Sn 50+ which corresponds to 5.4$\sigma$ separation.

![Fig. 1. (a) A SAMURAI PID spectrum with respect to Z and A/Q for non-reacted events with empty target cell. (b) Z distribution for all beam component and (c) A/Q distribution for Sn isotopes. The resolution of Z and A/Q are $\sigma_Z = 0.22$ and $\sigma_{A/Q} = 0.14$ % for 132Sn 50+, respectively.](image)

References
1) M. Sasano et al.; in this report.
2) J. Yasuda et al.; in this report.
Results of first online tests of small ion-surfing RF carpet gas cell at GARIS-II

P. Schury,*1 F. Arai,*1,*2 H. Haba,*1 Y. Ito,*1 I. Katayama,*1 D. Kaji,*1 K. Morimoto,*1 M. Reponen,*1 T. Sonoda,*1 M. Wada,*1 and H. Wollnik*1,*3

As part of the SLOWRI project, we have begun development of a new low-energy experimental facility, SlowSHE, for use with radioactive isotopes (RI), such as Super Heavy Elements (SHE), that are created via fusion-evaporation reactions. This new facility utilizes a small gas cell placed after the GARIS-II separator to thermalize the ions before they are transported to a multi-reflection time-of-flight mass spectograph. A very thin mylar film (2.4 µm thick) on a rotatable frame is placed before the gas cell for use as an adjustable degrader to remove, in combination with two thin (1.1 µm and 2.4 µm thick) mylar windows, a large fraction of the ions kinetic energy. The remaining kinetic energy is removed by collisions with He gas, which the cell is pressurized with up to 100 mbar.

In this first experiment, we desired to verify the combined stopping and extraction efficiency for a variety of chemical elements using isotopes with a wide range of half-lives. We first studied stopping and extraction of the long-lived 205Fr placed after the GARIS-II separator. A very thin mylar film (2.4 µm thick) on a rotatable frame is placed before the gas cell for use as an adjustable degrader to remove, in combination with two thin (1.1 µm and 2.4 µm thick) mylar windows, a large fraction of the ions kinetic energy. The remaining kinetic energy is removed by collisions with He gas, which the cell is pressurized with up to 100 mbar.

The degrader was initially replaced with a large silicon detector array to measure the incoming rate. The α-decay rate of 205Fr was calibrated against the rate of elastically scattered incoming beam near the reaction target. The detector was then replaced by the degrader and the rate of α-decay on a silicon detector placed after the gas cell was measured as a function of the degrader angle. The result, shown in Fig. 1, featured a flat plateau with efficiency peaking near 30%.

Of perhaps greater interest was the stopping and extraction efficiency for shorter-lived isotopes. This was studied with a Tantalum target using the reactions 181Ta(40Ar,p4n)216Th and 181Ta(40Ar,4n)217Pa to produce species with T1/2 of 26 ms and 3.5 ms, respectively. The α-decay spectra seen after the gas cell using a chopped beam and measuring decays during “beam off” are shown in Fig. 2. The red spectrum was measured by quickly pulsing the linac beam while the green spectrum was measured with longer period pulses. For the long period beam pulses, short-lived isotopes extracted during “beam on” decay prior to “beam off” and are suppressed.

For these beams, having higher-Z and lower energy than 205Fr, the degrader was inoptimally thick. However, we were able to set lower limits on the stopping and extraction efficiencies. For the short-lived 216Th, we were able to achieve ~15% combined efficiency, while for the extremely short-lived 217Pa ~12%.

These results were obtained with the gas cell operated at room temperature; we believe that using cryogenic temperatures should provide further improvements by reducing the possibility of charge exchange with gas impurities and reducing the rate of diffusion of the ion cloud as it transits the length of the gas cell. Even with the efficiencies reported herein, it should be possible to perform precision mass measurements of even trans-Uranium isotopes with exceedingly low production rates. First such measurements are planned to take place within calendar year 2015.

References
1) F. Arai et al., this volume

Fig. 1. Combined stopping and extraction efficiency for 205Fr as a function of degrader thickness. The thickness was varied by rotating the degrader. Gas cell was operated at room temperature.

Fig. 2. α-decay spectra seen on silicon detector after the gas cell. Pulsing the linac beam with a short period, a strong suppression of short-lived isotopes was observed.

- 22 -
Electron scattering spectrometer for the SCRIT project

K. Tsukada,*1.2 A. Enokizono,*1,3 K. Kurita,*1,3 S. Matsuo,*1,3 Y. Moriya,*1,2 T. Ohnishi,*1 T. Suda,*1,2 T. Tamae,*1,2 M. Togasaki,*1,3 T. Tsuru,*1,2 R. Toba,*1,4 K. Yamada,*1,3 S. Yoneyama,*1,2 and M. Wakasugi*1

We have developed the magnetic spectrometer system1), WiSES (Window-frame Spectrometer for Electron Scattering), for electron scattering on short-lived nuclei at the SCRIT electron scattering facility. The WiSES consists of a dipole magnet2,3), FDC(Front Drift Chamber), RDC(Rear Drift Chamber)4), plastic scintillator hodoscope, and a helium bag. Figure 1 shows a schematic view of the WiSES and SCRIT system5). The layer configuration of the drift chambers is XX’XX’ for FDC and VV’UU’XX’VV’UU’ for RDC. The gas of drift chambers are He+CH4(50:50) at this time. The combination of FDC and RDC enables reconstruction of the trajectory of electrons in the magnetic field and estimation of the momentum. Our goal of momentum resolution is \( \delta p/p \sim 1 \times 10^{-3} \) for 300 MeV electron. The solid angle of the spectrometer is evaluated to be 83 msr by a simulation. The plastic scintillator hodoscope is used to generate trigger signals. A detail of the data acquisition system is reported elsewhere6). The helium bag made of vinyl sheets of thickness 30 \( \mu \)m is installed between FDC and RDC to reduce the multiple scattering of electrons.

In December 2014, a commissioning experiment was carried out to evaluate the performance of the WiSES and the luminosity monitor system7). A tungsten wire of diameter 50 \( \mu \)m was mounted in the SCRIT, and its position could be controlled remotely; this wire was used as a target. Because the differential cross section of electron elastic scattering on the tungsten target is well known, we can estimate the performance of the spectrometer by checking the reproducibility of the differential cross sections. In Fig. 2, preliminary results for the electron beam energy at 150 MeV are shown. Electrons elastically scattered from the tungsten wire are found as a peak in the vertex point and momentum distribution, and their resolutions are evaluated to be approximately 10 mm and \( 6 \times 10^{-3} \), respectively. These resolutions will be improved by further analysis. The obtained angular distribution is well reproduced by a simulation in which the differential cross section of the elastic scattering on the tungsten target is estimated by a DWIA calculation.

References
4) S. Matsuo et al.: in this report.
6) A. Enokizono et al.: in this report.
7) S. Yoneyama et al.: in this report.

Fig. 1. Schematic view of the WiSES. A trajectory between FDC and RDC was reconstructed by a Runge-Kutta calculation. The space between FDC and RDC was filled with helium.

Fig. 2. Preliminary results for the electron energy at 150 MeV. (a) Vertex point distribution along the beam line. A clear peak of electrons scattered from the tungsten wire can be seen. (b) Momentum distribution of electrons from the tungsten wire. A clear peak corresponding to the elastic scattering can be seen. (c) Polar angle distribution of the elastically scattered electrons. The red line shows the simulation using the differential cross section estimated by a DWIA calculation.
Measurement of isochronism using α-source for the Rare RI Ring

Y. Abe,*1,*2 Y. Yamaguchi,*1 M. Wakasugi,*1 T. Uesaka,*1 A. Ozawa,*2 F. Suzuki,*1,*3 D. Nagae,*2 H. Miura,*3 and T. Yamaguchi*3

The Rare RI Ring was constructed at the RIBF to measure the masses of nuclei pertinent to the r-process.1) We performed an offline machine study using α-source (^241Am). The α-source was placed in the ring on the central orbit at the R-MD1 area after the first sector as shown in Fig. 1. First, we tried transporting the α particle in the ring and succeeded. Next, to confirm the isochronous field of the ring, we measured TOF after one revolution using two detectors. One was a carbon foil detector like a circulation detector of this ring,2) and the other was a plastic scintillator. The carbon foil detector consisted of thin carbon foil (60 µg/cm² thickness) and three wired plates. A schematic view of these detectors is shown in Fig. 1. The carbon foil detector was placed in front of the source, whereas the plastic scintillator was placed behind the source to detect the α particle after one revolution. A delayed signal from the carbon foil detector was used as a stop signal of TOF, and a signal from the plastic scintillator was used as a start signal.

Figure 2 shows the results of measurement and simulation by MOCADI.3) To evaluate the optimum gradient value, we fitted the results with a parabolic function. The obtained mean value of 0.207(2) is in very good agreement with the simulation result of 0.205. This shows that our isochronous field calculation was correct and an isochronous field is formed using trim coils. The final observed width had 0.61 ns standard deviation. However, the width was limited by the timing resolution of the detectors. Therefore, the achieved isochronism of the ring was less than 1.3 × 10⁻⁴.

Fig. 2. Results of measurement (closed circles) and comparison with simulation (dashed line). The solid line is the result of fitting with a parabolic function.

It is seen from our results in Fig. 2 that the standard deviation was saturated. This saturation was caused by the limitation of timing resolution of the detectors.

Currently, we are testing an injection system to store the α particle from the source for several revolutions. If we can measure the TOF after several revolutions, we would be able to confirm the isochronism with higher order even though the timing resolution of the detectors is limited. Furthermore we will perform a machine study using a heavy-ion beam in the next fiscal year.

References
Time-stamping system for nuclear physics experiments at RIKEN RIBF†

H. Baba,*1 T. Ichihara,*1 T. Ohnishi,*1 S. Takeuchi,*1 K. Yoshida,*1 Y. Watanabe,*1 S. Ota,*2 S. Shimoura,*2 and K. Yoshinaga,*3

At the RIKEN RIBF, a new time-stamping system has been developed for nuclear physics experiments. The time-stamping function is implemented in a logic unit for programmable operation (LUPO)†. One of the remarkable features is that it can attach the time-stamp information to an existing CAMAC/VME based DAQ system in RIBF‡. The timing resolution of the time-stamping system is 10 ns, which is sufficient to find the event correlation between separated DAQ systems. This specification enables us to merge obtained data separately on an event-by-event basis after the measurement.

The proposed time-stamping system was installed at RIKEN RIBF for use in β-decay experiments§–‖. In these experiments, a beam line detector set, a silicon detector array, and a germanium detector array were used. Since the triggers for these detectors are independent of each other, three separate DAQ systems were used. In this report, the results for the DAQ systems for the beam line detector set (BeamDAQ) and the silicon detector array (SiDAQ) are described. The beam line detector set is triggered by RI-beams, i.e., beam events. The silicon detector array is triggered by both implanted isotopes and β rays, i.e., beam events and β-decay events. For the silicon detector array, when both SiDAQ and BeamDAQ are triggered at the same time, the event can be identified as a beam event. On the other hand, if SiDAQ is triggered but BeamDAQ is not, the event is a β-decay event. In order to determine the relationship between the number of actually generated physics events and the number of events accepted by separate DAQ systems, the combined live time was investigated. An additional DAQ system named full-event monitor was installed to acquire the time stamps of all generated triggers. By using LUPO, trigger time stamps for each DAQ system are recorded without loss. BeamDAQ and SiDAQ store detector data together with the time stamps of accepted triggers. In contrast, the full-event monitor only accumulates time-stamp values of triggers generated for BeamDAQ and SiDAQ. The combined live times for beam events and β-decay events in the silicon detector array are determined as the ratio of the number of events identified using BeamDAQ and SiDAQ and the number of triggers recorded by the full-event monitor. Table 1 lists the measured and estimated combined live times for beam and β-decay events in the silicon detector array. The real event-occurrence rate (R) is unknown if the full-event monitor is not present. However, it is possible to estimate it by comparing the observed and simulated DAQ acceptance rates (Racc) when a trigger is accepted by both BeamDAQ and SiDAQ. Monte Carlo simulation was performed in order to estimate DAQ acceptance rates from a DAQ transaction time, which can be obtained using the scaler circuit in the experiment. The transaction times of BeamDAQ and SiDAQ were 210 and 108 μs, respectively. From the results of the Monte Carlo simulation, the assumed beam-event and β-decay event rates (R) are calculated to fit the observed DAQ acceptance rate (Racc = 82.2 events/s). These results indicate that for beam and β-decay events, the accuracy of the Monte Carlo simulation was good. Within this simulation, the systematic error in the simulated event rates was 0.2%.

In summary, a time-stamping system has been introduced in the RIKEN RIBF. This system is particularly useful for β-decay experiments. Although the combined live time for separate DAQ systems is not straightforward to determine, it can be measured by installing a full-event monitor. It was found that Monte Carlo simulations can estimate the true event rate with a high degree of accuracy.

Table 1. Event rates and combined live times for beam and β decay events in the silicon detector array.

<table>
<thead>
<tr>
<th></th>
<th>R (events/s)</th>
<th>P_L (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam events</td>
<td>Measured</td>
<td>87.5</td>
</tr>
<tr>
<td></td>
<td>Estimated</td>
<td>87.3</td>
</tr>
<tr>
<td>β decay events</td>
<td>Measured</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>Estimated</td>
<td>369</td>
</tr>
</tbody>
</table>

— Condensed from the article in Nucl. Instr. and Meth. A 777, 75 (2015)
*1 RIKEN Nishina Center
*2 Center for Nuclear Study, University of Tokyo
*3 Tokyo University of Science

References
First chemical synthesis and investigation of Sg(CO)$_6$†


Gas phase chemical studies of the superheavy elements have been limited to simple inorganic compounds so far.1) Due to challenging experimental conditions, access to other compound classes was limited. With the combination of physical preseparation with gas-phase chemistry techniques, parts of the experimental limitations could be overcome.2-3)

We succeeded in the synthesis of the first carbonyl complex of a superheavy element, namely seaborgium hexacarbonyl (Sg(CO)$_6$), at the GAs-filled Recoil Ion Separator GARIS. Sg(CO)$_6$ has been predicted to be stable and its adsorption behavior on SiO$_2$ surface is expected to be very similar to that of W(CO)$_6$.4) We therefore investigated Sg(CO)$_6$ along with W(CO)$_6$. Short-lived $^{164}$W, and $^{10}$s $^{265}$Sg were synthesized in the reactions $^{144}$Sm$^{(24}$Mg,$^{4}$n)$^{164}$W and $^{248}$Cm$^{(22}$Ne,$^{5}$n)$^{265}$Sg. The evaporation residues (EVRs) were separated from the primary beam and lighter transfer products within GARIS. At the focal plane of GARIS, a recoil transfer chamber (RTC) was installed. The EVRs passed the entrance window of the RTC and were thermalized in a He / CO atmosphere (~600 mbar) in the RTC. The free single ions of W and Sg reacted with CO, forming volatile complexes.5) The RTC was flushed continuously, transporting volatile compounds through a 10-m long capillary to the Cryo Online Multidetector for Physics and Chemistry of the Transactinides COMPACT,6) a thermochromatography detector array. The chromatography channel is formed by 32 pairs of silicon PIN diodes covered with a SiO$_2$ surface, kept at temperatures between 22 °C and -140°C. Volatile compounds adsorb at a certain temperature on the detector surface. The deposition pattern compared with Monte Carlo Simulations MCS, which allowed determining the adsorption enthalpy -$\Delta$H$_{\text{ads}}$, W as well as Sg were transported to COMPACT, hence, formed volatile compounds with the CO. In total 15 decay chains assigned to the decay of $^{265}$Sg plus three uncorrelated fission event assigned to originate from members of the $^{265}$Sg decay chain were observed under almost background free conditions at a total beam integral of 1.52$\times$10$^{19}$. Both, the W as well as the Sg complexes deposited mainly in the last third of the detector (see Fig. 1). The W chromatograms are in agreement with former experiments reported in 3), where the transported species was assigned to W(CO)$_6$. The Sg species shows the same adsorption behavior on SiO$_2$ as W(CO)$_6$, which strongly supports the assignment to Sg(CO)$_6$.7)

The experimental distribution and MCS are shown in Figure 1.

Fig. 1. Distribution of $^{164}$W (upper graph) and $^{265}$Sg (bottom graph). $^{164}$W was measured at 1L/min; the lower panel shows a combined chromatogram of all observed Sg events (flow rates between 1 L/min and 2.2 L/min). The black curve shows the result of the MCS (after [7]).

References
II. RESEARCH ACTIVITIES I
(Nuclear, Particle and Astro-Physics)
1. Nuclear Physics
Long-lived isomer in $^{126}\text{Pd}^\dagger$

H. Watanabe$^{*1,2}$ for the RIBF60&62R1 Collaboration

Spectroscopic studies of $^{126}\text{Pd}$ have been performed at the RIBF facility. Neutron-rich nuclei below $^{133}\text{Sn}$ were produced using in-flight fission of a $^{238}\text{U}(^{86}\text{Ni})$ beam at 345 MeV/nucleon with the intensity ranging from 7 to 12 pA, impinging on a beryllium target with a thickness of 3 mm. The nuclei of interest were separated and identified through the BigRIPS separator and the following ZeroDegree spectrometer. A total of $5.3 \times 10^4$ $^{126}\text{Pd}$ fragments were implanted into a highly segmented active stopper, named WAS3ABi, which consisted of eight double-sided silicon-strip detectors (DSSSD) stacked compactly. The DSSSDs also served as detectors for electrons following $\beta$-decay and internal conversion (IC) processes. Gamma rays were detected by the EURICA array that consisted of twelve Cluster-type detectors.

The decay schemes of the isomeric states in $^{126}\text{Pd}$ are exhibited in Fig. 1. For $^{126}\text{Pd}$, the $J^\pi = (5^-)$ and $(7^-)$ isomers at 2023 and 2110 keV, respectively, were reported in Ref. $^1$. In the present work, the $\gamma$ rays below these isomers, except for the 86-keV line, have been also observed in coincidence with electrons that were associated with the prior implantation of $^{126}\text{Pd}$, as demonstrated in Fig. 2(a). With gates on these $\gamma$ rays, a prominent peak can be found in an electron spectrum [marked with "I" in the inset of Fig. 2(b)]; this corresponds to the conversion electrons for the 86-keV, $E2$ transition ($\alpha_T = 2.374$). In Fig. 2(b), a $\gamma$-ray at 297 keV is clearly visible in addition to the $\gamma$ rays below the $(5^-)$ isomer by gating on the 86-keV IC peak. The appearance of the 297-keV peak is emphasized by taking a $\gamma$-ray time condition earlier than electron events, as is evident from the inset of Fig. 2(a), suggesting that this new $\gamma$ ray precedes the highly converted 86-keV transition. Furthermore, the 297-keV $\gamma$ ray is observed in coincidence with the other $\gamma$ rays in $^{126}\text{Pd}$ [see Fig. 2(c) as an example]. Thus, the long-lived isomer can be identified at an excitation energy of 2406 keV. A peak marked with "II" in the inset of Fig. 2(b) is expected to arise from the conversion electrons for the 297-keV transition, being most likely of an $E3$ character ($\alpha_T = 0.1197$).

The half-life ($T_{1/2}$) derived from the time distribution of the 297-keV $\gamma$ ray is in agreement with that of the 693-keV one within experimental errors, as illustrated in the insets of Fig. 2(c). Similar half-lives have been observed for six other $\gamma$ rays; these transitions are expected to belong to high-spin states in $^{126}\text{Ag}$ which are populated through the $\beta$ decay of the long-lived isomer in $^{126}\text{Pd}$. Therefore, the half-life is determined to be $23.0(8)$ ms by taking a weighted average of the respective values. Based on the observed mutual coincidence [see Fig. 2(d)] and $\gamma$-ray intensities, we propose the decay scheme from the long-lived isomer in $^{126}\text{Pd}$ to the high-spin states in $^{126}\text{Ag}$ as shown in Fig. 1.

Fig. 1. Decay schemes of the $J^\pi = (10^+)$ isomer in $^{126}\text{Pd}$.

Fig. 2. Gamma-ray spectra measured with various gate conditions within 50 ms after the $^{126}\text{Pd}$ implantation.

References


$^\dagger$ Condensed from the article in Phys. Rev. Lett. 113, 042502 (2014).

$^*$ RIKEN Nishina Center

$^\dagger$ IRCNPC, School of Physics and Nuclear Energy Engineering, Beihang University
Yrast $6^+$ Seniority Isomers of $^{136,138}$Sn

G.S. Simpson,*1,2,4,3 G. Gey,*3,4,5 A. Jungclaus,*6 J. Taprogege,*6,7,5 S. Nishimura,*5 K. Sieja,*8 P. Doornenbal,*5 G. Lorusso,*5 H. Sakurai,*5,*10 P.-A. Söderström,*5 T. Sumikama,*9 Z.Y. Xu,*10 on behalf of the RIBF-85 collaboration

The shell model plays a key role in allowing a microscopic description of many of the properties of atomic nuclei. Its two ingredients are single-particle energies and effective nucleon-nucleon interactions. Experimental studies of semi-magic Sn nuclei beyond the nuclei. Its two ingredients are single-particle ener-
a 345 MeV/nucleon value was more than a factor of 5 away for 136
134
were also correctly predicted for 136
134
states of
with a very similar delayed cascade previously reported
†

Fig. 1. Experimental (black squares) and theoretical reduced transition rates for $6^+_1 \rightarrow 4^+_1$ γ decays in $^{134-138}$Sn. The calculations used a realistic $V_{low-k}$ interaction (red filled circles), a pairing-modified $V_{low-k}$ interaction (blue open circles) and a pure $f_{7/2}$ seniority scheme (grey curve).

The near-constant energies of the $(2^+_1)$, $(4^+_1)$ and $(6^+_1)$ states of $^{134,136,138}$Sn are characteristic of dominant seniority 2 (one broken pair) excitations. The $B(E2)$ values of seniority-conserving transitions are expected to follow the shape of a symmetric positive parabola, as shown in Fig. 1. The results obtained with a realistic $V_{low-k}$ interaction follow a similar pattern to the seniority 2 scheme. Additional shell-model calculations have been performed which allowed particle-hole excitations from the neutron $v\theta_{11/2}$ and proton $0\theta_{9/2}$ shells to the $N = 82 - 126$ and $Z = 50 - 70$ valence spaces, respectively. These allowed the influence of core polarization effects on the transition rates of the neutron-rich Sn nuclei to be examined. However, the $B(E2;6^+_1 \rightarrow 4^+_1)$ value for $^{136}$Sn was still not correctly reproduced. Reducing the energies of the $\nu1f_{7/2}^2$ diagonal and off-diagonal matrix elements by $\sim 150$ keV allowed the $B(E2;6^+_1 \rightarrow 4^+_1)$ of $^{136}$Sn to be correctly predicted. This shift is equivalent to a reduction in the pairing strength. The results using this pairing-modified $V_{low-k}$ interaction are shown in Fig. 1. Similar modifications to pairing were necessary to reproduce the level schemes of $^{72,74}$Ni,[3] illustrating the need for additional theoretical efforts on the construction of effective interactions.

References

---

*1 Condensed from the article in Phys. Rev. Lett. 113, 132502 (2014)
*2 University of the West of Scotland
*3 SUPA
*4 LPSC, UJF, CNRS, INPG
*5 Institut Laue-Langevin
*6 RIKEN Nishina Center
*7 IEM, CSIC
*8 UAM
*9 IPHC
*10 Department of Physics, Tohoku University
*11 Department of Physics, University of Tokyo
Gamma-Spectroscopy around $^{100}$Sn

D. Lubos,$^{1,*}$ J. Park,$^{*,2}$ M. Lewitowicz,$^{*,4}$ R. Gernhäuser,$^{*,1}$ R. Krücken,$^{*,3}$ S. Nishimura,$^{*,2}$ H. Sakurai,$^{*,5}$ H. Baba,$^{*,2}$ B. Blank,$^{*,6}$ A. Blazhev,$^{*,7}$ P. Bouthackov,$^{*,8}$ F. Browne,$^{*,9}$ I. Celikovic,$^{*,4}$ P. Doornenbal,$^{*,2}$ T. Faestermann,$^{*,1}$ Y. Fang,$^{*,10,*}$ G. de France,$^{*,8}$ N. Goel,$^{*,8}$ M. Gorska,$^{*,8}$ S. Ililva,$^{*,11}$ T. Isobe,$^{*,2}$ A. Jungclaus,$^{*,12}$ G. D. Kim,$^{*,13}$ Y.-K. Kim,$^{*,13}$ I. Kojouharov,$^{*,8}$ M. Kowalska,$^{*,14}$ N. Kurz,$^{*,8}$ Z. Li,$^{*,15}$ G. Lorusso,$^{*,2}$ K. Moschner,$^{*,7}$ I. Nishizuka,$^{*,16,*}$ Z. Patel,$^{*,17,*}$ M. M. Rajabali,$^{*,4}$ S. Rice,$^{*,17,*}$ H. Schaffner,$^{*,8}$ L. Sinclair,$^{*,18,*}$ P.-A. Söderström,$^{*,2}$ K. Steiger,$^{*,1}$ T. Sumikama,$^{*,16}$ H. Watanabe,$^{*,19}$ Z. Wang,$^{*,3}$ J. Wu,$^{*,12,*}$ and Z. Y. Xu,$^{*,5,*}$

An experiment for studying the superallowed Gamow-Teller decay of the doubly magic nucleus $^{100}$Sn was performed in June 2013 at the high-resolution separator BigRIPS of the RIBF at the RIKEN Nishina Center. A 4-mm $^{9}$Be target was bombarded with a $^{124}$Xe beam of 345 MeV/n at intensities up to 36.4 pmA to produce $^{100}$Sn and a large cocktail$^{15}$ of its neighboring nuclei down to neutron numbers $N = (Z - 2)$ by fragmentation. The nuclei were implanted into the WAS3ABi silicon detector that consists of 3 detectors with high granularity extended by 10 additional single-sided, seven-fold segmented detectors in a closed stack geometry to absorb the emitted $\beta$-particles at a maximum efficiency. This WAS3ABi detector was surrounded by 84 Ge- and 18 LaBr-detectors of the 4m-$\gamma$-ray spectrometer EURICA.

In order to study the branching ratios of the $\beta$-decays, derive level schemes of exotic nuclei and determine isomeric ratios as well as lifetimes of the isomers, a reliable efficiency calibration has been performed. Owing to the special geometry of the WAS3ABi and the failure of several Ge-detectors, the calibration was rounded by 84 Ge- and 18 LaBr-detectors of the 4m-$\gamma$-ray spectrometer EURICA.

In previous works$^{11}$, using this $\gamma\gamma$-coincidence method are shown in Fig. 1.

In addition, greater precision of known isomer half-lives was attainable owing to high statistics in this experiment and preliminary half-lives of $8^+$ and $12^+$ isomers in $^{98}$Cd were determined as $181^{+35}_{-25}$ ns and $228^{+5}_{-6}$ ns, respectively. This would lead to better constraints on the transition strengths for the test of modern shell models. Previously reported $\gamma$-rays in the $\beta$-decay of $^{100}$Sn$^{1)}$ were reproduced, allowing an unprecedented $\beta\gamma\gamma$-coincidence analysis for $^{100}$In. Moreover a new high-spin isomeric state in $^{98}$Cd has been observed with a half-life of about 200 ns, with a decay branch into both, the $16^+$ isomer and the $(10^+)$ state, which has a prompt decay cascade to the ground state. Further analysis is underway to finalize experimental results and compare these to large-scale shell model calculations.

References

Identification of a millisecond isomeric state $^{129}$Cd via the detection of internal conversion and Compton electrons†

J. Taprogge,*1,*2,*3 A. Jungclaus,*1 H. Grawe,*4 S. Nishimura,*2 P. Doomenbal,*2 G. Lorusso,*2 E. Nácher,*1 G.S. Simpson,*5 P.-A. Söderström,*2 T. Sumikama,*6 Z.Y. Xu,*7 H. Sakurai,*2,*7 H. Watanabe,*7 on behalf of the RIBF-85 and RIBF-60&62R1 collaborations

Isomeric states near nuclear shell closures are a sensitive probe to study the position of single-particle orbitals and their evolution. In the present work we have studied for the first time excited states in $^{129}$Cd which decay via the emission of $\gamma$ rays. The neutron-rich $^{129}$Cd ions were produced at the Radioactive Isotope Beam Factory (RIBF), identified and separated in BigRIPS and then implanted in the active stopper WAS3ABi, consisting of eight closely packed DSSSD, which is surrounded by the germanium array EURICA.

Two types of events were recorded by the data acquisition system, the implantation of the ions into the active stopper WAS3ABi and their subsequent decays. In the decay of $^{129}$Cd a very short-lived component in the range of a few milliseconds was observed, much shorter than the previously reported half-lives of the two $\beta$-decaying states in $^{129}$Cd.1 The inspection of the energy spectrum of the Si detector in which the $^{129}$Cd ions were implanted for all decays observed in the first 10 ms (black) and from 30 to 40 ms (red) after the implantation.

Fig. 1. Energy spectrum of the Si detector in which the $^{129}$Cd ions were implanted for all decays observed in the first 10 ms (black) and from 30 to 40 ms (red) after the implantation.

The deduced decay scheme is compared to shell-model calculations employing state-of-the-art realistic interactions (NA-14, same as in Ref.2) in Fig. 2. The dashed lines represent the predicted positions of low-lying positive parity states as well as states with positive and negative parity in the spin range $17/2 - 23/2$. None of these states is predicted to be isomeric. Based on this comparison the new state was assigned to have spin and parity ($21/2^+$). The experimentally determined reduced transition strength of B(E3) = 0.50(3) W.u. for the ($21/2^+$) → ($15/2^-$) E3 transition is in perfect agreement with the value predicted by the SM calculations, B(E3) = 0.48 W.u..

References
Study of shape evolution in neutron-rich Cs isotopes using \(\beta\)-decay spectroscopy


Shape evolution in neutron-rich nuclei with the neutron number \(N>82\) and the proton number \(Z>50\) beyond the doubly magic \(^{136}\text{Sn}\) nucleus have been investigated along several isotopic chains. The EURIKA project\(^1\) provides us with an opportunity to study extremely neutron-rich nuclei using \(\beta\)-decay and isomer-decay spectroscopy. We reported the results of the isomer-search experiment for neutron-rich Cs isotopes\(^5\), where new isomers were found in \(^{145}\text{Cs}\), \(^{146}\text{Cs}\), \(^{147}\text{Cs}\), and \(^{148}\text{Cs}\). To understand the nuclear structure of these neutron-rich Cs isotopes in the low-spin states, we studied the \(\beta\) decay of neutron-rich Xe to Cs isotopes.

The neutron-rich Xe isotopes were produced through in-flight fission reaction using a 345-MeV/nucleon \(^{238}\text{U}\) beam. Particle identification was performed using the mass-to-charge ratio (\(A/Q\)) and the atomic number deduced from the information of time-of-flight (TOF), magnetic rigidity (\(BP\)) and energy loss of fission fragments through BigRIPS and ZeroDegree Spectrometer\(^5\). The isotopes were implanted into a stack of five double-sided Si-strip detectors (WAS3ABi)\(^1\). \(\beta\) rays emitted from the isotopes were also detected by WAS3ABi. The parent nuclei of the \(\beta\) decay were identified by position correlation on the WAS3ABi between the implanted fragments and the detected \(\beta\) rays. \(\gamma\) rays emitted after the \(\beta\) decay were detected by the \(\gamma\)-ray detector array which is called EURICA\(^1\).

![Fig. 1. \(A/Q\) spectrum of neutron-rich Xe isotopes.](image)

Figure 1 shows a spectrum of particle identification for the Xe (\(Z = 54\)) isotopes as a function of \(A/Q\). The fully-stripped \(^{148}\text{Xe}\) ions are separated from the hydrogen-like \(^{A-3}\text{Xe}\) ions owing to the high \(A/Q\) resolution.

Coincidence data of \(\beta-\gamma\) and \(\beta-\gamma-\gamma\) with particle identification of \(^{145}\text{Xe}\), \(^{146}\text{Xe}\), \(^{147}\text{Xe}\), \(^{146}\text{Xe}\), and \(^{147}\text{Xe}\) isotopes is analyzed. As an example, the \(\gamma\)-ray energy spectrum and the decay curve for the \(\beta\) decay of \(^{145}\text{Xe}\) to \(^{145}\text{Cs}\) are shown in Fig. 2. We found 11 new \(\gamma\) rays associated to the transitions in \(^{145}\text{Cs}\) emitted after the \(\beta\) decay of \(^{145}\text{Xe}\). These \(\gamma\)-ray peaks are represented as full circles in Fig. 2. Other peaks are mostly assigned to transitions in the granddaughters \(^{145}\text{Ba}\) nucleus. The inset in Fig. 2 shows the decay curve deduced by the time difference between the implantation of \(^{145}\text{Xe}\) and the detection of the \(\beta\) rays gated on newly found 5 \(\gamma\) rays in \(^{145}\text{Cs}\). The half-life of the \(\beta\) decay was determined to be 197(10) ms, which is consistent with the reported one in Ref. 4. Detailed analyses are in progress.

![Fig. 2. \(\gamma\)-ray energy spectrum and decay curve of the \(\beta\) decay of \(^{145}\text{Xe}\) to \(^{145}\text{Cs}\).](image)

References
Shell evolution in neutron-rich Te isotopes beyond doubly magic $^{132}$Sn


Within the context of the shell model, the nuclear structure is understood in terms of the shell orbital excitation across a large shell gap. In particular, the neutron-rich nuclei with a few valence nucleons at and near the doubly magic nuclei such as $^{132}$Sn always attract attention for testing the various nuclear models in view of the rapidly changing nuclear structure with neutron numbers. In this respect, Sb and Te isotopes, with one and two protons outside the $Z=50$ proton shell closure respectively, form an interesting set of nuclei to study the evolution of the nuclear structure beyond the $Z=50$ and $N=82$ shell closures. This work aims at determining the internal structures of the neutron-rich Sb and Te nuclei and observing the intrinsic nature of the nuclei such as isomerism, shape transition, and dynamic or static deformation.

The nuclei to be investigated were produced and isotope-separated with BigRIPS at the RIBF facility by the in-flight fission of a $^{238}$U beam on a $^{9}$Be production target at 345 MeV/nucleon. Measurements were focused on identification of $E(2^+)$ and/or $E(4^+)$ in even-even $^{138-140}$Te for investigating the $^{132}$Sn core shell evolution and search for level scheme in the nuclei of interest to study the single-particle and collective features based on the $\beta$-decay level scheme. Particle identification was made by BigRIPS on the basis of the $Bp$-EUROTOF method. Further, subsequent $\beta$ decays from the reaction products were detected after the Sb secondary beam was implanted into the active stopper, WASB$^{5}$ with the EURICA array in its stopped-beam configuration.

In the present experiment, we observed, for the first time, the $\beta$-delayed $\gamma$ decay for $^{138}$Sb as an example in Fig. 1. The deduced $\beta$-decay half-life for $^{138}$Sb agrees well with previously reported value, while the half-life of $^{138}$Sb needs more careful analysis to draw a conclusion. We found two new excited states above the known ($4^+$) state in $^{138}$Te and one candidate excited state in $^{140}$Te. We expect that this newly found spectroscopic information on excited states will provide crucial information on shell evolution of neutron-rich Te isotopes and pairing interaction around $N=82$ shell closure. Further analysis is in progress.

References

Fig. 1. Energy spectrum for $\beta$-delayed $\gamma$-decay associated with $^{138}$Sb obtained by coincidence gates on lower transitions in $^{138}$Te. Spectral lines marked by asterisks are newly identified $\gamma$ rays in this work. The inset shows a decay curve for the $\beta$-decay of $^{138}$Sb.
Decay spectroscopy of neutron-rich Z ≈ 60 isotopes


The neutron-rich A~150 region contains a wide variety of shape phenomena, including shape coexistence and possible static octupole and hexadecapole deformations. After the systematic studies of the excited levels of these isotopes, it was found that the nuclei beyond N = 90 or 92 in this region exhibit characteristics of strong quadrupole deformation, such as low-energy 2+ levels and the energy ratio of 4+ to 2+ levels of nearly 3.3. In addition, K isomers were systematically observed,∗1 which indicates stable axial-symmetric deformation because K is a good quantum number in such nuclei and large ΔK transitions are strongly hindered.

In our studies of neutron-rich Nd isotopes through isomer spectroscopy using the EURICA spectrometer,∗2 K isomers were systematically observed up to N = 100.∗3 Gamma rays decaying from the isomer and those of ground-state rotational bands in low-lying levels were observed. The trend of decreasing 4+ → 2+ transition energy with increasing neutron number may indicate the development of quadrupole deformation in neutron-rich Nd isotopes.

Such development of deformation will reflect in the configuration of the ground state, and therefore, the spin and parity of neighboring odd and odd-odd nuclei will be useful for the understanding of the deformed structure. This can be investigated through β-γ spectroscopy.

In order to study the β decay of neutron-rich Pr isotopes, which are parent nuclei of the Nd isotope, β-γ spectroscopic measurement was performed at RIBF. The in-flight fission of 238U at 345 MeV/u was employed to produce neutron-rich Pr isotopes and their neighbors. Nuclei of interest were selected and transported to the final focal plane, F11, using the BigRIPS fragment separator. These isotopes were stopped at the active stopper, WAS3ABi,∗4 and β-γ spectroscopy of these isotopes was performed using the EURICA setup at F11.

Figure 1 shows a γ-ray energy spectrum after the β decay of 156Pr. Gamma peaks at 67 and 155 keV are clearly identified in the spectrum, and they correspond to the previously reported 2+ → 0+ and 4+ → 2+ transitions of 156Nd,∗1 respectively. Based on the obtained results, we will assign the spin and parity of the parent nucleus, 156Pr. In addition, γ transitions associated with the non-yrast levels of 156Nd will be also investigated.

These data are currently being analyzed.

Fig. 1. Gamma-energy spectrum after β decay of 156Pr.

References

*1 Research Center for Nuclear Physics, Osaka University
*2 LPSC, Université Grenoble-Alpes, CNRS/IN2P3
*3 Center for Nuclear Study, The University of Tokyo
*4 RIKEN Nishina Center
*5 Department of Physics, The University of Tokyo
*6 Peking University
*7 Department of Physics, Tohoku University
*8 University of Oslo
*9 The University of Brighton
*10 Department of Physics, Osaka University
*11 ILL
*12 Department of Physics, Rikkyo University
*13 University of Tsukuba
*14 MTA Atomki, Debrecen, Hungary
*15 Hoseo University
*16 The University of Surrey
*17 University of York
*18 Instituto de Estructura de la Materia, CSIC
*19 Universidad Autónoma de Madrid
*20 Beihang University
Investigation of octupole correlations of neutron-rich $Z \sim 56$ isotopes through $\beta$-$\gamma$ spectroscopy


A recent study on the existence of static octupole deformation in Ra isotopes attracted much attention. The interaction between orbits with $\Delta J = \Delta L = 3$ is responsible for octupole correlations and thus the nuclei with orbits having the properties near the Fermi surface are expected to have large octupole correlations. This corresponds to $Z$ or $N \sim 34, 56, 88$, and 134, and neutron-rich Ba isotopes ($Z = 56, N \sim 88$) are also expected to have large octupole correlations. The Ba isotopes have been studied and octupole bands with enhanced E1 transition rates have been discovered. However, the previous study revealed that the E1 rates do not peak at $N = 88$, $^{148}$Ba has large E1 rates comparable to as much as those of $^{144}$Ba, while $^{146}$Ba has much smaller rates. Calculations of octupole correlation have large uncertainty and differ from each other. For example, ref predicts some $\beta_3$ values in $^{150}$Ba while ref argues that the $\beta_3$ of $^{150}$Ba is almost zero. Experimental investigations of neutron-rich isotopes in which no excited state is known, such as $^{150}$Ba, are important to understand the strange systematics of the E1 rates of the Ba isotopes.

We performed $\beta$-$\gamma$ spectroscopy on neutron-rich $Z \sim 56$ isotopes at RIBF. The neutron-rich isotopes were produced using in-flight fission of a 345MeV/nucleon $^{252}$Ce, respectively, after the emission of conversion electrons.

second stage of BigRIPS and by measuring the energy loss by using the ion chamber at the final focal plane, F11. The secondary beam was implanted into an active stopper WAS3ABi, which consists of five layers of double-sided-silicon-strip detectors. The $\gamma$ rays from the implanted nuclei were detected using EURICA, which is an array of 12-cluster Ge detectors in which each cluster consists of 7 crystals.

Figure 1 shows the $\gamma$-ray energy and timing spectroscopy of $\beta$-decay events after the implantation of $^{152}$La. Three known $\gamma$ rays were confirmed at 80.5, 182.5, and 274.6 keV; these had been reported as E2 decays from the 2+, 4+, and 6+ states of the ground-state band of $^{152}$Ce, respectively, by the spontaneous fission of $^{252}$Cf in ref. From this result for $^{152}$Ce, the feasibility of the measurement and analysis has been confirmed. Analysis of Ba isotopes is in progress, and the results may help us understand the octupole correlations of nuclei.

References
5) S. Nishimura et al.: RIKEN APR 46, 182 (2013)
Decay spectroscopy of neutron-rich rare-earth isotopes


The region in the nuclear chart between 50 < Z < 82 and 82 < N < 126 is the largest region between traditional nuclear shells and, thus, ideal to test the evolution of collectivity and K isomerism originating from the high-j orbitals around mid-shell. Neglecting any potential sub-shell closures, the nucleus with the largest number of valence particles in this region is 170Dy with proton number Z = 66 and neutron number N = 104. Accordingly it should be one of the most collective of all nuclei with A < 208, in its ground state. From the high degree of axial symmetry and large deformation we expect several long lived, pure K isomers. In particular, we expect a N = 104, K = 6+ isomer in 170Dy and a N = 106, K = 8− isomer in 172Dy, similar to the N = 102, K = 6− isomers in 166Gd and 164Sm recently published(1).

A EURICA experiment was carried out in November 2014, where a 345 MeV/u 238U beam impinged on a Be target and the fragments separated and identified in the BigRIPS separator and the ZeroDegree spectrometer and implanted in the WAS3ABI active stopper. The experiment was carried out with two settings, 13.5 hours centering on 170Dy and 45 hours centering on 172Dy. The combined PID is shown in Fig. 1.

In Fig. 2, the decay of the known N = 106, K = 8− isomer in 174Er(2) is shown. This shows the capabilities to measure very long lived isomers by triggering on conversion electrons in the 4+ → 2+ and 2+ → 0+ transitions, in this case populated by the β-decay of 174Ho. This is not only the heaviest nucleus that has been measured in EURICA but, with a half life of 4.0 s, it is also the longest lived isomer. Besides the 170Dy, 172Dy, and the previously known 174Er isomers, the experimental data set contains several new isomers, β-delayed γ-rays and new β-decay half-lives. All of these are currently under analysis.

References
Rotational level structure of sodium isotopes inside the “Island of Inversion”

P. Doornenbal,1 H. Scheit,1,2 S. Takeuchi,1 Y. Utsuno,3 N. Aoi,1 K. Li,1,2 M. Matsushita,1,4 D. Stepenbeck,1 H. Wang,1,2 H. Baba,4 E. Ideguchi,5 N. Kobayashi,6 Y. Kondo,6 J. Lee,1 S. Michimasa,5 T. Motobayashi,1 T. Otsuka,5 H. Sakurai,4 M. Takechi,1 Y. Togano,1 and K. Yoneda1

The study of neutron-rich Ne, Na, and Mg nuclei around the breakdown of the $N = 20$ neutron magic number, an area in the Segré chart termed “Island of Inversion”1) has provided a wealth of information on the evolution of nuclear shell structure away from the valley of β stability. Due to its location in the proximity of the neutron drip-line, accessing the “Island of Inversion” is an experimental challenge. In this paper, we report on the first γ-ray spectroscopy performed for the $N = 23, 24$ sodium isotopes $^{34,35}\text{Na}$ and a new transition in $^{33}\text{Na}$. For the latter nucleus, previous measurements suggested that the observed two transitions originate from a $7/2^+_1 \rightarrow 5/2^-_1 \rightarrow 3/2^+_s$ cascade and the energy ratio was found to be close to an ideal $K = 3/2$ rotational band in the strong coupling limit2).

A $^{48}\text{Ca}$ beam with an average intensity of 70 particle nA was accelerated by the Superconducting Ring Cyclotron to 345 MeV/u and incident on a 15 mm thick beryllium production target. A combination of two magnetic dipoles and a 15 mm thick aluminum degrader was utilized to filter a $^{36}\text{Mg}$ secondary beam with the BigRIPS fragment separator3) by applying the $Bp = \Delta E - Bp$ method. For further purification, a second aluminum degrader of 5 mm thickness was inserted at the dispersive focal point of the second BigRIPS stage. After passing BigRIPS, the secondary beams were incident on 2.54 g/cm² carbon and 2.13 g/cm² CH₃ (polyethylene) reaction targets, respectively. BigRIPS was operated with its full momentum acceptance of ±3% and the average intensity of $^{36}\text{Mg}$ was 90 particles per second. Gamma-rays emitted in coincidence with the secondary reactions were detected with the DALI2 array4), which was composed of 186 large-volume NaI(Tl) detectors. The secondary reaction products were identified with the ZeroDegree Spectrometer5).

In the present work, a third γ-ray transition was observed for $^{34}\text{Na}$ at 760(13) keV in addition to the two known ones, and forms a doublet with the $7/2^+_1 \rightarrow 5/2^-_1$ decay. For the odd-odd nucleus $^{34}\text{Na}$, a single γ-ray transition was observed at 451(7) keV, while the energy spectrum of $^{35}\text{Na}$ exhibited transitions at 373(5) and 641(16) keV. The level structure of the odd-even sodium isotopes was found to be well described by the SDPF-M effective interaction6).

References
Owing to the advent of intense radioactive isotope beams over recent years, it has become possible to study the structures of nuclei with large neutron-to-proton ratios using techniques including in-beam \( \gamma \)-ray spectroscopy and decay spectroscopy. One of the focal points of such studies has been the evolution of nuclear shell structure in exotic radioisotopes, where the nuclear ‘magic’ numbers in stable systems have been shown to deviate from their usual values. One such example is the onset of the new neutron magic number \( N = 16 \) in exotic oxygen. On the contrary, the disappearance of the standard magic number \( N = 28 \) has been investigated in \( ^{42}\text{Si} \). In the neutron-rich \( fp \) shell, development of a new subshell closure at \( N = 32 \) has been reported in \( ^{54}\text{Sc} \), \( ^{56}\text{Ti} \), and \( ^{56}\text{Ca} \) isotones, and more recently, a sizable subshell gap at \( N = 34 \) was reported in \( ^{54}\text{Ca} \).9

In the present study, the low-lying structure of \( ^{50}\text{Ar} \) \((Z = 18)\) was investigated using multi-nucleon removal reactions from a fast radioactive beam containing \( ^{54}\text{Ca} \), \( ^{56}\text{Sc} \), and \( ^{56}\text{Ti} \), among other constituents, with the technique of in-beam \( \gamma \)-ray spectroscopy, in order to gain further insight on the magnitude of the \( N = 32 \) subshell closure at \( Z < 20 \). The secondary beam was created using projectile fragmentation of \( ^{70}\text{Zn}^{30+} \) ions at 345 MeV/u and products were identified on an event-by-event basis using the BigRIPS separator. A 10-mm-thick \( ^{9}\text{Be} \) reaction target was placed at the eighth focal plane of BigRIPS to induce nucleon removal reactions and a high efficiency \( \gamma \)-ray detector array9) (DALI2) was employed to measure transitions from nuclear excited states populated by the reactions. Reaction products were identified by the ZeroDegree spectrometer; the particle identification plot for Ar isotopes is provided in Fig. 1. Data acquisition was triggered by the arrival of an ion at the end of ZeroDegree measured in coincidence with at least one \( \gamma \) ray in DALI2. Data were recorded to disk for offline analysis over a time period of approximately two days.

The Doppler-corrected \( \gamma \)-ray energy spectrum, deduced from the sum of the \( ^{9}\text{Be}(^{54}\text{Ca}, ^{56}\text{Ar}+\gamma)X \), \( ^{9}\text{Be}(^{56}\text{Sc}, ^{56}\text{Ar}+\gamma)X \), and \( ^{9}\text{Be}(^{56}\text{Ti}, ^{56}\text{Ar}+\gamma)X \) multi-nucleon removal reactions \((n \geq 1)\), is displayed in

![Fig. 1. Particle identification plot (A/q) for Ar isotopes measured using the ZeroDegree spectrometer.](image1)

![Fig. 2. Two transitions with energies of ~1.2 and, tentatively, ~1.6 MeV are present in the spectrum and are assigned to \(^{50}\text{Ar} \) in the present work. Details on the structure of \(^{50}\text{Ar} \) and the significance of the \( N = 32 \) subshell closure at \( Z < 20 \) will be presented elsewhere.](image2)

References
Experimental study of isoscalar and isovector dipole resonances in neutron-rich oxygen isotopes

N. Nakatsuka,$^{1,2}$ H. Baba,$^{2}$ N. Aoi,$^{10}$ T. Aumann,$^{3}$ R. Avigo,$^{5,11}$ S. R. Banerjee,$^{12}$ A. Bracco,$^{6,14}$ C. Caesar,$^{3}$ F. Camer,$^{5,11}$ S. Cerutti,$^{5,14}$ S. Chen,$^{13,14}$ V. Derya,$^{4}$ P. Doornenbal,$^{5,12}$ A. Giaz,$^{5,14}$ A. Horvat,$^{5}$ K. Ieki,$^{8}$ N. Inami,$^{7}$ T. Kawabata,$^{1}$ K. Yoneda,$^{8}$ N. Kobayashi,$^{8}$ Y. Kondo,$^{9}$ S. Koyama,$^{8}$ M. Kurata-Nishimura,$^{2}$ S. Masuoka,$^{7}$ M. Matsushita,$^{7}$ S. Michimasa,$^{7}$ B. Milon,$^{5}$ T. Motobayashi,$^{2}$ T. Murakami,$^{1}$ T. Nakamura,$^{3}$ T. Ohnishi,$^{11}$ H. J. Ong,$^{10}$ S. Ota,$^{7}$ H. Otsu,$^{2}$ T. Ozaki,$^{9}$ A. Saito,$^{9}$ H. Sakurai,$^{2,8}$ H. Scheit,$^{6,12}$ P. Schrock,$^{3}$ Y. Shiga,$^{11,12}$ M. Shikata,$^{9}$ S. Shimoura,$^{7}$ D. Steppenbeck,$^{2}$ T. Sumikama,$^{3}$ I. Syndikus,$^{3}$ H. Takeda,$^{12}$ S. Takeuchi,$^{2}$ A. Tamii,$^{10}$ R. Taniuchi,$^{8}$ Y. Togano,$^{9}$ J. Tsubota,$^{3}$ J. Tsubota,$^{8}$ O. Wieland,$^{5}$ K. Wimmer,$^{8}$ Y. Yamaguchi,$^{7}$ and J. Zenihiro$^{2}$

Giant resonance is one of the most important phenomena for understanding quantum many-body systems. Neutron-rich nuclei are predicted to have exotic giant resonances due to their smaller neutron separation energy and excess neutrons. One of the exotic giant resonances in neutron-rich nuclei is a dipole resonance found at excitation energies lower than 10 MeV. The nature of these resonances is of great interest. One of the method to understand the nature of these resonances is to investigate if they are iso-vector or iso-scalar resonances. In order to study the relationship between iso-vector and iso-scalar dipole resonances in neutron-rich oxygen isotopes, we performed an experiment at RIBF and measure the dipole resonances of the neutron-rich nuclei $^{20}$O, $^{22}$O, and $^{24}$O. These beams were produced via projectile fragmentation of a 345 MeV/nucleon $^{48}$Ca beam on $^{9}$Be targets with mass thicknesses of 2.8 g/cm$^2$, 2.8 g/cm$^2$, and 2.2 g/cm$^2$. γ rays from the excited beam particles were detected with large volume LaBr$_3$ crystals from INFN Milano in combination with DALI2. Two different targets, 5 g/cm$^2$ Au for coulomb excitation and 300 mg/cm$^2$ liquid helium for inelastic α particle scattering, were used to obtain the iso-vector and iso-scalar dipole strengths respectively.

A preliminary particle identification (PID) plot of Z versus A/Z for the $^{24}$O beam is shown in Fig. 1. PID was performed by the $B_\rho$-ΔE-TOF technique using the BigRIPS. The $B_\rho$ information was reconstructed from the time difference between the left- and right-hand sides of the plastic scintillator installed at the disper-

![Fig. 1. PID plot of the $^{24}$O beam setting](image)

sive focal plane. The achieved purity of $^{20}$O, $^{22}$O, and $^{24}$O was 73%, 66%, and 51%, respectively. PID of the outgoing beams was performed by the same $B_\rho$-ΔE-TOF technique using the ZD spectrometer. Low-pressure multi-wire drift chambers were used to measure $B_\rho$ of the outgoing beams. Figure 2 shows a preliminary PID plot of Z versus A/Z for the outgoing beam where an $^{24}$O beam is on a Au target. The reaction products are clearly observed. The analysis of γ rays is in progress.

![Fig. 2. PID plot of the $^{24}$O beam and the Au target setting on ZD spectrometer](image)

References
Study of the pygmy-dipole resonances of $^{132}$Sn and $^{128}$Sn in inelastic $\alpha$-scattering


Pygmy-dipole resonance is commonly considered as a dipole mode of the nucleus related to a vibration of excess neutrons against a core. As such, it should be related to the neutron richness of the nucleus as well as its neutron-skin thickness. So far, the experimental information on this low-lying dipole mode is astonishingly scarce, even for stable nuclei1). One interesting open question is the isospin character of the low-lying dipole strength. In an experiment with the stable $^{124}$Sn isotope2), it has been concluded that a large fraction of the pygmy strength is of isoscalar character, however significant differences in the strength distribution compared with photoexcitation have been observed.

In November 2014, the isoscalar mode of the pygmy-dipole resonances in $^{128}$Sn and $^{132}$Sn isotopes were measured in inelastic $\alpha$-scattering at RIKEN. The isotopes of interest were produced with a high-intensity primary $^{238}$U beam of 345 MeV/u impinging on a beryllium target. The resulting secondary beam with an energy of approximately 200 MeV/u was directed towards the liquid helium target with a thickness of approximately 300 mg/cm$^2$. The $\gamma$-rays, which are ejected at the target position, have been measured by 8 large-volume 3.5”×8”LaBr$_3$:Ce crystals from Hector INFN Milano3) and 95 large-volume NaI(Tl) DALLI$^2$ crystals. These crystals surrounded the target cham-

Fig. 1. Particle identification plot of the secondary beam after the liquid Helium target, gated on incoming $^{132}$Sn ions determined using the ZeroDegree spectrometer.
Coulomb excitation of $^{130}\text{Cd}$


The properties of the nuclei beyond $^{132}\text{Sn}$ have drawn considerable attention recently because this doubly magic nucleus lies far away the line of β stability. The evolution of the $N = 82$ shell gap to the “south” of $^{132}\text{Sn}$ has been discussed in several studies.\(^\text{1,2}\) For nuclear astrophysics, it has been suggested that the $N = 82$ shell closure affects the $\tau$-process abundance distribution around mass $A \approx 130\text{Sn}$. However, for the $N = 82$ magicity in the Cd ($Z = 48$) isotopes, the mass and the spectroscopy measurements show contradictory results. The $Q_\beta$ value of $^{130}\text{Cd}$ was better reproduced by a mass model assuming a quenched shell gap\(^3\). However, a good shell closure was suggested from the first $2^+$ state as the excitation energy of 1.3 MeV\(^4\) is close to those in other even-even $N = 82$ isotones. In order to investigate the magic character of $N = 82$ in $^{130}\text{Cd}$, we measured the reduced transition possibility $(B(E2))$ via the Coulomb excitation.

The secondary beams were produced from an in-flight fission reaction of a U primary beam at 345 MeV/nucleon incident on a 3-mm-thick Be target located at the object point of the BigRIPS fragment separator.\(^5\) The average beam intensity was about 10 particle nA. The fission products around $^{130}\text{Cd}$ were selected and purified by employing two wedge-shaped aluminum energy degraders with thicknesses of 8 and 2 mm, respectively, located at the dispersive foci. The momentum acceptance of BigRIPS was set to 5%. The secondary beam was identified event-by-event via the TOF $- B_\rho - \Delta E$ method using standard BigRIPS detectors. Figure 1 shows a two-dimensional plot of $Z$ versus $A/Q$ for the secondary beam in BigRIPS. The intensity of the $^{130}\text{Cd}$ beam was 15 counts/s with a purity of 1.3%. The beam energy was about 160 MeV/nucleon before the secondary target.

A 1-mm-thick Bi target was used to induce Coulomb excitation reactions. De-excitation $\gamma$ rays were detected by the DALI2 spectrometer,\(^6\) which surrounded the secondary target. Reaction residues were collected and analyzed by the ZeroDegree spectrometer.\(^5\) The spectrometer was optimized for the transportation of $^{130}\text{Cd}$. Particle identification was performed again using the TOF $- B_\rho - \Delta E$ method, as in BigRIPS. In addition, a LaBr$_3$(Ce) scintillation detector (Saint-Gobain BrilLanCe$^{TM}$380) located downstream of the ionization chamber was used for the total kinetic energy measurement.

The analysis for the $B(E2)$ value is currently in progress.

Fig. 1. Particle identification plot of the secondary beams in BigRIPS.

References

---

*1 RIKEN Nishina Center  
*2 RCNP, Osaka University  
*3 CNS, University of Tokyo  
*4 Department of Physics, Rikkyo University  
*5 Department of Physics, University of Tokyo  
*6 INFN, Italy  
*7 TU Darmstadt, Germany  
*8 Institute for Nuclear Research, Hungary  
*9 Instituto de Estructura de la Materia, CSIC  
*10 School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University  
*11 CEA Saclay, France  
*12 Department of Physics, Tohoku University
Search of E1 strength around threshold in $^{70}$Ni

R. Avigo,¹,² O. Wieland,³ A. Bracco,¹,² F. Camera,¹,² H. Baba,³ N. Nakatsuka,⁴ P. Doornenbal,⁷ Y. Togano,⁷
J. Tscheuschner,⁶ T. Aumann,⁶ G. Benzioni,⁴ N. Blasi,¹ K. Boretzky,⁷ S. Brambilla,¹ S. Ceruti,¹,² S. Chen,⁶
F.C.L. Crespi,¹,² N. Fukuda,⁷ A. Giaz,¹,² K. Ieki,⁷ N. Kobayashi,¹,² Y. Kondo,⁵ S. Koyama,¹ T. Kubo,³ S. Leoni,¹,²
M. Matsushita,¹¹ B. Million,¹ A.I. Morales,¹,² T. Motobayashi,³ T. Nakamura,¹ M. Nishimura,³ S. Nishimura,³ H. Otsu,³
T. Ozaki,² L. Pellegrini,¹,² A. Saito,² H. Sakurai,³ H. Scheit,⁶ P. Schrock,⁶ Y. Shiga,⁷ M. Shikata,³ D. Steppenbeck,⁵
T. Sumikama,¹² S. Takeuchi,³ R. Taniuchi,¹² J. Tsubota,¹ H. Wang,³ and K. Yoneda³

The structure and nature of the E1 strength distribution around the separation energy depends mainly on the neutron excess. Some information in stable nuclei has been obtained in the past but only very few data are available for exotic neutron rich nuclei using mainly Coulomb excitation techniques¹ and references therein.

There is an ongoing discussion on the possibility of extracting information on the neutron skin from the pygmy resonance strength². This quantity can be related to the isospin-dependent part of the nuclear equation of state (EOS) which in turn has relevant implications for the description of neutron stars. Furthermore, the presence of a strength with E1 character close to the particle threshold has important astrophysical implications in explosive nucleosynthesis scenarios.

In order to understand better the characteristics of this pygmy dipole strength it is important to study an isotopic chain of a nucleus with increasing neutron number. As the pygmy dipole strength distribution in $^{68}$Ni around the threshold has recently been studied¹,²,³, a new high intensity and high resolution experiment was performed on $^{70}$Ni at RIKEN Radioactive Isotope Beam Factory (RIBF) in November 2014.

A $^{238}$U primary beam was accelerated up to an energy of 345 MeV and made to impinge on a thick rotating Be production target. In BigRIPS⁴ the Bp-ÅE- Bp method was applied to select and purify a secondary beam of $^{70}$Ni (30 kcps with 40% purity at a beam energy of 260 MeV). The $^{70}$Ni isotope was incident on a 2 g/cm² thick gold secondary target. Reaction residues from the secondary target were identified using the ZeroDegree Spectrometer. Scattering angles were determined using parallel plate avalanche counters.

To detect gamma rays from the decay of different nuclear levels the reaction target was surrounded by a combination of the DALI2 array⁵ (consisting of 96 NaI(Tl) crystals) and 8 large volume 3.5” x 8” LaBr3:Ce detectors⁶ mounted at 30° in the forward direction. These latter detectors have a high efficiency, excellent energy resolution for high energy gamma rays and very good time resolution.

![Particle identification plot (Bp-ÅE- B TOF ) of the secondary beam in front of the Au reaction target. The $^{70}$Ni isotopes are labeled.](image)

Fig. 1 shows the particle identification plot taken during the experiment can be seen. The data are under analysis. The first preliminary outcome will be the 2+ state strength of $^{68}$Ni. This known 2$^+$ → 0$^+$, E2 transition strength will be taken as a benchmark for the determination of the unknown E1 transitions strengths below and above the threshold. Presently high energy gamma ray events in the LaBr3:Ce detectors and add back spectra in DALI2 are being analyzed. The determination of the E1 strength distribution of the measured $^{70}$Ni and the subsequent analysis of the relation between strength and neutron skin together with the data of the measured $^{68}$Ni will give a better and important contribution to the understanding of the features of the pygmy dipole strength.

References
1) O. Wieland et al. PRL 102, 092502 (2009).
6) A. Giaz et al. NIM A729, 910 (2013).
Structure at and beyond the dripline in the vicinity of the N=14 and 16 sub-shell closures


The structure of the neutron-rich nuclei in the vicinity of the N=14 and 16 sub-shell closures have attracted considerable interest in recent years. In particular, $^{19}$B and $^{22}$C represent the heaviest candidate two-neutron halo systems (1-3) whilst also spanning N=14 and 16 below doubly-magic $^{22,24}$O. In terms of the most neutron-rich oxygen isotopes, the behaviour beyond $^{20}$O, with the ultimate goal of investigating $^{28}$O, has taken on renewed interest in the light of recent improvements in sophisticated structure modelling (4,5). The present report describes the status of the analysis of data acquired during a series of three experiments undertaken with these goals in mind, as part of the initial phase of operation of the SAMURAI spectrometer (6) coupled to the large area neutron array NEBULA (7) and DALI2 (8) NaI array. One of the systems of particular interest in terms of modelling $^{22}$C and the evolution of the $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$ levels is $^{21}$C (9), the unbound sub-system of Borromean $^{22}$C. In the present work we have attempted to populate $^{21}$C via both neutron and proton removal from $^{22}$C and $^{22}$N respectively, whereby it is expected that the different valence neutron configurations of the projectile ground states should result in the population of correspondingly different final states. Figure 1 shows the reconstructed $^{20}$C+n invariant mass (or decay energy) spectra for the two reactions. As may be seen, the selectivity of the two reactions is markedly different, with neutron removal from $^{22}$C exhibiting in particular a rather narrow structure close to 1.5 MeV. We note that in comparison to the featureless, but very limited statistics spectrum of Ref. (10), the proton removal from $^{22}$N shows here a very pronounced structure at around 1 MeV.

The further analysis of these preliminary results is currently underway, including the extraction of the $^{20}$C+n momentum distribution for the neutron removal channel, which will shed light on the angular momentum of the removed neutron and hence the character of the corresponding $^{21}$C states. Analysis of the data acquired for two-proton removal from $^{22}$O is also in progress with the initial results exhibiting a decay.

![Fig. 1. Preliminary results for the $^{20}$C+n decay energy spectra obtained for neutron (upper) and proton (lower panel) removal reactions at 240 MeV/nucleon. The dotted line, normalised at high decay energy, represents an event-mixed estimate of the corresponding uncorrelated distribution.](image-url)
shows the preliminary results obtained for the 24-sis of the data obtained for proton removal from 26F at 212 MeV/nucleon. The solid curve shows the results of a fit assuming a single resonance (see text).

Table 1. Intensities, in terms of the 48Ca primary beam (354 MeV/nucleon) intensity (pmA), for the secondary beams employed to investigate 25,26O. The momentum acceptance of the BigRIPS separator is noted in each case as is the mean secondary beam energy.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (MeV/nucleon)</th>
<th>ΔP/P (%)</th>
<th>Intensity (kpps/100pmA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27F</td>
<td>241</td>
<td>±3</td>
<td>1.0</td>
</tr>
<tr>
<td>28Ne</td>
<td>212</td>
<td>±3</td>
<td>29</td>
</tr>
<tr>
<td>26F</td>
<td>212</td>
<td>±0.6</td>
<td>2.5</td>
</tr>
<tr>
<td>27Ne</td>
<td>240</td>
<td>±0.6</td>
<td>14</td>
</tr>
</tbody>
</table>

energy spectrum similar to that observed in single-proton removal from 22N.

Data was also acquired for reactions of 19B and 22C beams on a Pb target with the goal of deducing the E1 strength functions for the two-neutron dissociation channel. This should enable further constraints to be placed on the halo structure of both nuclei as well as insight into the halo neutron spatial configurations11. The analysis of the data is ongoing, with very preliminary results indicating that both nuclei exhibit considerable near threshold strength.

In the case of the heavy oxygen isotopes, the analysis of the data obtained for proton removal from a 26F beam to populate 25O is in its final stages. Figure 2 shows the preliminary results obtained for the 24O+n decay energy spectrum, including a comparison with the best fit results for an ℓ=2 resonance. A resonance energy of 0.75 MeV and width of 0.09 MeV have been estimated, which are in line with the results of earlier studies undertaken elsewhere employing the same reaction12,13.

Work is currently proceeding to finalise the analysis of the data acquired for single-proton removal from 27F to populate 26O. To date the 24O+2n decay energy spectrum has been successfully reconstructed after implementation of neutron cross talk rejection procedures based on kinematic conditions. The spectrum exhibits a feature at around 1.3 MeV, which represents the first observation of an excited (presumably 2+) state in 26O, together with a very sharp peak at threshold corresponding to the ground state13,14. A detailed analysis is being performed to determine the characteristics (energies and widths) of both states. The considerably higher statistics obtained in the present work should allow for a much more precise determination of the ground state energy. In the near future the data acquired for the two-proton removal from 27,28Ne will also be exploited in the hope of providing further insight into the structure of 25,26O.

We note that in an earlier report15, intensities were quoted for the secondary beams employed for the investigation of 25,26O. For reference, for future experiments, Table 1 lists updated determinations of the intensities.

The work described here relating to the investigation of 21C forms part of the PhD thesis of S. Leblond (LPC-Caen).

References
Study of neutron-unbound states of $^{19}$C at SAMURAI

J.W. Hwang,*1,2 Y. Satou,*1 S. Kim,*1,2 N. A. Orr,*3 T. Nakamura,*1,2 Y. Kondo,*1,2 N. L. Achouri,*3 T. Aumann,**4 H. Baba,*2 F. Delaunay,*3 P. Doorenbal,*2 N. Fukuda,*2 J. Gibelin,*3 N. Inabe,*2 T. Isobe,*2 D. Kameda,*2 D. Kanno,*4 N. Kobayashi,*1,2 T. Kobayashi,*1,2 T. Kubo,*2 S. Leblond,*3 J. Lee,*2 F. M. Marques,*1 R. Minakata,*1,2 T. Motobayashi,*2 D. Murai,*5 T. Murakami,*5 K. Muto,*6 N. Nakatsuka,*8 T. Nakashima,*1,2 A. Navin,*9 S. Nishi,*1,2 S. Ogoshi,*1,2 H. Otsu,*2 H. Sato,*2 Y. Shimizu,*2 H. Suzuki,*2 K. Takahashi,*6 H. Takeda,*2 S. Takeuchi,*2 R. Tanaka,*4,2 Y. Togano,*10,13 A. G. Tuff,*11 M. Vandenbroucke,*12 and K. Yoneda*2

The neutron-unbound region of the nuclear level structure has been investigated extensively in recent years, especially for nuclei near the neutron drip line. In this report, we provide the result of the experiment to study neutron-unbound states in $^{19}$C by using a one-neutron knockout reaction. The report contains the outcome of the succeeding research following the report in the previous year.1)

The experiment was performed at the RIBF facility. A $^{18}$C secondary beam at 280 MeV/nucleon separated by BigRIPS impinged on a 1.8 g/cm$^2$-thick carbon target. Neutron-unbound states of $^{19}$C produced by one-neutron knockout decays into a $^{18}$C ion and a neutron. $^{18}$C was identified and its momentum was measured using the SAMURAI spectrometer2) with the help of its experimental apparatus. Arrays of plastic scintillators for neutron detection (NEBULA) were used to measure the momenta of decay neutrons.3) The experimental setup is identical to that of Ref.1).

A preliminary relative energy spectrum for the system of $^{18}$C + n (filled circles). The black solid line is the result of the fit; the dashed lines are for the two resonances; the dot-dashed line is the assumed background. (see details in the text)

Fig. 1. Preliminary relative energy spectrum for the system of $^{18}$C + n (filled circles). The black solid line is the result of the fit; the dashed lines are for the two resonances; the dot-dashed line is the assumed background. (see details in the text)

cause of the significant threshold resonance. Three resonances were observed at $E_{\text{rel}} = 36 \pm 1$ keV, $0.84 \pm 0.02$ MeV and $2.33 \pm 0.01$ MeV, corresponding to the states of $E_x = 0.62(9)$ MeV, $1.42(9)$ MeV, and $2.91(9)$ MeV, respectively, based on the formula: $E_x = E^0_{\text{rel}} + S_n$, where $S_n$ is the one-neutron separation energy of $^{18}$C (0.58(9) MeV).) Note that all values are preliminary. While the first and second resonances are consistent with the $5/2^+_1$ and $5/2^+_2$ states reported by the knockout experiment5) and the inelastic scattering measurement7), respectively, the third one was observed for the first time in the present study. A next step of analysis is planned to obtain the parallel momentum distribution of the knockout residue to investigate spins and parities of the observed states.

References

*1 Department of Physics and Astronomy, Seoul National University

*2 RIKEN Nishina Center

*3 LPC-Caen, ENSICAEN, Université de Caen, CNRS/IN2P3

*4 Department of Physics, Tokyo Institute of Technology

*5 Institut für Kernphysik, Technische Universität Darmstadt

*6 Department of Physics, Tohoku University

*7 Department of Physics, Rikkyo University

*8 Department of Physics, Kyoto University

*9 GANIL, CEA/DSM-CNRS/IN2P3

*10 ExtreMe Matter Institute (EMMI) and Research Division, GSI

*11 Department of Physics, University of York

*12 Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS

*13 Present address: Department of Physics, Tokyo Institute of Technology

- 44 -
Measurement of unbound states in $^{17}$C at SAMURAI

S. Kim,$^{1,2}$ Y. Satou,$^{1}$ J.W. Hwang,$^{1,2}$ T. Nakamura,$^{2,3}$ N. A. Orr,$^{4}$ Y. Kondo,$^{2,3}$ J. Gibelin,$^{4}$ N. Kobayashi,$^{2,3}$ R. Tanaka,$^{2,3}$ R. Minakata,$^{2,3}$ S. Ogoshi,$^{2,3}$ S. Nishi,$^{2,3}$ D. Kanno,$^{2,3}$ T. Nakashima,$^{2,3}$ N. L. Achouri,$^{4}$ T. Aumann,$^{5}$ H. Baba,$^{2}$ F. Delaunay,$^{4}$ P. Doornenbal,$^{2}$ N. Fukuda,$^{2}$ N. Inabe,$^{2}$ T. Isobe,$^{2}$ D. Kameda,$^{2}$ T. Kobayashi,$^{6,2}$ T. Kubo,$^{2}$ S. Leblond,$^{4}$ J. Lee,$^{2}$ F. M. Marquès,$^{4}$ T. Motobayashi,$^{2}$ D. Murai,$^{7}$ T. Murakami,$^{8}$ K. Muto,$^{6}$ N. Nakatsuka,$^{8}$ A. Navin,$^{9}$ Y. Otsu,$^{2,3}$ H. Sato,$^{2,3}$ Y. Shimizu,$^{2}$ H. Suzuki,$^{2}$ K. Takahashi,$^{6}$ H. Takeda,$^{2,3}$ S. Takeuchi,$^{2,3}$ Y. Togano,$^{10,13}$ A. G. Tuff,$^{11}$ M. Vandebrouck,$^{12}$ and K. Yoneda$^{12}$

To study unbound states in $^{17}$C above the neutron separation energy of 0.735(18) MeV,$^{1}$ an experiment was performed at RIBF during the first physics run of the SAMURAI spectrometer.$^{2}$ The unbound states of $^{17}$C were produced using the one-neutron knockout reaction of $^{18}$C. The $^{18}$C beam was provided by BigRIPS. The beam intensity was typically 2300 pps with the energy of 250 MeV/nucleon under the momentum acceptance of $\pm$3%. Particle identification of the beam was carried out by employing the $B_{\rho}$-TOF-$\Delta E$ method with a mass resolution of $A/\Delta A = 770$ at 1 sigma. The unbound states of $^{17}$C populated by one-neutron knockout of $^{18}$C on a carbon reaction target with a thickness of 1.8 g/cm$^2$ immediately decays into a $^{16}$C fragment and a neutron. The particle identification of this fragment was also carried out using detector array DALI2$^3)$. The $^{16}$C was detected by a $\gamma$-ray detector array NEBULA consisting of neutron detectors (NEUT) and charged-particle veto detectors (VETO). For NEUT, the timing resolution was 270 ps in a flight length of approximately 11 m.

The relative energy ($E_{rel}$) of $^{17}$C was reconstructed using the momentum vectors of the $^{16}$C fragment and the neutron. To determine the positions of the resonances, responses were generated using a Monte Carlo simulation that considers the beam characteristics, reaction mechanism, and detector resolutions. From the simulation, the $E_{rel}$ resolution was evaluated as $\Delta E_{rel}$

$$= 0.4 \sqrt{E_{rel} \text{MeV}} \text{ in FWHM}.$$  

A preliminary result of the fitting to the experimental spectrum with three responses and a Maxwellian background is shown in Fig. 1 where resonances at $E_{rel} = 0.58(3), 2.01(2),$ and 3.30(6) MeV are observed. In this measurement, the resonance at $E_{rel} = 0.58(3)$ exhibited a correlation with a gamma line at 1.72(12) MeV, which corresponds to the $2^+$ state of $^{16}$C$^3)$. Consequently, the three resonances correspond to excited states at 3.04(12), 2.75(3), and 4.04(6) MeV. The excited states at 2.75(3) and 4.04(6) MeV are likely to correspond to the $2^+$ states of $^{16}$C$^3)$. Further analysis involving a comparison with Glauber model calculations is in progress to investigate the orbital angular momentum and spin-parity of the observed resonances.

References
Detailed analysis of tracking detectors for SAMURAI08 experiment

S. Koyama,*1,*2 H. Otsu,*2 for SAMURAI08 collaboration

We performed an experiment at SAMURAI to search for α-cluster levels in 16C.1) The levels were populated by bombarding a 16C secondary beam on a liquid He target. The excitation energies were reconstructed from the invariant mass of the 16C* → 12Be + 4He decay channel by measuring their four momenta. The four momenta were deduced from timing measurements and the tracking of drift chambers (DCs). For these DCs, the tracking efficiency and position resolution depend on the energy loss in the detector, which depends on the element number (Z) of penetrating fragments. In order to determine the four momenta accurately, the parameters for tracking should be separately optimized for each Z.

Figure 1 shows a particle identification (PID) plot of reaction products measured using the plastic scintillator array HODF and HODP.2) Note that 1 scintillator out of 32 of the array on which the secondary beam directly hits with an intensity of 2 × 106 is excluded.

Fig. 1. PID plot of reaction products. The vertical axis shows the mean light output and the horizontal axis shows the time of flight (TOF) between the plastic scintillator placed upstream of the target and HODF and HODP.

DCs consist of more than 3 planes with different kinds of wire orientations. FDC2,2) which was placed downstream of the SAMURAI magnet2) (B = 2.3 T at the center), has 6 X (vertical, 0°), 4 U (+30°) and 4 V (−30°) planes. The drift length on each plane is measured and the trajectories of fragments for one axial direction, x = a0 + a1z, are reconstructed by fitting a linear function, where x is the position orthogonal to the beam line, a0 and a1 are linear fitting parameters and z is the position along the beam line. The x positions of fragments in the k-th plane of a DC xk are deduced from the time-to-digital converter (TDC) spectrum with a space-time conversion (STC) function, which converts time information to drift length. The STC function is first obtained by integrating the TDC spectrum and is corrected in response to the result of tracking. Figure 2 (a) shows the two STC functions optimized for Z = 2 and Z = 4 fragments. The difference between the two functions is clear. The residue rk is defined as

\[ r_k = x_k - x_k' \]

where \( x_k \) is the position of the k-th plane. Figs. 2 (b) and (c) show how \( x_k - r_k \) correlation changes when a different STC function is applied for tracking. The positions are well reconstructed when the optimized STC function is applied (Fig. 2 (b)) while they systematically deviate from the case in which an inappropriate STC function is applied (Fig. 2 (b)).

The position resolution of the k-th plane of a DC \( \Delta x_k \) can be evaluated using the standard deviation of the residue of the plane \( \Delta r_k \) as follows:

\[
\Delta r_k = \sqrt{1 - \frac{S_{zz} - 2S_z z_k + S_z z_k^2}{D}} \Delta x,
\]

where \( S_1 = \sum_k S_{zz} \), \( S_z = \sum_k z_k \), \( S_{zz} = \sum_k z_k^2 \), and \( D = S_1 S_{zz} - S_z^2 \). It is assumed that \( \Delta x_k \) has the same value \( \Delta x \) in the same wire-oriented planes of a DC to deduce Eq. 1. Table 1 summarizes the position resolutions of X, U, and V planes with the optimized STC function for each Z. The position resolution of FDC2 is 120 µm2) for Z = 6. Note that the value of the high voltage (2.4 kV) is not optimized for one Z to measure fragments with different Z in this experiment.

Table 1. Resolution of each plane of FDC2

<table>
<thead>
<tr>
<th>Wire orientation</th>
<th>Resolution (µm)</th>
<th>Resolution (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z=2</td>
<td>Z=4</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>342</td>
<td>309</td>
</tr>
<tr>
<td>U</td>
<td>255</td>
<td>195</td>
</tr>
<tr>
<td>V</td>
<td>257</td>
<td>199</td>
</tr>
</tbody>
</table>

References
Fission Barrier Studies of Neutron-Rich Nuclei via the (p,2p) Reaction: Status of NP1306-SAMURAI-14 Experiment


The aim of NP1306-SAMURAI-14 is to experimentally determine fission barrier heights in neutron-rich nuclei “north east” of doubly-magic $^{208}\text{Pb}$ using RIB’s at RI Beam Factory (RIBF) at RIKEN. The results will drastically improve our experimental knowledge on fission barriers away from stability which is poor at present. Neutron-rich nuclei around Z ≈ 82 and N > 126 are good subjects to be studied because the isospin dependence of fission barriers in those nuclei are quite controversial: The Rotating Liquid Drop Model predicts an increase of barrier heights with neutron number, while modern, more microscopic fission models make completely different and, depending on the model, quite varying behaviors (see e.g.1) and references therein). The behavior of fission barriers towards neutron-rich nuclei has a direct impact on the r-process2), which is believed to produce about half of the stable heavy elements in the universe.

The basic idea is to use the quasi-free (p,2p) reaction in inverse kinematics to excite the nuclei of interest. Heavy neutron-rich nuclei provided at the RI Beam Factory bombard a hydrogen target and measurements of proton four-momenta tells us an excitation energy of the neutron-rich isotopes. In case that fission takes place, the two fission fragments are detected and analyzed with the large-acceptance SAMURAI spectrometer3). This allows to extract a threshold energy for the fission process.

For this experiment, heavy secondary beams must be produced from a primary $^{238}\text{U}$ beam and identified using BigRIPS. This is a difficult task as the secondary fragments after the production target have very similar A/Q ratios compared to the primary beam, which has to be stopped in the beam dump after the D1 magnet. A first test was performed from the BigRIPS team in autumn 2014 to produce neutron-rich Polonium (Z=84) nuclei (N. Inabe et al. in the present volume of this APR).

In April 2014, we performed a one day test at the SAMURAI setup using a stable $^{238}\text{U}$ beam. The experimental setup was basically identical to the one used for experiment NP1306-SAMURAI-17 (M. Sako in the present volume of this APR). To keep the beam intensity below $5\cdot10^3$ pps in the SAMURAI area, the $^{238}\text{U}$ beam was produced as a secondary beam, using a 5 mm Be production target. The best setting was found by choosing the Q=87+ charge state after the target, followed by a Q=90+ charge state after a thin aluminum degrader. In this way, 40 kHz beam rate after BigRIPS was achieved using 0.75 pnA primary beam intensity. The beam purity was better then 98 %. The beam hit a 1 cm liquid hydrogen target. A multiplicity trigger of the WINDS array (see reports of the present volume of the APR) was used to trigger on possible (p,2p) events close to the target. These data are currently analyzed by S. Reichert. Indeed, based on time-of-flight and QDC information, coincident protons follow the expected kinematics of quasi-free scattering. However, in order to achieve the desired missing mass resolution, a new high-resolution proton-detection system is currently under development in collaboration of the TU Munich and RIKEN. The status of the development of this setup can be found in the report of S. Reichert et al. in the present volume of this APR.

The test experiment also gives first results about the response and performance of various detectors of the SAMURAI setup on high-Z beams. The mass and charge resolution for the identification of fission fragments is currently analyzed by M. Sako (see report in the present volume of this APR). Furthermore the data allow us to study the tracking efficiency of coincident fission fragments. A first analysis about the identification of fission fragments using the FDC1 detector was done by S. Reichert (see report in the present volume of this APR).

References
Identification of fission fragments from tracks measured by the FDC1


The purpose of the experiment NP1306-SAMURAI14 is to characterize parameters of fission of neutron rich heavy nuclei, like the fission barrier heights and the fragment distributions. As a first step, we performed in April 2014 a 24-hour beamtime experiment using 238U as primary beam at 250 MeV/u and an intensity of 5 × 10^7 pps. A liquid hydrogen target in the setup of NP1306-SAMURAI17 was used as a secondary target.

In this report we present a method to identify fission fragments by the forward drift chamber 1 (FDC1) which is positioned upstream in front of the SAMURAI spectrometer. In the beam direction, the FDC1 has 14 layers. For each layer the positions of the particles passing the active volume are determined. The most likely trajectory is defined as the composition of the available positions in all layers which has the smallest \(\chi^2\). When two fission fragments are incident, there are two possible positions for all the layers and their tracks are given by the two smallest \(\chi^2\) values.

In Fig. 1 we show examples of trajectories through the 14 layers in beam axis of the FDC1. In Fig. 1(a) the number of possible positions of the particles in each layer is one. Hence the track corresponds to a beam-like particle, showing no fission reaction is induced. The situation in Fig. 1(b) is totally different where each layer has two entries and two tracks with a large gap can be reconstructed. Such events are interpreted as two particles crossing the FDC1 at the same time.

For these cases the distance \(b\) between their intersection points and the first layer of the FDC1 in beam direction is obtained by

\[
b = \frac{a_1 + a_2}{\tan \theta_1 + \tan \theta_2}
\]

where \(\theta_1/2\) are the angles of the two fission fragments 1 and 2 in respect to the beam axis and \(a_{1/2}\) are defined as their most probable intersection point with the first layer of the FDC1.

The results for two 1/2 h runs with each with the

---

*1 Technical University Munich  
*2 RIKEN Nishina Center  
*3 ASRC JAEA  
*4 Technical University Darmstadt  
*5 Center for Nuclear Studies, University of Tokyo  
*6 ANL  
*7 Tohoku University  
*8 Tokyo Institute of Technology  
*9 Kyoto University
Our experimental program NP1306-SAMURAI4) is the first attempt to determine fission barrier height for neutron-rich heavy nuclei such as 212Bi or 213Po. In this experiment, we use missing mass spectroscopy to determine the excitation energy of the fissioning nucleus produced by the (p,2p) reaction in combination with the SAMURAI spectrometer.

In this report, we show preliminary results of data analysis for the test experiment performed using a primary 238U beam with a typical intensity of 5×10^4 pps and at a beam energy of 250A MeV. Liquid hydrogen with a 10-mm thickness was used as the secondary target to study the proton induced (p,2p) reaction.

Figure 1(a) shows the layout of the experimental setup in the downstream part of the SAMURAI spectrometer2,3): the forward drift chamber 2 (FDC2), the ion chamber for fragment (ICF), the hodoscope (HODS), and the total energy detector (TED). HODS has seven slats of plastic scintillators. Here, we label the slats with IDs from 0 (lower rigidity side) to 6 (higher rigidity side). TED is an array of 8×4 CsI crystals, labeled from 0 to 7 corresponding to HODS for the second row from the bottom side.

Figure 1(b) shows the energy deposition for the slit ID = 1 in HODS without any constraint on the HODS multiplicity, while Fig. 1(c) is constrained by multiplicity = 2. A peak around 3000 ch in Fig. 1(b) corresponds to 238U beam, which disappears with the multiplicity gate. A bump structure around 1000 ch corresponds to fission fragments in Fig. 1(c).

Figure 2 shows two-dimensional histograms of the ∆E-E correlation for fission fragments. Slats ID = 1 (left) and 6 (right) in HODS are selected for ∆E, while the crustal ID = 1 and 6 are selected for total E. The multiplicity gate is applied to Fig. 2 (b) and (d). The test experiment was successful to measure the fission fragments associated with the (p,2p) reaction.

References
The study of neutron-proton (np) correlations in nuclei is very important to understand the nuclear structure. Direct two-nucleon knockout reactions offer a powerful tool for quantitative measurements of the np correlations in N = Z nuclei. The measured inclusive two-nucleon knockout cross sections show significant enhancement of np (T = 0 & 1) over np (T = 1) correlations in 12C. The shell-model calculation for the two-nucleon overlaps within the p shell can reproduce the inclusive cross sections for like-nucleon pair removal, but underestimates the np-pair removal cross section by a factor of two. This discrepancy implies insufficient description of the T = 0 np interactions in the shell-model wave functions. A recent calculation using the no-core shell model that exploits modern chiral effective field theory NN+3N interactions suggests that the final-state-exclusive np-knockout cross sections from 12C to the T = 0 states can provide an immediate test of the np-shell-model wave function. The experiment was carried out at RIBF. The secondary 12C beam (presently not available as the primary beam for SRC-use experiments) was produced by fragmentation of an 18O primary beam at 250 MeV/u using a 5-mm thick Be target. The ions of interest were selected using the BigRIPS fragment separator by measuring the energy loss (ΔE) and time of flight (TOF) with plastic scintillators at the intermediate focus F3 and F13. The incident angle and position of the beam on a 1.879-g/cm2 thick Be target were determined by two drift chambers, BDC1 and BDC2. The target was surrounded by the DALI2 γ-ray spectrometer. One hundred and fifty-nine crystals of DALI2 were employed with an azimuthal angular coverage from 25° to 154°. The mid-target energy of 12C was approximately 190 MeV/u. Reaction products were transported to the SAMURAI spectrometer and identified with the Bp-ΔE-TOF method. The magnetic rigidity Bp was determined from the measured positions at the forward drift chambers, FDC1 and FDC2. ΔE and TOF were measured by using the plastic scintillator hodoscopes, HODF and HODP. Fig. 1 shows the particle identification of reaction residues. It should be noted that the reaction channels of interest were measured simultaneously because of the large acceptance of SAMURAI.

The preliminary ratio of inclusive np- to pp-removal cross sections was obtained, which is consistent with the previous result within errors. Currently, the γ-ray spectrum analysis is ongoing. Further, the partial cross sections will be extracted.

References
Measurement of the $^{132}$Sn$(p,n)$ reaction at 270 MeV/nucleon

M. Sasano,*1 J. Yasuda,*2 R.G.T. Zegers,*5 H. Baba,*1 W. Chao,*1 M. Dozono,*1 N. Fukuda,*1 N. Inabe,*1 T. Isobe,*1 G. Jhang,*1,13 D. Kamae,∗1 T. Kubo,*1 M. Kurata-Nishimura,*1 E. Milman,∗1 T. Motobayashi,*1 H. Otsu,*1 V. Panin,∗1 W. Powell,∗1 M. Sako,∗1 H. Sato,∗1 Y. Shimizu,∗1 L. Stuhl,∗1 H. Suzuki,∗1 T. Suwats,*1 T. Takenaka,*1 T. Uesaka,*1 K. Yoneda,∗1 J. Zenihiro,∗1 T. Kobayashi,∗1 T. Sumikama,∗4 T. Takano,*4 T. Nakamur,∗5 Y. Kondo,∗5 Y. Tokago,∗5 M. Shikata,∗6 J. Tsutoba,∗5 K. Yako,∗6 S. Shimoura,∗6 O. Ota,∗6 S. Kawase,∗6 Y. Kubota,∗6 M. Takaki,∗6 S. Michimasa,∗6 K. Kisamori,∗6 C.S. Lee,∗6 H. Tokieda,∗6 M. Kobayashi,∗6 S. Koyama,∗7 N. Kobayashi,∗7 H. Sakai,∗8 T. Waka,∗2 S. Sakaguchi,∗2 A. Krasznahorkay,∗9 T. Murakami,∗10 N. Nakatsuka,∗10 M. Kaneko,∗10 Y. Matsuda,∗11 D. Mucher,∗12 S. Reichert,∗12 D. Bazin,∗3 and J.W. Lee*13

Among the collective modes1), the Gamow-Teller (GT) giant resonance is an interesting excitation mode. It is a $0\hbar\omega$ excitation characterized by the quantum-number changes of orbital angular momentum ($\Delta L = 0$), spin ($\Delta S = 1$), and isospin ($\Delta T = 1$), and induced by the transition operator $\sigma_T$. In the stable nuclei in medium or heavier mass regions ($A > 50$), the collectivity in this mode exhibits the GT giant resonance (GTGR), which gives information that is critically important for understanding the isovector part of the effective nucleon-nucleon interaction2) and the symmetry potential of the equation of the state3).

The goal of the NP1306-SAMURAI17 experiment performed in Spring 2014 was to extract the GT and spin-dipole (SD) transition strengths over a wide excitation range covering their giant resonances on the key doubly magic nucleus $^{132}$Sn via the charge-exchange $(p,n)$ reaction at 270 MeV/nucleon in inverse kinematics. This is an essential step toward establishing comprehensive theoretical models for nuclei situated between $^{78}$Ni and $^{208}$Pb; at the same time, this is a milestone for extending the research on various phenomena in stable nuclei such as GT quenching, and nuclear weak processes of astrophysical interest, to the neutron-rich region far from the beta stability. An experimental technique based on the missing mass spectroscopy4,5) was employed to reconstruct the excitation energy spectra for the reaction.

In the experiment, a secondary beam of $^{132}$Sn at 270 MeV/nucleon was produced through an abrasion-fission reaction with a 345 MeV/nucleon primary beam of $^{238}$U. The resulting cocktail beam had a total intensity of $1.4 \times 10^4$ pps, containing $^{132}$Sn with a purity of 45%. The particle identification (PID) was performed on an event-by-event basis by measuring the energy loss in the ionization chamber at the F7 focal plane, and the magnetic rigidity and the time of flight of the beam particles in the BigRIPS spectrometer.

Figure 1 shows a top view of the experimental setup around the SAMURAI spectrometer6). The secondary beam was impinged on a liquid hydrogen target7) before the entrance of the SAMURAI magnet. The recoil neutrons were detected by using the Wide-angle Inverse-kinematics Neutron Detectors for SHARAQ (WINDS) surrounding the target. The PID of the reaction residues was performed with the SAMURAI spectrometer and the decay neutrons from the residues were detected with the NEBULA. Detailed reports on the WINDS setup, the PID analysis in the SAMURAI spectrometer, and the NEBULA DAQ based on a fast clear mode are given in other reports in the current volume of the APR. The analysis is in progress. In preliminary results, the kinetic curves corresponding to the $(p,n)$ reaction are clearly observed; this indicates that the experiment worked as planned.

References
Experimental study on neutron-neutron correlation in Borromean nuclei via the \((p, pn)\) reaction at intermediate energy with the SAMURAI spectrometer

Y. Kubota,\textsuperscript{1,2} A. Corsi,\textsuperscript{3} G. Antchev,\textsuperscript{3} H. Baba,\textsuperscript{2} C. Caesar,\textsuperscript{4} D. Calvet,\textsuperscript{3} A. Delbart,\textsuperscript{3} M. Dozono,\textsuperscript{1} J. Feng,\textsuperscript{5} F. Flavigny,\textsuperscript{6} J.-M. Gheller,\textsuperscript{3} J. Gibelin,\textsuperscript{7} A. Gillibert,\textsuperscript{3} K. Hasegawa,\textsuperscript{8} T. Isobe,\textsuperscript{2} Y. Kanaya,\textsuperscript{9} S. Kawakami,\textsuperscript{9} D. Kim,\textsuperscript{10} Y. Kiyokawa,\textsuperscript{11} M. Kobayashi,\textsuperscript{11} N. Kobayashi,\textsuperscript{11} T. Kobayashi,\textsuperscript{8} Y. Kondo,\textsuperscript{12} Z. Korkut,\textsuperscript{13} S. Koyama,\textsuperscript{11} V. Lapoux,\textsuperscript{3} Y. Maeda,\textsuperscript{9} F. M. Marquès,\textsuperscript{7} T. Motobayashi,\textsuperscript{2} T. Miyazaki,\textsuperscript{11} T. Nakamura,\textsuperscript{12} N. Nakatsuka,\textsuperscript{14,15} Y. Nishio,\textsuperscript{15} A. Obertelli,\textsuperscript{3} A. Okhura,\textsuperscript{15} N. A. Orr,\textsuperscript{17} S. Ota,\textsuperscript{1} H. Otsu,\textsuperscript{2} T. Ozaki,\textsuperscript{12} V. Panin,\textsuperscript{2} S. Paschalidis,\textsuperscript{4} E. C. Pollacco,\textsuperscript{3} S. Reichert,\textsuperscript{16} J.-Y. Roussé,\textsuperscript{3} S. Saito,\textsuperscript{12} S. Sakaguchi,\textsuperscript{15} M. Sako,\textsuperscript{2} C. Santamaría,\textsuperscript{3} M. Sasaki,\textsuperscript{2} H. Sato,\textsuperscript{2} M. Shibata,\textsuperscript{15} Y. Shimizu,\textsuperscript{12} Y. Shindo,\textsuperscript{15} L. Stuhl,\textsuperscript{2} T. Sumikama,\textsuperscript{8} M. Tabata,\textsuperscript{15} Y. Togano,\textsuperscript{12} J. Tsubota,\textsuperscript{15} T. Uesaka,\textsuperscript{2} Z. Yang,\textsuperscript{5} J. Yasuda,\textsuperscript{15} K. Yoneda,\textsuperscript{2} and J. Zenihiro\textsuperscript{12}

Dineutron correlation is one of the symbolic phenomena expected to appear in neutron drip-line nuclei. It has been studied using different approaches, such as the transfer reaction and the break up reaction. However, currently available data seem to be insufficient to study the neutron-neutron correlation in terms of (i) the decomposition of high-angular-momentum components, (ii) the extraction of a core excitation, (iii) and the effect of final state interactions (FSIs).\textsuperscript{15} In this study, (i) the MINOS\textsuperscript{2}) was used for higher luminosity, (ii) \(\gamma\) rays were detected to tag the core excitation, (iii) and the quasi-free \((p, pn)\) reaction was employed to minimize the FSI.

The experiment was performed at RIBF. Secondary beams were produced and separated by the BigRIPS, by projectile fragmentation of a \(^{48}\text{Ca}\) primary beam at 345 MeV/nucleon with a typical intensity of 400 particle nA in a 20-mm or a 30-mm thick Be target. They were detected and identified using plastic scintillators at the focal planes F3, F5, F7, and F13 and multi-wire drift chambers (MWDCs) at F13 (BDC). The sufficient number of beam particles required, which are large enough as indicated, is listed in Table 1. The ratio of \(^{3}\text{He}\) in the beam at F13 was typically 14%.

Figure 1 shows a schematic view of the experimental setup. The reaction point in a 15-cm thick liquid hydrogen target was determined from the tracks of charged particles reconstructed from signals from the detectors.

**Table 1. Number of beam particles on the target.** \(\Delta p/p\) denotes the momentum acceptance of the BigRIPS.

| Beam | Energy [MeV/nucleon] [%] Required Obtained |
|------|---------------------------------|-----------------|-----------------|
| \(^{6}\text{Li}\) | 246 | 3.2 | \(9.5 \times 10^3\) | \(1.6 \times 10^{10}\) |
| \(^{14}\text{Be}\) | 265 | 3.2 | \(1.8 \times 10^3\) | \(2.3 \times 10^9\) |
| \(^{18}\text{B}\) | 277 | 3.2 | \(8.6 \times 10^7\) | \(1.6 \times 10^9\) |
| \(^{18}\text{B}\) | 224 | 3.2 | \(4.3 \times 10^7\) | \(9.8 \times 10^8\) |

MINOS TPC and the BDC. The momenta of decay neutrons, a knocked-out neutron, and a recoil proton were determined respectively by the NEBULA,\textsuperscript{3} the WINDS,\textsuperscript{4} and a recoil proton detector (RPD) setup consisting of an MWDC and a plastic scintillator array. The charged fragments were identified and momentum analyzed by the SAMURAI spectrometer\textsuperscript{5} using the two MWDCs (FDC1 and FDC2) followed by the hodoscopes (HOFD and HODP). \(\gamma\) rays emitted from the excited core were detected by the DALI2.\textsuperscript{6}

Data analysis is currently in progress.

We thank the staff of accelerators and BigRIPS for their effort and support. The theoretical support and discussion provided by Y. Kikuchi and K. Ogata are highly appreciated.

References
Simulations for experimental studies of breakup reactions on neutron-deficient isotopes relevant to the astrophysical $rp$-process

V. Panin, 1 K. Yoneda, 1 T. Uesaka, 1 M. Kurokawa, 1 T. Motobayashi, 1 H. Otsu, 1 Z. Elekes, 2 A. Saastamoinen, 3 and B. C. Rasco 4

Our experimental program aims to investigate explosive nucleosynthesis in the $rp$-process occurring in type I X-ray bursts related to the most frequent type of stellar explosions in the Galaxy. 1) Indispensable experimental information related to resonant structures in most sensitive proton-capture reactions with extremely neutron-deficient isotopes will result in the advancement of the existing X-ray burst models by providing a reliable nuclear-data input 2). A particular focus of this research is to obtain spectroscopic information about proton-unbound excited states in $^{66}$Se and $^{58}$Zn, which are expected to be involved in the breakup from the waiting-point nuclei $^{64}$Ge and $^{56}$Ni through the sequential two-proton capture 3). Single-neutron removal reactions from $^{67}$Se and $^{59}$Zn at 250 MeV/nucleon beam energy will be deployed to populate the states above one- and two-proton separation energy in $^{66}$Se and $^{58}$Zn, respectively. Proton decay in-flight of these highly excited states will then be measured in complete kinematics using High-Resolution (HR) 90° mode of the SAMURAI magnetic spectrometer 4) in combination with the existing tracking systems and the custom-designed Si-strip detectors for simultaneous detection and tracking of heavy ions and protons.

The conceptual design of the setup was examined by detailed Geant4 simulations, aiming to achieve an experimental resolution of about 100 keV (sigma) for a single resonance and a total detection efficiency of at least 20%. The multidimensional parameterization and fit algorithm was developed to reconstruct the total momentum of every particle and eventually the proton-fragment relative energy $E_{rel}$ in their rest frame. Compromising the resulting $E_{rel}$ resolution, detection efficiency, and construction cost, an appropriate experimental configuration was worked out after systematical variation of the setup parameters such as the geometry and location of the tracking detectors, target thickness, magnetic field strength, etc. In addition, specific simulations were performed to study the effect of $\delta$-electrons on the measurements by the Si trackers. In particular, the interference with a proton signal is studied together with various options to suppress this effect by placing compact kick-off magnets between the Si-trackers, by adjusting the relative distance between the detectors, and/or by track discrimination using track information in the proton-tracking system after the magnet. Based on these studies, the minimum requirements for the design of a vacuum chamber for the Si trackers (i.e., its size, position relative to the target, and internal locations of the detectors) were specified and the following conclusions were drawn:

1) The HR-mode is suitable for the heavy-ion-proton (HI-p) experiments with beam energies ranging from 200 to 250 MeV/nucleon.
2) The value of acceptance efficiency in the HR-mode can be comparable to that of the standard “Day one” configuration (≈40% for one-proton decay with $E_{rel}$=1 MeV and beam energy of 250 MeV/nucleon).
3) The HR-mode provides a better mass (momentum) resolution (≈1/1500) for heavy ions.
4) The momentum resolution for protons and $E_{rel}$ resolution can be determined mainly by the straggling in the target and by the position resolutions of the proton-tracking detectors.
5) $E_{rel}$ resolution (sigma) of approximately 100 keV can be achieved at $E_{rel}$=1 MeV along with the beam energies between 200 and 250 MeV/nucleon.

These results together with the LISE++ simulations were used in the experimental proposal that was reviewed and approved by the 14th NP-PAC in June 2014. In a similar way, feasibility studies and experimental optimizations were performed for other potential HI-p experiments involving one- and two-proton breakup of $^3$C, $^{28}$S, $^{32}$Ar, $^{44}$Ca, $^{35}$K, $^{36}$K and $^{36}$Ca. A common setup configuration for all HI-p experiments was figured out and presented by the collaborators in the 15th NP-PAC. Thus, we intend to perform a total of four HI-p experiments in the next two years, ideally as campaign-type measurements, which will provide a wealth of experimental data that can significantly enrich our knowledge and understanding of nucleosynthesis in type I X-ray bursts.

References
2) A. Parikh, J. Jose, G. Sala, and C. Iliadis: Prog. Par. and Nucl. Phys., Vol. 69 (2013), 225-223
Future plan to study light nuclei near the neutron drip line via charge-exchange (p,n) reactions in inverse kinematics


We plan to investigate the isovector residual interaction and the effect of spatial distribution of neutron skin or halo on spin-isospin responses will be studied using charge-exchange (p,n) reactions, at intermediate energies (260-280 MeV/nucleon) in inverse kinematics. The Gamow-Teller (GT) and spin-dipole (SD) transitions including their giant resonances will be measured. Experimentally, the (p,n) reactions at intermediate beam energies can selectively excite GT states up to high excitation energies in the final nucleus. There is a close proportionality between the cross-sections at 0° and the transition strengths B(GT) in these reactions. Therefore, the (p,n) reactions provide a powerful method to study the B(GT) distributions.

An experimental approach to study the variation of the spin-isospin collectivity is the energy difference between the GT giant resonance (GTGR) and isobaric analog state (IAS) over a wide range of (N-Z)/A. Measurements on stable nuclei show that the GTGR is a few MeV higher than the IAS. This difference gives access to spin-isospin residual interaction strength. However, it is expected to differ at higher (N-Z)/A. The GTGR energy decreases below the IAS energy. It is a compelling interest to obtain new experimental data on nuclei with high (N-Z)/A along the neutron drip line to clarify how the spin-isospin residual interaction strength changes and whether it is related also to the skin or halo structures. With only two pioneer experiments this effect is not well studied and further experimental data are needed.

A new experimental technique developed at NSCL, MSU°, will be applied to measure the (p,n) reaction in inverse kinematics which enables us to achieve a high luminosity using a thick target without losing the information on the recoil neutron momentum necessary for the missing mass reconstruction. The setup using BigRIPS, WINDS (Wide-angle Inverse-kinematics Neutron Detectors for SHARAQ) and the SAMURAI spectrometer together with a 10-mm thick liquid hydrogen target will allow us to extract the GT and SD transition strengths from the low-lying region up to 40 MeV excitation energies. The use of the SAMURAI is crucial for covering all decay channels simultaneously and for obtaining conclusive data on the GT strengths of the nuclei of interest.

By using WINDS placed at a distance of 1 m (1.25 m) from the target position both on left and right (top and bottom) sides with respect to the beam line, we detect recoil neutrons from the (p,n) reaction. From the measured neutron TOF and recoil angle, the excitation energy and center-of-mass scattering angle can be deduced. The reaction products will be momentum-analyzed by the SAMURAI spectrometer. The particle identification for the reaction residues will be made using the TOF and energy loss information measured by hodoscopes (HODF, HODP). The energy loss information will be complementary used. The NEBULA detector will be used for tagging the neutron decay of the reaction products.

Our proposal has been presented at the 15th Program Advisory Committee for Nuclear Physics experiments at RI Beam Factory (NP-PAC). The NP-PAC approved 5 days of beam time.

References
Spin-dipole response of $^4$He by using ($^8$He, $^8$Li($1^+$))

H. Miyazaki,¹ K. Kimamori,¹ M. Assié,² H. Baba,² T. Baba,³ D. Beaumel,³ M. Dozono,¹ T. Fujii,² N. Fukuda,² S. Go,¹ F. Hammache,³ E. Ideguchi,³ N. Inabe,² M. Itoh,³ D. Kameda,² S. Kawase,¹ T. Kawabata,¹ M. Kobayashi,¹ Y. Kondo,¹ T. Kubo,² Y. Kubota,¹ C. S. Lee,¹ Y. Maeda,³ H. Matsubara,³ S. Michimasa,¹ K. Miki,¹ S. Nishi,¹ M. Kurata-Nishimura,² S. Ota,¹ H. Sakai,² S. Sakaguchi,¹ M. Sasano,² H. Sato,² Y. Shimizu,³ H. Suzuki,² A. Stolz,¹ M. Takaki,¹ H. Takeda,² S. Takeuchi,² A. Tamii,⁵ H. Tokieda,¹ M. Tsumura,⁴ T. Uesaka,² K. Yako,¹ Y. Yanagisawa² and R. Yokoyama¹

The spin dipole (SD) ($\Delta S = \Delta L = 1$) of spin-isospin responses is connected with the tensor correlation in nuclei. Especially, on a double-closed nucleus, the SD excitation contribution is large because of the nucleon configuration. The SD excitation function was measured on $^4$He which is the lightest double-closed nucleus. This is important for the study of supernova nucleosynthesis with the neutrino-nucleus reaction.

We conducted the exothermic charge-exchange (CE) reaction of $^4$He($^8$He, $^8$Li($1^+$))$^4$H. CE reactions are powerful tools to study the spin-isospin responses. The spin-flip transition of $^8$He($0^+$) $\rightarrow$ $^8$Li($1^+$) can be identified by measuring the de-excited $\gamma$-rays ($E_\gamma = 0.98$ MeV) from the first $1^+$ state of $^8$Li. The beam energy region of 100–300 MeV/nucleon is suitable for the study of the spin-isospin responses.

The experiment was performed at the RIKEN RIBF facility by using BigRIPS, the high-Resolution beamline, and the SHARAQ spectrometer. The $^8$He beam, which was produced via a projectile-fragmentation reaction with an $^{18}$O beam and $^9$Be target, was transported to the secondary target position at an intensity of 2 MHz. We used the liquid-$^4$He target with a thickness of 120 mg/cm². In order to determine the excitation energy using missing mass method, the momenta of $^8$He and $^8$Li were measured at the beamline and SHARAQ within the low-pressure multi-wire drift chamber (LP-MWDC) and cathode readout drift chamber. The $\gamma$-ray detector array DALLi2 was placed around the target position to measure the 0.98 MeV $\gamma$-ray.

Figure 1 shows the missing mass spectrum of the ($^8$He,$^8$Li) reaction (black line). The contribution of both the $^4$He target and hydrogen is included in this spectrum. The region around 10 MeV and −17 MeV shows the $^4$He $\rightarrow$ $^4$H and $^1$H $\rightarrow$ n reactions, respectively. The $^1$H $\rightarrow$ n reaction originates at the plastic scintillator installed at the upstream of the target. The amount of contamination (red line) was estimated by using the energy loss of the LP-MWDC placed between the scintillator and the target. Thus, the $^4$He($^8$He, $^8$Li)$^4$H reaction was obtained.

Further analysis to obtain the angular distribution and double differential cross-sections is now in progress to obtain the isovector SD strength of $^4$He.

References
Spectroscopy of Single-Particle States in Oxygen Isotopes via \(^{16}\text{O}(\vec{p},2p)\) Reaction with Polarized Protons


We performed \(^{14,22-24}\text{O}(\vec{p},2p)\) reaction measurements (SHARAQ04 experiment) with a polarized proton target at RIBF to measure single-particle spectra and to determine spin-orbit splitting of lp proton single-particle orbits in \(^{14,22-24}\text{O}\) as a function of their neutron number. For the experimental setup, see ref.\(^1\). In this report, current status of the analysis for \(^{22}\text{O}(p,2p)\) is described.

The \((p,2p)\) reaction was identified via the particle identifications of incident nuclei and two scattered protons. Particles were identified via the Time-of-Flight (TOF)-\(\Delta E\) method on an event-by-event basis. Then the proton separation energy of the incident nuclei and the excitation energy of the residual nuclei were calculated from scattering angles and TOF of scattered protons.

Position of the residual nuclei and TOF from the target are also measured at a focal plane S1 at the

\[\text{Fig. 1. Correlation between the excitation energy of } ^{21}\text{N} \text{ and } x_{S1}.\]

\[\text{Fig. 2. Excitation energy spectrum for } ^{22}\text{O}(p,2p) \text{ for each } x_{S1} \text{ region. The red lines show the background estimated from the } 2p \text{ coincidence events occurred in the carbon target.}\]

downstream of the reaction point for the identification of the residual particle in order to improve the S/N ratio and to separate the excited states of \(^{21}\text{N}\). Figure 1 shows the correlation between the excitation energy and the position of the residual nuclei at the S1 focal plane (\(x_{S1}\)) after applying a TOF gate. At S1, particles with larger \(Bp\) come to the smaller \(x_{S1}\) region. There are two clear loci in the \(x_{S1}\) region of \((-130,-60)\) and \((-60,10)\). The former corresponding to \(^{21}\text{N}\) and the latter should be \(^{19}\text{N}\) or \(^{20}\text{N}\) generated through the neutron emission of \(^{21}\text{N}\). It will be clarified by \(Bp\) analysis.

Figure 2 shows the excitation energy spectra of \(^{21}\text{N}\) for different \(x_{S1}\) regions. The red lines show the background originated from the carbon contamination of the polarized target and obtained from the measurement with a carbon target. At least two discrete states are observed in these plots.

The cross sections, spectroscopic factors, and the spin-polarization observables such as the vector analyzing power are expected to be obtained through subsequent analyses in the near future.

References

Status on residual analysis of SHARAQ04 experiment


Proton knockout reaction on radioactive fluorine and oxygen isotopes was performed in SHARAQ04 experiment at RIBF, RIKEN Nishina Center. The analyses on $^{15}$O and $^{22}$O have been reported by S. Kawase et al. The identification of residual nuclei at downstream (S1 focal plane of the SHARAQ spectrometer) serves an important role in identifying the reaction channel and separating the strengths in the excitation energy spectrum. The objective of the present analysis is particle identification via Z vs A/Q plot. We will explain the conversion from the energy loss ($\Delta E$) vs time-of-flight (TOF) plot to the Z vs A/Q plot.

Fig. 1. Experimental setup before S1 focal plane of SHARAQ spectrometer.

The conversion from $\Delta E$-TOF to Z-A/Q is based on the following equations,

$$Z = \beta \frac{L}{g + h L},$$

(1)

$$A \frac{Q}{Q} = \left( \frac{C}{u} \right) \frac{1}{\gamma \beta} \left( B_{D1} \right) \left( 1 + \frac{x}{(x(\delta))} \right),$$

(2)

where $\beta$ and $\gamma$ are the Lorentz factors of residual nuclei; $L$ is the light output of Nyoki; $g$ and $h$ are the parameters from the Birks formula, which correct the non-linearity of light-output and energy loss; $c$ is the speed of light in vacuum; $\mu$ is the atomic mass unit; $(B_{D1})$ is the magnetic rigidity of the D1 magnet (6.5269 Tm); $x$ is the x-position on MWDC-S1; and $(x(\delta))$ is the dispersion of the S1 focal plane.

Figure 2 shows the Z vs A/Q plots for the beam without reaction. The left plot is from downstream and the right plot is from upstream. The accuracy and resolution of both Z and A/Q in the downstream plot are bad compared with those in the upstream plot. The resolution of Z is 0.3 in the downstream plot, while it is 0.1 for the upstream plot. The resolution of A/Q is 0.1 for the downstream plot, and it is 0.01 for the upstream plot.

Fig. 2. Z vs A/Q plots under beam trigger; (left) downstream; (right) upstream.

The analysis is still in progress. We are focusing on improving the accuracy and resolution by 1) better estimation of the parameters such as $g$, $h$, and $x(\delta)$; 2) better calculation on flight-length; and 3) better tracking of SMWDC-S1.

References
2) S. Kawase et al.: in this report.

---

\*1 Center of Nuclear Study (CNS), University of Tokyo
\*2 RIKEN Nishina Center
\*3 Institut de Physique Nucléaire d’Orsay
\*4 Department of Physics, Kyushu University
\*5 Oak Ridge National Laboratory
\*6 Department of Physics, Kyungpook National University
\*7 Department of Physics, Toho University
\*8 Department of Applied Physics, University of Miyazaki
\*9 CEA Saclay
\*10 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
\*11 CYRIC, Tohoku University
Parity-transfer reaction for study of spin-dipole $0^-$ mode


The spin-dipole (SD) $0^-$ excitation has recently attracted theoretical attention owing to its strong relevance in the tensor correlations in nuclei. For example, self-consistent HF+RPA calculations in Ref.13 predict that the tensor correlations produce a strong hardening (shifting toward higher excitation energy) effect on the $0^-$ resonance. It is also predicted that the effect is sensitive to the magnitude of the tensor strength. Thus experimental data of the SD $0^-$ resonance analyzed by using the SHARAQ spectrometer is in progress. The particles produced by the decay of $^{16}\text{F}$ were measured in coincidence. The particles were momentum analyzed by using the SHARAQ spectrometer.

The experiment was performed at the RIKEN RI Beam Factory (RIBF) by using the SHARAQ spectrometer and the high-resolution beam line. Figure 1 shows a schematic layout of the experimental setup. A primary $^{16}\text{O}$ beam at 250 MeV/nucleon and $10^7$ pps from the superconducting RING cyclotron (SRC) was transported to the S0 target position. The beam line to the spectrometer was set up for dispersion-matched transport. We used a segmented plastic scintillation detector as an active $^{12}\text{C}$ target. This detector consisted of 16 plastic scintillators with a size of $30\text{ mm} \times 5\text{ mm} \times 1\text{ mm}$, and it was used to determine the $x$-position of the beam on the target. The outgoing $^{15}\text{O} + p$ particles produced by the decay of $^{16}\text{F}$ were measured in coincidence. The particles were momentum analyzed by using the SHARAQ spectrometer. The $^{15}\text{O}$ particles were detected with two low-pressure multi-wire drift chambers (LP-MWDCs) at the S2 focal plane, while the protons were detected with two MWDCs at the S1 focal plane.

We reconstructed the relative energy $E_{\text{rel}}$ between the $^{15}\text{O}$ and the proton. A preliminary result is shown in Fig. 2. The obtained $E_{\text{rel}}$ resolution was 150 keV in FWHM at $E_{\text{rel}} = 535\text{ keV}$, and the $0^-$ ground state of $^{16}\text{F}$ was clearly separated from other excited states. In order to identify the $^{12}\text{C}(0^-, 9.3\text{ MeV})$ state, data analysis for obtaining the $^{12}\text{C}(^{16}\text{O}, ^{16}\text{F}(0^-, \text{g.s.}))$ spectrum and its angular distributions is in progress.

Fig. 1. Schematic layout of the experimental setup.

Fig. 2. Preliminary result of the relative energy between the $^{15}\text{O}$ nucleus and the proton from the decay of $^{16}\text{F}$.

References
Direct mass measurements of neutron-rich Ca isotopes beyond $N = 34$


The shell evolution in nuclei far from stability is one of the main subjects of nuclear physics. Nuclear mass is one of the most fundamental quantities providing information on the shell structure. The neutron numbers of 32 and 34 have been suggested to be candidates of new magic numbers in the Ca isotopes$^1$. Recently the masses of $^{53}$Ca and $^{54}$Ca were measured, and the shell closure at $N = 32$ was established$^3$. The present work aims at studying the nuclear shell evolution at $N = 32, 34$ by direct mass measurements of neutron-rich nuclei in the vicinity of $^{54}$Ca.

The experiment was performed at the RIKEN RI Beam Factory (RIBF). The masses were measured directly by the TOF-$Bp$ method. Neutron-rich isotopes were produced by fragmentation of a $^{70}$Zn primary beam at 345 MeV/nucleon in a $^9$Be target. The fragments were separated by BigRIPS, and transported in the High Resolution Beam Line to the SHARAQ spectrometer. The beam line and SHARAQ were operated in the dispersion matching mode allowing a momentum resolution of 1/14700.

Fig. 1. Schematic view of the beamline and the detectors used in the experiment.

A schematic view of the beamline with the detectors used in the experiment is shown in Fig. 1. The TOF was measured with newly developed diamond detectors$^3$ installed at BigRIPS-F3 and the final focal plane of SHARAQ (S2). The flight path length between F3 and S2 is 105 m along the central ray. We installed two low pressure multi-wire drift chambers (LP-MWDCs)$^5$ at both F3 and S2 to correct the flight pass lengths using the tracking information on an event-by-event basis. The $Bp$ value was measured by a parallel plate avalanche counter (PPAC) located at the target position of SHARAQ (S0). At S2, we mounted two silicon strip detectors for identification of the atomic numbers of the fragments. To identify the isomers, which leads to a systematic shift towards higher masses, we placed a plastic stopper downstream of S2 and a $\gamma$-detector array consisting of 2 Ge clover and 16 NaI(Tl) detectors. Details of this system can be found in Ref.$^5$

Figure 2 shows the preliminary particle identification of the secondary beams. The total yield of $^{55}$Ca was on the order of several thousands. Many species of reference nuclei over a broad range of $A$ and $Z$ were observed, which were used in the mass calibration. Further analysis is in progress.

Fig. 2. Particle identification of the secondary beams.

References
5) Y. Kiyokawa et al.: in this report.
Gamma-ray detector array for isomer tagging at SHARAQ


Mass measurement of neutron-rich short-lived nuclei was performed by employing the TOF-Bρ technique at the RIKEN RI Beam Factory (RIBF). A beam of 70Zn at 345 MeV/nucleon bombarded a 9Be target to produce neutron-rich nuclei with atomic numbers (Z) ranging from 10 (Ne) to 23 (V) and A/Q from 2.5 to 2.9. Nuclei of interest were separated and particle identified on an event-by-event basis by using the BigRIPS separator coupled with the SHARAQ spectrometer. Details of this experiment can be found in Ref.1.

Herein, we report on an isomer tagging gamma-ray detector array to assist in particle identification. Furthermore the array was used to search for new isomeric states. Figure 1 shows a schematic view of the γ-ray detector array, installed in the air downstream of the final focal plane (S2) of the SHARAQ spectrometer. The array consisted of 2 clover-type HPGe detectors, each surrounded with 8 NaI(Tl) scintillators. A 20-mm-thick plastic scintillator was placed as an active beam stopper for Sc isotopes at the center of the detector array. An 12-mm-thick aluminium degrader was installed upstream to adjust the stopping range of the nuclei of interest. A veto scintillator was installed downstream of the γ-ray detector array to reject the events where the nuclei penetrated the stopper. The dynamic range of HPGe and NaI(Tl) detectors covers γ-rays up to 3 MeV. The energy resolution of the HPGe [NaI(Tl)] detectors was about 3.8 keV [60 keV] at 1333 keV [662 keV] in FWHM and full-energy peak efficiencies were 0.6% [9.7%] for 1.2-MeV γ rays. The decay time window for gamma-ray spectra was set to 100 ns – 15 μs after the particles arrived at S2. The data acquisition (DAQ) system for the γ-ray detector array was separate from the one for the mass measurement and ran with single triggers from HPGe or NaI(Tl) detectors. For making an event correlation between the two DAQs used for isomer tagging and for particle identification, a common time stamp was recorded in both DAQ systems.

Figure 2 shows the delayed γ-ray spectra measured by HPGe in (a) 50K and (b) 43S used for the particle identification. The energies of the observed gamma rays were consistent with those of previous works, Refs.2,3.

Further analysis for the identification of new isomeric states and isomeric ratios is in progress.

Fig. 1. Schematic view of the isomer tagging system downstream of the final focal plane of SHARAQ(S2).

Fig. 2. Delayed γ-ray spectra measured by HPGe in (a) 50K and (b) 43S used for the particle identification.

References
1) M. Kobayashi et al.: in this report.
Quadrupole collectivity in island-of-inversion nuclei $^{28,30}$Ne and $^{34,36}$Mg$^1$


We report here on the in-beam γ-ray spectroscopy in very neutron-rich even-even nuclei of $^{28,30}$Ne and $^{34,36}$Mg by proton inelastic scattering using a liquid hydrogen target in inverse kinematics. The $^{30}$Ne nucleus has a conventional magic number of 20, and $^{36}$Mg is located in the middle of the shell closures of $N = 20$ and 28. The $^{30}$Ne and $^{36}$Mg are closer to the neutron drip line than the nuclei belonging to the so-called “island of inversion (IOI)”. We have studied the evolution of quadrupole deformation on the side with more neutrons and less protons than IOI. The report is a condensed version of our published paper$^1$.

The experiment was performed using the RIPS beamline at the RI Beam Factory. A radioactive secondary beam, containing neutron-rich nuclei $^{32,34,36}$Mg and $^{28,30}$Ne, was produced by fragmentation reactions from 63-MeV/nucleon $^{48}$Ca. Details of the experimental setup around the secondary target and beam conditions are provided in Ref.$^1$.

The angle-integrated cross sections for population of the $2^+_1$ states were obtained from the yields of the $2^+_1 \rightarrow 0^+_1$ transitions with γ-detection multiplicity equal to one. The spectra are shown in Figs. 3–6, 8 in Ref.$^1$. The deduced cross sections and deformation lengths are summarized in Table 1.

The present results extended the measurements of quadrupole collectivity along Ne and Mg isotopic chains by providing deformation lengths with improved accuracies for $^{28,30}$Ne, $^{34}$Mg and a new measurement for $^{36}$Mg. The systematic trends of the deformation lengths are displayed in Fig. 1(a) and (b). The filled and open circles indicate the deformation lengths deduced in the present work and those that have been estimated from the previous results using the WP09 potential$^6$, respectively. The thin black and thick orange error bars represent statistical and systematic errors, respectively. The squares indicate previous results of Coulomb excitation experiments.

Figures 1(a) and (b) also display several theoretical results that can be compared to the experimental results. The solid-blue and dashed-red lines are predictions by AMPGCM$^3$ and the shell model with the SDPF-M effective interaction$^4$, respectively. The shell model calculations in a $0\hbar\omega$ model space are shown by the green dotted$^5$ and orange dotted$^6$ lines. For Mg isotopes, the AMPGCM and SDPF-M calculations, which implement configuration mixing around $N = 20$, reproduce the systematic trend of experimental deformation lengths in a satisfactory manner. In addition, they agree with the trend for the Ne isotopic chain, although they both systematically overestimate the experimental values.

Table 1. Angle-integrated cross sections for the $2^+_1$ states and deduced deformation lengths in $^{28,30}$Ne and $^{32,34,36}$Mg.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$\sigma(2^+_1)$ (mb)</th>
<th>$\delta(p,p')$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}$Ne</td>
<td>23(2)</td>
<td>1.33 ± 0.06 (stat) ±0.05 (syst)</td>
</tr>
<tr>
<td>$^{30}$Ne</td>
<td>37(4)</td>
<td>1.59±0.09 (stat) ±0.07 (syst)</td>
</tr>
<tr>
<td>$^{32}$Mg</td>
<td>40$^+$$^9$</td>
<td>1.85 ± 0.20 (stat) ±0.08 (syst)</td>
</tr>
<tr>
<td>$^{34}$Mg</td>
<td>63(5)</td>
<td>2.30±0.10 (stat) ±0.16 (syst)</td>
</tr>
<tr>
<td>$^{36}$Mg</td>
<td>47(8)</td>
<td>1.90±0.16 (stat) ±0.16 (syst)</td>
</tr>
</tbody>
</table>

Fig. 1. Systematics of deformation lengths around the IOI region. Panels (a) and (b) show deformation lengths of Ne and Mg isotopes, respectively. Details are described in the text.

References

Study of nuclear structure in proton-rich carbon isotopes


The structures of the proton-rich carbon isotopes 8C and 9C were studied by the neutron transfer 10C(p,t) and 10C(p,d) reactions, respectively. The experiment was aimed at measuring the unknown excited states in 8C, which had not been achieved in the previous studies1–4) and identifying the decay property of the unbound first excited state in 9C.

The experiment was performed in 2013 at the RIKEN RIPS facility5). A 10C secondary beam at 51 AMeV was impinged on the hydrogen gas target system (CRYTPA)6,7). Recoiled tritons and deuterons were identified by using the ∆E-E method, with the help of the Dubna telescope consisting of an annular double-sided strip silicon detector and 16 CsI(Tl) scintillators. The reaction residues were identified by the ∆E-E method using a four-plastic-scintillator array at 0 degree5).

The excitation energy spectrum of 8C after subtracting the background is shown in Fig. 1. The ground state of 8C was observed. The deduced mass excess of the 8C nucleus was 34.9(1.1) MeV, which is consistent with the values reported in previous works1–4). The differential cross-section of the 10C(p,t)8Cg.s. reaction will be analyzed in order to deduce the transferred angular momentum in the reaction.

The background-subtracted excitation energy spectrum of 9C is shown in Fig. 2. The known ground and first excited states in 9C were observed. The deduced excitation energy of the first excited state in 9C was 2.4(5) MeV, which is consistent with the value obtained in the previous experiment9). By tagging the residual nucleus separated by the detectors at 0 degree, the decay paths of the first excited states in 9C will be determined.

In summary, the ground state of 8C and the ground and first excited states of 9C were observed by using the 10C(p,t) and 10C(p,d) reactions, respectively. Their excitation energies were consistent with the previous results. In future studies, observation of the excited states in 8C with higher statistics, better energy resolution, and higher S/N ratio is expected.

Fig. 1. The excitation energy spectrum of 8C.

Fig. 2. The excitation energy spectrum of 9C.

References
Triton contamination in the $^{10}$C secondary beam produced by RIPS

T. Miyazaki,*1 H. Otsu,*2 M. Niikura,*1*2 for DA13-03-01 collaboration

We have performed missing mass spectroscopy on $^8$C to measure its excited states populated by the two-neutron transfer reaction from $^{10}$C, $^{10}$C$(p,t)^8$C, in an inverse kinematics.1,2) In this experiment, an unexpected triton contamination was found to occur in a proton-rich $^{10}$C secondary beam produced and separated by the RIKEN Projectile-fragment Separator (RIPS).3)

The $^{10}$C secondary beam was produced by the projectile-fragmentation of a $^{12}$C beam with an energy of 70 MeV/nucleon impinging on a 94.2-μg/cm²-thick $^9$Be production target. The secondary beam was first separated by its magnetic rigidity ($B\rho$) using the first dipole magnet (D1) and a slit at the dispersive focal plane (F1) of the RIPS. A wedge-shaped aluminum degrader of 321-μg/cm² thickness was placed at F1 for further selection of the beam through analysis of its $B\rho$ using the second dipole magnet (D2) and a slit at the achromatic focus (F2). The widths of the F1 and F2 slits were adjusted to ±24 mm and ±5 mm, and magnetic rigidities of D1 and D2 were set to 1.9858 Tm and 1.8262 Tm, respectively. We expected to obtain nearly pure $^{10}$C beam using this RIPS setting.

The secondary $^{10}$C beam was injected into a cryogenic $^4$He gas target (CRYPTA)4) to induce the $(p,t)$ reaction. The recoil tritons were detected with a Dubna telescope consisting of an annular double-sided strip silicon detector followed by cesium iodide scintillators. The telescope was installed downstream of the CRYPTA target. The excitation energy of the proton-unbound $^8$C nucleus of was reconstructed by measuring the scattering angle and the total kinetic energy (TKE) of the recoil tritons.

Figure 1 shows the TKE spectra of tritons detected with the Dubna telescope. The solid line represents the TKE spectrum measured with the $^4$He gas target (target run) and the shaded histogram represents that without the target (empty run) normalized by the beam intensity. The peak at 55 MeV ($G_{g.s.}$), which is found only in the target run, corresponds to the ground state of $^8$C produced by the two-neutron transfer reaction. The mass excess of the ground state of $^8$C deduced from this peak is consistent with previous studies.5–8) Hence, the peak at 48 MeV ($G_0$) should not originate from the $(p,t)$ reaction.

To identify the origin of the $G_0$ peak, the position of the excited triton on the Dubna telescope is plotted by gating on $G_0$ and $G_{g.s.}$, as shown in Fig. 2 (a) and (b), respectively. While tritons produced by the transfer reaction were found to distribute through the entire region of the Dubna telescope, tritons in $G_0$ were detected only at the inner rings of the telescope. In addition, the TKE of tritons having $B\rho$ of D2 is 52 MeV, which is close to the measured TKE of $G_0$. Therefore, we concluded that a triton contaminant was present in the proton-rich $^{10}$C secondary beam.

In the present experiment, data acquisition was triggered by timing signals of the plastic scintillator placed upstream of the target (P1F3) coincident with the Dubna telescope. Since the threshold of P1F3 was set to be much higher than the energy loss for the tritons, the triton contaminants on the Dubna telescope were obtained as an accidental-coincidence events and the count rate of the tritons could not be estimated. The contaminants were removed by gating on the prompt timing of the Dubna telescope for further analysis.

In conclusion, we observed the unexpected triton contaminant in the proton-rich $^{10}$C secondary beam, even though a large $A/Q$ difference exists between $^{10}$C and triton.

References

*1 Department of Physics, the University of Tokyo.
*2 RIKEN Nishina Center.
The erosion of $N = 28$ shell gaps has been suggested from several spectroscopic experimental data. In particular, the $^{41}$S nucleus is of considerable interest because shape coexistence is expected to occur, which is key to understanding the evolution of shell gaps far from stability. The isomeric state of $^{43}$Cl at 320 keV is suggested to have a shape close to spherical with a spin-parity of $7/2^-$, but both the spin-parity and deformed parameter of the ground state have not been determined directly. To investigate the mechanics leading to such an anomalous nuclear structure, we aim to measure the ground-state nuclear moment of $^{41,43}$S. First, $\mu$ of $^{41}$S was measured using the $\beta$-ray detected nuclear magnetic resonance ($\beta$-NMR) method, combined with a technique to produce spin-polarized RI beams.

The experiment was carried out at the RIPS facility at RIBF. The RI beam of $^{41}$S was produced by the fragmentation of a primary beam of $^{48}$Ca at an energy of $E = 63$ MeV/nucleon on a primary target of $^9$Be with a thickness of 0.52 mm. The typical intensity of the $^{48}$Ca beam at the target was 200 pA. To realize the spin polarization in $^{41}$S, an emission angle of $\theta_F > 1^\circ$ and a momentum window of $p_F = p_0 \times (1.015 \pm 0.025)$ were selected, where $p_0$ represents the central momentum of the fragment $^{41}$S. Under this condition, the particle identification of the secondary beam was performed on an event-by-event basis with information regarding time of flight (TOF) and energy loss ($\Delta E$) as shown in Fig. 1. The beam was pulsed with durations of beam-on and beam-off periods of 2.9 s and 2.9 s, equally.

The $^{41}$S beam was then transported to the final focal plane and implanted into a stopper crystal of CaS with which $A P = -0.14\%$ was observed previously, where $A$ and $P$ denote the asymmetry parameter for the $\beta$-ray emission and the degree of polarization of $^{41}$S, respectively. The CaS stopper was mounted between the poles of a dipole magnet that produces an external magnetic field of $B_0 = 0.5$ T. $\beta$ rays emitted from the stopper were detected using plastic scintillator telescopes located above and below the stopper. An oscillating radio-frequency field $B_1$ was applied perpendicular to $B_0$ using a pair of coils. The frequency of $B_1$ was swept over a certain region, and spin reversal occurred when the region included the Larmor frequency. The spin reversal was detected through the change of the up/down ratio $R$ of the $\beta$-ray counts at the two telescopes. Because the range within which the $g$-factor of $^{41}$S is predicted theoretically is quite wide, a fast switching system for changing the tank-circuit frequency was used. In this experiment, the $g$-factor search was conducted in the region where $0.2 < g < 0.8$. The results of the NMR measurements are under analysis.

References
**β-NMR measurement in coincidence with β-delayed γ rays of 41S**

Y. Ichikawa,*1 Y. Ohtomo,*1,2 Y. Ishibashi,*1,3 T. Suzuki,*2 T. Sato,*2 K. Imamura,*1,4 T. Fujita,*5 T. Furukawa,*6 K. Asahi,*2 T. Egami,*7 C. Funayama,*2 M. Hayasaka,*8 C. Hirao,*2 S. Kojima,*2 T. Komine,*2 M. Matsumoto,*8 Y. Sakamoto,*2 A. Takamine,*9 D. Tominaga,*7 H. Yamazaki,*1 and H. Ueno*1

We aim to measure the magnetic moment of the ground-state 41S, by combining the technique to produce spin-polarized RI beams1) and the method of β-ray-detected nuclear magnetic resonance (β-NMR). In the previous experiment, the spin polarization realized in the 41S beams implanted in a CaS crystal was measured to be AP = −0.14(4)%2) using the adiabatic field rotation (AFR) device3). Since the AP value is the product of the asymmetry parameter A for the β-ray emission and the degree of polarization P of 41S, the small AP value may be attributed to a cancellation of A when various β-decay branches are mixed. Indeed, the decay scheme of 41S has not been established other than the observation of several β-delayed γ rays4). In order to avoid a possible cancellation of the A parameter, we have attempted to perform the β-NMR measurement in coincidence with the β-delayed γ rays, along with the normal β-NMR measurement5).

The experiment was carried out at the RIPS at RIBF. The beam production of 41S and experimental setup are common to the normal β-NMR measurement. The β-delayed γ rays emitted from 41S in the CaS crystal located at the center of poles of the dipole magnet were detected with two Ge detectors set at a distance of 20 cm from the crystal. Each Ge detector has a relative efficiency of 35%. The data acquisition system triggered by a γ-hit event defined by a logical OR of signals from the Ge detectors.

In this experiment, we have observed 3 β delayed γ rays of 41S with large yields, with energies of 131, 554 and 761, as shown in Fig. 1 (a), (b) and (c), respectively. To confirm the origin of these γ rays, the half lives associated with these γ rays were deduced from the decay curve spectra synchronized with the beam pulsing: 2.9 s for beam-on and 2.9 s for beam-off. Figure 2 shows the decay-curve spectra for the 131-keV γ ray in the beam-off period. The decay-curve was fitted to an exponential function on a constant background, and then, the half life was preliminarily determined to be 1.99(5) s, which is in good agreement with the previous value4), and the origin was confirmed to be 41S. Further analysis to obtain the NMR spectra in coincidence with these γ rays is in progress.

---

*1 RIKEN Nishina Center  
*2 Department of Physics, Tokyo Institute of Technology  
*3 Department of Physics, University of Tsukuba  
*4 Department of Physics, Meiji University  
*5 Department of Physics, Osaka University  
*6 Department of Physics, Tokyo Metropolitan University  
*7 Department of Physics, Hosei University  
*8 Department of Physics, Tokyo Gakugei University  
*9 Department of Physics, Aoyama Gakuin University

![Graph](image_url)

**Fig. 1.** β-delayed γ rays of 41S with energy of (a) 131 keV, (b) 554 keV and (c) 761 keV.

**Fig. 2.** Decay-curve spectrum for 131-keV γ ray. The half life was preliminarily determined to be 1.99(5) s.

References
Interaction of $^8$B, unstable and loosely bound, with $^{208}$Pb: scattering and breakup


The main motivation of this experiment was to investigate of the reaction dynamics induced by the radioactive ion-beam $^8$B, extremely loosely bound with $S_p=137$keV, at Coulomb barrier energy: i.e., reaction cross section deduced from elastic scattering, as well as the transfer and/or breakup processes. The $^8$B beam, provided by the CRIB facility, was produced via the inverse kinematics reaction $^3$He($^6$Li, n)$^8$B. The primary $^6$Li beam intensity ranged from 1 to 3 e$\mu$A, resulting in a $^8$B intensity of $\sim$10$^4$ Hz, with an energy of 50±1 MeV. The $^6$Li ion source had to be retuned twice owing to the total consumption of the lithium material. This resulted in a beamtime loss of two days, allowing us to accumulate statistics for four days beamtime on target. As expected, the $^8$B beam was contaminated by $^7$Be, via the $^3$He($^6$Li, p)$^7$Be reaction, by $^3$He, recoiling from the $^3$He material of the production gas target, and by some $^6$Li halo (originating from the primary beam, that was around 10$^8$ times more intense than the secondary one); thus, the $^8$B beam purity achieved was approximately 20%. The contaminations were not problematic since each beam species was identified via a time of flight technique. The light charged particles produced in the reaction were detected and identified with six $\Delta$E-E telescopes, consisting of 40–50 $\mu$m + 300 $\mu$m double sided silicon strip detectors. The detectors were arranged symmetrically around the target at a distance of approximately 11 cm. All the detectors with the related electronics were brought from Italy, INFN1. For the $\Delta$E detectors we utilized for the first time, ASIC digital electronics, whereas we used for the E-detectors low-noise electronics; these electronics were also fully developed in Italy2,3. The charged particles identified were $^8$B, $^7$Be, $^6$Li, $^4$He, $^3$He, and protons (Fig. #1), confirming our preliminary estimates: namely, the existence of a consistent amount of transfer (p transferred with $^7$Be out) and breakup processes ($\rightarrow^7$Be+p, and possible subsequent $^7$Be breakup $\rightarrow^3$He+$^4$He). Preliminary data from the angular distribution of the $^8$B elastic scattering confirm our expectations of a strong absorption occurring in the $^8$B-induced reactions.

In all the runs we were able to verify the good capabilities of the homemade electronics2,3 for identifying the various ions detected by the $\Delta$E silicon via the built-in risetime detection. Fig. #2 shows a typical spectrum: signal rise time vs. $\Delta$E, with the related ion identification.

Fig. 1. $\Delta$E-$E_{\text{rec}}$ identification of the different ions produced in the scattering of the cocktail $^8$B-$^7$Be-$^3$He beam onto a $^{208}$Pb target.

Fig. 2. Performances of the homemade electronics of the thin $\Delta$E detectors. The measurement of the risetime signal vs. the energy loss allows for clear ion identification.

References
First production of $^{10}$Be beam at CRIB and $^{10}$Be+$\alpha$ resonant elastic scattering

H. Yamaguchi,*1 D. Kahl,*1 S. Hayakawa,*1 Y. Sakaguchi,*1 and T. Nakao,*2 for CRIB collaboration

$\alpha$-cluster states are known to occur in many nuclei, including isotopes of the carbon nucleus. Among the $\alpha$-cluster states, linear-chain cluster states have been considered as exotic and of interest for a long time. Although there have been many theoretical investigations, no clear experimental evidence has been obtained for such states thus far.

By performing an antisymmetrized molecular dynamics (AMD) calculation, Suhara and En’yo$^{1,2}$ obtained a band ($0^+_1$, $2^+_1$, $4^+_2$) that could be explained as linear-chain cluster levels of $^{14}$C. It was predicted that these levels appear a few MeV or more above the $^{10}$B+$\alpha$ threshold, unlike the prolate bands in the study of Oertzen et al.$^3$ The investigation$^3$ shows that the AMD wave function has a configuration in which two $\alpha$ particles and two neutrons are located close to each other, while the remaining $\alpha$ particle is relatively far away. This implies that states having such a linear-chain configuration could be accessed from the $^{10}$Be+$\alpha$ channel.

The aims of the present work are 1) to search for a linear-chain configuration via $^{10}$Be+$\alpha$ resonant scattering, and 2) to determine the resonant parameters of the high excited states (13-18 MeV) of $^{14}$C, which are still mostly unknown, in order to elucidate on the cluster-band structure. The experimental method is similar to that used in previous studies.$^4,5$

The study was conducted at the low-energy radioactive-isotope (RI) beam separator CRIB. The $^{10}$Be beam at CRIB was first produced on January 17-19, 2014. Using a 5.57 MeV/u primary $^{11}$B beam from the AVF cyclotron and a 500-Torr cryogenic deuterium target, $^{10}$Be particles were produced via the $^{11}$B($d$, $^3$He)$^{10}$Be reaction in inverse kinematics. The $4^+$ charge state was selected using the D1 dipole magnet of CRIB. The produced $^{10}$Be$^{1+}$ beam was contaminated with a small amount of $^{10}$B$^{4+}$, which was mostly excluded by inserting a 0.7 $\mu$m-thick Mylar film as a charge stripper at the F1 focal plane. The highest $^{10}$Be beam production rate was $2 \times 10^4$ pps at the final focal plane (F3). The beam energy was 3.51 MeV/u before reaching parallel-plate avalanche counters (PPACs) installed for the beam monitoring.

We also performed a test measurement of $\alpha$ resonant scattering using a chamber filled with helium gas at 760 Torr, which served as the target for elastic scattering. The chamber had a window covered with a 25 $\mu$m-thick Mylar film at the beam entrance. A pair of silicon detectors, which had thicknesses of 20 $\mu$m and 480 $\mu$m, were placed in the gas-filled chamber, consisting of a “$\Delta$E-E” telescope. The telescope was located at 482 mm from the Mylar entrance window, exactly in the direction of the beam axis. The energy of the beam degraded and the beam was stopped by the thick gas target and $\alpha$ particles originating from elastic scatterings reached the telescope. The energy spectrum of the $\alpha$ particles exhibited several peaks, as shown in Fig. 1. In principle, $\alpha$-cluster like resonances including theoretically predicted ones should be observed as peaks in the present measurement. In particular, two distinct peaks that likely correspond to resonances in $^{14}$C are observed at excitation energies of 14.3 MeV and 16 MeV; however, the resonant features of those are yet to be investigated. The peak at the highest energy of approximately 17 MeV could be due to background events arising from impurities in the $^{10}$Be beam and should be eliminated in the main run.

In summary, we successfully produced a $^{10}$Be beam at CRIB for the first time and also showed that the resonant scattering measurement is feasible. The actual measurement for 7.5 days will be performed in 2015.

References
Investigation of the waiting point $^{22}\text{Mg}$ in the rp-process

N. N. Duy,*1, L. H. Khiem,*2 S. Kubono,*3 H. Yamaguchi,*4 D. Kahl,*4 and N. K. Uyen*5

Nucleosynthesis in stars occurs via several reaction chains, including a combination of the ($\alpha$,p)-process, (p,$\gamma$)-process, and $\beta^+$-decay. A nucleus is a waiting point if the ($\alpha$,p) or (p,$\gamma$) reaction rate is so low that the nuclear processing has to wait for $\beta^+$-decay. Since the nucleosynthesis grows to the $^{22}\text{Mg}$ nucleus via the following reaction chains, $^{14}\text{O}(\alpha,p) ^{18}\text{Ne}(\alpha,p) ^{22}\text{Mg}$, (p,$\gamma$)$^{25}\text{Si}(\alpha,p) ^{29}\text{Si}(\alpha,p) ^{33}\text{Ar}(\alpha,p) ^{37}\text{K}$, there are three possible ways by which the reactions can proceed through $^{22}\text{Mg}$: $^{22}\text{Mg}(\alpha,p) ^{25}\text{Al}$, $^{22}\text{Mg}(p,\gamma) ^{23}\text{Al}$, and $^{22}\text{Mg}(p,\gamma) ^{24}\text{Al}$. Because of the small Q-value ($Q = 0.125$ MeV) of the (p,$\gamma$)-reaction, it is thought that the photodisintegration of $^{23}\text{Al}$ prevents a significant part of the flow through this reaction. In addition, at high-temperature condition, i.e., $T_9 = 1 – 10$ GK, the $^{22}\text{Mg}(\alpha,p) ^{25}\text{Al}$ reaction was thought to be dominant. If the reaction rate of $^{22}\text{Mg}(\alpha,p) ^{25}\text{Al}$ is lower than the rate of beta decay, the nucleosynthesis must await the decay from $^{22}\text{Mg}$, and subsequently, the $^{22}\text{Mg}$ nucleus becomes a waiting point.

To investigate the potential waiting of $^{22}\text{Mg}$, we measured the $^{22}\text{Mg}(\alpha,p)$ reaction and determined the resonance states of $^{26}\text{Si}$ under such stellar conditions. According to the results of a previous work, we could estimate the rate of the ($\alpha$,p)-process, (p,$\gamma$)-process, and $\beta^+$-decay in $^{22}\text{Mg}$. According to the rates obtained in the previous work, we could determine the speed of the (p,$\gamma$) reaction. The results show that in the temperature range of $T_9 = 1 – 10$ GK, the (p,$\gamma$) reaction is the dominant. Table 1 compares the three processes.

$$N_i(<\sigma \nu>) = 8.08 \times 10^{-9} (\mu T_e)^{3/2} \sum_i (\omega r) \exp \left( -\frac{11605E_i}{T_e} \right)$$

where $\mu$, $\omega r$, $E_i$, and $T_e$ are reduced mass, resonance strength, resonance states, and temperature in million Kelvin, respectively. The resonance strength was calculated by assuming that of the proton occupied 10% of the total width. As shown in Fig. 1, the rates of the ($\alpha$,p) reaction corresponding to the first resonance is the highest. The reaction rate is low under concerned stellar conditions, with a value in the range of $10^{-30} – 10^{-7}$. The speed of the (p,$\gamma$) reaction, which depends on the abundance of isotopes in the stellar environment, and that of beta decay were obtained from the following equations:

$$R_{up} = \left( \frac{pX_p}{m_p} \right) N_i(<\sigma \nu>)_up$$

$$R_{\beta^+} = \ln 2 / T_{1/2}$$

Fig. 1. Rates of the reaction $^{22}\text{Mg}(\alpha,p) ^{25}\text{Al}$ calculated by using the resonance states of $^{26}\text{Si}$ via alpha scattering of $^{22}\text{Mg}$.

Table 1. Speed of the reactions and beta decay

<table>
<thead>
<tr>
<th>$T_9$ (GK)</th>
<th>$R_{up}$ (reaction/s)</th>
<th>$R_{pp}$ (reaction/s)</th>
<th>$R_{\beta^+}$ (decay/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.99E-06</td>
<td>7.80E+03</td>
<td>0.1789</td>
</tr>
<tr>
<td>1.5</td>
<td>1.79E-04</td>
<td>2.47E+04</td>
<td>0.1789</td>
</tr>
<tr>
<td>2.0</td>
<td>1.26E-03</td>
<td>4.92E+04</td>
<td>0.1789</td>
</tr>
<tr>
<td>2.5</td>
<td>3.90E-03</td>
<td>7.80E+04</td>
<td>0.1789</td>
</tr>
<tr>
<td>10</td>
<td>7.50E-02</td>
<td>----</td>
<td>0.1789</td>
</tr>
</tbody>
</table>

Since the speed of the (p,$\gamma$) reaction is much higher than that of the others, it does not wait for beta decay. Therefore, under the conditions of X-ray burst and Type-II supernovae, the $^{22}\text{Mg}$ nucleus does not act as a waiting point. Subsequently, beta decay does not occur. Once the beta decay is skipped, the $^{22}\text{Na}$ unstable isotope which decays beta-plus ($\beta^+$) to the excited state of $^{22}\text{Ne}$, which de-excites to ground state by emitting gamma rays with energy of 1.275 MeV, cannot be formed. Therefore, such gamma rays have not been observed by satellites up to date. In addition, the $^{22}\text{Ne}^{24}\text{Ne}$ ratio changes, which is one of the causes of the Ne-E problem.

References

Production of Lv isotope in the hot fusion reaction of 248Cm+48Ca at \(E^* = 38.4\) MeV

D. Kaji,\(^1\) K. Morita,\(^1\),\(^2\) K. Morimoto,\(^1\) C. Berner,\(^1\),\(^3\) H. Haba,\(^1\) Y. Komori,\(^1\) M. Murakami,\(^1\),\(^4\) Y. Narikiyo,\(^1\),\(^5\) M. Takeyama,\(^1\),\(^6\) K. Tanaka,\(^1\),\(^6\) T. Tanaka,\(^1\),\(^6\) Y. Wakabayashi,\(^1\) and S. Yamaki\(^1\),\(^7\)

In 2013, a gas-filled recoil ion separator (GARIS) was employed to study the production of Lv (Livermorium, \(Z=116\)) isotopes in the hot fusion reaction of 248Cm+48Ca at the excitation energy of compound nucleus \(E^* = 41.5\) MeV\(^1\). As a result, five correlated decay chains were observed. On the basis of the assignments of the precedent studies\(^2\)–\(^4\), two of the events were attributed to the decays of 293Lv (3n), and three of them were assigned to the decays of 292Lv (4n). With the aim of clear identification of these nuclides, we started to measure the excitation function in the reaction of 248Cm+48Ca → 290Lv*.

The experimental setup was almost the same as that used in our previous work\(^3\) using 48Ca\(^{11+}\) beam with 261.6 MeV. In this work, the 248Cm target was irradiated with a 258 MeV 48Ca\(^{11+}\) beam from RIKEN heavy-ion linear accelerator RILAC. Total beam dose was 5.0 × 10\(^{18}\) during a net irradiation time of 14.2 days. The average beam intensity on the target was 0.68 particle μA. The reaction products were separated in-flight from projectiles and other by-products using GARIS, and then they were guided into the focal plane detection system after they passed through the time-of-flight (TOF) detector\(^5\). The separator was filled with He gas at 73 Pa. Magnetic rigidity for measuring the Lv isotope was set to be 2.174 Tm. Then, the typical trigger rate at the focal plane was 58 cps at 0.89 particle μA.

Seventy-three events, which were anti-coincided with TOF detectors, with energies above 100 MeV were observed. Two events among their fission events were found to be correlated with preceding α-particles and implanted evaporation residue (ER). Observed decay chains are shown in Fig. 1. The first chain, which was observed on September 22, 2014, consists of three consecutive α-decays followed by SF. Decay properties of all nuclides in the first chain agree well with those of the decay chain from 293Lv reported in early works\(^2\)–\(^4\).

The second chain consists of two consecutive α-decays followed by SF. Assuming the first α originating from 293Lv is not detected in the second chain, the chain looks the same as the first series because decay properties of two α and SF in the second chain agree well with those of α\(_2\) and α\(_3\) followed by SF in the first one. However, the missing probability is estimated to be 0.3% by considering the dead time for data acquisition and counting rate of the FPD. By the low missing probability, we can not conclude whether the second chain is from 293Lv or the other nuclide that is provided directly (and emitted the 9.71 MeV α-particle).

The cross-section was deduced to be 0.9\(^{+1.0}_{-0.7}\) pb for 3n evaporation channel assuming the transmission of GARIS to be 35%. The cross section agrees well with the previously reported value of 1.1\(^{+1.7}_{-0.7}\) pb at \(E^* = 40.9\) MeV\(^2\)–\(^3\). On the other hand, we did not observe the decay chain originating from 4n. The cross-section limit was 1.64 pb for 4n although the reported value is 3.3\(^{+2.5}_{-1.4}\) pb.

For further understanding from the reaction mechanism, we will measure the excitation function at an energy higher than 41.5 MeV.

References
Production of $^{215}\text{U}$ and $^{216}\text{U}$ and attempt to produce $^{219}\text{Np}$ and $^{220}\text{Pu}$

Y. Wakabayashi,*1 K. Morimoto,*1 D. Kuji,*1 H. Haba,*1 M. Takeyama,*1,+2 S. Yamaki,*1,+3 K. Tanaka,*1,+4 K. Nishio,*5 M. Asai,*5 Y. Komori,*1 M. Murakami,*1,+6 T. Tanaka,*7 A. Yoneda,*1 and K. Morita*1,+7

Theory predicts that nuclei with $N = 126$ exist up to $Z = 100$ because of the fission barrier arising from the ground-state shell effect. The heaviest $N = 126$ nuclei reported so far is $^{218}\text{U}$ ($Z = 92$). In this program to study nuclei with $N = 126$, we attempt to produce heavier nuclei such as $^{220}\text{Pu}$. In previous experiments, a new isotope $^{216}\text{U}$, which is the daughter nucleus of $^{220}\text{Pu}$ and $^{215}\text{U}$, were observed.

We performed an experiment at the RIKEN Linear Accelerator (RILAC) facility. We used $^{82}\text{Kr}$ ion as an incident beam and $^{136,137,138}\text{BaCO}_3$, $\text{Na}_2\text{La}_2\text{O}_4$, and $\text{Na}_2\text{CeO}_3$ as targets to study the $^{82}\text{Kr}$ + $^{136,137,138}\text{Ba}$, $^{139}\text{La}$, and $^{140}\text{Ce}$ reactions. Each target material was prepared by sputtering on 0.8–1.1-μm-thick aluminum foils so as to achieve a thickness of 300–500 μg/cm², and it was also covered with 40 μg/cm² of aluminum. The $^{82}\text{Kr}$ beams with energies of 365, 381 and 386 MeV were used to bombard these target foils mounted on a rotating target.

Evaporation residues (ERs) were separated from the beam particles and other products using a gas-filled recoil ion separator (GARIS), and they were implanted into a position-sensitive strip detector (PSD; 58 × 58 mm²). The PSD was boxed in four Si detectors (SSD) to catch α particles escaping from the PSD. Two timing detectors were set in front of the PSD to measure the time-of-flight (TOF) of the ERs. Time information was also used to distinguish between the α-decay events in the PSD and the recoil implantations. A Ge-detector was placed 6 mm behind the PSD to measure the γ-rays coinciding with the α-decays. The isotopes were identified by using an α-decay chain with known α-decay properties of the descendants and the position correlations between the implanted ERs in the PSD and the subsequent α-decays.

In this experiment, we confirmed the production of $^{215}\text{U}$ and $^{216}\text{U}$ by observing one chain and six chains, respectively, including the candidates of new transitions. For the decay chains of $^{216}\text{U}$, the α-decay energies and decay times are shown in Fig. 1. These decay events and cross sections are summarized in Table 1, and we labeled the decay energies with $E_{\alpha1}$, $E_{\alpha2}$, and $E_{\alpha3}$ temporarily. For a new transition, $E_{\alpha2}$ of $^{216}\text{U}$ may be a transition from isomer-state in $^{216}\text{U}$ to ground-state in $^{215}\text{Th}$ and also as an isomer state of $^{218}\text{U}$ with the α-decay energy of 10678 keV. In the attempt to produce $^{219}\text{Np}$ and $^{220}\text{Pu}$ using the $^{82}\text{Kr}$ + $^{139}\text{La}$ and $^{140}\text{Ce}$ reactions, cross section upper limits of 28 pb and 46 pb, respectively, were obtained. Further discussion, such as the interpretation of new transitions, is ongoing.

Table 1. α-decay events of $^{215}\text{U}$ and $^{216}\text{U}$. The time and position difference between the implanted ERs and the α-decay are $\Delta T$ and $\Delta X$, respectively. $E_{\alpha}$ represents the $^{82}\text{Kr}$ beam energy at the center of the target.

<table>
<thead>
<tr>
<th>$E_{\alpha}$ (keV)</th>
<th>$\Delta T$ (μs)</th>
<th>$\Delta X$ (mm)</th>
<th>Reaction $E_{\alpha}$ &amp; Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{215}\text{U}$</td>
<td>$E_{\alpha1}$ = 8408</td>
<td>6.98</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>$E_{\alpha2}$ = 8371</td>
<td>3.95</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{216}\text{U}$</td>
<td>$E_{\alpha1}$ = 10518</td>
<td>2.50</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>$E_{\alpha2}$ = 10450</td>
<td>0.43</td>
<td>2.3</td>
</tr>
<tr>
<td>$^{218}\text{U}$</td>
<td>$E_{\alpha1}$ = 8254</td>
<td>1.81</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>$E_{\alpha2}$ = 8265</td>
<td>3.40</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Sum energy of PSD and SSD.

References

---

*1 RIKEN Nishina Center
*2 Department of Physics, Yamagata University
*3 Department of Physics, Saitama University
*4 Tokyo University of Science
*5 Japan Atomic Energy Agency
*6 Department of Chemistry, Niigata University
*7 Department of Physics, Kyushu University
Search for new isotopes in the region around \(Z = 33\) using the in-flight fission of a \(^{238}\text{U}\) beam at 345 MeV/nucleon

Y. Shimizu,\(^{1}\) T. Kubo,\(^{1}\) N. Inabe,\(^{1}\) D.S. Ahn,\(^{1}\) N. Fukuda,\(^{1}\) K. Kusaka,\(^{1}\) D. Murai,\(^{1,2}\) M. Ohtake,\(^{1}\) H. Suzuki,\(^{1}\) H. Takeda,\(^{1}\) Y. Yanagisawa,\(^{1}\) K. Yoshida,\(^{1}\) Y. Hirayama,\(^{3}\) Y. Ichikawa,\(^{1}\) N. Imai,\(^{4}\) T. Isobe,\(^{1}\) N. Iwasa,\(^{5}\) S.C. Jeong,\(^{3}\) D. Kim,\(^{6}\) E.H. Kim,\(^{6}\) H. Miyatake,\(^{5,3}\) M. Mukai,\(^{5,3}\) H. Otsu,\(^{1}\) H. Sato,\(^{1}\) T. Sonoda,\(^{1}\) and A. Yagi\(^{7}\)

A new isotope search experiment in the neutron-rich region around \(Z = 33\) was performed in November 2014, aiming to expand the frontier of accessible neutron-rich exotic nuclei. In this experiment, the nuclei of interest were produced by the in-flight fission of a 345 MeV/nucleon \(^{238}\text{U}\) beam colliding with a 4.00-mm-thick Be target. The primary beam intensity was 10.8 particle nA on average. Fission fragments were separated and identified using the superconducting in-flight separator BigRIPS\(^{1}\). In order to separate and purify the RI beams, two wedge-shaped energy degraders were placed at the F1 and F5 dispersive foci. The typical counting rate at the F3 and F7 achromatic foci were 30.1 kHz and 1.88 kHz, respectively. Table 1 summarizes the experimental conditions.

Table 1. Summary of the experimental conditions.

<table>
<thead>
<tr>
<th>Target (mm)</th>
<th>Be 4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B\rho) (Tm)</td>
<td>8.087</td>
</tr>
<tr>
<td>Degrader at F1 (mm)</td>
<td>Al 2.82</td>
</tr>
<tr>
<td>Degrader at F5 (mm)</td>
<td>Al 2.99</td>
</tr>
<tr>
<td>F1 slit (mm)</td>
<td>+64.2 / −64.2</td>
</tr>
<tr>
<td>F2 slit (mm)</td>
<td>+20.0 / −12.0</td>
</tr>
<tr>
<td>F5 slit (mm)</td>
<td>+120.0 / −120.0</td>
</tr>
<tr>
<td>F7 slit (mm)</td>
<td>+15.0 / −15.0</td>
</tr>
<tr>
<td>Central particle</td>
<td>(^{94}\text{As})</td>
</tr>
<tr>
<td>Irradiation time (h)</td>
<td>97.3</td>
</tr>
<tr>
<td>Live time of DAQ (%)</td>
<td>66.1</td>
</tr>
<tr>
<td>Trigger rate (kHz)</td>
<td>1.24</td>
</tr>
<tr>
<td>Total dose</td>
<td>(2.35 \times 10^{16})</td>
</tr>
</tbody>
</table>

\(^{a}\) The values from the magnetic fields of the first dipole magnet.

Particle identification (PID) was performed using the \(\Delta E\)-TOF-\(B\rho\) method in which the energy loss (\(\Delta E\)), time of flight (TOF), and magnetic rigidity (\(B\rho\)) were measured to allow the event-by-event determination of atomic number \(Z\) and mass-to-charge ratio \(A/Q\) of fragments\(^{2}\). The PID was confirmed by measuring the delayed \(\gamma\)-rays emitted from short-lived isomers, such as \(^{95}\text{Kr}\) and \(^{94}\text{Br}\), by using two clover-type high-purity germanium detectors placed at the F7 achromatic focus; this technique is called isomer tagging.

Figure 1 shows a two-dimensional PID plot of \(Z\) versus \(A/Q\). The solid red line indicates the limit of previously identified isotopes. The relative root mean square (rms) \(Z\) resolution and the relative rms \(A/Q\) resolution achieved were typically 0.57\% and 0.055\%, respectively. We can see some candidates for new isotopes such as \(^{93}\text{As}\), \(^{96}\text{Se}\), and \(^{99}\text{Br}\).

Detailed analysis is currently in progress.

References

\(^{1}\) RIKEN Nishina Center
\(^{2}\) Department of Physics, Rikkyo University
\(^{3}\) High Energy Accelerator Research Organization (KEK)
\(^{4}\) Center for Nuclear Study (CNS), University of Tokyo
\(^{5}\) Department of Physics, Tohoku University
\(^{6}\) Institute for Basic Science (IBS)
\(^{7}\) Department of Physics, Osaka University
Search for new neutron-rich isotopes with $Z \sim 55–70$
using a 345 MeV/nucleon $^{238}$U beam

N. Fukuda,*1 N. Inabe,*1 D. Kameda,*1 H. Suzuki,*1 H. Takeda,*1 D.S. Ahn,*1 D. Murai,*1,∗2 K. Yoshida,*1 K. Kusaka,*1 Y. Yanagisawa,*1 M. Ohtake,*1 Y. Shimizu,*1 Y. Sato,*1 H. Sato,*1 H. Otsu,*1 H. Baba,*1 G. Lorusso,*1 P.-A. Söderström,*1 T. Isobe,*1 N. Inami,*3 M. Mukai,*1,∗4 S. Kimura,*4 H. Miyatake,*4 N. Iwasa,*5 A. Yagi,*6 R. Yokoyama,*3 O.B. Tarasov,*7 H. Geissel,*8 and T. Kubo*1

Since the commissioning of the BigRIPS separator1) in 2007, an extensive search for new isotopes has been conducted to expand the region of accessible exotic nuclei. By the end of 2013, about 100 new neutron-rich isotopes had been observed using the in-flight fission of a $^{238}$U beam2–4), and 4 new neutron-deficient nuclei had been observed by the projectile fragmentation of a $^{124}$Xe beam5). In April 2014, we searched for new neutron-rich isotopes with the atomic number $Z \sim 55–70$ for the second time since the 2011 experiment5), with an increased beam intensity.

The neutron-rich isotopes were produced by the in-flight fission of a $^{238}$U beam at 345 MeV/nucleon. The maximum beam intensity was approximately 12.5 pnA. The fission fragments were collected and separated with the BigRIPS. The experimental conditions are summarized in Table1. We adopted two different $B\rho$ settings of the separator, each targeting new isotopes around $^{161}$Pr (Pr setting) and $^{180}$Er (Er setting). The settings were determined using the measured cross sections6) and the detailed simulations with the code LISE++7).

Table 1. Summary of the experimental conditions.

<table>
<thead>
<tr>
<th>Setting</th>
<th>Pr setting</th>
<th>Er setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production target</td>
<td>$^{161}$Pr</td>
<td>$^{180}$Er</td>
</tr>
<tr>
<td>Isotope tuned</td>
<td>$^{161}$Pr</td>
<td>$^{180}$Pr</td>
</tr>
<tr>
<td>$B\rho$ of D1</td>
<td>7.527 Tm</td>
<td>6.811 Tm</td>
</tr>
<tr>
<td>Degrader at F1</td>
<td>Al 1.4 mm</td>
<td>Al 0.98 mm</td>
</tr>
<tr>
<td>Degrader at F5</td>
<td>Al 1.4 mm</td>
<td>Al 0.96 mm</td>
</tr>
<tr>
<td>F1 slit</td>
<td>±64.2 mm</td>
<td>+32.1/−42.8 mm</td>
</tr>
<tr>
<td>F2 slit</td>
<td>+10/−3 mm</td>
<td>+4/−3 mm</td>
</tr>
<tr>
<td>F3 slit</td>
<td>±120 mm</td>
<td>±120 mm</td>
</tr>
<tr>
<td>F7 slit</td>
<td>±25 mm</td>
<td>±25 mm</td>
</tr>
<tr>
<td>Average intensity</td>
<td>12.6 pnA</td>
<td>3.39 pnA</td>
</tr>
<tr>
<td>Running time</td>
<td>54.6 h</td>
<td>44.2 h</td>
</tr>
<tr>
<td>Total dose of $^{238}$U</td>
<td>$1.55 \times 10^{16}$</td>
<td>$3.36 \times 10^{15}$</td>
</tr>
</tbody>
</table>

Particle identification (PID) was based on the TOF-$B\rho$-$\Delta E$ method to deduce $Z$ and the mass-to-charge ratio ($A/Q$)8). The preliminary PID plots of $Z$ versus $A/Q$ are shown in Fig.1. The relative root mean square $A/Q$ and $Z$ resolutions are typically 0.037% and 0.45%, respectively, for the $^{161}$Pr setting, and 0.047% and 0.88%, respectively, for the $^{180}$Er setting. A total of 18 new isotopes have preliminarily been identified ranging from $Z = 56$ to 69. Further analysis is currently in progress.

References
Study of particle identification and RI beam separation for the Z~80 region using projectile fragmentation of $^{238}$U

N. Inabe,*1 N. Fukuda,*1 H. Takeda,*1 H. Suzuki,*1 Y. Shimizu,*1 D. Murai,*2 D. S. Ahn,*1 H. Sato,*1 Y. Sato,*1 K. Kusaka,*1 Y. Yanagisawa,*1 M. Ohtake,*1 K. Yoshida,*1 M. Sako,*1 N. Imai,*1 S. Kimura,*1 M. Mukai,*3 H. Miyatake,*1 N. Iwasa,*4 and T. Kubo*1

An atomic number of Z~80 produced through a projectile fragmentation of $^{238}$U is the next area for RI beam production at the BigRIPS. In this area, charge-state distributions are broad, which causes some problems for production concerned with both particle identification (PID) and isotope separation. To study this effect, we performed a test experiment to produce RI beams of high Z.

The test experiment was carried out using a 345 MeV/u $^{238}$U beam. To study PID, RI beams were produced by the $^{238}$U beam in low counting rates of ~2 x 10^5 pps so as to make PID easy by sometimes mixing the $^{238}$U primary beam of the charge state 92+ at F1. The production target was 5.79-mm-thick Be and the magnetic rigidity (Bp) of the first dipole D1 was 6.001 Tm. Degraders were not used at F1 and F5. The F1 slits were set to produce a momentum byte in the range between -3% and 0.1% when the primary beam was not mixed and between -3% and 0.5% when mixing it. The PID was performed by determining Z and A/Q on an event-by-event basis using the $\Delta E$-TOF-Bp method. $\Delta E$ was measured by MUSIC at F7 and TOF was measured using two plastic scintillators at F3 and F7. Bp was determined by track reconstruction using positions and angles measured by FPACs located at F3, F5, and F7. Total kinetic energy (TKE) was also measured using NaI at F7 to determine A.

Figure 1a and b show the PID spectra of A/Q vs. Z for Z > 30 and Z > 85, respectively. We can see not only projectile fragments but also fission fragments below Z~70 in Fig. 1a. Fig. 1c shows the similar plot as Fig. 1b when primary beams are mixed. We can clearly see four charge states of $^{238}$U, which are produced by changing the charge state from 92+ in the scintillator at F3. Resolutions of Z are 0.58 % for Z~90 and 0.41 % for Z~50. The worse resolution in the high-Z area might be attributed to charge state straggling, which broadens energy loss spectra when passing through a detector with some charge states.

We performed the PID of U isotopes. Fig. 2 shows an A/Q spectrum of U produced by cutting with Z= 92±0.3. We identified the main peaks of A/Q > 2.55 but could not assign those of low A/Q because of overlap with isotopes of Z~91. The resolution of A/Q is 0.05%. We tried to examine whether other small peaks exist in large peaks, for example, $^{234}$F$^{38+}$ in the $^{234}$F$^{0+}$ peak but we could not determine this because of the quenching of the TKE counter.

In order to study isotope separation, we produced RI beam of which the central orbit was $^{208}$Bi$^{52+}$ with the 7-mm-thick Be target. Bp of the first dipole was 6.13 Tm. The degrader at F1 of 0.3 mm and momentum acceptance of ±3% were used to produce many types of isotopes at the same time such as a search for new isotopes. The isotopes were not well-separated in this experiment owing to large unexpected contaminants of fission fragments with Z~60 and high counting rates of ~100 kHz/pnA. These phenomena have not been predicted by the simulation.

References
Production cross section measurements of radioactive isotopes produced from a $^{124}$Xe beam at 345 MeV/u by the BigRIPS separator

H. Suzuki,*1 N. Fukuda,*1 H. Takeda,*1 D. Kameda,*1 Y. Shimizu,*1 D.S. Ahn,*1 D. Murai,*1,2 H. Sato,*1 K. Yoshida,*1 K. Kusaka,*1 Y. Yanagisawa,*1 M. Ohtake,*1 Y. Sato,*1 N. Inabe,*1 and T. Kubo*1

We have measured the production rates and the production cross sections for a variety of radioactive isotopes (RIs), which were produced from a $^{124}$Xe beam at an energy of 345 MeV/u using the BigRIPS separator.1) Proton-rich isotopes with atomic numbers $Z = 34 - 52$ were produced by the projectile fragmentation of the beam on a 4-mm thick Be production-target. The particle identification of RIs was based on the TOF-$B\rho$-$\Delta E$ method.2)

The production cross sections were deduced from the measured production rates and the transmission efficiency in the BigRIPS separator, which was simulated with the LISE++ code.3) In the LISE++ simulation, the parametrization for momentum distribution was adjusted, because the exponential tails in the low-momentum regions fell off faster than those in the LISE++ calculation with the original parametrization for the 345-MeV/u $^{124}$Xe + Be reaction.4)

Figure 1 shows the production cross sections of RIs obtained in three experiments, including our first $^{124}$Xe-beam experiment4) with predictions of the EPAX empirical cross-section formulae. The type of symbols represents the experiment from which the data were obtained. The filled symbols indicate that the distribution peak is located inside the slit opening at each focus, while the open symbols indicate that the peak is located outside the opening. The deduced cross sections of the same isotopes obtained in different settings / experiments were fairly consistent with each other, even though some isotopes were accepted only their low-momentum tails in the separator. This indicates the reliability of our measurements and simulations with LISE++.

The solid and dashed lines in Fig. 1 show the cross sections predicted from the empirical formulae EPAX3.1a5) and EPAX2.15,6) respectively. EPAX3.1a predicts the cross sections better than EPAX2.15, which overestimates them. The measured cross sections of RIs with a wide range of $Z$ are fairly well reproduced by EPAX3.1a, although some isotopes show systematic discrepancies in the highly neutron-deficient region. For $^{100}$Sn, our experimental cross section at 345 MeV/u is approximately 1/6 of that predicted by EPAX3.1a. Further, the discrepancy becomes significant in the large $Z$ region.

References

*1 RIKEN Nishina Center
*2 Department of Physics, Rikkyo University
Production cross section measurements for fragments of $^{70}\text{Zn}$ beam

D. S. Ahn,$^{*,1}$ H. Suzuki,$^{*,1}$ N. Fukuda,$^{*,1}$ H. Takeda,$^{*,1}$ Y. Shimizu,$^{*,1}$ D. Murai,$^{*,1,2}$ K. Yoshida,$^{*,1}$ D. Kameda,$^{*,1}$ H. Sato,$^{*,1}$ Y. Sato,$^{*,1}$ Y. Yanagisawa,$^{*,1}$ K. Kusaka,$^{*,1}$ M. Ohtake,$^{*,1}$ N. Inabe,$^{*,1}$ and T. Kubo$^{*,1}$

We measured the production yields and production cross sections of radioactive isotopes (RIs) in the neutron-rich region with the atomic number $Z = 16 \sim 24$ produced from an $^{70}\text{Zn}$ beam at an energy of 345 MeV/nucleon by using the BigRIPS separator$^1)$. Neutron-rich RIs were produced through projectile fragmentation on a 10-mm Be target, and the particle identification (PID) of RIs was performed using the TOF-\(B\rho-\Delta E\) method. The energy loss (\(\Delta E\)) was measured using an ion chamber at F7. The time-of-flight (TOF) between F3 and F7 was measured using plastic scintillators and the trajectory was measured at F3, F5, and F7 by using Parallel Plate Avalanche Counters (PPACs).

The $B\rho$ of BigRIPS was set to the rigidity corresponding to the center of the momentum distribution of $^{56}\text{Ca}$, and the PID was confirmed by the isomers of $^{56}\text{Sc}$ and $^{59}\text{Ti}$. The experimental conditions for $^{56}\text{Ca}$ setting are listed in Table 1. Figure 1 is a PID plot showing the relation between the atomic number \((Z)\) and mass-to-charge ratio \((A/Q)\). Background events were eliminated by the correlations among phase-space profiles by using the PPAC, pulse-height, and timing signals from the plastic scintillators; reaction loss events in the ionization chamber; pile-up events using plastic scintillators and the ionization chamber; particle trajectories between two different foci; and charge state change at F5.

<table>
<thead>
<tr>
<th>Table 1. Experimental conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center particle</td>
</tr>
<tr>
<td>Target</td>
</tr>
<tr>
<td>F1 degrader</td>
</tr>
<tr>
<td>F5 degrader</td>
</tr>
<tr>
<td>$B\rho$01</td>
</tr>
<tr>
<td>Momentum acceptance</td>
</tr>
</tbody>
</table>

The production cross sections were obtained using the transmission efficiency calculated using LISE++ code$^3$ and production yields. In Figure 2, the red circles represent the experimental result of RIs produced from the $^{70}\text{Zn}$ beam. The solid and dashed lines in Fig. 2 represent the production cross sections calculated with empirical formulae EPAX3.1a$^4$ and EPAX2.15$^5$, respectively. EPAX3 is proposed as the universal empirical formula, and it shows better agreement with experimental data for the most neutron-rich fragments than EPAX2 does. Overall, our experimental measurements of cross sections are in good agreement with the EPAX parameterizations. The production cross sections are consistent with EPAX2.15 for $Z < 20$ and with EPAX3.1a for $Z > 20$.

Fig. 1. Particle identification plot of atomic number $Z$ versus mass-to-charge ratio $A/Q$ for projectile fragmentation in the reaction of $^{70}\text{Zn} + \text{Be}$ at an energy of 345 MeV/nucleon.

Fig. 2. Production cross section for fragments of the $^{70}\text{Zn}$ beam. The solid and dashed lines represent EPAX parameterizations, and the red circles represent experimental results.

References
3) O. B. Tarasov et al.: http://lise.nscl.msu.edu
On-line test of rotating magnetic field system for $\beta$-NMR method

Y. Ishibashi,*1,*2 D. Nagae,*1 Y. Abe,*1,*2 Y.E. Ichikawa,*1 K. Sawahata,*1 A. Ozawa,*1 and H. Ueno*2

The $\beta$-ray detected nuclear magnetic resonance ($\beta$-NMR) method is an efficient method to measure the nuclear magnetic ($\mu$) moment of unstable nuclei. The absolute value of $\mu$ moments are measured for various nuclei by using $\beta$-NMR. However, the sign of $\mu$ moments are rarely measured in experiment. In the $\beta$-NMR method, a linear oscillating magnetic field (RF), which can be a superposition of a right- and left-rotating RF, is applied to invert the direction of spin polarization. Thus, only the absolute value of $\mu$ moments is estimated from the applied frequency of the linear RF. Therefore, to determine the sign of a $\mu$ moment, applying a rotating RF is necessary. A rotating RF system has been under development (2,3) to determine the sign of a $\mu$ moment by using the $\beta$-NMR method. The rotating magnetic field is obtained using two Helmholtz-like coils with axes crossed at right angles. The experimental apparatus to produce the rotating RF is shown in Fig. 1, and a detailed description is given in Ref. 2 and 3.

In the present work, the performance of the system was studied with spin-polarized $^{20}$F ($I^\pi = 2^+$, $T_{1/2} = 11.163$ s, $\mu(20F) = +2.09335(9) \mu_N$) nuclei at the Research Center for Nuclear Physics, Osaka University. A spin-polarized $^{20}$F nucleus was produced in the $^{19}$F($d$, p)$^{20}$F reaction. In this reaction, the polarization of the beam particles is transferred to each nucleus. The $d$ beam was produced using a polarized ion source (3), and accelerated at $E/A = 10$ MeV using the AVF cyclotron. The polarized beams were impinged on a CaF$_2$ crystal (0.5 mm$^2$) to produce the polarized $^{20}$F. The crystal was placed at the center of the $\beta$-NMR apparatus (See Fig. 1) at room temperature with a static magnetic field $B_0 = 500$ mT applied.

The $\beta$-rays emitted from $^{20}$F nuclei were detected with plastic scintillator telescopes located above and below the crystal. The up/down ratio $R$ of the $\beta$-ray counts is written as $R_0 \approx a(1 + A_\beta P)/(1 - A_\beta P)$, where $a$ denotes a constant factor representing asymmetries in counter solid angles and efficiencies and $A_\beta$ and $P$ denote the $\beta$-ray asymmetry parameter and the degree of spin-polarization, respectively. A rotating RF perpendicular to $B_0$ is applied to $^{20}$F by using the two pairs of coils. If the frequency and direction of the rotating RF correspond to the resonance values, the direction of the spin polarization is inverted ($P \to -P$) by the NMR. Thus, the up/down ratio is changed as $R \approx a(1 - A_\beta P)/(1 + A_\beta P)$. When the polarization is altered because of the resonant spin change, a change appears in the ratio $R_0/R$. The $\beta$-ray asymmetry $A_\beta P$

is written as $A_\beta P = \sqrt{(R_0/R) - 1/\sqrt{(R_0/R)}} + 1$.

Fig. 1. Block diagram of the RF system for the rotating magnetic field and a schematic layout of the $\beta$-NMR setup.

The $d$ beam was pulsed with beam-on and beam-off periods of 16 s and 22.02 s, respectively. In the beam-off period of a cycle, RF was applied for the first 10 ms. Subsequently, the $\beta$-rays were counted for 22 s, and in the last 10 ms of the beam-off period RF was applied again to restore the spin direction. First, we measured $R_0$ without RF and then, we measured $R$ with RF. This cycle was repeated until the required measurement statistics were attained.

In this experiment, we first measured a $\mu$ moment by using $\beta$-NMR applied to the linear RF using tank circuit (a); then, measured it using another one. Figure 2 shows obtained $A_\beta P$ values. Next, we attempted to measure the sign of $\mu(20F)$ by applying a rotating RF. Analysis of the results is in progress.

Fig. 2. Obtained $A_\beta P$ value of $^{20}$F with applied linear RF field.

References
2) T. Niwa et al.: UTTAC 81, 5 (2012)

*1 Institute of Physics, Univ. of Tsukuba
*2 RIKEN Nishina Center
Probing the critical behavior in the evolution of GDR width at very low temperatures in A ∼ 100 mass region†


Although a wealth of data exists on the angular momentum dependence of width of giant dipole resonance (GDR) in different mass regions, the measurement of the GDR width at low temperatures (T < 1 MeV) is rather scarce due to the experimental difficulties in populating the nuclei at low excitation energies. The present work aims at providing systematic experimental data on the GDR width, specifically, at this very low temperature region. It is also our endeavor to systematically assess the different theoretical models and understand the complete nature of the damping mechanism as a function of T inside the atomic nucleus.

The increase of the GDR width as a function of T is described reasonably well within the Phonon Damping Model (PDM)1). The GDR damping mechanism is caused by coupling of the GDR to noncollective particle-hole (ph) and particle-particle (pp) [hole-hole (hh)] configurations. The coupling to the various ph configurations leads to the quantal width (exists even at T = 0), whereas the thermal width arises owing to the coupling to pp and hh configurations which appear at T > 0 because of the distortion of the Fermi surface. Thermal pairing since is also included, since in finite systems it does not collapse at the temperature of the superfluid-normal phase transition in infinite systems, but decreases monotonically as T increases. The macroscopic Thermal Shape Fluctuation Model (TSFM)2–3), on the other hand, is based on the fact that large-amplitude thermal fluctuations of the nuclear shape play an important role in describing the increase of the GDR width as a function of T. The TSFM, however, cannot explain the T dependence below 1.5 MeV in different mass regions. Recently, by modifying the phenomenological parameterization (pTSFM)3), a new fitting formula, called the Critical Temperature included Fluctuation Model (CTFM), was proposed4), which gives a good description of the GDR width behavior for both T and J in the entire mass region.

In this work, a systematic measurement of the apparent GDR width has been carried out in the unexplored region (T = 0.8 – 1.5 MeV) for 97Tc using alpha induced fusion reactions. This is the first measurement of the GDR width at finite temperature in A ∼ 100 mass region both above and below the critical point

† Condensed from the article in Phys. Lett. B 731, 92 (2014)
*1 Variable Energy Cyclotron Center, Kolkata
*2 Department of Physics, Barasat Govt. College, Kolkata
*3 Department of Physics, Raniganj Girls’ College, Kolkata
*4 RIKEN Nishina Center
*5 School of Engineering, Tan Tao University

and can be effectively used to verify the existing theoretical models. The experiments were performed at the Variable Energy Cyclotron Centre (VECC), Kolkata. A self supporting 1 mg/cm² thick 93Nb target was bombarded with alpha beams produced by the K-130 cyclotron. Four different beam energies of 28, 35, 42 and 50 MeV were used to form the compound nucleus (CN) 97Tc at the excitation energies of 29.3, 36, 43 and 50.4 MeV, respectively. The high energy γ-rays from the decay of 97Tc were detected using the high energy photon spectrometer LAMBDA.

The data have been compared with the TSFM, CTFM and PDM. Interestingly, the CTFM and PDM give the similar results and agree with the data, whereas the TSFM differs significantly even after incorporating the shell effects (Fig. 1).

References
2. Nuclear Physics (Theory)
Hoyle band and $\alpha$ condensation in $^{12}$C

Y. Funaki$^{*1}$

The Hoyle state, the second $J^\pi = 0^+$ state at 7.65 MeV in $^{12}$C, is a typical example of cluster states and had a long history since it was predicted by F. Hoyle and subsequently observed by Cook et al. as a key state in the synthesis of $^{12}$C in stellar evolution. In the last decade, the aspects of the $\alpha$ condensate, in which $\alpha$ clusters occupy an identical S-orbit, has attracted great interest since the so-called Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function$^3$, which has the 3$\alpha$ condensate character, was shown to be equivalent to the Hoyle state wave function obtained by solving the equations of the full 3$\alpha$ resonating group method (RGM) or generator coordinate method (GCM)$^2$. In addition to the Hoyle state, the nature of the other positive-parity excited states were recently highlighted by many experiments$^3$–$^6$.

In this report, we investigate the structures of the positive parity excited states above the 3$\alpha$ threshold by using an extended version of the THSR wave function, which includes the 3$\alpha$ condensate and $^8$Be + $\alpha$ asymptotic configurations, with a treatment of resonances$^7$. In particular, we focus on the structures of the “Hoyle band” states as well as the $2^+_2$($3^-$–$5^-$) and $4^+_2$($5^+$–$6^+$) states, which were recently observed above the Hoyle state, in addition to the structures of the $0^+_3$ and $0^+_4$ states, which were also quite recently identified in experiment$^5$.

In Fig. 1, the calculated energy levels for the five states are denoted by red diamonds. The calculated energy levels for the five states are denoted by red diamonds.

In Fig. 1, the calculated energy levels are plotted as a function of $J(J + 1)$, together with the experimental data. We can observe that the $0^+_2$, $2^+_2$, and $4^+_2$ states roughly follow a $J(J + 1)$ trajectory both in theory and experiment, which gives a support to the rotational picture. In fact, we found the very strong $E2$ transitions inside the Hoyle band $B(E2; 4^+_2 \rightarrow 2^+_2) = 591$ $e^2$fm$^4$ and $B(E2; 2^+_2 \rightarrow 0^+_2) = 295$ $e^2$fm$^4$.

On the other hand, the $J^\pi = 0^+$ band head in experiment seems to be fragmented into the Hoyle state and the $0^+_3$ state, and the calculated levels also have a similar tendency concerning the $B(E2)$ transition from the $2^+_2$ state, the Hoyle state being located slightly below and the $0^+_3$ state slightly above the $J(J + 1)$ line. Accordingly, the transition between the $2^+_2$ and $0^+_3$ states is also very strong $B(E2; 2^+_2 \rightarrow 0^+_3) = 104$ $e^2$fm$^4$.

This suggests that the Hoyle band, especially in what concerns the $0^+$ band head-state, cannot be considered a simple rotational band. This results from the fact that the 3$\alpha$ condensate structure in the Hoyle state is not the same as the usual $^8$Be$(0^+) + \alpha$ rotation, in which the remaining $\alpha$ cluster orbits outside the $^8$Be core. Namely, in the Hoyle state, the remaining $\alpha$ cluster also orbits inside the $^8$Be core, and independent 3$\alpha$-cluster motion in an identical 0S-orbit is realized. Consequently, the Hoyle state gains extra binding energy, and hence its energy position is considered to be pushed below the $J(J + 1)$ line, as shown in Fig. 1. The same effect is also argued to occur in the study of $^{16}$O$^{9,10}$, in which the 4$\alpha$ condensate is identified as a “complete condensate” and the $^{12}$C($0^+_3$) + $\alpha$ state as a “local condensate”. Because of the existence of the “complete condensate”, a higher $0^+$ excited state, which is shown to have a prominent $^8$Be$(0^+) + \alpha$ structure$^7$–$^{10}$ with the remaining $\alpha$ cluster orbiting outside the $^8$Be core, appears as a higher nodal state, the $0^+_3$ state excited from the Hoyle state with a very strong monopole transition strength calculated to be $M(E0; 0^+_2 \rightarrow 0^+_3) = 35$ fm$^2$.

References


$^{*1}$RIKEN Nishina Center
Energy and mass-number dependence of hadron-nucleus total reaction cross sections

A. Kohama,*1 K. Iida,*1,*2 and K. Oyamatsu*1,*3

The size of an atomic nucleus is one of the most fundamental quantities that characterize the bulk properties of nuclei. It is well known for $\beta$ stable nuclei in the ground state thanks to systematic measurements of electron and proton elastic differential cross sections. This helps clarify the equation of state of nuclear matter near the saturation point.\(^1\)

In this work, we systematically analyze nuclear reaction data that are sensitive to nuclear size, namely, proton-nucleus total reaction cross sections $\sigma_R(p + A)$ and differential elastic cross sections, using a phenomenological black-sphere (BS) approximation of nuclei that we are developing. In this framework, the radius of the black sphere “$a$” is found to be a useful length scale that simultaneously accounts for the observed $\sigma_R(p + A)$ and first diffraction peak in the proton elastic differential cross section. This framework is expected to be applicable to any kind of projectile that is strongly attenuated in the nucleus. On the basis of a cross-section formula constructed within this framework (BS cross-section formula)\(^2\) as function of the target mass number $A$ and the proton incident energy $T_p$, we find that a less familiar $A^{1/6}$ dependence of $\sigma_R$ plays a crucial role in describing the $T_p$ dependence.

In order to illustrate the $A$ dependence of $\sigma_R$, in Fig. 1, we compare the values of the BS cross-section formula with those obtained by using the square-well potential of the same radius “$a$” within the eikonal approximation for the cases of $^{natu}\text{C}$ and $^{natu}\text{Pb}$. By noting that $a$ very well scales as $A^{1/3}$, we examine the difference in the $A$ dependence between the two expressions. As a result of expansion in $A$, the leading term is proportional to $A^{2/3}$, while the subleading term is proportional to $A^{1/3}$ multiplied by an $A$ dependent exponential suppression factor in the eikonal approximation, which causes a different $T_p$ dependence from the solid curve in each panel of Fig. 1. This difference results from the $A^{1/6}$ dependence in $\sigma_R$.

By comparing the solid curves in the upper and lower panels of Fig. 1, one can see the relatively weaker $T_p$ dependence for the case of $^{natu}\text{Pb}$. The cross section itself becomes $\sim A^{2/3}$, while the $T_p$-dependent term is proportional to $\sim A^{1/6}$, leading to $O(A^{-1/2})$ corrections to the $O(A^{2/3})$ term. Thus, the relative change in the cross section by $T_p$ is suppressed. This is the reason why the slope toward a lower $T_p$ becomes steeper for the case of $C$ than that of $\text{Pb}$. The latest empirical values of $\sigma_R$\(^4\) apparently support the presence of the $O(A^{1/6})$ correction term in $\sigma_R$.

A part of this work was already reported in Ref.\(^5\).

References

5) A. Kohama \textit{et al}.: RIKEN Accel. Prog. 43, 59 (2009).

\textsuperscript{1} Condensed from the article in arXiv: 1411.7737
\textsuperscript{*1} RIKEN Nishina Center
\textsuperscript{*2} Dept. of Natural Science, Kochi University
\textsuperscript{*3} Dept. of Human Informatics, Aichi Shukutoku University

![Fig. 1. Comparison of the BS cross-section formula (solid curve) with the eikonal approximation based on the square-well potential (dashed curve) for $\sigma_n(p + ^{natu}\text{C})$ (upper) and $\sigma_n(p + ^{natu}/^{208}\text{Pb})$ (lower) as a function of $T_p$. We adopt both the BS radius at 800 MeV and the square-well radius as 2.70 fm for carbon and 7.40 fm for lead. The values of $\sigma_{BS}(=\pi a^2)$, which are represented by squares with crosses, are obtained from the measured peak angle of the first diffraction maximum of the proton elastic scattering. They are consistent with the measured $\sigma_R(s^0, x^0)$, which are supported by the measured empirical values of $\sigma_R$)](image-url)
Systematic calculation of $T = 1$ triplets with proton–neutron mixed energy density functionals

K. Sato,*1 J. Dobaczewski,*2,*3,*4 T. Nakatsukasa,*1,*5 and W. Satula*2,*4

We performed a systematic calculation for $T = 1$ isobaric analog states (IASs) based on energy density functionals (EDFs) including proton-neutron (p-n) mixing. Recently, we developed a new model to calculate IASs on the basis of the Skyrme EDFs that include mixing. In this framework, single-particle states are generalized as superpositions of proton and neutron components. In connection with this extension of single particles, density functionals are also extended to those with mixing between protons and neutrons1). In this work, we consider an extension of EDFs including p-n mixing only in the particle-hole (p-h) channel, with both the rotational and isospin symmetries conserved. Our ultimate goal, however, is to develop a consistent symmetry-unrestricted EDF approach including p-n mixing both in the p-h and pairing channels.

We developed a code for the p-n mixing calculation by extending the code “HFODD,”3) which solves the nuclear Skyrme–Hartree–Fock(–Bogolyubov) problem by using the Cartesian deformed harmonic-oscillator basis. In this p-n mixing calculation, we perform isocranking calculation by adding the isocranking term to the Hamiltonian: 
\[ \hat{h}' = \hat{h} - \lambda \hat{I}_Z. \]
Here, \( \hat{I}_Z \) is the isospin operator. The isocranking term is analogous to that used in the standard tilted-axis-cranking calculations for high-spin states. By adjusting the isocranking frequency \( \lambda \), we can control the size and direction of the isospin of the system.

In Ref. 1), we developed an efficient method for determining the isocranking frequency and successfully applied the isocranking model to the IASs in even-even \( A = 40 \) – 56 and odd-odd \( A = 14 \) isobars. Thus, we demonstrated that the p-n mixed single-reference EDF approach is capable of quantitatively describing the isobaric analog excited states. Among the results in Ref. 1), that of odd-odd \( T = 1 \) IASs is of particular interest (See Fig. 4 in Ref. 1)). We calculated the energies of the \( I = 0^+, T = 1 \) triplet of states in the \( A = 14 \) isobars, \( ^{14}\text{C} \), \( ^{14}\text{N} \), and \( ^{14}\text{O} \) by using the SkM* EDF. We found that there is asymmetry between the energy differences \( |E(T_z = 0) - E(T_z = -1)| \) and \( |E(T_z = 0) - E(T_z = 1)| \), which may be related to charge asymmetry and independence of the NN interaction. To investigate this point, in this study, we performed a systematic calculation of the \( T = 1 \) triplets in \( A = 4n + 2 \) nuclei. We calculated the triple energy difference (TED)\(^4\) \( 2E(T_z = 0) - E(T_z = 1) - E(T_z = -1) \) with several Skyrme parameter sets. In this model, while the \( T_z = \pm 1 \) IASs are obtained with the standard Hartree-Fock calculation without p-n mixing, the \( T_z = 0 \) IAS is calculated using the isocranking model and is described by a single time-even Slater determinant consisting of p-n mixed single particles.

Figure 1 shows examples of the results of the calculation. We plot the deviation of the calculated TEDs from the experimental data in the \( A = 14 - 58 \) region. The TEDs in the \( T = 1 \) triplets calculated with the SLy4, SIII, and SkM* parameter sets are shown. One can see a systematic underestimation of the TEDs in Fig. 1. In this calculation, we used isoscalar EDFs, which are invariant under rotation in isospin space, plus the Coulomb energy functional. This systematic deviation may imply that we need to extend functionals further to include isospin breaking terms. We already started performing a calculation including the isospin breaking interaction, which will be reported elsewhere.

References
Correlated two-neutron emission in decay of unbound nucleus $^{26}\text{O}$

K. Hagino$^1$ and H. Sagawa$^{2,*3}$

We study the two-neutron decay of the unbound $^{26}\text{O}$ nucleus with a three-body model assuming an inert $^{24}\text{O}$ core and two valence neutrons. In order to describe the decay properties of the neutron unbound nucleus, we take into account the couplings to the continuum by using the Green’s function technique.

In the experiment of Ref.$^3$, the $^{26}\text{O}$ nucleus was produced in a single proton-knockout reaction from a secondary $^{27}\text{F}$ beam. Therefore, we first construct the ground state of $^{27}\text{F}$ with a three-body model, assuming the $^{25}\text{F}+n+n$ structure. We then assume a sudden proton removal; that is, the $^{25}\text{F}$ core changes to $^{24}\text{O}$ keeping the configuration for the $n+n$ subsystem of $^{26}\text{O}$ to be the same as that in the ground state of $^{27}\text{F}$. This initial state, $\Psi_i$, is then evolved with the Hamiltonian for the three-body $^{24}\text{O}+n+n$ system for the two-neutron decay.

We consider two three-body Hamiltonians, one for the initial state $^{25}\text{F}+n+n$ and the other for the final state $^{24}\text{O}+n+n$. For both cases, we use the Hamiltonian

$$H = \hat{h}_{nc}(1) + \hat{h}_{nc}(2) + v(1,2) + \frac{\vec{p}_1 \cdot \vec{p}_2}{A_cm}, \quad (1)$$

where $A_c$ is the mass number of the core nucleus, $m$ is the nucleon mass, and $\hat{h}_{nc}$ is the single-particle (s.p.) Hamiltonian for a valence neutron interacting with the core. We use a contact interaction between the valence neutrons. See ref.$^2$ for details of the parameters of Eq. (1) and the contact interaction between the neutrons.

With the initial wave function from the three-body model, the decay energy spectrum can be computed as

$$\frac{dP}{dE} = \frac{1}{\pi} \Im(\langle \Psi_f | G(E) | \Psi_i \rangle), \quad (2)$$

with $G(E) = G_0(E) - G_0(E)v(1 + G_0(E)v)^{-1}G_0(E)$, where $\Im$ denotes the imaginary part. $G(E)$ is the perturbed Green’s function, while $G_0(E)$ is the unperturbed Green’s function given by

$$G_0(E) = \sum_{1,2} \frac{\langle j_1j_2|0^+\rangle \langle j_1j_2|0^+\rangle}{E_1 + E_2 - E - i\eta}, \quad (3)$$

where the sum includes all independent two-particle states coupled to the total angular momentum $J = 0$ with positive parity, as described by the three-body Hamiltonian for $^{24}\text{O}+n+n$.

Figure 1 shows the decay energy spectrum obtained with Eq. (2). The solid line shows the correlated spectrum, in which the final–state $nn$ interaction is fully taken into account, while the dotted line shows the result without the final–state $nn$ interaction. The latter corresponds to the term $G_0(E)$ in $G(E)$. Without the final–state $nn$ interaction, the two valence neutrons in $^{26}\text{O}$ occupy the s.p. resonance state of $1d_{3/2}$ at 770 keV, and the peak in the decay energy spectrum appears at twice this energy. When the final–state $nn$ interaction is taken into account, the peak is drastically shifted towards a lower energy and appears at 0.14 MeV, in good agreement with the experimental data. The figure also shows with the dashed line the result obtained by including only the $(d_{3/2}d_{3/2})^{(0^+)}$ configurations in the unperturbed Green’s function of Eq. (3). This corresponds to the case without the dineutron correlation in the final state, as the dineutron correlation is caused by an admixture of several configurations with different parities. The dineutron correlation shifts the peak position further down, making the peak appear at an energy close to the threshold, as shown by the solid line.

We discuss the role of neutron-neutron correlation in the decay probability as well as in the energy and the angular distributions of the emitted neutrons in Ref.$^2$.

References

Three-body model calculation of the $2^+$ state in $^{26}$O$^+$

K. Hagino$^{*1,*2}$ and H. Sagawa$^{*3,*4}$

We discuss the $2^+$ state of $^{26}$O using a three-body model of an $^{24}$O+$n+n$ system with full account of the continuum. The decay energy spectrum for a given angular momentum $I$ can be evaluated as

$$\frac{dP_I}{dE} = \sum_k |\langle \Psi_k^{(I)}|\Phi_{ref}^{(I)} \rangle|^2 \delta(E - E_k),$$

(1)

where $\Psi_k^{(I)}$ is a solution of the three-body model Hamiltonian with angular momentum $I$ and energy $E_k$, and $\Phi_{ref}^{(I)}$ is the wave function for a reference state with the same angular momentum. For a reference state we use the uncorrelated state of $^{27}$F with the neutron $\{1d_{3/2} \otimes 1d_{3/2}^{(1I)}\}$ configuration, which is dominant in the ground state of $^{27}$F.

With a contact interaction, the continuum effects on the decay energy spectrum can be taken into account in terms of the Green’s function. Notice that Eq. (1) can be expressed as

$$\frac{dP_I}{dE} = -\frac{1}{\pi} \sum_k \frac{(\Phi_{ref}^{(I)}|\Psi_k^{(I)}\rangle)}{E_k - E - i\eta} (\Psi_k^{(I)}|\Phi_{ref}^{(I)}\rangle),$$

(2)

where $\Im$ denotes the imaginary part and $\eta$ is an infinitesimal number and $G^{(I)}(E)$ is the correlated Greens’s function. The correlated Greens’s function will be constructed using the unperturbed Green’s function.

The upper panel of Fig. 1 shows the decay energy spectrum of $^{26}$O for $I = 0$ (dashed line) and $I=2$ (solid line). For presentation purposes, we set $\eta$ in Eq. (2) to be a finite value, i.e., $\eta = 0.21$ MeV$^{-1}$. For comparison, we also show the spectrum for the uncorrelated case with a dotted line, which gives the same spectrum both for $I = 0$ and $I = 2$. For the uncorrelated case, the spectrum has a peak at $E = 1.54$ MeV, which is twice the single-particle resonance energy, 0.77 MeV. With the pairing interaction between the valence neutrons, the peak energy shifts towards lower energies. The energy shift $\Delta E$ is larger in $I = 0$ than in $I = 2$, i.e., the peak in the spectrum appears at $E = 0.148$ MeV ($\Delta E = -1.392$ MeV) for $I = 0$ and at $E = 1.354$ MeV ($\Delta E = -0.186$ MeV) for $I = 2$.

We have shown that the $2^+$ state appears at approximately $E = 1.35$ MeV. This $2^+$ energy is close to, but slightly smaller than, the unperturbed energy, $E = 1.54$ MeV, and thus the energy shift from the unperturbed energy is much smaller than the energy shift for the $0^+$ state. We have argued that this is a typical spectrum well understood by the single-$j$ model with the pairing residual interaction. Many shell model calculations such as the ab initio$^3$ and USDA and USDB$^4$ calculations have predicted the excitation energy of the $2^+$ state in $^{26}$O in the opposite trend, i.e., they have predicted a higher energy than the unperturbed energy. The energy of the $2^+$ state needs to be urgently confirmed experimentally$^5$ in order to clarify the validity of nuclear models and effective interactions in nuclei on and beyond the neutron drip-line.

Fig. 1. (upper panel) The decay energy spectrum for the two-neutron emission decay of $^{26}$O. The dashed and solid lines represent the $0^+$ and $2^+$ states, respectively. The dotted line shows the uncorrelated spectrum obtained by ignoring the interaction between the valence neutrons. (lower panel) The decay energy spectrum obtained by superposing the $I = 0$ and $I = 2$ components. The dashed line is the decay energy spectrum for the pure $I = 0$ configuration. The experimental data, normalized to the unit area, are taken from Ref.$^2$.

References

5) Y.Kondo and T.Nakamura, private communications.

\textsuperscript{1} Condensed from the article in Phys. Rev. C 90, 027303(2014)
\textsuperscript{*1} Department of Physics, Tohoku University
\textsuperscript{*2} Research Center for Electron Photon Science, Tohoku University
\textsuperscript{*3} RIKEN Nishina Center
\textsuperscript{*4} Center for Mathematics and Physics, University of Aizu
Proton-neutron pairing vibrations in $^{40}$Ca: Precursory soft mode of the isoscalar spin-triplet pairing condensation

K. Yoshida$^{*1}$

The pairing correlation plays a central role in low-energy nuclear phenomena. The correlation is so strong that the fluctuations of the pairing gap around its zero equilibrium value develop in nuclei near the closed shell, and the systems get deformed eventually in gauge space when more nucleons are added. The collective pairing vibration emerging in the closed-shell nuclei is thus associated with the occurrence of the pairing condensation.

It is in the isovector and spin-singlet ($T = 1, S = 0$) channel that the pairing correlation has been extensively studied. With the advent of the radioactive-isotope beam technology, heavy proton-rich nuclei along the $N = Z$ line have received considerable attention. The isoscalar and spin-triplet ($T = 0, S = 1$) pairing correlation is expected to be visible in $N \sim Z$ nuclei because the shell structures around the Fermi levels of both neutrons and protons are similar to each other and the spatial overlap between the neutron and proton single-particle wave functions would be large to form a proton-neutron ($pn$) Cooper pair$^1)$. Because of the strongly attractive $pn$ interaction in the $^3S_1$ channel, the possible $T = 0$ pairing condensate has been discussed theoretically in heavy $N \sim Z$ nuclei$^2-4)$.

I investigate the possibility of a collective $T = 0$ $pn$-pairing vibrational mode in the “normal” phase where the $T = 0$ pairing gaps are zero. The $pn$ pair excitations are described microscopically based on the nuclear energy-density functional (EDF) method. More precisely, the $pn$-pairing vibrational modes are obtained out of the solutions of the $pn$ particle-particle random-phase approximation (ppRPA) equation, and are described as elementary modes of excitation generated by two-body interactions acting between a proton and a neutron. Then, I show that the strongly collective $T = 0$ $pn$-pairing vibrational mode emerges when the interaction is switched on.

Figure 1 shows the strength distributions for the monopole ($L = 0$) $pn$-pair-addition and removal transfer $\langle |Z \pm 1, N \pm 1; \lambda | \hat{P}_{T,S} \hat{P}_{T,S} | Z, N \rangle |^2$ as functions of the RPA frequency $\omega_\lambda$ in $^{40}$Ca. In the present calculation, the SGII interaction is used for the particle-hole (ph) channel. For the pp channel, the density-dependent contact interactions are employed. The pairing strength in the $T = 1$ channel is fixed as $V_0(T=1) = -390$ MeV fm$^3$. The pairing strength in the $T = 0$ channel is given as $V_0(T=0) = f \times V_0(T=1)$.

Factor $f$ is changed to see the effect of the interaction in the $T = 0$ channel.

It is clearly visible that the RPA frequency of the $T = 0$ $pn$-pairing vibrational mode becomes lower on increasing the pairing strength $f$. The pairing collectivity generated is sensitive to the shell structure as well as to the interactions. The critical strength is found to be $f_c = 2.04$. A rapid lowering of the RPA frequency seen here indicates the occurrence of true vacuum giving the $T = 0$ pairing gaps $\Delta \equiv \langle \hat{P}_{T=0,S=1} \rangle \neq 0$ in the limit of the strong pairing interaction $f > f_c$.

Another direct measure of the collectivity is the $pn$ transfer strength. One can also see an exponential enhancement in the transition strengths when approaching the critical strength $f_c$. Therefore the $1^+$ state in $^{38}$K and $^{42}$Sc can be considered as a precursory soft mode of the $T = 0, S = 1$ pairing condensation.

References

---

$^1$ Condensed from the article in Phys. Rev. C 90, 031303(R) (2014).
$^{*1}$ Graduate School of Science and Technology, Niigata University.
Study of low-frequency negative-parity vibrational excitations of superdeformed rotational band in $^{40}$Ca using cranked Skyrme-RPA calculations

M. Yamagami*1 and K. Matsuyanagi*2

An atomic nucleus is a unique quantum system. A nucleus exists in various modes with diverse shapes and collective motions by adding only a small percentage of the total binding energy. The diversity also increases with additional isospin and angular momentum.

$^{40}$Ca is a representative nucleus: the ground state is spherical with a spherical magic number $N = Z = 20$; however a superdeformed (SD) band built on the excited $0^+$ state at 5.2 MeV was found. The large octupole collectivity can be expected in the SD state associated with the SD shell structure that consists of approximately an equal number of positive- and negative-parity levels.

The description of diverse nuclear phenomena through a single theoretical framework is a challenging subject. Toward this direction, we have developed the first computer code of the cranked random phase approximation with Skyrme density functional (cranked Skyrme-RPA). Using this code, once the Skyrme density functional is fixed, we can simulate consistently the ground state as well as the rotational and vibrational excitations in nuclei across the nuclear chart.

We adopt the single-particle Hamiltonian with the triaxially deformed potential that uniformly rotates about the $x$-axis with a rotational frequency $\omega_{\text{rot}}$; $h' = h - \omega_{\text{rot}}J_x$. The Skyrme SLy4 interaction is employed for $h$. Two discrete symmetries, the parity and rotation about the $x$-axis at the angle $\pi$, are imposed on the single-particle wave functions. The wave functions are represented through Fourier-series expansion in order to effectively treat the configurations involving unbound single-particle states.

We solve the RPA equation in the matrix form with a residual interaction derived from the Skyrme force through the Landau-Migdal approximation. The octupole transition operators $O_{3K}^{(\xi,\zeta)}$ can be classified by the $z$-component $K$ of its angular momentum and the $x$ ($z$) - signature $\xi$ ($\zeta$) = ±1 representing the symmetry of rotation about the $x$ ($z$) - axis. The Coriolis coupling mixes the different $K$ and $\zeta$ modes. The excitations can be classified into two types by $\xi$.

We study the low-frequency negative-parity vibrational excitations of the SD rotational band in $^{40}$Ca. The upper part of Fig. 1 shows the six vibrational states with $\xi = -1$ for vibrational energy $E_{\text{vis}} < 5$ MeV. The isoscalar octupole transition strength $B(IS: O_3)$ changes as a function of $\omega_{\text{rot}}$, and the maximum value for each vibrational state exceeds 50 Weisskopf units (W.u.) within the region from $\omega_{\text{rot}} = 0$ to 1.6 MeV/$h$.

The vibrational energy of the first excitation decreases as a function of $\omega_{\text{rot}}$. The $B(IS: O_3)$ value is 66.5 W.u. at $\omega_{\text{rot}} = 0.4$ MeV/$h$ and then decreases slowly. This $\omega_{\text{rot}}$ dependence is associated with the rotational alignment of $[440]_1/2$ particle states: This effect reduces the SD shell gap at $N (Z) = 20$ by 42.4 (40.4) percent while $\omega_{\text{rot}}$ changes from 0 to 1.5 MeV/$h$. The $B(IS: O_3)$ value is dominated by the $\zeta = +1$ component $B(IS: O_3^{(\xi=+1)})$ consisting of $O_3^{(-1,+1)}$ and $O_3^{(-1,-1)}$.

It is quite interesting to investigate what will happen if $\omega_{\text{rot}}$ is increased further; however we could not obtain reliable RPA solutions. A better method for eliminating the spurious center of mass component may be required. Nevertheless, it seems reasonable to assume that the above discussion will continue: the vibrational energy will decrease further and cross the yrast line. This may indicate an instability of the SD shape, leading to a transition to a non-axial reflection-asymmetric shape.

References

Self-consistent Hartree-Fock and RPA Green’s function method for monopole response of neutron-rich Ni isotopes†

I. Hamamoto*1,† and H. Sagawa*1,‡

We discuss low-energy monopole strength of Ni isotopes using the self-consistent Hartree-Fock calculation and the RPA Green’s function method with Skyrme interactions. This study is strongly motivated by a recent observation of monopole strength by inelastic alpha scattering at 50 A MeV on the unstable nucleus 68Ni.1) The observation of soft monopole mode is reported at 12.9 ± 1.0 MeV, in addition to the isoscalar giant monopole resonance (ISGMR), for which the centroid is placed at 21.1 ± 1.9 MeV. To study the properties of low-energy monopole strength, the continuum effect must be properly taken into account in the theoretical calculations. Therefore, we perform the self-consistent HF+RPA calculations with the Skyrme interactions in coordinate system. The strength distributions $S(E)$ are obtained from the imaginary part of the RPA Green function, $G_{RPA}$, as

$$S(E) = \sum_n |<n|Q|0>|^2 \delta(E - E_n)$$

$$= \frac{1}{\pi} \text{Im} Tr(Q^\dagger(\vec{r}) G_{RPA}(\vec{r};\vec{r}';E) Q(\vec{r}'))$$

where $Q$ expresses one-body operators

$$Q^{\lambda=0,\tau=0} = \frac{1}{\sqrt{4\pi}} \sum_i r_i^2$$

for isoscalar monopole strength. The calculated results are shown in Fig. 1. Note that the widths of all responses are due to the coupling to the continuum without any smearing factor. It is concluded that sharp monopole peaks with width on the order of 1 MeV can hardly be expected for 68Ni in the low energy region below 20 MeV. Instead, a broad shoulder of monopole strength consisting of neutron excitations to non-resonant one-particle states (called threshold strength) with relatively low angular momenta $(\ell,j)$ is obtained in the continuum energy region above the particle threshold, which is considerably lower than that of the isoscalar giant monopole resonance. In the monopole excitations of 68Ni there are no unperturbed particle-hole states below 20 MeV, in which the particle is placed in either a bound or a resonant state. It is emphasized that in the theoretical estimation a proper treatment of the continuum is extremely important.

Fig. 1. (Color online) Monopole strength function (1) of 68Ni. (a) Unperturbed monopole strength and isoscalar monopole RPA strength. The RPA strength denoted by the solid curve includes all strengths due to the coupling between bound and unbound states in RPA. In the unperturbed response, the p-h strengths, in which both particle and hole orbits are bound, are not included. The energies of those unperturbed p-h excitations are the $1d_{5/2} \rightarrow 2d_{5/2}$ excitation at 27.60 MeV for neutrons and the excitations of $1p_{3/2} \rightarrow 2p_{3/2}$ at 27.58 MeV and $1p_{1/2} \rightarrow 2p_{1/2}$ at 27.46 MeV for protons. In addition, the proton excitation at 27.3 MeV from the bound $1d_{5/2}$ orbit to the one-particle resonant $2d_{5/2}$ orbit has such a narrow width that the strength is not plotted. The narrow peaks at 24.1 and 24.7 MeV in the unperturbed strength curve are the proton $2s_{1/2} \rightarrow 1s_{1/2}$ and $1d_{3/2} \rightarrow 2d_{3/2}$ excitations, respectively. (b) Unperturbed neutron threshold strengths, which contribute to the total unperturbed strength below the energy of ISGMR in Fig. 1a, are shown for respective occupied hole orbits.

References


† Condensed from the article in Phys. Rev. C 90, 031302(R)(2014)
*1 RIKEN Nishina Center
*2 Division of Mathematical Physics, Lund Institute of Technology at the University of Lund
*3 Center for Mathematics and Physics, University of Aizu

\footnotesize

\begin{thebibliography}{9}
\end{thebibliography}
Origin of fusion hindrance in heavy systems

K. Washiyama*1

In fusion reactions in heavy systems whose charge product $Z_p Z_T$ is larger than 1600, it has been observed1) that the formation of a compound nucleus is strongly hindered around the Coulomb barrier energy, compared with $Z_p Z_T < 1600$ systems. In such heavy systems, an additional energy is needed to achieve fusion, which is called the extra-push energy,2) The most probable reason behind the fusion hindrance phenomenon is the occurrence of the quasi-fission process, which involves reseparation without the formation of a compound nucleus after two nuclei touch each other, in heavy systems. A macroscopic fluctuation–dissipation model using a Langevin equation has been developed3) to analyze quasi-fission and fusion dynamics especially in the synthesis of superheavy elements. Recently, the quasi-fission process was analyzed using the microscopic time-dependent Hartree-Fock (TDHF) model,4)

The aim of this study is to analyze in detail the origin of fusion hindrance in heavy systems by using the microscopic TDHF model. To this end, we employ our method5) to extract nucleus–nucleus potential and one-body energy dissipation from the relative motion of colliding nuclei to internal degrees of freedom in the entrance channel of fusion reactions from TDHF evolution. We reported in Ref.6) that the nucleus–nucleus potential extracted from TDHF in the $^{96}$Zr+$^{124}$Sn system monotonically increases as the relative distance decreases, and that the potential shows no ordinary barrier. In this report, we present results of our systematic study for fusion in heavy systems and discuss a possible origin of fusion hindrance.

First, we perform systematic calculations for estimating the extra-push energy by TDHF for several heavy systems. We define the extra-push energy using TDHF as the difference between the fusion threshold energy and the potential barrier obtained from the frozen density approximation, $E_{\text{extra}} = E_{\text{thres}} - E_{\text{FD}}$. The frozen density potential is estimated while keeping the projectile and target densities frozen to their respective ground-state densities. We confirm that the obtained extra-push energies agree well with those deduced from experimental observations. Then, we extract the nucleus–nucleus potential $V(R)$ and friction coefficient $\gamma(R)$ as a function of the relative distance between two nuclei $R$ for those systems. We find that the property of the extracted potentials is similar to that in the $^{96}$Zr+$^{124}$Sn system,6) i.e., monotonic increase and no barrier structure in the potential. Finally, we analyze the fusion hindrance in heavy systems. We extract $V(R)$ and $\gamma(R)$ at the fusion threshold energy. We stop the extraction at $R_{\text{min}}$ where the remaining kinetic energy reduces as much as possible in the TDHF simulations. At $R_{\text{min}}$, we can identify the extra-push energy as a sum of the remaining kinetic energy, accumulated dissipation energy estimated from $\gamma(R)$5), and increase in potential due to the frozen density barrier, denoted by $\Delta V = V(R_{\text{min}}) - V_{\text{FD}}$. In Fig. 1, the increase in potential $\Delta V$ and dissipated energy $E_{\text{diss}}$ are plotted for the $^{100}$Mo+$^{92}$Mo, $^{104}$Ru, $^{110}$Pd and $^{96}$Zr+$^{124}$Sn, $^{130}$Xe systems.

Fig. 1. Increase in potential $\Delta V$ (red circle) and accumulated dissipation energy $E_{\text{diss}}$ (blue diamond) for the $^{100}$Mo+$^{92}$Mo, $^{104}$Ru, $^{110}$Pd and $^{96}$Zr+$^{124}$Sn, $^{130}$Xe systems.

References

*1 RIKEN Nishina Center
Pairing effect in thermal shape fluctuation model on the width of giant dipole resonance†

A.K. Rhine Kumar,*1 P. Arumugam,*1 and N. Dinh Dan†2

The study of nuclear properties at high temperature, spin and isospin has gained much of interest in recent times. Apart from these extremes, there are still some unexplored regimes of hot nuclei. The properties of nuclei at very low temperatures and the phase transitions associated with that belong to such area where conclusive experimental results are scarce. At such low temperatures, the shell (quantal) and pairing effects are quite active though being modified by thermal effects. In hot nuclei, thermal fluctuations are expected to be large since the nucleus is a tiny finite system. Thermal shape fluctuations and fluctuations in the pairing field are the dominating fluctuations and have been so far studied separately within different models. Both of these fluctuations are expected to be present at low temperatures. However, the interplay between them has not been investigated so far. The present work addresses this subject and we study the influence of this interplay on the experimental observables, namely the width of giant dipole resonance (GDR). The thermal shape fluctuation model (TSFM), which is often used by experimentalists, describes the increase of the GDR width of giant dipole resonance (GDR). The thermal shape fluctuation model (TSFM), which is often used by experimentalists, describes the increase of the GDR width with temperature by averaging the GDR cross section over all the quadrupole shapes. However this model is known to largely overestimate the GDR width in open-shell nuclei at low temperatures. The success of a proper pairing approach1,2 suggests the necessity of including pairing correlations to cure this shortcoming of the TSFM. This is done in the present work.

We employ the thermal shape fluctuation model built on Nilsson-Strutinsky calculations3 with a macroscopic approach to GDR and examine the inclusion of the fluctuations in the pairing field. The nuclear shapes are related to the GDR observables using a model comprising an anisotropic harmonic oscillator potential with separable dipole-dipole interaction. In this formalism the GDR Hamiltonian can be written as $H = H_{\text{osc}} + \eta D^1D + \chi P^1P$, where $H_{\text{osc}}$ stands for the anisotropic harmonic oscillator hamiltonian, the parameter $\eta$ characterizes the isovector component of the neutron and proton average field and $\chi$ denotes the strength of the pairing interaction. The pairing interaction changes the oscillator frequencies $\omega_{\nu \nu}^{\text{osc}}(\nu = x, y, z)$ resulting in the new set of frequencies $\omega_{\nu} = \omega_{\nu \nu}^{\text{osc}} - \chi \omega^P$, where $\omega^P = \left( \frac{Z \Delta P + N \Delta N}{Z + N} \right)^2$ with $\chi$ having the units of MeV$^{-1}$. Alternatively, the role of pairing is to renormalize the dipole-dipole interaction strength such that, $\eta = \eta_0 - \chi_0 \sqrt{\omega^P}$, with $\chi_0$ having the units of MeV$^{-5/2}$. The effective GDR cross-sections is calculated by averaging all the cross-sections obtained from thermal fluctuations of quadrupole shapes by using the formula for the expectation value of an observable $\mathcal{O}$ as $\langle \mathcal{O} \rangle_{\beta, \gamma, \Delta P, \Delta N} = \int \mathcal{O}[W(T, \beta, \gamma, \Delta P, \Delta N)]d[\alpha]/\int W(T, \beta, \gamma, \Delta P, \Delta N)d[\alpha]$, where $W(T, \beta, \gamma, \Delta P, \Delta N) = \exp[-F(T; \beta, \gamma, \Delta P, \Delta N)/T]$, $F(\alpha) = \beta|\sin 3\gamma|d\beta d\gamma d\Delta P d\Delta N$. The total free energy ($F_{\text{TOT}}$) at a fixed deformation is calculated using the expression $F_{\text{TOT}} = E_{\text{LDM}} + \sum_{p,n} \delta F$. The liquid-drop energy ($E_{\text{LDM}}$) is calculated by summing up the Coulomb and surface energies corresponding to a triaxially deformed shape defined by the deformation parameters $\beta$ and $\gamma$. The shell correction ($\delta F$) is obtained with exact temperature dependence using the single-particle energies given by the triaxial Nilsson model.

The results of our calculations for $^{97}$Tc, $^{120}$Sn and $^{208}$Pb demonstrate that the TSFM can be quite successful if the shell effects (with explicit temperature dependence) and the pairing ones are properly incorporated in the free energy (See Fig. 1).

References

† Condensed from the article in Phys. Rev. C. 90, 044308 (2014)
*1 Department of Physics, Indian Institute of Technology Roorkee, Uttarakhand
*2 RIKEN Nishina Center
Shell-model study of Gamow-Teller transition from $^{100}$Sn

M. Honma,*1 T. Otsuka,*2,3,4 T. Mizusaki,5 Y. Utsuno,*6 N. Shimizu,*3 and M. Hjorth-Jensen*4,*7

In the previous report1, we presented the results of shell-model calculations with an effective interaction determined for the use around $^{100}$Sn. We adopted the model space consisting of four orbits 1p1/2, 0g9/2, 1d5/2 and 0g7/2 assuming a hypothetical “core” $^{76}$Sn. Starting with a G-matrix interaction,2) the Hamiltonian parameters were modified by iterative fits to experimental energy data. The shell-model results reasonably described the systematics of energy levels and electromagnetic transitions for nuclei around $^{100}$Sn.

As a next step, we report on the Gamow-Teller (GT) transition from $^{100}$Sn using the same shell-model framework. Since $^{100}$Sn is a doubly-magic, jj-closed $N=Z$ nucleus, some similarity to $^{56}$Ni is expected. In the case of $^{56}$Ni, the GT transition is dominated by the $\pi f_{7/2} \rightarrow \nu f_{5/2}$ excitation, and in the extreme single-particle picture the final state is described by a $1p$-$1h$ configuration on top of the closed $^{56}$Ni core. However, according to the realistic shell-model calculations, the GT strengths are distributed over many states due to the configuration mixing. We have reported3) that the “double-peak” structure in the strength distribution becomes significant after including 4$p$-$4h$ components. Therefore it is interesting to examine whether the similar structure could be seen in the case of $^{100}$Sn.

Since the GT transition from $^{100}$Sn should be dominated by the $\pi g_{9/2} \rightarrow \nu g_{7/2}$ excitation, we can expect a reasonable description in the present model space. At the price of the lack of some (possibly minor) components such as the $\pi d_{5/2} \rightarrow \nu d_{3/2}$, the present model space allows us to take into account the effects of sufficiently many $np$-$nh$ configurations. The calculated GT strength distribution is shown in Fig.1. Although we don’t see clear “double-peak” structure in this case even at the $t=5$ truncation level, the splitting of the strength becomes significant as more and more particle-hole configurations are included.

In the recent $\beta$-decay experiment of $^{150}$Sn,4) a possible “superallowed” GT transition corresponding to $B(GT)=7.6^{+2.5}_{-2.2}$ was observed. The analysis was made under the assumption that the GT decay goes into the single final $1^+$ state of $^{100}$In. This assumption was supported by large-scale shell-model calculations in the $gds$ model space, which predict the concentration of a large part (69%) of the GT strengths on the lowest $1^+$ state. In the present calculation, the GT decay goes mainly into the lowest three states, and the $1^+_3$ state carries the largest strength as shown in Fig.1 ($B(GT)=2.8$ including the standard quenching factor of 0.74). Further analysis is desired for clarifying the GT strength distribution and the corresponding closed-core structure.

Fig. 1. The GT transition strength from $^{100}$Sn calculated by the shell model varying the truncation order $t$, which stands for the number of nucleons allowed to excite from the lower orbits ($p_{1/2}$, $g_{9/2}$) to the higher orbits ($d_{5/2}$, $g_{7/2}$). The discrete strengths indicated by thick vertical bars are obtained by the prescription in Ref.5) through 100 Lanczos iterations, and they are folded by Gaussian of $\sigma=0.5$MeV as shown with a smooth curve. No quenching factor is considered for the purpose of comparison. The shell-model results are obtained by using the efficient code MSHELL64*6).

References
Reentrance phenomenon of superfluid pairing in hot rotating nuclei

N. Quang Hung,∗1 N. Dinh Dang,∗2 B.K. Agrawal,∗3 V.M. Datar,∗4 A. Mitra,*4 and D.R. Chakrabarty∗4

When a nucleus rotates (total angular momentum \( J \) and/or rotational frequency \( \omega \) are not zero), the nucleon (proton and neutron) pairs located around the Fermi surface will scatter to the empty levels nearby and lead to the decreasing of pairing correlation. When the \( J \) or \( \omega \) is sufficiently high, i.e., equal to the critical value \( J_c \) or \( \omega_c \), the scattered nucleons completely block the single-particle levels around the Fermi surface. Consequently, pairing correlation disappears. However, when \( J \) is slightly higher than \( J_c \) (or \( \omega \geq \omega_c \)), the increase of temperature \( T \) will relax the particles scattered around the Fermi surface and causes some levels become partially unoccupied, making them available for scattered pairs. As a result, the pairing correlation reappears at some critical value \( T_1 \). As \( T \) goes higher, e.g., at \( T_2 > T_1 \), the newly created pairs will be eventually broken down again. This phenomenon is called the pairing reentrance. The recently developed FTBCS1 theory that includes the effect due to quasiparticle-number fluctuations in the pairing field and angular momentum \( z \) projection at \( T \neq 0 \) has predicted the pairing reentrance effect in some realistic nuclei\(^1\). The shell-model Monte Carlo calculations have suggested that the pairing reentrance effect can be observed in the nuclear level density in a form of a local maximum at low \( T \) (or excitation energy \( E^* \)) and high \( J \) (or \( \omega \)). Recently, an enhancement of level density of \(^{104}\text{Pd}\) at low \( E^* \) and high \( J \) has been experimentally reported\(^2\). In this work we try to see whether the enhancement observed in the extracted level density of \(^{104}\text{Pd}\) is an experimental evidence of pairing reentrance phenomenon in atomic nuclei.

The FTBCS1 equations at finite temperature and angular momentum are derived based on the variational method to minimize the expectation value of the pairing Hamiltonian \( H = \sum_k \epsilon_k (a^\dagger_k a_{k+} + a^\dagger_{-k} a_{-k}) - G \sum_{k\bar{k}} a^\dagger_k a_{\bar{k}+} a_{k-} a_{\bar{k}+} / \lambda N - \omega M \), in the grand-canonical ensemble. This Hamiltonian describes a system rotating about the symmetry axis, which is chosen to coincide with its \( z \) component. The particle-number operator \( \hat{N} \) and the \( z \) projection \( \hat{M} \) of the total angular momentum \( \hat{J} \) (which coincides with \( \hat{M} \) for spherical nuclei) are defined as \( \hat{N} = \sum_k (a^\dagger_k a_{k+} + a^\dagger_{-k} a_{-k}) \), \( \hat{M} = \sum_k m_k (a^\dagger_k a_{k+} - a^\dagger_{-k} a_{-k}) \), where \( a^\dagger_k \) (\( a_{k+} \)) are the creation (annihilation) operators of a particle in the \( k \)-th deformed state, whereas \( \epsilon_k, \lambda, \) and \( \omega \) are respectively the single-particle energies, chemical potential, and rotational frequency. The FTBCS1 equation for the pairing gap has the final form as \( \Delta_k = \Delta + \Delta_k \), where \( \Delta = G \sum k_v u_k v_k (1 - n^+_k - n^-_k) \), \( \Delta_k = G \delta \Lambda^2 u_k v_k / (1 - n^+_k - n^-_k) \), with \( u_k, v_k, \) and \( n_k \) being the Bogolyubov’ \( a, \) \( v \) coefficients and quasiparticle occupation numbers, respectively. The total level density \( \rho(\mathcal{E}, J) \) is calculated as \( \rho(\mathcal{E}, J) = \rho(\mathcal{E}, M = J) - \rho(\mathcal{E}, M = J + 1) \), where \( \rho(\mathcal{E}, M) \) is obtained by using the inverse Laplace transformation of the grand partition function.

Because of quasiparticle number fluctuations, the FTBCS1 gaps decrease monotonically with increasing excitation energy \( E^* \) and do not collapse at \( E^* = E_c^* \) as in the case of the FTBCS. Within the FTBCS1, the pairing reentrance is seen very clearly at \( J = 20h \) for neutrons and at \( J = 30h \) for protons. Consequently, there appear local enhancements in the FTBCS1 level densities at around \( 2 < E^* < 5 \text{ MeV} \) at these two values of \( J \) (Fig. 1). The FTBCS1 level densities agree fairly well with the experimental data at all \( J \) values considered in present work.

References
Giant dipole resonance in highly excited nuclei\textsuperscript{1}

N. Dinh Dang*\textsuperscript{1}

The present work summarizes the achievements of the Phonon Damping Model (PDM)\textsuperscript{1} in the description of the GDR width and shape at finite temperature $T$ and angular momentum $J$. The GDR parameters predicted by the PDM and experimentally extracted are also used to calculate the shear viscosity of finite hot nuclei.

The PDM’s Hamiltonian consists of the independent single-particle (quasiparticle) field, GDR phonon field, and the coupling between them. The Woods-Saxon potentials at $T = 0$ are used to obtain the single-particle energies $\epsilon_k$.

The GDR width $\Gamma(T)$ is a sum: $\Gamma(T) = \Gamma_Q + \Gamma_T$ of the quantal width, $\Gamma_Q$, and thermal width, $\Gamma_T$. In the presence of superfluid pairing, the quantal and thermal widths are $\Gamma_Q = 2\gamma_Q(E_{GDR}) = 2\pi F_1 \sum_{ph} [u_{ph}^+(1 - u_p - u_h)\delta(E_{GDR} - E_p - E_h) + \Gamma_T = 2\gamma_T(E_{GDR}) = 2\pi F_2 \sum_{s > s'} [v_{ss'}^+)(n_{s'} - n_s)\delta(E_{GDR} - E_s + E_{s'})]$, where $u_{ph}^+ = u_p v_h + u_h v_p$ and $v_{ss'}^+ = \delta(E_{GDR} - \omega_q - P_q(E_{GDR}) = 0)$, where $\omega_q$ is the energy of the GDR phonon before the coupling between the phonon and single-particle mean fields is switched on, and $P_q(\omega)$ is the polarization operator owing to this coupling.

In numerical calculations the representation $\delta(x) = \lim_{\epsilon \to 0} \varepsilon/[\pi(x^2 + \varepsilon^2)]$ is used for the $\delta$-function with $\epsilon = 0.5$ MeV.

In the verification of the condition for applying hydrodynamics to nuclear system, the quantum mechanical uncertainty principle requires a finite viscosity for any thermal fluid. It has been conjectured that the ratio $\eta/s$ of shear viscosity $\eta$ to the entropy volume density $s$ is bounded at the lower end for all fluids, namely the value $\eta/s = h/(4\pi k_B)$ is the universal lower bound (KSS bound or unit). From the viewpoint of collective theories, one of the fundamental explanations for the giant resonance damping is the friction term (or viscosity) of the neutron and proton fluids.

The exact expression for the shear viscosity $\eta(T)$ in terms of the GDR’s parameters at zero and finite $T$ was obtained as $\eta(T) = \eta(0)[\Gamma(T)/\Gamma(0)][E_{GDR}(0)^2 + \Gamma(0)/2^2]\{E_{GDR}(T)^2 + \Gamma(T)/2^2\}$. The predictions for the GDR width and the ratio $\eta/s$ by the PDM, pTSFM, AM, and FLDM for $^{120}$Sn are plotted as functions of $T$ in Figs. 1 and 2 in comparison with experimental data.

### References

Theoretical analysis of $^{132}$Xe by generator coordinate method

N. Yoshinaga, K. Higashiyama, and E. Teruya

Xe, Ba, and Ce nuclei in the mass $A \sim 130$ region exhibit $\gamma$-instability in low-lying states, which is characterized by energy staggering of the even-odd spin states in the quasi-$\gamma$ band and by some forbidden transition rates between the yrast and quasi-$\gamma$ bands. The energy levels and decay properties of the low-lying states were discussed in the framework of the interacting boson model\(^\text{1)}\), where quadrupole collective excitations are described in terms of the angular momenta zero ($s$) and two ($d$) bosons.

Another characteristic feature of even-even nuclei is the irregular level sequence in the yrast band, i.e., the backbending phenomenon, which is interpreted as band crossing between the ground-state band and the $s$ band originating from the alignment of two neutrons in $0h_{11/2}$ orbitals. Sudden decreases in the level spacing and the $E2$ transition rates are observed around the states of spin 10. Recently, full-fledged shell-model calculations have been performed for the even-even, odd-mass and doubly-odd nuclei in this mass region\(^\text{2)}\). The shell-model calculations well reproduce the experimental energy levels and electromagnetic transition rates.

In the present study, we apply the quantum-number-projected generator coordinate method (GCM) to $^{132}$Xe under the same interaction used in the previous shell model studies\(^\text{3)}\). All the five orbitals, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $0h_{11/2}$ and $2s_{1/2}$, in the major shell of $50 \leq N(Z) \leq 82$ are considered, and valence neutrons (protons) are treated as holes (particles).

In the present scheme, spins of the neutron and proton systems $(I_\nu$ and $I_\tau$) are projected separately, and the total spin is constructed by angular momentum coupling. To generate functions for the GCM in a neutron or proton system $(\tau = \nu$ or $\pi$), we employ the Nilsson BCS intrinsic states $|\Phi_\pi(\beta, \gamma)\rangle$, where $\beta$ and $\gamma$ indicate axial and triaxial quadrupole deformations, respectively. The $\nu$th GCM wave function with angular momentum $I_\tau$ in neutron or proton space is given by

$$|\Psi_{I_\tau M_\nu}(I_\nu I_\pi)\rangle = \sum_i \sum_{K_\nu=-I_\nu} \mathcal{F}_{K_\nu,\rho}^{I_\nu I_\pi} \hat{P}_{M_\nu K_\nu} \hat{P}_{N_\nu} |\Phi_\pi(\beta_\nu, \gamma_\nu)\rangle,$$

where $\hat{P}_{M_\nu K_\nu}$ is the spin projection operator, $\hat{P}_{N_\nu}$ is the particle-number projection operator, $\mathcal{F}_{K_\nu,\rho}^{I_\nu I_\pi}$ is the weight function to be determined by solving the Hill-Wheeler equation, and $i$ stands for a representative point with deformation $(\beta, \gamma)$. Then, the wave function for an even-even nucleus can be written as

$$|\Psi_{1M}(I_\nu I_\pi)\rangle = \left[|\Psi_{\nu I_\nu}(\rho)\rangle \otimes |\Psi_{\pi I_\pi}(\sigma)\rangle \right]_M,$$

where $I$ is the total spin and $M$ is its projection. GCM calculations are carried out for two cases: (i) triaxial deformations (9 points) with $\beta = 0.10$, $0.20$, $0.30$, $\gamma = 10^\circ$, $30^\circ$, $50^\circ$; (ii) only axial deformations (49 points) with $\beta = 0.00$, $0.02$, $0.04$, $0.06$, $0.08$, $0.10$, $0.12$, $0.14$, $0.16$, $0.18$, $0.20$, $0.22$, $0.24$, $0.26$, $0.28$, $0.30$, $0.32$, $0.34$, $0.36$, $0.38$, $0.40$, $0.42$, $0.44$, $0.46$, $0.48$, $0.50$, $0.52$, $0.54$, $0.56$, $0.58$, $0.60$.

In Fig. 1, experimental energy levels are compared with the shell-model results, and those in the GCM. In both cases of triaxial and axial deformations, the GCM well reproduces the experimental energy levels of the even-spin yrast band and those obtained by the shell model. In the case of other excited states, the GCM calculations performed by assuming triaxial deformation are in good agreement with the shell model results, those in the GCM, and those in the triaxial GCM (triaxial), and those in the axial GCM (axial).

Fig. 1. Comparison of the experimental energy levels (expt.) with the shell-model (SM) results, those in the triaxial GCM (triaxial), and those in the axial GCM (axial).

References


\textsuperscript{*1} Department of Physics, Saitama University

\textsuperscript{*2} Department of Physics, Chiba Institute of Technology

\textsuperscript{*3} RIKEN Nishina Center
Tops-on-top model applied to TSD bands in $^{164}\text{Lu}$

K. Sugawara-Tanabe,*1,*2 K. Tanabe,*1,*3 and N. Yoshinaga*3

The top-on-top model with moments of inertia (MoI) dependent on angular-momentum ($I$) works quite well in describing triaxially strongly deformed (TSD) bands in odd-mass nuclei.1–3 In this paper, the top-on-top model is extended to the tops-on-top model for an odd-odd nucleus $^{164}\text{Lu}$, in which one proton and one neutron in each single-$j$ orbital are coupled to the triaxial rotor.

Both positive- and negative- parity TSD bands in $^{164}\text{Lu}$ are well reproduced by taking account of attenuation factors in the Coriolis interaction, which includes the effect of the partially filled single-$j$ shell. In order to observe the effect of the attenuation factor, we compared numerical results with and without the attenuation factor and confirmed its importance for the excitation energies relative to the reference, i.e., $E^* - aI(I+1)$ with $a=0.0075$ MeV.4,5

For a pure-rotor case without single-particle potentials, an explicit algebraic formula for the TSD band levels is obtained. The level is classified by three quantum numbers ($n_\alpha, n_\beta, n_\gamma$), where $n_\alpha$ is related to the rotor wobbling quantum number, and $n_\beta$ and $n_\gamma$ to the precession quantum numbers for a proton and a neutron. Under the condition of $D_2$-invariance,6 three quantum numbers take limited integers depending on the value of $I - j_1 - j_2$ and $n_\alpha - n_\beta - n_\gamma$. As an example, we assume $j_1 = j_2 = 13/2$, and compare the energy eigenvalues from this boson model with the result obtained from the exact diagonalization of the rotor Hamiltonian in Fig. 1 for odd number $I$ where $I - j_1 - j_2$ is even. In this case $n_\alpha$ and $n_\gamma$ appear as the combination $n_\alpha = n_\beta + n_\gamma$. The yrast has quantum numbers $(0,0)$ and the yrare $(0,2)$. On the other hand, for even number $I$ where $j_1 - j_2$ is odd, the yrast has quantum numbers $(1,0)$ and the yrare $(2,1)$. The boson model reproduces the exact results in good accuracy.

It is easy to derive the stability condition for a pure-rotor case. We found that there is no wobbling around the axis with the intermediate MoI. The wobbling motion exists only around the axis with the maximum or minimum MoI, which agrees with the result in classical mechanics.7 Consequently, we can state that there is no stable rotation around the axis with the intermediate MoI, and that stable rotational motion exists only around the axis with the maximum or minimum MoI.

The difference in quantum numbers between the yrast and yrare TSD bands in $^{164}\text{Lu}$, in which single-particle potentials are included, is confirmed by direct estimation of spin alignments. It is confirmed that the yrast TSD band with even $I - j_1 - j_2$ has quantum numbers $(n_\alpha, n_\beta, n_\gamma) = (0,0,0)$, while the yrare TSD band with odd $I - j_1 - j_2$ has $(1,0,0)$.

The electromagnetic transition rates of $B(M1)$ are reduced by a factor of 1/20 because the signs of g-factors of a proton and a neutron are different in comparison with the odd-A case, while the electromagnetic transition rates of $B(E2)$ are in the same order but reduced by a factor of 1/2. These reductions of electromagnetic transition rates will make the observation of TSD bands in even-even nuclei difficult.

References
Recent progress and open issues on pseudospin and spin symmetries†

H. Z. Liang,*1 J. Meng,*1,*2 and S.-G. Zhou*3

Pseudospin symmetry (PSS)†,2) was introduced to explain the near degeneracy between pairs of nuclear single-particle states with the quantum numbers \( (n - 1, l + 2, j = l + 3/2) \) and \( (n, l, j = l + 1/2) \). They are regarded as pseudospin doublets by defining the quantum numbers \( \tilde{n} = n - 1, \tilde{l} = l + 1, j = l \pm 1/2 \), as illustrated in Fig. 1.

This observation raised a fascinating question whether such near degeneracy is accidental (a degeneracy not explained by an obvious symmetry) or due to symmetry breaking (more descriptively hidden symmetry). Since PSS was recognized as a relativistic symmetry in the 1990s,3) many special features, including the spin symmetry (SS) for anti-nucleons,4) and many new concepts have been introduced in relevant studies, which led to several exciting discoveries during the past decade.

In this review article,† we intended to systematically provide a comprehensive overview on the recent progress. The PSS and SS in various systems and potentials were discussed based on the following aspects:

- From stable nuclei to exotic nuclei
- From non-confining to confining potentials
- From local to non-local potentials
- From central to tensor potentials
- From bound states to resonant states
- From nucleon spectra to anti-nucleon spectra
- From nucleon spectra to hyperon spectra
- From spherical nuclei to deformed nuclei

Then, three of the open issues in this field were selected and discussed in detail, i.e., the perturbative nature of PSS, the puzzle of intruder states, and the supersymmetric (SUSY) representation of PSS.

For the perturbative nature of PSS, we emphasized that the symmetry breaking behaves perturbatively depending on whether an appropriate symmetry limit is chosen and an appropriate symmetry-breaking term is identified. As long as an appropriate symmetry limit is chosen, the nature of PSS is indeed perturbative.5)

For the puzzle of intruder states, we showed several different features about this puzzle, i.e., the bound states in the non-confining or confining potentials, the bound and resonant states identified by the zeros of Jost function,6) a continuous transformation between SS and PSS, and the SUSY transformation of the PSS scheme. By doing so a number of “contradicting” results in the literature for the spin (pseudospin) partners have been clarified explicitly.

For the SUSY representation of PSS, we pointed out one of the promising ways for understanding the PSS and its symmetry breaking, by combining the similarity renormalization group, the SUSY quantum mechanics, and the perturbation theory.7) Meanwhile, application of the SUSY technique directly to the Dirac equations, which have non-trivial scalar and vector potentials, remains an interesting and open proposition.

Another important issue is the experimental signals of these symmetries. So far, several nuclear structure phenomena have been interpreted directly or implicitly by the PSS, including nuclear superdeformed configurations, identical bands, quantized alignment, and pseudospin partner bands. The relevance of PSS in the structure of halo nuclei and superheavy nuclei was also pointed out. More experimental evidences for PSS are highly desired for future studies.

References

Fig. 1. Schematic nuclear single-particle spectrum. Pairs of single-particle states in braces are defined as the pseudospin doublets.
Nuclear moment of inertia in super-normal phase transition region

K. Tanabe*1,∗2 and K. Sugawara-Tanabe*1,∗3

The purpose of this paper is to derive the analytic expression for the angular momentum (I) dependence of the moment of inertia (MoI) from the microscopic many-body theory both for even-even and odd-mass nuclei. The I-dependence of MoI has been proved to be essential in simulating triaxial, strongly deformed (TSD) bands in a series of papers.1–4)

We adapt the approximation developed for the gap (Δ) dependence of the ratio of MoI (J) to the rigid-body value (Jrig).5,6) It assumes that only large matrix elements of single-particle angular momentum of (jα) arise contribute to J with a common excitation energy of δ = Eβ − Eα, where Eα denotes the single-particle energy of the level α. We apply this approximation to the gap equation including the Coriolis anti-pairing (CAP) effect7) through the second-order perturbation to the cranking term.8,9)

When Δ is larger than half of the single-particle level distance d, we can apply a definite integral for the gap equation with the CAP effect. When Δ is smaller than half of d, we propose the finite sum method with the pickup-fence approximation for the level distribution. In this case, it is proved that Δ never tends to zero, and there is no sharp phase transition from the superconducting state to the normal state. Neglecting the higher order in 2Δ/δ for the case Δ < d/2 (finite sum method), we express MoI as an analytic function of I.

In Fig. 1, we compare the approximate solution between even-even and odd-mass nuclei as functions of d measured from the band-head angular momentum I0. Usually, I0 = 0 for even-even nucleus, while I0 ≠ 0 for odd-mass nucleus, for example, I0 = 13/2 for the TSD yrast band in 163Lu.10) We choose the single-particle energy for a valence nucleon as eγ = 0.6 MeV above the Fermi surface, and the initial pairing gap at I = I0 for odd mass as 0.6 MeV, smaller than 0.8 MeV for even-even nucleus (blocking effect). The blocking effect reduces the starting value of Δ and increases that of the MoI. In odd-mass case, there is a term that correlates the single-particle state of l with α through (jα)2l. The matrix element of (jα)2l is chosen to be 12 for εα > εγ and 10 for εα < εγ. The other parameters are the same as those for the even-even case. We have started both approximate solutions with Δ = 0.15 MeV corresponding to I − I0 ≈ 15, while d = 0.4 MeV.

As is seen in Fig. 1, the main difference between even-even (dashed line) and odd-mass (solid line) nuclei is from the blocking effect. Then, both curves increase gradually, and approach the value 1. The MoI of odd-mass case is chosen to be slightly larger than that of the even-even case. The curves become convex upward before they reach to rigid-body values. This upward convexity is also necessary for explaining the energy sequence of TSD bands.5) For the case of Δ ≥ d/2 (definite integral), J goes to Jrig around I − I0 ≈ 17 or 18 (sharp phase transition). Even in this case, odd-mass nuclei show an upward convexity before the phase transition at I ≈ 17 – 18. Because of larger I0, the slow phase transition occurs at larger I for odd-mass nuclei than for even-even nuclei.

References
5) A. Bohr and B. R. Mottelson: Nuclear Structure (Benjamin, Reading, MA, 1975), Vol. II.
Joint project for large-scale nuclear structure calculations in 2014

N. Shimizu,*1 T. Otsuka, *1,*2 T. Togashi,*1 N. Tsunoda,*2 and Y. Utsuno*1,*3

A joint project for large-scale nuclear structure calculations has been promoted since the year 2002 based on a collaboration agreement between the RIKEN Accelerator Research Facility (currently RIKEN Nishina Center) and the Center for Nuclear Study, the University of Tokyo. Currently, we maintain 16 PC servers with Intel CPUs for large-scale nuclear shell-model calculations. One of the servers has 40 CPU cores and 1TB main memory. Based on this project, we performed shell-model calculations of the various nuclides which had been measured at the RIKEN RI Beam Factory, such as $^{31}$Ne, $^{33}$Mg, and $^{50}$Ar under collaborations with many experimentalists.1) Since the results of these collaborations are presented in other reports, here we introduce four theoretical achievements of this project in 2014: development of a shell-model code, shell-model analyses of the isomeric states of $^{43,44}$S and high-spin states of neutron-rich Cr, Fe isotopes, and an application of the extended Kuo-Krenciglowa (EKK) method in understanding the island of inversion.

We developed a new code, named “KSHELL” for large-scale shell-model calculations on state-of-the-art supercomputers. In nuclear shell-model calculations, we solve an eigenvalue problem of the Hamiltonian matrix, whose dimension tends to be huge, by including many-body correlations fully inside the model space. The newly developed code enables us to solve this eigenvalue problem by using many CPU cores efficiently.

We have investigated the structure of exotic nuclei in the $N \sim 28$ region, which attracts much attention in experimental studies using RIBF. In our most recent work,3) we focus on the nature of exotic isomeric states in neutron-rich S isotopes, in particular strongly hindered $E2$ decay from $4f_1^\pi$ and $2g_9^\pi$ in $^{44}$S.4) This study is based on shell-model calculations using the SDPF-MU interaction5) which was developed in this joint project. In order to extract intrinsic states from the shell model, we carry out the variation after angular-momentum projection (AM-VAP). The AM-VAP calculation shows that the $4f_1^\pi$ level is dominated by a $K = 4$ intrinsic state and that this is the origin of the strong $E2$ hindrance. The $4f_1^\pi$ level in $^{44}$S is the lightest high-$K$ isomer among the ones ever identified in the $A \sim 100$, $A \sim 130$, $A \sim 180$, and $A \sim 250$ regions.

We have performed large-scale shell model calculations for natural- and unnatural-parity states in Cr and Fe isotopes with $N \leq 35$.6) Unnatural positive-parity states in odd-mass Cr and Fe nuclei with $N \leq 35$ were observed experimentally from low-lying energy levels to high-spin ones. These states are dominated by one-particle one-hole excitation across the $N = 40$ shell gap. The model space of our calculation is composed of $fp$-shell + $0g_{9/2} + 1d_{5/2}$ orbits with the truncation allowing $1\omega$ excitation of a neutron. It effectively describes and predicts the energy levels up to the high-spin states. The effective single-particle energies of $\nu 0g_{9/2}$ in Cr and Fe isotopes are rather constant in the region with $N \leq 35$. This indicates that the sharp drop of the $9/2^+$ levels in this mass region, which is discussed as an indication of the evolution of $\nu 0g_{9/2}$, is explained by the Fermi surface approaching the $\nu 0g_{9/2}$ orbit with the increase of neutron number.

Investigation of the neutron-rich nuclei starting from the fundamental nuclear force has been accomplished by the newly constructed EKK method.7) To construct the effective interaction for the shell model starting from the nuclear force, we usually utilize the many-body perturbation theory, but the standard perturbation theory ends up with a series of divergences when applied to a large shell-model space, for example, the model space spanned by two major shells. The EKK method avoids a divergence with a re-summation of the perturbative series and makes it possible to construct the effective interaction for more than one major shell. We constructed the effective interaction for the sd$\nu$f-shell, starting from the N3LO interaction with the EKK method. The contribution from the three-body force is also added as effective two-body interactions. We found that this interaction consistently describes the ground state energies and low-lying levels of even-even nuclei (O, Ne, Mg, Si isotopes). In particular, the disappearance of the $N = 20$ gap of Ne, Mg isotopes and the restoration of the $N = 20$ gap of Si and S isotopes are well described.

References
3. Nuclear Data
Development of a new EXFOR editor system

A. Sarsembayeva,¹,² S. Imai,¹,² S. Ebata,¹,² M. Chiba,³ K. Katō,¹ N. Otuka,⁴,⁵ and M. Aikawa¹

The International Network of the Nuclear Reaction Data Centers (NRDC)¹ is a worldwide network of nuclear data centers organized under the auspices of the International Atomic Energy Agency (IAEA). NRDC was established to collect experimental data from all over the world, initially addressing the data needs of the fission reactor industry.

The present aim of the NRDC is to encompass all types of nuclear reaction data, including neutron- and charged particle-induced data, as well as photonuclear data. Such data are required for many nuclear applications such as accelerator-driven systems, fusion reactors, nuclear medicine, materials analysis, environmental monitoring, and basic research.² Since the early 80s, the Nuclear Reaction Data Centre of Hokkaido University (JCPRG, formerly Japan Charged-Particle Nuclear Reaction Data Group)³ is an active member of the NRDC.

Under the NRDC, experimental nuclear reaction data are compiled in a unified format EXFOR (EXchange FORmat) and stored in the library.⁴ EXFOR is the main source of experimental nuclear reaction data and covers results published as early as in the 1930s.²

In order to make EXFOR compilation easy, various editor systems have been developed within the NRDC community. ANDEX⁵ developed by IAEA-NDS (Vienna) and ERES by CNDC (Beijing)⁶ are such systems developed in the 1990s. An EXFOR editor developed by CNPD (Sarov) in 2000s is currently used by many EXFOR compilers. In JCPRG, a web-based nuclear data input system HENDEL (Hyper Editor for Nuclear Data Exchange Libraries) was developed for the compilation of experimental nuclear reaction data in EXFOR and NRDF formats.⁷ The latter is the original database in JCPRG and is being used as a standard compilation editor system at JCPRG since 2001.⁸ For the beginners of EXFOR compilation, the HENDEL system is very useful because it requires only an elementary knowledge of EXFOR. It is now also used by young EXFOR compilers in Kazakhstan and Mongolia. While the current HENDEL system is well designed to create outputs in both NRDF and EXFOR formats, some extra input forms for the creation of NRDF outputs could be rather confusing for foreign compilers. Therefore, development of HENDEL specialized for EXFOR outputs is of our interest.

Recently, we have started to develop a new HENDEL system using the Java programming language for a stand-alone application type. Java is platform independent and an object-oriented programming language. Note that EXFOR compilers emphasized in a recent EXFOR compilation workshop (6-10 Oct. 2014, Vienna) that it is important to develop an OS-independent EXFOR editor system.⁹

We adopt Java Swing API for building a GUI (graphical user interface) application. A main page of the new HENDEL editor under development is shown in Fig. #1. Contents of the editor will be organized in a Tree format. The contents of the editor consist: Bibliography, information commonly applied to all data sets of the EXFOR entry (Subentry 001), and information applied to each data set of the EXFOR entry independently (Subentry 002, 003, ...). The Bibliography section consists of Title, Author, Affiliation, and Reference. One of the new improvements in this editor is that the Affiliation and Reference part in the Bibliographic section can be multiplied by “+” button, as shown in Fig. 1.

![Fig. 1. Bibliography section of a Java-based Hendel system.](image)

In the current stage, the design of the user interface and inclusion of utilities (e.g., checking tools) have been completed.

References
1) N. Otuka (ed.): Report INDC(NDS)-0401 Rev.6, IAEA (2014).
Thick-target yields derived from inverse kinematics toward transmutation

S. Imai,*1 M. Aikawa,*2 and S. Ebata*1

Nuclear transmutation of long-lived fission products (LLFP) into stable and short-lived isotopes is considered as an important technique for reducing nuclear wastes in nuclear power plants1). Thick-target yields (TTY) on radioactive targets are fundamental and key information for establishing such a technique, although experiments on such radioactive targets suffer from high radioactivity. Recent progress in experimental techniques now allow the utilization of beams composed of radioactive isotopes (RI) including LLFP. In fact, an experiment has been performed at RIBF to obtain cross section data relating to 90Sr and 137Cs2). Unstable nuclei of astrophysical interests have also been applied to obtain cross sections deduced from the thick-target method of elastic scattering3).

We therefore suggest an estimation method for the TTY on a radioactive target based on inverse kinematics. In the case that the projectile is stopped inside the thick target, the TTY denoted by \(Y\) is obtained by the integration value of cross-section \(\sigma\) and density \(\rho\) of the target, up to the projectile penetration length. While the energy decrease of the projectile is described by the stopping power \(S(E) = -\frac{dE}{dx}\) at a certain point \(x\), the TTY can be expressed as:

\[
Y(\epsilon_{in}) = \frac{N_A A_P}{A_T} \int_0^{\epsilon_{in}} \sigma(\epsilon) \frac{1}{S(\epsilon)} d\epsilon, \tag{1}
\]

which leads to:

\[
\frac{dY(\epsilon)}{d\epsilon} = \frac{N_A A_P}{A_T} \sigma(\epsilon) \frac{1}{S(\epsilon)}, \tag{2}
\]

where the Avogadro constant \(N_A\), the number of the target \(A_T\), the energy per nucleon \(\epsilon = E/A_P\) with the mass number of the projectile \(A_P\) and its incident energy \(\epsilon_{in}\) are used. In this report, we call this system the forward kinematics and its TTY \(Y_{for}\).

The inverse kinematics with an RI beam suggests that by swapping roles of the radioactive target and incident particle, we can obtain the TTY of the inverse kinematics system denoted by \(Y_{inv}\). The ratio of the TTYs between differential yields, \(R(\epsilon)\), at the same energy \(\epsilon\) is given by:

\[
R(\epsilon) \equiv \frac{dY_{for}(\epsilon)}{dY_{inv}(\epsilon)} = \frac{A_T^2}{A_P^2} \frac{S_{for}(\epsilon)}{S_{inv}(\epsilon)}. \tag{3}
\]

Since the \(\sigma(\epsilon)\) of both systems are the same and are canceled out in the ratio, the TTY for \(Y_{inv}\) can be estimated without cross-section if we know \(Y_{inv}\) (\(Y_{for}\)). Note that the stopping powers \(S_{for}\) and \(S_{inv}\) can be computed by SRIM 2008 code4).

Fig. 1. Cross-section of natCu(12C,X)24Na with experimental data5) with spline fitting in (a), and the evaluated ratio \(R(\epsilon)\) by SRIM 20084) in (b) as functions of \(\epsilon\).

<table>
<thead>
<tr>
<th>(\epsilon(\text{MeV}))</th>
<th>(Y_{for}(\epsilon_{in}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 MeV</td>
<td>0.94 \times 10^{-5}</td>
</tr>
<tr>
<td>100 MeV</td>
<td>0.113 \times 10^{-3}</td>
</tr>
</tbody>
</table>

Table 1. TTY \(Y_{for}\) at two incident energies evaluated from Eq. (4) taking \(R \simeq 1.1\) and from Eq. (1).

We show the example of natCu(12C,X)24Na5). In order to calculate \(Y_{for}\) and \(Y_{inv}\) using Eq. (1), the cross-section \(\sigma(\epsilon)\) and stopping power \(S(\epsilon)\) should be known (see in Fig. 1). \(R(\epsilon)\) shown in Fig. 1 (b) converges at a constant value at a high energy of more than 50 MeV/A. This simple behavior of \(R(\epsilon)\) at a high energy and small \(\sigma(\epsilon)\) at a low energy allows us to use a more convenient conversion method as:

\[
Y_{for}(\epsilon_{in}) \simeq \tilde{R} Y_{inv}(\epsilon_{in}), \tag{4}
\]

where \(\tilde{R}\) is a constant value of \(R(\epsilon)\) at the high energy. Indeed, these are in good agreement with values derived from Eq. (1) (Table 1).

This conversion method will be applied to radioactive isotopes, such as 137Cs, and used to search suitable projectiles for transmutation of LLFP.

References
2) H. Wang et al.: In this report.

*1 Meme Media Laboratory, Hokkaido University
*2 Faculty of Science, Hokkaido University
Compilation of nuclear reaction data from the RIBF

D. Ichinkhorloo,*1 M. Aikawa,*2 S. Ebata,*1 N. Furutachi,*3 S. Imai,*1 K. Katō,*2 A. Makinaga,*4 M. Odsuren,*5 N. Otuka,*6,7 A. Sarsembayeva,*1 and B. Zhou*1

Nuclear reaction data, such as cross sections, angular and energy distributions of secondary particles, and resonance parameters, are required to be compiled into a database for their users for a large variety of applications and research fields. A nuclear reaction database that fulfills this requirement is the EXFOR library, which is maintained by the International Atomic Energy Agency (IAEA) and the International Network of Nuclear Reaction Data Centres (NRDC). The NRDC members are involved in data compilation and software development for nuclear data users. Each member is responsible for compiling data about neutrons, charged particles, and photon-induced reactions. This responsibility is assigned to members according to area where the experimental facility to obtain data is located.

One of the NRDC members is the Hokkaido University Nuclear Reaction Data Centre (JCPRG).1) JCPRG covers nuclear reaction data except neutron-induced data obtained in Japan and contributes about 10% of charged-particle nuclear reaction data in the EXFOR library.2) At the JCPRG, the compiled nuclear reaction data are stored in two databases, NRDF and EXFOR libraries, simultaneously. The former is the original database of JCPRG and the latter is the collaborative one among the NRDC. Both databases are available and searchable online on the JCPRG website.

In addition to the NRDC, we have also collaborated with the RIKEN Nishina Center for data compilation from January 2010 to March 2014. The purpose of this collaboration is to increase the availability of nuclear reaction data produced at the RIBF. The compiled data produced at the RIBF are translated into EXFOR format and available online for the benefit of nuclear data users. In this article, we report on our activities in 2014 concerning the compilation of experimental nuclear reaction data from the RIBF.

In 2014, we compiled 28 new papers, data of which were obtained in Japan. 14 of them contain RIBF data and match the compilation scope of the EXFOR library. 10 papers were published in 2013 and 2014 and their compilation reflects recent activities of the RIBF. On the contrary, the remaining 4 papers were published before 2009 and compiled for completeness of data published by the RIBF. Especially, 2 papers are written in Chinese and were published in 2005 and 2006. All data are accessible by the accession numbers listed in Table 1. For higher quality of the contents, numerical data are requested from the corresponding authors of the compiled papers. Most of the compiled RIBF data in 2014 are provided by the authors. Such additional information is also available with the list of compiled RIBF data on the JCPRG website.

During the four-year fruitful collaboration, we could establish a good procedure to compile new publications. Therefore, most of recent experimental nuclear reaction data from the RIBF have successfully been compiled in the EXFOR library. As a next step, we are focusing on the improvement of the completeness and usability of the data produced at the RIBF. In addition, we are developing a new data format using XML technology. The new format will allow us to communicate with experimentalists for proofreading compiled information.

References
1) http://www.jcprg.org/
2) http://www.jcprg.org/exfor/
4. Hadron Physics
**Performance improvement of PHENIX MUID**

S. Han,*1,2 S. Caussin,*1,3 I. Nakagawa,*1 and the PHENIX collaboration

PHENIX Muon Identifier, MUID, is one of the PHENIX detectors. It has north and south arms, and each arm consists of 5 layers of alternating energy absorbers and low-resolution ionization chambers. The chamber is composed of many bunches of larocci tubes.1)

During the RHIC-Run 13, the efficiency of the MUID dropped to less than down under 60% under conditions of high beam luminosity, as shown in Fig. 1. The high voltage supply system is implemented with 400 M Ω current-limiting resistors, and thus, the voltage is sagged at the tube as a function the drawing current, which results in the efficiency drop. The latest performance of MUID indicated a possible degradation of the efficiency from what was observed at the early stage of MUID operation a decade ago.

In order to update the performance, we executed the high voltage(HV) scan in July 2014. The resulting efficiency curve as a function of HV values demonstrated that the current operation voltage (4400V) is almost the edge of the plateau curve and an additional current draw immediately leads to a substantial efficiency drop, as shown in Fig. 2. Overall, more than 50% of the HV chains showed degraded efficiency performance as compared to that observed in 2004. All these phenomena signify that the plateau of the MUID became narrower than observed initially. Thus, it is obvious that an improvement of the MUID performance is required before starting the RHIC-Run 16. We aim to measure Drell-Yan using a high luminosity beam at a collision energy of 500GeV. The MUID efficiency is a topic of much concern because detection efficiency affects on square for this measurement.

One of the ways to improve the aforesaid situation is to reconsider the operating HV condition, i.e., if a higher voltage can be set away from the edge of the plateau. To define the current plateau region, we explored the higher voltage region and evaluated hit rates vs HV values, as shown in Fig. 3.

Fig. 1. Efficiency drop with an increase in BBC novertex rate. BBC is the beam luminosity monitoring device.

Fig. 2. Efficiency versus high voltage for south arm gap 0, panel 5, plane 0. New data (green, black, red points) indicate a steeper drop than the efficiency turn on curve (blue solid line) observed in 2004.

One of the ways to improve the aforesaid situation is to reconsider the operating HV condition, i.e., if a higher voltage can be set away from the edge of the plateau. To define the current plateau region, we explored the higher voltage region and evaluated hit rates vs HV values, as shown in Fig. 3.

Fig. 3. Hits per sec graph range of 4400V to 4900V at north arm gap 0, panel 0, plane 0.

Fig. 3. shows the result of the scan up to 4900V. It is obvious that the operation voltage should not be pushed over 4600V, because a plateau region is created from 4400V to 4600V. The observed plateau runs up to 4550 - 4600V depending on the HV chain. The results obtained thus far indicate that the MUID can be operated at a higher voltage of +100V to +200V with a relatively small increase in the noise hit rates. HV optimization is currently in progress.

**References**


---

*1 RIKEN Nishina Center
*2 Ewha Womans University
*3 ENSICAEN
PHENIX Run13 Local Polarimetry

M. Kim\(^\dagger\),\(^\ddagger\) for the PHENIX collaboration

One of the most important goals of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) is to study the proton spin structure by measuring spin asymmetries during particle production. The Run13 PHENIX experiment collided longitudinally polarized protons at \(\sqrt{s} = 510\) GeV. Helicity asymmetry measurements of various probes from the experiment are ongoing.

RHIC is capable of running polarized proton beams, and each beam polarization \(P\) is measured by RHIC polarimeters using left-right asymmetry in elastic scattering in the Coulomb Nuclear Interference (CNI) region. Since the stable beam polarization direction in the RHIC rings is vertical, the beam polarization direction is kept vertical in RHIC except in experimental halls. For each ring, Spin Rotators, which consist of superconducting helical dipole magnets, rotate the beam polarization direction 90 degrees at the entrance and the exit of the PHENIX experimental hall.

Since beam polarization may not purely be longitudinal at the experimental hall, we require measurements of transverse and longitudinal component of \(P(P_{\perp}, P_{\parallel})\) at the experimental hall, which is local polarimetry, as they introduce systematic error. Local polarimetry is especially important in \(A_{LL}\) measurements for studying gluon polarization in a proton since \(A_{LL}\) is very small, and \(P_{\perp}\) has potential to introduce significant error.

PHENIX Local Polarimetry uses large transverse single spin asymmetry (left-right asymmetry) \(e_N\) of forward neutron production. Left-right asymmetry originates from the interference between spin flip and non-flip amplitudes. One Pion Exchange (OPE) models describe the production cross section of forward neutron reasonably well, but the pion exchange amplitude is fully spin flip.\(^3\) Theoretical study is still ongoing.

PHENIX Local Polarimeter measures energies and trajectories of forward neutrons. The local polarimeter consists of Zero Degree Calorimeters (ZDCs), and Shower Max Detectors (SMDs). ZDC consists of W-Cu alloys and PMMA (polymethyl methacrylate) based optical fibers, and collects Cherenkov photons produced by charged secondary particles from neutron showers. SMD is an X-Y plastic scintillator strip hodoscope. It is located between the 1st and 2nd ZDC modules, where the approximate hadronic shower is maximum. X-Y position of a neutron is reconstructed by using shower profile on SMD. Those detectors are located 1800 cm away from the collision point, and cover 10 cm x 10 cm of a transverse plane at each zero degree area.

The observed left-right asymmetry \(e_N\) of forward neutron production is defined as \(e_N = P_{\perp} A_{LL}^{\text{eff}}\), where \(A_{LL}^{\text{eff}} = f_{\text{smear}} A_N\). \(f_{\text{smear}}\) is the smearing effect, correlated to the neutron energy-dependent position resolution\(^1\). \(f_{\text{smear}}\) is assumed to be constant during the Run13 experiment. We measure \(A_{LL}^{\text{eff}}\) at transversely polarized proton beam collisions, where \(P_{\perp} = P\) so that it is measured by RHIC polarimeters. After that, we measure \(e_N\) with the local polarimeter to obtain \(P_{\perp}\) of longitudinally polarized beams.

Fig. 1 shows \(e_N\) plots. The left (right) plot shows \(e_N\) of transversely (longitudinally) polarized proton beam collisions.

As a final result, \(\frac{P_{\perp}}{P_{\perp}}\frac{P_{\parallel}}{P_{\parallel}}\) is \(\sim O(10^{-3})\) and \(\frac{P_{\perp}}{P_{\perp}}\frac{P_{\parallel}}{P_{\parallel}}\) is \(\approx 0.999\) in the Run13 experiment. The measured double helicity asymmetry becomes

\[
A_{LL}^{\text{measured}} \approx \frac{1}{P_{\perp}} \frac{1}{P_{\parallel}} \left( P_{\perp}^Y P_{\parallel}^B A_{LL} + P_{\perp}^Y P_{\parallel}^A A_{TT} \right) \tag{1}
\]

\[
\approx 0.999 A_{LL} + O(10^{-3}) A_{TT} \tag{2}
\]

where \(Y\) and \(B\) represent two colliding beams, and \(A_{TT}\) is the double transverse spin asymmetry. This analysis suppressed the systematic error of \(A_{TT}\) term to \(O(10^{-3})\). \(A_{LL}\) measurements have been done up to \(O(10^{-4})\) so far\(^2\), and \(O(10^{-3}) A_{TT}\) is orders of magnitude smaller than \(10^{-4}\).\(^3\) Therefore, \(P_{\perp}\) does not significantly contribute to systematic error in \(A_{LL}\) measurements in Run13.

References

\(^\dagger\) RIKEN Nishina Center
\(^\ddagger\) Department of Physics and Astronomy, Seoul National University
Hadronic backgrounds pattern study for $W^\pm \rightarrow \mu^\pm$ analysis in PHENIX

C. Kim,*1,*2 Y. Goto,*2 S. Caussin,*2,*3 S. Han,*2,*4 M. Kim,*2,*5 T. Moon,*2,*6 T. Murakami,*7 J. Murata,*8 T. Nagashima,*2,*8 I. Nakagawa,*2 S. Park,*2,*5,∗ R. Seidl,*2 W. Saito,*2,*8 K. Tanida,*2,*5 I. Yoon*2,*5

The ongoing $W^\pm \rightarrow l^\pm$ analysis at PHENIX aims to precisely constrain the sea quark spin contribution to the proton spin of $1/2$. The main observable of this analysis is single longitudinal spin asymmetry among muons ($A_L$), which directly decayed from $W$ boson\(^1\).

To measure the desired asymmetry precisely S/BG needs to be estimated as accurately as possible. However, observing a distinct Jacobian peak in $W^\pm \rightarrow \mu^\pm$ is not expected due to the large momentum and charge smearing in the muon reconstruction in addition to dominant backgrounds from various sources. As a result, conventional S/BG estimation is not available; thus, we use a partially indirect method based on likelihood to the $W$ (Wness), which is calculated by using NLO level signal Monte Carlo (MC) and data itself.

In an actual S/BG estimation, we perform an unbinned maximum likelihood fit (UMLF) by using six probability density functions (PDFs) from a pair of kinematic variables ($\eta$ (pseudorapidity) and $dw_{23}$ (reduced azimuthal bending)) and three processes (signal, muonic BG, and hadronic BG).

Among these PDFs, the hadronic BG process is modeled from the data itself owing to the difficulty in hadronic MC production. To obtain the expected hadronic distribution among the final muon candidates, we modeled each kinematic variable’s distribution from the BG dominant region in the data ($0.1 < \text{Wness} < 0.9$), and then extrapolated it into the signal dominant region (Wness $> 0.9$). For the validity of the method, each variable’s distribution along Wness should be understood precisely. However, as there exists a serious Wness dependence of $dw_{23}$ (Fig. 1) unlike $\eta$, a specific pattern study was required to reflect its shape along Wness.

A typical $dw_{23}$ in a certain Wness range (ex. $0.1 < \text{Wness} < 0.2$) can be described by a stack of two Gaussians. To understand its development along Wness, we collected $dw_{23}$ over a certain Wness range, performed a fit using two Gaussians, and then parameterized each Gaussian’s parameters (maximum, center, and FWHM) along Wness. Then we fed it back during the hadronic BG $dw_{23}$ modeling process as explained above.

Fig. 1. An example of $dw_{23}$ vs. Wness.

![Fig. 1. An example of $dw_{23}$ vs. Wness.](image1)

Fig. 2. Comparison between fit results before (top) and after (bottom) the pattern study for $W^+ \rightarrow \mu^+$ measured in the North muon arm. The gray-hatched area of the solid line indicates the uncertainty of the final PDF itself.

![Fig. 2. Comparison between fit results before (top) and after (bottom) the pattern study for $W^+ \rightarrow \mu^+$ measured in the North muon arm.](image2)

Figure 2 shows the results of a 2D UMLF projection onto $dw_{23}$ in the final sample before and after the pattern study. A noticeable improvement was observed in the fit’s $\chi^2$, and we plan to apply the pattern study in $W^\pm \rightarrow \mu^\pm$ analysis for both the 2012 and 2013 datasets.

References

W→μ parity violating asymmetries from the 2013 running period in the PHENIX experiment

R. Seidl* for the PHENIX collaboration

During the 2013 data taking period 277 pb⁻¹ of longitudinally polarized proton collision data at a center of mass energy of 510 GeV were accumulated with an average beam polarization of 53% per beam at the PHENIX experiment at RHIC. This data corresponds to the largest data sample available for the polarized W data analysis. In order to access the sea quark polarization in the nucleon real W boson production is an elegant way. The parity violation of the weak interaction directly selects the helicity of the quarks and anti-quarks and the charge of the produced W boson selects the quark and anti-quark flavors. For example the W⁻ gets produced by a left-handed d quark and a right-handed anti-u quark. While the u and d quark helicities are already reasonably well known the sea quark helicities are only very poorly determined and the question whether the polarized light sea is symmetric or not has been predicted rather differently in various nucleon models. The analysis of W decay muons in the forward and backward muon arm detectors of PHENIX is not as straightforward as at central rapidities as there is no clean W decay signature such as a Jacobian peak at half the W mass. Also a large number of background sources exist such as heavy flavor decay muons and hadrons decaying within the tracking volume mimicking a high momentum muon as previously reported. With the help of kinematically different variables for signal and backgrounds candidate events were pre-selected by a likelihood ratio where only high signal likelihood events were kept. Then the relative signal and background contributions were fit by a maximum unbinned likelihood fit. From those preliminary pp → W± X cross sections were extracted which turned out to be consistent with NLO predictions, see Fig. 1.

After correcting the raw single spin asymmetries for beam polarization and dilution by background the preliminary results for the single spin asymmetries were obtained as seen in Fig. 2. The results are in good agreement with the parameterizations and will eventually be used in future iterations of the global helicity fits to all the existing deep inelastic scattering and proton-proton collision data. The 2013 PHENIX W results are currently being prepared for publication and it is expected that the systematic uncertainties which are dominated by the uncertainties on the signal to background ratio still.

Fig. 1. Total pp → W± X × BR(W → ℓ) cross sections for forward muon and previously published W → e results by PHENIX1 and STAR2 as well as predictions by Pythia3, CHE4 and RHICBOS5.

Fig. 2. Single spin asymmetries of W+Z decay leptons as a function of lepton rapidity. The preliminary PHENIX electron and muon results from the 2013 data taking period (red) and the published STAR electron results from 2012 (green)7 are shown as well as various helicity parameterizations.

References
1) A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 106 (2011) 062001
6) F. Giordano [PHENIX Collaboration], to appear in JPCS (Spin 2014 proceedings).
7) L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 113 (2014) 072301

* RIKEN Nishina Center
Neutral pion double helicity asymmetry†

K. Boyle†

A major goal of the RHIC Spin program is to determine the gluon spin distribution in the proton. The quark spin contribution to the proton spin ($\Delta \Sigma$) is only about 25%, and so the remaining spin must be carried by the gluon spin ($\Delta G$), or by the gluon and quark orbital angular momentum ($L_q$ and $L_g$, respectively):

$$S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$$  \hspace{1cm} (1)

written in units of $\hbar$.

At RHIC, $\Delta G$ can be probed directly through measurements of the double helicity asymmetry in polarized $p + p$ collisions, in this case for neutral pions:

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$  \hspace{1cm} (2)

where $P_B$ and $P_Y$ are the polarizations of the two proton rings at RHIC, $N$ is the yield of neutral pions, $\pi^0$, ++ and +− indicate same and opposite helicity combinations of the two beam helicities, and $R$ is the relative luminosity, defined as $R = L_{++}/L_{+-}$, which is required to normalize differences in the luminosity $L$ between RHIC proton bunches.

In 2009, RHIC PHENIX recorded 14 pb$^{-1}$ with an average polarization of 56%. The $\pi^0 A_{LL}$ was measured, and found to be consistent with previous results. The combined results from 2005, 2006 and 2009 are plotted in Fig. 1. The systematic uncertainty from relative luminosity in 2009 was larger than in previous years, and for the lowest $\pi^0$ transverse momentum, $p_T$, was larger than the statistical uncertainties.

The combined data set are shown in Fig. 1 and Fig. 2 compared to several theoretical expectations based on fits to the world polarized scattering data. In the case of $\pi^0$, the RHIC 2005 and 2006 $\pi^0$ data are also included. In fits that do not use RHIC data, such as GRSV, LSS and BB, there is large uncertainty in $\Delta G$ and therefore in the expected $\pi^0 A_{LL}$. Fits including some RHIC data, such as DSSV and NNPDF, find a smaller range of possible $\Delta G$. These data therefore offer significant constraint on $\Delta G$. Recently, the RHIC 2009 data have been included in an updated version of DSSV, and indicate that the gluon spin contribution to the proton spin is about the same size as that of the quarks.

Fig. 1. Results for $\pi^0 A_{LL}$ vs. $p_T$ from the combined 2005, 2006 and 2009 PHENIX data sets. The data are compared with several theoretical expectations.

Fig. 2. Results for $\pi^0 A_{LL}$ vs. $p_T$ from the combined 2005, 2006 and 2009 PHENIX data sets. The data are compared with several theoretical expectations.

References

† Condensed from the article in Phys. Rev. D 90, no. 1, 012007 (2014)

*† RIKEN BNL Research Center
Preliminary results of $A_{LL}^\pi$ measurement at $\sqrt{s} = 510$ GeV at mid-rapidity through a PHENIX experiment

I. Yoon$^{1,2}$ for the PHENIX collaboration

One of the important functions of the relativistic heavy ion collider (RHIC) longitudinally polarized proton program is to constrain the gluon-spin component of the proton ($\Delta G$) by measuring the double helicity asymmetry ($A_{LL}$) of $\pi^0$ and jet production. Based on the results of deep inelastic scattering experiments, the quark-spin component of proton is only $0.330 \pm 0.011(\text{Theo.}) \pm 0.025(\text{Exp.}) \pm 0.028(\text{Evol.})$. The remaining spin might be carried by gluons or orbital momentum. However, $\Delta G$ has not been measured in detail as yet.$^2$

The measurement of $A_{LL}$ for $\pi^0$ production ($A_{LL}^\pi$) at $\sqrt{s} = 200$ GeV has been successfully published and has contributed to constraining $\Delta G$.$^3$ To explore the lower Bjorken $x$ region, where dominant uncertainty remains, longitudinally polarized proton-proton collisions in 2013 (Run13) were successfully carried out with increased energy, i.e. $\sqrt{s} = 510$ GeV. Because of the increased energy, the measurement at $\sqrt{s} = 510$ GeV can reach a lower $x$ range, $0.01 < x < 0.08$, while the previous measurement could reach only $0.02 < x < 0.1$. The measurement at $\sqrt{s} = 510$ GeV is ongoing and preliminary results have been released.

$A_{LL}^\pi$ can be defined in terms of differences in cross-sections as

$$A_{LL}^\pi = \frac{d\Delta \sigma^{\pi^0}}{d\sigma^{\pi^0}} = \frac{d\sigma^{\pi^0}_{+} - d\sigma^{\pi^0}_{-}}{d\sigma^{\pi^0}_{+} + d\sigma^{\pi^0}_{-}}$$

(1)

where $\sigma^{\pi^0}_{+}(-)$ stands for $\pi^0$ cross-section with the same(opposite) helicity proton collisions. Because $\sigma^{\pi^0}$ can be described by the parton distribution function, the partonic reaction cross-section and fragmentation function and most of $\pi^0$'s are from quark-gluon or gluon-gluon scattering at mid-rapidity region, gluon helicity distribution ($\Delta G$) is accessible by measuring $A_{LL}^\pi$. This description is verified by comparing the $\pi^0$ cross-section between theoretical and experimental data.

Equation 1 can be rewritten in terms of experimental observables as

$$A_{LL} = \frac{1}{PB_{\text{DY}}} \frac{N_{++} - RN_{-+}}{N_{++} + RN_{-+}}, R = \frac{L_{++}}{L_{-+}}$$

(2)

where $P_{\text{DY}}$ is the polarization of RHIC’s “Blue(Yellow)” beam, $N_{+}(-)$ is the yield of the $\pi^0$ candidate from the same (opposite) helicity collisions, and $R$ is the relative luminosity of the same and opposite helicity collisions.

As the collision rate increases in Run13, the effect of multiple collisions on one beam crossing becomes sizable. The effect of multiple collisions is fully taken into account for the relative luminosity measurement. Luminosity miscount by the finite resolution of the vertex width of luminosity detector is also considered. The uncertainty of the relative luminosity is a dominant systematic uncertainty of the measurement.

To reduce the combinatorial background in diphoton invariant distribution, several cuts are applied. Hits by a charged track, hadron, and previous crossings are rejected. To evaluate $A_{LL}$ for the remaining background, $A_{LL}$ of the background is also measured and is subtracted to obtain physical asymmetry.

Fig. 1 shows preliminary results of $A_{LL}^\pi$ measurement at $\sqrt{s} = 510$ GeV. The result covers $2$ GeV/c $< P_T < 20$ GeV/c ($0.008 < x_T < 0.08$, where $x_T = 2P_T/\sqrt{s}$). The DSSV14 theory curve is shown and it agrees with experimental data within uncertainty. The measurement at $\sqrt{s} = 200$ GeV is also shown for comparison. Larger asymmetry is observed at higher collision energy.

Further analysis is ongoing to obtain the final result.

References

$^1$ RIKEN Nishina Center
$^2$ Seoul National University
Cross section and asymmetry measurement of very forward neutral particle production at RHIC

Y. Goto\textsuperscript{*1} for the RHICf Collaboration

Although air shower observations at the surface of the earth have been carried out to understand the origin of the ultrahigh energy cosmic rays, these observations have uncertainties in the interpretation of the observed data from the present phenomenological nuclear collision models. The LHCf experiment has been performed at LHC for understanding cosmic ray generation from the collider experiment data\textsuperscript{1–3}. Precision measurements of the very forward particle production in the collider experiments improve the understanding of particle production processes in the nuclear collisions, and largely affect the interpretation of the observed data and the origin of the cosmic rays.

A large 10\% single transverse-spin asymmetry (SSA) in neutron production from transversely polarized proton collisions was found at RHIC in 2002\textsuperscript{4}). This provides an important clue to study elementary processes in air shower generation because the large SSA indicates that there are dominant contributions from processes that strongly interfere with each other. Because the SSA measurement of neutron production provides interference measurement with one pion exchange with a spin flip, it is sensitive to a meson exchange without spin flip\textsuperscript{5)}. Although the SSA of very forward neutrons at collision energies of 62 GeV, 200 GeV, and 500 GeV was measured at RHIC, the transverse-momentum resolution of the data was limited.

We will perform a new collider experiment at RHIC, the so called RHICf experiment, which uses a LHCf detector (which is called the RHICf detector) with a high resolution and wide coverage of transverse-momentum measurements in order to improve the studies performed at RHIC and LHC. RHIC is a dedicated machine for QCD physics and it allows flexible operation to achieve our physics goals. In the RHICf experiment, we will have an improved transverse-momentum resolution using the RHICf detector. The LHCf experiment has measured very forward neutral particle cross section at collision energies of 0.9 TeV and 7 TeV. We will obtain precision measurements of very forward neutral particles (neutron, photon, neutral pion) at a collision energy of 510 GeV at RHIC. These data of various collision energies will provide an understanding of air shower generation and the limitations in the origin of the ultrahigh energy cosmic rays.

The RHICf detector will be located in front of the Zero-Degree Calorimeter (ZDC) in the north side, 18 m from the PHENIX collision point. In this area, all charged particles are swept out by the last dipole magnet for colliding beams at RHIC, and only neutral particles are detected. The RHICf detector consists of two sampling EM (electromagnetic) calorimeters with 44 interaction-length tungsten, 16 layers of scintillators, and 8 layers of silicon strip detectors; one with 25 mm × 25 mm and another with 32 mm × 32 mm cross sectional area. The ZDC detector is a sampling hadron calorimeter composed of Cu-W alloy absorbers with PMMA (Polymethyl methacrylate)-based optical fibers. The detection, identification, and energy measurement of photons and neutrons are performed using EM and hadron calorimeters. A schematic view of the RHICf detector installation and the structure of the calorimeter are shown in Fig. 1.

We have proposed to perform a dedicated run for 1 week in 2016 with 510 GeV polarized proton collisions\textsuperscript{6)}, and we are preparing for it. In the dedicated RHICf run, we will use the normal accelerator condition of the RHIC, except the beta function value at the PHENIX collision point, $\beta^* = 10$ m, in order to obtain parallel beam collisions. We need 12 h to achieve sufficient luminosity for cross section measurements of photons, neutrons, and neutral pions including the transverse-momentum scan. The SSA can be measured with the same data set with higher statistics than the measurements in the past.

References
6) Y. Itow et al. [RHICf Collaboration], arXiv:1409.4860 [physics.ins-det].

\*1 RIKEN Nishina Center
Fragmentation function measurements in Belle


Fragmentation functions allow us to study the process of nearly free partons fragmenting into final state hadrons as they also exist in visible matter. While the theory of the strong interaction, QCD, is generally accepted as the force governing all hadronic matter around us, only high energy processes are directly calculable. Parton distribution functions as well as fragmentation functions need to be obtained by experiment. Of particular interest is, how a parton of a certain flavor fragments into certain types of hadrons, how initial parton spin gets translated into the distribution of final state hadrons and how transverse momentum is generated relative to the initial parton.

In the Belle experiment one can study these aspects well since the underlying process of electron-positron annihilation provides a clean initial state without any hadrons to study the emerging final state hadrons. However, normally the quark flavor is not directly accessible as both a quark and an antiquark are created and at least for light flavors (u, d and s quarks) tagging techniques are not reliable. A first way around this limitation was already performed in the Collins type analysis where two charged pions in opposite hemispheres were studied. Having two hadrons in opposite hemispheres mostly ensures, that one hadron was fragmenting from the quark and another from the antiquark. The ratio of same over opposite charges then revealed the differences of favored and disfavored polarized and un-polarized fragmentation functions. This method was extended for pion-kaon and kaon-kaon combinations to obtain sensitivity of the strange quark Collins functions as well as disfavored u, d quark to kaon Collins fragmentation functions. Preliminary results have been obtained in 2014 as shown in Fig. 1 and are expected to be published soon.

Furthermore the unpolarized fragmentation functions $D_{h,q}^A(z,s)$ can be studied in a similar way and first results have been prepared for all combinations of charged pions and kaons either in opposite hemispheres or also the same for comparison. Here, $z = 2E_h/\sqrt{s}$ is the fractional energy the hadron $h$ carries relative to the initial parton $q$ and $\sqrt{s}$ is the center of mass energy. In the thus obtained cross sections as a function of fractional energy $z$ the ratios between same and opposite sign pion pairs in opposite hemispheres essentially provide the ratio of dis-favored over favored fragmentation from $u, d$ quarks to pions. Favor ed fragmentation relates to fragmentation into a hadron with valence content the same as the initial parton (ie $u$ to $\pi^+$ = $|u\bar{d}|$) and dis-favored fragmentation with valence content not the same (ie $d$ to $\pi^+$). First results have been obtained and are expected to be shown as preliminary results and be published soon. The expected precision is such, that even the ratios at fractional hadron energies $z$ above 0.8 have still reasonably small uncertainties.

In addition an analysis of transverse momenta of one hadron relative to a second hadron is ongoing which should help improve the rather large uncertainties and assumptions of any transverse momentum dependent distribution and fragmentation functions. These are needed for the analysis of quark transversity and Sivers function data of semi-inclusive deep inelastic scattering and hadron collision experiments. These explicit transverse momentum dependent measurements are also expected to obtain preliminary status this year.

References
Measurement of direct photon azimuthal anisotropy in $\sqrt{s_{NN}}=200\text{GeV} \ \text{Au+Au}$ collisions in RHIC-PHENIX experiment

S. Mizuno$^{\dagger,\star}$ for the PHENIX collaboration

High-energy heavy-ion collision experiments have been carried out since 2000 at the Relativistic Heavy Ion Collider (RHIC), to study the properties of quark-gluon plasma (QGP). Direct photons are defined as all photons except for those coming from hadron decays. Photons do not strongly interact with the medium. Furthermore, they are emitted from various sources, such as initial hard scattering, jet fragmentation, and thermal radiation, during all stages of collisions. Thus, direct photon is a powerful tool to study QGP.

Direct photon $p_T$ spectra have been measured via a calorimeter method$^{\dagger}$, virtual photon method$^{\dagger}$, and conversion photon method$^{\dagger}$. It is found that the $p_T$ spectra of Au+Au collisions include an additional exponential $p_T$ spectra compared to those of $p+p$ collisions scaled by the number of binary collisions. The effective temperature is obtained from the inverse slope of the exponential $p_T$ spectra, it is approximately 240 MeV. It is found that photons mainly originate from a very hot medium in the early stage of collisions, since the kinetic freeze-out temperature obtained is approximately 100 MeV.

Azimuthal anisotropy is defined as the relative amplitude of anisotropic azimuthal distribution with respect to the event plane. To quantify the anisotropy, Fourier series is used for the azimuthal distribution of the number of emitted particles.

\[
dN/d\phi = N_0[1 + \sum_{n=2}^n 2v_n \cos{n(\phi - \Psi_n)}], \quad (1)
\]

\[
v_n = \langle \cos{n(\phi - \Psi_n)} \rangle, \quad (2)
\]

where $\phi$ is the azimuthal angle of photons, and $v_n$ and $\Psi_n$ are the strength and event plane of the $n^{\text{th}}$-order harmonic azimuthal anisotropy, respectively. The mechanism of azimuthal anisotropy has been studied, and it is understood that it strongly depends on the initial geometry shape. The photon emission angle is expected to depend on the photon sources and initial geometry of the participant shape: thermal photons have $v_2 > 0$, photons fragmented from a jet have $v_2 > 0$, and prompt photons have zero $v_2$. Direct photon $v_2$ is measured$^{\dagger}$ to identify the photon sources. It is found that the strength of direct photon $v_2$ at around 2 GeV/c is comparable to that of hadron $v_2$. Because photons are emitted during all stages of collisions, emitted photons should include photons emitted from the medium, which is not yet expanded. This is why direct photon $v_2$ was predicted to be smaller than hadron $v_2$ in many theoretical models. Since a photon has large $v_2$, the results suggest that photons in the low $p_T$ region are mainly generated from the late stage of collisions.

There is a discrepancy called “photon puzzle”. There are no models to explain both the results simultaneously. In order to constrain the photon production mechanism, the third-order azimuthal anisotropy $v_3$ is measured. Figure 2 shows direct photon $v_3$ for $p_T < 4$ GeV/c. It is found that the strength of direct photon $v_3$ is comparable to that of hadron $v_3$. It shows a similar trend to direct photon $v_2$. It can be interpreted that photons emitted in the late stage of collisions are dominant in the low $p_T$ region. These results would be helpful for understanding the photon puzzle.

---

References

4) A. Adare et al.: P.R.L. 109, 122302 (2012)
Charged hadron elliptic and triangular flow in Cu+Au at \( \sqrt{s_{NN}} = 200 \text{GeV} \)

H. Nakagomi\(^{1,2} \) for the PHENIX collaboration

Quark-gluon-plasma (QGP) is considered to be a hot and dense nuclear matter which is a phase of matter in quantum chromodynamics. A QGP was created by colliding nuclei at the Relativistic Heavy Ion Collider (RHIC).

One of the strong evidence to prove the formation of QGP is that the low momentum particle production is anisotropic. Azimuthal anisotropy originates from initial spatial geometry. For low momentum particles, anisotropic collective flow is considered to result from the hydrodynamic expansion of QGP. Further the strength of azimuthal anisotropic flow has been used to determine the specific viscosity over entropy ratio (\( \eta/s \)) of QGP and the initial spatial condition by comparing it with the theoretical model. Thus measuring the azimuthal anisotropic flow is a good method to investigate the bulk property of QGP and the space time expansion mechanism.

The produced particle distribution is expressed as a Fourier expansion series as follows

\[
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))
\]

where \( v_n = (\cos(n(\phi - \Psi_n))) \) corresponds to the strength of anisotropic flow, \( \phi \) is the azimuthal angle of the produced particle, \( \Psi_n \) is the \( n \)th order event plane that is the average of all emitted particles angles. So far the 2nd order flow harmonic \( v_2 \) which is called elliptic flow has been studied in symmetric systems such as \( \text{Au+Au} \), the 3rd order flow harmonic \( v_3 \) which is called triangular flow was not predicted to exist because initial geometry was considered to be symmetric. However recently, a large \( v_3 \) was measured at RHIC. The \( v_3 \) is assumed to have originated from the initial spatial fluctuation.

In 2012, a Cu+Au collision was performed at RHIC. In Cu+Au collisions, the initial spatial geometry is asymmetric. The pressure gradient is predicted to be different for the Au and Cu sides. Thus the different expansion at the Au and Cu sides will lead to the asymmetric emission of particles. The \( v_n \) in the Cu+Au collision could help determine \( \eta/s \) and the initial spatial condition.

Figure 1 illustrates the \( N_{part} \) dependence of \( v_2 \) and \( v_3 \) for three collision systems. The system size dependence of \( v_2 \) is clearly seen. The \( v_2 \) values in Cu+Au collisions are between those in Au+Au and Cu+Cu data sets and \( v_2 \) in all systems increases as \( N_{part} \) decreases, the difference of \( v_2 \) values between the different systems reduce with a decreasing \( N_{part} \). The \( N_{part} \) dependencies of \( v_2 \) and \( v_3 \) could be expected from those of 2nd and 3rd order initial spatial anisotropies (\( \epsilon_2 \) and \( \epsilon_3 \)). The \( \epsilon_2 \) and \( \epsilon_3 \) are calculated using a Glauber Monte Carlo simulation. Figure 2 illustrates comparison between \( v_2 \) and \( v_3 \) as a function of \( p_T \) with event-by-event hydrodynamical calculation with \( \eta/s \) for 20-30% centrality bin. In this hydrodynamical calculation, Glauber Monte Carlo simulations are employed as the initial spatial condition and \( 4\pi/s = 1 \) or \( 4\pi/s = 2 \) is used. The hydrodynamical calculation with \( 4\pi/s = 1 \) has better agreement with \( v_2 \) and \( v_3 \) at low \( p_T \) than \( 4\pi/s = 2 \), whereas at high \( p_T \) hydrodynamical calculation with \( 4\pi/s = 2 \) has better agreement with \( v_2 \) and \( v_3 \) than \( 4\pi/s = 1 \).

\hspace{1cm}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig1.png}
\caption{Comparison of \( v_2 \) and \( v_3 \) as a function of \( N_{part} \) for four centrality bins in Au+Au, Cu+Cu and Cu+Au}
\end{figure}

\hspace{1cm}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{\( v_2 \) and \( v_3 \) as a function of \( p_T \) for 20-30% centrality bin. Comparison of PHENIX experimental data points and hydrodynamical calculation}
\end{figure}

References
Commissioning and operation of silicon vertex detector for PHENIX experiment in RHIC Run-14

M. Kurosawa,*1 Y. Akiba,*1 H. Asano,*2 J. Bryshawskyj,*3 T. Hachiya,*1 M. Lentz,*4 B. Miljko,*5 T. Moon,*1 H. Nakagomi,*6 R. Nourcer,*4 C. Pancake,*7 P. Stankus,*5
T. Sumita,*1 A. Takedani,*1 M. Wysocki,*5 and the PHENIX VTX group

The PHENIX experiment aims to elucidate the spin structure of nucleons and the property of the hot and dense matter at the Relativistic Heavy Ion Collider (RHIC). A silicon vertex detector (VTX) was successfully installed in 2010 as a key element in the spin and, hot and dense matter physics. The VTX comprises a four-layer barrel detector built from two inner silicon pixel detectors and two outer silicon strip detectors. As mentioned in our previous report, the silicon pixel detectors were repaired and the active area of VTX was improved from 60% to 90% before Run-14. This report presents the results of the commissioning and the performance of silicon pixel detectors in Run-14.

The silicon sensor module is an assembly of a silicon pixel sensor and four readout chips bump-bonded to the sensor with soldering bumps. Most of the dead area 10% results from the defects of soldering bumps caused by a thermal stress during operation. The pixel response at the boundary between the active and the dead areas is unstable, and those pixels become noisy because they have high resistivity caused by a week electrical connection. The main tasks in the commissioning stage are the determination of the threshold level and mask of noise pixels for all readout chips for minimizing fake hits.

Figure 1 shows the threshold dependence of a hit event rate for a readout chip. The threshold is represented as a DAC value. The higher the DAC value, the lower the number of electrons. The average of the optimized threshold for all readout chips was 180, which corresponds to 3,700 electrons. The average was substantially low compared with that for the 14,000 electrons of Minimum Ionizing Particle (MIP).

Pedestal data was taken with a random trigger to detect noise pixels. The location of noise pixels were determined by detecting pixels that have a high hit rate. Since the noise level is dependent on the threshold level, a threshold and noise scan were iterated several times. Figure 1 shows the plot after removing pixels that have high hit rate. Approximately 0.03% of all pixels were masked and the probability of the noise-hit per event was reduced to $10^{-5}$.

Figure 2 illustrates a performance plot that shows the correlation of the z vertex between beam-beam counter (BBC) and VTX. The BBC is a Cherenkov counter and determines the z vertex with a precision of 5 mm. The position resolution of VTX is less than 80 μm at over 1 GeV/c. The width of the plot depends on the resolution of the BBC.

The 200 GeV Au+Au collision run was started in March and it ended in the middle of June. The VTX took about 20 billion events of physics data keeping the active area of 90% without any serious issues during this period.

References
2) T. Moon et al.: In this report.
Alignment of the PHENIX Silicon Vertex Tracker (VTX) in the 2014 RUN

T. Moon,*1,*2 A. Adare,*3 Y. Akiba,*1 H. Asano,*1,*4 S. Bathe,*1 J. Bryslawskyj,*5 T. Koblesky,*3 T. Hachiya,*1 M. Kuro savsa,*1 D. Meginley,*5 H. Nakagomi,*1,*6 R. Nouicer,*1 T. Rinn,*7 Z. Rowan,*5 T. Sumita,*1 A. Taketani,*1 and the PHENIX VTX group

During the 2014 run, PHENIX has recorded a large number (∼20B) of events with the PHENIX silicon vertex tracker (VTX)1–2 and the Forward VTX (FVTX) combined. This dataset is also the best quality dataset of VTX since it was installed in 2011.

The VTX is located close to the interaction point of the two incoming particles. It consists of four coaxial cylindrical layers, with radii between 2.63 and 16.69 cm, covering the pseudo-rapidity range $|\eta| < 1.2$ and azimuthal angle $\Delta \phi \sim 2\pi$. The two innermost layers consist of silicon pixel sensors, and the two outermost layers are made of silicon strip-pixel sensors.

The VTX is designed to reconstruct primary and secondary vertices with a resolution better than 100$\mu$m for $p_T > 1$GeV/c as well as to significantly improve tracking performance in conjunction with other detectors, particularly the drift chamber (DC). The VTX, thus, is necessary for charm and bottom separation, and for direct measurement of $D^0$ meson using a distance of closest approach (DCA) of the reconstructed track from the primary vertex position.

In reality, the actual installed detector position cannot be measured by our high-precision surveys. Thus there exists a relatively large mis-alignment that will significantly degrade the resolution of the measurement.

Alternatively, the mis-alignment can be improved through the track-to-hit based alignment via software. The ideal geometry of the VTX for pixel and strip-pixel is first known by measurements of sensor positions in surveys and the design positions, respectively. The position of (hits on) the sensor is represented in a VTX coordinate system. On the other hand, the track for the alignment is reconstructed by the DC in a global (DC) reference coordinate system regardless of the VTX, and it is projected to the primary vertex. The relative position between the VTX and the DC is determined by measuring a beam center in each coordinate system and then (hits on) the sensor, and the track projection is represented in the global reference coordinate system. Residual (distance between the tracks and the measured hit on the sensor plane) is used to evaluate the mis-alignment in the VTX geometry.

Fig. 1. DCA distributions in X-Y plane as a $p_T$ after the alignment

Fig. 2. Resolution of DCA in X-Y plane as a function of $p_T$ after the alignment

References
Distance of closest approach analysis with VTX at RHIC-PHENIX

H. Asano,*1,∗2 A. Adare,*3 Y. Akiba,*2 S. Bathe,*4,∗2 J. Bryslawskyj,*4 T. Hachiya,*2 T. Koblesky,*3 M. Kurosawa,*2 D. McGlinchey,*3 T. Moon,*7,∗2 H. Nakagomi,*10,∗2 R. Nouicer,*11,∗2 T. Rinn,*8 Z. Rowan,*4 T. Sumita,*2 A. Taketani,*2 and the PHENIX VTX group

Heavy quark production is being studied via a PHENIX experiment by measuring of electrons from semi-leptonic decays of hadrons containing charm and bottom quarks. A large suppression and strong elliptic flow of single electron heavy flavor has been observed in Au+Au collisions at \( \sqrt{s} = 200 \text{ GeV} \). In past measurement, PHENIX was unable to distinguish electrons from charm and bottom quarks.

In order to understand the medium effects in more detail, the Silicon Vertex Tracker (VTX) was developed and installed in year 2011 in the RHIC-PHENIX experiment. The VTX can measure charm and bottom separately using the distance of closest approach (DCA) to the primary vertex. After the preliminary result of the fraction of \( b \rightarrow e/(b \rightarrow e+c \rightarrow e) \) in Au+Au collision was reported\(^2\), we improved the DCA analysis to obtain the final result.

(i) In the high multiplicity environment, hits on the VTX can be associated with uncorrelated tracks. They are one of the main sources of background of DCA distribution. We studied the chi-square distribution of track fitting using real data and a Monte Carlo simulation. We determined the threshold of the chi-square value of tracks to reject random association candidates as much as possible. The real tracks are expected to be removed around 5% from the simulation study.

(ii) Electrons from photon conversion and Dalitz decay of neutral mesons are also the background source in the electron DCA measurement. We identify \( e^+e^- \) pairs by VTX and removed these pairs from the DCA distribution. The tagging efficiency of the conversion and the Dalitz decay are estimated thorough the simulation. The yield of the remaining electrons and the shape of the DCA distribution from conversions and Dalitz decays are also estimated using the past measurement data\(^1\) and the simulation.

(iii) Electrons from \( J/\psi \) and Kaon also cause small background noise. The yield of these electrons and the shape of DCA distribution are estimated using the past measurement data and the simulation.

After completing the study, we decomposed electron DCA distribution. In Fig. 1, the shape of each component is obtained through the simulation and each component is overlaid on the DCA distribution of real data. Currently, the ratio of charm and bottom quarks are based on theoretical prediction. The fraction of each DCA background (conversion, Dalitz, Kaon, \( J/\psi \ldots \)) is obtained from (ii) and (iii). The sum of those DCA distribution values describes the shape of the electron DCA distribution in real data very well.

To obtain the precise ratio of \( b \rightarrow e/(b \rightarrow e+c \rightarrow e) \) as a function of transverse momentum and momentum distribution of parent mesons (D and B mesons) from DCA measurement, an invariant yield of heavy flavor electrons and DCA distribution are being analyzed simultaneously. The results will be published soon.

![Fig. 1. Electron DCA distribution at 2.0-2.5 GeV/c.](image)

2.00 < \( p_T \) < 2.50

References
Current status of bottom and charm measurements using VTX at RHIC-PHENIX

T. Hachiya,*1 A. Adare,*2 Y. Akiba,*1 H. Asano,*1,8 S. Bathe,*1,8 J. Brylsawskeyj,*4 T. Koblesky,*2 M. Kuroswawa,*1 D. Mccginchey,*1 T. Moon,*1,8 H. Nakagomi,*1,6 R. Nouicer,*7 T. Rimm,*8 Z. Rowan,*4 T. Sumita,*1 and A. Taketani*1

One of the most noteworthy results at RHIC was the strong suppression of inclusive open heavy quarks (bottoms and charms) at high $p_T$ in central Au+Au collisions. It was expected that heavy quarks would be less suppressed due to their large mass. However, the results showed that the suppression was comparably strong with pions. In order to study the suppression in detail, we developed a silicon vertex tracker (VTX) at PHENIX. VTX can measure bottoms and charms separately using the distance of closest approach (DCA) to the primary vertex.

We reported the preliminary result of the fraction $(b \rightarrow e)/(b \rightarrow e + c \rightarrow e)$ using VTX in Au+Au collisions. Numerous improvements of the analysis for the final result are underway. Here, we have listed a few of these improvements:

1) Rejecting photon conversions and Dalitz decays: Photon conversions and Dalitz decays of light neutral mesons are the main background sources in single electron measurement. Electron pairs from the backgrounds are generated with small opening angles and the pair makes correlated hits in VTX. Therefore, VTX can significantly reject the backgrounds by requiring pair-wise hits in VTX. On the other hand, heavy flavor electrons $(b \rightarrow e$ and $c \rightarrow e)$ rarely make the correlated hits. Figure 1 shows the fraction of heavy flavor electrons to inclusive electrons before and after VTX installation. This plot indicates that VTX could reject the background effectively and provide a good signal to noise ratio.

2) Unfolding of DCA distribution: We developed an unfolding method to decompose bottom and charm contributions. The method is a Bayesian approach using the Markov chain Monte Carlo sampler. Using this method, the bottom and charm yields are obtained by fitting both the DCA and the $p_T$ distribution of heavy flavor electrons simultaneously. The DCA shape is correlated with the $p_T$ distribution of the parent $B$ and $D$ mesons because the DCA is determined by the convolution of two effects: the decay length of the parent particle and the decay $p_T$ kick relative to the parent momentum. As a consistency test, we verified if the known input can be reproduced using a simulation.

3) Detector efficiency: The detector efficiency was determined by full GEANT simulation with the actual dead map. The raw $p_T$ spectrum of heavy flavor electrons was corrected using the efficiency, and the corrected spectrum is consistent with the published data.

4) DCA smearing by random association: The DCA shape is smeared and modified by the random association of electron tracks with VTX. The smearing effect was studied by embedding simulated electron tracks into real events. Then, we found that the unphysically large DCA tail in the data was explained by the smearing effect.

The current analysis of Au+Au data will be completed for publication soon. We took 20 billion Au+Au data in year 2014, which is 20 times larger statistics. This new dataset will be analyzed. The alignment calibration of the dataset was completed and the data production was started.

![Fraction of heavy flavor electrons to inclusive electrons before (closed) and after (open) the VTX installation.](image)

Fig. 1. Fraction of heavy flavor electrons to inclusive electrons before (closed) and after (open) the VTX installation.

References

3) A. Adare et al.: Quark Matter 2014 poster.
4) G. Choudalakis.: arXiv:1201.4612v4
5) H. Asano at al.: In this report.
6) T. Moon at al.: In this report.

*1 RIKEN Nishina Center
*2 Department of Physics, University of Colorado, Boulder
*3 Department of Physics, Kyoto University
*4 Department of Natural Science, Baruch College, CUNY
*5 Department of Physics, Tohoku University
*6 Department of Physics, University of Tsukuba
*7 Brookhaven National Laboratory
*8 Department of Physics, Iowa State University
Development of the FVTX high multiplicity trigger system for the PHENIX experiment

T. Nagashima,*1,*2 Y. Fukushima,*1,*2 S. Hasegawa,*3 I. Nakagawa,*1 W. Saito,*1,*2

and the PHENIX FVTX group

Protons and neutrons, which are the components of familiar substances, are composed of quarks and gluons that bind quarks together. Immediately following the big bang, under extremely high-density and high-temperature conditions, quarks and gluons are considered to escape from the boundary of nucleons. This liquid-like state is called Quark Gluon Plasma (QGP).

The PHENIX group investigates the behavior of matter in such a high-density and high-temperature state produced by collision using Relativistic Heavy Ion Collider (RHIC). In particular, in Au+Au and Pb+Pb collisions, the particle angular correlation exhibits a similar azimuthal pattern throughout the wide range of the rapidity region, referred to as "ridge." The ridge correlation is considered as a consequence of the hydrodynamic flow of products, and it is interpreted as a characteristic of QGP. Certain experiments at the LHC have recently reported that the ridge was observed especially in high-multiplicity events in small colliding systems, such as p+p.1) Similar ridge phenomena were observed in d+Au and He3+Au at RHIC. However, they have not yet been observed in p+p.

Previous experiments demonstrated high-multiplicity events are the key to observe the ridge in p+p collisions. In PHENIX, the Forward Silicon Vertex Detector (FVTX) is suitable to select such high-multiplicity events since it is the tracker closest to the vertex point. The FVTX trigger design is shown in Fig. 1. The trigger signal is generated on FPGAs implemented on FVTX readout electronics,2) Front End Module (FEM) and FEM Interface Board (FEM-IB). Using the feature that each FEM corresponds to an azimuthal slice of the FVTX sensor, each FEM judges whether there is any track, following which the FEM-IB counts the number of track flag sent from the FEM, and finally the FVTX trigger fires when the number of track is greater than that of our interest.

The trigger algorithm in the FEM FPGA was tested through evaluation of the process efficiency depending on the number of hits on the detector. The hits were generated by using a calibration pulse that injects typically 13 strips per detector per event. Fig. 2 shows the correlation between the number of hits per event measured from offline data analysis and the trigger state; the vertical axis shows the trigger flag at an FEM that is supposed to give 1 for the events where the number of hits is greater than the threshold. The efficiency, defined as the number of trigger events divided by the number of events with more hits than the trigger threshold, was 94%, and a few fake triggers were observed.

New serial line cables for FEM - FEM-IB communication were installed in the trigger system, and their signal transmission test was performed. Performance was monitored by scanning the signal rate, and the cables exhibited good performance up to a trigger rate of 4.7 MHz. The timing of the trigger signal was tuned with GL1. It was found that GL1 does not recognize the trigger signal depending on timing. It is adjusted using the BBC trigger signal, which is already used as a trigger.

References
1) V. Khachatryan et al.: CMS Collaboration, JHEP 1009 (2010) 091
Study of direct photon polarization to shed on strong magnetic field in heavy ion collisions at PHENIX†

T. Hoshino*1,*2

A strong magnetic field is expected to be created in non-central heavy-ion collisions. This field is created by the effect of both of the collision participants and spectators. The field direction is perpendicular to the collision reaction plane. The magnitude of the field created in the collisions at BNL-RHIC top energy is estimated to reach as high as $10^{14}$ teslas. If the magnitude of the magnetic field in heavy-ion collisions is compared with the QED critical magnetic field ($B_c = m_e^2/c = 4 \times 10^9$ teslas) and the surface of magnets ($10^{11}$ teslas), the field magnitude is much higher in heavy ion collisions. The field magnitude is decreased rapidly but keeps the magnitude above the critical field of an electron for about 3 fm/c.

Creation of a strong magnetic field in heavy ion collisions was first expected in 1976†. The strong magnetic field in heavy ion collisions has recently attracted the interest of researchers in theories and experiments in recent years for the following reasons. First, the magnetic field can reach beyond the critical field and interesting phenomena such as Chiral magnetic effects and non-linear QED effects can appear in such a strong field. Second, quark-gluon plasma (QGP) is expected to be created in a strong magnetic field thus the evolution of the plasma may have an effect by the strong magnetic field. The state of the initial stage is another topic of recent interest. Measuring the effect of the field should be the key to understanding the initial stage.

Chiral magnetic effect is measured by experiments using charged particle asymmetry with respect to the reaction plane which is reported by STAR and ALICE experiments2)3). However the field has not yet been directly detected by experiments. If the effects of the magnetic field can be detected, we can directly access to the initial stage of collisions. Electromagnetic particles are a clean probe for accessing the initial stage because they are not affected by the strong interaction.

Dilepton production rate in an external magnetic field is calculated using a photon vacuum polarization tensor, and the production rate depends on the direction of the field. The production rate is higher in perpendicular direction to the field than that parallel to the field.

Dilepton polarization is also measured to understand the production mechanism of quarkonia. The PHENIX experiment measured $J/\psi$ polarization with dielectron4). While the physics motivation and mechanism are different between the measurement of quarkonia and virtual photon polarization, we are now using the same parametrization with that analysis.

$$\frac{dN}{d\cos(\theta)} \propto 1 + \lambda \cos(\theta) \quad (1)$$

where $\theta$ is the angle between the positive lepton in a dilepton rest frame and a certain polarization axis, and $\lambda$ is the polarization parameter; if $\lambda$ is positive (negative), polarization is transverse (longitudinal).

Three definitions of polarization frames are usually used. In the helicity (HX) frame, the axis is the dilepton momentum in the laboratory frame. In the Collins-Soper (CS) frame, the axis is the bisector between two beams in the dilepton rest frame. In the Gottfried-Jackson (GJ) frame, the axis is the direction of the beam in the dilepton rest frame.

We use the data set of Au+Au and $p+p$ at 200 GeV/nucleon pair collected in 2004 and 2006, respectively. The PHENIX experiment has excellent electron identification capabilities and has succeeded in measurement of direct virtual photons.

The direct virtual photon is the probe and $\pi^0$ and $\eta$ Dalitz decay electrons are candidates of control probes because they are from a later stage of the collisions. Polarization measurement in $p+p$ collisions can also act as a control probe since a field is not created in the collisions.

We are measuring polarization with the following mass regions, $0.12 < M_{ee} < 0.3$ (containing virtual photon) and $M_{ee} < 0.12$ GeV/c² ($\pi^0$ Dalitz decay dominant). The acceptance effect is included in the $\cos(\theta)$ distribution. Thus we need to correct the effect with simulation. Since the simulation does not contain the effect of the magnetic field, we can estimate the effect. We are now estimating the acceptance effect with single particle simulations.

References

*1 RIKEN Nishina Center
*2 Department of Physical Science, Hiroshima University

Fig. 1. Definitions of polarization axis
Measurement of dielectron production in $\sqrt{s_{NN}} = 5.02$ TeV p-Pb collisions by using the ALICE detector

S. Hayashi,*1,*2 H. Hamagaki,*2 and T. Gunji*2

Heavy quark (charm and bottom quarks) measurements in heavy ion collisions provide key information on the properties of the deconfined matter, the quark gluon plasma (QGP). Since heavy quarks are produced via gluon fusion, gluon splitting, and flavor excitation, cold nuclear matter effects (CNM) cannot be negligible. In p-Pb collisions at the Large Hadron Collider (LHC), correlations between electrons from heavy flavor decays and charged hadrons in p-Pb collisions show the correlations in rapidity space, which may be due to the gluon saturation or collective expansion of the system. In the electron-positron pair (dielectron) mass spectrum, dielectrons from semi-leptonic decays of heavy quarks are dominant at $m_{ee} > 1$ GeV/c$^2$ and can be affected by CNM effects. The Transition Radiation Detector (TRD) in ALICE provides online electron trigger. ALICE recorded 1.4 nb$^{-1}$ with the TRD trigger in p-Pb collisions in 2012-2013, which is 20 times larger statistics than the minimum bias data (0.067 nb$^{-1}$).

In the ALICE detector, charged tracks are reconstructed by the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Electrons are identified by $dE/dx$ in the TPC and hadrons are rejected by a time-of-flight (ToF) detector. To extract the raw dielectron spectrum, the background is estimated using the same event like-sign pairs corrected by the relative acceptance difference between unlike-sign and like-sign pairs, which is evaluated using an event-mixing technique. Pair acceptance and detection efficiency are evaluated with the fast Monte Carlo simulation. First, the single electron efficiency is obtained from the full Monte Carlo calculation using the DPMJET event generator and GEANT3 simulations. Pair efficiency is extracted by the product of the single electron efficiency. Dielectrons from light meson decays ($\pi^0, \eta, \rho, \omega, \eta'$, $\phi$) are generated from EXODUS according to the measured charged pion spectrum in p-Pb collisions and $m_T$ scaling. For heavy quarks contribution, dielectrons are generated using PYTHIA with the parametrization tuned for the NLO calculation. Figure 1 shows the pair efficiency as a function of invariant mass. Circles and boxes correspond to the pair reconstruction efficiency and TRD trigger efficiency for pairs, respectively.

Figure 2 shows the inclusive invariant yield of dielectrons as a function of invariant mass. The next step is to take into account the azimuthal angle and rapidity dependence of the single electron efficiency in the pair and trigger efficiency calculations. After the invariant yield is extracted, $c\bar{c}$ and $b\bar{b}$ cross-sections will be extracted and compared with the theoretical models to understand the dielectron production in p-Pb collisions.

References
Measurement of neutral pion $v_2$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE experiment

In central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the Large Hadron Collider (LHC) in CERN, the yield of particles at high transverse momentum ($p_T$) is observed to be strongly suppressed as compared with the expected yield from $p+p$ collisions scaled by the average number of the binary collisions. This suppression is explained by the energy loss of hard scattered partons in the medium created in heavy ion collisions. This suppression is called jet quenching. This suppression is induced by the path length dependence of the energy loss. For a better understanding of the energy loss mechanisms, measurement of the path length dependence of the energy loss is crucial. $v_2$ is obtained by fitting the azimuthal angular distribution of $\pi^0$ with

$$N(\Delta \phi, p_T) = N(1 + 2v_2 \cos(2\Delta \phi)).$$

This work

Fig. 1. $v_2$ of $\pi^0$ values as a function of $N_{part}$. The data points represent $v_2$ of $\pi^0$ measured by the LHC-ALICE experiment. Solid and dashed lines indicate model calculations using pQCD and Ads/CFT, respectively. $N_{part}$ at 6 GeV < $p_T$ < 20 GeV. The analysis is performed by using semi-central triggered data recorded in 2011 Pb-Pb collisions. Solid and dashed lines represent model calculations from pQCD-based (weakly coupled medium) and AdS/CFT-based (strongly coupled medium) energy loss models, respectively. In this plot, the $v_2$ of $\pi^0$ values shows the same tendency as the $v_2$ values of the charged particles qualitatively. Comparison of the model calculations and experimental results for $v_2$ of $\pi^0$ is currently in progress.

References
Long-range correlation in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV with the ALICE detector

Y. Sekiguchi,*1,∗2 H. Hamagaki,*2 and T. Gunji*2

Measuring of the correlations in particle production in the azimuthal angular space and rapidity space is very useful for investigating the underlying mechanism and dynamics of particle production in high-energy nucleus-nucleus collisions. The long-range correlations in the rapidity space in near-side angular pairs in di-hadron correlations was first observed in Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV at RHIC.1,2 This long-range correlation was derived from the collective expansion of the initial geometry fluctuations. Unexpectedly, a similar structure has also been observed in high-multiplicity p-p collisions at \(\sqrt{s}=7\) TeV with the LHC-CMS experiment.3 This high-density gluon fields in a small \(x\) of nucleus and the collision of two high-density gluon sheets can explain the long-range correlation.4 It is very interesting to study the correlation in p-Pb collisions since the initial gluon density and magnitude of the collective expansion are very different from those in other collision systems (pp and Pb-Pb).

A Large Ion Collider Experiment (ALICE) is dedicated to understand the state of matter as it existed shortly after the Big Bang, called Quark Gluon Plasma (QGP). The main subsystems in the ALICE for the study are the inner tracking system (ITS), time projection chamber (TPC), and time of flight (TOF). The ITS consists of 6 layers of silicon detectors for vertex finding and tracking. The TPC is the main tracking detector and is used for particle identification by measuring the specific energy loss dE/dx. The TOF is used to identify particles by measuring the time of flight. They have a common acceptance $|\eta|<0.9$.

The correlation function as a function of $\Delta \eta$ and $\Delta \phi$ between two charged particles is defined as:

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{asso}}}{d\Delta \eta d\Delta \phi} = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

(1)

where this correlation function is studied for different $p_T$ intervals and different event classes according to the event multiplicity, and $N_{\text{trig}}$ is the total number of triggered particles in the event class and $p_T,\text{trig}$ interval. The signal distribution $S(\Delta \eta, \Delta \phi) = 1/N_{\text{trig}} d^2 N_{\text{same}}/d\Delta \eta d\Delta \phi$ is the associated yield per trigger particle for particle pairs from the same event. The background distribution $B(\Delta \eta, \Delta \phi) = \alpha 1/N_{\text{trig}} d^2 N_{\text{mzg}}/d\Delta \eta d\Delta \phi$ corrects for pair acceptance, pair efficiency, and uncorrelated pairs. It is constructed by correlating the trigger particle in one event with the associated particles from other events in the same event multiplicity class. The $\alpha$ factor is chosen so that it is unity for pairs at $(\Delta \eta, \Delta \phi) = (0, 0)$. The correlation function in peripheral collisions (low-multiplicity event class) is subtracted from that in central collisions (high-multiplicity event class) to remove the auto-correlations from jets. Figure 1 shows the associated yield per trigger particle in 0-20% event class subtracted by 60-100% event class with $1<p_{T,\text{trig}}<2$ GeV. The projection onto $\Delta \phi$ averaged over $0.8<|\Delta \eta|<1.6$ on the near side and $|\eta|<1.6$ on the away side is shown in Fig. 2. The double ridge structure is observed.

Measurements of the correlation functions by tagging identified hadrons and strange baryons are ongoing to evaluate the collectivity in p-Pb collisions and the initial state effects.

![Fig. 1. Associated yield per trigger particle in 0-20% event class subtracted by 60-100% event class with $1<p_{T,\text{trig}}<2$ GeV](image1)

![Fig. 2. Projection onto $\Delta \eta$ averaged over $0.8<|\eta|<1.6$ on the near side and $|\eta|<1.6$ on the away side](image2)

References

3) CMS Collaboration, JHEP 09 (2010) 091

*1 RIKEN Nishina Center
*2 Center for Nuclear Study, the University of Tokyo
Azimuthal distributions of jets with respect to high-$p_T$ neutral pion triggers in $pp$ collisions at $\sqrt{s} = 7$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from ALICE

D. Watanabe$^{1,*2}$ and T. Chujo$^2$

Jet measurements play a critical role in probing the hot and high energy density matter created in heavy ion collisions. Energy loss of patrons can be studied by measuring changes in the jet structure during jet suppression.

In general, the energy loss of recoil jets and leading jets depends on the path length in the medium. For example, jet pairs with a large energy asymmetry in the final states can be from the surface of the medium. While leading jets escape the medium from the surface, recoil jets traverse in the medium with loss to its energy. We can use this surface bias to obtain deeper insight into the properties of the medium. The stronger the surface bias, the greater is the path length in the dense medium of the recoiling jet at the opposite azimuth. By measuring the full jets in the recoil side rather than measuring high-$p_T$ leading hadrons, we can perform a more comprehensive and direct study of jet interactions with the medium.$^1$

In this paper, we report the jet azimuthal distribution with neutral pion trigger in $pp$ collisions at $\sqrt{s} = 7$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from LHC-ALICE. The ALICE detector was built to exploit the unique physics potential of nucleus-nucleus interactions at the LHC.$^2$ This analysis used the central tracking devices, ITS and TPC, for charged particle track measurements, and the electromagnetic calorimeter EMCal for $\pi^0$ measurements.

This analysis used the shower shape and cluster splitting method$^3$ to identify high $p_T$ $\pi^0$. Using this method, high $p_T$ $\pi^0$ around 40 GeV/c can be identified with a signal-to-noise ratio of 90%.

Jets are reconstructed with the anti-$k_T$ jet algorithm of the FastJet$^4$ package combining charged tracks measured in the central tracking devices and a cone size parameter of $R=0.4$. The contribution of underlying events is subtracted from the reconstructed jets using the average background momentum method.

Figure 1 and 2 show the azimuthal correlation between trigger $\pi^0$ and jet in $pp$ and PbPb collisions, respectively, with three different trigger $\pi^0$ regions and two different associated jet $p_T$ thresholds. Two clear jet peaks are observed, indicating that high $p_T$ production is correlated with jet production. Both near and away-side widths decrease with increasing $p_T$ of the trigger $\pi^0$. The decrease is stronger for the away-side correlation width. As the next step, we plan to study the path length dependence by selecting different trigger $\pi^0p_T$ in the ratio of the per-trigger yield ($I_{AA}$).

Fig. 1. $\pi^0$-jet azimuthal correlations in $pp$ collisions at $\sqrt{s} = 7$ TeV normalized by number of trigger $\pi^0$ for trigger $\pi^0$ regions $8 < p_T^{\pi^0} < 12$ GeV/c, $16 < p_T^{\pi^0} < 20$ GeV/c, $24 < p_T^{\pi^0} < 36$ GeV/c, and associated jet thresholds $p_T^{asso} > 10, 20$ GeV/c

Fig. 2. $\pi^0$-jet azimuthal correlations in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV normalized by number of trigger $\pi^0$. Trigger $\pi^0p_T$ regions and associated jet $p_T$ thresholds are same as Fig.1.

References

1) ALICE collaboration, An Addendum to the EMCal Technical Design Report (DCAL), CERN-LHCC-2010-011
2) ALICE collaboration, Performance of the ALICE Experiment at the CERN LHC, arXiv:1402.4476v2

$^*$ RIKEN Nishina Center
$^*$ University of Tsukuba
Study of ion backflow with 2GEMs + MICROMEGAS for the ALICE-TPC upgrade

K. Terasaki,*1,*2 H. Hamagaki,*2 and T. Gunji*2

ALICE is a dedicated experiment to study Quark Gluon Plasma (QGP), a hot and dense Quantum chromodynamics (QCD) medium, via heavy ion collisions at LHC. The ALICE Time Projection Chamber (ALICE-TPC),1) which is the main device in the central barrel for tracking and particle identification of charged particles, consists of a 90 m$^3$ cylinder filled with Ne/CO$_2$/N$_2$ (90/10/5).

Secondary ions generated in an electron-avalanche process in the TPC return to the drift space, known as “Ion Backflow (IBF).”2) Because IBF distorts the electric field in the drift space, its reduction is essential to achieve good performance of the TPC. A gating grid system is widely employed to reduce IBF; however, it limits the data acquisition rate to the order of kilohertz. The rate of heavy-ion collisions at the LHC will be 50 kHz from 2019. The ALICE-TPC will be upgraded to read out the data of Pb-Pb collisions continuously, which requires IBF and energy resolution for $^{55}$Fe to be less than 1.0% and 12%, respectively, at a gain of 2000 for Ne-based gas mixtures.2)

The performance of quadruple GEM stacks as a readout chamber is being investigated for this upgrade. In addition, investigations with 2GEMs + MICROMEGAS are being carried out. The MICROMEGAs structure (MICROMEGAS)3) has a micromesh ~100 µm above a readout. Electrons are multiplied through application of a potential difference between the mesh and the readout ($\Delta V_{\text{MM}}$). Secondary ions are absorbed efficiently on the mesh when the electric field above the mesh is considerably smaller (by a factor of 100) than that below the mesh.

A schematic of the measurement setup with 2GEMs + MICROMEGAS is shown in Fig. 1. Our MICROMEGAS has a 400 LPI (Lines Per Inch) mesh located 128 µm above 120 readout pads (8 × 10 mm$^2$) and the current from all the readout pads is summed up. Two 50 µm-thick GEMs are placed above MICROMEGAS. IBF is defined as $I_e/I_a$, where $I_e$ and $I_a$ are the current at the cathode plane and that at the anode pads, respectively. Gain is calculated as $I_a/(N_{\text{seed}} \times R \times e)$, where $N_{\text{seed}}$, $R$, and $e$ are the number of seed electrons for $^{55}$Fe in Ne gas, the rate of X-ray from $^{55}$Fe, and the charge of an electron, respectively.

The correlation between energy resolution and IBF for Ne/CO$_2$ (90/10) and Ne/CO$_2$/N$_2$ (90/10/5) with different voltage setups is shown in Fig. 2. Different measurements are indicated by different markers; for example, the GEM1-MM scan represents the points corresponding to variations of both $\Delta V_{\text{GEM1}}$ and $\Delta V_{\text{MM}}$ to maintain the gain of 2000. It shows that certain points meet the requirement for Ne/CO$_2$ (90/10) and IBF is less than 0.5% at an energy resolution of ~ 12% for Ne/CO$_2$/N$_2$ (90/10/5). Additional nitrogen leads to better IBF because a larger potential difference is required to achieve the gain of 2000 and subsequently the field ratio of MICROMEGAS decreases. The evaluation for Ne/CO$_2$/N$_2$ (90/10/5) at a better energy resolution (and worse IBF) is in progress. Eventually, the performance of a MICROMEGAS that has a 780 LPI micromesh and 90 µm gap will be evaluated.

References

*1 RIKEN Nishina Center
*2 Center for Nuclear Study, Graduate School of Science, University of Tokyo
Search for dark photons from neutral meson decays in $p+p$ and $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV

Y. Akiba$^1$ and Y. Yamaguchi$^{2,3}$ for PHENIX Collaboration

The standard model (SM) of particle physics provides unprecedented numerical accuracy for quantities such as the anomalous magnetic moment of the electron $(g-2)_e$. Hence, measurements that lie outside SM predictions warrant a special investigation. One such result is the measured value of $(g-2)_e$, which deviates from SM calculations by 3.6σ. An intriguing explanation for this discrepancy has been proposed by adding a “dark photon”\textsuperscript{1}. This possibility has recently gained more relevance because it provides a simultaneous explanation of various beyond-the-standard-model phenomena in addition to $(g-2)_\mu$. These include the positron excess observed by PAMELLA, FERMI, and AMS-2 satellite experiments.

A simple formulation of the dark sector postulates a “dark photon” $U$ of mass $m_U$ that mixes with the QED photon via the “kinetic coupling” term in the Lagrangian
\[ \mathcal{L}_{\text{mix}} = -\frac{\varepsilon}{2} F^\mu_\nu \tilde{F}_{\mu\nu} + \lambda_\mu F^\mu_{\text{dark}}, \]

where $\varepsilon$ parameterizes the mixing strength. Dark photons can then mix with the QED photon through all processes that involves QED photons.

The PHENIX experiment searched for possible decays of $\pi^0$, $\eta \rightarrow \gamma U$, $U \rightarrow e^+e^-$ by examining the invariant mass $m_{ee}$ of $e^+e^-$ pairs in a large sample of Dalitz decays, $\pi^0, \eta \rightarrow \gamma e^+e^-$ for $30 < m_U < 90$ MeV/c\(^2\) in the dark photon parameter space. The weak coupling of the dark photon with the QED photon implies that the natural width of the dark photon is very narrow. Thus if the dark photon mass is in this range, a clear dark photon signal should appear as a narrow peak in the $e^+e^-$ mass spectrum.

We used the data set of $p+p$ collisions in the 2006 and 2009 runs and $d+Au$ collisions in the 2008 run, at $\sqrt{s_{NN}} = 200$ GeV, but did not find any significant signal. Thus, we set the upper limit on the mixing parameter $\varepsilon^2$ as a function of the dark photon mass $m_U$.

Fig.\textsuperscript{1} shows the limits determined by the PHENIX along with the 90% confidence level (CL) limits from other experiments and the 2\(\sigma\) upper limit theoretically calculated from $(g-2)_\mu$. The band indicates the range of parameters that would allow the dark photon to explain the $(g-2)_\mu$ anomaly with 90% CL. The PHENIX experiment limits exclude the values of the coupling favored by the $(g-2)_\mu$ anomaly above $m_U > 36$ MeV/c\(^2\). Recently, BABAR reported stricter limits from a search of the reaction $e^+e^- \rightarrow \gamma U, U \rightarrow t^+t^-$, excluding values of the preferred $(g-2)_\mu$ region for $m_U > 32$ MeV/c\(^2\). As a result, nearly all the available parameter space that would allow the dark photon to explain the $(g-2)_\mu$ results are ruled out at 90% CL by independent experiments. The entire parameter space to explain the $(g-2)_\mu$ anomaly by the dark photon can be excluded at 85% CL by the PHENIX data alone. The level of compatibility between our data and the coupling strength favored for the $(g-2)_\mu$ anomaly is 10% with a statistical test.

In summary, the PHENIX results set limits for the coupling of a dark photon to the QED photon over the mass range $30 < m_U < 90$ MeV/c\(^2\). Combining with the BABAR results, the dark photon is ruled out at 90% CL as an explanation for the $(g-2)_\mu$ anomaly for $m_U > 32$ MeV/c\(^2\), leaving only a small remaining part of the parameter space in the region $29 < m_U < 32$ MeV/c\(^2\).

References

---

\textsuperscript{1} Condensed from the article in Phys. Rev. C\textbf{91}:031901(R)(2015)
\textsuperscript{2} RIKEN Nishina Center
\textsuperscript{3} Stony Brook University
Progress in probing flavor asymmetry of antiquarks in protons in the 
E906/SeaQuest experiment at Fermilab

K. Nagai,∗1 Y. Goto,∗2 Y. Miyachi,∗3 S. Miyasaka,∗1 K. Nakano,∗1 S. Nara,∗3 S. Sawada,∗2,∗4 T.-A. Shibata∗1,∗2
for the E906/SeaQuest Collaboration

E906/SeaQuest is a Drell–Yan experiment at Fermi National Accelerator Laboratory (Fermilab). SeaQuest aims to measure the flavor asymmetry of antiquarks ( ¯d/ ¯u) in protons at large Bjorken x more accurately than the E866 experiment, which is the Drell–Yan experiment conducted previously at Fermilab.1) The flavor asymmetry is derived from the ratio of the Drell–Yan cross sections in proton-proton (pp) and proton-deuteron (pd) reactions, as shown below:

$$\frac{\sigma_{pd}}{2\sigma_{pp}} \sim \frac{1}{2} \left[ 1 + \frac{\bar{d}}{\bar{u}} \right]. \quad (1)$$

We use a 120-GeV proton beam extracted from Fermilab Main Injector and liquid hydrogen and deuterium as targets. Carbon, iron, and tungsten are also used as targets for measuring nuclear effects on the parton distribution. The Drell–Yan process creates a µ+µ− pair, and therefore the muons are measured to count the number of Drell–Yan events. SeaQuest acquired data for 10 months in 2013 and 2014 (called “Run 2”).

Data acquired over two months of the data were analyzed as an initial step. Results of the analyzed data and prospects are discussed in this report.

We succeeded in reconstructing the mass distribution of di-muons with all the targets (black points). It is fitted with four components (red, green, yellow, and black lines).

We started acquiring another set of data for two years in November 2014. After data acquisition, we will obtain 20 times more statistics than the set of data we analyzed. The result that will be obtained using the SeaQuest experiment will considerably improve the understanding of the internal structure of protons.

References
Results of the $K^-pp$ bound-state search in J-PARC E15$^{1\text{st}}$

T. Hashimoto,*1 K. Itahashi,*1 M. Iwasaki,*1 Y. Ma,*1 H. Ohmishi,*1 S. Okada,*1 H. Outa,*1 F. Sakuma,*1 M. Sato,*1 M. Tokuda,*1 and Q. Zhang,*1 for the J-PARC E15 collaboration

The interaction between a nucleon and an anti-kaon ($K$), the lightest hadron with a strange quark, is one of the keys to understanding meson-baryon interactions in low energy quantum chromodynamics (QCD) incorporating three flavors in the nuclear system. Precise investigations of $K^-p$ system are currently hot topics. The $K^-p$ bound state, a bound system of a negative kaon and two protons, is theoretically considered the simplest $K$ nuclear system. Precise measurements of elementary $K^-p$ interactions and investigations of $Kp$-nucleus bound systems ($K$ nuclei) are currently hot topics. The $K^-pp$ state, a bound system of a negative kaon and two protons, is theoretically considered the simplest $K$ nucleus, and thus it has attracted special interest. We are searching for the $K^-pp$ bound state by using an in-flight reaction as the J-PARC E15 experiment. The first physics data acquisition (E15$^{1\text{st}}$) was performed in May 2013, with $5 \times 10^9$ kaons at 1 GeV/c on a liquid $^3$He target.

Figure 1 shows the obtained semi-inclusive neutron spectrum at $\theta_n^{\text{lab}} = 0^\circ$. Here, we detected the neutron by using a plastic scintillator array placed $\sim 15$ m away from the target. To reconstruct the reaction vertex for the time-of-flight measurement, at least one charged track is required in a cylindrical detector system (CDS) surrounding the target. The $K^0$-tagged spectrum, shown in the inset of Fig. 1, is attributed to the charge-exchange $K^-p \rightarrow K^0n$ reaction, and demonstrates that the detector resolution and the missing-mass scale are well understood.

The observed yield in the deeply bound region, corresponding to $K^-pp$ binding energies larger than 80 MeV, was in good agreement with the evaluated backgrounds originating from 1) accidental hits and neutral particles other than neutrons, 2) reactions on the target cell, and 3) neutrons produced via charged $\Sigma$ decay. In this mass region, upper limits on the production cross section of a bound state were evaluated, assuming a $K^-pp \rightarrow \Lambda\pi$ isotropic decay. They were determined to be 30-270 mb/sr, depending on the mass and the decay width. The upper limits obtained are much smaller compared to the theoretical calculation. The ratios of the upper limits to cross sections of the quasi-elastic channels are $(0.5-5\%)$ (quasi-elastic) and $(0.3-3\%)$ (charge exchange). These ratios are rather small compared to the sticking probability of the usual hypernuclear formation. On the other hand, a significant excess was observed around the $K^-pp$ binding threshold. However, in spite of the observed large yield corresponding to $\sim 1$ mb/sr, structures suggested in theoretical spectral functions cannot be identified from only the semi-inclusive measurement.

We also analyzed the $\Lambda\pi$ events detected using the CDS to investigate the $K^-pp$ decay. A $\Lambda$ was reconstructed from a $\pi^-p$ pair detected using the CDS to be almost free from the background. Missing-neutron events were identified by the $^3$He($K^-,\Lambda\pi$)$X$ missing mass, with $\sim 20\%$ $\Sigma^0\pi^0$-event contamination (\Sigma$^0\rightarrow\Lambda\gamma$). The preliminary $\Lambda\pi$ invariant-mass spectrum, obtained with $\sim 10$ MeV/c$^2$ resolution, consists of a flat component widely distributed in the three-body phase space and an enhancement around the threshold. The threshold structure mainly originates from events with a low-momentum transfer, and it might be evidence for the $K^-pp$ bound state.

In 2015, we plan to conduct the 2nd-stage physics run with 10 times the number of beam-kaons in the 1st stage, as well as calibration runs with hydrogen and deuterion targets. With the new data set, we will further investigate the structure around the $K^-pp$ binding threshold.

![Diagram](image)

Fig. 1. $^3$He($K^-,\Lambda\pi$)$X$ semi-inclusive missing-mass distribution at $\theta_n^{\text{lab}} = 0^\circ$. $A_{\text{CDS}}$ denotes the charged-tagging acceptance of the CDS. The inset shows the $K^0$-tagged spectrum.

References

*1 RIKEN Nishina Center
Measurement of the proton Zemach radius from the hyperfine splitting energy in ground-state muonic hydrogen

M. Sato,1 S. Aikawa,2 K. Ishida,1 M. Iwasaki,1,3 S. Kanda,3 Y. Ma,4 Y. Matsuda,4 T. Matsuzaki,1 K. Midorikawa,5 Y. Oishi,1 S. Okada,1 N. Saito,5 A. Takamine,6 K. Tanaka,1,4 H. Ueno,1 and S. Wada5

Studies of the proton electromagnetic structure have recently attracted great interest stimulated by the proton radius puzzle, which is a 7σ discrepancy in the proton charge radius determined using two different methods. One is a traditional determination method using e − p scattering and the atomic hydrogen spectroscopies as compiled in CODATA1). The other is a method of laser spectroscopy of the Lamb shift in muonic hydrogen2). To understand this inconsistency between “electronic” and “muonic” methods, there are several hypotheses including physics beyond the Standard Model. However, none of them are conclusive, and the puzzle is still an unsettled question.

Since the proton charge radius is defined only from the electric distribution in the proton, it is a curious question as to how we can determine the magnetic distribution of a proton probed with muons, which may become a clue to solve the puzzle. Therefore, we focus on the proton Zemach radius, which contains information on both the charge and magnetic-moment distributions in the proton. The proton Zemach radius, RZ, is expressed as

\[ R_Z = \int d^3r |r| \int d^3r' \rho_E(r') \rho_M(r - r'), \]

where \( \rho_E \) and \( \rho_M \) denote spatial distributions of the charge and magnetic moment of the proton, respectively. This Zemach radius can be determined from the hyperfine splitting energy of a hydrogen-like atom. Thus, we determine the proton Zemach radius from the laser spectroscopy of the hyperfine splitting energy of muonic hydrogen.

The experimental principle is as follows. When negative muons are stopped in hydrogen, they form muonic hydrogen atoms and are quickly deexcited to the ground state. Its energy level is split into hyperfine sublevels by the spin combination of the proton and muon: the spin singlet (F = 0) and the triplet (F = 1) states. The splitting energy is \( \sim 0.183 \) eV, which corresponds to a mid-infrared frequency of 44.2 THz and wavelength of 6.78 μm. We will measure this energy through a laser spectroscopy. To search for the resonance frequency, the spatial asymmetry of spin-polarized muon decays is used. To populate the spin polarization in F = 1, we use a circularly polarized laser. A specific F = 1 state is selectively excited because of the conservation of the total angular momentum. The electrons from polarized muon decays are detected to find the decay asymmetry during the laser frequency scan.

A conceptual drawing of the experimental setup is shown in Fig. 1. Negative muons with momenta of 40 MeV/c are stopped in a gas hydrogen target. The density of the hydrogen gas is optimized to be 0.01% of LHD (liquid hydrogen density) to suppress the collisional quench process, which is a deexcitation from F = 1 to F = 0 through a collision with a neighboring atom. The mid-infrared laser is injected from the side of the target \( \sim 1 \) μs after the stopped \( \mu^- \) timing. The laser power is a key issue to achieve sufficient polarization through a laser-induced excitation. The laser system is under development in RIKEN3), and the achievable laser performance is a power of 40 mJ and bandwidth of 50 MHz with a repetition rate of 50 Hz. For further enhancing the effective laser power by multiple reflection, a multi-pass cavity consisting of two mirrors facing each other is installed in the hydrogen target, as schematically illustrated in the figure. The mirror reflectivity is assumed to be 99.95% and the resulting polarization is \( \sim 16\% \).

The yield estimation and a feasibility study of the present measurement are nearing completion. A beam study with negative muons in RIKEN-RAL is scheduled for the next fiscal year.

Fig. 1. Conceptual drawing of the experimental setup.

References
5. Hadron Physics (Theory)
Strong enhancement of jet-medium coupling in the quark-gluon plasma near transition temperature\(^1\)

J. Liao\(^{*1,*2}\)

A new, deconfined form of QCD matter known as the quark-gluon plasma is created in relativistic heavy ion collisions. In such collisions, highly energetic jets provide unique probe of the quark-gluon plasma properties. The observable quantifying jet energy loss is the nuclear modification factor, \(R_{AA}\), as well as its azimuthal anisotropy characterized by its second harmonic coefficient \(v_2\). Both RHIC and LHC measurements have shown a sizable \(v_2\) in the high \(p_T\) region.

Recently the temperature dependence of jet-medium coupling, which may be quantified by the so-called jet transport coefficient \(\hat{q}(T)\), has attracted significant interest. As was first found in\(^3\), the geometric anisotropy \(v_2\) at high \(p_T\) is particularly sensitive to such temperature dependence, and a simultaneous description of high \(p_T\) \(R_{AA}\) and \(v_2\) at RHIC requires a strong enhancement of jet-medium coupling in the near-\(T_c\) region. Furthermore, the near-\(T_c\) enhancement predicts a visible reduction of average opaqueness of the fireball from RHIC to LHC which was confirmed by analyzing how the \(R_{AA}\) evolves with beam energy\(^2,3\). Therefore phenomenologically there are robust evidences for such near-\(T_c\) enhancement, while a precise theoretical determination of such nontrivial T-dependence has not been known owing to the highly nonperturbative dynamics in the near-\(T_c\) regime.

One important approach for strongly coupled quark-gluon plasma is to use holographic QCD models. It is particularly important to introduce non-conformal physics that is most prominent around \(T_c\). By constructing such a model\(^4\), we have found that: 1) there are strong non-conformal, non-perturbative dynamics going on in the near-\(T_c\) region; 2) such dynamics leads to non-monotonic behavior in QGP thermodynamics as shown by the strong near-\(T_c\) peak of trace anomaly (which is well modeled by holography); 3) the same dynamics leads to non-monotonic behavior in QGP transport properties and in particular strong near-\(T_c\) enhancement of jet-medium coupling \(\hat{q}/T^3\) (see Fig.1).

More recently we have developed a new jet quenching framework, CUJET3.0\(^5\), that is shown to account well for both high \(p_T\) single inclusive hadron suppression \(R_{AA}\) and its azimuthal anisotropy \(v_2\) at both RHIC and the LHC energies. CUJET3.0 model includes two new nonperturbative effects in the QCD transition temperature range \(T \sim 140 - 250\) MeV: (1) the Polyakov loop suppression of color-electric scatter-

---


\(^*1\) Physics Department and Center for Exploration of Energy and Matter, Indiana University

\(^*2\) RIKEN Nishina Center

---

Fig. 1. Temperature dependence of jet-medium coupling from a non-conformal holographic QCD model\(^5\).

Fig. 2. Temperature dependence of jet-medium coupling from the CUJET3.0 model\(^5\).

References
4) D. Li, J. Liao and M. Huang, Phys. Rev. D 89, no. 12, 126006 (2014).
Magnetic moments of light nuclei from lattice QCD†

S. Beane,*1 E. Chang,*2 S. Cohen,*2 W. Detmold,*3 H. Lin,*1 K. Orginos,*4 A. Parreno,*5 M. Savage,*2 and B. Tiburzi*6

The structure and dynamics of nuclei have been extensively probed using electromagnetic interactions. Magnetic moments historically helped support a picture of light nuclei as collections of weakly interacting nucleons, which led to the phenomenologically successful shell-model description of nuclei. At a fundamental level, however, nuclei are bound states of the quark and gluon degrees of freedom of QCD. Nuclear forces emerge from QCD as a consequence of confinement and chiral symmetry breaking. Yet, nuclei are not simply collections of quarks and gluons determined by global quantum numbers; rather, nuclei have the structure of interacting nucleons, and this feature remains to be understood at a deep level. Knowledge of the quark structure of nuclei, moreover, is required to turn nuclei into laboratories for probing fundamental symmetries, structure of nuclei, and pushing the limits of the Standard Model.

We have computed magnetic moments of the lightest few nuclei using lattice QCD. These calculations, the first of their kind, have been performed at unphysically light-quark masses. All three light-quark masses in our computation were set equal to the physical strange quark mass. At this SU(3) flavor-symmetric point, the resulting pion mass is \( m_\pi \approx 800 \text{ MeV} \). Further details of the lattice action and gauge configurations are found in Ref.2). To compute magnetic moments, \( U(1)_Q \) gauge links giving rise to a uniform magnetic field were post multiplied onto each QCD gauge field. While quenching sea quark electric charges is an approximation, there are no contributions to magnetic moments resulting from coupling the magnetic field to sea quarks in our computation. This fact owes to the three degenerate quark flavors with their non-singlet electric charge matrix, \( Q = \text{diag}(1, \frac{2}{3}, -\frac{1}{3}) \). Sub-percent QED effects, however, have been neglected in our computation. The combined gauge fields were used to compute up and down (\( \equiv \) strange) quark propagators, which were then contracted to form the required nuclear correlation functions using the techniques of Ref.3). Finally, nuclear correlation functions were projected onto spin components with respect to the direction of the magnetic field.

The ground-state energy of a non-relativistic hadron having mass \( M \), and charge \( Qe \) is given by

\[
E(B) = M + \frac{e}{2M} |Q\vec{B}| - \vec{\mu} \cdot \vec{B} + O(B^2). \tag{1}
\]

The field-dependent terms appearing above are due to the lowest Landau level and Zeeman interaction, which is proportional to the hadron’s magnetic moment, \( \mu \). To isolate magnetic moments with good statistical precision, the long Euclidean-time limit of correlator ratios was utilized. For a spin-half hadron, e.g., we consider the ratio

\[
\mathcal{R}^{(B)}(\tau) = \frac{C_{\uparrow}^{(B)}(\tau)}{C_{\downarrow}^{(B)}(\tau)} \sim e^{-2\mu|B|\tau}, \tag{2}
\]

as a function of the applied magnetic field. Extracted magnetic moments are shown in Fig. 1 in lattice nuclear magnetons, i.e. units of \( \frac{e}{2M} \), where \( M_N \) is the lattice nucleon mass, \( M_N \approx 1.6 \text{ GeV} \). When scaled in this fashion, results are remarkably close to experimental values. In particular, evidence for shell-model configurations suggests that this property of nuclei may extend over a broad range of quark masses.

References
Nucleon structure in lattice QCD near physical mass

S. Ohta\textsuperscript{a1, a2, a3} for RBC and UKQCD Collaborations

The RIKEN-BNL-Columbia (RBC) collaboration continue numerical lattice-QCD investigations of nucleon structure\textsuperscript{1-6}). Here, I report results obtained from ensembles\textsuperscript{7-9}) generated jointly with the UKQCD collaboration near the physical pion mass. In these ensembles the strange quark mass is set very close to its physical value while the degenerate up and down quark is varied toward the physical mass, resulting in pion mass ranging from about 420 to 170 MeV. Isovector observables such as vector- and axialvector-current form factors and some low moments of structure functions are calculated.

The isovector axial charge, \( g_A \), is about the most important observable concerning nucleon structure. It determines the neutron life and pion-nucleon interaction through the celebrated Goldberger-Treiman relation. And as such it determines nuclear abundance and much of nuclear physics. Lattice-QCD calculations have experienced difficulty reproducing this quantity: they generally underestimate the experimental value of 1.2723(23)\textsuperscript{10}). Our latest results do not escape this problem, as summarized in Fig. 1: About 10\% deficit is persistent across the mass range investigated, and possibly worsens toward the physical mass.

Much of our efforts during the past year were concentrated in understanding this\textsuperscript{11)}, starting with the long-range autocorrelation observed at the lightest-mass ensemble at pion mass \( m_\pi = 170 \) MeV. This ensemble is at the smallest finite-size scaling parameter, \( m_\pi L = 3.9 \), where \( L \) is the linear extent of the lattice volume. That weaker but similar auto-correlation was seen at heavier mass, \( m_\pi = 330 \) MeV, with the second smallest finite-size scaling parameter, \( m_\pi L = 4.6 \), but not at a lighter mass of 250 MeV with larger \( m_\pi L = 5.8 \), hints this autocorrelation may be related to too small lattice volume.

We found weaker but similar autocorrelation in isovector transversity, \( 1 \langle \delta u - \delta d \rangle \), that differs by only one extra Dirac \( \gamma \) matrix factor from the axialvector current. This, together with the axial charge observation, suggests the virtual pion cloud around the nucleon may not be well contained within the lattice volume. The other observables, including the isovector vector-current form factors and isovector quark momentum fraction, \( \langle x \rangle_{u-d} \), and isovector quark helicity fraction, \( \langle x \rangle_{\Delta u-\Delta d} \), do not show such autocorrelation at any mass.

A possible cause for such a long-range autocorrelation is interference from the gauge-field topology that is known to have long autocorrelation. However the axial charge and topological charge are not found to be correlated\textsuperscript{11}).

We also looked at how the axial charge fluctuates spatially by dividing the volume into halves with lower and higher \( x, y, \) or \( z \)-coordinates\textsuperscript{11}); we found that it fluctuates rather wildly.

At the pion mass of about 170 MeV the virtual pion cloud around the nucleon may not be well contained in our lattice box with linear extent of about 4.5 fm.

Fig. 1. The ratio, \( g_A/g_V \), of isovector axia charge, \( g_A \), to isovector vector charge, \( g_V \), calculated in our recent lattice-QCD ensembles plotted against calculated pion mass squared, \( m_\pi^2 \)\textsuperscript{6}).

\begin{itemize}
  \item[\textsuperscript{1}] Institute of Particle and Nuclear Studies, KEK
  \item[\textsuperscript{2}] Department of Particle and Nuclear Physics, SOKENDAI
  \item[\textsuperscript{3}] RIKEN BNL Research Center, BNL
\end{itemize}

References

Holographic heavy-quark symmetry†

K. Hashimoto,∗1,†2 N. Ogawa,∗1 and Y. Yamaguchi∗1

Hadrons containing heavy quarks, i.e., charm and bottom quarks, have attracted much interest in hadron and nuclear physics. Accelerator experiments have found rich spectra of heavy hadrons for conventional states, three-quark baryons and quark-antiquark mesons, and exotic hadrons having complex structures such as multiquark states and hadronic composite states1). Various structures of heavy hadrons are generated by the nature of internal quark potentials and/or hadron-hadron interactions which result from fundamental phenomena of quantum chromodynamics (QCD).

In heavy quark sectors, a new symmetry that has not been appeared in the light-quark sector is expected to be important. It is called heavy-quark spin symmetry2), and it emerges because of the suppression of the spin-dependent interaction between quarks, which is inversely proportional to quark masses. This symmetry leads to a specific feature: mass degeneracy of heavy hadrons having different spins. In the case of mesons, we find small mass splittings between spin-0 pseudo-scalar mesons and spin-1 vector mesons in experimental results, e.g., the mass splitting of $BB^*$ ($\sim$45 MeV) in the bottom-quark sector is much smaller than that of $KK^*$ ($\sim$ 400 MeV) in the strange-quark sector. The symmetry also affects decays and productions of heavy hadrons with different spins. Hence, the heavy-quark spin symmetry plays a significant role in heavy-hadron spectroscopy.

The spectra of heavy hadrons have been studied using various theoretical approaches, such as the quark model and lattice QCD. In addition, we found that the gauge/gravity correspondence3) is a promising approach because it provides powerful methods to deal with strongly coupled theories.

The gauge/gravity correspondence has been applied to investigate hadron spectra by introducing dynamical quarks described by excitations on probe D-branes. For example, $N = 2$ hypermultiplet flavors (= quark multiplets) added to $N = 4$ SU($N_c$) super Yang-Mills theory are realized by introducing $N_f$ probe D7-branes on the AdS5 × $S^5$ background (generated by $N_c$ D3-branes) on the gravity side4). In this model, the quarks are given as fundamental strings stretched between D3- and D7-branes. The masses of pseudo-scalar and vector mesons are obtained as fluctuations of the scalar and vector fields on the flavor D-branes4).

In the gauge theory holding supersymmetry, however, both pseudo-scalar and vector mesons are members of the same multiplet, and the masses are completely degenerate regardless of the value of the quark mass. Even when the supersymmetry is broken by finite temperature, Shark-Schwartz compactification, etc., the supersymmetry is recovered in the heavy-quark limit (i.e., in the UV limit) in most of the top-down models. Hence, the presence of the heavy-quark spin symmetry has not been obvious in the gauge/gravity duality. In order to determine whether the heavy-quark spin symmetry exists, we need to investigate meson mass degeneracies in theories that are non-supersymmetric even in the UV region.

In this study, we propose a semi-bottom-up, deformed D3-D7 model. The background geometry is deformed from the conventional AdS5 × $S^5$ and obtained as

$$\begin{align*}
&ds^2 = r^2 \eta_{\mu\nu} dx^\mu dx^\nu + R^2 r^{-2\beta} \left( \frac{dr^2}{r^2} + r^{2\alpha} d\Omega_5^2 \right),
&\phi = g_0 r^{-\gamma},
\end{align*}$$

in the string frame, where $R$ corresponds to the radius of AdS5, $d\Omega_5^2$ represents the metric of $S^5$, and $\phi$ is the dilaton. Here $r$ is the non-dimensional coordinate. The background geometry is given in the UV leading form and generally holds no supersymmetry or conformal symmetry. We introduce 4 deformation parameters ($\alpha$, $\beta$, $\gamma$) for the background, but they are constrained by several conditions so that the theory would have physically reasonable properties. The standard D3 background corresponds to $(\alpha, \beta, \gamma) = (1, 0, 0, 0)$. We investigate the spectra of the pseudo-scalar and vector quarkonia at the limit $m_Q \to \infty$, computed as the fluctuations of the fields on the flavor D7-brane placed on this background.

We observed a slight mass difference between pseudo-scalar and vector quarkonia, which is at most $\approx 1.5\%$, even in the non-supersymmetric analysis. The mass degeneracy is found in not only ground states but also excited states.

References

† Condensed from the article in arXiv:1412.5590 [hep-th]
*1 RIKEN Nishina Center
*2 Department of Physics, Osaka University
Possibility of ferromagnetic neutron matter†

K. Hashimoto*1,†2

Ferromagnetic order in nature always attracts interest for study as it manifests microscopic structure of matter and materials. Among observed magnetic fields in nature, perhaps the strongest stable magnetic field is on the surface of magnetars, which goes up to $10^{15}$ [G] and more. The mechanism for generating such a strong field is yet to be uncovered, and it is natural to resort the origin to the high density of neutrons of which the neutron stars consist. In fact, after the discovery of pulsars, the possibility of ferromagnetism at neutron stars was proposed. However, numerical simulations of neutron matter with realistic inter-nucleon potentials have not shown the ferromagnetic phase. So the possibility of the ferromagnetic phase at high density neutron matter, if exists in nature, waits for a new mechanism of the spontaneous magnetization.

In this paper, we study the possibility of the ferromagnetic phase at high density of neutrons, by using the simplest but general chiral effective action. Low energy dynamics of neutrons is governed by the chirally symmetric interactions through pions and the spin-magnetic coupling with magnetic fields. Our model consists of dense neutrons coupled with neutral pions and magnetic fields, together with the chiral anomaly term. These are indispensable ingredients, and we will see the outcome for the magnetic phase from this minimal model.

The reason for choosing the neutral pion is simply for the realization of the ferromagnetism, as other pion condensations such as charged pion condensation have not been shown to exhibit a ferromagnetism. In addition, with a neutral pion condensation of the form $\Pi_0(x) \propto \sin k \cdot x$, a neutron lattice is formed with an alternating layer structure (ALS)1), then the neutron spins cancel each other, and macroscopic magnetization would not emerge. In this paper, instead, we analyze a neutral pion condensation of the different form $\Pi_0(x) = q \cdot x$ following Dautry and Neyman2), and generalize the study to include magnetic fields and QCD anomaly.

Our study is motivated by the earlier work3) in which, together with M. Eto and T. Hatsuda, the author proposed a mechanism for a ferromagnetic phase at high density of neutrons. The mechanism utilizes a neutral pion domain wall coupled to the magnetic field through the QCD chiral anomaly. A spontaneous magnetization was shown in3) in the approximation of a single wall and one-loop neutrons. In this paper, we generalize the idea, and study in the simplest chiral model the Fermi energy of the dense neutrons and its back-reaction due to the pion condensation and the magnetic fields. A successive array of the domain walls can be approximated by the linear pion condensation of Dautry and Neyman.

Let us summarize what we find in this paper.

- Toy model of neutral fermions. First we provide a toy model of a neutral fermion with a Zeeman coupling to magnetic fields. Under the assumption of the spatial homogeneity, we calculate the energy density of the ferromagnetic phase and show that it is favored compared to the ordinary fermion matter.
- Simplest chiral model and ferromagnetic order. The toy model of the neutral fermions is the essential part of the chiral model of neutrons and pions. We analyze the simplest chiral effective model of dense neutrons and neutral pions, together with the magnetic field coupling and the QCD anomaly. We find that the neutral pion condensation of form proposed by Dautry and Neyman is precisely in the same place as the magnetization, under the assumption of the spatial homogeneity. The energy density of the ferromagnetic-pion-condensation phase is lower than the ordinary neutron matter at high density around $\rho > 5\rho_0$ where $\rho_0$ is the generated magnetic field is $\sim 40$ [MeV] $\sim O(10^{17})$[G].
- Comparison to ALS. We compare our energy density with that of the inhomogeneous ALS phase (which does not exhibit a magnetization), and find that the ALS phase is favored. The energy gain of the ALS is by several times greater than that of our ferromagnetic phase.
- Axial vector meson condensation. To seek for the possibility of the ferromagnetism, we look at the axial vector meson condensation accompanied by our model. Indeed, any axial vector meson plays the same role as the neutral pions, and the axial vector meson condensation further reduces the energy density of the ferromagnetic phase significantly.

References
Pion and Kaon form factors in the NJL model

Y. Ninomiya,*1 W. Bentz,*1,∗2 and I. C. Cloët∗3

In this work we study the dressed quark mass dependence of the pion and kaon electromagnetic form factors at the quark level using the Nambu-Jona-Lasinio (NJL) model, which is a powerful chiral effective quark model of QCD1). We choose the proper-time regularization scheme and introduce an infrared cut-off as in previous studies2,3) in order to include one important aspect of quark confinement. In the calculation there is one free model parameter, which we take as the dressed light quark (u and d) mass M. The constituent quark model suggests that M is about 0.3–0.4 GeV, and it is often fixed as 0.4 GeV in NJL model calculations. However, in this work we show that the description of the pion and kaon form factors, as well as other physical quantities, are sensitive to the dressed light quark mass, and can be greatly improved if the dressed light quark mass is taken to be M ≃ 0.25 GeV.

We first explore the quark condensates ⟨q̅q⟩, the kaon decay constant fK, and the light (m) and strange (ms) current quark masses using various values of the dressed quark mass. Our results for these quantities are shown in Table I. It is revealed that our results for the three ratios ms/m, fK/fπ and ⟨ss⟩/(|ℓℓ|) are in excellent agreement with recent experimental analyses and lattice QCD calculations, if the mass of the dressed light quark is approximately M ≃ 0.25 GeV. Therefore, it is interesting to study the pion and kaon form factors for the case where M is assumed to be smaller than the usually adopted values.

Figs. 1 and 2 show our calculated results for the pion and kaon form factors for the case M = 0.25 GeV. In each figure the dotted line denotes the result when the quark-photon vertex is treated as point-like (bare); the dash-dotted line includes effects from the pion cloud; and the dashed line is the full result which also includes the vector mesons contributions to the quark-photon vertex. The solid line shows the monopole functions which are determined so as to reproduce the empirical charge radii. From these figures it is clear that the data and the monopole functions can be reproduced very well by choosing M ≃ 0.25 GeV and including both the pion cloud and vector meson contributions. Such good agreement can not be attained for the case of M ≃ 0.4 GeV.

Table I. Results for the current quark masses, kaon decay constant and quark condensates, for various values of the dressed light quark mass M. Masses and fK are in units of GeV, and quark condensates in units of GeV3.

| M (GeV) | m (GeV) | m* (GeV) | fK (GeV) | ⟨|ℓℓ|⟩ GeV3 | ⟨ss⟩ GeV3 |
|--------|--------|--------|--------|-------------|---------|
| 0.20   | 0.0041 | 0.131  | 0.128  | −0.275      | −0.329  |
| 0.25   | 0.0086 | 0.227  | 0.110  | −0.214      | −0.224  |
| 0.30   | 0.0123 | 0.293  | 0.010  | −0.190      | −0.180  |
| 0.35   | 0.0150 | 0.331  | 0.004  | −0.177      | −0.159  |
| 0.40   | 0.0168 | 0.357  | 0.091  | −0.170      | −0.148  |

References

W.B. acknowledges support by the Grant in Aid for Scientific Research (Kakenhi) of the Japanese Ministry of Education, Culture, Sports, Science and Technology, project no. 20168769.

Fig. 1. Pion form factor for the case M = 0.25 GeV.

Fig. 2. Kaon form factor for the case M = 0.25 GeV.

2 Department of Physics, School of Science, Tokai University
3 RIKEN Nishina Center
4 Physics Division, Argonne National Laboratory
Chiral Magnetic and Vortical Effects at Weak Coupling

H. U. Yee

Chiral magnetic and vortical effects are parity-odd transport phenomena in the hydrodynamics of a plasma of chiral massless fermions, which are macroscopic manifestations of the underlying microscopic chiral anomaly. For the plasma of a single right-handed Weyl fermion, the chiral magnetic effect dictates a current along an applied external magnetic field $\vec{B}$ as

$$J = \frac{\mu}{\sqrt{\pi}} \vec{B}$$

where $\mu$ is the chemical potential, and in the case of chiral vortical effect, the vorticity of fluid $\vec{\omega} = (1/2)v \times \vec{v}$ plays a role similar to the magnetic field, $\vec{J} = (\mu^2 + \pi T^2/3)\vec{\omega}$. These effects are robust due to the topological nature of chiral anomaly, and should persist both in weak and strong coupling limits. Demonstrating the expected universality of these phenomena in weak and strong coupling limits is an interesting and non-trivial test of the topological nature of chiral anomaly. While the strong coupling limit provided by AdS/CFT correspondence has successfully confirmed the universality of these effects, the weak coupling picture, albeit more intuitive, contains more subtleties that need to be carefully taken into accounts.

In general, one can define the chiral magnetic conductivity

$$\tau_{\chi}(\omega, k)$$

by $J = \tau_{\chi}(\omega, k)\vec{B}(\omega, k)$ where $(\omega, k)$ are frequency and longitudinal momentum of the in-homogeneous time-dependent magnetic field $\vec{B}(\omega, k)$. One expects the zero frequency-momentum limit of $\tau_{\chi}(\omega, k)$ to reproduce the topologically robust result of chiral magnetic effect,

$$\lim_{\omega \to 0, k \to 0} \tau_{\chi}(\omega, k) = \frac{\mu^2}{\sqrt{\pi}}.$$ 

In the interaction-free limit, both diagrammatic and kinetic approaches give a result for $\tau_{\chi}(\omega, k)$ such that

$$\lim_{\omega \to 0} \lim_{k \to 0} \tau_{\chi}(\omega, k) = \lim_{\omega \to 0} \lim_{k \to 0} \tau_{\chi}(\omega, k) = \frac{1}{\pi} \cdot \frac{\mu}{\sqrt{\pi}}$$

while a hydrodynamic argument indicates that there should not be such a difference between the two limits. Since hydrodynamic regime exists only in an interacting theory, it is natural to study this issue in an interacting theory going beyond the non-interacting limit. In Ref. we showed in both kinetic and diagrammatic approaches that the above difference between two limits disappears in the presence of relaxation dynamics caused by interactions, confirming the expectation from the hydrodynamics argument.

It is interesting to understand how chiral magnetic and vortical effects arise in the quasi-particle picture of kinetic theory of chiral fermions. The essential ingredient that is responsible for chiral anomaly is the Berry’s curvature in momentum space

$$\vec{b} = \nabla_p \times \vec{A}_p = \vec{p}/2|\vec{p}|^3,$$

where $\vec{A}_p$ is the Berry’s connection of momentum-dependent chiral spinors. We showed in Ref. that the quasi-particle energy in the presence of magnetic field is dictated to be $\epsilon(\vec{p}) = |\vec{p}| - \vec{B} \cdot \vec{p}/2|\vec{p}|^2$ by Lorentz invariance where the second term is a spin-magnetic moment interaction. This term brings about several interesting consequences. Since the equilibrium distribution is $f^{eq}(\vec{p}) = 1/(\exp[\beta \epsilon(\vec{p})] + 1)$ the distribution becomes distorted by the magnetic field, which causes a net current along the magnetic field. This effect turns out to explain 1/3 of the full chiral magnetic effect. On the other hand, the equation of motions of quasi-particles with the Berry’s curvature is given by

$$\sqrt{G} \vec{x} = \partial \epsilon / \partial \vec{p} + (\vec{b} \cdot \partial \epsilon / \partial \vec{p}) \vec{B}$$

where $\sqrt{G} = 1 + \vec{b} \cdot \vec{B}$ is the modified phase space density. The second term proportional to $\vec{B}$ induces a net current along the magnetic field even with spherically symmetric equilibrium distribution. This contribution gives the rest 2/3 of the full chiral magnetic effect.

Interestingly, a similar feature also exists in the chiral vortical effect. With the fluid vorticity $\vec{\omega}$, a detailed valance in the Boltzmann equation with conservation of angular momentum

$$\vec{L} = \vec{x} \times \vec{p} + (1/2)\vec{p}^2/\vec{\omega},$$

where the second term is the spin angular momentum, dictates the equilibrium distribution to be

$$f^{eq} = 1/(\exp[\beta / \epsilon - \vec{\omega} \cdot \vec{p}] + 1),$$

which induces a net current proportional to $\vec{\omega}$: the result comprises 1/3 of the full chiral vortical effect. From the spin-magnetic moment interaction term in the energy, $-\vec{B} \cdot \vec{p}/2|\vec{p}|^2$, one can obtain a contribution to the current by the variation of the quasi-particle action with respect to external gauge potential, the result of which takes a form

$$\Delta J = \int \frac{d^3p}{(2\pi)^3} \left( \vec{\nabla} f \times \vec{p} / (2|\vec{p}|^2) \right).$$

With distribution function $f = f^{eq}(\epsilon - \vec{\omega} \cdot \vec{p})$, the resulting current along $\vec{\omega}$ constitutes the rest 2/3 of the chiral vortical effect.

In space-time dimensions higher than four, there are generalizations of chiral magnetic and vortical effects. A weak coupling computation of them in real-time formalism was performed in Ref., which successfully confirmed the hydrodynamics prediction in Ref.

References
Collinear parton splitting for early thermalization and chemical equilibration in heavy-ion collisions

A. Monnai*1 and B. Müller*2,*3

High-energy heavy-ion collisions at the BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) are the gateway to the early universe, where quarks and gluons are deconfined from hadrons. The strong elliptic flow observed suggests that the system is thermally equilibrated within a very short time $\tau_{th} = 0.5-1 \text{ fm}/c$, at which point relativistic hydrodynamics becomes a valid description of the bulk medium. The mechanism that leads to the early equilibration, on the other hand, is still not well known. A theoretical explication of the formation of a QCD droplet is of high importance in collider physics.

In this work, we propose a phenomenological description of the local early equilibration based on collinear parton splitting and recombination$^1$). Equilibration of a heavy-ion system requires (i) thermalization, (ii) chemical equilibration, and (iii) isotropization since the colliding nuclei are described as the color glass condensate where gluons are saturated up to the typical momentum $p \simeq Q_s$. Collinear splitting introduces two low-momentum partons from a high-momentum incident parton. This is suitable for the description of the first two types of equilibration because the thermal distribution has a relatively large number of low-momentum partons. The processes we consider are (a) splitting of a gluon into two gluons, (b) gluon emission by quarks and (c) quark-antiquark pair production. Momentum fraction in a splitting is governed by the parton splitting functions$^3$). The rate of splitting in a dimensional analysis is given as $\Gamma \simeq \alpha_s (q/p)^{1/2}$, where $\alpha_s$ is the QCD coupling and $\hat{q}$ is the transport coefficient for momentum diffusion. The recombination processes are introduced phenomenologically; hence, the equations of motion for the quark and the gluon phase-space distributions satisfy the second law of thermodynamics. The effects of elastic scattering, which creates off-shell partons, are encoded in the model via the Focker-Planck equation. The detailed expressions of the equations of motion can be found here$^1$).

We perform numerical estimations with a non-expanding $(1+1)$-dimensional geometry to investigate the qualitative properties of the equilibration model. Figure 1 shows the gluon distribution of a pure gluon system before and after time-evolution. The effective degrees of freedom are included in the definition of the phase-space distribution. Here, the initial condition is a color-glass-like one where $f^g(p = 0) \simeq 1/\alpha_s$ and $Q_s \simeq 2 \text{ GeV}$. The system almost thermalizes at 0.8 fm/c when the initial time is 0.2 fm/c. Next, we consider the case when $N_f = 3$ and obtain the gluon and the quark distributions shown in Fig. 2. Here, the system approaches the thermalized state rather quickly, but the effective numbers of degrees of freedom remain far from those in equilibrium owing to the slowness of the quark chemical equilibration process. For the current parameter settings, the typical time required for chemical equilibration is estimated as $\tau_{chem} \simeq 2 \text{ fm}/c$. The results imply that collinear parton splitting and recombination play an important role in the early-time dynamics of heavy-ion collisions, and the quark-gluon plasma at the onset of hydrodynamic evolution can be gluon-rich.

Future prospects include improvement of the model parameters and development of a $(3+1)$-dimensional numerical model for quantitative description of isotropization in such QCD systems.

References

*1 RIKEN Nishina Center
*2 Physics Department, Duke University
*3 Brookhaven National Laboratory
Chemical equilibration of QCD medium for photon $v_2$ puzzle

A. Monnai

Discovery of the quark-gluon plasma (QGP), a deconfined phase of QCD, at BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider is a milestone in hadron physics. The produced medium is considered to be strongly coupled because the momentum anisotropy in hadronic spectra is large enough to validate hydrodynamic description. This is quantified by elliptic flow $v_2$ defined as a Fourier expansion coefficient of the yield $N$:

$$\frac{dN}{d\phi} = \frac{N}{2\pi} [1 + 2 \sum_{n=1} v_n \cos(n\phi - \Psi_n)],$$

where $\phi$ is the azimuthal angle in momentum space and $\Psi_n$ is the $n$-th harmonic event plane. On the other hand, direct photon $v_2$ is found to be a few times larger than hadron production predictions, which is recognized as the “photon $v_2$ puzzle.” Of direct photons, thermal photons from the QGP medium are the dominant source of anisotropy because prompt photons from initial hard processes do not have it intrinsically.

In this work, I have considered the effects of chemical equilibration in the QGP on thermal photon $v_2$. A heavy-ion system before the collision is described as the color glass condensate, a state of saturated gluons. Several early equilibration models indicate that chemical equilibration is slower than thermalization. This implies that the quark number at the onset of hydrodynamic evolution is smaller than that under equilibrium. Since photons are coupled to quarks, late chemical equilibration suppresses the emission of thermal photons in the early stages where flow anisotropy is still small. Consequently, thermal photon $v_2$ can become effectively large owing to the contribution from later times.

I have developed a new $(2+1)$-dimensional ideal hydrodynamic model and coupled it to the rate equations for the parton number densities. The number changing processes are (a) $g \leftrightarrow gg$, (b) $g \leftrightarrow q\bar{q}$, and (c) $q(q) \leftrightarrow gg(qg)$. Here, the vanishing net baryon number limit is considered. The relaxation equations are:

$$\partial_\mu n_q^\mu = 2r_a n_g - 2r_b n_g^q \frac{n^q_g}{(n^q_g)^2} n^2_q,$$

$$\partial_\mu N_q^\mu = (r_a - r_b) n_g - r_a \frac{1}{n_g} n^2_g + r_b \frac{n^q_g}{(n^q_g)^2} n^2_g + r_c n_q - r_c \frac{1}{n_q} n^2_q,$$

where $r_a$, $r_b$, and $r_c$ are the reaction rates. Since pair production is the only quark number-changing process, chemical equilibration time would be given by $\tau_{\text{chem}} = 1/r_b$. Here, the rates are parametrized as $r_a = c_0 T$. The equation of state is a hyperbolic interpolation of those for hadron and parton gases with $N_f = 2$. The thermal photon emission rate is also derived from those for the hadron and QGP phases.

Figure 1 shows the elliptic flow of thermal photons for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the impact parameter $b = 7$ fm. The chemical reaction parameters are chosen as $c_0 = 0.2, 0.5$, and $2.0$, where $c_{a,c} = 1.5$. Thermal photon $v_2$ can be visibly enhanced by late quark chemical equilibration. For the suggested chemical equilibration time $\tau_{\text{chem}} = 2$ fm, $c_0 = 0.5$ follows from $T \sim 0.2$ GeV. The dependences on the gluon number-changing processes characterized with $r_a$ and $r_c$ are found to be small as expected. The particle spectrum of thermal photons is not affected much by chemical non-equilibrium with the current parameter settings. This implies that late quark chemical equilibration is important to explain the photon $v_2$ problem. It should be noted that the mechanism can also be an explanation to the large photon $v_2$ recently observed in the experiments.

Future prospects include the introduction of a dynamical equation of state, improved initial conditions, and chemical equilibration effects. Effects of viscosities would also be important in quantitative discussion because thermal photons are sensitive to early-time fluid dynamics where off-equilibrium corrections are large because photons can pass through the QCD medium.

References


Fig. 1. Thermal photon $v_2$ with different quark chemical equilibration rates.
Refraction of light in the quark-gluon plasma

A. Monnai∗

Electromagnetic probes in high-energy heavy-ion collisions provide us with important information on the quark-gluon plasma (QGP) because experimental data indicate that the hot medium is color opaque but electromagnetically transparent. An important discovery regarding such probes is the excessive yield of direct photon elliptic ($v_2$) and triangular flow ($v_3$).1) Direct photons consist of prompt photons created in the initial hard processes and thermal photons emitted from the medium. Flow harmonics is defined as a Fourier expansion coefficient of particle spectra in the azimuthal angle and is induced by geometrical anisotropy in the system via medium interaction. Since hadronic flow harmonics follows hydrodynamic description and is considered as an evidence for the existence of a strongly coupled medium, quantitative understanding of the direct photon flow harmonics is an important issue in heavy-ion phenomenology.

I have investigated the effect of refraction on prompt photons by the QGP medium in the transverse plane (Fig. 1).2) The emission rate for prompt photons is derived from $p\bar{p}$ collision data.3) The path of a ray in a medium with the refractive index $n$ is given as $d^2x/dx^2 = (1/2)dn^2/dx$ according to Fermat’s principle. The dynamical evolution of an inhomogeneous medium should be considered, because the typical lifetime and size of the system are comparable. Here, I use a (2+1)-dimensional ideal hydrodynamic model with Monte-Carlo Glauber initial conditions and a lattice QCD equation of state. The initial time is 0.4 fm/c and the freeze-out temperature is 0.15 GeV. The temperature and frequency dependence of the refractive index is parametrized as $n^2(T,\omega) = 1 - \omega^2_D/\omega^2$, where the plasma frequency is parametrized as $\omega^2_D = a^2T^2$. In the high-temperature limit, $\omega^2_D \sim m_D^2 \sim \epsilon^2T^2$ is obtained using the Debye mass $m_D$. This implies $a^2 \sim 10^{-4}$ since $\epsilon^2 = 4\pi\alpha_{EM}$. The frequency $\omega$ is Doppler-shifted from the original frequency as $\omega = \omega_0/(1 + \beta \cos \Delta\phi)$, where $\Delta\phi$ is the angle between the flow and the direction of a ray. It should be noted that the phase velocity in the QGP medium, $v_{ph} = 1/n$, exceeds the speed of light, but causality is not violated because the group velocity remains smaller than unity. When $n^2 < 0$, the medium does not bend a ray but partially absorbs it.

The elliptic flow of prompt photons is shown in Fig. 2. When there is no refraction, the quantity vanishes. For non-unitary refractive indices, on the other hand, positive $v_2$ is observed above plasma frequencies. The magnitude, however, is not large enough to account for the large photon $v_2$ found in collider experiments. Below the plasma frequency, the high-

References
Transverse single-spin asymmetries in proton-proton collisions and the role of twist-3 fragmentation†

D. Pitonyak,*1 K. Kanazawa,*2 Y. Koike,*3 and A. Metz*2

The field of transverse single-spin asymmetries (SSAs) in hard semi-inclusive processes began close to 40 years ago at Fermilab. People noticed early on that the collinear parton model cannot generate the large effects that were found. It was then pointed out that SSAs for single-particle production in hadronic collisions are genuine twist-3 observables for which, in particular, collinear 3-parton correlations have to be taken into account. This formalism later on was worked out in more detail and applied to SSAs in processes like light hadron production in proton-proton collisions, \( p/p \rightarrow hX \). Here we focus on SSAs in such reactions, which have been complemented by many experiments, including those at RHIC.

For quite some time it was believed that effects inside the transversely polarized proton dominate the transverse SSA in \( p/p \rightarrow hX \) (typically denoted by \( A_N \))1–4. In particular, the so-called Quensterman function \( T_F \) was thought to be the main non-perturbative object that generates this observable. \( T_F \) can be related to the transverse-momentum dependent (TMD) Sivers parton density \( f_{1T}^{s} \). Because of this relation, one can extract \( T_F \) from data on either \( A_N \) or on the Sivers transverse SSA in semi-exclusive deep-inelastic scattering (SIDIS) \( A_{SIDIS}^{Sv} \). It therefore came as a major surprise when an attempt failed to simultaneously explain both \( A_N \) and \( A_{SIDIS}^{Sv} \) — the two extractions for \( T_F \) actually differ in sign5, a puzzle that has become known as the “sign mismatch”.

At this point one may start to question the dominance of \( T_F \). In fact, data on the neutron target transverse SSA in inclusive DIS6/7 seem to support this point of view7. Therefore, we study here the potential role of fragmentation effects, whose resultant activity in the twist-3 formalism was first worked out in 8). It involves the non-perturbative functions \( \hat{H}, \hat{H}_{FU}^3, \) and \( H \), where the first is related to the TMD Collins function and the third can be written in terms of the other two.

In Fig. 1 we show our results from fitting the collinear 3-parton fragmentation correlator \( \hat{H}^3_{FU} \) to data for \( A_N^{0} \) from STAR9–11 and \( A_N^{+} \) from BRAHMS12. Our fit describes the data very well; moreover, one can see without \( \hat{H}^3_{FU} \), one cannot obtain the rise in \( A_N \) at large \( x_F \) that is characteristic of the data. Therefore, we have demonstrated for the first time that twist-3 factorization actually can describe high-energy RHIC data for \( A_N^{0} \) if one takes

References
Left-right spin asymmetries in lepton-nucleon collisions†

D. Pitonyak,*† L. Gamberg,*‡ Z.-B. Kang,*§ A. Metz,*∥ and A. Prokudin*∥∥

The field of transverse single-spin asymmetries (SSAs) in hard semi-inclusive processes began close to 40 years ago when large effects were found at FermiLab that could not be generated within the collinear parton model. Here we focus on the left-right azimuthal asymmetry that can be defined in single-inclusive leptoproduction of hadrons if the nucleon is transversely polarized, $\ell N \rightarrow hX$. This asymmetry is similar to the transverse single-spin asymmetry $A_N$ that occurs in $p^+p \rightarrow hX$, which has been intensely studied at RHIC. Recently, the HERMES Collaboration1) and the Jefferson Lab Hall A Collaboration2) reported the first ever measurements of $A_N$ in lepton-nucleon scattering. In general, one may expect that $A_N$ in this reaction could give new insight into the underlying mechanism of $A_N$ in hadronic collisions that is the subject of longstanding discussions.

We compute $A_N$ for $\ell N \rightarrow hX$ in collinear factorization, where one can have twist-3 effects in the transversely polarized nucleon or in the unpolarized outgoing hadron. The former involves the so-called Quark-Sterman function $F_{FT}$ — a specific quark-gluon-quark correlator that has an intimate connection with the transverse momentum dependent (TMD) Sivers function $f_1^{\perp T}$, while the latter arises from parton fragmentation, specifically through the functions $H, H, and H_{FU}^3$, where the first is related to the TMD Collins function. Both of these mechanisms have been studied in $p^+p \rightarrow hX$ within collinear factorization, e.g., in 3–6). Note that $\ell N \rightarrow hX$ has also been computed in the so-called Generalized Parton Model (GPM) (most recently in 7), which uses TMD parton correlation functions.

We will estimate $A_N$ based on leading-order formulas, which we refrain from showing here explicitly for brevity, and study the contributions from the distribution term involving $F_{FT}$, and the fragmentation term involving $H, H$, and $H_{FU}^3$. It is important to realize that for the process at hand, $\ell N \rightarrow hX$, only the hadron transverse momentum $P_{h\perp}$ can serve as the hard scale. Here we give a sample of our results, namely some for HERMES and an EIC. In Fig. 1 we plot (in the top panel) $A_N$ as a function of $x_F^H = -x_F$ for $\pi^+$ production with $1 < P_{h\perp} < 2.2$ GeV ($\langle P_{h\perp} \rangle \approx 1$ GeV) for lepton-proton collisions at HERMES energy $\sqrt{S} = 7.25$ GeV. Also shown (in the bottom panel) is our prediction for $\pi^0$ production at EIC energy $\sqrt{S} = 63$ GeV and $P_{h\perp} = 3$ GeV. Note that for $p^+p \rightarrow \pi X$ in the forward region ($x_F > 0$) very large values for $A_N$ have been observed. We find that a non-zero $A_N$ is predicted in this region at an EIC.

We see that our theoretical estimates for $A_N$ agree with the HERMES results in sign and roughly in shape, but in terms of magnitude they are typically above the data. Such a discrepancy cannot be considered a failure of the collinear twist-3 formalism, but rather shows the need for a next-to-leading order calculation, especially in the region of lower $P_{h\perp}$. It will also be important to better constrain the 3-parton fragmentation correlator $H_{FU}^3$ through measurements, e.g., of $A_N^{\pi^0}$, which might allow one to test the recent extraction of $H_{FU}^3$ that can play a crucial role in $A_N$ in pp collisions6), and to discriminate between the GPM and the twist-3 frameworks.

References
Twist-3 double-spin asymmetries in lepton-nucleon collisions

D. Pitonyak,*1 K. Kanazawa,*2 A. Metz,*2 and M. Schlegel*3

Hadrons, the strongly interacting particles that comprise almost all of the visible matter in the universe, have been shown to possess a complex inner-structure that goes beyond a simple quark picture. For example, experimental results in the 1970s on transverse single-spin asymmetries (SSAs) revealed the crucial role that quark-ghon-quark correlations could play in hadrons. This is a consequence of the fact that such observables are twist-3 effects. Much work over the last 40 years has been performed in the study of transverse SSAs from both the experimental and theoretical sides. In addition, one also has twist-3 double-spin asymmetries (DSAs), namely those where one particle is longitudinally polarized and the other is transversely polarized. We will denote these by $A_{LT}$. The classic process for which this effect has been analyzed is $A_{LT}$ in inclusive deep-inelastic lepton-nucleon scattering (DIS). In that case the entire result can be written in terms of the collinear twist-3 function $g_T(x)$. Furthermore, this asymmetry has been studied in the Drell-Yan process involving two incoming polarized hadrons\textsuperscript{2–4}; in inclusive lepton production from $W$-boson decay in proton-proton scattering\textsuperscript{5}; for jet production in lepton-nucleon collisions\textsuperscript{6}; and for direct photon production\textsuperscript{7}, jet/hadron production\textsuperscript{8}, and $D$-meson production\textsuperscript{9} in nucleon-nucleon collisions.

Here we consider the reaction $\bar{e}N \rightarrow hX$, where one can have twist-3 contributions from both the distribution (incoming nucleon) and the fragmentation (outgoing hadron) sides. The leading-order (LO) analytical formulas for these terms are new results from this work, but we refrain from showing them explicitly for brevity. Based on this computation we will give numerical estimates for $\bar{e}N \rightarrow \pi X$, where $N = p, n$. We will only look at the distribution piece, where we need LO input for the non-perturbative functions $D_1(z)$ (unpolarized fragmentation function), $\tilde{g}(x)$ (“worm-gear”-type function), $g_T(x)$, and $g_1(x)$ (helicity distribution), where $\tilde{g}(x)$ is the last known of these functions and has gained quite some interest over the years.

Since we have little information on $\tilde{g}(x)$, we look at two scenarios: i) using the approximate relation $\tilde{g}(x) \approx -f_{LT}^{(W^\prime)}(x)$, where $f_{LT}^{(W^\prime)}$ is the Sivers function; and ii) using a Wundzura-Wilczek (WW)-type approximation $\tilde{g}(x) \approx x \int_x^1 \frac{dy}{y} g_1(y)$, which was also used elsewhere in the literature and holds relatively well in certain models. In both cases for $g_T(x)$ we use the WW approximation, $g_T(x) \approx x \int_x^1 \frac{dy}{y} g_1(y)$. In Fig. 1 we show a sample of our results, namely for HERMES and JLab6, where finalized data is expected soon from both groups.

We see from our plots that the “Sivers” and “Wundzura-Wilczek” input can give quite different results due to the different behavior of $\tilde{g}(x)$. Thus, even a qualitative comparison of our predictions with experiment could help distinguish between the Sivers and WW scenarios. Moreover, if the magnitude of the data is in line with our results, one could have direct access to the “worm-gear”-type function $\tilde{g}(x)$, which has received some attention recently. If the magnitude is not in agreement, this observable could give insight into the importance of quark-ghon-quark correlations in the nucleon and/or twist-3 fragmentation effects in unpolarized hadrons. However, one always has to keep in mind the potential large impact of next-to-leading order terms. In general, we found the best chance to measure a nonzero asymmetry is at HERMES, JLab, and COMPASS, as the high center-of-mass energy of an EIC leads to a very small effect. We expect this conclusion to be rather robust.

References


\textsuperscript{1} Condensed from the article arXiv:1411.6459 submitted to PLB
\textsuperscript{*1} RIKEN Nishina Center
\textsuperscript{*2} Department of Physics, Temple University
\textsuperscript{*3} Institute for Theoretical Physics, Tübingen University
Strong binding and shrinkage of single and double $\bar{K}$ nuclear systems ($K^-pp$, $K^-ppn$, $K^-K^-p$ and $K^-K^-pp$) predicted by Faddeev-Yakubovsky calculations

S. Maeda,*1 Y. Akaishi,*2,3 and T. Yamazaki*2,4

Non-relativistic Faddeev and Faddeev-Yakubovsky calculations were made for $K^-pp$, $K^-ppn$, $K^-K^-p$ and $K^-K^-pp$ kaonic nuclear clusters, where the quasi bound states were treated as bound states by employing real separable potential models for the $K^-K^-$ and the $K^-nucleon$ interactions as well as for the nucleon-nucleon interaction$^1$.

The binding energies and spatial shrinkages of these states, obtained for various values of the $KN$ interaction, were found to increase rapidly with the $KN$ interaction strength. Their behaviors are shown in a reference diagram, Fig. 1, where possible changes by varying the $KN$ interaction in the dense nuclear medium are given. Using the $\Lambda(1405)$ ansatz with a PDG mass of 1405 MeV/$c^2$ for $K^-p$, the following ground-state binding energies together with the wave functions were obtained: 51.5 MeV ($K^-pp$), 69 MeV ($K^-ppn$), 30.4 MeV ($K^-K^-p$) and 93 MeV ($K^-K^-pp$), which are in good agreement with previous results of variational calculation based on the Akaishi-Yamazaki coupled-channel potential$^{2–5}$. The $K^-K^-pp$ state has a significantly increased density where the two nucleons are located very close to each other, in spite of the inner $NN$ repulsion. Relativistic corrections on the calculated non-relativistic results indicate substantial lowering of the bound-state masses, especially of $K^-K^-pp$, toward the kaon condensation regime. The fact that the recently observed binding energy of $K^-pp$ is much larger (by a factor of 2) than the originally predicted one may infer an enhancement of the $KN$ interaction in dense nuclei by about 25%, possibly due to chiral symmetry restoration. In this respect some qualitative accounts are given based on “clearing QCD vacuum" model of Brown, Kubodera and Rho.$^8$

References

New way to produce dense double-antikaonic dibaryon system, $K^-K^-pp$, through $\Lambda(1405)$-doorway sticking in $p+p$ collisions

M. Hassanvand,*1,*2 Y. Akaishi,*1,*3 and T. Yamazaki*1,*4

A recent successful observation of a dense and deeply bound $\bar{K}$ nuclear system, $K^-pp$, in the $p+p \rightarrow K^+ + K^-pp$ reaction in a DISTO experiment1) indicates that the double-$\bar{K}$ dibaryon, $K^-K^-pp$, which was predicted to be a dense nuclear system2,3), can also be formed in $p+p$ collisions.

![Fig. 1](image)

Fig. 1. Reaction diagrams in the center-of-mass system of $pp$ collisions. a) For $pp \rightarrow K^+ + K^-pp$ and b) for $pp \rightarrow K^+ + K^+ + K^-K^-pp$. The $\Lambda(1405)$ resonance particle as a doorway is indicated by $\Lambda^*$. We have formulated and calculated the differential cross section for the formation of the simplest double-$\bar{K}$ nuclear cluster system, $K^-K^-pp$, in the reaction process

$$p+p \rightarrow K^+ + K^- + \Lambda^* + \Lambda^*,$$

$$\rightarrow K^+ + K^+ + K^-K^-pp,$$

$$\rightarrow K^+ + K^+ + \Lambda + \Lambda,$$

where $\Lambda^*$ is a quasi-bound $K^-p$ state corresponding to the $\Lambda(1405)$ resonance4,5). From a comprehensive study of the calculated effects of the binding and density of $K^-K^-pp$ on the cross section, we find that the bound-state peak of $K^-K^-pp$ dominates over the spectrum when and only when the system is dense. This is understood as the two $\Lambda^*$ doorway particles interact immediately within a short distance, assisted by a large momentum transfer ($\sim 1.8 \text{ GeV}/c$) and a short collision length ($\sim 0.3 \text{ fm}$), which helps to enlarge the $\Lambda^* - \Lambda^*$ sticking into a dense $K^-K^-pp$ system. See details in Ref.4,5. This mechanism is similar to that for a single $\bar{K}$ cluster ($K^-pp$) formation6,7), which has just been proven by the DISTO experiment.

Fig. 2. (Color online) Differential cross sections for various bound-state energies, $E$, of the $K^-K^-pp$ system for $T_p = 7.0 \text{ GeV}$, $\Gamma = 150 \text{ MeV}$, $b = 0.3 \text{ fm}$ and $\theta_{12} = 180$.

References
Theoretical analysis of $\Lambda(1405) \rightarrow (\Sigma \pi)^0$ mass spectra produced in $p + p \rightarrow p + \Lambda(1405) + K^+$ reactions

M. Hassanvand, S. Z. Kalantari, Y. Akaishi, and T. Yamazaki

We formulated the $\Lambda(1405)$ (abbreviated as $\Lambda^*$) $\rightarrow (\Sigma \pi)^0$ invariant-mass spectra produced in $p + p \rightarrow p + \Lambda^* + K^+$ reactions, in which both the incident channel for a quasi-bound $K^-p$ state and its decay process to $(\Sigma \pi)^0$ were taken into account realistically. We calculated $M(\Sigma \pi)$ spectral shapes for various theoretical models for $\Lambda^*$. They are asymmetric and skewed, and were compared with recent experimental data of HADES. The nearly isotropic proton distribution observed in DISTO$^3$ and HADES is ascribed to a short collision length in the production of $\Lambda^*$, which justifies the high sticking mechanism of $\Lambda^*$ and the participating proton into $K^-pp$.

In the present work we formulate the spectral shape of the $(\Sigma \pi)^0$ mass to provide theoretical guides to analyze experimental data of $(\Sigma \pi)^0$ mass spectra from the above reaction. We take into account both the formation and the decay processes of $\Lambda^*$ in $pp$ reactions realistically, following our $KN-\Sigma\pi$ coupled-channel formalism. In this way, we derive the general form of the spectral function, which is not symmetric, but skewed with respect to the pole position. Then, we analyzed $(\Sigma^+\pi^-)^0$ spectra from HADES at $T_p = 3.50$ GeV, and obtained: $M(\Lambda^*) = 1405_{-9}^{+11}$ MeV/$c^2$ and $\Gamma = 62 \pm 10$ MeV, where the interference effects of the $KN-\Sigma\pi$ resonance with $I = 0$ and 1 $\Sigma\pi$ continuum are considered. Whereas the HADES spectrum shows a very broad peak centered around 1385 MeV/$c^2$, significantly lower lying than 1405 MeV/$c^2$, we have clarified that it is due to kinematical distortion. The present result on $M$ and $\Gamma$ is in good agreement with the PDG12 and PDG14 values. The Hyodo-Weise (HW) spectra, shown as the curves (c) and (d) in the figure, do not account for the experimental spectrum.

References

6. Particle Physics
It is very important to determine if the SM (Standard Model)-like Higgs boson discovered at the LHC (Large Hadron Collider) in 2012 is the SM Higgs boson or the Higgs boson of New Physics. This is the most important issue in the present particle physics world. In this report based on our paper, we study the possibility that it is the lightest Higgs boson $h^0$ of the Minimal Supersymmetric Standard Model (MSSM), by focusing on the width of the decay $h^0 \rightarrow c \bar{c}$. We compute the decay width at a full one-loop level in the $\overline{DR}$ renormalization scheme in the MSSM with nonminimal Quark Flavor Violation (QFV).

We take our reference QFV scenario as shown in Table 1 in Ref. In this scenario, we contain large $c - t$ (charm-stop) mixings and large QFV trilinear couplings of squark-squark Higgs boson, and (ii) it satisfies the strong constraints on QFV from the B meson data, where charm [stop] is the supersymmetry (SUSY) partner of the charm [top] quark. In this scenario, the lightest up-type squarks $\tilde{u}_1$ and $\tilde{u}_2$ are strong mixtures of $\tilde{c}_1 - \tilde{t}_1 - h^0$, $\tilde{c}_2 - \tilde{t}_2 - h^0$, $\tilde{t}_1 - \tilde{t}_2 - h^0$ couplings) are large; therefore, $\tilde{u}_{1,2} - \tilde{u}_{1,2} - h^0$ couplings are large. This leads to an enhancement of the $\tilde{u}_{1,2} - \tilde{u}_{1,2} - \tilde{g}$-loop vertex correction to the decay amplitude of $h^0 \rightarrow c \bar{c}$ shown in Fig. 1, where $\tilde{g}$ is a gluino, which is a hypothetical supersymmetric partner of a gluon. Thus, this results in a large deviation of the MSSM prediction for the decay width $\Gamma(h^0 \rightarrow c \bar{c})$ from the SM prediction.

In Fig. 2, we show the contour plot of the deviation of the MSSM prediction from the SM prediction $\Gamma_{SM}(h^0 \rightarrow c \bar{c}) = 0.118$ MeV in the $\delta_{23}^{23} - \delta_{23}^{23}$ plane, where $\delta_{23}^{23}$ and $\delta_{23}^{23}$ are the $\tilde{c}_1 - \tilde{t}_1$ and $\tilde{c}_2 - \tilde{t}_2$ mixing parameters, respectively. We see that the MSSM prediction is very sensitive to the QFV parameters $\delta_{23}^{23}$ and $\delta_{23}^{23}$, and that the deviation of the MSSM prediction from the SM prediction can be very large (as large as $\sim 35\%$). We have found that the MSSM prediction becomes nearly equal to the SM prediction if we switch off all the QFV parameters in our reference QFV scenario.

The observation of any significant deviation of the decay width from its SM prediction indicates new physics beyond the SM. It is important to estimate the theoretical and experimental uncertainties of the width reliably in order to confirm such a deviation. The relative error of the SM width is estimated to be $\sim 6\%$. The relative error of the MSSM width is estimated to be $\sim 6\%$. As seen in Fig. 2, the deviation of the MSSM width from the SM width can be as large as $\sim 35\%$. Such a large deviation can be observed at a future $e^+ e^-$ collider ILC (International Linear Collider) with a CM energy 500 GeV and an integrated luminosity of 1600 fb$^{-1}$, where the expected experimental error of the width is $\sim 3\%$. A measurement of the width at LHC is a hard task because of the difficulties in charm-tagging.

In this report, we have shown that the full one-loop corrected decay width $\Gamma(h^0 \rightarrow c \bar{c})$ is very sensitive to the QFV parameters in the MSSM. In a scenario with large $c - t$ mixings, the width can differ up to $\sim 35\%$ from its SM value. After estimating the uncertainties of the width, we conclude that an observation of these MSSM QFV effects is possible at ILC. Therefore, we have a good opportunity to discover the QFV SUSY effect in this decay $h^0 \rightarrow c \bar{c}$ at ILC.

Fig. 1. Gluino-loop vertex correction to $h^0 \rightarrow c \bar{c}$.

Fig. 2. Contour plot of the deviation of the full one-loop level MSSM width $\Gamma(h^0 \rightarrow c \bar{c})$ from the SM width $\Gamma_{SM}(h^0 \rightarrow c \bar{c})$ for our reference QFV scenario.

References
Update on lattice QCD calculation of neutral $B$ meson mixing in static limit of $b$ quark

T. Ishikawa,*1 Y. Aoki,*2,*1 T. Izubuchi,*3,*1 C. Lehner,*3 and A. Soni,*3 for RBC Collaboration

The Cabibbo–Kobayashi–Maskawa (CKM) matrix is a key part of elementary particle physics, and constraints on the elements $V_{ts}$ and $V_{td}$ can be obtained from $B^0 - \bar{B}^0$ mixing, where highly nonperturbative hadronic weak matrix elements play an essential role. We perform simulations on this subject using static heavy quark as the treatment of $b$ quark.1)2) The final values of $B$ meson decay constants and mixing matrix elements and $\xi$ parameter in the static $b$ quark limit are summarized as

$$f_B = 218.8(6.5)_{\text{stat}}(16.1)_{\text{sys}} \text{ [MeV]}, \quad f_{B_s} = 263.5(4.8)_{\text{stat}}(18.7)_{\text{sys}} \text{ [MeV]}, \quad f_{B_s}/f_B = 1.193(20)_{\text{stat}}(35)_{\text{sys}},$$

$$f_B\sqrt{B_B} = 240(15)_{\text{stat}}(17)_{\text{sys}} \text{ [MeV]}, \quad f_{B_s}\sqrt{B_{B_s}} = 290(09)_{\text{stat}}(20)_{\text{sys}} \text{ [MeV]}, \quad \xi = 1.208(41)_{\text{stat}}(44)_{\text{sys}},$$

where statistical (stat) and systematic (sys) errors are given. In Fig. 1, the error budget is presented. Among the uncertainties presented in Fig. 1, a large portion of the error consists of statistical error, chiral extrapolation uncertainty, and renormalization uncertainty; it is thus important to reduce them to obtain more reliable results.

The first step in improving the current results is reducing the statistical errors using the All-Mode-Averaging (AMA) technique.3) This involves locating many source points in the measurement but using an approximation in obtaining quark propagators to greatly reduce computational cost. We show the preliminary results of the AMA calculation in Fig. 2 and compare them with the current results (without AMA). Although the AMA calculation is still ongoing, the presented error reduction is quite encouraging.

The systematic uncertainties involve chiral extrapolation and renormalization error. For the chiral extrapolation, we are currently focusing our effort on physical pion simulation, where we use RBC/UKQCD’s 2+1 flavor $48^3 \times 96$ domain-wall fermion ensemble. By this calculation, most of the chiral extrapolation uncertainty is removed. Currently, the renormalization error is large for non-ratio quantities because only one-loop perturbation is employed. We are, however, investigating a possibility of nonperturbative method for the matching using RI/MOM scheme and coordinate space method,4) where removing power divergence is essential to the existence of the static heavy quark.

Although the static limit is a good approximation for $b$ quark, it is known to have $O(\Lambda_{QCD}/m_b) \sim 10\%$ uncertainty. To obtain precise results, we need to remove or reduce this uncertainty systematically. The heavy quark expansion of a heavy-light quantity $\Phi_{hQ}$, which has a finite asymptotic limit as $m_Q \rightarrow \infty$, is written as

$$\Phi_{hQ}(1/m_Q) = \Phi_{hQ}(0) \exp \left[ \sum_{p=1}^{\infty} \gamma_p \left( \frac{\Lambda_{QCD}}{m_Q} \right)^p \right],$$

where $m_Q$ is the heavy quark mass, which is heavier than the QCD scale $\Lambda_{QCD}$. Our project finally includes simulations in light quark mass region (typically $c$ quark mass region) for obtaining expansion parameters $\gamma_p$. Combining the static result with the lighter quark mass enables us to obtain results with much less uncertainty, where our static limit results play a crucial role as a valuable “anchor point”.

References
Progress toward an *ab initio*, Standard Model calculation of direct CP-violation in K-decays

C. Kelly\textsuperscript{*1} for the RBC and UKQCD collaborations

Recent theoretical and computational advances in the field of lattice QCD have opened the door to an *ab initio* determination of $\epsilon'$, the measure of direct CP-violation in Standard Model $K \to \pi\pi$ decays. New sources of direct CP-violation are required to explain the observed matter-antimatter asymmetry in the Universe, and $\epsilon'$ is particularly sensitive to the contributions introduced by many Beyond the Standard Model theories. A comparison of the Standard Model value to the precisely measured experimental number may therefore provide evidence of new physics.

In $K \to \pi\pi$ decays, the final $\pi\pi$ state can have either isospin $I = 2$ or 0 and $\epsilon'$ manifests as a difference in the complex phases of the corresponding amplitudes, $A_2$ and $A_0$ respectively: $\epsilon' \propto \left( \frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right)$.

The RBC and UKQCD collaborations have successfully performed calculations of $A_2$ with 10% total errors\textsuperscript{1}, and only $A_0$ remains to be determined. This is significantly more difficult than $A_2$, firstly because the $\pi\pi$ state can mix with the vacuum, leading to disconnected diagrams in which the two pions annihilate and are recreated at a later time. Such diagrams are typically extremely noisy and require advanced techniques such as all-to-all (A2A) propagators. The second difficulty is in creating a $\pi\pi$ state that is degenerate with the kaon such that the decay occurs with physical kinematics. This requires the pions to be moving, necessitating the use of G-parity spatial boundary conditions\textsuperscript{2} (GPBC) to control the statistical noise.

Efficient use of GPBC and A2A introduces a large number of computational challenges that must be overcome. To this end, we developed parallel code highly optimized for the IBM Blue Gene/Q machines at ANL, ANL and Edinburgh University and have, to date, generated $O(100)$ independent measurements of the $K \to \pi\pi$ amplitude. The measurements were performed on a custom generated ensemble with a (4.6 fm$^3$, lattice spacing of $0.143$ fm lattice spacing. We use a three-flavor chiral action with degenerate up and down quarks and a physical strange quark.

With our chosen lattice parameters we obtain a measured pion mass of $m_\pi = 142.4(1.3)$ MeV and a kaon mass of $m_K = 489.9(2.4)$ MeV, very close to their physical values of 135 MeV and 495 MeV respectively. We use GPBC in all three spatial directions and obtain a $\pi\pi$ energy of $E_{\pi\pi} = 524(45)$ MeV, which agrees with the kaon mass within errors, suggesting a near-physical decay.

In Fig. 1 we plot the contributions to $A_0$ from the $Q_2$ and $Q_6$ operators, which respectively dominate $\text{Re}A_0$ and $\text{Im}A_0$. Here we use a $K \to \pi\pi$ time separation of 12, and fit to the plateau between $t = 4\text{--}8$; outside of this region the signal is contaminated by excited states. Our analysis also includes measurements with $K \to \pi\pi$ time separations of 10 and 14. Preliminary results from our current, somewhat limited, data set suggest a $\sim50\%$ statistical error on our result for $\text{Re}A_0$ and $\sim40\%$ for $\text{Im}A_0$. The error is almost completely dominated by the disconnected diagrams, despite our use of A2A methods, and can only be resolved with more statistics. We anticipate doubling the statistics within the next 6 months.

The systematic errors on our results are dominated by the discretization error and the error on the Wilson coefficients. The former arises because the measurement is performed on a single, coarse lattice, and is expected to be $O(20\%)$; in future calculations this can be removed by performing a continuum extrapolation over results computed at different lattice spacings. The Wilson coefficients are involved because we match the low-energy lattice calculation to the three-flavor Weak effective theory where the charm has been integrated out perturbatively; as the charm is comparatively light, it is not clear how reliable this is. We intend to study this by comparing $A_0$ computed using cheaper lattice calculations with stationary pions and both three and four dynamical flavors. Ultimately we intend to repeat the calculation with a dynamical charm quark.

References


---

\textsuperscript{*1} RIKEN Nishina Center, Brookhaven National Laboratory
Collisional Energy Loss in Semi-Quark Gluon Plasma

S. Lin,† R. D. Pisarski,*1,†2 and V. V. Skokov*3

Quantum chromodynamics (QCD) above the deconfinement temperature \( T_c \) is in quark gluon plasma (QGP) phase. The QGP produced in the relativistic heavy ion collider (RHIC) and large hadron collider (LHC) remains in a temperature window \( T \approx 2T_c \) for much of its lifetime. This is a regime where high-temperature perturbation theory becomes inappropriate. The regime is called semi-QGP, which is characterized by a non-trivial Polyakov loop. A matrix model with background color charges \( A_0^q \) has been proposed to describe the physics in the regime\(^1\)). The background color charges can be viewed as imaginary chemical potentials for quarks and gluons, which effectively suppress their number density as compared to high-temperature QGP. In this letter, we considered how the suppression of quark and gluon number density affects heavy-quark collisional energy loss in semi-QGP.

It is known that heavy quarks lose their energy by Coulomb scattering and Compton scattering, in which heavy quarks scatter off gluons and a light quarks respectively. Both processes contribute to total energy loss. The presence of background color charges suppresses light quark and gluon number densities differently, resulting in different suppression factors for energy loss corresponding to the two processes. For Coulomb scattering, we found that the energy loss per unit length, to the leading logarithmic order, is given by a \( Q \)-dependent factor \( S_q^q(Q) \) times the energy loss at \( Q = 0 \):

\[
\left. \frac{dE}{dx} \right|_Q \bigg|_q^k = S_q^q(Q) \left. \frac{dE}{dx} \right|_Q \bigg|_q^k .
\]

The energy loss, to the leading logarithmic order, at \( Q = 0 \) is as follows\(^2\):

\[
\left. \frac{dE}{dx} \right|_Q \bigg|_q^k \bigg|_{Q=0} = \frac{2}{9} \pi \alpha_s^2 T^2 N_f \ln \left( \frac{ET}{m_D^2} \right),
\]

where \( N_f \) and \( \alpha_s \) are respectively the number of light quark flavors and strong coupling constant. \( m_D \) is the gluon Debye mass. \( S_q^q(Q) \) is the infinite sum of traces of the Wilson loop \( \bar{L}_q \equiv \text{tr} e^{-i \int d^4x A_0^q} \bar{L}_q^\top \text{tr} A_0^q \):

\[
S_q^q(Q) = \frac{4}{\pi^2} \sum_{n=1}^{\infty} \frac{(-)^{n+1}}{n^2} \text{tr} \bar{L}_q^n .
\]

The energy loss from Compton scattering also factorizes to a \( Q \)-dependent factor and the energy loss at \( Q = 0 \) to leading logarithmic order.

\[
\left. \frac{dE}{dx} \right|_Q \bigg|_q^i = S_q^i(Q) \left. \frac{dE}{dx} \right|_Q \bigg|_{Q=0} .
\]

The energy loss at \( Q = 0 \) can be expressed as follows\(^2\):

\[
\left. \frac{dE}{dx} \right|_Q \bigg|_{Q=0} = \pi \alpha_s^2 T^2 \left( \frac{4}{3} \ln \left( \frac{ET}{m_D^2} \right) + \frac{8}{27} \ln \left( \frac{ET}{M^2} \right) \right),
\]

where \( M \) is the mass of heavy quark. \( S_q^i(Q) \) again involves an infinite sum of traces of the Wilson loop

\[
S_q^i(Q) = \frac{1}{8} \left( \frac{6}{27} \sum_{n=1}^{\infty} \frac{|\text{tr} \bar{L}_q^n|^2}{n^2} - 1 \right). \tag{6}
\]

Fig. 1. Suppression factors for Coulomb scattering \( S_q^q \) and Compton scattering \( S_q^i \).

The suppression factors \( S_q^q(Q) \) and \( S_q^i(Q) \) are both functions of temperature through \( Q \), whose temperature dependence is extracted from results of lattice simulation on Polyakov loop. Fig. 1 shows the plots of \( S_q^q(Q) \) and \( S_q^i(Q) \) versus \( T \). We found that Coulomb scattering and Compton scattering are significant suppressed as QGP approaches \( T_c \) from temperature above \( T_c \). It is also noteworthy that the suppression is much greater for Compton scattering than for Coulomb scattering.

References


2 RIKEN Nishina Center
3* Department of Physics, Western Michigan University

*1 Department of Physics, Western Michigan University
Entropic destruction of heavy quarkonium in non-Abelian plasma from the holographic correspondence†

K. Hashimoto*1,*2 and D. E. Kharzeev*3

The studies of heavy quarkonium at finite temperature are expected to advance the understanding of QCD plasma and to clarify the nature of the deconfinement transition. It was originally proposed1) to use the quarkonium suppression in heavy ion collisions as a way to detect the Debye screening in the quark-gluon plasma. The subsequent experimental studies of quarkonium production at different energies however revealed a puzzle—the charm quark-antiquark pair placed in the quark-gluon plasma. This entropy of the heavy quark-antiquark pair acts as an eyewitness of the black hole formation after a deconfinement transition. It is absent in the conformal $\mathcal{N} = 4$ super-symmetric Yang-Mills theory, but emerges in a confining Yang-Mills theory obtained by compactification of the fifth dimension. On the boundary, this entropy has to be attributed to long-range, delocalized excitations entangled with the heavy quark pair that can indeed be described as the “long string”.

The origin of this peak in the holographic description is intriguing—it arises because the heavy quark pair acts as an eyewitness of the black hole formation in the confining (at low temperatures) bulk geometry. This process of black hole formation is the dual holographic representation of the deconfinement transition on the boundary. From this viewpoint, the entropy associated with the quark-antiquark pair is the right quantity to detect the temperature at which the deconfinement occurs.

We also study the entropic force in holographic setup of strongly coupled gauge theories. It turns out that the entropic force associated with the distribution of the quarks is at a sub-leading order in the strong coupling expansion in terms of the 'tHooft coupling constant, while the entropic force of the QCD string is comparable to the quark-antiquark force. However a reasonable evaluation of the sub-leading term shows that the Einstein entropic force increases such that the critical distance of the quark pair to be destructed entropically is shortened.

Our proposal of using the entropy associated with the heavy quark-antiquark pair to detect the deconfinement transition is somewhat similar to the idea of using the entanglement entropy as an order parameter of deconfinement. The difference is that the order parameter discussed in is the von Neumann entanglement entropy of a spatial region with a boundary, while we consider the Gibbs entropy. In terms of the boundary theory, the entropy of the quark-antiquark pair likely emerges from the entanglement of a “long string” connecting the quark and antiquark with the rest of the system. It would be interesting to clarify this issue further as it may improve our understanding of both deconfinement and confinement.

References

† Condensed from the article in Phys. Rev. D90, 125012 (2014)

*1 RIKEN Nishina Center
*2 Department of Physics, Osaka University
*3 Department of Physics and Astronomy, Stony Brook University
Magnetic instability in AdS/CFT: Schwinger effect and Euler-Heisenberg Lagrangian of Supersymmetric QCD†

K. Hashimoto,*1,∗3 T. Oka,*2 and A. Sonoda*3

The renowned Schwinger effect1 creation process of electron-positron pairs in strong electric fields, is a big challenge in the field of non-linear quantum field theory. Although the Schwinger limit \( E \sim m_e^2 \) has not been reached by the direct experiments such as strong lasers, similar effective setups in materials are actively investigated. Theoretical foundation of the Schwinger effect was to evaluate the imaginary part of the effective action of QED under a constant electromagnetic field, the Euler-Heisenberg Lagrangian2 which dates back to 1936. The Euler-Heisenberg Lagrangian is a generating function of nonlinear electromagnetic responses of the vacuum. In its expression, the electric field couples to the magnetic field in a complicated and nonlinear manner, and the total effective Lagrangian is a starting point in the research of strong fields in QED, including the non-perturbative Schwinger effect.

In our previous paper3, two of the present authors derived an Euler-Heisenberg Lagrangian for a supersymmetric QCD in the strong coupling limit, by using the AdS/CFT correspondence but the Maxwell electric field is applied, a quark antiquark pair is created. The nontrivial part is the gluon interaction at strong coupling in QCD. The quarks are confined, and between the quark and the antiquark a confining force (a QCD string) is present to bind them. If the electric field is strong enough, the quarks are liberated. This truly nonperturbative process is of importance, not only because it can be a realistic phenomenon occurring in the universe, but also because it may be a touchstone for understanding the quark confinement.

There are at least two cases in which the QCD Schwinger effect may play an important role: First, the heavy ion collision experiment, and second, magnetars (neutron stars with a very strong magnetic field). In the heavy ion collisions, very strong electric fields are generated by the electric current induced by heavy ions passing by each other. Since the magnetic field is time dependent, there appears strong electric field as well, and it may be related to the formation of the quark gluon plasma. On the other hand, the quark and the antiquark a confining force (a QCD string) is present to bind them. If the electric field is strong enough, the quarks are liberated. This truly nonperturbative process is of importance, not only because it can be a realistic phenomenon occurring in the universe, but also because it may be a touchstone for understanding the quark confinement.

In the heavy ion collisions, very strong electric fields are generated by the electric current induced by heavy ions passing by each other. Since the magnetic field is time dependent, there appears strong electric field as well, and it may be related to the formation of the quark gluon plasma. On the other hand, magnetars are known to be the most dense place in the universe, and the strong magnetic field accompanied by some electric field can occur and affect the core structure of the stars, possibly having a quark phase inside. In these examples, the understanding of QCD and Schwinger effect in strong electric and magnetic fields can be tested by experiments/observations and serves as a playground at which we can test our theoretical knowledge on strongly coupled quantum field theories.

The result of Ref.3 is summarized as follows; The Euler-Heisenberg Lagrangian of strongly coupled \( \mathcal{N} = 2 \) supersymmetric QCD at large \( N_c \) limit was calculated in the presence of a constant electric field using the AdS/CFT correspondence. Its imaginary part explicitly evaluated is found to agree with large electric field expansion of the Schwinger effect of \( \mathcal{N} = 2 \) supersymmetric QCD (once the QCD string tension is replaced by the electron mass). However, there, only the electric field was considered. In this paper, we include the full dependence of the magnetic field, which is important as is obvious from the physical situations explained above.

Here we summarize the finding of the present paper:

- We obtain the Euler-Heisenberg Lagrangian of the \( \mathcal{N} = 2 \) supersymmetric QCD in a constant electromagnetic field, at strong coupling and large \( N_c \) limit.
- We evaluate the imaginary part of the Euler-Heisenberg Lagrangian, and find that the rate of the quark antiquark creation diverges at zero temperature for massless quarks.
- The divergent rate can be regularized, i.e., the vacuum is unstable but the lifetime becomes finite, by either introducing finite temperature or a quark mass.
- We compute the real part of the Euler-Heisenberg Lagrangian, and show the disappearance of Cotton-Mouton effect in an expansion with the electromagnetic field.
- The imaginary part of the Euler-Heisenberg Lagrangian for a small quark mass is shown to coincide with that of \( \mathcal{N} = 2 \) supersymmetric QED, at the leading order in electron mass. The agreement is found also for the real parts responsible for the Cotton-Mouton effect.

References
1) J. S. Schwinger, Phys. Rev. 82, 664 (1951).
2) W. Heisenberg and H. Euler, Z. Phys. 98, 714 (1936)
Turbulent meson condensation in quark deconfinement†

K. Hashimoto,*1,∗2 S. Kinoshita,*3 K. Murata,*4 and T. Oka*5

Quark confinement is one of the most fundamental and challenging problems in elementary particle physics, left unsolved. Although quantum chromodynamics (QCD) is the fundamental field theory describing quarks and gluons, their clear understanding is limited to the deconfined phase at high energy or high temperature limits due to the asymptotic freedom. We may benefit from employing a more natural description of the zero temperature hadron vacuum. A dual viewpoint of quark confinement in terms of the “fundamental” degrees of freedom at zero temperature - mesons, is a plausible option.

The mesons appear in families: they are categorized by their spin/flavor quantum numbers, as well as a resonant excitation level $n$ giving a resonance tower such as $\rho(770), \rho(1450), \rho(1700), \rho(1900), \cdots$. In this Letter we find a novel behavior of the higher meson resonances, i.e., mesons with large $n$. In the confined phase, when the deconfined phase is approached, we observe condensation of higher mesons. In this state, macroscopic number of the higher meson resonances, with a characteristic distribution, are excited. The condensed mesons have the same quantum number as the vacuum. The analysis is done via the anti-de Sitter space (AdS)/conformal field theory (CFT) correspondence, one of the most reliable tools to study strongly-coupled gauge theories. By shifting our viewpoint from quark-gluon to meson degrees of freedom, we gain a simple and universal understanding of the confinement/deconfinement transition, with a bonus of solving mysteries in black holes physics through the AdS/CFT.

The system we study is the $\mathcal{N} = 2$ supersymmetric $SU(N_c)$ QCD which allows the simplest AdS/CFT treatment. The deconfinement transition is induced by external electric fields. In static fields, the confined phase becomes unstable in electric fields stronger than the Schwinger limit $E = E_{\text{Sch}}$ beyond which quarks are liberated from the confining force. We find that this instability is accompanied by the condensation of higher mesons. A striking feature is revealed for the case of an electric field quench: The kick from the quench triggers a domino-like energy transfer from low to high resonant meson modes. This leads to a dynamical deconfinement transition even below the Schwinger limit. The transfer we find resembles that of turbulence in classical hydrodynamics as higher modes participate; thus we call it a “turbulent meson condensation” and suggest it being responsible for deconfinement. See Fig.1.

We remind that the $\mathcal{N} = 2$ theory is a toy model: The meson sector is confined and has a discrete spectrum while the gluon sector is conformal and is always deconfined. Here, we concentrate on the deconfinement of heavy quarks and not the gluons. Note that the mesons with low spins in this theory are described by a confining potential and an effective QCD string exists, whereby we define our “quark confinement”.

The higher meson resonances are naturally interpreted as long QCD strings, therefore our finding is consistent with interpreting deconfinement as condensation of QCD strings$^9$. Under the condensation, a quark can propagate away from its partner antiquark by reconnecting the bond QCD string with the background condensed strings. The gravity dual of the deconfined phase is with a black hole, so given the relation with long fundamental strings, our result may shed light on the issue of quantum black holes; In particular, our time-dependent analysis gives a singularity formation on the flavor D-brane in AdS, a probe-brane version of the Bizon-Rostworowski turbulent instability in AdS geometries$^3$.

References

Meson turbulence at quark deconfinement from AdS/CFT†

K. Hashimoto,*1,2 S. Kinoshita,*3 K. Murata,*4 and T. Oka*5

How the quarks are confined at the vacuum of quantum chromodynamics (QCD) is one of the most fundamental questions in the standard model of particle physics. We would like to find a universal feature of the deconfinement. To understand the nature of the quark confinement, we need a proper observable which exhibits a universal behavior irrespective of how we break the confinement. In this paper, we propose a universal behavior of resonant mesons and name it meson turbulence.

Following our previous paper1), we find that a particular behavior of resonant mesons (excited states of mesons) can be an indicator of the deconfinement. The meson turbulence is a power-law scaling of the resonant meson condensations. For the resonant meson level \( n = 1, 2, \cdots \), the condensation of the meson \((\varepsilon_n(x,t))\) with its mass \( \omega_n \) causes the \( n \)-th meson energy \( \varepsilon_n \) scaling as \( (\omega_n)^\alpha \) with a constant power \( \alpha \). This coefficient \( \alpha \) will be unique for a given theory, and does not depend on how one breaks the confinement. In particular, for the theory which we analyze in this paper, that is \( \mathcal{N} = 2 \) supersymmetric Yang-Mills as its gluon sector at large \( N_c \) at strong coupling, the universal power-law scaling parameter \( \alpha \) is found to be

\[
\langle \varepsilon_n \rangle \propto (\omega_n)^\alpha, \quad \alpha = -5,
\]

where \( \varepsilon_n \) is the energy of the \( n \)-th meson resonance. Normally, for example at a finite temperature, the energy stored at the \( n \)-th level of the resonant meson should be a thermal distribution, \( \varepsilon_n \propto \exp[-\omega_n/T] \). The thermal distribution is Maxwell-Boltzmann statistics, in which the higher (more massive) meson modes are exponentially suppressed. However, we conjecture that this standard exponential suppression will be replaced by a power-law near any kind of the deconfinement transitions. If we think of the meson resonant level \( n \) as a kind of internal momentum, then the energy flow to higher \( n \) can be regarded as a so-called weak turbulence. This is why we call the phenomenon meson turbulence, and the level \( n \) can be indeed regarded as a momentum in holographic direction in the AdS/CFT correspondence.

The reason we came to the universal power behavior is quite simple. We combined two well-known things,

- Mesons are excitations of an open QCD string.
- Deconfinement phase is described by a condensation of long strings.

Combining these two leads us to the conjecture that the deconfinement of quarks is indicated by a condensation of higher meson resonances. More precisely, we claim that the condensation should be turbulent: the higher mode condensation is not suppressed exponentially but behaves with a power-law.

We shall investigate various deconfining transitions in this paper, to check the universality of our conjecture of the meson turbulence. First, we work with a static case. A nonzero electric field is a good example since a strong electric field can make the quark-antiquark pair dissociate. Then we investigate time-dependent setup. The virtue of the AdS/CFT correspondence is that time-dependent analysis is possible, as opposed to lattice simulations of QCD. To demonstrate the universality of the meson turbulence, we work in two examples: (1) electric-field quench, and (2) quark-mass quench. In all cases, we find numerically the meson turbulence and the universal power law with the power \( \alpha = -5 \).

The universality we found in this paper strongly indicates that the meson turbulence is a universal phenomena which is independent of how one breaks the confinement.

References

---

1 Condensed from the article in arXiv:1412.4964
*1 RIKEN Nishina Center
*2 Department of Physics, Osaka University
*3 Osaka City University Advanced Mathematical Institute
*4 Keio University
*5 Department of Applied Physics, University of Tokyo

Fig. 1. A schematic picture of the deconfinement phase as condensation of QCD strings. Left: we add a meson (a pair of a quark and an anti-quark connected by a QCD string) to the system. Right: due to the background condensed QCD strings, the QCD string can be reconnected, and the quark can freely propagate away from the anti-quark.
Electromagnetic instability in holographic QCD†

K. Hashimoto,*1,∗3 T. Oka,*2 and A. Sonoda∗3

Schwinger effect(2) is one of the most interesting phenomena in particle physics. This is a phenomenon that a pair creation of charged particles occur under an external field such as an electromagnetic field. Schwinger obtained the creation rate of an electron positron pair by evaluating the imaginary part of Euler-Heisenberg Lagrangian(3), which is an effective Lagrangian for a constant electric field. This rate $\Gamma$ is derived as $\Gamma \sim \exp (-\pi m_e^2/eE)$ to leading order and has a form with a negative power in the gauge coupling $\epsilon$. So the Schwinger effect is a non-perturbative effect. Here, $m_e$ is the electron mass and $E$ is an electric field. A critical electric field necessary energy for the electron positron pair creation is $E_{cr} \sim m_e^2 c^3/\epsilon h$, and the strength is about $10^{18}$ [V/m]. So, it is a phenomenon which shows up only under strong electromagnetic fields.

Recently, we have seen advance in research on a strong electromagnetic field in both theoretical and experimental aspects of hadron physics. At the heavy ion collision in RHIC and LHC, it is expected that a strong magnetic field is generated by a collision of charged particles accelerated at about the speed of light.

Within the AdS/CFT framework, the quark pair creation rate in the strongly coupled $\mathcal{N} = 4$ supersymmetric Yang-Mills theory was obtained in(3). On the other hand, two of the present authors obtained the vacuum decay rate, which can be identified as the creation rate of quark-antiquark pairs, in $\mathcal{N} = 2$ supersymmetric QCD(SQCD) by using a different method(4) in AdS/CFT correspondence: the imaginary part of the probe D-brane action. D3-D7 brane system corresponds to $\mathcal{N} = 4$ supersymmetric $SU(N_c)$ Yang-Mills theory including an $\mathcal{N} = 2$ hypermultiplet in the fundamental representation of the $SU(N_c)$ gauge group. They obtained the creation rate of the quark antiquark in the $\mathcal{N} = 2$ SQCD under a constant electric field by evaluating the imaginary part of the D7-brane action. Then, the present authors evaluated the imaginary part of the D7-brane action including not only a constant electric field but also a constant magnetic field. The results in SQCD showed similarities with the creation rate of the electron positron pair in $\mathcal{N} = 2$ supersymmetric QED(SQED) in constant electromagnetic field.

In this paper, we study the quark antiquark pair creation in non-supersymmetric QCD at large $N_c$ at strong coupling, and the imaginary part of D8-brane action in a constant electromagnetic field. The holographic models are the Sakai-Sugimoto model(6) and its deformed version. Our findings in this paper are as follows:

- We derive the Euler-Heisenberg Lagrangian for confining gauge theories: the Sakai-Sugimoto model and the deformed Sakai-Sugimoto model. We obtain the creation rate of the quark antiquark pair under the electromagnetic field, by evaluating the imaginary part of the D-brane actions.
- The imaginary part is found to increase with the magnetic field parallel to the electric field, while it decreases with the magnetic field perpendicular to the electric field. So the vacuum instability strongly depends on the direction of the applied magnetic field relative to the electric field.
- We obtain a critical value of the electric field, i.e., the Schwinger limit, by using the condition that the D-brane action has the imaginary part.

As for the first part among above, a result with only an electric field was reported in Ref. 7. We analyze generic electric and magnetic fields in this paper.

References
1) J. S. Schwinger, Phys. Rev. 82 (1951) 664.
2) W. Heisenberg and H. Euler, Z. Phys. 98 (1936) 714 [physics/0605038].

† Condensed from the article in arXiv:1412.4254
*1 RIKEN Nishina Center
*2 Department of Applied Physics, University of Tokyo
*3 Department of Physics, Osaka University
Electric Field Quench in AdS/CFT†

K. Hashimoto,∗1,∗2 S. Kinoshita,∗3 K. Murata,∗4 and T. Oka∗5

In this paper, we analyze response of the strongly coupled gauge theory against an electric field quench, by using the AdS/CFT correspondence. The system is $\mathcal{N} = 2$ supersymmetric QCD with $\mathcal{N} = 4$ super Yang-Mills as a gluon sector, and has a confining spectrum for the meson sector (while the gluon sector is always deconfined). We turn on the electric field in a time-dependent manner, and find that the system develops to a deconfinement phase of mesons.

We study time-dependent behavior of various observables such as electric current carried by the quarks and the quark condensate. We define the thermalization time scale and the deconfinement time in terms of the gravity dual side: the thermalization is with the Hawking temperature, and the deconfinement is with the strong redshift.

Among our findings, the most interesting is the fact that the deconfinement transition of the mesons occurs even with a small electric field once it is applied time-dependently. In the static electric field, there exists a critical value of the electric field beyond which the electric current flows and the system is deconfined. In our time-dependent quench, if the quench is made sufficiently fast, even with a final electric field which is smaller than the critical value, the system goes to a deconfinement phase — there appears a strong red shift region in the gravity dual.

In the dual gravity picture, this phenomena can be understood as the D-brane version of the weakly turbulent AdS instability. The wave packet on the D-brane is getting sharp as time increases and, eventually, collapses into the naked singularity. Accordingly, we also found a curious behavior of the deconfinement time — the time scale when a strong redshift region appears on the D7-brane. The deconfinement time takes only discrete values.

Furthermore, the potential implication of the present study of nonequilibrium dynamics in QCD to strongly correlated electron system is suggestive. Then, it is tempting to speculate that the formation of naked singularity explained in the previous section is an indication of the “meson Mott transition”, i.e., the QCD version of the exciton Mott transition. We plot a schematic phase diagram obtained by this analogy in Fig. 1 with three regions (i), (ii), and (iii).

(i) Confinement phase with coherent oscillation. When the field is weak, the system is always in the confinement phase. However, when the ramp speed is fast (small $\Delta V$), the field induces a coherent oscillation of vacuum polarization due to meson excitation.

(ii) Transient deconfined state (“meson Mott transition”). This is the speculated “meson Mott transition” regime. When the meson amplitude becomes large, the confinement force becomes relatively weak due to screening. The quarks become liberated and deconfinement takes place in the meson (quark) sector.

(iii) Deconfined nonequilibrium phase above QCD Schwinger limit. When the electric field is stronger than the confining strength (= QCD Schwinger limit), the confinement phase becomes unstable against direct pair creation of quark and antiquarks.1) This state is a static nonequilibrium phase with finite current.

In summary, by studying the dynamics of supersymmetric QCD in strong electric fields, we observed many interesting, and universal nonequilibrium physics. Our finding implies similarities between possible formation mechanism of quark gluon plasma in heavy ion collision experiments to laser induced phase transitions in condensed matter, which helps us understand the physics more deeply.

References

† Condensed from the article in JHEP 1409 (2014) 126

∗1 RIKEN Nishina Center
∗2 Department of Physics, Osaka University
∗3 Osaka City University Advanced Mathematical Institute
∗4 Keio University
∗5 Department of Applied Physics, University of Tokyo

Fig. 1. Schematic "dynamical phase diagram" of states realized in the present study by a static electric field $E_f$ following an initial ramp (parametrized by the time parameter $\Delta V$). See text for details.
Holographic entanglement and causal shadow in the time-dependent Janus black hole†

Y. Nakaguchi,∗1,∗2 N. Ogawa,∗3 and T. Ugajin∗4

The relation between entanglement and the black hole interior has been attracting attention recently. For eternal AdS black holes, some interior information is captured by the entanglement entropy of an interval on the dual theory, i.e., a thermofield doubled CFT1).

In some kinds of black holes, the interior appears even more difficult to access since they have “causal shadow” regions inside. In this work, we consider one such black hole, called the three-dimensional time-dependent Janus black hole2),

\[
ds^2 = L^2 \left[ dy^2 + \frac{r_0^2}{g(y)^2 \cosh^2 r_0 t} (-dt^2 + d\theta^2) \right],
\]

\[
\hat{g}(y) = \sqrt{\frac{2}{1 + \sqrt{1 - 2\gamma^2 \cosh 2y}}},
\]

where \( \gamma \) is a deformation parameter from the BTZ black hole. This is a solution of the Einstein-scalar theory and it corresponds to a pair of two entangled 2D CFTs, whose coupling constants are different from each other.

This geometry has a horizontally extended Penrose diagram as shown in Fig. 1. The remarkable property of this geometry is the existence of a so-called “causal shadow region,” which is causally inaccessible from both boundaries.

We studied the time-evolution of the same entanglement entropy in this system in a holographic manner, by using the Ryu-Takayanagi formula. As in the BTZ black hole, there are two candidate extremal surfaces in the bulk, whose area gives the entanglement entropy. One of the extremal surfaces, which we call the connected surface, connects two asymptotic boundaries and probes the black hole interior. The other extremal surface, which we call the disconnected surface, localizes near each of the asymptotic boundaries.

In the Janus black hole, when the deformation from the BTZ black hole is not so large, we found a similar behavior but with the critical time \( t_c \) shorter than that of the BTZ black hole. Roughly speaking, this is because the deformation makes the wormhole region longer and results in a longer connected surface. The results for the time evolution of the entanglement entropy of each phase are plotted in Fig. 2.

In addition, we also found that with a sufficiently large deformation, the disconnected surface is always dominant, and that the holographic entanglement entropy is already proportional to the size of the subsystem from the initial time. This means that the entanglement entropy of this subsystem does not probe the black hole interior.

\[
A(t, \theta = 5)
\]

Fig. 2. The time \( t \) dependence of the extremal surface area \( A \) for a subsystem \( \theta = 5 \), in the disconnected phase (black dotted line, numerically obtained) and in the connected phase (gray line).

References
Radion stabilization in the presence of Wilson line phase†

Y. Abe,*1 T. Inami,*2,3 Y. Kawamura,*1 and Y. Koyama*4

In a higher-dimensional gravity theory, a scalar field \( \phi \) called “radion” appears in the extra-dimensional graviton components, and its vacuum expectation value is related to the size of the extra space. The stabilization of the radius is crucial for the solution to the hierarchy problem in the Randall-Sundrum model†1 and inflation based on the radion†2. The stabilization is realized by the quantum effects of a graviton and fermions in a 5D model \( M_4 \times S^{1,3} \).

In a higher-dimensional gauge theory, the extra-dimensional components of gauge bosons are massless at the tree level because of gauge invariance, and their zero modes become dynamical degrees of freedom called the Wilson line phases \( \theta \) and are stabilized by quantum corrections†4. There is a possibility that realistic gauge symmetries including the standard model ones survive after the stabilization of the Wilson line phases. The Wilson line phase receives finite radiative corrections in its mass and can play the role of the Higgs boson†5, providing a solution to the gauge hierarchy problem. An inflation model has been proposed based on the idea that the Wilson line phase becomes the inflaton†6.

We investigate how the Wilson line phase and the Casimir energy from various bulk fields are involved in the stabilization of the radion in a different setup. Particularly, we study the stabilization of the extra-dimensional radius of \( S^1 \) in the presence of a Wilson line phase of the extra \( U(1) \) gauge symmetry in 5D space-time with a flat background metric and without branes, by using the effective potential \( V \) for \( \phi \) and \( \theta \) at the one-loop level.

Our model consists of the 5D graviton \( \hat{g}_{MN} \), a \( U(1) \) gauge boson \( B_M \), \( c_1 \) charged fermions \( \psi_i \) (\( i = 1, \cdots, c_1 \)), and \( c_2 \) \( U(1) \) neutral fermions \( \eta_l \) (\( l = 1, \cdots, c_2 \)). We take \( M^4 \times S^1 \) as the background 5D space-time and impose periodic boundary conditions on every field. We obtain the one-loop potential

\[
V(\phi, \theta) = -\frac{6}{\pi^2} \frac{1}{\phi^2} L_4^\pi C(5) + c_2 \frac{3}{\pi^2} \frac{1}{\phi^2 L_4} \left[ L_5 \left( e^{-L_\mu \phi^{1/3}} \right) + L_\mu \phi^{1/3} L_4 \left( e^{-L_\mu \phi^{1/3}} \right) + \frac{1}{3} L^2 \mu^2 \phi^{2/3} L_3 \left( e^{-L_\mu \phi^{1/3}} \right) \right]
\]

\[
+ c_1 \frac{3}{\pi^2} \frac{1}{\phi^2 L_4} \text{Re} \left[ L_5 \left( e^{-L_m \phi^{1/3}} e^{i\theta} \right) + L_m \phi^{1/3} L_4 \left( e^{-L_m \phi^{1/3}} e^{i\theta} \right) + \frac{1}{3} L^2 m^2 \phi^{2/3} L_3 \left( e^{-L_m \phi^{1/3}} e^{i\theta} \right) \right],
\]

where \( L, m \) and \( \mu \) are the compactification circumference, the mass of the charged fermions and the neutral fermions, respectively. The potential has a finite minimum in the presence of neutral fermions the number \( c_2 \) of which is larger than \( c_1 + 2 \) and the radion is stabilized at a certain finite value of \( \phi \). A typical shape of \( V(\phi, \theta) \) is depicted in Fig. 1. From this figure, we see that the true minimum of the potential is located on the line \( \theta = \pi \). The values of \( \phi \) and the potential at the minimum depend on the parameters \( m, \mu \) and \( L \). Their values do not drastically modify the shape of the potential drastically.

In this work, we investigated the behavior of the potential for both large and small values of the radion and found that the potential does not have a finite minimum in the case with only charged fermions as matter fields. The radion stabilization is realized in the presence of neutral fermions whose number is larger than the number of charged ones by two.

The remaining subject is the application of our potential \( V(\phi, \theta) \) to an inflation model. By identifying the extra-dimensional scalar component of the 5D gauge field and/or the scalar component of the 5D metric as the inflaton, we examine whether the potential reproduces realistic inflation parameters. The radion properties differ from those of the Wilson line phase.

† Condensed from the article in PTEP 2014 7, 073B04(2014).
*1 Department of Physics, Shinshu University
*2 RIKEN Nishina Center
*3 Department of Physics, National Taiwan University
*4 Department of Physics, National Tsing Hua University

References
Is cosmological constant screened in Liouville gravity with matter?

T. Inami, Y. Koyama, Y. Nakayama, and M. Suzuki

Recent observation of dark energy in our universe has led to the conviction that the cosmological constant \( \Lambda \) has an infinitesimal positive value. It means that our space-time is de Sitter (dS) space with the Hubble constant \( H \) being \( \sqrt{\Lambda} \). It has been proposed that the strong infrared (IR) divergence property of quantum corrections on dS space may explain the smallness of \( \Lambda \) in our current universe (so called cosmological constant problem). The Einstein equation describes the relation between the space-time Ricci tensor \( R_{\mu\nu} \) and the energy momentum (EM) tensor \( T_{\mu\nu} \) due to the presence of matter. In vacuum, where \( T_{\mu\nu} \) is proportional to the metric, the Einstein equation takes the form

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda_{\text{eff}} = 0, \quad \Lambda_{\text{eff}} = \Lambda - \frac{\kappa}{D} T^\rho_\rho, \quad (1)
\]

where \( R \) is the scalar curvature, \( \kappa = 8\pi G \) with \( G \) being Newton’s constant. The vacuum contribution of \( T_{\mu\nu} \) is now combined with \( \Lambda \) to define the effective cosmological constant \( \Lambda_{\text{eff}} \).

In view of this expression, we may wonder if a large value of \( \Lambda_{\text{eff}} \) cancels the large value of \( \Lambda \), yielding a very small value of \( \Lambda_{\text{eff}} \) that we observe today.\(^1\) We study this question in 2-dimensional (2D) Liouville gravity.

We are interested in the dS solution of Liouville gravity, which can describe the interaction between scalar field and gravity. The 2D cosmological constant has two components: the coupling of the Liouville potential and the trace of the EM tensor. By using Weyl transformation to 2D metric \( g_{\mu\nu}(g_{\mu\nu} = e^{2\phi} \hat{g}_{\mu\nu}) \), we obtain the equation,

\[
S_{L+\text{max}}[\Phi, \phi] = -\int d^2x \sqrt{-\hat{g}} \left[ \frac{1}{4\pi b^2} \hat{g}^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi + \frac{Q}{4\pi b} \hat{R} \Phi \right. \\
\left. + \frac{\Lambda}{\kappa} e^{2\phi} + \frac{1}{2} \hat{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + e^{2\Phi} V(\phi) \right]. \quad (2)
\]

The first three terms are Liouville gravity. At this point, it is important to note that the negative value of \( \Lambda \) corresponds to dS space in Liouville gravity.

As a concrete matter Lagrangian, we have studied a massless scalar field theory with \( \lambda \phi^4 \) interaction minimally coupled to Liouville gravity,

\[
L = -\frac{1}{2} \hat{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \sqrt{-\hat{g}} - \frac{1}{4!} \lambda \phi^4 \sqrt{-\hat{g}} + \Delta L, \quad (3)
\]

where \( \Delta L \) consists of counter-terms. In dS space, the massless scalar propagator contains IR divergence in the long wavelength limit and the IR logarithm appears because the cutoff regularization of the IR divergence. Based on the in-in formalism, we have computed the VEV of the EM tensor to the order of \( \lambda^2 \).

\[
\Lambda_{\text{eff}} \sim \Lambda + (\text{Weyl anomaly}) + \frac{\kappa \lambda}{32\pi^2} \ln^2 \eta \alpha(\eta) \quad + \frac{1}{8\pi(4\pi)^2 H_t^4} \ln^4 \alpha(\eta), \quad (4)
\]

where \( \alpha = -\frac{1}{\pi} \) is the scale factor and \( \eta = -\frac{1}{\eta} e^{-H_t t} \) is conformal time. The resulting VEV has time dependence through the IR logarithms, and as a consequence, the effective cosmological constant shows the screening effect at late time such that the absolute value decreases with time. This should be in contrast with the situations where \( D > 2 \), in which the cosmological constant is anti-screened in the \( \lambda \phi^4 \) theory.\(^5\)

To claim that the observed dS breaking effects are physical, we need to find whether they may be eliminated from the local counter-terms. Here, we discuss rather unfamiliar time-dependent IR counter-terms. This possibility plays a crucial role to understand the (in)equivalence between the Sine-Gordon model and the massive Thirring model in dS space. We are indeed able to recover the dS invariance by adding time-dependent IR counter-terms to the naive perturbative computations using the dS breaking propagator. Within the perturbation theory we have studied, however, a similar mechanism does not seem to be workable in \( \lambda \phi^4 \) theory. This fact supports the claim that the observed screening mechanism of the cosmological constant should be physical. This sensitive issue will be further discussed in our future publication.

References

Effective Higgs interactions of composite dark matter†

E. T. Neil*1,+2 for the LSD Collaboration

The recent discovery of the Higgs boson has placed significant and direct constraints on models which predict new physics near the electroweak scale. At the same time, recent dark matter direct-detection experiments have greatly improved their sensitivity, pushing into the region of parameter space where dark matter interacts with the standard model through exchange of a Higgs boson.

These new constraints are particularly interesting in the context of composite dark matter models (e.g.1). In such a model, the lightest stable bound state of a strongly-coupled gauge sector provides a dark matter candidate. Although the bound state itself must be net electroweak neutral due to direct-detection experimental constraints, its constituents may carry electroweak charges; the resulting interactions with the standard model in the early universe can explain the observed dark matter abundance, while scattering from present-day direct detection experiments is through suppressed higher-dimensional operators3).

If the dark gauge interaction spontaneously breaks a continuous symmetry, then some of the bound states will be massless Nambu-Goldstone bosons, which are ruled out by experiment if they are electroweak charged. A realistic composite dark matter model thus requires a mechanism for mass generation of the constituents. In most models the constituents are fermions, and they can be given mass through the Higgs mechanism; depending on the assignment of charges, “vector-like” mass terms may also be allowed3). The Higgs couplings required for mass generation are directly constrained by direct-detection experiment, in terms of the Higgs coupling of the dark matter bound state itself.

We consider for concreteness a model consisting of an SU(4) dark gauge force, and a set of degenerate fermions $m_f$ carrying electric charge $Q = \pm 1/2$. The dark matter candidate is a neutral baryon-like bound state of four such fermions, and has total mass $m_B$. The coupling of the Higgs boson to this baryon-like state is given by the formula

$$g_{h,B} = \frac{m_B}{v} \left( \sum_f \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h} \right) f_f^{(B)}$$

(1)

where $v = 246 \text{ GeV}$ is the vacuum expectation value of the Higgs field. The factor $f_f^{(B)}$ contains the scalar matrix element of the fermions inside the baryon-like state, $\langle B|\bar{f}f|B \rangle$. This matrix element can be extracted using the Feynman-Hellmann theorem from the slope of the baryon mass, $\partial m_B/\partial m_f$, this is a non-perturbative quantity, and is calculated using lattice simulations of the SU(4) theory. We find $0.15 \lesssim f_f^{(B)} \lesssim 0.34$ in the range of fermion masses simulated.

Finally, the term in parentheses,

$$\alpha = \frac{v}{m_f} \frac{\partial m_f(h)}{\partial h} \bigg|_{h=v}$$

(2)

is entirely model-dependent, and parameterizes the fraction of the fermion mass $m_f$ which is generated due to the Higgs mechanism; if there are no “vector-like” mass terms, then $\alpha = 1$. The current upper bound on $\alpha$ in this model, based on our lattice calculation of $f_f^{(B)}$ and the latest experimental results from LUX4), is shown in Fig. 1. For the entire range of models considered, this constraint is significantly less than 1, indicating that generation of $m_f$ in this model requires more than the Higgs mechanism alone.

References

† Condensed from the article in Phys. Rev. D89, 094508 (2014)
*1 RIKEN Nishina Center
*2 Department of Physics, University of Colorado, Boulder
Effective field theory for spacetime symmetry breaking†

Y. Hidaka,*1 T. Noumi,*1 and G. Shiu†2,*3

Symmetry and its spontaneous breaking play an important role in various areas of physics. In particular, the low-energy effective field theory (EFT) based on the underlying symmetry structures provides a powerful framework for understanding the low-energy dynamics in the symmetry broken phase.

For internal symmetry breaking in Lorentz invariant systems, the EFT based on coset construction had been established in 1960’s1,2). When a global symmetry group $G$ is broken to a residual symmetry group $H$, the corresponding Nambu-Goldstone (NG) fields $\pi(x)$ are introduced as the coordinates of the coset space $G/H$ and the general effective action can be constructed from the Maurer-Cartan one form,

$$J_\mu = \Omega^{-1} \partial_\mu \Omega \quad \text{with} \quad \Omega(x) = e^{i \pi(x)} \in G/H.$$ (1)

Such a coset construction was also extended to spacetime symmetry breaking3,4) accompanied by the inverse Higgs constraints5) and has been applied to various systems. Although the coset construction captures certain aspects of spacetime symmetry breaking, its understanding seems incomplete compared to the internal symmetry case.

For example, a naive counting of broken spacetime symmetries based on the global symmetry picture contains redundant fields and causes a wrong counting of NG modes. For conformal symmetry breaking, it is known that the inverse Higgs constraints compensate such a mismatch of NG mode counting. It is also argued recently that the inverse Higgs constraints eliminate not only the redundant fields but also the massive modes, which nonlinearly transform under the broken symmetries (see, e.g., 6–8)). In addition to the massless modes, such massive modes associated with the symmetry breaking can be relevant in the construction of phenomenological models (e.g. massive fields with a Hubble scale mass are nonnegligible in cosmology).

In this work, we discussed the effective field theory for spacetime symmetry breaking from the local symmetry point of view. By gauging spacetime symmetries, the identification of NG fields and the construction of the effective action are performed based on the breaking pattern of diffeomorphism, local Lorentz, and (an)isotropic Weyl symmetries as well as the internal symmetries including possible central extensions in nonrelativistic systems. Such a local picture distinguishes, e.g., whether the symmetry breaking condensations have spins and provides a correct identification of the physical NG fields, while the standard coset construction based on global symmetry breaking does not. We illustrated that the local picture becomes important in particular when we take into account massive modes associated with symmetry breaking, whose masses are not necessarily high.

We also revisited the coset construction for spacetime symmetry breaking. Based on the relation between the Maurer-Cartan one form and connections for spacetime symmetries, we classify the physical meanings of the inverse Higgs constraints by the coordinate dimension of broken symmetries. Inverse Higgs constraints for spacetime symmetries with a higher dimension remove the redundant NG fields, whereas those for dimensionless symmetries can be further classified by the local symmetry breaking pattern.

We are now working on several applications of our approaches for spacetime symmetry breaking. For example, there are some recent discussions that inhomogeneous chiral condensations may appear in the QCD phase diagram. Using our EFT framework, we discuss the dispersion relation of the NG field in such a phase. Another ongoing application is inflation. We are e.g. trying to classify the source of primordial gravitational waves (which potentially affect the B-mode polarization of cosmic microwave backgrounds) by the symmetry breaking point of view. We hope to report those applications in near future.

References
4) V. I. Ogievetsky, Proc. of X-th Winter School of Theoretical Physics in Karparcz 1, 117 (1974).

† Condensed from the article in arXiv:1412.5601.
*1 RIKEN Nishina Center
*2 Department of Physics, University of Wisconsin, Madison
*3 Center for Fundamental Physics and Institute for Advanced Study, Hong Kong University of Science and Technology
Dynamical breaking of shift-symmetry in supergravity-based inflation†

A. Mazumdar,*1 T. Nouni,*2 and M. Yamaguchi*3

The observations of the cosmic microwave background (CMB) temperature anisotropies1,2) now strongly support the occurrence of primordial inflation in the early Universe. The observed temperature anisotropy can be well fitted by the primordial perturbations generated during inflation and the auto-correlation of the temperature (T) and E-mode polarization has been stretched on superhorizon scales1,2). In addition, very recently, BICEP2 reported the detection of the primordial tensor perturbations through the B-mode polarization as3)

\[ r = 0.20^{+0.07}_{-0.05} \ (68\% \text{CL}), \] (1)

where \( r \) is the tensor-to-scalar ratio. To explain this large tensor-to-scalar ratio is challenging for cosmology and particle physics because of the Lyth bound4): one would expect a super-Planckian excursion of the inflaton field in order to generate large \( r \).

Generally speaking, the super-Planckian excursion of the inflaton is problematic from the effective field theory (EFT) point of view. In particular, within string theory there are many scales, the string scale, \( M_s \), the compactification scale, \( M_c \) and the derived 4 dimensional Planck scale, with a spectrum, \( M_s \leq M_c \leq M_P \). Beyond \( M_s \) there are quantum corrections not only to the inflaton potential but also to the inflaton kinetic term which can lead to various complications. Even if we assume that we have only one fundamental scale, such as \( M_p \), there are many issues pertaining to the validity of an EFT when the field’s VEV goes beyond \( M_p \). In principle, a gauge singlet inflaton can couple to many degrees of freedom, including the Standard Model and the hidden sector degrees of freedom. Typically, the individual inflaton’s couplings to matter has to be smaller than \( 10^{-3} \) to maintain the flatness of the inflaton potential and also to match the density perturbations created during inflation.

In spite of all these challenges, we wish to ask the question - whether can we explain at least a such small inflaton couplings to matter, and large inflaton’s VEV during inflation within an EFT approach by invoking some symmetry such as shift-symmetry, \( \phi \to \phi' = \phi + c \), where \( \phi \) is the inflaton and \( c \) is a constant. Within EFT, one has to ensure that the inflaton’s and all other field’s kinetic terms are small, and here we simply assume so in some patch of the Universe just to be within the EFT regime. Such a shift-symmetry has been for the first time introduced in the context of chaotic inflation in supergravity (SUGRA)5,6). However, based on the same token if shift-symmetry remains unbroken inflation would never occur in our patch of the universe. The shift-symmetry has to be broken, but in such a way that the breaking remains soft, which could be understood via some dynamics of the fields. A hard breaking can be introduced5,6), but the predictions can be lost or one has to resort to some anthropic arguments.

The purpose of this work is to illustrate a concrete model of dynamical shift symmetry breaking. We showed that it is indeed possible to break the shift-symmetry dynamically within 4 dimensional supergravity prior to a long phase of inflation. Thanks to the shift-symmetry, the leading contribution to the inflaton potential is free from the dangerous exponential factor even after its breaking, which is the main obstacle to realizing the super-Planckian inflation in supergravity. In our simple mode, the resulting effective inflaton potential schematically takes the form \( V_{\text{eff}}(\phi_{\text{inf}}) \sim \cos \frac{\phi_{\text{inf}}}{\mu} \) with \( \mu \) being the dynamical symmetry breaking scale. This potential can induce an inflationary epoch with the inflaton excursion \( \Delta \phi_{\text{inf}} \sim \mu \). Unfortunately, in this model, it is difficult to realize the super-Planckian inflation \( \Delta \phi_{\text{inf}} > M_P \) as long as the dynamical symmetry breaking scale \( \mu \) is sub-Planckian. We hope to extend our simple model to realize the super-Planckian inflation, in near future.

References

---

*1 Physics Department, Lancaster University
*2 RIKEN Nishina Center
*3 Department of Physics, Tokyo Institute of Technology
Non-Gaussianities of primordial perturbations and tensor sound speed†

T. Noumi†1 and M. Yamaguchi†2

Inflation is now widely accepted as a paradigm of early Universe to explain the origin of the primordial perturbations as well as to solve the horizon and the flatness problems of the standard big-bang cosmology. The current observational data such as the cosmic microwave background (CMB) anisotropies support almost scale-invariant, adiabatic, and Gaussian primordial curvature fluctuations as predicted by inflation. While the paradigm itself is well established and widely accepted, its detailed dynamics, e.g. the identification of an inflaton, its kinetic and potential structure, and its gravitational coupling, are still unknown.

The non-Gaussianities of primordial curvature perturbations are powerful tools to give such informations. For example, it is well-known that the equilateral type of bispectrum of primordial curvature perturbations is enhanced by the inverse of their sound speed squared \(^1,2\). The null observation of the equilateral type by the Planck satellite, characterized as \(f^\text{NL}_{\text{equi}} = 42 \pm 75\) (68% CL),\(^3\), yields stringent constraints on the sound speed of the curvature perturbations as \(c_s \geq 0.02\) (95% CL).\(^3\)

Inflation generates not only primordial curvature perturbations but also primordial tensor perturbations \(^4\). Very recently, it was reported that primordial tensor perturbations have been found and the tensor-to-scalar ratio \(r\) is given by \(r = 0.20^{+0.07}_{-0.05}\) (68% CL)\(^5\), though it is constrained as \(r < 0.11\) (95% CL) in the Planck results\(^6\). Their amplitude directly determines the energy scale of inflation, so it is estimated as \(V^{1/4} \simeq 2.2 \times 10^{18}\) GeV given \(r \simeq 0.23\) and \(P_s \simeq 2.2 \times 10^{-9}\)\(^5\). If we go beyond the powerspectrum, it is known that the bispectra of primordial tensor perturbations enable us to probe the gravitational coupling of the inflaton field\(^7\). Such a non-trivial gravitational coupling easily modifies the sound speed of primordial tensor perturbations, \(c_s\), and it can significantly deviate from unity\(^8\). Then, one may wonder if the small sound velocity of primordial tensor perturbations can enhance their non-Gaussianities as in the case of the curvature perturbations. In this work, we addressed this issue.

The relation between the sound speed and the non-Gaussianities of primordial curvature perturbations can be clearly understood by use of the effective field theory (EFT) approach to inflation\(^9\). Inflation can be characterized by the breakdown of time-diffeomorphism invariance due to the time-dependent cosmological background and the general action for inflation can be constructed based on this symmetry breaking structure. The primordial curvature perturbation can be identified with the Goldstone mode \(\pi\) associated with the breaking of time-diffeomorphism invariance. The symmetry arguments require that modification of the sound speed \(c_s\) induces non-negligible cubic interactions of the Goldstone mode \(\pi\), and hence the sound speed and the bispectrum of the curvature perturbations are directly related.

In this work, we investigated the relation between the sound speed of tensor perturbations and the bispectrum of primordial perturbations, based on the EFT approach. We first identified what kind of operators can modify the tensor sound speed. Then, we clarify which type of non-Gaussianity arises associated with the modification and can be used as a probe for the tensor sound speed. We found that the tensor sound speed is not directly related to tensor bispectra, in contrast to the scalar sound speed case. We also discussed primordial trispectra as a possible probe of tensor sound speed.

References

1) D. Seery and J. E. Lidsey, JCAP 0506, 003 (2005) [astro-ph/0503692].

† Condensed from the article in arXiv:1403.6065.
†1 RIKEN Nishina Center
†2 Department of Physics, Tokyo Institute of Technology
Spin operator and entanglement in quantum field theory

K. Fujikawa,*1 C.H. Oh,*2 and C. Zhang*2

Entanglement is studied in the framework of Dyson’s S-matrix theory in relativistic quantum field theory, which leads to a natural definition of entangled states of a particle-antiparticle pair and the spin operator from a Noether current. As an explicit example, the decay of a massive pseudo-scalar particle into an electron-positron pair is analyzed. Two spin operators are extracted from the Noether current. The Wigner spin operator characterizes spin states at the rest frame of each fermion and, although not measurable in the laboratory, gives rise to a straightforward generalization of the low energy analysis of entanglement to the ultra-relativistic domain. In contrast, if one adopts a (modified) Dirac spin operator, the entanglement measured using spin correlation becomes maximal near the threshold of the decay, while the entanglement is replaced by the classical correlation for the ultra-relativistic electron-positron pair by analogy to the case of neutrinos, for which a hidden-variables-type description is possible. Entanglement in this sense depends on the energy scale involved. Chiral symmetry which is fundamental in particle physics differentiates the spin angular momentum and the magnetic moment. The use of weak interaction, which can measure helicity, is suggested in the analysis of entanglement at high energies instead of a Stern-Gerlach apparatus, which is known to be useless for the electron. A difference between the electron spin at high energies and the photon linear polarization is also noted.

We formulate the entanglement in the framework of relativistic quantum field theory, or more precisely, in the S-matrix theory defined by Dyson.1 In the S-matrix theory, we treat only asymptotic states that contain particles far apart from each other.

We consider the decay of a very massive pseudo-scalar particle $P$ into an electron-positron pair by an interaction Hamiltonian, $H_I(t) = g \int d^3x : P(x)\bar{\psi}(x)\gamma_5\psi(x) :$ with a coupling constant $g$. The Dyson formula for the S-matrix gives the state $\Psi = -ig \int d^3x : P(x)\bar{\psi}(x)\gamma_5\psi(x) : |P(\bar{0})\rangle$, where we assume a small $g$. We then obtain for the fixed momentum direction of the electron,

$$\Psi(\vec{p}) \equiv \frac{1}{\sqrt{2}}[a^\dagger(\vec{p}, s)b^\dagger(-\vec{p}, -s) + a^\dagger(\vec{p}, -s)b^\dagger(-\vec{p}, s)]|0\rangle.$$ 

This shows a way to prepare a desired state in the framework of local and causal relativistic field theory. All the properties of the asymptotic state are accounted for in the framework which is consistent with locality, causality and the uncertainty principle; in particular, it is important to recognize that we integrate over the entire Minkowski space in defining $\Psi$; that is, we have no information about when and where the particle decayed.

**Spin Operator**

The conserved angular momentum operator (Noether charge) of the Dirac action is given by $\vec{J} = \int d^3x : \psi^\dagger(x)[\vec{L} + \vec{S}]/(x) :$, which is written as

$$\int d^3p \sum_{s,s'} \frac{1}{2} \{\xi(s')\vec{a}\xi(s)a^\dagger(\vec{p}, s')a(\vec{p}, s) - \xi(-s)\vec{a}\xi(-s')b^\dagger(\vec{p}, s')b(\vec{p}, s)\} + \int d^3p \sum_s (a^\dagger(\vec{p}, s) \left(\vec{L}_a(\vec{p}, s)\right) + b^\dagger(\vec{p}, s) \left(\vec{L}_b(\vec{p}, s)\right)).$$

The first term is called the Wigner spin operator, which is not directly measured in the laboratory. We instead define the (modified) Dirac spin operator

$$\tilde{\vec{S}}(\vec{p}) = \sum_{s,s'}\left\{\frac{1}{2} m \xi^\dagger(s')\vec{a}\xi(s) + \frac{1}{2} \vec{p}\xi^\dagger(s)(\vec{a}\cdot\vec{p})\xi(s)\right\} \times a^\dagger(\vec{p}, s')a(\vec{p}, s) - \frac{1}{2} m \xi^\dagger(-s')\vec{a}\xi(-s) + \frac{1}{2} \vec{p}\xi^\dagger(-s)(\vec{a}\cdot\vec{p})\xi(-s') \times b^\dagger(-\vec{p}, s')b(-\vec{p}, s),$$

which is close to what is measured in the laboratory. A salient feature of this spin is that it approaches the helicity state proportional to the momentum direction $\vec{p}$ for $E \to \infty$. That is, the spin correlation at high energies becomes similar to the correlation of neutrinos. The spin correlation of two neutrinos, which can have only two states $h = \pm$, does not define the entanglement in the conventional sense. That is, the high energy electron states behave like classical particles, which show the correlation but not entanglement. This transition to helicity states may be measured using weak interactions.2

References
Hardy proposed a characterization of entanglement that does not use inequalities by EPR-type arguments. It is however disturbing that his scheme, which is intended as a measure of entanglement, completely fails for the maximally entangled case,1

The local hidden-variables model in $d = 4 = 2 \times 2$ dimensions of the Hilbert space is defined by2)

$$\langle \psi | a \sigma \otimes b \sigma | \psi \rangle = \int \rho(\lambda) d\lambda a(\psi, \lambda)b(\psi, \lambda),$$  \hspace{1cm} (1)

where $a$ and $b$ are 3-dimensional unit vectors, $\sigma$ stands for the Pauli matrix, and $a(\psi, \lambda)$ and $b(\psi, \lambda)$ are dichotomous variables assuming the eigenvalues $\pm 1$ of $a \sigma$ and $b \sigma$, respectively. One can show that this local hidden-variables model does not satisfy the linearity of the quantum mechanical probability measure in the sense $$\langle \psi | a \sigma \otimes b \sigma | \psi \rangle + \langle \psi | a \sigma \otimes b' \sigma | \psi \rangle = \langle \psi | a \sigma \otimes (b + b') \sigma | \psi \rangle$$ for non-collinear $b$ and $b'$. If the linearity of the probability measure is strictly imposed, which is tantamount to asking that the non-contextual hidden-variables model in $d = 4$ gives the CHSH inequality $|B| \leq 2$ uniquely,3 it is shown that the hidden-variables model can describe only separable quantum mechanical states4)

$$\langle \psi | a \sigma \otimes b \sigma | \psi \rangle = \int \rho_1(\lambda_1) d\lambda_1 a(\psi, \lambda_1) \times \int \rho_2(\lambda_2) d\lambda_2 b(\psi, \lambda_2).$$  \hspace{1cm} (2)

In this case, it is shown that Hardy’s model becomes trivial. Although Hardy’s paradox is interesting as an experimental test of local realism, its mathematical basis is less solid than hitherto assumed.

**Hardy’s model**

Hardy defines the projection operators1

$$\hat{U}_i = | u_i \rangle \langle u_i |, \quad \hat{D}_i = | d_i \rangle \langle d_i |,$$  \hspace{1cm} (3)

with $i = 1, 2$, and

$$| u_i \rangle = \frac{1}{\sqrt{\alpha + \beta}} \left[ \beta \sqrt{1/2}|+\rangle_i + \alpha \sqrt{1/2}|-\rangle_i \right],$$  \hspace{1cm} (4a)

$$| d_i \rangle = \frac{1}{\sqrt{\alpha^2 + \beta^2}} \left[ \beta \sqrt{3/2}|+\rangle_i - \alpha \sqrt{3/2}|-\rangle_i \right]$$  \hspace{1cm} (4b)

for the entangled state $| \psi \rangle = \alpha|+\rangle_1|+\rangle_2 - \beta|\rangle_1\rangle_2$ with $\alpha^2 + \beta^2 = 1$.

He then shows the relations

$$\frac{\langle \psi | \hat{U}_1 \hat{U}_2 \hat{D}_1 | \psi \rangle}{\langle \psi | \hat{D}_1 | \psi \rangle} = 1,$$  \hspace{1cm} (5)

$$\frac{\langle \psi | \hat{U}_2 \hat{D}_1 \hat{D}_2 | \psi \rangle}{\langle \psi | \hat{D}_2 | \psi \rangle} = 1,$$  \hspace{1cm} (6)

$$\frac{\langle \psi | \hat{D}_1 \hat{D}_2 \hat{D}_1 | \psi \rangle}{\langle \psi | \hat{D}_1 | \psi \rangle} = 1 - \frac{\alpha\beta}{(1 - \alpha\beta)},$$  \hspace{1cm} (7)

$$\langle \psi | \hat{U}_1 \hat{U}_2 | \psi \rangle = 0,$$  \hspace{1cm} (8)

with $0 < \alpha \beta \leq 1/2$.

In the hidden-variables model, the projection operators are assigned their eigenvalues; for example, $\hat{D}_1(\psi, \lambda) = 1$ or 0, depending on the hidden-variable $\lambda$. Relation (7) implies $\int d\lambda \rho(\lambda) \hat{D}_1(\psi, \lambda) \hat{D}_2(\psi, \lambda) \neq 0$ for $0 < \alpha \beta < 1/2$ and thus

$$\hat{D}_1(\psi, \lambda) = 1 \text{ and } \hat{D}_2(\psi, \lambda) = 1$$  \hspace{1cm} (9)

for some $\lambda$, while (8) implies $\int d\lambda \rho(\lambda) \hat{U}_1(\psi, \lambda) \hat{U}_2(\psi, \lambda) = 0$ and thus

$$\hat{U}_1(\psi, \lambda) \hat{U}_2(\psi, \lambda) = 0$$  \hspace{1cm} (10)

for all $\lambda$. On the other hand relations (5) and (6) imply

$$\hat{D}_1(\psi, \lambda) = 1 \Rightarrow \hat{U}_2(\psi, \lambda) = 1,$$  \hspace{1cm} (11a)

$$\hat{D}_2(\psi, \lambda) = 1 \Rightarrow \hat{U}_1(\psi, \lambda) = 1,$$  \hspace{1cm} (11b)

respectively, where $\Rightarrow$ means "inevitably implies".

For the entangled state with $0 < \alpha \beta < 1/2$, except $\alpha \beta = 1/2$, which implies the maximum entanglement, the relations (9)-(11) are inconsistent.1 This is called Hardy’s paradox, which shows the inconsistency of local realism with entanglement except for the maximally entangled case without referring to inequality.

On the other hand, for a pure state, Bell’s theorem $|B| \leq 2$ with $B = a \sigma \otimes (b + b') + \sigma \otimes (b - b') - \sigma$ for any $a$, $a'$, $b$, and $b'$ implies5 relation (2), namely, the separable state. The separable state in Hardy’s model, which is consistent with local realism, implies $\alpha = 1$ and $\beta = 0$, for example, for which $| \psi \rangle = |+\rangle_1 |+\rangle_2$ while $\hat{U}_1 = |+\rangle_1 \langle+| \rangle_2$ and $\hat{D}_1 = |+\rangle_1 \langle+| \rangle_2$. In this case,

$$\langle \hat{U}_1 \rangle = \langle \hat{U}_2 \rangle = \langle \hat{D}_1 \rangle = \langle \hat{D}_2 \rangle = 0,$$  \hspace{1cm} (12)

and all the correlations vanish; thus, Hardy’s model becomes mathematically trivial. Hardy’s model is inconsistent with local realism by construction.

References
2) J. S. Bell: Physics 1, 195 (1965).
SSD and the infinite circumference limit of CFT†

T. Tada∗1

Among all the Virasoro generators of Conformal Field Theory (CFT), three of them, \( L_0, L_1 \) and \( L_{-1} \), form a subalgebra that is isomorphic to \( \mathfrak{sl}(2, \mathbb{R}) \) and corresponds to the global conformal transformation. The Casimir operator of the subalgebra can be expressed as

\[
C_2 = L_0^2 - L_1^2 - L_{-1}^2,
\]

where

\[
L_+ = \frac{L_1 + L_{-1}}{2}, \quad L_- = \frac{L_1 - L_{-1}}{2i}.
\]

In analogy with the 2+1 dimensional Lorentz transformation, the space spanned by \( L_0, L_+ \) and \( L_- \) is apparently divided into three distinctive regions. The first region is the “time-like” region that contains \( L_0 \) and small perturbations around it. Any vector within this region can be transformed to \( L_0 \) up to some numerical multiplication, by the global conformal transformation or the \( \mathfrak{sl}(2, \mathbb{R}) \). This is actually the region one would have in mind, when one demanded the invariance of the vacuum on the basis of the physical equivalence for the states connected by the global conformal transformation. The second is the “space-like” region, which contains the linear combination of \( L_+ \) and \( L_- \). The region between these two is the last one, and could be called the “light-cone” region. This region is represented by either \( L_0 - L_+ \) or \( L_0 - L_- \).

If one further invokes the analogy with the Lorentz geometry, the “time-like” region corresponds to the “massive” representation. Since one observes the spectrum of \( L_0 \) in this region, the “mass” in this case should be the inverse of the circumference, or the finite scale of CFT1,2). Then, it is natural to induce that the “light-cone” region corresponds to the “massless” representation and the infinite circumference. In this letter, we will argue that if one takes the generator in the “light-cone” region, say \( L_0 - L_+ \) (plus anti-holomorphic part \( L_0 - L_- \), to be exact), as a Hamiltonian, one can obtain a CFT with the infinite circumference.

Should we adopt a generator that corresponds to \( L_0 - L_+ \) as a Hamiltonian, we can define the following conserved charges:

\[
\mathcal{L}_\kappa \equiv \frac{1}{2\pi i} \oint_{\text{const.}} dz (-\frac{1}{2}(z - 1)^2) e^{\frac{\pi i}{\kappa} T(z)},
\]

where \( T(z) = T_{zz}(z) \) is the energy momentum tensor of the original CFT. Note that for \( \kappa = 0 \)

\[
\mathcal{L}_0 = \frac{1}{2\pi i} \oint_{\text{const.}} dz (-\frac{1}{2}(z - 1)^2) T(z)
\]

One can further calculate the commutation relations among the charges defined above using the operator product expansion of the energy momentum tensor

\[
T(z)T(w) \sim \frac{c/2}{(z-w)^2} \frac{2T(w)}{z-w} + \frac{\partial w T(w)}{z-w} + \cdots.
\]

The result reads

\[
[\mathcal{L}_\kappa, \mathcal{L}_{\kappa'}] = (\kappa - \kappa') \mathcal{L}_{\kappa + \kappa'} + \frac{c}{12} \kappa^3 \delta(\kappa + \kappa').
\]

We have thus obtained the continuous Virasoro algebra with the central charge \( c \), establishing that we have the theory that exhibits the continuous spectrum. This is consistent with the argument presented at the beginning.

This also nicely explains the feature observed in the phenomena called sine-square deformation (SSD) at least for the case that involves CFT. It was found 3–6 that a certain class of quantum systems, systems with closed and open boundary conditions, have identical vacua provided that the coupling constants of the open-boundary system are modulated in a specific way. In particular, SSD works for two-dimensional conformal field theories and it’s implications for string theory were discussed by the present author7,8). SSD for CFT adopts exactly (4) as the (holomorphic part of ) Hamiltonian. At that time, it had been somewhat enigmatic that these two systems with different boundary conditions share the same vacuum state, but this can be explained through the discovery of the continuous spectrum for the SSD system. Because the continuous spectrum suggest that SSD system has an infinitely large space, the distinction between the open and closed condition at the ends that located at infinitely away, is no longer physically relevant.

References

*1 RIKEN Nishina Center
Towards $U(N|M)$ knot invariant from ABJM theory

B. Eynard*1,*2 and T. Kimura*1,*3

The knot invariant can be realized using the Wilson loop operator in Chern–Simons gauge theory. Especially for the invariant for unknot and torus knot, there exists an integral representation analogous to the $U(N)$ symmetric matrix model. Recently it was pointed out that the partition function of ABJM theory on $S^3$ can be written as a supermatrix integral.

Thus the integral representation for the unknot Wilson loop in ABJM theory is now written as a supermatrix integral.

\[
\begin{align*}
Z &= \frac{1}{N!^2} \int [dx]^N [dy]^N \det_{1 \leq i,j \leq N} \left( \frac{1}{2 \cosh \frac{x_i - y_j}{2}} \right)^2,
\end{align*}
\]

where $[dx] = \frac{dx}{2\pi} e^{-\frac{1}{2\pi} x^2}$ and $[dy] = \frac{dy}{2\pi} e^{-\frac{1}{2\pi} y^2}$ with the string coupling constant $g_s = 2\pi i/k$.

In this expression the Wilson loop operator in the representation $R$ is given by the corresponding character of $U(N|M)$ group, $W_R \to \text{Str}_R U(x; y)$ with the holonomy matrix $U(x; y) = \text{diag}(e^{x_1}, \ldots, e^{x_N}, -e^{y_1}, \ldots, -e^{y_N})$. When the partition $\lambda$, corresponding to the representation $R$, satisfies $\Lambda_{N+1} > N$, this character is decomposed into that for $SU(N)$ which is written in terms of the Schur function,

\[
\text{Str}_R U(x; y) = s_{\lambda}(e^x) s_{\gamma}(e^y) \prod_{i,j=1}^N (e^{x_i} - e^{y_j}),
\]

where $\mu_i = \lambda_{i+N}^t$ and $\nu_i = \lambda_{i+N}$. We consider this case in particular. Thus the integral representation for the unknot Wilson loop in ABJM theory is now written

\[
\begin{align*}
\langle W_R(K_{\text{unknot}}) \rangle = \int [dx]^N [dy]^N \det_{1 \leq i,j \leq N} \left( \frac{1}{2 \cosh \frac{x_i - y_j}{2}} \right)^2 \prod_{i=1}^N e^{x_i, y_i, \eta_i, \xi_i} \eta_i, \xi_i.
\end{align*}
\]

with $\xi_i = \lambda_i - i + 1/2$, $\eta_i = \lambda_i^t - i + 1/2$. We can compute this integral by applying the Fourier transform formula $1/\cosh w = \int \frac{dz}{2\pi} e^{2i\omega z/\pi} / \cosh z$.

\[
\begin{align*}
\langle W_R(K_{\text{unknot}}) \rangle &= k^{-N} q^{\frac{N}{2} C_2(\mu) - C_2(\nu)} \times \prod_{1 \leq i,j \leq N} \left( q^{\frac{1}{2}(\xi_i + \eta_i)} + q^{-\frac{1}{2}(\xi_i + \eta_i)} \right),
\end{align*}
\]

where the parameter is defined as $q = e^{g_s}$ and $C_2(\lambda) = \sum_{\lambda} \left( (\lambda_1 + i + \frac{1}{2})^2 - (-i + \frac{1}{2})^2 \right)$ is the second Casimir operator, corresponding to the framing factor. This shows that the $U(N|M)$ character average is factorized into that for $U(1|1)$ theory. This kind of property is called Giambelli compatibility.

In order to see the connection to the ordinary knot invariant in $U(N)$ from the determinantal expression (4), it is convenient to rewrite as follows,

\[
k^{-N} q^{\frac{N}{2} C_2(\mu) - C_2(\nu)} \prod_{1 \leq i,j \leq N} \left( q^{\frac{1}{2}(\xi_i + \eta_i)} + q^{-\frac{1}{2}(\xi_i + \eta_i)} \right)^{-1} \times \prod_{1 \leq i,j \leq N} \left( q^{\frac{1}{2}(\xi_i - \xi_j)} - q^{-\frac{1}{2}(\xi_i - \xi_j)} \right) \left( q^{\frac{1}{2}(\eta_i - \eta_j)} - q^{-\frac{1}{2}(\eta_i - \eta_j)} \right).
\]

The last two factors coincide with the Wilson loop average in $U(N)$ theory, which is given by the quantum dimension of the representation $R$, up to the normalization constant.

The integral formula shown above can be generalized to the situation for the torus knot, which is labeled by two coprime integers $(P, Q)$. In this case the partition function is slightly modified

\[
\begin{align*}
Z_{(P,Q)} &= \frac{1}{N!^2} \int [dx]^N [dy]^N \det_{1 \leq i,j \leq N} \left( \frac{1}{2 \cosh \frac{x_i - y_j}{2}} \right)^2 \det_{1 \leq i,j \leq N} \left( \frac{1}{2 \cosh \frac{x_i - y_j}{2}} \right).
\end{align*}
\]

We can show this torus knot partition function is just given by the symplectic transform of the original unknot partition function. Thus it can be shown that they are related in a simple way, $Z_{(P,Q)} = (PQ)^N Z_{(1,1)}$. Since there exists the $U(N|M)$ character, written in terms of the Schur function, $s_{\lambda}^R(u; v) = \sum_{\mu} c_{\lambda, \mu} s_{\mu}(u; v)$, as well as the ordinary $U(N)$ theory, finally the torus knot Wilson loop average can be expressed as a linear combination of that for the fractionally framed unknot,

\[
\begin{align*}
\langle W_R(K_{P,Q}) \rangle = \sum_{\nu} e^{\nu} \langle W_R(K_{1,f}) \rangle
\end{align*}
\]

with the framing number $f = Q/P$. This is just a supersymmetric version of the Rosso–Jones formula for the torus knot invariant.

References

Duality and integrability of supermatrix model with external source

T. Kimura*1,*2

In quantum field theory, in order to compute correlation functions, it is convenient to introduce the generating function by adding an extra source term. Such a generating function is defined in the sense of path integral, and thus it is quite difficult to compute in general. However, in the matrix model, just a zero dimensional theory, a number of methods for computation are established, which are also applicable to the model with the external source. In this report we generalize the duality of the matrix model with the external source. In this report we generalize the theory, a number of methods for computation are established, which is originally found in the Gaussian matrix model,1) to the supermatrix model with an arbitrary matrix potential.

The correlation function of the characteristic polynomial average is given by

\[ \Psi_{N,M;p,q} = \int dZ \, e^{-i S_{\text{tr}} W(Z)} \prod_{j=1}^{N} \text{Sdet}(\lambda_j - Z) \prod_{j=1}^{M} \text{Sdet}(\mu_j - Z) \] (1)

where \( Z \) is a size \( N + M \) Hermitian supermatrix, and the external source is \( C = \text{diag}(a_1, \ldots, a_N, b_1, \ldots, b_M) \). This formula includes several useful situations, e.g., the ordinary characteristic polynomial average (\( M = q = 0 \)), the average of inverses (\( M = p = 0 \)), and the ratio average (\( M = 0 \)). Therefore it provides a master formula for the characteristic polynomial average in various matrix models.

The measure in the integral is invariant under the supergroup transformation, \( dZ = d(UZU^{-1}) \) with \( U \in U(N|M) \), which is expressed in terms of eigenvalues, \( dZ = \Delta_{N,M}(x,y) 2^{N} x^{M} dU \). Here the Jacobian is given by the Cauchy determinant,

\[ \Delta_{N,M}(x,y) = \prod_{i<j}(x_i - x_j) \prod_{i<j}(y_i - y_j) \prod_{i,j}(x_i - y_j) . \] (2)

Then, to compute the integral, we now introduce the Harish-Chandra–Itzykson–Zuber formula for the supergroup \( U(N|M)^{F,T} \)

\[ \int_{U(N|M)} dU \, e^{S_{\text{tr}} Z U U^{-1}} = \frac{\text{det} e^{x_{i a_i}} \text{det} e^{-y_{j b_j}}}{\Delta_{N,M}(x,y) \Delta_{N,M}(a;b)} . \] (3)

Applying this formula, we obtain the following expression for the matrix integral in terms of eigenvalues

\[ \Psi_{N,M;p,q} = \int dX \, dY \, e^{-i \int W(x_i) + \int W(y_j) + x_i a_i - y_j b_j} \times \frac{\Delta_{N+p,M+q}(x,\lambda;y,\mu)}{\Delta_{N,M}(a;b)\Delta_{p,q}(\lambda;\mu)} . \] (4)

Since the Cauchy determinant can be written as a determinant

\[ \Delta_{N,M}(x;y) = \det \left( \frac{x_i^{k-1}}{(x_i - y_j)^{-1}} \right) \] (5)

with \( i = 1, \ldots, N, j = 1, \ldots, M, k = 1, \ldots, N = M \), if \( N \geq M \), we obtain the determinant formula for the characteristic polynomial average

\[ \Psi_{N,M;p,q} \left( \{a_j\}_{j=1}^{N}, \{b_j\}_{j=1}^{M}; \{\lambda_j\}_{j=1}^{p}, \{\mu_j\}_{j=1}^{q} \right) \]

\[ = \frac{1}{\Delta_{N,M}(a;b)\Delta_{p,q}(\lambda;\mu)} \det \left( \begin{array}{cc} Q_{1-k}(a_i) & P_{k-1}(\lambda_i) \\ R(a_i; b_j) & S_{R}(\lambda_i; b_j) \end{array} \right) 
\frac{1}{\Delta_{N,M}(a;b)\Delta_{p,q}(\lambda;\mu)} \det \left( \begin{array}{cc} Q_{1-k}(a_i) & P_{k-1}(\lambda_i) \\ R(a_i; b_j) & S_{R}(\lambda_i; b_j) \end{array} \right) , \] (6)

where we have introduced auxiliary functions:

\[ P_{i-1}(x) = x^{i-1}, \quad \tilde{R}(x;y) = \frac{1}{x - y}, \] (7)

\[ Q_{i-1}(a) = \int dx \, P_{i-1}(x) e^{-\frac{i}{\lambda(x)} W(x) + x a} , \] (8)

\[ R(a;b) = \int dy \, \tilde{R}(x;y) e^{-\frac{i}{\lambda(y)} W(x) + x a - y b} , \] (9)

\[ S_{L}(\lambda;a) = \int dx \, \frac{1}{x + \mu} e^{-\frac{i}{\lambda(x)} W(x) + x a} , \] (10)

\[ S_{L}(\lambda;b) = \int dy \, \frac{1}{\lambda + y} e^{\frac{i}{\lambda(y)} W(y) - y b} . \] (11)

The formula (6) actually shows a duality between the external source and the characteristic polynomial, which is just given by Laplace (Fourier) transforms,

\[ \Psi_{N,M;p,q} \left( \{a_j\}_{j=1}^{N}, \{b_j\}_{j=1}^{M}; \{\lambda_j\}_{j=1}^{p}, \{\mu_j\}_{j=1}^{q} \right) \]

\[ \overset{F,T}{=} \Psi_{p,q,N,M} \left( \{\lambda_j\}_{j=1}^{p}, \{\mu_j\}_{j=1}^{q}; \{\alpha_j\}_{j=1}^{N}, \{\beta_j\}_{j=1}^{M} \right) . \] (12)

This is because the auxiliary functions transform to each other through the Fourier transformation:

\[ P_{i-1}(x) \leftrightarrow Q_{i-1}(a), \quad R(x;y) \leftrightarrow R(a;b), \quad S_{L}(\lambda;b) \leftrightarrow S_{R}(\alpha;a). \]

References
Bulk angular momentum and Hall viscosity in chiral superconductors†

A. Shitade*1 and T. Kimura*2,†

Chiral superfluids and superconductors (SCs) are exotic states whose time-reversal symmetry is spontaneously broken and Cooper pairs carry nonzero angular momentum (AM). There is a long-standing problem on the AM in chiral ℓ-wave SCs, the so-called intrinsic AM paradox, which is summarized as \( L_z = \hbar m N_0 / 2 \times (\Delta_0 / E_F)^\gamma \), where \( |m| \leq \ell \), \( N_0 \), \( \Delta_0 \), \( E_F \), \( \gamma \) are the magnetic quantum number, the total number of electrons, the gap strength, the Fermi energy, and the exponent characterizing the dependence on the SC gap. \( \gamma = 0 \) is the most natural if all electrons from Cooper pairs with the AM \( \ell_z = \hbar m \). On the other hand, \( \gamma = 1 \) is intuitively plausible if a electrons near the Fermi surface from Cooper pairs. One of the obstacles is that the physical quantities involving the position operator are ill defined in periodic systems, and we have to manage an inevitable divergence in the bulk limit. An interesting clue to the AM is the Hall viscosity (HV), which has been intensively discussed in the context of the quantum Hall effect. The important relation \( m_1 = \hbar N_0 \delta / 2 \) holds in general gapped systems at zero temperature, in which the orbital spin \( \delta \) is equal to \( \ell^2 / 2 \) in chiral ℓ-wave SCs. In this report, we derive the Berry-phase formulas for the AM and the Hall viscosity (HV) to apply to chiral SCs in two and three dimensions, which allow us to deal with the bulk systems.

We examine an angular velocity from the gauge-theoretical viewpoint. Now that the system is rotated, we have to deal with a theory in a curved spacetime. We use the Cartan formalism, consisting of two gauge potentials, a vielbein and a spin connection. Since we are now interested in the orbital AM, we do not consider the spin connection corresponding to the internal AM for simplicity. A vielbein \( h^a \) is a gauge potential corresponding to local spacetime translations, while a spin connection is that corresponding to local Lorentz transformations. The spatial component of a vielbein is related to a displacement vector. Since a vielbein is a gauge potential, it induces a field strength called torsion,

\[
T^l_{j0} = \partial_j h^l_0 - \partial_0 h^l_j, \quad T^l_{ij} = \partial_i h^l_j - \partial_j h^l_i.
\]

The former is “electric.” The first term describes an angular velocity if \( l \) and \( j \) are antisymmetric, while the second term describes a strain-rate tensor if symmetric. On the other hand, the latter is “magnetic” characterizing edge and screw dislocations in crystals.

Based on this formalism, we derive the momentum polarization, at zero temperature in a gapped fermion system,

\[
P_k^i = \sum_{\text{occ}} \frac{d^3\pi}{(2\pi\hbar)^3} \pi_k^i A_n^{\pi^i} \tag{2}
\]

where \( \pi \) is the momentum, the summation is taken over the occupied states, the Berry connection is given by \( A_n^{\pi^i} = i\hbar \langle \partial_{n\pi^i} | \partial_{n\pi^i} u_{n\pi} \rangle \), and \( u_{n\pi} \) is the Bloch eigenstate. Then the AM is obtained by the antisymmetric part of the momentum polarization,

\[
L_k = \epsilon_{ijk} P^{ji} = \sum_{\text{occ}} \frac{d^3\pi}{(2\pi\hbar)^3} \epsilon_{ijk} A_n^{\pi^i} \pi^j \tag{3}
\]

Since the Berry connection is regarded as the expectation value of the position operator in the Wannier basis, this Berry-phase formula really indicates \( \vec{L} = \vec{x} \times \vec{p} \) in the momentum space.

Here we define the nonsymmetric viscosity by \( \eta_k^{ij} = \frac{1}{\hbar} \epsilon^{ijm} \sum_{\text{occ}} \frac{d^3\pi}{(2\pi\hbar)^3} \pi_k \pi_l \Omega_{n\pi^m} f_{n\pi} \),

\[
\eta_k^{ij} = \frac{1}{\hbar} \epsilon^{ijm} \sum_{\text{occ}} \frac{d^3\pi}{(2\pi\hbar)^3} \pi_k \pi_l \Omega_{n\pi^m} f_{n\pi} \tag{4}
\]

where \( f_{n\pi} = f(\epsilon_{n\pi} - \mu) \) is the Fermi distribution function and the Berry curvature is defined by \( \Omega_{n\pi k} = i\hbar^2 \epsilon_{ijk} \left( \partial_{n\pi^i} u_{n\pi} \partial_{n\pi} u_{n\pi} \right) \). The proper HV is obtained as its symmetric part. Especially in two dimensions, the antisymmetric part yields

\[
\eta_{\pi} = \frac{1}{4\hbar} \sum_{\text{occ}} \frac{d^2\pi}{(2\pi\hbar)^2} \pi^2 \Omega_{n\pi^m} f_{n\pi} \tag{5}
\]

These expressions are quite analogous to that for the Hall conductivity, corresponding to the charge transport. The integrand just differs in the factor of \( \pi \).

By applying these formulas to the Bogoliubov–de Gennes system, we obtain the AM for gapped chiral SCs at zero temperature

\[
L_z = -\hbar \sum_k (\vec{A}_k \times \vec{k})_z = \hbar m N_0 / 2 \tag{6}
\]

which is consistent with \( \gamma = 0 \), and shows the relation to the HV, \( L_z = 2\eta_{\pi} \). See, for example, for the recent microscopic studies suggesting \( \gamma = 0 \).3)

References

† Condensed from the article in Phys. Rev. B90 134510 (2014)
*1 Department of Physics, Kyoto University
*2 Institut de Physique Théorique, CEA Saclay
*3 RIKEN Nishina Center
7. Astrophysics and Astro-Glaciology
Assessments of climate sensitivity to projected greenhouse gas concentrations underpin environmental policy decisions, with such assessments often based on model simulations of climate during recent centuries and millennia\textsuperscript{1-3)}. These simulations depend critically on accurate records of past aerosol forcing from global-scale volcanic eruptions, reconstructed from measurements of sulphate deposition in ice cores\textsuperscript{4-6)}. Non-uniform transport and deposition of volcanic fallout mean that multiple records from a wide array of ice cores must be combined to create accurate reconstructions. Here we re-evaluated the record of volcanic sulphate deposition using a much more extensive array of Antarctic ice cores. In our new reconstruction, many additional records have been added and dating of previously published records corrected through precise synchronization to the annually dated West Antarctic Ice Sheet Divide ice core\textsuperscript{7)}, improving and extending the record throughout the Common Era. Whereas agreement with existing reconstructions is excellent after 1500, we found a substantially different history of volcanic aerosol deposition before 1500; for example, global aerosol forcing values from some of the largest eruptions (for example, 1257 and 1458) previously were overestimated by 20–30\% and others underestimated by 20–50\%.

References

\textsuperscript{†} Condensed from the article in Nature Climate Change 4, 693–697 (2014)
Variation in chemical composition induced by solar energetic particle events in the middle atmosphere

Y. Nakai,*1 Y. Motizuki,*1 M. Maruyama,*1 H. Akiyoshi,*2 and T. Imamura*2

Recently, the influences of super solar flares on the earth environment have been extensively investigated. One of the areas of focus in such investigations is the change of chemical composition in the terrestrial atmosphere induced by energetic particles generated in the super solar flares. The bombardment of solar energetic particles (SEPs) to the atmosphere is called an SEP event, where a large amount of X-rays, gamma-rays, protons, and heavier ions from the surface of the sun intrude the terrestrial atmosphere. In particular, high-energy protons come down into the stratosphere and induce dissociation of nitrogen molecules followed by an increase of odd nitrogen oxides (NOx) and reactive odd nitrogen species (NOy). Consequently, the increase of NOx and NOy affects the ozone concentration over a period longer than SEP events.

We have performed simulations to investigate variation in chemical composition in SEP events by solving a large number of rate equations for the concentrations of chemical species in air.1) We adopt 77 chemical species including ions and about 480 chemical reactions (ionic reaction processes, neutral reactions, photolysis, etc.) in the present simulation. A large number of ionic processes, including recombination in the stratosphere, were treated for the first time, to the best of our knowledge. No transport processes are taken into account. This model is referred to as the Box-model hereafter. We carried out calculations using commercial software for solving complex chemical reaction systems (FACSIMILE, MCPA Software Ltd).

In order to estimate the yields of prompt products by the SEP protons, we used the G-values (amount of products per absorbed energy of 100 eV) investigated by radiolysis studies2,3), based on the assumption that the prompt product yields are determined only by the energy deposit of the SEP protons in air. The prompt products are assumed to be charged products (positive atomic ions, positive molecular ions, and electrons) and neutral products (ground-state and the metastable atoms) generated from nitrogen and oxygen molecules in air. The energy deposit was estimated using the calculations of ion-pair creation by the SEP protons4).

During an SEP event, both the photochemical reactions induced by the UV and visible radiation from the sun and the reactions induced by the SEP protons are considered in the simulation. The variation in chemical composition in an SEP event is estimated as the difference between the result obtained through simulation including the radiolysis processes due to the SEP protons and that obtained under consideration of only photochemical reactions using the same initial condition.

Figure 1 shows a tentative result of the variation in the ozone concentration at the 50 km altitude in the northern polar region for the SEP event in October-November 2003. The energy deposit in the SEP event continued for six days. A sharp decrease of the ozone concentration is observed immediately after the SEP event starts. On the third day of the event, when the energy deposit also reaches the maximum, the decrease of the concentration reaches the maximum and increases back gradually after that. The ozone concentration does not completely recover and remains depleted for a few weeks or more. This depletion of the ozone presumably corresponds to a very slow recovery of the NOx concentrations. The NOx concentration begins to increase when an SEP event starts. It continues to increase for four days and is almost maintained constant after the SEP event. The depletion of ozone is thought to continue after the SEP event since the ozone is consumed in the catalytic reaction cycle involving NOx, e.g., NO+O3→NO2+O2.

In the near future, we will investigate the global and long-term influence of SEP events on the atmospheric chemical composition. In our approach, we will estimate short-term variations during an SEP event using our Box-model, and the estimated variations will then be input into a three-dimensional (3D) chemical climate model (CCM)5) as instantaneous perturbation of the chemical composition. This is because the transport of chemical species treated in 3D is essential for investigating the global and long-term influence.

Figure 1. Tentative result for the variation in the ozone concentration at the 50km altitude caused by SEP (see text).

References

*1 RIKEN Nishina Center
*2 National Institute for Environmental Studies
Measurements of nitrogen isotope ratios in samples with very low nitrate concentrations from the Dome Fuji ice core (Antarctica) drilled in 2010

Y. Motizuki,¹ S. Okamoto,¹,² K. Takahashi,¹ Y. Nakai,¹ A. Makabe,³,⁴ K. Koba,³ and H. Motoyama⁵

Nitrate (NO₃⁻) in ice core samples is known to provide a variety of information on past and present atmospheric conditions. For instance, NO₃⁻ data for samples from the Talos Dome ice core (Antarctica) exhibited a highly significant relationship with cosmic ray fluxes.¹ In addition, several research groups²,³ have measured the δ¹⁵N of NO₃⁻ in surface snow in Antarctica to quantify the extent of isotopic fractionation due to photolytic processes after precipitation. However, there is little information available about the depth profiles of the δ¹⁵N of NO₃⁻ in ice core samples from Antarctica.

Our goal was to precisely analyze the δ¹⁵N and δ¹⁸O of NO₃⁻ in ice cores to clarify the history of solar activity and cosmic events. However, it is difficult to measure the δ¹⁵N and δ¹⁸O of NO₃⁻ in Antarctic ice cores because the NO₃⁻ concentrations are low (typically <0.4 μmol/L), and the available sample volume is limited. In this study, as a feasibility study, we used a denitrifier method⁶ to perform highly sensitive measurements of the δ¹⁵N of NO₃⁻ in samples from the DFS10 ice core, which was drilled in 2010, 7 km south of Dome Fuji Station (DFS), to obtain a profile of the δ¹⁵N of NO₃⁻. The NO₃⁻ concentration in the core was approximately 0.35 μmol/L. In what follows, we will introduce the outline of the results for 70 samples collected from the ice core of depths of Dome Fuji at 3.3–7.6 m. The sampling procedure was the same as that described by Motizuki et al. (2014)⁷ for the ice core drilled at Dome Fuji in 2001. We assume that these samples correspond to approximately the time interval from AD 1900 to 1960. Each sample segment cut from the ice core corresponds to a time interval of approximately 0.7–1.0 year. A 10 mL aliquot of each sample was used; NO₃⁻ in the sample water was quantitatively converted to N₂O by the denitrifying bacteria, Pseudomonas aureofaciens, which lack N₂O reductase. The isotopic composition of the N₂O gas produced by the bacteria was measured using a mass spectrometer (IsoPrime100) with a purge-and-trap introduction system. The isotope ratios were referenced to the internationally recognized standards USGS32, USGS34, and USGS35 provided by IAEA (International Atomic Energy Agency). Nitrate concentrations were analyzed by ion chromatography (ICS2000) with error limits of 2 or 3%.

The amount of nitrogen used for the analysis ranged from 2.1 to 4.8 mmol. δ¹⁵N ranged from 144.8 to 332.0‰ and the maximum error was ± 2.5‰. The high, positive δ¹⁵N values obtained in the study were therefore attributed to a post-depositional effect on NO₃⁻. Figure 1 shows the depth profiles of NO₃⁻ concentrations and δ¹⁵N values. Despite the lack of any correlation between NO₃⁻ concentrations and δ¹⁵N values, their depth profiles appear to be related for several depth intervals. For example, both profiles are convex in the depth intervals 3.3–4.0 and 5.5–6.0 m. It has been reported that NO₃⁻ concentration decreases as δ¹⁵N values increases near the surface of snow because of photolysis in the surface snow (vide supra).² There was no negative correlation between NO₃⁻ concentration and δ¹⁵N values for our ice core samples, which indicates that the variations of δ¹⁵N and NO₃⁻ concentration in ice core samples below 3 m do not reflect post-depositional fractionation of nitrogen isotopes. Instead, the depth profiles of δ¹⁵N and NO₃⁻ concentration likely preserve the corresponding variations in the original precipitation.

![Fig. 1 The depth profiles of δ¹⁵N and NO₃⁻ concentration.](image)

We intend to continue the measurements of nitrogen and oxygen isotopes in NO₃⁻ for samples collected from deeper in the ice core. We expect that the depth profiles of nitrogen and oxygen isotopes will reflect the variations in the chemical and physical characteristics of past precipitation, indicate the origin of the NO₃⁻ production in the stratosphere, and provide important information that will help elucidate the history of solar activity and cosmic events.

References
5) Y. Motizuki et al.: Cryosphere Discuss. 8, 769 (2014).

¹ RIKEN Nishina Center
² National Institute for Environmental Studies
³ Tokyo University of Agriculture and Technology
⁴ JAMSTEC
⁵ National Institute of Polar Research
X-ray and Optical/UV Correlation Studies of Active Galactic Nuclei

H. Noda,*1 and T. Minezaki,*2 on behalf of the AGN Optical–X-ray Monitoring Collaboration

Almost all galaxies in the universe are considered to harbor, at their center, a supermassive Black Hole (BH) with a mass of \( \sim 10^{9−10} M_\odot \), where \( M_\odot \) is Solar mass. In Active Galactic Nuclei (AGNs), a considerable amount of gas accretes onto the BH, and multi wavelength signals, including optical, UV, and X-ray, are generated with bolometric luminosity of \( \sim 10^{40−46} \) erg s\(^{-1}\). The X-ray is presumably generated, via inverse comptonization in high-temperature electron clouds (coronae) formed near the BH, while the optical/UV emissions via black body processes of an optically thick and geometrically thin accretion disk extending out to farther radii from the BH. Although a combination of the accretion disk and coronae has been known as “the central engine” creating a large amount of energy in AGNs, its properties including geometries, physical conditions, and heating mechanisms are still unclear.

Applying a timing method\(^1\) to Suzaku\(^2\) data of an AGN called NGC 3227, we found that a Hard Primary Component (HPC) dominated X-ray emission in the faint phase, while a Broad-band Primary Component (BPC) appeared in addition to the HPC in the bright phase (Fig. 1a). This demonstrates that at least two X-ray emitting regions with distinct properties exist near a BH, and one emitting the HPC is always visible, while the other radiating the BPC shows up only when the amount of accreting gas is large\(^3\). However, the geometries of the HPC and BPC creating regions can be hardly identified with only the X-ray information.

To study the geometries, we focus on correlations between the fluxes of primary X-ray and optical/UV, because a better correlation possibly reflects a stronger geometrical connection of an X-ray radiating region with the accretion disk. In 2013–2014, we performed optical and X-ray simultaneous monitoring on an AGN called NGC 3516 with Suzaku and five Japanese ground-based telescopes. As a result, a significant correlation was discovered between fluxes of HPC and the optical signals. The result will be discussed elsewhere.

Optical–UV data derived by Swift\(^4\) are useful as well. Almost all Suzaku observations of NGC 3227\(^5\) were simultaneously followed up by Swift; therefore X-ray flux in the faint and bright phase, identified by Suzaku (Fig. 1a), can be individually compared with those in optical/UV. First, we extracted UV count rates from a 5"-radius circle centering at the nucleus on UV images obtained with the UVW2 filter. Next, we extracted 2–10 keV count rates from the Suzaku and Swift datasets derived at the same time as the UV images. Figure 1(b) shows a count-count plot between the UV and X-ray count rates with different colors between the faint (purple) and bright (green) phases. When we fitted the faint-phase plots (Fig. 1b purple) with a linear function, including systematic errors of 3% into the UV count rates, the fit almost succeeded with \( \chi^2/\nu = 13.4/6 \). However, in fitting all the plots (Fig. 1b purple plus green) again with a linear function, after including the 3% systematic errors into the UV count rates, the result degraded giving \( \chi^2/\nu = 61.5/9 \). This might indicate that the HPC flux is strongly correlated with UV, while the BPC flux is little correlated.

Because the HPC was found to deeply relate with black body photons from the accretion disk, it may come from an hot accretion flow, and if so, the faint phase corresponds to the low/hard state\(^5\). On the other hand, the origin of the BPC still remains unclear, because it did not appear for long enough in the previous observations of NGC 3516 and NGC 3227. To examine the bright phase in detail, we perform another X-ray and optical monitoring with Suzaku, and the systematic analyses of AGN data in the Swift archive.

References


---

*1 RIKEN Nishina Center
*2 Institute of Astronomy, School of Science, The University of Tokyo
Time-variable Fe K emission lines from accreting white dwarf binaries

T. Yuasa*1

Accretion of gas from a normal star in a binary system onto a compact star liberates a vast amount of gravitational potential energy. This often results in heating of the gas and high-energy electromagnetic radiation. By observing the emission, properties of the compact star can be studied because the emission occurs from regions close to the star.

We have been studying the mass-accreting white dwarf system that is considered to be an important candidate of type Ia supernovae. In particular, our focus has been on measuring the mass of a white dwarf in a binary system by modeling X-ray spectra of heated gas. For details of the modeling and initial results, see our previous publication (Yuasa et al. 2010).

To further improve the accuracy of the mass measurement, it is crucial to understand the geometry and profiles of density, temperature, and bulk velocity of the X-ray emitting plasma. In April 2014, we were awarded a 180k-second observation of the magnetic accreting white dwarf V1223 Sgr by using the Japanese Suzaku X-ray telescope. The aim of the observation is to assess the geometry assumed in the model calculation based on precise measurement of time variation of Doppler energy shifts and intensities of the Fe atomic lines after the previous marginal report (Hayashi et al. 2011).

After the standard data selection, we obtained high-photon-statistics spectrum as presented in Fig. 1. To disentangle Doppler energy shifts of lines caused by in-falling bulk velocity of the X-ray emitting gas and other effects such as white dwarf spin and subsequent line-of-sight viewing angle variation, we performed phase resolved spectral fitting by splitting the total observation time into four phase bins with a period of 754 s (corresponding to the spin period of the white dwarf in V1223 Sgr). No statistically significant time variation was observed for the centroid energies of the lines, in contrast to the previous report (Hayashi et al. 2011), due to long-term degradation of the energy resolution of the instrument. On the other hand, as shown in Fig. 2, the line intensities varied over spin phases although statistical fitting errors are still large due to phase resolving (resulting shorter integration time per phase bin).

These time variations can be interpreted to be caused by the resonance-trapping beaming effect (Terada et al. 2001) where the optical thickness of the X-ray emitting hot plasma becomes greater than unity only for resonance line photons and trapped within the plasma while continuum photons exit the plasma region almost freely (i.e., the plasma is optically thin for continuum photons). In this scheme, the optical thickness is sensitive to the plasma density, the geometrical shape, and the white dwarf mass. Therefore, we are continuing to perform detailed analyses and comparison with Monte Carlo radiation transfer simulation results to utilize this resonance-beaming feature as an alternative constraint for measuring the white dwarf mass and related physical quantities of the binary system such as the mass accretion rate.

Fig. 1. Time-average X-ray CCD spectrum of V1223 Sgr. Thermal bremsstrahlung continuum and three atomic emission lines from neutral Fe (6.4 keV) and highly ionized Fe ions (6.7 and 6.9 keV).

Fig. 2. Crosses are intensities of the three Fe emission lines over white dwarf spin phases (ordinate presents the equivalent width, which is a measure of the line intensity). Solid curves are the best-fit sinusoidal functions.

References
2) Hayashi T., et al. 2011, PASJ, 63, 739

*1 RIKEN Nishina Center
Spectral and Temporal Approach to Physics of Neutron Stars

T. Enoto,*1,∗2,∗3 T. Tanagawa,*1 T. Kitaguchi,*1,∗4 A. T. Hayato,*1 T. Yuasa,*1 W. B. Iwakiri,*1 H. Noda,*1 A. Yoshikawa,*1 Y. Takeuchi,*1 M. Kubota,*1 and K. Nishida*1

Astronomical observations of neutron stars provide us an unique approach to investigate the fundamental physics under extreme condition. Degenerate matter inside neutron stars exceeds the nuclear density, and the equation of state of high density matter is observationally constrained via measurements of stellar mass and radius. Neutron stars are also characterized by strong gravity (gravitational redshift $z \sim 0.2$), fast rotation (up to $P \sim 1$ ms), and strong magnetic field ($B \sim 10^{12}$ T). Recent progress of X-ray observations further indicates an strongly magnetized subclass of neutron stars, called magnetars1). There are accumulating evidence for 2–3 orders of magnitude higher magnetic field than that of canonical neutron stars, with peculiar flare and burst activities interpreted as dissipation of the magnetic energy2). Neutron stars are, thus, an ideal laboratory in our universe3).

We are now about to enter the age of precise astrophysical measurement of neutron stars. The ASTRO-H X-ray observatory4), expected to be launched in 2015, will realize a ultra-high spectral resolution of $\Delta E \sim 7$ eV in the $\sim0.3$–$10$ keV band (cf., $\sim130$ eV FWHM at 6 keV of the X-ray CCD onboard Suzaku). This will enable us to search for a proton cyclotron feature as direct evidence for the strong field and for a gravitationally-redshifted absorption feature to determine the equation of state of neutron stars. One year after the ASTRO-H, the Neutron star Interior Composition Explorer (NICER)5) will be attached to the International Space Station (ISS). The NICER project will provide us unprecedented high-precision data of neutron stars with very large photon statistics, and is expected to reveal the equation of state of neutron stars. In addition to these spectral and temporal improvements, polarization is expected to open a new observational window of the X-ray astronomy.

Prior to the ASTRO-H launch, we have started investigations of scientific topics and possible candidates of observations, and published it as the ASTRO-H White Paper7). Hard X-ray from magnetars is listed as one of the good candidates of ASTRO-H8). We are also preparing the handbook for the high spectral data handling, called the “Cookbook”. As international cooperation for future missions, we have also collaborated with the NICER and X-ray polarimeter groups at NASA Goddard Space Flight Center, mainly contributing to calibration of the NICER X-ray mirror and developments of the X-ray polarimeter9). As our collaborative relationship grows, FUture Cooperation is a Key element for the Spectral and Temporal Approach to Physics for neutron stars.

In 2014, we reported a signature of the toroidal field embedded in the magnetar interior10) from 4U 0142+61 (see Fig 1), and also studied how neutrino emission coupled with the toroidal field affects spin evolution of neutron stars11). We studied the magnetic field and accretion mechanism of the slowest rotating X-ray pulsar, 4U 1954+3912), and iron line emission from the prototypical X-ray pulsar, Heraculis X-1 (Her X-1)13).

References

*1 RIKEN Nishina Center
*2 JSPS SPD Fellow
*3 NASA Goddard Space Flight Center
*4 Department of Physical Science, Hiroshima University

Fig. 1. Schematic view of a magnetar, a subclass of neutron stars with extremely strong magnetic field.
Timing analysis of solar flares in hard X-ray and soft $\gamma$-ray bands measured by the Suzaku Wide-band All-sky Monitor

W.B. Iwakiri,*1 on behalf of Suzaku WAM team

Hard X-ray and $\gamma$-ray observations have proved to be a powerful tool to study the physics of particle acceleration and transfer in solar flares. These high-energy photons are often observed in X-class flares defined by the GOES satellite. The origin of emission is thought to be the thick-target bremsstrahlung of high energy particles accelerated by magnetic reconnection. Prior to the ASTRO-H launch, we have started investigations of scientific topics and possible candidates as one of the good candidates of ASTRO-H.*4

In 2014, we reported a signature of the toroidal magnetic field and accretion mechanism of the slowest spin evolution of neutron stars.*11 The energy-dependent time delays can be explained through the trap plus precipitation model.*1 First, the model suggests that electrons accelerated by magnetic reconnection are injected into a magnetic loop and trapped (magnetic mirror trap). Next, the trapped electrons escape the loop by pitch-angle scattering and precipitate to the chromosphere. As a result, hard X-ray photons are produced by thick-target bremsstrahlung. If Coulomb collisions represent the dominant pitch angle scattering for trapped electrons, the collisional deflection time $\tau$ can be represented as$^2$

$$\tau(E) \propto E^{1.5}. \quad (1)$$

In this progress report, we performed a timing analysis of the Sept 24 2011 solar flare observed by the Wide-band All-sky Monitor (WAM)$^3$ onboard Japanese fifth X-ray satellite Suzaku from 80 keV to 7 MeV.

The WAM consists of four lateral walls composed of bismuth germanium oxide $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) crystals. The event data are recorded with a 1-s time resolution in the 55 energy band. The WAM has a large effective area that reaches 400 cm$^2$ at 1 MeV. This is the largest area in among currently working $\gamma$-ray spectrometers on-board astronomical satellites. Therefore, WAM is suitable for hard X-ray and soft $\gamma$-ray observation of solar flares$^4$. Figure 1 shows the energy-resolved time profiles of the solar flare on Sept 24 2011 observed by WAM. The lightcurves show that the main peak has shifted progressively later at the higher energy band.

In order to evaluate the time lag quantitatively, we measured the delay using a cross correlation technique between the 80 - 130 keV lightcurve and the other eight energy-resolved lightcurves (130 - 7000 keV band). Before the analysis, we used a low-pass filter for each lightcurve by running an average of 10 bins (the time bin size is 1 s) to exclude the higher frequency component, because the observed fast structures are caused by the difference of electron time-of-flight from directly precipitating electrons$^1$. The derived time delays as a function of energy are shown in Fig. 2. The results show the energy dependence of the time delays are clearly changed around 1000 keV. In the lower energy band, the relation is roughly consistent with $E^{1.5}$, which is predicted by the pitch angle scattering of Coulomb collision$^2$. On the other hand, above 1000 keV, the relation becomes more flat. If we fit the results using the broken power-law model and the power-law index of the lower energy is fixed at 1.5, the derived index of the higher energy band is 0.253±0.008 with a cutoff energy of 598±9 keV (the errors are 90% confidence). The estimation of systematic errors caused by a pile up effect is currently in progress.

![Fig. 1. Background-subtracted lightcurves of solar flare triggered on Sept 24 2011 09:35:00 UT observed by Suzaku-WAM in nine energy bands.](image)

![Fig. 2. The measured energy-dependent time delay of the Sept 24 2011 flare using the cross correlation method.](image)

References
Spurious shear from tree-rings on LSST CCD

Y. Okura,∗1,∗2, A. Plazas,∗3,∗4, M. May∗3 and T. Tamagawa∗1

Charge-Coupled Device (CCD) detectors in observational instruments are composed of a silicon layer, which changes photons from astronomical objects into electrons. The electron signal is amplified and contains information about the objects. Impurity gradients in the silicon that originate when it is grown produce transverse electric fields that bend the electron path. The bending creates flux modulation, position displacement and shape distortion of objects. The tree-ring effect is caused by circularly symmetric impurity gradients in the silicon wafer, which induce flux modulation, position displacement, and shape distortion of the observed astronomical objects. The tree-ring effect in some recent observational instruments (DESa), HSCb) are smaller than the pixel scale, inducing small changes in object images. Future high precision cosmology by the LSSTc) needs high precision measurement of astronomical objects. One of the methods for studying cosmology is the measurement of weak lensing shear (Schneider et al., 20061), which changes the shape of the image of objects from a large scale structure (cosmic shear). Statistics of the cosmic shear depend on the cosmological parameters, which characterize the initial state and future of the Universe. However, the tree-ring effect causes systematic error in the measurement because it changes the shape of images (Plazas et al., 20142)). We studied the impact of the tree-ring effect on the LSST test CCDs for high-precision cosmology.

We are the first to quantify the tree-ring effect on the LSST prototype sensors. We used flat images that contain data taken with uniform illumination where concentric flux modulation (tree rings) can be observed. We found the center of the tree-ring effect near the corner of the CCD (Fig. 1) and measured the one-dimensional profile by averaging by angle (blackline in Fig. 2). If the flux modulation or position displacement are concentric, shape distortion (spurious shear) can be obtained (Okura et al in preparation) as

\[ \gamma_{\text{rad}}^T(r) \approx -\frac{1}{2} f(r), \] (1)

where \( f(r) \) and \( \gamma_{\text{rad}}^T(r) \) are the profiles of flux modulation and spurious shear, respectively. We show the measured spurious shear in Figure 2, and the blue line indicates the measured spurious shear. As typical scale of the spurious shear is 0.005%, it is much smaller than the cosmic shear which has typical scale of approximately 1-2 %.

Next, we calculated the two-point correlation of the spurious shear because, in cosmological analysis, we calculate the two-point correlation of the cosmic shear for obtaining the statistics of the cosmic shear. Figure 3 shows the two-point correlation of the spurious shear in the field of view of LSST (189 CCDs, 60000 × 60000 pixels) with a sampling scale of 50 pixels. The typical scale of the correlation is approximately \( 10^{-13} \), which is much smaller than the two-point correlation of the cosmic shear (\( 10^{-6} \)). Therefore, the tree-ring effect on the LSST CCDs will not degrade the constraining of the cosmological parameters.

References

Performance test of TPC Polarimeter for cosmic X-ray sources at BNL NSLS-1


Cosmic X-ray polarimetry is believed to be a powerful measurement technique for studying the physics in extreme environments such as strong gravitational fields and magnetic fields in the universe. However, soft X-ray polarization has not succeeded so far except for a few detections in the 1970’s 1). To study such an unexploited polarization, we have proposed two different ROB designs.

When an incident X-ray interacts with a gas atom, a photoelectron is ejected preferentially in the direction of the electric field vector of the incident photon according to a cosine² probability distribution. Thus, we can determine the polarization degree and the phase by obtaining a track image and initial direction of the photoelectron. A schematic view of TPC polarimeter is shown in Fig 1. To ensure high efficiency for the polarization signal, the charge detection plane of the TPC polarimeter consists of the Gas Electron Multiplier (GEM) designed by RIKEN 4) mounted over strip anodes parallel to the incident X-rays. Two-dimensional images of photoelectron are created using a one-dimensional strip readout and by timing the arrival of the charge²). For a small satellite mission of cosmic X-ray polarimetry, we have proposed two different ROB designs. One design uses two gold-plated titanium frames with “tongue in groove” to secure the strips under tension 3). The performance of the polarimeter using this type of ROB has been verified and meets all mission requirements 5). To reduce cost and risk by further simplifying the assembly more, the other design one has used epoxy adhesives to hold the strips under tension to the lower frame.

We carried out the performance test for the polarimeter at the Brookhaven National Laboratory (BNL) Synchrotron Light Source-1 facility in September 2014. The polarimeter was filled with 190 torr dimethyl ether (DME). To make the pixels of the track image square-shaped, the electrical drift region was selected as 196 V/cm, which is the drift velocity equal to the 121 μm divided by the 50 ns sampling time. The transfer field between the GEM and the ROB was selected as 660 V/cm considering the collection efficiency of the charge. The detector was irradiated with linear-polarized monochromatic X-rays at eight energy bands. The total number of the events is 5 × 10⁶ for individual measurement. Further, to calibrate the polarimeter, we also acquired 2.7 keV unpolarized events.

Fig.2 shows the derived modulation curves for three energy bands and the 2.7 keV unpolarized data at 8 mm from GEM, which corresponds to the detector optical axis. The results have subtracted the pedestal and common mode noise and deconvolved the electronics response. The S/N achieved 5 σ levels. To correct the asymmetry caused by the difference of the drift velocity between the drift and the transfer region, the results are corrected using Gaussian convolution in the time axis. The Gaussian σ value is 46 μm which is optimized using the 2.7 keV unpolarized data 5). As an indicator of the polarization sensitivity, we introduce a modulation factor μ, which is defined as

\[ \mu = \left( \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}} + f_{\text{min}}} \right) \]

where \( f_{\text{max}} \) and \( f_{\text{min}} \) are maximum and minimum values of the modulation curve, respectively. The derived modulation factors of 2.7 keV, 4.5 keV, and 6.4 keV are 21.3±0.6%, 37.9±0.6%, and 46.6±0.6%, respectively. The results are consistent with previous ROB design 5) and meet the measurement requirement. The estimation of the systematic error for the detector position is still under discussion.

Fig. 2. Modulation at three energy bands measured at BNL using TPC polarimeter.

References
Fabrication of a TPC X-ray Polarimeter and Preliminary Testing with the Synchrotron Radiation Light Source at Spring-8

A. Hayato,*1 T. Tamagawa,*1 T. Kitaguchi,*1,2 E. Teruaki,*1,3 W. B. Iwakiri,*1 Y. Takeuchi,*1,4 M. Kubota,*1,4 and K. Nishida*1,2

X-ray polarimetry is expected to provide unique information about stars, such as strong gravitational fields around black holes. However, it is far behind in technology in comparison to radio/optical polarimetry, and the observation of Crab nebula by OSO-8 satellite 40 years ago has been the only detection of X-ray polarization among astronomical objects1. NASA and RIKEN have been developing the X-ray polarimeter using the time projection chamber (TPC) technique with the sensitivity 10 times greater than the OSO-8 polarimeter, for the Gravity and Extreme Magnetism Small explorer (GEMS), an X-ray polarization telescope mission2. Although we have already built the flight model2, a detailed study is still needed in order to fully understand the characteristics of the TPC polariometer. We therefore fabricated an in-house TPC polarimeter at RIKEN (RIKEN polarimeter) for tests in various situations. In this report, we present a brief overview and the basic performance of the RIKEN polarimeter.

The TPC polarimeter is a gas-based detector with sensitivity in the energy range of 2 – 10 keV. The polarimeter can image a photoelectron and reconstruct its initial direction, where the azimuth angle distribution depends on the linear polarization degree/angle of the incoming X-ray3. The design of the RIKEN polarimeter is originally based upon the GEMS polarimeter1, although handy materials (e.g., bare aluminum instead of copper-tungsten or gold-plated aluminum) are used for easier machining. Another modification is that we adopted the Scalable Readout System (SRS), manufactured by CERN/RDS51, instead of a custom-made ASIC as the strip readout. A SRS consists of APV25(s) with a sampling rate of 40 MHz, ADC card(s), and a Front-End Card. Figure 1 shows the photoelectron track taken by the RIKEN polarimeter.

What we actually measure with the polarimeter is a modulation curve, an azimuth angle distribution of the photoelectron. The modulation factor µ is derived from \((f_{\text{max}} - f_{\text{min}}) / (f_{\text{max}} + f_{\text{min}})\), where \(f_{\text{max}}\) and \(f_{\text{min}}\) are the maximum and minimum counts in the curve. The modulation factor of the polarimeter \(\mu_{\text{pol}}\), which represents the sensitivity of polarimetry, is defined as \(\mu\) which should be measured with a 100% polarized source. The first step of our study is to determine \(\mu_{\text{pol}}\) of the RIKEN polarimeter.

We performed two experiments: (a) to measure \(\mu\) with highly (≈85%) polarized source at BL32B2 SPring-8, and (b) to confirm the flat modulation with unpolarized line emission produced by an X-ray generator. We took measurements at 4.5, 5.5, 6.4, 7.0, and 7.5 keV for (a) and 4.5 and 6.4 keV for (b), although we focus on only the result of the 4.5 keV data here.

Figure 2(a) shows the modulation curve taken with the well-collimated (200×200 \(\mu\)m²) 4.5-keV polarized X-ray at the middle height of the active volume, and (b) shows that with the 4.5-keV unpolarized X-ray under the same condition. The obtained \(\mu_{\text{pol}}\) at 4.5 keV is 0.3×0.85/\(p_{\text{beam}}\), where \(p_{\text{beam}}\) is the polarization degree of the X-ray beam, while the observed flat modulation is 0.0±0.02. Meanwhile, the determination accuracy for the polarization angle is about 4° at a certain drift height. A detailed comparison with the GEMS polarimeter and other performance studies (e.g., detector angle dependency for the sensitivity) are in progress.

References
We develop a photoelectric tracking gas detector using a time projection chamber technique for a cosmic X-ray polarimetry. To calibrate the X-ray polarimeter at a synchrotron facility, the polarization degree of the incident X-ray beam should be known. In order to measure the beam polarization, we build a Compton polarimeter based on the X-ray scattering processes, where the angular distribution of the scattered X-rays is sensitive to the polarization direction of the incident X-rays. The Compton polarimeter can accurately measure the beam polarization owing to its high analyzing power. We use the Compton polarimeter to measure the beam polarization of the BL32B2 beamline at the SPring-8 synchrotron facility where the gas X-ray polarimeter is verified.

Figure 1 shows the schematic view of the experimental setup. The Compton polarimeter consists of a cylindrical Be scatterer and two X-ray detectors, i.e., a Si sensor and a CdTe sensor, that face each other across the scatterer. Each detector is located 1 cm away from the Be scatterer and has a diameter of 4 mm and an effective length of 4 mm. Incident X-rays from left to right, as shown in Fig. 1, are scattered by the Be cylinder and then detected by these sensors. As the detectors rotate around the scatterer through a rotation stage, the count rates modulate with the minimum rate in the direction of the electric field vector (i.e., the polarization direction) of the incident X-rays and the maximum rate perpendicular to the vector. The count rate shows a sinusoidal curve as a function of the rotation angle (modulation curve). The polarization degree of the incident X-rays is derived from the modulation curve. We measure the polarization degree of the incident X-rays at 4.5, 6.4, and 8.0 keV.

Figure 2 shows the modulation curve for 4.5 keV X-rays. The data points are fitted by a sinusoidal model with a constant offset: \( f(\theta) = a \cdot \cos(2 \cdot (\theta - b)) + c \), where \( \theta \) is the rotation angle. The free parameters \( a, b, \) and \( c \) represent the amplitude, polarization direction, and offset, respectively. The observed beam polarization degree, \( \mu_{\text{obs}} \), is calculated using the equation: \( \mu_{\text{obs}} = a/c \). We define zero degree in the detector coordinate system when the Si detector is on top. In order to reduce the systematic error caused by beam misalignment, we calculate the average of the count rates obtained from two angles 180 degrees apart from each other. To calculate the beam polarization, \( P \), we need to know the modulation factor, \( M_{\text{sim}} \), which is 100% for a perfect polarimeter and 0% for an insensitive detector. We estimate it using the Geant4 Monte Carlo toolkit. The obtained parameters, \( \mu_{\text{obs}}, M_{\text{sim}}, \) and \( P \), are listed in Table 1. The beam polarization degrees at 4.5, 6.4, and 8.0 keV are estimated to be 75.9 ± 0.1%, 77.1 ± 0.2%, and 77.0 ± 0.1%, respectively.

![Fig. 1. Experimental setup to measure the synchrotron X-ray beam polarization. The two X-ray detectors are the AMPTEK XR100CR Si detector and the XR100T CdTe detector.](image)

![Fig. 2. Modulation curve of polarized X-rays with an energy of 4.5 keV. The red line indicates the best-fit model.](image)

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>( \mu_{\text{obs}} ) (%)</th>
<th>( M_{\text{sim}} ) (%)</th>
<th>( P ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>69.2 ± 0.1</td>
<td>91.21 ± 0.10</td>
<td>75.9 ± 0.1</td>
</tr>
<tr>
<td>6.4</td>
<td>70.6 ± 0.2</td>
<td>91.62 ± 0.05</td>
<td>77.1 ± 0.2</td>
</tr>
<tr>
<td>8.0</td>
<td>72.1 ± 0.1</td>
<td>93.67 ± 0.02</td>
<td>77.0 ± 0.1</td>
</tr>
</tbody>
</table>

References

*1 RIKEN Nishina Center
*2 Department of Physics, Tokyo University of Science
*3 NASA/GSFC
Performance test of Modulated X-ray Source using UV-LED and Channel Electron Multiplier

W.B. Iwakiri,*1 K. Gendreau,*2 A. Hayato,*1 Y. Takeuchi,*1,∗3 K. Nishida,*1,∗3 M. Kubota,*1,∗3 and T. Tamagawa*1

A Modulated X-ray Source (MXS) with Channel Electron Multiplier (CEM) developed by NASA is a newtype of X-ray generator that uses UV-LED1). MXS has many advantages compared with radioactive sources or X-ray generators that require hot filaments. For example, the timing of the X-ray output can be controlled using the modulated LED. Moreover, electronic amplification by CEM leads to the generation of short X-ray pulses (tens of nanosecond). These advantages make the calibration of an X-ray detector considerably easy. For example, we can determine the drift velocity of an electron in a gas using high-precision X-ray photon emission timing. It is important to calibrate an X-ray polarimeter using the Time Projection Chamber technique2). In this progress report, we show the performance of MXS with CEM.

A basic layout of MXS with CEM is shown in Fig 1. When an UV-photon emitted from an LED hits a photocathode, the photon converts to a photoelectron. The photoelectron is accelerated onto a target through a potential difference and it produces an X-ray. In fact, the modulation of the LED provides modulated photoelectron and it leads to the generation of modulated X-rays eventually. The X-ray spectrum can be controlled by choosing the target material and the accelerating potential. To amplify the photoelectron, i.e., to obtain a high X-ray flux, CEM is set between a photocathode and the target. Figure 2 shows the MXS made at RIKEN. The assembly is based on the SUS304 cuboid that is 67×34×34 mm. We adopted MgO as the photocathode and Ti as the target.

To verify the performance of the MXS quantitatively, first, we checked the output X-ray flux. The pressure in the MXS is set at 10−7 torr with pumping. The voltage of the CEM and target are set as −2.25 kV and 10 kV, respectively. The frequency of the input pulse is fixed at 10 kHz. We used a Si detector, AMPTEK XR100CR, to evaluate the output X-ray. Figure 3 (left) shows the relation between the width of the input pulse with 10 kHz for the LED and the output X-ray flux. The results show that these two parameter have a linear relationship. When the width of the input pulse is 500 ns, the observed X-ray flux is 4000 counts/s/mr.

Next, we evaluate the duration of the output X-ray pulse using a Time-to-Digital Converter (TDC). We measured the time interval between the leading time of input pulse for LED (used as the start signal of the TDC) and the arrival time of the output X-ray photon (used as the stop signal of the TDC). Figure 3 (right) shows the derived TDC histogram at 5 different widths of the input pulse (50, 100, 200, 400, and 600 ns). The bin size of the histograms are 62.5 ns. The width of each histogram corresponds to the pulse width of the output X-rays. It means that the MXS output is controlled by choosing the input pulse, and we can provide a X-ray photon when needed at precisely known times. To reduce the cost and size, currently, we are developing a new MXS using a carbon nanotube instead of LED and CEM.

Fig. 1. Schematic view of MXS with CEM.

Fig. 2. MXS with CEM developed by our group.

Fig. 3. Left : Output X-ray flux as a function of the width of input pulse for the LED (the frequency of the input pulse is fixed at 10 kHz). Right : TDC histogram at five different input pulse widths. The start and stop signal are the input pulse and the arrival timing of the output X-ray, respectively.

References
Property of LCP-GEM in pure dimethyl ether at low pressures

Y. Takeuchi,*1,2 T. Tamagawa,*1,2 T. Kitaguchi,*1 S. Yamada,*1 W. Iwakiri,*1 F. Asami,*1,2 A. Yoshikawa,*1,2 K. Kaneko,*1,2 T. Enoto,*1,3 A. Hayato,*1 T. Kohmura,*4 and the GEMS/XACT team

We developed a photoelectric X-ray polarimeter onboard X-ray advanced concepts testbed (XACT) sounding rocket, the first dedicated NASA rocket mission for high sensitivity observation of cosmic X-ray polarization.1,2 The polarimeter uses a time projection chamber technique to obtain the distribution of photoelectron emissions from which the polarization of the incident X-rays can be measured. A key device of the polarimeter is a 100-µm-thick gas electron multiplier (GEM) foil with a copper-clad liquid crystal polymer insulator (LCP-GEM),3,4 which amplifies the signal that keeps the track image of photoelectrons. The required gain of the LCP-GEM for the polarimeter is 3,000 without discharge. Fine photoelectron track images are essential for a highly sensitive measurement of X-ray polarization. By extending the track length using a low-pressure gas, high-resolution photoelectron track images can be obtained. On the other hand, the low-pressure gas decreases the X-ray detection efficiency of the polarimeter. We anticipate that the optimum gas pressure of pure dimethyl ether (DME) is 50–150 Torr by considering the trade-off between the detected count rate and the modulation factor.1,3 However, LCP-GEMs have never been operated below 190 Torr in DME gas. Under such low gas pressures, discharge is one of the most significant risks to the successful operation of GEMs. To explore this unknown regime, we performed a systematic investigation of the gain properties of a 100-µm-thick LCP-GEM in DME at low pressures for the first time.

We developed a prototype gas-chamber detector, which possesses the same geometry as the flight model of XACT. By irradiating the chamber with 6.4 keV X-rays, we obtained the spectrum from the readout pad and fitted it with a Gaussian model. An energy resolution of approximately 20% at the FWHM was achieved. The highest gain under stable operation at 190 Torr was 2 × 10^4 at dV_GEM = 560 V, while that at 20 Torr was approximately 300 at dV_GEM = 470 V. Above 50 Torr, the highest gain exceeded 3000, which meets our requirements for the XACT polarimeter. The gain curves could be reproduced by exponential functions; however, a change of slope with pressure was observed. In addition, we determined the real GEM gain derived from the sum of charge amounts induced in the readout pad and GEM anode using the same data set. The real gain represents the amplification degree of electron drifting in the GEM hole, while the effective gain is the real gain multiplied by the amplified electron collection efficiency of the readout pad.5 The real gain is approximately twice the effective one because the charge amount of the GEM anode is almost the same as that of the readout pad.5 The highest gain at 190 Torr is 4 × 10^4, while that at 20 Torr is around 600. These real gain curves also show deviation from an exponential function.

To comprehensively characterize the gain variations with different gas pressures and GEM voltages, we derived the first Townsend coefficient, α. Fig. 1 shows the observed α as a function of E_GEM/P superposed with the results of Magboltz calculations.7 E_GEM is the electric field applied to the GEM. The data points can be roughly reproduced by an exponential function, although they show deviation from it in the higher E_GEM/P range. This is because the DME ions gain sufficient kinetic energy from such a strong electric field to ionize the DME gas and emit additional electrons that are amplified in the GEM hole. The measured α values were approximately 80% of those derived from Magboltz calculations, which suggests that the length over which the number of electrons were amplified in the GEM hole was different from the GEM thickness but close to 80 µm.

References
3) T. Tamagawa et al.; NIM, A560 418 (2006)
4) T. Tamagawa et al.; NIM, A608 390 (2009)
6) Y. Takeuchi et al.; JINST, 7 C03042 (2012)
Measurement of the electron drift velocity in DME gas

M. Kubota,*1,∗2 T. Kitaguchi,*1 A. Hayato,*1 W. Iwakiri,*1 T. Enoto,*1,∗3 K. Nishida,*1,∗2 Y. Takeuchi,*1,∗2 A. Yoshikawa,*1,∗2 and T. Tamagawa*1

We have developed a photoelectric tracking type gas X-ray polarimeter using a time projection chamber technique for cosmic X-ray polarimetry.1) We select dimethyl ether (DME) as target gas of the polarimeter because the electron drift velocity in DME is relatively slow. The polarimeter chamber, filled with DME gas under a pressure of 190 Torr, consists of three components: drift plane, gas electron multiplier (GEM), and readout strips. When an X-ray interacts with a DME gas atom, a photoelectron is ejected in a direction according to a cosine probability distribution aligned with the electric field vector of the incident X-ray. Secondary electrons produced by photoelectron ionization are drawn by the electric field to the GEM, amplified by a factor ~3000 with the strong electric field in the GEM hole, and then collected by readout strips. The 2-d image of the photoelectron track created by the readout strip position and timing enables measurement of the polarization degree of incident X-rays. In order to square the pixel size of the 2-d image, the electron drift velocity is optimized to be 0.242 cm/µs, which is derived from a strip pitch of 121 µm over a sampling rate of 50 ns. Thus, we accurately measure the electron drift velocity in DME gas under a pressure of 190 Torr as a function of applied electric field.

Figure 1 shows a schematic view of experimental setup. We generated X-rays with a modulated X-ray source (MXS), whose X-ray radiation can be controlled by a switching LED2) with a pulse generator. Generated X-rays were collimated and directed parallel to the GEM foil. The drift distance of electrons to the GEM foil changed by moving it up and down the chamber using the Sigma Koki Z-stage. We measured the time interval between the leading edge of the pulse, which turned on the LED, and a discriminator signal created by charges induced on the GEM cathode. The drift velocity can be determined by dividing the X-ray beam position difference by the time interval difference. Figure 2 shows time interval as a function of stage position. The drift velocity is calculated by the slope of this plot.

The observed drift velocities, \( v_{\text{obs}} \), at various electric field are listed in Table 1. The drift velocities are determined with an accuracy of < 0.5%, and are consistent with the Magboltz prediction3), \( v_{\text{sim}} \), under the DME gas condition of 190 Torr and 25°C. We determined that the electric field, where the drift velocity is 0.242 cm/µs, is 196.3 V/cm by interpolating the observed values. Reproducibility of the results should be checked in further experiments.

Fig. 1. Experimental setup to measure the electron drift velocity in DME gas.

Fig. 2. Time difference as a function of stage position. The drift velocity is calculated by the slope of this plot.

Table 1. Comparison of simulated drift velocity and measured velocity.

<table>
<thead>
<tr>
<th>( E_d ) (V cm(^{-1}))</th>
<th>( v_{\text{obs}} ) (cm µs(^{-1}))</th>
<th>( v_{\text{sim}} ) (cm µs(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>156</td>
<td>0.1918(6)</td>
<td>0.1916(2)</td>
</tr>
<tr>
<td>176</td>
<td>0.2161(10)</td>
<td>0.2158(2)</td>
</tr>
<tr>
<td>186</td>
<td>0.2291(8)</td>
<td>0.2285(3)</td>
</tr>
<tr>
<td>196</td>
<td>0.2405(8)</td>
<td>0.2411(3)</td>
</tr>
<tr>
<td>205</td>
<td>0.2525(9)</td>
<td>0.2532(3)</td>
</tr>
<tr>
<td>215</td>
<td>0.2650(8)</td>
<td>0.2651(3)</td>
</tr>
</tbody>
</table>

References

*1 RIKEN Nishina Center
*2 Department of Physics, Tokyo University of Science
*3 NASA/GSFC
The Soft X-ray Spectrometer (SXS)\textsuperscript{1)} onboard the 6th Japanese X-ray satellite ASTRO-H\textsuperscript{2)} covers an 0.3–12 keV band with an unprecedentedly high energy resolution of 7 e\textsuperscript{V} (the target value is 4 e\textsuperscript{V}). The performance of X-ray spectroscopy is achieved using micro-calorimeter technology at a low temperature of $\sim$ 50mK, which is maintained through the following cooling chain. Stirling coolers, called Shield Coolers (SCs) and Pre-Coolers (PCs), decrease the temperature from $\sim$ 290K to $\sim$ 20K, and subsequently, a Joule-Thomson cooler (JT) further decreases the temperature to $\sim$ 4.5K. Then, the temperature is cooled down to $\sim$ 1.2K with superfluid helium and/or an Adiabatic Demagnetization Refrigerator (ADR), and finally the temperature is reduced to $\sim$ 50mK using two-stage ADRs at the front end of the chain.

Electric power derived by a satellite bus is supplied to SCs, PCs, and the JT via cooler drivers named SC Driver (SCD), PC Driver (PCD), and JT Driver (JTD), respectively\textsuperscript{1)}. The cryo-coolers and cooler drivers are connected by multiple harnesses, and the numbers of particularly important harnesses for driving the cryo-coolers are 4 in SCD, 4 in PCD, and 2 in JTD (10 in total). Because a part of the dewar surface is placed in front of a window of the satellite panel (Fig. 1\textsuperscript{2}), the harnesses are partly exposed to space, and hence, Micro Meteoroids and Orbital Debris (MMODs) of various sizes can collide with the harnesses. If one of the important harnesses is destroyed because of collision with an MMOD, the cooling chain fails to work as required, significantly degrading the SXS performance. Thus, the design needs to satisfy the requirement that the number of MMODs passing through an important harness per year must be lower than 0.1. In the present document, we roughly estimate the probabilities with 1-digit accuracy in cases with and without a Kevlar measure\textsuperscript{3)}, and we determine whether the requirement can be satisfied.

The probability that a harness is penetrated by an MMOD can be estimated by multiplying an area exposed to space, a solid angle against space, and flux of MMODs. In each harness, the part exposed to space commonly has a length of $\sim$ 2 m and a solid angle of $\sim$ 0.5$\pi$ against space, while the sum of widths of important parts driving the cryo-coolers is $\sim$ 1–3 mm (for simplicity, we hereafter employ a width of 3 mm for all the harnesses). According to a debris flux model, MASTER2009\textsuperscript{4)}, developed by the European Space Agency (ESA), the MMOD flux drastically changes with their sizes. Because the critical MMOD size is determined as the smallest diameter penetrating a harness, the flux depends on the toughness of the harnesses. According to the JAXA space debris protection manual\textsuperscript{3)}, the critical MMOD size for a commonly used harness cable is $\sim$ 0.2 mm, while that for the same cable covered by a 1-layer Kevlar fiber is calculated to be $\sim$ 0.4 mm. Therefore, the MMOD fluxes can be determined to be $\sim$ 10 and $\sim$ 1 collisions/m$^2$/year for harnesses without and with the 1-layer Kevlar coverage, respectively.

We calculated the probabilities that one of the important harnesses is penetrated per year. The case without Kevlar coverage has the probability

$$10 \text{ pieces} \times 2 \text{ m} \times 0.003 \text{ m} \times \frac{0.5\pi}{2\pi} \times 10 \text{ collisions/m}^2/\text{year} \approx 0.2 \text{ collisions/year},$$

while the probability for the case with the 1-layer Kevlar fiber decreases to

$$10 \text{ pieces} \times 2 \text{ m} \times 0.003 \text{ m} \times \frac{0.5\pi}{2\pi} \times 1 \text{ collisions/m}^2/\text{year} \approx 0.02 \text{ collisions/year}.$$ 

Thus, we successfully confirmed that the design with the 1-layer Kevlar fiber coverage is effective to satisfy the requirement, and we have employed the measures for all the SCD, PCD, and JTD important harnesses.

References
1) K. Mitsuda et al. SPIE 7732, 77321I (2010)
2) T. Takahashi et al. SPIE, 9144, 914425 (2014)
3) JAXA space debris protection manual, 2009, JERG-2-144-HB001
4) ESA MASTER: http://www.master-model.de
8. Accelerator
Emittance measurements for RIKEN 28 GHZ SC-ECRIS†

Y. Higurashi,*1 J. Ohnishi,*1 K. Ozeki,*1 and T. Nakagawa*1

During the last several years, we have been working on increasing the intensity of highly charged uranium (U) ion beams and we have produced intense beams (≈180 eµA for U35+ and ≈230 eµA for U33+) using the sputtering method 1). It is obvious that the emittance of highly charged U ion beams should be sufficiently smaller than the acceptance of the accelerators of the RIKEN RIBF for safe acceleration. Therefore, to minimize the extent of emittance for intense beams of U ions, we intensively studied the effect of the ion source parameters on the emittance. If the magnetic field distribution affects the ion dynamics and the trajectory of the extracted beams,2) it may also affect the emittance of highly charged heavy ions.

Emittance was measured using an emittance monitor, which consists of a movable thin slit and wires (beam profile monitor).

The root mean square (rms) emittance is defined as
\[ \varepsilon_{\text{rms}} = \sqrt{\langle x'^2 \rangle / \langle x'^2 \rangle} \]
\[ \varepsilon_{\text{rms}} = \sqrt{\langle y'^2 \rangle / \langle y'^2 \rangle} \]

In these equations, the averages of the phase-space coordinates of position (x, y) and divergence (x', y') are weighted by the beam intensity 3).

To investigate the magnetic field distribution effect, we measured the emittance for various magnetic field distributions with 18- and 28-GHz microwaves.

The magnitude of maximum mirror magnetic field strength at the beam extraction side (Bext) was changed from ≈1.8 T to ≈1.4 T, while keeping the other magnetic field strengths constant (B inj≈3.1 T, B min≈0.65 T and B r≈1.8 T) for investigating the B ext effect with 28-GHz microwaves. The RF power and the extraction voltage were ≈1.5 kW and 22 kV, respectively. Figure 1 shows the normalized rms y-emittance as a function of B ext. The emittance drastically changed from ≈0.07 to ≈0.17 π mm mrad as B ext decreased from ≈1.4 T to ≈1.8 T. The beam intensity also depended on Bext. It changed from ≈60 eµA to 40 eµA as Bext decreased from ≈1.8 T to ≈1.4 T. In this figure, open circles denote the averaged emittance for various drain currents (2.5-4.5 mA), which is proportional to the extraction current. The error bars (emittance spread ≈0.015 π mm mrad) are the standard deviations.

The magnitude of B inj was changed from ≈1.5 T to 3.1 T, while keeping the other magnetic field strengths constant (B ext≈1.45 T, and B min≈0.65 T, B r≈1.8 T) for investigating the B inj effect. Figure 2 shows the results for rms y-emittance. The emittance increased from ≈0.09 to ≈0.17 π mm mrad as B inj increased.

We measured the emittance of U35+ ions for various ion source conditions. The extent of emittance was independent of the drain current and extraction electrode position. On the other hand, it strongly depended on the magnetic field distributions. The study of the B inj effect may yield some novel information, implying that the emittance of U35+ ions is not influenced by the extraction conditions, but rather by the ion dynamics in the plasma modified by B inj. On the other hand, for less heavy ions such as Xe, Kr, and O ions, preliminary experimental results did not show any strong effects of the magnetic field distributions as for U35+ ion beams. The magnetic field distribution may affect only highly charged very heavy ions. Additional research is required to understand these phenomena.

References

†Condensed from the proceeding of ECRIS 2014, 21st International Workshop on ECR Ion Sources August, 24-28,Nizhny Novgorod, Russia
*1 RIKEN Nishina Center
Supply of $^{70}$Zn beam from 18-GHz ECRIS using the micro-oven

K. Ozeki,*1 Y. Higurashi,*1 and T. Nakagawa*1

In the 18-GHz electron cyclotron resonance ion source (ECRIS)1), we have achieved the practical use of the micro-oven to supply high-intensity and stable $^{48}$Ca beams for a long term.2-4) In the process of the operational tests, we found that the temperature of our oven could be increased up to about 1000°C without damaging the oven. At that temperature, the vapor pressure of ZnO is expected to reach a level high enough to extract the Zn beam with adequate intensity. Therefore, we conducted the supply test of Zn beam using the micro-oven.

In contrast to the Ca beam, in which the Al powder is mixed to the CaO powder to reduce CaO, only the powder of ZnO was placed in the crucible because the vapor pressure of ZnO is sufficiently high. The hot liner5), which plays an important role in reducing the material consumption rate when supplying the $^{48}$Ca beam, is not used when supplying the $^{70}$Zn beam because even if the oven current is increased, the beam intensity hits a peak at an inadequate level when installing the hot liner into the ECRIS.

When increasing the oven current gradually, the water evaporated first. By increasing the oven current, the production of the Zn beam was observed at the oven current lower than that at which the Ca beam was produced. This production seems to be due to the metallic Zn existing slightly in ZnO. The production of the Zn beam at this oven current was terminated after a short time. By further increasing the oven current, the production of the Zn beam was observed again at the oven current higher than that at which the Ca beam was produced.

The $^{70}$Zn$^{15+}$ beam produced by the micro-oven was first supplied for the experiment at the RIBF, from May to June 2014. The beam intensity at the exit of ECRIS and the oven current are shown in Fig. 1. As an example, the power applied to the oven for the oven current of 2.45 A (May 16 to May 19) is estimated to be 39 W. The RF power fed to the ECRIS was 550 W. During the experiment, the sudden increases in pressure in the ECRIS, followed by either the increase in beam intensity or runaway of the ECRIS, occurred several times. These phenomena seem to be due to the grain size of the ZnO (in this experiment, the material was prepared by chipping sintered ZnO rod. The grain size was up to about 1 mm in diameter). Assuming that a grain had a metallic Zn core and a ZnO shell, the inner pressure of the grain increases. The shell becomes thinner with the evaporation of ZnO and cracks at some point to cause a sudden increase in pressure in the ECRIS. This instability problem seems to be prevented by chipping the grains as fine as possible.

Because there was a break period (“CGS failure” in Fig. 1), the material was replaced just to be safe. The statuses of beam supply before and after the break are summarized in Table 1. The consumption rate all through the experiment was 0.14 mg/h.

Table 1. Status of beam supply.

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity [electric μA]</td>
<td>30</td>
</tr>
<tr>
<td>Amount of ZnO placed in the crucible [mg]</td>
<td>1007</td>
</tr>
<tr>
<td>Amount of ZnO consumed [mg]</td>
<td>59</td>
</tr>
<tr>
<td>Consumption rate of ZnO [mg/h]</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The vapor pressures among Ca, Zn, and ZnO are in the following order: Zn > Ca > ZnO. In order to evaporate ZnO, an oven temperature higher than that for Ca is required. But after being decomposed into Zn and O by the plasma, a vapor pressure higher than that of Ca is obtained. Sufficiently low consumption rate without the hot liner seems to stem from the above relation of vapor pressures.

Fig. 1. Long-term supply of the $^{70}$Zn beam for the experiment at the RIBF. The beam intensity for $^{70}$Zn$^{15+}$ (gray) and the oven current (black) are shown.

References

*1 RIKEN Nishina Center
Current status of the RIKEN 18-GHz superconducting ECR ion source

T. Nagatomo,*1 K. Kobayashi,*2 M. Nishimura,*2 T. Kageyama,*1 Y. Kotaka,*2,3 Y. Ohshiro,*3 V. Tzoganis,*1,4 O. Kamigaito,*1 and T. Nakagawa*1

The RIKEN 18-GHz superconducting electron cyclotron resonance ion source (18-GHz SC-ECRIS) provides comparatively light ions to the RIKEN AVF cyclotron1), which is used as an injector at the RI Beam Factory (RIBF) as well as for investigations in low-energy nuclear physics, material sciences, and biological irradiations and RI productions for commercial use. The 18-GHz SC-ECRIS was designed as a liquid-He-free system, and similar ion sources were constructed at the end of the 1990s2). The SC-ECRIS consists of four superconducting solenoid coils and a permanent Nd-B-Fe hexapole magnet, which generate the so-called minimum-B magnetic mirror geometry. A high-power 18-GHz microwave (~ 500 W) is used to heat up the electrons in the plasma, so that highly charged heavy ions can be produced. The superconducting solenoid coils whose filaments are made of Nb-Ti alloy are cooled with a 4.2-K Gifford-McMahon (GM) refrigerator (0.7 W). In addition, the high-$T_c$ superconducting current leads are cooled with another 20-K GM (4 W).

Last summer, these coils could not be cooled below 100 K after 21 days of cooling. This happened just after the annual maintenance of the cryostat systems, and so, we suspected that the thermal insulation surrounding the solenoid coils might be degraded. That is why the whole set of the solenoid coils and the vacuum insulation including the cryostat systems have been replaced with another set that was used in the past and was held in reserve. The replacement was carried out last October, following which the superconducting coils could successfully be cooled to 4 K.

The permanent hexapole magnet had a length of 350 mm and an outer diameter of 199 mm. The hexapole magnet has been replaced with a larger one with an outer diameter of 210 mm so that the radial magnetic field increases from 1.0 T to 1.1 T at the magnet pole face to enhance the plasma confinement for the 18-GHz operation.

The klystron power amplifier (KPA), which was used to generate the high-power 18-GHz microwave, also showed degradation over time. Moreover, the output power was unstable, which directly led to fluctuation of the extracted beam intensity. That is why we have introduced a traveling-wave tube amplifier (TWTA) instead of the KPA even though the maximum output power of the TWTA (750 W) is half of that of the KPA. As a result of this replacement, new remote control functions and additional interlocks to protect the ion source were appended to the existing remote operating system.

The beam emittance extracted from the 18-GHz SC-ECRIS does not seem to be well matched with the acceptance of the low energy beam transport (LEBT) system of the AVF cyclotron. Transverse emittances are crucial parameters and can be optimized by matching the emittance with the acceptance of the LEBT. Moreover, decoupling any inter-plane correlation in the transverse 4D emittance is important to increase the beam brightness3). At present, no device to measure the emittance is installed in the beam line following the 18-GHz SC-ECRIS. Because of a spatial limitation to install a new device, we have started to develop a compact emittance meter based on the pepper-pot method4). The prototype emittance meter was installed behind the analyzing magnet. As the first step, we have obtained an image of beam spots of 6.52-keV $p^+$ (∼ 80 $c\mu A$) as shown in Fig. 1. The transverse r.m.s emittances were measured to be about 40 mm mrad. Further developments and investigations are in progress to establish the emittance meter which can be applied for diagnostics of the low-energy highly charged heavy-ion beam extracted from ECR ion sources.

Fig. 1. An image of beam spots obtained using the prototype pepper-pot emittance meter.

References
Transmutation of long-lived fission products included in the radioactive waste into short-lived or stable nuclei is one of the fundamental issues for future nuclear energy. In order to design a reasonable process for transmutation, fundamental data on nuclear reactions, such as the neutron capture cross section over a wide energy range, are crucial. Acceleration of such radioactive nuclei would help in obtaining the fundamental data through nuclear reaction studies using radioactive beams.

The biggest obstacle in the acceleration of such nuclei is their high radioactivity, which limits the available amount of radioactive material in an ion source. The solution to this problem is to mix a very small amount (several tenths of micrograms) with the usual ion source materials, and accelerate them by pilot-beam acceleration. In this machine study, the feasibility of pilot-beam acceleration was investigated for $^{235}\text{U}$, which is included in natural uranium (natural abundance of 0.7204%), using $^{238}\text{U}$ as the pilot beam. As shown in Fig. 1, the $^{235}\text{U}$ isotope is present in such minute quantities that it is impossible to be identified by the analyzing system of the RIKEN 28-GHz Superconducting Electron Cyclotron Resonance Ion Source (28-GHz SC-ECRIS).\(^1\)

![Fig. 1. Charge distribution of the uranium ions with a slit aperture of ±0.1 mm. $^{235}\text{U}$ ions are expected to appear at the position indicated by the red arrow, but they cannot be identified.](image)

As the first step of the machine study, the $^{238}\text{U}^{35+}$ beam, which was used as a pilot beam, was extracted from the RIKEN Ring Cyclotron (RRC).\(^2\) Next, the aperture of the slit installed at the exit of the 28-GHz SC-ECRIS (SL-U10) was decreased, and the excitation current of the analyzing magnet of the 28-GHz SC-ECRIS was swept. Then, a small peak speculated to be due to $^{235}\text{U}^{35+}$ was identified by the profile monitor installed at downstream of SL-U10 (PF-U10b). The extraction voltage of the 28-GHz SC-ECRIS and acceleration voltage of the RIKEN Linear Accelerator 2 (RILAC2)\(^3\) were multiplied by $235/238$ to extract and accelerate the particles comprising the peak. The $^{235}\text{U}^{35+}$ beam was successfully observed downstream of the RILAC2 (B61).

Since the $^{235}\text{U}^{35+}$ beam with an intensity of several electric nA was observed with the main differential probe (MDP) moved to the injection region, we tried to accelerate $^{235}\text{U}^{35+}$ by tuning only the phase of RF and the excitation current of the main coils of the RRC, while keeping the signal of the MDP as constant as possible. However, because of our insufficient tuning skill, it was difficult to go beyond the radii of 2 m; hence, we gave up this acceleration procedure.

Therefore, the SL-U10 was fully opened. A beam intensity of about 100 electric nA was observed with the MDP, which was enough to obtain the signal from the phase probe (PP). By tuning the isochronism, we achieved acceleration of the $^{235}\text{U}^{35+}$ beam in the RRC. The turn pattern of the circulating $^{235}\text{U}^{35+}$ beam measured by the MDP is shown in Fig. 2. The extraction efficiency was about 75%.

![Fig. 2. Turn pattern of the circulating $^{235}\text{U}^{35+}$ beam in the RRC.](image)

Besides our insufficient operational ability, the difficulty in the acceleration test mentioned above stemmed from the fundamental fact that isochronism cannot be achieved by changing only the main coil current. The magnetic field calculation revealed that several trim-coil currents should be changed over a wide range to accommodate the mass difference of more than 1% of the uranium ions. In our subsequent study, we plan to accelerate $^{234}\text{U}^{35+}$ by using $^{235}\text{U}^{35+}$ as the pilot beam, based on an accurate magnetic field calculation.

References
2) H. Kamitsubo: Cyclotrons’86, 17 (1986).
Modification of septum electrode for RRC-EDC

K. Yamada,*1 S. Ishikawa,*2 T. Nakamura,*2 M. Nishida,*2 and H. Okuno*1

Electric deflection channel (EDC) is an important device to extract the circling ion beam in a cyclotron by using high-static electric field up to 10 MV/m. The circling beam and the extracting beam in the cyclotron are separated by a septum electrode, which is a thin ground electrode of the EDC and only the extracting beam is affected by the electric field and deflected. Because major beam loss in the cyclotron occurs on the septum electrode, the heat load restricts the maximum beam intensity accelerated by the cyclotron. Especially for the uranium beam acceleration at the RIBF, turn separation of the circling beam in the RIKEN ring cyclotron (RRC) is about 7 mm due to the low acceleration voltage and the short stopping range of ions in a material causes melting of the septum electrode, as happened in fiscal year 2012. Therefore, a new septum electrode for the RRC-EDC was introduced in order to improve the heat-load durability of the beam loss.

We fabricated the septum electrode with a V-cut entrance as shown in Fig. 1. The septum electrode was made of oxygen-free copper and divided into two pieces, the entrance side and the remainder, to facilitate the replacement of the damaged entrance side. Thickness of the beam-pass area on the septum electrode was 0.8 mm for the entrance side, 1.6 mm for the central part, and 5 mm for the exit. The cooling water pipes between the two pieces were connected by a VCR1) tube fitting. Ten points of E-type thermocouple devices were mounted on the septum electrode for thermal interlock.

Figure 2 shows the results of the 3D heat transfer calculation for the original and the new septum electrode assuming turbulent forced convective heat transfer by cooling water. The range of both plots is from 0 °C to 1100 °C. For the original septum electrode, which is a simple flat plate, the maximum temperature was about 850 °C assuming 4.0 mm(height)×0.8 mm(thickness)×0.05 mm(range) uniform distribution of 300 W heat load at the entrance, and assuming the heat transfer coefficient of 20000 W/(m²·K) on the inside of cooling water pipe. On the other hand, the maximum temperature was reduced to 670 °C for the new septum electrode assuming 500 W uniform heat load for the same dimensions and same heat transfer coefficient. For both cases, the peripheral temperature was set to 25 °C. The original septum electrode was replaced by the new one, and the old driving motors for the RRC-EDC were also changed to new stepping motors. The modified RRC-EDC was used for the machine time from the winter of 2013, including the RIBF experiment. No failure was found on the new septum electrode with about 4.5 kW of 238U35+ beam and 1.6 kW of 48Ca beam.

In order to extend the capability for further intensity growth, we have started to develop a mass-less septum electrode by arranging numerous thin tungsten ribbons. A test piece of a 50-µm-thick tungsten ribbon was irradiated by varying the intensity of 238U35+ beam with an energy of 10.7 MeV/u provided by the RRC in November 2014 to investigate the melting boundary. The tungsten ribbon melted at an intensity of about 50 µA. The result will be compared with the heat transfer calculation and the prototype septum electrode will be fabricated.

Fig. 1. New septum electrode with a V-cut entrance.

Fig. 2. Results of the 3D heat transfer calculation around the beam entrance side for the original (upper panel) and the new (lower panel) septum electrode.

References
1) Product of Swagelok Co.
Construction of new amplifiers for RILAC

K. Suda,*1 E. Ikezawa,*1 N. Sakamoto,*1 K. Yamada*1 Y. Touch,*2 T. Ohki,*3 K. Oyamada,*3 K. Kaneko,*3 M. Tamura,*3 H. Yamauchi,*3 A. Yusa,*3 and O. Kamigaito*1

RILAC consists of six variable frequency cavities (tanks) constructed in 19781). The first amplifier was constructed in 1977 as a prototype for tank #1. Five other amplifiers were constructed the next year. The #5 and #6 amplifiers were upgraded in 1999 for experiments super heavy element synthesis. Three final-stage plate DC power supply (plate PS) were upgraded at the same time; one PS supplies DC voltage to two amplifiers.

In recent years, several issues related to amplifiers #1 to #4 were encountered, such as water leaks from cooling pipes and damages to the socket for the tetrode caused by insufficient contact. The contact between the socket and tetrode is shallow and a careful alignment is necessary. In particular, the design of the #1 amplifier was the oldest, so it became difficult to maintain it. Therefore, the amplifier #1 was upgraded in FY 2013 along with #2, because the plate PS was common for #1 and #2, and its control system had to be upgraded at the same time.

The new amplifier, as well as those for #5 and #6 are based on a tetrode RS2042SK coupled with a RS2012CJ from THALES/SIEMENS with a grounded grid circuit, that were originally designed for RRC2). The maximum RF signal of 0.01 W (10 dBm, 18 to 40 MHz) is amplified by pre-, driver- and, final-stage amplifiers up to 150 kW. In 14 years of operation of the RILAC #5 and #6, we have experienced several parasitic modes, which might damage the tank and/or the amplifier itself. One is caused by a coupled oscillation between the 99-MHz G1-G2 resonance of RS2042SK and the output circuit including a feeder line to the tank. The other example is the 7th harmonic mode observed in RILAC #5. In order to avoid such parasitic modes, a 50 kW dummy load was installed at a plate stub.

In a factory, matching conditions for input and output circuits of driver- and final-stage amplifiers were measured and/or tuned. (1) The gain of the input circuit for a driver amplifier called as “All Pass Network” was measured and confirmed to be sufficient. (2) An input circuit for the final amplifier was tuned by a vacuum variable capacitor (INCAP) and a movable shorting stub located at a cathode input. The following was performed after installation in an accelerator hall: (3) An output impedance of the final amplifier was matched by changing a plate stub and a capacitor (OUTCAP). Details are described in Ref.3).

The old amplifiers were removed in December 2013, and the new ones were installed in January 2014. Dummy load and power tests were performed in February 2014. In dummy load tests, a water-cooled 250 kW dummy load was connected to the output of the amplifier. It succeeded in obtaining an output power of 150 kW at three frequencies (Fig. 1). Then, load tests were performed at 36.5 MHz. The required acceleration voltages of RILAC #1 and #2 were successfully obtained. Beam service using the new amplifiers started on schedule on March 10th, 2014. A few problems occurred during operations. One was the leakage of cooling water from a rf power feeder of #14). This was partly due to heating at the output flange of the amplifier. The parameters of the amplifier were tuned, so that the temperature of the flange decreased. The other problem was that an automatic tuning control system stopped its sequence abnormally. This happened in both amplifiers in some cases since May 2014. The PLC program was corrected in October 2014.

References
4) E. Ikezawa et al., In this report.

*1 RIKEN Nishina Center
*2 Sumitomo Heavy Industries
*3 SHI Accelerator Service Ltd.
Magnet system for a new beam transport line from IRC to E5 experimental room

K. Kumagai, N. Fukunishi, and S. Fukuzawa

We constructed a new beam transport line to provide high-energy beams accelerated by the IRC to the E5 experimental room in the Nishina building for biological experiments. The magnet system of the beam transport line was designed on the basis of the following factors: (1) For economic reasons, magnet power supplies were not produced, and existing power supplies were used by switching. (2) The new transport beam line was connected to the second half of the existing RRC to the E5 beam line. (3) As a part of the new beam transport line uses the existing IRC bypass beam line in the opposite direction, the beam line optics was designed to reduce the number of magnets that require polarity change. (4) In order to be able to switch a large number of magnets or magnet polarity with a simple procedure, nineteen switches assembled in two control panels were laid out in one place.

Figure 1 shows the layout of the new beam transport line. The magnet power supplies were prepared in the following way:

• The DAKR magnet (1500 A-26 V) used the old DC power supply previously used for the fRC-MIC2. As this power supply could operate at various currents and voltages, it was installed in front of the RRC room so that it could be utilized as a spare of the several power supplies for the RRC when it was not used for the DAKR.

• The polarity switches were added to the power supplies for DMR3, DMR4, and DMR5 dipole magnets on the bypass beam line.

• Three dipole magnets, DMR6, DMR7, and DMR8, were connected in series and excited by the old fRC main power supply removed in 2012 for the enhancement of the fRC.1) The auxiliary power supplies built into the power supply were used for fine adjustment of the magnetic field of individual magnets. The transistor banks in the auxiliary power supplies had to be modified to match the output power of each magnet.

• As the maximum current (300 A) of the existing power supply for the DMD5 dipole magnet immediately before entering the E5 room was insufficient, the 420 A-150 V power supply for RIPS-Q11 was used by switching.

• Fourteen new quadrupole magnets used the power supplies for quadrupole magnets on the IRC-SRC transport line by switching. The cables from the power supplies were wired to the magnets on the new beam transport line and the IRC-SRC transport line through load switching panels.

• The first steering magnet right after the IRC named STR00 used the power supply for STK01 on the IRC-SRC transport line by switching.

• All magnets on the new beam line except STR00 used the dedicated 10 A-60 V power supplies controlled by a Linux-based PLC named F3RP61.

Boring for the wiring through experimental vaults and relocation of the power supplies were completed in 2013. Wiring and an operation test of the power supplies were performed in the summer of 2014. In December 2014, the polarity check and excitation test for all magnets were performed. In January 2015, we planned to carry out the commissioning of the new transport line using the 160MeV/u 16OAr beam.

At present, the switching of the dipole and quadrupole magnets and their polarity is performed manually. In FY2015, we plan to operate switching automatically using buttons.

References

Fig. 1. Layout of the new beam transport line from IRC to E5.
**Improved-flatness beryllium disk stripper for uranium acceleration at RIKEN RIBF**

H. Hasebe,*1 H. Okuno,*1 H. Kuboki,*1 H. Imao,*1 N. Fukunishi,*1 M. Kase,*1 and O. Kamigaito*1

We have successfully provided a stable uranium beam during long-term operation in November 2012 (totally $1.18 \times 10^{18}$ particles in 37 days) using a rotating beryllium disk stripper with a thickness of 0.1 mm as the second stripper. The number of irradiating particles and disk conditions are summarized in Table 1 along with those of other disks described below. This first used Be disk is denoted as Disk 1 in the Table. However, emittance growth due to the nonflatness of the disk exceeded the accepted levels for subsequent cyclotrons (IRC, SRC)1).

To realize flatter disks, we prepared a Be disk subjected to diamond polishing (Disk 2) in March 20132). Also, disk thickness was reduced from 0.1 mm to 0.085 mm, which was suited for the IRC injection energy. Therefore, transmission efficiencies of the IRC and SRC were improved. The Be disk was still usable even after the totally $9.29 \times 10^{17}$ U-particle irradiation during the 30-day beam operation3).

Disk 2 was used again for the U beam time in March 2014. The lifetime of this disk ended and was determined to be additional 21 days (Fig. 1: Right). The total number of U beam particles was 1.68 $\times 10^{18}$ during 51 days (including 30 days in 2013) as written in Table 1. Many cracks were observed along the beam irradiation traces.

The Be disk was replaced with a new one (Disk 3), which was identical to Disk 2 (0.085-mm-thick, diamond polished), for the remaining beam time. Irradiation with an additional $8.83 \times 10^{17}$ U particles was carried out in 17 days. Beam transmission efficiency was improved, but since the thermal load to the disk was increased from 90 W to 230 W because of the increased beam intensity, the disk was greatly deformed. The difference in the deformation is shown in Fig. 1 (Right: Disk 2, Left: Disk 3).

In October 2014, we introduced the Be disk with a special design2) (Disk 4) to reduce the thermal deformation. Due to this improvement, this Be disk survived after the U beam time with approximately $9 \times 10^{17}$ U-particle irradiation in 20 days. Main changes were as follows: 1) The outer diameter of the disk was 110 mm (from 120 mm), 2) 12 areas with cuts existed around the disk circumference, 3) the disk holder was made of copper (from aluminum) with an outer diameter of 65 mm, and 4) 12 holes with 2-mm diameter existed around the holder. Beam availability was further improved by the suppression of the beam fluctuation. The conditions of U beam irradiation are listed in Table 1 (Disk 4). This Be disk is still usable and exhibits no problem. Figure 2 shows the special-design Be disk: left) new and (right) after usage.

![Fig. 1. Polished Be disks after irradiation (Right: Disk 2, Left: Disk 3).](image-url)

![Fig. 2. (a) New specially designed Be disk and (b) after irradiation. Deformation was moderated.](image-url)

### Table 1. Summary of four Be disk used.

<table>
<thead>
<tr>
<th>Be Disk</th>
<th>Irradiation current Total beam particle</th>
<th>Days</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be Disk 1</td>
<td>Not polish 0.1-mm thick</td>
<td>4 - 5 $\mu$A 1.18$\times 10^{18}$</td>
<td>37</td>
</tr>
<tr>
<td>Be Disk 2</td>
<td>Diamond polish 0.085-mm thick</td>
<td>4 - 12 $\mu$A 1.68$\times 10^{18}$</td>
<td>51 (30+21)</td>
</tr>
<tr>
<td>Be Disk 3</td>
<td>Diamond polish 0.085-mm thick</td>
<td>12 $\mu$A 8.83$\times 10^{17}$</td>
<td>17</td>
</tr>
<tr>
<td>Be Disk 4</td>
<td>Diamond polish 0.085-mm thick</td>
<td>8 $\mu$A 9$\times 10^{17}$</td>
<td>20</td>
</tr>
</tbody>
</table>

**References**

2) PASCAL CO., LTD.

   URL: http://www.pascal-co-ltd.co.jp/home.html


---

*1 RIKEN Nishina Center
Thinning effect of gas strippers for high-intensity very heavy ion beams

H. Imao,*1 H. Okuno,*1 H. Kuboki,*1 O. Kamigaito,*1 H. Hasebe,*1 R. Koyama,*1+2 and M. Kase*1

Intensity upgrade of very heavy ions beams, such as U and Xe beams, is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF). In the acceleration of the very heavy ion beams, the possible output intensities have been limited mainly by the lifetime problem of the carbon foil strippers. In previous years, the realization of gas strippers was an important breakthrough for the intensity upgrade of very heavy ion beams. In order to achieve higher intensities of very heavy ion beams, we must understand the application limit of the gas stripper. Density reduction of the gas along the trajectories of the beams, caused by the heat load (thinning effect), is a factor determines the application limit of the gas stripper. To validate the thinning effect at the present intensities, we measured the velocities of the uranium beams after the stripper as a function of the beam intensities.

In the measurements, $^{238}\text{U}^{35+}$ beams up to 1-particle µA at 10.8 MeV/u were injected into the helium gas stripper placed after the RIKEN ring cyclotron. The arrival time of the beams before and after the stripper were measured using the phase probe. The measured time difference ($\propto$ gas density and gas temperature) depends on the output beam current, as shown in Fig. 1, where the beam current is changed with the duty of a beam chopper. For the higher beam current, the velocities of the output beams are higher because of gas density reduction due to higher heat deposition. The saturation of the time difference depends on the chopping frequency $f$, as shown in Fig. 1. The beam structure for the chopping frequency $f$ is also shown in Fig. 1. A simplified differential equation for the temperature rise $T$ is given as $dT/dt = Q/C - c_p m \dot{m}/C$, where $Q$ is the heat load of the beams, $C$ is the heat capacity of helium, $c_p$ is the specific heat of helium for constant pressure and $\dot{m}$ is the mass flow rate. At $Q=0$ (timing of beam off), the temperature reduces with the time constant $\tau = C/c_p \dot{m} = M/\dot{m}$. The saturation also depends on $\dot{m}$ in the beam region.

Figure 2 shows the dependence of the temperature rise of the helium gas stripper on the beam current. The chopping frequency was fixed with 1 kHz in these measurements. Although the temperature rise depends slightly on the beam profile, all measured values were lower than those expected from the calculations (dotted line) with flow-3D (computational fluid dynamics simulation software). A possible explanation may be some suppression mechanisms of heat on helium. Due to vacuum ultraviolet light emission from the excited helium atoms and molecules or energetic delta electrons emission.

In summary, we clearly observed the thinning effect of helium gas stripper by 1-particle µA uranium beams. Our results have important implications for lower heating efficiencies obtained with some suppression mechanisms.

Fig. 1. The dependence of the arrival time difference on the beam duty for various chopping frequencies (up) and the beam structure of the chopped beam (down).

Fig. 2. Dependence of the temperature rise of helium on the beam current. Dotted line indicates the calculated values.

References
1) H. Imao et al., IPAC 2013, Shanghai (2013).

*1 RIKEN Nishina Center
*2 SHI Accelerator Service Ltd.
Control and monitoring system of gas strippers

R. Koyama\textsuperscript{a,1,2} and H. Imao\textsuperscript{a1}

We report on the control and monitoring system of a gas stripper, a new RIBF charge stripper using a gas target. A gas stripper has been developed as an alternative to a traditional carbon-foil stripper for increasing the intensity in very heavy ion beams such as uranium or xenon beams at the RIBF. A recirculating helium gas stripper\textsuperscript{1} and an air stripper\textsuperscript{2} are installed at the A02 site after the RRC and at the M04 site after the fRC (GS-A02 and GS-M04), respectively.

The schematic block diagram of their control and monitoring system is shown in Fig. 1.

![Schematic block diagram of control and monitoring system for gas strippers](image)

Fig. 1. Schematic block diagram of control and monitoring system for gas strippers.

We developed a user-friendly GUI program using the LabVIEW for the system, which includes the following:

- Remote control of the pressure and/or flow rate of the target gas
- Monitoring of the pressure of each differentially pumped section
- Monitoring of buffle current BF1–BF5 (beam loss monitor) via the EPICS control system\textsuperscript{3,4}
- Monitoring of the temperature of orifices OT1–OT8 and mechanical booster pumps PT1–PT3
- Signal output to the beam interlock system in response to the monitoring value via the NI CompactDAQ
- Data recording to the MyDAQ2 system\textsuperscript{3)

The developed system allows us to remotely optimize the target pressure of gas strippers with the assistance of the online beam monitoring system\textsuperscript{8). Figure 2 shows the correlation among the target pressure of GS-A02, beam timing, and beam intensity nondestructively observed by a phase probe (PP).

In this case, the beam timing at PP-D15 (31 m downstream of the GS-A02) gradually varied owing to the energy loss reduction in the GS-A02 as its target pressure decreased\textsuperscript{9), resulting in a 10% decrease in beam intensity at PP-G01 (5 m downstream of the SRC). The beam intensity was recovered by twice fine controlling the target pressure by observing the beam monitoring system, as indicated by the arrows in Fig. 2. The pressure should be regulated with ±1% accuracy by the control unit, however, it got out-of-control at the end of the machine time, so we speculate that its accuracy was reduced owing to irradiation damage to the regulating valve EVR 116 near the GS-A02 in the RRC vault. EVR 116 has been replaced with radiation-proof RME 005 A.

References

6) H. Imao et al.: in this proceedings.
Beam Energy and Longitudinal Beam Profile Measurement System at the RIBF†

T. Watanabe, †M. Fujimaki, †N. Fukunishi, †H. Imao, †O. Kamigaito, †M. Kase, †M. Komiyama, †N. Sakamoto, †K. Suda, †M. Wakasugi, †and K. Yamada†

Monitors with plastic scintillators as sensors (scintillation monitors) were fabricated to measure the energy and longitudinal profiles of heavy-ion beams at the RIKEN RI beam factory (RIBF). Six pairs of two scintillation monitors installed in the transport lines were used to measure the particle time-of-flight (TOF) between the paired monitors to determine the acceleration energy of the heavy-ion beams. The energy of the beam can be calculated from the measured TOF. In addition, five scintillation monitors were installed to measure the longitudinal profiles of the heavy-ion beams. Longitudinal beam profiles were obtained by using a time-to-digital converter (TDC), which digitizes the detected signals from the scintillator and the RF clock signal. Recently, to help users operate the system more easily, a new embedded processor with a higher-performance CPU has been introduced, and a new user interface has been constructed using the LabVIEW program.

For data acquisition and control of the scintillation monitors, we developed a compactPCI system that uses a Windows-based PC†. Signals from the detectors are amplified and converted to logic pulses by a constant-fraction discriminator. The TDC digitizes this pulse along with the RF clock and stores the events into the memory of the TDC. The TDC (TC890) has two memory banks based on a so-called ping-pong memory architecture that enables data readout while the module continues to acquire events. When a bank is ready to be read, an interrupt is generated, and the readout starts in the direct memory access mode.

Fig. 1. Longitudinal profiles the $^{19}$F$^{9+}$ beam measured at C20 (upstream) and C22 (downstream) in the AVF cyclotron beam transport line as displayed on the graphical user interface.

Fig. 2. Gaussian functions fit to the rightmost beam profiles at C20 and C22 in Fig. 1.

The programs for the data acquisition, control, and for showing results are written in LabVIEW (Windows7). The PCs are connected to a laptop in the main control room located 100 m from the Riken ring cyclotron (RRC) hall via Ethernet and remote desktop connection. The EPICS system controls insertion of the monitor into the beam line or its retraction from the beam line and it monitors these statuses.

We measured the energy of a $^{19}$F$^{9+}$ beam accelerated by the AVF cyclotron by using the TOF method. The $^{19}$F$^{7+}$ beam was used to produce element 105, $^{262}$Db from a target of $^{248}$Cm$^{2+}$. Because the sequential double pulse resolution was 15 ns, the $^{19}$F$^{9+}$ beam was attenuated to be under 1 M s$^{-1}$ using beam attenuators. The longitudinal profile of the $^{19}$F$^{9+}$ beam was measured at C20 (upstream) and C22 (downstream) in the AVF cyclotron beam transport line were displayed on the graphical user interface as shown in Fig. 1. The rightmost longitudinal profiles obtained at C20 and C22 in Fig. 1 are expanded and plotted in Fig. 2. By fitting the profiles in Fig. 2 with Gaussian functions, we determined the center times $T_{C20}$ and $T_{C22}$ of the profiles and the longitudinal phase widths (1-$\sigma$), as shown in Fig. 2. The beam kinetic energy ($T_{TOF}$) obtained by measuring the TOF was 6.81 MeV/u. In addition, the beam kinetic energy ($T_{BP}$) can be determined by the magnetic field of the bending magnet that bends the $^{19}$F$^{9+}$ beam because the field was already known as a function of the exciting current. In this measurement, the hysteresis effect was not taken into account. The kinematic energy $T_{BP}$ was determined to be 6.80 MeV/u. These energies are in good agreement, with a difference between $T_{TOF}$ and $T_{BP}$ of 0.1%.

References

†Condensed from the proceedings in 5th International Particle Accelerator Conference (IPAC14)
*†RIKEN Nishina Center
Maintenance and development of the RIBF control system

M. Komiyama,*1 A. Uchiyama,*1 M. Fujimaki,*1 K. Kumagai,*1
N. Fukunishi,*1 M. Hamanaka,*2 and T. Nakamura*2

We report on the maintenance work and development of the RIBF control system, which include addressing a problem experienced with a beam interlock system (BIS), upgrades for two types of control boards used for magnet power supplies and an extension of the control system to install a new beam transport line.

The RIBF control system consists of two parts according to the development of RIBF. One of them is used for the old facility, once called the RIKEN Accelerator Research Facility (RARF), which started its operation in 1986. The other is the new facility that started its operation in 2006. A BIS was developed to protect the hardware of the RIBF accelerator complex from unallowable beam losses for high-power heavy ion beams. The BIS is composed mainly of Melsec PLCs that process many interlock signals, such as failure signals sent from rf systems used in our cyclotrons, magnet power supplies, and vacuum gate valves in beam transport lines, within 1ms. At the RIBF facility, there are two sets of BIS working for the old facility and the new facility as well as the control system. In 2014, we experienced for the first time a serious problem in which several interlock conditions were changed without any command inputs. After careful investigations, the cause of this malfunction, a failure of the CPU module used in the BIS, was rectified by replacing the existing CPU module with a spare one. Because the hardware used in the BIS is aging and the trigger of this malfunction is unclear, we prepared spare CPU modules in preparation for similar troubles in the future; this would be effective in reducing downtimes during RIBF operation.

The second topic is upgrades for the Network-I/O (NIO) system. The NIO is a commercially available control system manufactured by Hitachi Zosen Corporation. It is widely used to control many magnet power supplies used in the new facility and a part of the old facility. The NIO system consists of several types of controllers. The NIO-S board is directly attached to a magnet power supply and controls it according to a signal from an upper-level control system. About 500 NIO-S boards are used in RIBF. The NIO-C board works as a master board of NIO-S boards and is designed to run in VME computing machines. The NIO-C and the NIO-S are connected by an optical cable through a branch board. The existing NIO system has been working stably but production of the present NIO-S board was terminated because some parts are unavailable today. Therefore, we developed a successor of the existing NIO-S board in 2013 and this year we ran its performance tests. This successor was designed to be compatible with the existing NIO-S board but the performance tests revealed that some types of magnet power supplies cannot be controlled by the successor because the widths of some output pulses produced by the successor are slightly different from those given by the existing one. Currently, finding a solution to stably control these magnet power supplies is under consideration.

On the other hand, production of the NIO-C has also been completed for the same reason as in the case of NIO-S. Hence, we should also develop a successor board of the present NIO-C. Its R&D started in 2014. The specifications required for the new board are essentially the same as for the existing one, but we decided to design the new board to run in a control system constructed by PLC modules instead of the VME computing environment currently used, in order to achieve cost reduction and functional scalability.

We started the design of its prototype in 2014, which is scheduled to be delivered in March 2015. Software developments required for the successor board are scheduled in 2015, where some new features will be added.

The third topic is extension of the control system to cover a new beam transport line now under construction, aiming at increasing the available beam energies in the existing beam irradiation port dedicated to biological experiments. The new beam line transports a beam extracted from the intermediate stage ring cyclotron (IRC) to the E5 experimental vault (hereafter, IRC-E5 BL). The control system for the IRC-E5 BL is constructed as a natural extension of the existing control system of the RIBF accelerator complex by adding the new components used in the IRC-E5 BL to the existing control system because no new types of components are installed in the IRC-E5 BL. Magnet power supplies are controlled by the NIO system and F3RP61,3) which is a Linux-based PLC-CPU module manufactured by Yokogawa Electric Corporation, on which EPICS programs can be executed. Vacuum systems and beam diagnostic devices such as beam profile monitors are controlled using in-house controllers’ Network Device Interface Module (N-DIM4) as well as the other beam transport lines of the RIBF accelerator complex. Regarding the beam interlock signals of the IRC-E5 BL, we incorporate them into BIS. Beam commissioning is scheduled in January 2015.

References
2) http://www.mitsubishielectric.co.jp/fa/products/cnt/plcq/items/
3) http://www.yokogawa.co.jp/rtos/Products/rtos-prdcpu9-ja.htm

*1 RIKEN Nishina Center
*2 SHI Accelerator Service Ltd.
Development of new operational log system for RIBF operation

A. Uchiyama,*1 M. Komiyama,*1 and N. Fukunishi*1

The operational log system is one of the electric log systems for recording and viewing the accelerator operation time and contents of an operated device. Zlog (Zope-based log system) developed by KEK was utilized as the operational log system for the RIKEN RIBF control system. Zope is an open-source Web server and Web application framework written in Python programming language. Using the Web application, information on accelerator operation is designated by a character string on Web browsers. However, the displayed string character on the Web browser will be complex for accelerator operators because many parameters are changed in accelerator operation, though the Web-based system has many advantages. For smoother accelerator operation, an ergonomically designed operational log system is required. Additionally, it is not always easy to set the many monitored parameters for Zlog without omission, because the user must code with Python programming language for one monitored parameter in the case of the Zlog system. Therefore, we developed a new operational log system for RIBF control system.

When the monitored operation status, such as the DAC value of a magnet power supply, is changed, the status is stored as operational information into the database. As one of the features, the monitor program acquires the event signal via the EPICS PV gateway because EPICS input/output controllers (IOCs) require much system resources when a large number of calMonitors are connected to EPICS IOCs. In order to construct a Web application as the user interface for providing operational information, the Apache Web server and Bootstrap Web framework, are used by the system. Therefore, it is possible to provide operational logs with a variety of rich GUI components.

As of now, the operational log system has been working for accelerator operation by monitoring approximately 3,000 points as the EPICS record without any serious problem since November 2013. As an example, the user interface of the operational log for magnet power supplies is shown in Fig. 2. The operational log is displayed by using a character string and line chart on a Web browser (Firefox). In the near future, we will update the system for improving the usability to fully satisfy the requirements of users.

Fig. 1. Outline of the new operational log system.

In addition to the Zlog system, the PostgreSQL-based database, which is one of the major relational databases, is adopted for recording logs in the new operational log system. In order to ensure compatibility with Zlog, the new operational log system uses the same database table configuration as in Zlog. The system chart of new operational log system is shown in Fig. 1. The RIBF control system consists of a distributed control system constructed using the Experimental Physics and Industrial Control System (EPICS). Therefore, the feature to store the data into the database is developed on the basis of caMonitor, which is an event driven program using EPICS channel access (CA) protocol.

Fig. 2. User interface showing operational log for magnet power supply.

References

2) http://www.zope.org/
5) http://getbootstrap.com/

*Riken Nishina Center
Commissioning of the Laser Ion Source for RHIC EBIS †

M. Okamura *1,*2 and T. Kanesue *1

The electron beam ion source (EBIS)-based heavy ion preinjector (RHIC-EBIS) served for RHIC and NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) 1). The NSRL is a facility that simulates the effect of galactic cosmic radiation (GCR), which consists of highly energetic heavy ions of various kinds in space. The RHIC-EBIS is required to provide fast switching between heavy-ion species for this purpose. A new laser ion source (LIS), named “LION,” is funded by NASA to expanding the range of ion species available for fast switching. Fast switching can be accomplished by switching the laser-irradiation position on different target materials 2,3).

LION consists of a high-power pulsed laser, a target chamber, a 3-m-long plasma drift region with a solenoid magnet, and an extraction chamber. The ion extraction voltage may be up to 40 kV. The laser is equipped with two identical Q-switched Nd:YAG laser oscillators (850 mJ/6 ns at FWHM, 1062 nm wavelength ). A built-in laser combiner merges the two laser beams into one laser path to aim at the same position. The laser is focused on a solid state target plate. The laser spot on the target is 5 mm in diameter. Different laser energies in the range 500 ~ 700 mJ is used depending on the species to achieve singly charged ions. In a target chamber, several targets are held on a tungsten target holder, as shown in Fig.1, which is mounted on an x-y linear stage. The stage allows the laser to irradiate different positions on different target materials. The solenoid magnet is used to reduce the diverging angle of the expanding plasma. The typical magnetic field to be used is only several Gauss. With this drift length, an ion beam with a pulse width of a few hundred microseconds is achieved.

The commissioning of the beam was started on March 7, 2014 with an Fe target. LION was isolated from the EBIS beam line to prevent RHIC gold run as a precaution. The platform voltage was set to 12 kV for the first beam test. The Fe beam extracted from the LION was very close to what we expected. No breakdown caused by the generated plasma was observed.

From March 14, the operation mode of EBIS was adjusted for LION. The transport line and the EBIS injection timing were investigated to capture ions. The first beam extracted from the EBIS was observed on March 16.

On March 26, the first beam at the NSRL target room was observed with a Ta beam. The beam intensity was sufficiently high for an NSRL run. Hence, we decided to use the LION for an NSRL run.

† Condensed from the article in Proceeding of IPAC2014 (2000)

*1 Collider-Accelerator Department, BNL
*2 RIKEN Nishina Center

References
NISHINA RIBF water-cooling system 2014

T. Maie,*1 K. Kusaka,*1 M. Ohtake,*1 Y. Watanabe,*1 E. Ikezawa,*1 M. Kase,*1 M. Oshima,*2 H. Shiraki,*2 K. Kobayashi,*3 and J. Shibata *3

1. Operation condition
In the fiscal year 2014, the Nishina and RIBF water-cooling installation was operated for one hundred and fifty days and five months, respectively. These operation periods correspond to the scheduled beam service time of RIBF, which is five months. In addition, Nishina’s cooling installation was used not only for the full RIBF operation but also for the AVF standalone operation, RILAC + RRC operations, RILAC2+ RRC operations, and AVF + RRC operations. During FY2014, there were no severe problems that caused beam service interruption for the Nishina and RIBF cooling water system. However, mind problems were often encountered, these are reported here.

2. Trouble report
Water leakage in the cooling system was a problem, particularly water leakage from a connection part of the flange portion and coupler in the cooling laying of the pipes. Another problem is the deterioration due to aging of the slack and the flange packing of the bolt by the vibration of the coolant pump, electrolytic corrosion, corision of the cooling plumbing is important. However, with the cooling facilities at the Nishina center, a water leakage sensor is attached to the outside of the accelerator and a beam line, the point of the cooling plumbing and, regardless of the whole stop, a member of driving of the accelerator discovers it easily while driving and comes to be able to cope. Other problems, include issues with the inverter, pressure gauge, and flowmeter, as well as problems with the packing of the coolant pump and damage of the mechanical seal; control is the main problem that occurred in 2014. In some cases, damage to the motor of the cooling tower fan occurred at snowy weight by the snow. Other factors affecting cooling facilities other than the above-mentioned problems include a affected by cooling facilities than a stop of steam and the cold water supplied from rolling blackouts and the cogeneration in the place. SRC and the Big RIPS He-refrigerator do not become if they do not always cool off, and it is necessary for pro-backup, to change the power supply and coolant beforehand to prevent one from being affected by a blackout and suspension of the water supply, which 2-3 times occurs in a year.

3. New establishment, improvement
Even during periodical maintenance, etc. when the accelerator is stopped, the RIBF cooling facilities have various new establishments and show, improved construction. It is built the cooling facilities for return beam lines as a representative thing by new construction sequentially from the year before last; As an example of the improved construction, I improved the cooling plumbing for the ability for cooling reinforcement pro-IRC and SRC exc. cooling and cooling reinforcement of SRC-MDC1 sequentially from last year.

4. Summary
I intend to minimize the problems associated with cooling facilities in future, while aiming for stable cooling facilities without problems, and suggesting the enforcement of effective maintenance, and undertaking premeditated deterioration measures.

References
1) T. Maie et al.: RIKEN APR .47
2) Y. Watanabe et al.: RIKEN APR .48

*1  RIKEN Nishina Center
*2  Nippon Kucho Service Co., Ltd
*3  SHI Accelerator Service Co., Ltd
Charge State Selective Ion Beam Acceleration Using the RFQ Linac

Y. Fuwa,∗1,∗2 S. Ikeda,∗1,∗3 T. Kanesue,∗4 M. Okamura,∗4 and Y. Iwashita∗5

In the field of Heavy ion beam Inertial Fusion (HIF) 1), one of the promising ion species as the driver beam is Bi2+. Considering a scenario based on the RF accelerator, a laser ion source with the Direct Plasma Injection Scheme (DPIS) 2) has the advantage to provide high-intensity heavy ion beams 3). Ion charge states produced by laser ion sources has distribution 4). With DPIS, all charge states of ions can be injected into an RFQ linac. However, in the case of Bi2+ production, Bi1+ and Bi3+ would also be injected. These unnecessary ions would waste RF power and/or cause unexpected radioactivation. Thus, charge-state-selective acceleration using the RFQ linac is desired. In this study, a scheme to achieve charge-state-selective ion beam acceleration is discussed.

In the case of accelerating ions with a charge state \( q \) and a mass number \( A \) different from the desired particle with \( q_0 \) and \( A_0 \), the condition for stable acceleration is described as below 5):

\[
\frac{q}{A} \cos(\phi_s) = \frac{q_0}{A_0} \cos(\phi_{s0}),
\]  

(1)

where \( \phi_s \) is the synchronous phase of a particle with charge-to-mass ratio \( q/A \), and \( \phi_{s0} \) is that of the desired particle. Then, the condition of capture for the case of \( A = A_0 \) is

\[
0 < \frac{q_0}{q} \cos(\phi_{s0}) < 1.
\]  

(2)

Usually, the synchronous phase of the desired particle in the accelerating section of the RFQ linac is approximately −30°. Therefore, by choosing Bi2+ as the desired particle (\( q_0 = 2 \)), Bi1+ (\( q = 1 \)) has no stable phase and would not be accelerated, while unwanted Bi3+ will be accelerated. The results of a particle tracking simulation show that more than 30% of Bi3+ are captured and accelerated by a conventionally designed RFQ for Bi2+.

One of the solutions to accelerate only Bi2+ is the following scheme: 1) The ions are injected into the RFQ with different momentums depending on charge state \( q \). Using this initial momentum difference between Bi2+ and Bi3+, these ions can be pre-bunched separately in the longitudinal phase space. 2) The modulation or acceleration voltage is raised when Bi2+ ions are in the acceleration phase and Bi3+ ions are in the deceleration phase, and Bi2+ ions would gain energy while Bi3+ ions would be decelerated. 3) Due to the energy difference between Bi2+ and Bi3+, only Bi2+ ions would be captured in the RF bucket and be stably accelerated. To realize this scheme, we varied cell lengths in the bunching section. An example of the sequence of the designed cell parameters is shown in Fig. 1. Fig. 2 shows the particle tracking simulation results with the cell parameters shown in Fig. 1. The capture rate of Bi3+ could be suppressed by up to 3 %.

References
Investigation of the effect of solenoidal magnetic field on Fe plasma flux for application to laser ion source

S. Ikeda,*1,*2 M. Okamura,*3 and K. Horioka*2

Laser ablation plasma has been studied as a highly charged ion source for nuclear physics experiments1) and as a high flux ion source for heavy ion inertial fusion,2) and it is used as an ion source at Brookhaven National Laboratory3). In a typical configuration of the source, plasma flux at an extractor varies as a function of time. The time-dependent flux results in the changes in the ion beam current and its optics within a beam pulse. To prevent the changes, we propose to apply a pulsed magnetic field. Enhancement of the flux after passing through a static solenoidal magnetic field was observed4). The enhancement depended on the magnetic intensity. Therefore, if we apply the fast-rising magnetic field in accordance with the transient flux level of the plasma, we will be able to make the flux level flat.

To predict the optimal pulsed magnetic field, we first investigated the effect of a static magnetic field that was driven by quasi-stationary current during the plasma passing through the coil. We scanned a biased ion probe detecting plasma flux transversely or normal to the plasma drifting direction by applying a magnetic field.

Figure 1 is a brief schematic diagram of the experimental setup. A Nd:YAG laser irradiated an iron target with a pulse width of 6 ns and intensity of $4.0 \times 10^8$ W/cm$^2$. At this irradiation level, the laser mainly produces singly charged ions in the chamber evacuated to $4 \times 10^{-4}$ Pa. The coil was driven by a pulse circuit. During the plasma passing through the coil, the decrease in magnetic flux density was less than 10% and we can regard the magnetic field as almost constant during the interaction. A 2-mm-diameter aperture and a metal mesh whose transparency was 90.3%, were grounded and placed in front of the probe.

Figure 2 shows the transverse distribution of plasma flux whose longitudinal velocity $v_z$ is 14 mm/$\mu$s at 870 mm away from the target. $v_z$ was estimated by division of the distance by the time of flight. Horizontal axis is the distance $x$ from the center axis. Each point is an average of 3 data. The red squares are data with no magnetic field and green ones are in the presence of magnetic field. The magnetic flux density at the center of the coil is estimated to be 40 G using a simulation code (OPERA). When the magnetic field was applied, two peaks and decrease in the flux near the center axis were observed. The formation of two peaks around $x = -15$ and 20 mm means that the plasma collected around the radius. The collection indicates that the magnetic field had focusing force that increases nonlinearly with increasing $x$. On the other hand, the decrease in the flux around the center ($x = 0$ mm) may mean that the magnetic field does not converge the plasma within a certain value of $x$. The difference in the magnetic field effect on the plasma with respect to $x$ may result from the shape of the magnetic field. We need to investigate this difference in order to increase the ion flux with minimum emittance growth. The discussion of the enhancement mechanism will help optimize the parameters of pulsed magnetic field.

References
9. Instrumentation
The first cooling down of the superconducting SAMURAI magnet was done by TOSHIBA in April 2011, and we had maintained the operation of the cryogenic systems of the magnet. However, the magnet was warmed up in September 2013 in order to save the operation time of the cryocoolers. Therefore, the magnet was cooled down again in February 2014 for the coming experiments. The cooling operation was performed by ourselves in order to save the cost.

Firstly, the pumping of the vacuum vessels of the cryostats was started. We waited for 8 days until the vacuum level reached $2 \times 10^{-5}$ Torr. Secondly, the cooling-down procedure was started. The temperature of each point in the cryostat, excluding the coil, was monitored by thermometers. The temperature of the coil was monitored by measuring the resistance of the coil using the correlation shown in Fig. 1. Although the temperature below 9 K cannot be measured with this method, there is no problem for the cooling-down operation because the temperature of the coil vessel is also monitored.

![Resistance vs Temperature Graph](image)

Fig. 1. Correlation between resistance and temperature of the superconducting coil. The upper and lower insets are an enlarged graph of below 20 K and a schematic diagram of the measurement of the resistance, respectively.

Figure 2 shows the trend of the temperature, pressure in the helium vessels, and liquid helium level. It took one month to complete the cooling-down operation, and 7,125 L of liquid nitrogen (LN$_2$) and 3,145 L of liquid helium (LHe) were used in total. The graph of the lower coil exposes our inexperience of the cooling of the magnet. This led to imperfect removal of LN$_2$, resulting in the dissipation of LHe. However, we gathered technical know-how during the cooling-down procedure of the lower coil.

1) The cooling-down speed during LN$_2$ transfer should be around 10 K/h. (2) Special care must be taken when checking the residual LN$_2$. (3) The pressure of gaseous He should be 0.03–0.05 MPa when pushing and removing LN$_2$. (4) The coil vessels should be evacuated to be $-99$ kPaG before replacing the residual gaseous N$_2$ in the coil vessels with gaseous He. It takes about 30 min. (5) The position of the transfer tube in the service port is very important in order to transfer LHe without loss. (6) The pressure of gaseous He should be 0.03–0.05 MPa, and that of the LHe Dewar should be 0.028–0.034 MPa (4–5 psi) when transferring LHe. These were successfully applied to the cooling of the upper coil. In our next operation, the period of the cooling down will be shortened, and the amount of LN$_2$ and LHe will be reduced with the experience gained in this study.

References
Operational status of the superconducting SAMURAI magnet

H. Sato,*1 K. Kusaka,*1 M. Ohtake,*1 and T. Kubo*1

The first cooling down of the superconducting SAMURAI magnet1) was done by TOSHIBA in April 2011, and we had maintained the operation of the cryogenic systems of the magnet. However, the magnet was warmed up in September 2013 in order to save the operation time of the cryocoolers2). Therefore, the magnet was cooled down again in February 2014 for the coming experiments. The cooling operation was performed by ourselves in order to save the cost.

Firstly, the pumping of the vacuum vessels of the cryostats was started. We waited for 8 days until the vacuum level reached $2 \times 10^{-5}$ Torr. Secondly, the cooling-down procedure was started. The temperature of each point in the cryostat, excluding the coil, was monitored by thermometers. The temperature of the coil was monitored by measuring the resistance of the coil using the correlation shown in Fig. 1. Although the temperature below 9 K cannot be measured with this method, there is no problem for the cooling-down operation because the temperature of the coil vessel is also monitored.

Figure 2 shows the trend of the temperature, pressure in the helium vessels, and liquid helium level. It took one month to complete the cooling-down operation, and 7,125 L of liquid nitrogen (LN$_2$) and 3,145 L of liquid helium (LHe) were used in total.

The graph of the lower coil exposes our inexperience of the cooling of the magnet. This led to imperfect removal of LN$_2$, resulting in the dissipation of LHe. However, we gathered technical know-how during the cooling-down procedure of the lower coil. (1) The cooling-down speed during LN$_2$ transfer should be around 10 K/h. (2) Special care must be taken when checking the residual LN$_2$. (3) The pressure of gaseous He should be 0.03–0.05 MPa when pushing and removing LN$_2$. (4) The coil vessels should be evacuated to be $-99$ kPaG before replacing the residual gaseous N$_2$ in the coil vessels with gaseous He. It takes about 30 min. (5) The position of the transfer tube in the service port is very important in order to transfer LHe without loss. (6) The pressure of gaseous He should be 0.03–0.05 MPa, and that of the LHe Dewar should be 0.028–0.034 MPa (4–5 psi) when transferring LHe. These were successfully applied to the cooling of the upper coil. In our next operation, the period of the cooling down will be shortened, and the amount of LN$_2$ and LHe will be reduced with the experience gained in this study.

References

*1 RIKEN Nishina Center

Fig. 1. Correlation between resistance and temperature of the superconducting coil. The upper and lower insets are an enlarged graph of below 20 K and a schematic diagram of the measurement of the resistance, respectively.

Fig. 2. Trend graph of the upper and lower coil during the cooling. $T_c$ means the temperature of each part1). $P_{\text{He}}$ means the pressure in the helium vessel. Liquid He means the LHe level (100%≈240 L). The notation “CC” means 20 K, 80 K, PL cryocoolers, and “GM/JT” the GM/JT cryocoolers1).
Preparation status of the \((p, 2p)\) fission experiment with the SAMURAI spectrometer

S. Reichert,∗1,∗2 M. Sako,∗2 M. Sasano,∗2 D. Mücher,∗1,∗2 A. Andreyev,∗1 T. Aumann,∗4 H. Baba,∗2 M. Böhmer,∗1 M. Dozono,∗5 N. Fukuda,∗2 R. Gernhäuser,∗1 W. F. Hennig,∗6 K. Hirose,∗3 N. Inabe,∗2 D. Kameda,∗2 N. Kobayashi,∗2 T. Kobayashi,∗7 Y. Kondo,∗6 T. Kubo,∗2 Y. Kubota,∗2,∗5 R. Lang,∗1 L. Maier,∗1 Y. Matsuda,∗9 S. Mitsuoka,∗4 T. Motobayashi,∗2 T. Nakamura,∗8 N. Nakatsuka,∗9 S. Nishimura,∗2 I. Nishinaka,∗3 K. Nishio,∗∗3 R. Orlandi,∗3 H. Otsu,∗2 V. Panin,∗2 S. Sakaguchi,∗2 H. Sato,∗2 Y. Shimizu,∗2 L. Stuhl,∗2 T. Sumikama,∗2 H. Suzuki,∗2 H. Takeda,∗2 Y. Togano,∗2 T. Uesaka,∗2 J. Yasuda,∗2 K. Yoneda,∗2 and J. Zenihiro∗2

The experiment NP-1306-Samurai14 is the first attempt at determining fission barrier heights for unstable nuclei like \(^{212}\)Bi or \(^{213}\)Po\(^1\)). For this the missing mass spectroscopy of the two protons from the \((p, 2p)\) reaction in inverse kinematics provides a suitable method of determining the threshold for the fission barrier height unambiguously and directly. We report on the development status of the experimental setup for measuring the \((p, 2p)\) reaction using the heaviest projectiles.

The goal for the resolution power of the setup is to achieve an energy resolution of \(\sigma = 1\) MeV for the reconstructed excitation energy. The systematic uncertainty in the reconstructed missing energy should be less than 0.1 MeV. To realize this goal we need to measure the opening angle and energies of two emitted protons with resolutions of \(\sigma_{\theta, p} < 3\) mrad and \(\sigma_{E, p} / E_p < 2\%\).

The design of the \((p, 2p)\) setup is schematically shown in Fig. 1. The setup consists of a vacuum chamber containing a liquid hydrogen target and three layers of single-sided detectors on two arms with respect to the beam line. The reaction point and the emission angles of emitted protons are determined by the silicon detectors in connection with the beam trackers of the standard SAMURAI setup, BDC1 and BDC2. The setup has additional plastic scintillation detectors at a distance of 1.6 m from the target and outside the vacuum chamber to measure the time of flight (TOF) of protons in order to determine their kinetic energies.

We prepare two types of silicon detectors with the same dimensions of 51 \(\times\) 78 mm; the first type (type A) is segmented to 768 strips parallel to the short side with a 100 \(\mu\)m pitch, whereas the other type (type B) has 498 strips parallel to the long side with the same pitch size as type A. The three layers in one arm are structured in this way: The closest one to the target is type A, from which two sets of type A and B detectors are placed at a center distance of 10 cm to fit the solid angle coverage. They are mounted in parallel with the beam line as shown by the red lines in Fig. 1, aligning the shorter side of the detector vertically.

The type A and B detectors are used to determine horizontal and vertical positions of proton tracks, respectively. To meet the requirements on the open-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig1}
\caption{Target chamber (top view) including three layers of one-dimensional silicon strip detectors on each side.}
\end{figure}

References


---

\*1 Technical University Munich
\*2 RIKEN Nishina Center
\*3 ASRC JAEA
\*4 Technical University Darmstadt
\*5 Center for Nuclear Studies, University of Tokyo
\*6 ANL
\*7 Tohoku University
\*8 Tokyo Institute of Technology
\*9 Kyoto University
Slow neutron detector WINDS for \((p,n)\) reaction in inverse kinematics with SAMURAI


In April 2014, we performed the SAMURAI17 experiment\(^1\) at RIKEN RIBF to study Gamow-Teller transition on \(^{132}\)Sn by using \((p,n)\) reaction with the Wide-angle Inverse-kinematics Neutron Detectors for SHARAQ (WINDS)\(^2\) and the SAMURAI spectrometer.

Figure 1 shows a schematic view of the experimental setup around the target. The secondary beam was transported to a 10 mm thick liquid hydrogen target, which was surrounded by the WINDS to detect recoil neutrons. From the measured neutron time-of-flight (TOF) and recoil angle, the excitation energy and center-of-mass angles are determined.

The WINDS consists of 61 plastic scintillators with sizes of \(600 \times 100 \times 30 \text{ mm}^3\). In this experiment 12 scintillators of the ELENS\(^3\) with sizes of \(1000 \times 45 \times 10 \text{ mm}^3\) were also installed. The left and right walls with respect to the beam line covered the angular region from 20 to 122 degrees with 5 degree steps. Top and bottom walls covered the angular region from 16 to 74 degrees with 3.5 degree steps. Each detector is placed such that the 30-mm-wide (WINDS) or 10-mm-wide (ELENS) plane is oriented to the target direction and placed at a distance of 900 mm (1200 mm) from the target for left and right (top and bottom) walls.

The charge signal from each PMT is digitized by a CAEN V792 QDC. The timing signal is processed by a leading-edge discriminator (LeCroy 4143) and digitized by CAEN V1190 TDC. In order to maintain a low threshold of neutron detection, the PMT voltage is kept to be as high as possible, typically -2700V and -2500V for H7195 and H7415. The threshold for light output in the scintillator was set to be 70 keV proton energy.

The timing resolution of WINDS bar was estimated by using prompt \(\gamma\) ray from the liquid hydrogen target. The timing reference was taken from the plastic scintillators SBT1,2 whose timing resolution is typically 40 ps in FWHM. The observed peak width of the prompt \(\gamma\) ray was 800 ps in FWHM which is most due to the timing resolution of WINDS. This timing resolution corresponds to energy resolution of \(\Delta E/E = 11\%\).

The neutron-detection efficiency depends on the energy of neutrons as well as the threshold on light output. The typical efficiency with a threshold of 60 keV was estimated by using the Monte Carlo code of MCNP\(^4\), and it varied from 40% at 0.6 MeV neutron to 20% at 4 MeV neutron. The efficiency calibration was performed by locating a neutron source of \(^{252}\)Cf at the target position with a NE213 liquid scintillator whose absolute efficiency as well as energy and threshold dependence are well known. The data analysis is currently in progress.

References
1) M. Sasano et al., in this report.
4) Monte Carlo NParticle Transport Code System, MCNP5-1.60 and MCNPX-2.7.0.
Integration of GET system for SπRIT-TPC

T. Isobe,∗1 M. Kurata-Nishimura,∗1 H. Baba,∗1 N. Nakatsuka,∗2 T. Murakami,∗2 W.G. Lynch,∗3 J. Barney,∗3 J. Estee,∗3 S. Tangwancharoen,∗3 G. Jhang,∗4 W. Powell,∗5 and Y. Ayyad,∗6 for the SπRIT Collaboration

A Time Projection Chamber (TPC) has been produced as the main detector of the SAMURAI-SπRIT project for the study of the nuclear equation of state using heavy ion collision experiments1). As the readout system for the SπRIT-TPC, we have integrated the Generic Electronics for TPC (GET) system2), which was developed mainly by a France and USA collaboration3). For the integration of GET electronics, development of interfaces in terms of both hardware and software are necessary.

Since the GET system was developed for general usage, the interface of the GET electronics to a TPC depends on the specifications of each detector, such as connector types and the signal characteristics of the detector, and this interface has to be developed for each project. We call such an interface a ZAP board, which serves as an adapting connector between the GET electronics and the TPC, as well as providing protection for the electronics. Thus GET electronics can be mounted on any TPC by just making the ZAP board. There are several requirements for designing the ZAP board. In the case of SπRIT-TPC, the board was designed to fit in the space on the TPC which is supposed to be installed in the SAMURAI chamber, to reduce the noise in order to increase the dynamic range, and to reduce the distortion of gain among the different channels. It is especially important to reduce noise since it strongly affects the electrical treatments of a signal. Here the electrical treatments of each signal are: 1. hit pattern register which is made by the discriminator on each signal after the pre-amplification, 2. internal trigger which is made with the hit pattern register, and 3. zero-suppression of digitized signal. The quality of the internal trigger strongly depends on noise level, which is strongly affected by the design of the ZAP board.

To satisfy our requirements, prototypes of several types of interface boards were made and the above requirements were checked quantitatively by using the minimum GET system composed of CoBo+AsAd+ZAP boards. The AsAd board is for the amplification and digitization of an analog signal3). The AsAd must be installed near the TPC in order to reduce noise. The CoBo board is for handling the trigger, controlling the AsAd and managing data3).

To fit the AsAd board on the SπRIT-TPC within the limited vertical space of ∼17 cm, a prototype flexible ZAP made of a thin Cu plate (10 µm) and polyimide (12.5 µm) was first made. The noise level of the flexible board, which can be estimated through RMS of pedestal, is not small. This is most likely due to the large capacitor made by the noise shield and signal line (50~100 pF/ch). The capacitance of each signal line can be roughly calculated as a plane parallel plate capacitor. Ultimately it was decided to use a ZAP board made of conventional rigid electric board which has a short signal line and small capacitor on each signal line of 10~20 pF/ch. The achieved noise level is 4 ADC under the configuration of a dynamic range of 12 bit, 120 fC and a shaping time of 233 nsec. It can be reduced to be 2~3 ADC after the subtraction of a fixed noise pattern (FPN) line which is not connected to TPC pads. Without this ZAP, the GET electronics exhibit and average noise level of 3 ADC. This noise level is small enough for the SπRIT experiment, and so the production of ZAP has started and the mounting of GET electronics on the TPC is ongoing.

The user of the GET system is not only responsible for the interface to their TPC, but they must also integrate or develop the DAQ. For the SπRIT project, NARVAL4) is planned to be employed as the DAQ system. By employing NARVAL, large amounts of data of more than 100 MByte/sec from SπRIT-TPC can be handled. The development of an interface to send data from Babirl to NARVAL is being developed so that raw data from Babirl can be merged with data from GET system by using NARVAL.

We have performed a test experiment using the GET system on another TPC with the final ZAP at HIMAC during November 2014. NARVAL was not used in this test experiment. The analysis result of the test experiment is reported by G. Jhang in this APR. In the test experiment, we took benchmark test data of the GET system. We read out 756 channels with a sampling rate of 25 MHz and 256 time buckets. A partial readout mode using the hit pattern register was used to increase the data acquisition rate as much as possible. A data acquisition rate of 600 Hz and a data rate of 1 GByte/min were achieved, which is sufficient for the first experiment of SπRIT project.

References
Performance evaluation of GET readout electronics for heavy ion collision experiments at RIBF


GET(Generic Electronics for TPCs) will be used as the front-end readout for the newly constructed SrRIT-TPC(SAMURAI pion Reconstruction Ion-Tracker Time Projection Chamber). The GET electronics has been recently developed by the GET collaboration for the particle and nuclear physics experiments and its performance is yet to be evaluated. We performed a test experiment at the Heavy Ion Medical Accelerator in Chiba(HIMAC) facility using the BRAHMS-TPC(TPM1) to evaluate the performance of the GET electronics. The TPC has the multi-wire configuration similar to the SrRIT-TPC: anode wires for signal multiplication, gating grid wires to reduce the background noise.

We used 300 AMeV $^{132}$Xe beam with 500 mg/cm$^2$ CsI target surrounded with the multiplicity trigger array of 60 scintillator plastics. To evaluate the resolution in both wire and drift directions, in the first setup the BRAHMS-TPC(TPM1) was placed at 60 degrees off the beam axis and we took data with different sampling rate of 5, 10, 25, 50, 100 and 200 MHz and shaping time of 70, 232, 502 and 1014 ns. Due to breakdown of the $\mu$-TCA power supply, only one AsAd board(256 channels) is used in this configuration.

In the second setup the BRAHMS-TPC(TPM1) was located at 0 deg. We replaced the broken power supply and took data with three AsAd boards(768 channels) controlled by a full CoBo(Control Board for 4 AsAd boards). We tested the gating grid drivers with beam intensities varying from $10^2$ to $10^5$ pps. We placed five 3 mm thick Al plates in front of the TPC to stop the beam and heavy fragments so that only the light charged particles with $Z < 3$ can reach the TPC at the intensity $10^4$ and $10^6$ pps. Finally, with beam intensity $10^4$ and $10^5$ pps we took data under the SrRIT-TPC experimental condition: sampling rate of 25 MHz, shaping time of 232 ns, 256 time buckets(10.24 $\mu$s), and zero suppression mode.

Figure 1 shows the preliminary result in the first setup. The resolution is presented as a function of the layer numbers, where one layer means a row of 96 pads perpendicular to the beam axis and the BRAHMS-TPC has 12 layers. To obtain the resolution we selected three successive layers and calculated the difference between the hit position on the middle layer and the average position of hits on the first and the third layers assuming that the resolution of each pad is the same as $\delta x$. For example, $x = 0$ means the resolution is calculated with the layer number 0, 1, and 2 by accumulating $x_1 - (x_0 + x_2)/2$ values for all events. By the error propagation the RMS value of the distribution, $\sigma$, and the resolution, $\delta x$, have the relation: $\sigma = \sqrt{3/2}\delta x$.

![Resolution of the wire and drift direction as a function of the layer number $x$, which is the first layer number among three layers.](image)

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Direction (\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRAHMS</td>
<td>310</td>
</tr>
<tr>
<td>SrRIT</td>
<td>217±10</td>
</tr>
</tbody>
</table>

Comparison between the result from both collaborations is summarized in Table 1. Our result is better because the GET electronics is 12 bit ADC while the BRAHMS collaboration used 10 bit ADC.

Further analyses in the second setup are ongoing.

References
**Status of S\(\pi\)RIT-TPC**

M. Kurata-Nishimura,\(^1\) R. Shane,\(^2\) A. McIntosh,\(^3\) T. Isobe,\(^4\) J. Barney,\(^2\) J. Estee,\(^2\) G. Jhang,\(^1\) W. Powell,\(^5\) W.G. Lynch,\(^2\) M.B. Tsang,\(^2\) T. Murakami,\(^6\) S. Tangwancharoen,\(^2\) S.J. Yennello,\(^2\)

for S\(\pi\)RIT-TPC collaboration

The SAMURAI Pion-Reconstruction and Ion-Tracker Time-Projection Chamber (S\(\pi\)RIT-TPC)\(^1\) was constructed at Michigan State University and transferred to RIKEN RIBF-SAMURAI in February 2014. The main aim of this project is to constrain the symmetry energy term in the nuclear-matter equation of state (EoS) at supra-saturation density. The S\(\pi\)RIT-TPC is capable measuring the momentum of pions and light particles emitted in heavy nuclear collisions, such as \(^{132}\text{Sn} + ^{112}\text{Sn}\) at beam energies of hundreds of MeV/nucleon.

In summer 2014, an installation procedure for the S\(\pi\)RIT-TPC into the SAMURAI magnet chamber was developed and verified. The S\(\pi\)RIT-TPC is designed to maximize the coverage in the SAMURAI magnet chamber. The internal height of SAMURAI chamber is designed to be 800 mm. Bolts, covered by 25 mm high caps, surround the magnet pole on top and bottom to prevent the chamber from crushing due to the pressure difference when the chamber is under vacuum. On the other hand, the design height of the S\(\pi\)RIT-TPC is 742 mm and thus there is a very small margin of error for installing it into the SAMURAI chamber. Thus the confirmation of the installation is one of the most important issues in this project. Also confirmation of safe operation in the magnetic field is critical.

The setup for installation of the S\(\pi\)RIT-TPC in the chamber is shown in Fig. 1. In this figure, the SAMURAI magnet was oriented at 30 degrees, it is most common experimental configuration. However, the SpiRIT TPC was designed to sit inside the SAMURAI magnet chamber when it is oriented at zero degree. To test the installation procedure without expending a lot of resources to reconfigure the SAMURAI magnet, the S\(\pi\)RIT-TPC was inserted from one half side of the chamber extended toward the downstream window with the oblique angle. Rails placed in the chamber where additional rails were located on tables. The S\(\pi\)RIT-TPC was set on a slider which moves along rails with negligible friction. It was able to be pushed and pulled in the chamber using dual hydraulic jacks. When the S\(\pi\)RIT-TPC was installed inside the chamber, it was raised up about 25 mm to the beam height. Installing and dismounting the S\(\pi\)RIT-TPC was completed in about 20 minutes.

An operational test in the magnetic field was also performed. Before hand, all magnetic material items on the S\(\pi\)RIT-TPC were removed. The read out electronics described in Ref.\(^2\) were set up. Finally, charged particle tracks of cosmic rays and beta source were detected in a magnetic field ranging from 0.1 to 0.5 T. Figure 2 shows a part of a helical track produced by a cosmic ray was observed within the detection area read out by one AsAd electronics board.

Furthermore, a remote controlled target ladder was mounted inside the TPC-enclosure. The target position is determined by reading the voltage drop between the fixed and movable contacts on a resistive strip.

The overall geometry and position of the field cage and the target ladder relative to the enclosure were measured using photogrammetry\(^2\). The deviation from the design value was evaluated as less than 200 µm.

In summary, significant progress on the preparation for the S\(\pi\)RIT-TPC experiment has been achieved.

---

Fig. 1. Picture of the S\(\pi\)RIT-TPC inserted into the SAMURAI chamber. Left top: picture in the chamber. Left bottom: schematic view of the installation method.

Fig. 2. Event display for a cosmic ray detected by the S\(\pi\)RIT-TPC in the SAMURAI magnet at 0.3 T. Enlarged view of the track is on the right.

---

References
2) http://www.geodetic.com/products/systems/v-stars-s.aspx
3) T. Isobe et al.: in this report.
Test of prototype crystals of the γ-ray detector CATANA

Y. Togano,*1,+2 M. Shikata,*1 T. Ozaki,*1 Y. Kondo,*1,+2 and T. Nakamura*1,+2

The γ-ray detector CATANA (CAesium iodide array for γ-ray Transitions in Atomic Nuclei at high Isospin Asymmetry) has been developed to measure γ ray associated with highly excited states like the pygmy dipole resonance and/or giant dipole resonance. CATANA will be used with SAMURAI at RIBF.1) The excitation energy will be reconstructed by combining the invariant mass of the reaction products measured by SAMURAI and γ-ray energies from CATANA.

The CATANA array consists of CsI(Na) crystals and has between 10 and 15 cm thickness. The crystals are housed in 0.5-mm-thick aluminum boxes. The photomultipliers for the scintillation light from the crystals are the photo multiplier tubes (PMTs) R580 and R11265 from Hamamatsu Photonics. A detailed description of CATANA can be found in ref.2)

The position dependence of light collection efficiency can be significant for the crystals of CATANA, because the crystals have relatively large volumes. We have tested the position dependence of the light collection efficiency of the prototype CsI(Na) crystals by using γ rays from $^{137}$Cs, $^{22}$Na, and $^{60}$Co sources. The geometry of the tested crystals is shown in Fig. 1. To evaluate the position dependence, the collimated γ rays irradiated the crystals from a direction perpendicular to the $x-z$ plane defined in Fig. 1. The collimator was a 10 cm thick lead with a 1-cm-diameter hole. The test was performed for two crystals from different companies. The two crystals have almost identical geometry. We tentatively name the two crystals as A and B in this report. Figure 2 shows the typical response of the crystals A and B to the uncollimated 511 and 1275 keV γ rays from $^{22}$Na. Crystal A has a better energy resolution than crystal B. The position dependence of the light collection efficiency along crystal length z of the crystals A and B to the γ rays from $^{22}$Na is shown in Fig. 3. The light output of the crystal B is larger at larger z. This tendency is due to the optical focusing caused by the reflection of lights at the polished surface of crystal B.3) To obtain a better position dependence and energy resolution, changes in the reflectivity of the crystal A surfaces were realized by roughening the crystal surfaces.

The fabrication of the CsI(Na) crystals for CATANA will start in spring 2015, and finish in late 2015.

![Fig. 1. Geometry of the tested prototype crystals. The definition of the axis in the test is also shown. PMT was attached to the top of the crystals.](image)

Fig. 1. Geometry of the tested prototype crystals. The definition of the axis in the test is also shown. PMT was attached to the top of the crystals.

![Fig. 2. Typical response of the crystals to the $^{22}$Na source.](image)

Fig. 2. Typical response of the crystals to the $^{22}$Na source.

![Fig. 3. Position dependence of the light collection efficiency for the crystals A (red) and B (black) along the crystal length z. Crystal B shows larger position dependence of the light collection efficiency.](image)

Fig. 3. Position dependence of the light collection efficiency for the crystals A (red) and B (black) along the crystal length z. Crystal B shows larger position dependence of the light collection efficiency.

References
Isotope separation with new ion-optics mode

H. Takeda,*1 T. Kubo,*1 N. Fukuda,*1 H. Suzuki,*1 N. Inabe,*1 and H. Geissel*2

Two-stage structure is an important feature of the in-flight fragment separator BigRIPS.1) The first stage, which consists of two dipoles (D1 and D2) and four superconducting triplet quadrupoles (STQs) (STQ1-4), is located between the production target F0 and achromatic focus F2 with the momentum dispersive focus F1. The second stage, which consists of four dipoles (D3-D6) and eight STQs (STQ7-14), is located between the achromatic foci F3 and F7 with the momentum dispersive foci F4, F5, and F6. The stage between F2 and F3, which consists of two STQs (STQ5-6), acts as a matching section. Rare-isotope (RI) beam is produced and separated in the first stage with an energy-loss degrader at F1, and particle identification and momentum analysis are performed in the second stage.1,2) Another energy-loss degrader placed at F5 is often effective when unwanted isotopes are transmitted as a result of the charge state change or the secondary reaction in the first degrader at F1. The thicknesses and shapes of the degraders at F1 and F5 are chosen so as to optimize the RI beam according to the experimental requirements.

The two stages act independently and their isotopic separation power can be added or subtracted, depending on the experimental condition. When the separation powers of the two stages are subtracted, the horizontal spatial distance of the separated isotopes becomes small at the final focus F7. Adding the isotopic separation powers of the two stages would increase the horizontal spatial distance. Because widths also increase, improvement of the final resolving power will depend on the experimental condition.

The ion-optical solution for adding the separation power can be realized by having either one or three foci in the matching section F2-F3, which have two foci (F2 and F3) in the standard mode. At least one focus in the standard mode is abandoned in the former case. It is not desirable because both F2 and F3 are important for slits and diagnostics of the RI beam. Therefore, here we present the solution having three foci.

Figure 1 shows the horizontal (X) and vertical (Y) tracks of the beam from F0 to F7 obtained from the solution of the first-order ion-optical calculation. In this solution, ion-optical conditions of the two stages (F0-F2 and F3-F7) are the same as the ones in the standard mode. Only the matching section F2-F3 is modified to have an additional focus in the X direction at the midpoint “F2.5” between F2 and F3, while the beam is not focused in the Y direction at F2.5 to reduce excitation currents of STQ5 and STQ6. Reversing the polarity of all quadrupoles of the two STQs is also necessary to reduce the currents. The maximum magnetic rigidity (Bρ) of 8.7 Tm is achieved in this solution. The value is almost the same as the maximum Bρ of the second stage (8.8 Tm). There is a trade-off between achieving high Bρ and large acceptance.

Figure 2 shows an example of horizontal distributions of tin isotopes at F7, simulated with LISE++.1,2) In a 238U + Be 4 mm reaction at 345 MeV/nucleon using 3 mm- and 2.2-mm-thick aluminum degraders at F1 and F5, respectively. The spectrometer is tuned for 132Sn with D1 Bρ = 7.49 Tm. The left and right panels show the results in the standard and new modes, respectively. In the standard mode, all isotopes accumulate in the center (X = 0) because of the subtraction of the separation power. In contrast, the isotope separation is improved in the new mode.

Note that the difference between the two modes is small for separation of isotones because they often collect at approximately the same position at F2. Altering the combination of energy and degrader thickness is required for isotope separation.

A machine study for the new ion-optical mode proposed here had been scheduled in November 2014, but was cancelled. We expect to perform this study in the next year.

References
A NaI(Tl) detector array for measurements of γ rays from fast radioactive isotope beams

S. Takeuchi,*† T. Motobayashi,*† Y. Togano,*‡ M. Matsushita,*§ N. Aoi,*∥ K. Demichi,*∥ H. Hasegawa,*∥ and H. Murakami*‡

The recent development of fast radioactive ion (RI) beams requires a new type of γ-ray detector array for in-beam spectroscopic studies. Experiments are performed in inverse kinematics by using fast RI beams with a high velocity of \( v/c \approx 0.3 - 0.6 \) that causes a large Doppler shift for γ rays emitted. In order to extract the transition energy in the rest frame of the projectile, precise measurements of emission angles of γ rays as well as a good intrinsic energy resolution are required. Another requirement for γ-ray detection is high efficiency, because the secondary-beam intensity for nuclei far from stability is typically low. The RIKEN RIBF provides the world's highest intensity exotic beams to study unstable nuclei. To capitalize on the performance of RIBF, we have constructed a new γ-ray detector array called DALI2 (Detector Array for Low Intensity radiation 2) for in-beam γ-ray spectroscopy experiments.

The design of the DALI2 array follows a concept similar to the original array DALI1,2,† which was developed for experiments at the old facility at RIKEN that provides light exotic beams with \( v/c \approx 0.3 \). In experiments performed at the new RIBF facility providing higher-velocity exotic beams with \( v/c \approx 0.6 \), the performance of DALI1 is not optimized. Therefore, DALI2 was designed to fulfill the required conditions for experiments performed at the RIBF facility by improving the angular resolution and the detection efficiency. In order to compromise on requirements such as intrinsic resolution, detection efficiency, and cost, we adopted NaI(Tl) as the detector material. The DALI2 array consists of a large number of detectors, 160-186, which, depending on the experimental conditions, are at various distances from the target. As shown in Fig. 1, the detectors are arranged to form twelve layers that are set perpendicularly to the beam axis, and a detector matrix covers the forward angles. Each layer consists of 6-14 detectors and the forward matrix consists of 64 detectors. In this standard configuration, DALI2 can cover a polar angle between 15° and 160°.

The performance of DALI2 was examined by using measurements with standard γ sources and by performing the Monte Carlo simulations with the GEANT3 code.3 Simulations reproduce measurements well, including results obtained by in-beam experiments. A typical full-energy-photopeak resolution of 10% (FWHM) and 20% efficiency are achieved for 1-MeV γ rays emitted from moving nuclei with \( v/c \approx 0.6 \) without applying add-back analysis. This resolution is satisfactory for spectroscopy of low-lying states in even-even nuclei. The high efficiency enables γ-γ coincidence measurements even for beam intensity as low as 1 Hz. The DALI2 array has been applied successfully to a variety of experiments at the old RIKEN facility and more recently at the new RIBF facility. This will be used in many more experiments to study nuclear structures of exotic nuclei at RIBF. Further spectroscopic studies of heavy or odd-mass nuclei, the SHOGUN array with superior energy resolution is planned.4

References

---

*† RIKEN Nishina Center
*‡ Department of Physics, Tokyo Institute of Technology
*§ CNS, University of Tokyo
*∥ RCNP, Osaka University
*‡ Department of Physics, Rikkyo University
Development of a total-kinetic-energy counter for high-rate experiments at ZeroDegree spectrometer

R. Taniuchi,*1,*2 H. Wang,*2 N. Aoi,*1 H. Baba,*2 S. Koyama,*1,*2 M. Kurokawa,*2 M. Matsushita,*4 S. Momiyama,*1,*2 M. Niikura,*1 Y. Shiga,*2,*5 and S. Takeuchi*2

A total-kinetic-energy (TKE) counter for particle identification at the ZeroDegree (ZD) spectrometer was tested in 2014. The detector is aimed at the discrimination of not fully stripped ions for the mass region A \(\gtrsim\) 100. For example in the case of \(^{136}\)Sn (RIBF31), the mass-to-charge ratios \((A/Q)\) of \(^{133}\)Sn\(^{59+}\) and \(^{136}\)Sn\(^{50+}\) are similar and the resolution of \(A/Q\) obtained by the TOF\(−\)\(\Delta E\) method is not sufficient to separate them. In order to separate the fully stripped ions from the neighboring charge-state contaminants, the TKE counter is required to have the mass resolution of 1% (FWHM).

Considering the beams with high counting rate (~100 kcps), the counter should have a short decay time and radiation resistance. For this purpose, a \(\phi^3\) \(\text{LaBr}_3(\text{Ce})\) scintillator\(^*3\) with a 0.5-mm\(^3\) aluminum housing is prepared\(^b\). It is mounted downstream of the F11 multiple sampling ionization chamber (MUSIC). In previous studies\(^1\)-\(^3\), the feasibility of charge-state identification using this scintillator was tested. The mass resolution was not as good as 1% (FWHM). Simultaneously, a quenching phenomenon was observed\(^3\), namely, the light yield per energy deposition of the incident beam decreased as a function of \(Z\). To obtain higher resolution, the degree of the quenching phenomenon should be known for the optimization of the amplification factor of the light readout.

In 2014, two types of light readouts were tested. For the first case (tested in the experiments RIBF31R1 and DA14-01-01), five PIN-photodiodes (S3204-08, HPK) were aligned on the downstream surface of the scintillator\(^b\). For the second setting (tested in the experiments RIBF61, RIBF51R1 and RIBF56R1), the read-out consisting of a \(\phi^3\) PMT (R6091HA, HPK) and a tapered-type divider (E5859, HPK) were coupled with the scintillator. In this report, the result of the second setting is discussed.

During three experiments, the amplitudes of the signal of the PMT were measured using an oscilloscope with several high-voltage (HV) settings. The ZD spectrometer were set for \(^{132}\)Sn (20.8 GeV), \(^{70}\)Ni (15.2 GeV), and \(^{22}\)O (5.21 GeV), for the respective experiments. Figure 1 shows the signal amplitudes as a function of applied HV for different isotopes. For reference, data of \(\gamma\)-ray calibration before and after the experiment with \(^{22}\)Na, \(^{60}\)Co and \(^{137}\)Cs sources are also plotted. They are normalized by the energy of the \(\gamma\)-ray, namely, the amplitudes per 1 MeV.

For the \(^{132}\)Sn and \(^{22}\)O settings, owing to the frequent implantation rate (~40-100 kcps) and high light yield, the PMT output was saturated with overcurrent of the divider circuit when the HV value was above 700 V. On the other hand, the slopes below 700 V are similar to the one of \(\gamma\)-ray. This ensures that the PMT has linearity even for the lower operation voltage.

By extrapolating the \(\gamma\)-ray results to the lower-voltage region, the light yield of the scintillator is compared with heavy ions. The values in the center column of Table 1 are the signal amplitudes per the kinetic energies when the HV is set at 650 V. The quenching phenomena of the light yield are observed obviously.

According to this result, optimum gain of the PMT can be discussed. A new divider circuit designed from this result will be tested in 2015.

References
4) He Wang et al., in print.

Table 1. Signal amplitudes per unit energy.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Amplitude (mV/GeV)</th>
<th>Quenching factor(^*2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma)-ray</td>
<td>124</td>
<td>1</td>
</tr>
<tr>
<td>(^{22})O</td>
<td>40</td>
<td>0.32</td>
</tr>
<tr>
<td>(^{132})Sn</td>
<td>19</td>
<td>0.16</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>15</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\(*2\) the ratio of the signal amplitudes per energies of heavy ions to that of \(\gamma\)-ray.

\(*3\) \(\text{LaBr}_3(\text{Ce})\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.

\(\phi^3\) scintillator.
Low-pressure MWDC system for ESPRI experiment

Y. Matsuda,*1,2 J. Zenihiro,*2 W. Chao,*2,3 H. Sakaguchi,*2,4 J. Tanaka,*4 M. Tsumura,*2,5 and N. Nakatsuka*2,5

Elastic scattering of protons with RI beams (ESPRI) has been used to study the ground-state properties of unstable nuclei1). In order to achieve good energy resolution in the experiment, position and angular resolutions of 100 µm and 0.1 mrad are required at a position of the solid hydrogen target. The typical energy and intensity of the beam are 200-300 MeV/nucleon and 10^5-6 particles per second (pps), respectively. This report describes a multi wire drift chamber (MWDC) system newly constructed for this purpose.

Figure 1 shows a schematic layout of the system, and Table 1 shows the specification of the MWDC. Two MWDCs are installed inside a vacuum chamber at a distance of 1 m. Through the SHV connectors, negative potentials are applied to the cathode planes and the potential wires against the anode wires. Signals from the anode wires are converted into LVDS signals by the ASDs (GND, GNA-210), and fed to multihit TDCs.

The chamber including the MWDCs, with volume of about 25 L, is filled with 100% quench gas (CH_4, C_2H_6, i-C_4H_{10}) at low pressures to reduce multiple scattering of the beam. Figure 2 shows a schematic diagram of the gas handler system. The pressure of the gas is controlled with a pressure controller (MKS, 640B), and measured with two vacuum gauges (INFICON CDG025D-X3). The flow rate is adjusted with a metering valve (Swagelok, SS-4MG / SS-4L).

Basic characteristics of the system were evaluated with a ^{132}Xe beam at HIMAC. Figure 3 shows the detection efficiency as a function of the bias voltage when i-C_4H_{10} (99.5%) was used at 6666 Pa. Definition of symbols in Fig. 3 is the same as in Ref. 3. The flow rate was about 100 cc/min at 1 atm to maintain the purity of more than 99%. The efficiency reached 100% without any electric discharge. In addition, position resolution for each plane was about 60 µm (rms).

In summary, we constructed a low-pressure MWDC system. By using the ^{132}Xe beam and the i-C_4H_{10} gas, basic characteristics were evaluated for the beam intensities of 10^4-4 pps. We will further study these quantities for the beam intensities of 10^5-6 pps.

Table 1. Specification of each MWDC. The design was based on the MWDC for SAMURAI2).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>X-X’-Y-Y’-X-X’-Y-Y’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective area</td>
<td>77.5 mm(X) × 77.5 mm(Y)</td>
</tr>
<tr>
<td>Drift length</td>
<td>2.5 mm (Anode-Potential)</td>
</tr>
<tr>
<td>Gap</td>
<td>4.8±0.1 mm (Cathode-Cathode)</td>
</tr>
<tr>
<td>Anode wire</td>
<td>W-Re / Au (Diameter: 16 µm)</td>
</tr>
<tr>
<td>Potential wire</td>
<td>Al / Au (Diameter: 80 µm)</td>
</tr>
<tr>
<td>Cathode foil</td>
<td>Kapton / Al (Thickness: 7.5 µm)</td>
</tr>
<tr>
<td>Window foil</td>
<td>Aramid (Thickness: 4 µm)</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic layout of the MWDC system: (a) vertical sectional, (b) cross sectional, (c) front views.

Fig. 2. Schematic diagram of the gas handler system.

Fig. 3. Detection efficiency for the 200 MeV/nucleon Xe beam. The beam intensity was 6×10^3 particles per pulse (pulse width 1 s). The threshold voltages of the ASDs were ~20 mV. Definition of the symbols is the same as in Ref. 3.

References
NiGIRI: Identification of n, p, d, t, $^3$He, $^6$Li, and $\gamma$-rays†

H. Matsuzawa,*1,2 S. Nishimura,*2 T. Isobe,*2 G. Lorusso,*2 M. Kurata-Nishimura,*2 and K. Ieki*1

The azimuthal angle correlation of neutrons and charged particles with respect to the reaction plane in heavy-ion collisions is expected to provide essential information on the equation of state (EOS) of high density nuclear matter in supernovae and neutron star.

A new scintillation detector NiGIRI (Neutron, ion, and $\gamma$-ray Identification for Radioactive Isotope beam), comprises two types of PMTs (Hamamatsu H11265-200, R8520-20-12) attached on both sides of a plastic scintillator EJ299-33 (30×55×127 mm$^3$), is designed to measure the positions and energies of neutrons ($\geq 100$ keV) and charged particles ($\pi^\pm$, p, d, t, $^3$He, $^6$Li, ...) with pulse-shape discrimination (PSD) capability1–3).

A feasibility study of the NiGIRI detectors was performed using $^{132}$Xe + CsI collisions at energies of 400 AMeV at HIMAC. The energies and positions of charged particles were reconstructed and identified using the correlations of energy losses ($\Delta E$), timings, and PSDs among the different layers of NiGIRI detectors. Sixty four signals (32 NiGIRI detectors x 2 PMTs), recorded with a synchronized wave-dump mode of four flash ADC modules (CAEN V1730B; 500 MHz with 14 bits), were analyzed to deduce the integrated charge, timing, and PSD offline.

Figure 1 demonstrates the particle identification of low energy p, d, t, $^3$He, and $^6$Li in the energy correlation of the 1st layer of NiGIRI (E) and a charged-particle veto plastic scintillator (CPV: 2 mm$^2$; $\Delta E$). The punch-through charged particles with higher energy were identified using up to 8 layers of NiGIRI detectors.

Particle identification of neutrons was tested using the PSD, which is the ratio of the total charge-integral (gate width = 385 ns) and tail charge-integral (gate width = 360 ns; delay = 24 ns) of each PMT signal. The energy dependences of the PSD for charged-particles (Fig. 2a: events with CPV signal) and neutral particles (Fig. 2b: events with no CPV signal) show separation of particles among (p-d-t)-(He)-(Li) and ($\gamma$)-(n), respectively. The energies of these ions can be deduced using the time-of-flight (TOF) between the CsI target and the NiGIRI detectors, which is also useful for the consistency check with the energy losses in the NiGIRI detectors. $\pi^\pm$ production can also be studied by tagging stopped $\pi$ decays in wave-dump signals of the last NiGIRI detector.

Figure 3 shows the proto-type NiGIRI arrays arranged with full azimuthal coverage. Upgraded NiGIR detectors will be applied at RIBF to study the neutron-proton differential flow at target rapidity in neutron-rich nucleus collisions, where reaction plane will be determined by measuring the squeeze-out out-of-plane flow in mid-rapidity region.

References
Proposal of novel delayed-neutron branching ratio measurements using MRTOF

M. Wada,*1 P. Schury,*1 and Y. Ito,*1

The astrophysical r-process plays important roles in synthesis of heavy elements in the universe1). The r-process pathway is dominantly determined by the neutron separation energies of neutron-rich nuclei and the abundance of the elements strongly depends on the half-life of the nuclei in the pathway. In addition to these two dominant nuclear properties, the delayed neutron emission probabilities \( P_n \) and the neutron capture cross sections \( \sigma_n \) contribute partially to the element abundance. The cross section does not contribute during equilibrium, but strongly affects the freeze-out stage. However, direct neutron capture cross sections of very neutron rich nuclei is so far very difficult to determine experimentally2). During freeze-out, the \( \beta \)-decay path towards stability is defined by \( P_n \). Although almost all nuclei in the r-process pathway have non-negligibly finite \( P_n \), only a limited number of them are experimentally determined.

So far the experimental \( P_n \) values have been determined by a limited variety of methods: direct detection of delayed-neutron by \(^{3}\)He gas counters, detection of recoil ions in an ion trap3), and radiochemical identification of daughter nuclei. We propose a novel method using a gas catcher cell and a multi-reflection time-of-flight mass spectrograph (MRTOF-MS). The principle is the same as the radiochemical method. All daughter nuclides are identified and the yields are compared to determine \( P_n \). In the radiochemical method, characteristic \( \gamma \)-rays and their branching ratios are needed to obtain the yields, however, they are often unknown in such very neutron rich nuclei. In the new method, we identify the daughters and remaining precursor ions by the MRTOF-MS. Figure 1 shows a schematic drawing of the experimental setup. The injected precursor nuclear ions are first thermalized in the gas catcher and decay in the cell. The decay products are also thermalized in the cell and then extracted from the cell using an rf-carpet and transport to the MRTOF-MS. The recoil products are identified by the mass spectrograph. Figure 2 shows a schematic mass spectrum for the case of \(^{94}\)Br. Note that remaining precursor and \( \beta \) decay recoil, single neutron decay recoil, two neutron decay recoil and their daughters (grand daughters of the precursor) are all identified in a single spectrum. It is especially important that the isobaric pair of the precursor and the \( \beta \)-decay product (without neutron emission) can be clearly separated. Such simultaneous detection of multiple atomic mass numbers along with separation of isobaric ions is a unique feature of MRTOF-MS4). It is difficult to achieve such capabil-

References
1) E. Burbidge et al, Rev. Mod. Phys., 29 (1957) 547.

*1 RIKEN Nishina Center
Advanced development of GARIS-II using He-H$_2$ mixture as a filled gas toward the study of superheavy element

D. Kaji,$^{*1}$ K. Morimoto,$^{*1}$ H. Haba,$^{*1}$ Y. Wakabayashi,$^{*1}$ M. Takeyama,$^{*1, *2}$ S. Yamaki,$^{*1, *3}$ K. Tanaka,$^{*1, *4}$ and K. Morita$^{*1, *5}$

Performance of a gas-filled recoil ion separator (GARIS-II) has been investigated using various asymmetric fusion reactions$^{1–5}$. The studies have indicated that the separator has a large transmission under a low-background condition in comparison with GARIS and that the separation of unwanted particles is improved using He-H$_2$ mixture as a filled gas. The low-background condition is very important for identifying superheavy elements (SHE) produced with a low cross section of pb-order. Therefore, the usefulness of He-H$_2$ mixture as a filled gas toward the study of SHE was investigated further in this work. As a typical example, results for $^{214}$Th, which was produced via the reaction of $^{197}$Au($^{23}$Na,6n), are given here.

The reaction products of $^{214}$Th were separated in-flight from projectiles and other by-products using GARIS-II, and then they were guided into a double sided silicon detector after passing through a time-of-flight detector$^{1–3}$. The separator was filled with He-H$_2$ mixture gases with various H$_2$ mixing ratios (0, 10, 20, and 36%). The gas pressure was maintained 47 Pa.

The yields of $^{214}$Th, which was assigned from an $\alpha$-transition of 7.678 MeV, were measured by varying the fraction of H$_2$ composition from 0 to 36% as shown in Fig. 1. Each yield is plotted against the magnetic rigidity $B\rho$. The optimum $B\rho$ value was determined by fitting to the data points using a Gaussian function. The optimum $B\rho$ value was shifted from 1.711 to 1.821 Tm by increasing the mixing ratio of H$_2$ from 0 to 36%, and the yields of $^{214}$Th were enhanced 1.43 times.

The shift of the optimum $B\rho$ value implies that the equilibrium charge state $\overline{q}$ of recoil ions moving in a filled gas becomes small. The $\overline{q}$, which was deduced from the optimum $B\rho$ values, are plotted against the mixing ratio of H$_2$ in Fig. 2. The $\overline{q}$ was decreased with increasing H$_2$ composition. The $\overline{q}$ in pure H$_2$ can be estimated to be 3.58 by using empirical systematics, which was obtained using a Dubna gas-filled recoil separator DGFRS$^{6)}$. Interpolated values of $\overline{q}$ between 4.28 and 3.58 in the case of pure He and H$_2$ are indicated as a broken line in Fig. 2. The interpolation well agrees with the obtained $\overline{q}$ values using various mixing ratios within an error bar. On the other hand, the transmission is improved with increasing the mixing ratio of H$_2$, although the width parameter $\Delta B\rho/B\rho$ becomes slightly worse from 8.4% to 9.4%. To establish a suitable condition to study SHE using the He-H$_2$ mixture, further investigation is in-progress.

Fig. 1. Yield curve of $^{214}$Th as a function of magnetic rigidity for various He-H$_2$ mixture gases (○:pure He, ▽:10% H$_2$, □:20% H$_2$, △:36% H$_2$). Each solid curve is a Gaussian function fitted to data points.

Fig. 2. Equilibrium charge state of $^{214}$Th ions moving in a He-H$_2$ mixture. Interpolation between experimentally obtained $\overline{q}$ of 4.28 and estimated $\overline{q}$ of 3.58 from DGFRS’s work$^{6)}$ is indicated as a broken line.

References
4) D. Kaji et al.: RIKEN Accel. Prog. Rep 47, (2014) [In print].

$^{*1}$ RIKEN Nishina Center
$^{*2}$ Department of Physics, Yamagata University
$^{*3}$ Graduate School of Science, Tokyo University of Science
$^{*4}$ Department of Physics, Saitama University
$^{*5}$ Department of Physics, Kyushu University
Pulse shape analysis for short-lived decay of superheavy elements

S. Yamaki,*1,†2 K. Morimoto,*1 D. Kaji,*1 Y. Wakabayashi,*1 M. Takeyama,*1,†3 K. Tanaka,*1,‡4 H. Baba,*1 T. Yamaguchi,*2 T. Suzuki,*2 and K. Morita*1,†5

In heavy or superheavy element research, it is important to know the α decay energies and half-lives of the nuclei to confirm that objective nuclei have been formed. The α decay half-lives of these nuclei are very short (0.1-1 μs) for heavier Z according to some theoretical calculations. However, in the traditional system, the combination of a shaping amplifier and PH-ADC cannot separate sequential events within 1 μs. To measure the α decay properties of such short-lived nuclei, a digital data acquisition system with flash-ADC was implemented in the GARIS-II read-out system. In the new system, waveforms from a preamplifier are directly registered with flash-ADC SIS3301 to avoid the summing phenomena caused by pileup in the shaping amplifier. Figure 1 shows the PH-ADC read-out and flash-ADC read-out systems. The DAQ systems for the PH-ADC and flash-ADC are operated independently. Separately obtained data are synchronized by the LUPO time-stamp module.

In a recent study, a pulse shape analysis (PSA) algorithm for the waveforms from the GARIS-II read-out system was developed. PSA was tested using off-line tests. 241 Am α was implanted in a Si PIN photodiode (Hamamatsu S3204) and the signal was preamplified by the Clear Pulse 579. The sampling rate was 100 MHz. Some pileup events occurred when the α source was set close to the detector. Figure 2(a) shows an example of a pileup pulse. In order to distinguish pileup events from single events, the weighted mean in time over threshold (MTOT) method for the differentiated waveforms was developed and applied. MTOT is defined as:

$$MTOT = \frac{\sum_{t=0}^{T} t w_t}{\sum_{t=0}^{T} w_t}$$

where \( t \) is the time, \( t_m \) is the sampling period (800 clock), \( v_t \) is the voltage, \( v_{th} \) is the voltage threshold, and \( T \) is the minimum time when \( v_t = 1 \). Figure 2(b) shows a histogram of the MTOT. The peak that corresponds to single events is seen around 17 clock (= 170 ns). The larger MTOT events from this peak correspond to pileup ones. For example the MTOT for the waveform in Fig.2(a) is calculated as \( (\sum_{t=83}^{305} t + \sum_{t=83}^{305} t)/(\sum_{t=83}^{305} + \sum_{t=83}^{305} - 83 = 109.8 (> 17) \). Therefore, this event is treated as a pileup one.

In the second stage, template fitting for each pulse was performed. The template was made by averaging 10000 241 Am α waveforms for each channel. The fitting function is given as:

$$f(t) = A[0] \cdot \text{template}(t - A[1]) + \text{baseline},$$

where the free parameters \((A[i]: i = 0, 1)\) represent the pulse height and time offset. The baseline is an average of the data from \( t = 0 \) to the start of the pulse. For a single pulse, an energy resolution of 25 keV (FWHM) for 5486 keV α was obtained, while a resolution of 20 keV was obtained using the original PH-ADC system. In addition the shortest time interval between sequential events identified by PSA was 349 ns (Fig. 3). The energies of the first and second pulses were 5494 keV and 5444 keV, respectively. Further development of PSA is now underway.

References
Performance of ion surfing rf-carpet for high-energy RI beam gas catcher

F. Arai,*1,*2 Y. Ito,*2 I. Katayama,*2 M. Reponen,*2 P. Schury,*2 T. Sonoda,*2 M. Wada,*2 and H. Wollink*2,*3

High-energy radioactive isotopes have been used in ion trap-based precision experiments after being stopped in a large gas cell. The stopped ions of these isotopes can be extracted from the large gas cell as a low-energy ion beam. To transport and extract these ions quickly and efficiently, electric fields are required to guide them. In this respect, an rf-carpet (RFC) method utilizing a dc potential gradient is a standard technique.1) However, such a method is restricted to longer half-life isotopes because of the transport time owing to the upper limit on the dc gradient that can be supported before electric discharges occur in the large gas cell. To study short half-life isotopes, an RFC featuring faster transport is required. Recently, a hybrid technique wherein the dc gradient is replaced by a traveling potential wave was proposed, called ion surfing.2)

Recently, we have demonstrated the transport and extraction of K+ ions using a circular RFC in 20 mbar of He gas pressure.3) However, in a practical gas cell, the gas pressure is higher by one order of magnitude.

In this study, the transport and extraction of K+ and Cs+ ions with the ion surfing method were tested in high pressure He gas using a 100 mm cylinder electrode to create a push electric field Epush and a circular RFC of 80 mm diameter. In addition, we compared the effect of an RFC of a fine pitch with one of a rough pitch. The fine pitch RFC consists of 0.08 mm wide ring electrodes with 0.16 mm pitch and 0.32 mm diameter orifice, whereas the rough pitch RFC consists of 0.16 mm wide ring electrodes with 0.32 mm pitch and 0.64 mm diameter orifice.

Fig. 1. Sketch of the transport and extraction efficiency measurement scheme. An rf frequency of 9.3 MHz and rf amplitude of 104 Vpp are typical operating conditions.

Figure 1 illustrates the scheme used to test the efficiency of this method. The study required measuring two ion currents: the current reaching the RFC electrodes (with rf off), IFRC and the ion current reaching a Faraday Cup (FC), IF. The FC was biased at −10 V to pull ions out from the extraction orifice.

We define the combined transport and extraction efficiency as IF/IFRC. Figure 2 shows the efficiency for K+ and Cs+ ions with the fine pitch RFC and the rough pitch RFC as functions of the He gas pressure PHe. Above a maximum pressure, the efficiency decreases with increasing pressure because the effective repelling force decreases because of stronger damping effect at high He gas pressures; the push electric field then exceeds the effective repelling field of the RFC causing ions to hit the RFC. The efficiency for Cs+ is always higher than for K+ because the effective repelling force scales with the mass-to-charge ratio. The fine pitch RFC is more efficient than the rough pitch RFC at higher He gas pressures. This indicates that the effective repelling force is stronger for finer pitch at higher He gas pressures.

We obtained an ion collection efficiency up to nearly 100% within a wide range of He gas pressures. To allow operation at higher PHe, a larger effective repelling force is needed.

We applied the ion surfing RFC to a superheavy element gas cell. The results are presented elsewhere in this journal.4)

References
4) P. Schury et al.: In this report.

-216-
Evaluation of effects of a large energy deposition on Deuterium gaseous active target for a high-intensity ion beam injection


A deuterium gaseous active target, CNS Active Target (CAT)\(^1\times2\), has been under development for measuring the Isoscalar Giant Monopole Resonance (ISGMR) in unstable nuclei via the (d, d') reaction. In order to extract the ISGMR component by using the multipole decomposition analysis, a wide angular coverage of the distribution of the differential cross-section is required. The CAT consists of GEM-TPC and Si detectors. In the center-of-mass frame, the scattering angular region of recoil particle of \(\theta_{CM}\) around 2 degrees was covered by the GEM-TPC, while the region of \(\theta_{CM} \geq 5\) degrees was covered by the Si detectors. In the previous experiment\(^3\) at HIMAC using a \(^{132}\)Xe beam with a high intensity of around 1 MHz at 115-MeV/u incident energy, we experienced instabilities of the CAT; a sudden jump of the current value of the field cage and a fluctuation of the baseline of Si signals were observed. The instabilities can be considered as the effect of high energy-loss density in the active gas target caused by a heavy ion beam. For evaluating of such effect, we bombarded the CAT with a very intense 3-MeV proton (\(H^+\)) beam provided by a pelletron in RIKEN. In this paper, the experiment and the results are reported.

![Fig. 1. A schematic view of the setup at pelletron, RIKEN.](image)

Figure 1 shows a schematic view of the experimental setup. The CAT was connected to the exit of the pelletron beam port with a 12-\(\mu\)m-thick Al-mylar foil. An Al flange of the chamber at the exit of the CAT was used as a Faraday Cup (FC). A copper plate was employed to collect the charges multiplied by three thick GEMs (THGEMs) for evaluating the effective gas gain. The current outputs of the FC and the Cu plate were measured using picoammeters (ADVANTEK TR8641). The voltage and current values of each high-voltage supply were recorded using a multimeter (KEITHLEY 2701). Four Si detectors with an effective area of \(9 \times 9\) cm\(^2\) and thickness of 0.5 mm were surrounding the field cage. The Si signals were amplified using a preamplifier (mesytec MPR-32) and read out using an oscilloscope. The energy of the \(H^+\) beam was 3 MeV, and its intensity was varied from 1 to 60 pA. The GEM-TPC was operated at an effective gas gain of about 60 in 0.4-atm H\(_2\).

Baseline fluctuations were observed in the signals of the Si detectors for a beam intensity of 20-pA, as shown in the left panel in Fig. 2. This beam condition provides an energy-loss density equivalent to a \(^{132}\)Xe beam with an intensity of 1.2 MHz and energy 115 MeV/u. The fluctuation disappeared, when, with the same beam condition, a 10-\(\mu\)m-thick Al-mylar foil was placed in front of each Si detector. Therefore, we understand that the fluctuation is possibly due to radioactive noise. At 60-pA 3-MeV \(H^+\) beam injection, the fluctuations became smaller.

![Fig. 2. Preamplifier outputs of Si detectors for a 20-pA 3-MeV \(H^+\) beam injection without Al-mylar foil cover (left) and with Al-mylar foil cover (right).](image)

Figure 3 shows the variation of current in the Cu plate and field cage during the 20-pA 3-MeV \(H^+\) beam injection. The current of the field cage increased by 4.5 \(\mu\)A immediately after the injection of the high-intensity beam and gradually increased during the beam irradiation. This may be explained by the effect of the initial ions from the beam and the ion back flow (IBF) from the THGEMs. Although the field cage had tripped (the current limit was 1 mA) several times, a sudden jump of the current value seldom happened. This may be caused by the difference between a heavy-ion and a light-ion, such as \(\delta\)-ray creation. The effect of \(\delta\)-rays on both Si detectors with Al-mylar covers and the GEM-TPC will be evaluated by using a high-intensity heavy-ion beam in the near future.

![Fig. 3. Current variation of the Cu plate (left) and the field cage (right) during a 20-pA 3-MeV \(H^+\) injection.](image)

References


\(^1\) Center for Nuclear Study, The University of Tokyo
\(^2\) RIKEN Nishina Center
\(^3\) Department of Physics, The University of Tokyo
Design of a thin-film polarized proton target system for low-energy RI beam experiments

E. Milman, S. Sakaguchi, S. Chebotaryov, W. Kim, K. Tateishi and T. Uesaka

The search for unknown resonances of unbound $^{10}\text{N}$ via $^9\text{C}+\text{p}$ elastic resonant scattering is proposed. Theoretically, four broad and overlapping low-lying $^{10}\text{N}$ resonances that may not be clearly identifiable in the $^9\text{C}+\text{p}$ excitation function are expected. The vector analyzing power is measured to determine these broad resonances\(^4\). The level information obtained in the experiment is useful for discussing resonances in $^{10}\text{Li}$ since $^{10}\text{N}$ and $^{10}\text{Li}$ are mirror nuclei that are expected to have a similar structure. The $^{10}\text{Li}$ structure provides us with valuable information for constructing the three-body model of the borromean $^{11}\text{Li}$ nucleus.

A polarized target is required for the measurement of the analyzing power. A polarized proton solid target for low-energy beam experiments\(^2\) has been designed based on an existing system for intermediate energies \(^3\). In the target, proton polarization is obtained by transferring the electron polarization of photo-excited triplet state of pentacene to protons of p-terphenyl. Polarization transfer is done by microwave irradiation that satisfies the condition that the Rabi frequency of electron spin is matched to the Larmor frequency of the proton\(^2\).

We select a magnetic field strength of 0.2 T. This value is a tradeoff between the magnitude of proton polarization and magnetic field effect for the trajectory of recoil particles. At this field strength, the resonance frequency of electron spins is $\sim 4.8$ GHz and the proton resonance frequency is $\sim 8.5$ MHz.

For the detection of low-energy recoil protons emitted with respect to $\pm 22.5^\circ$ where the analyzing power is expected to be the largest, the microwave resonator must be sufficiently short to avoid interference with the trajectory of scattered protons. A three-loop two-gap resonator\(^4\) (LGR) was chosen as the microwave resonator, as shown in Fig. 1 (Left). Its structure allows us to sufficiently shorten the resonator and to implement NMR coil close to the resonator without affecting its performance\(^4\).

We conducted a simulation of the LGR using the electromagnetic field simulation software CST Microwave Studio. In the simulation, the LGR was placed inside a brass shield to reduce microwave radiation losses, as shown in Fig. 1 (Right). The shield was designed to allow beam particles and recoil protons to pass through the resonator freely. The LGR was excited by an antenna placed close to one of edge loops.

The resonance frequency of LGR and the strength of the oscillating microwave field were simulated at 1-W incident power. The power required for optimal polarization transfer was evaluated. Simulations were performed for different central loop diameters. We found that the resonator with 18-mm diameter and 5-mm length was the tradeoff between the target size and required incident power of 20 W.

The thickness of the target was chosen to be 110 $\mu$m to cover the range of the $^8\text{C}$ beam with an energy of 5.6 MeV/nucleon. A novel thin crystal production method is proposed. In this method, the crystal prepared by the Bridgmann method is placed in a vacuum tube and heated. The crystal sublimates and its thickness slowly decreases. The sublimation speed is controlled by the heater temperature. A test sample prepared by the sublimation method is shown in Fig. 2. The sample thickness is approximately 700 $\mu$m.

References
Kinetic parameters of photo-excited triplet state of pentacene determined by dynamic nuclear polarization

T. Kawahara,*1,*2 S. Sakaguchi,*1,*3 K. Tateishi,*1 T. L. Tang,*4 and T. Uesaka*1

A polarized proton target prepared by dynamic nuclear polarization (DNP) techniques, which is a means of transferring electron spin polarization to nuclei by microwave irradiation, has been extensively used in particle and nuclear physics experiments.1) However, in these studies, DNP is carried out at a cryogenic temperature of <4.2K and in a high magnetic field of several Tesla. On the other hand, DNP using photo-excited triplet states (Triplet-DNP) can produce high nuclear spin polarization without such equipment, by using the non-equilibrated electron spin polarization in the lowest photo-excited triplet state generated by laser irradiation.2)

In this paper, we determined kinetic parameters of the triplet electron spin of pentacene, which is mainly used as a polarizing agent in Triplet-DNP, to optimize the polarization transfer sequence for maximizing the polarization of the target. Although the polarization of the triplet electrons is initially higher than 70%, it decreases as a function of time after the optical excitation. There are two processes relevant to this phenomenon: one is the decay from the triplet state to the ground state, while the other is the relaxation to the thermal equilibrium in the triplet state. The time constants are referred to as lifetimes (τ, i= +1, 0, -1: i represents the sublevels in the triplet state) and spin-lattice relaxation time (T1).

We determined the time constants of pentacene doped into p-terphenyl in 0.3 T and at room temperature, based on the NMR signal intensities of proton spins enhanced by Triplet-DNP. A continuous-wave Ar-ion laser pulsed by an optical chopper is used for optical excitation. We first measured the delay-time (the timing of microwave irradiation for polarization transfer) dependence (Fig. 1(a)). Analysis using only this data revealed a difficulty in separating the contributions of τ and T1. We thus utilized the pulse-structure (the duty and the repetition rate of laser pulse) dependence data as additional information (Fig. 1(b)). The combined analysis of these data allowed us to separate the contributions of the parameters. The values of τ and T1 were determined to be 22.3 µs±3.0 µs and 88 µs±13 µs, respectively (Fig. 1(c)). The value of T1 was found to be longer than 300 µs. It was also found that the proton signal enhancement is limited at a high repetition rate owing to the partial cancellation of the electron spin polarization by the remaining population produced by the preceding laser pulses.

References

*2 RIKEN Nishina Center
*3 Department of Physics, Toho University
*4 Department of Physics, Kyushu University

Fig. 1. (a) the delay-time dependence of the NMR signal intensities of proton spins enhanced by Triplet-DNP. (b) the pulse-structure (the duty and the repetition rate of laser pulse) dependence of the signal intensities. (c) Variation of the chi square values of τ0, τ−, and T1.
Development of single-crystal CVD diamond detector for time-of-flight measurements


Production and identification techniques for radioactive isotope (RI) beams are important for nuclear physics experiments involving exotic nuclei that are very unstable. RI beams are generally produced as secondary beams from high-energy heavy-ion reactions using in-flight fragment separators. In these devices, a charged-particle detector with a fast response and high radiation hardness is required to measure the time of flight (TOF) of ions for identifying the RI beams in high-dose environments.

Diamond is one of the most promising materials for fabricating a charged-particle detector for performing accurate timing measurements under high-intensity beam conditions. Fast signals for superior timing resolution can be obtained because of the high breakdown electrical field strength and high carrier saturation velocities of the diamond crystal. Additionally, high radiation hardness to large charged-particle fluxes can be expected because of the higher displacement energy of diamond.

In this study, we fabricated a single-crystal (sc) chemical-vapor-deposited (CVD) diamond detector and evaluated the intrinsic timing resolution of the detector. Figure 1 shows the block diagram of the electronic circuit used for evaluating the timing resolution. Two diamond detectors were placed in the E7B beam line at the RIKEN accelerator facility. The detectors were fabricated using an sc-diamond of approximately 4×4 mm$^2$. In brief, the detector has a layer structure of Pt/sc-diamond/Ti/Au. The thickness of the diamond crystals are 90 μm and 139 μm for the front-side and rear-side of the detector, respectively.

8.6 MeV/nucleon-7Li beams penetrated two diamond detectors. The pulses induced from the detector were read out using a broadband amplifier with an analog bandwidth of 1 MHz–2 GHz (CIVIDEC C2 Broadband Amplifier). The amplifier signals were processed with a leading edge discriminator, a time-to-amplitude-converter (TAC), and 8 k-multi-channel analyzer (MCA) for TOF measurement. The timing resolution of the measurement system was estimated to be 7.8 ps (σ) using a constant time difference generated by the fast-pulser signal and cables.

Figure 2 shows the measured TOF spectrum. The width of the peak was estimated to be 45 ps (σ). The intrinsic timing resolution of the detector was evaluated by dividing the width of the peak by $\sqrt{2}$ and subtracting the timing resolution of the measurement system. Here, the same performance of the two detectors was assumed. The intrinsic timing resolution was estimated to be 31 ps (σ).

References

Efficient excitation of photo-excited triplet electrons of pentacene for dynamic nuclear polarization

K. Tateishi,*1 T. Tsukihana,*2 Y. Urata,*2 S. Wada,*2 and T. Uesaka*1

Dynamic Nuclear Polarization (DNP) has been successfully applied to a polarized target. DNP is a method of transferring spin polarization from electrons to nuclei with microwave irradiation. However, as long as electron spins in thermal equilibrium are used as a polarizing agent, cryogenic temperatures of approximately 4.2 K will be required for hyperpolarization in the order of 10% even under strong magnetic fields of several Tesla.1) One approach for overcoming the limitation is to use non-thermalized electron spins as a polarizing agent instead.

DNP using the photo-excited triplet-electron spin of pentacene2) requires neither a cryogenic system nor a superconducting magnet, but a laser for creating hyperpolarized electron spins. There are four important requirements in the light source: wavelength, pulse width, repetition rate, and output power. The wavelength affects the excitation efficiency from the ground state to the excited singlet state. The pulse width influences the transition efficiency from the excited singlet state to the triplet state. The repetition rate is related to the initial buildup rate of 1H spin polarization. The output power is determined by the number of excited electrons, i.e., the sample volume.

To this end, a new laser system is developed, which is constructed using two neodymium-doped yttrium aluminum garnet (YAG) lasers with wavelengths of 1064 nm and 1319 nm and a LiB3O5 crystal for sum-frequency generation (Fig. 1).3) The wavelength, pulse width, repetition rate, and output power are 589 nm, 126 ns, 3 kHz, and 1 W, respectively. We developed oscillators independently using laser diode pumped YAG crystals. The acousto-optic Q-switch (A/O Q-sw) was chosen to generate light pulses because of the high repetition frequency. The pulse width can be varied by adjusting the input current of the laser diode, and in this experiment we used final output pulse widths of 84 and 126 ns. In order to generate 589-nm light, the infrared lights were overlapped at the LiB3O5 crystal. Finally, residual infrared lights were separated by visible-coated mirrors.

Using a single crystal of p-terphenyl doped with deuterated pentacene4), we carried out the DNP experiments in 0.35 T and at 300 K with laser pulses of 84 ns and 126 ns. The maximum polarization of a 84 ns laser pulse is 16% with a repetition rate of 400 Hz. The maximum polarization of the 126 ns laser pulse is 22% with a repetition rate of 600 Hz. The optimal repetition rate was different because the excited electrons play not only the role of a polarized agent but also that of a relaxation source. When the repetition rate was increased, the initial buildup rate increases, but the paramagnetism accelerates spin-lattice relaxation of 1H spins. The final achievable polarization is determined by the balance of these two effects. Furthermore, to obtain higher 1H spin polarization, our results indicated that a longer laser pulse width to increase the initial buildup rate or a higher external magnetic field to decrease the spin-lattice relaxation of 1H spins is necessary.

References
2) K. Takeda: Triplet State Dynamic Nuclear Polarization (VDM Verlag, 2009).
Realization of $^1$H spin polarization of 40% at room temperature

K. Tateishi,*1 T. Tsukihana,*2 Y. Urata,*2 S. Wada,*2 and T. Uesaka*1

Dynamic Nuclear Polarization (DNP) is a means of transferring spin polarization from electrons to nuclei. As a method for enhancing bulk nuclear spin polarization, DNP has been successfully applied to areas ranging from fundamental physics to materials science, biology, and medical science. The conventional DNP, which is used radical as a polarizing agent, is carried out in the strong magnetic field and at cryogenic temperature (e.g. 3.35 T and 1.4 K) to polarize electron spins in the order of 10%. One approach for overcoming the limitation of the experimental conditions is to use non-thermalized electron spins instead. DNP with electron spins in the photo-excited triplet state (triplet-DNP) can achieve hyperpolarization independent of the magnetic field strength and temperature.

We employed pentacene as a polarizing agent, which has an electron spin polarization of 73%, and p-terphenyl as a host material because of its stability at room temperature and large pentacene capacity.

In this study, we focused on realizing the highest $^1$H spin polarization at room temperature. The finally achievable nuclear spin polarization with triplet-DNP is determined by the balance between the spin-lattice relaxation time of the nuclear spin ($^1$H in this report) and the speed of the polarization transfer.

In order to suppress the spin-lattice relaxation time, we used pentacene-d$_{14}$ as the polarizing agent (Fig. 1(a)). The triplet electrons played the role of a polarizing agent as well as contributed to $^1$H spin-lattice relaxation through a perturbation of the local field of the $^1$H spins in the vicinity. In addition, we synthesized p-terphenyl-2',3',5',6'-d$_4$ (Fig. 1(b)). The $^1$H spin-lattice relaxation in p-terphenyl-h$_{14}$ was mainly due to the pendulum motion of the central benzene ring, which modulates the local dipolar field of the $^1$H spins in and near the central ring.

A high-repetition-rate laser system was developed to increase the speed of polarization transfer, and it consists of two Neodymium-doped Yttrium Aluminum Garnet (YAG) lasers with wavelengths of 1064 nm and 1319 nm and LiB$_3$O$_5$ crystal for sum-frequency generation. The wavelength, pulse width, repetition rate, and output power were 589 nm, 126 ns, 3 kHz, and 1 W, respectively.

Using a single crystal of p-terphenyl-d$_4$ doped with pentacene-d$_{14}$ and the new laser, we conducted the triplet-DNP in 0.65 T and at room temperature. The buildup curve is shown in Fig. 1(c). 40% of $^1$H spin polarization was obtained in 15 minutes, which corresponded to the 20,000-fold enhancement under the same conditions.

Hyperpolarization techniques using photo-excited triplet electrons can be used to simplify DNP experiments. The NMR sensitivity of samples that prefer ambient temperatures can be boosted significantly. Bulk nuclear hyperpolarization in such low magnetic fields is also desirable to achieve the polarized target for RI beams and the polarized filter for neutron beams.

References
2) K. Takeda: Triplet State Dynamic Nuclear Polarization (VDM Verlag, 2009).
Production of spin polarization of atoms in superfluid helium using a pulsed Ti: sapphire laser

M. Hayasaka,*1,2 T. Furukawa,*1 H. Tomita,*4 T. Takamatsu,*4 K. Imamura,*2,5 T. Fujita,*6 T. Kobayashi,*7 H. Uematsu,*1 H. Ueno,*2 and Y. Matsuo*8

We are developing a new laser spectroscopic technique “OROCHI” to determine nuclear spins and moments of RI atoms. In this technique, superfluid helium (He II) is used as a material for trapping short-lived RI atoms. We utilize optical pumping to produce atomic spin polarization, and laser - radio frequency (RF) /microwave double resonance method to investigate Zeeman and hyperfine splittings of the RI atoms, respectively. In He II spin polarization can be maintained for a long time (>2 s in the case of Cs),1 which enables us to produce high degree of spin polarization. As for optical pumping, CW lasers are generally used to produce spin polarization. High-repetition-rate pulsed lasers can be superior in producing spin polarization owing to the large pumping rate. Using pulsed lasers, we expect to produce spin polarization efficiently for various atomic species that have not been spin-polarized yet. We here report on the production of spin polarization and RF resonance of Rb atoms in He II using a tunable pulsed Ti: sapphire (Ti: Sa) laser operated at 1-3 kHz.

We have constructed a pulsed Ti: Sa laser with a z-shaped cavity2 originally developed at Mainz University (see Fig. 1). The Ti: Sa laser can lase in wide range of wavelength from 670 to 1050 nm3 and UV output can be easily obtained by second harmonic generation. The Ti: Sa crystal is pumped by a second harmonic output of a Nd: YLF laser. The laser cavity contains four mirrors for light of wavelength ranging from 750 to 850 nm. The tunable range of wavelength using a birefringent filter is 749-790 nm. For the Rb experiment, the laser is tuned to the excitation wavelength of Rb atoms in He II (780 nm)4. At this wavelength the achieved output power is >150 mW at 1 kHz, and >200 mW at 2 and 3 kHz.

Fig. 1. Schematic diagram of the Ti: sapphire laser layout

Fig. 2. RF resonance of 85Rb obtained by applying RF frequency of 2.35 MHz. We can see the resonance peak at B = 5.4(9) Gauss and peak of LIF intensity with no spin polarization at B = 0 Gauss. The repetition rate of the pulsed laser was 3 kHz and the output power was 7.5 mW.

Using this pulsed Ti: Sa laser, we conducted experiments for Rb atoms in He II with optical pumping and laser-RF double resonance method.

Figure 2 shows laser induced fluorescence (LIF) signal from Rb atom by the magnetic field swept from 0 to 7 Gauss. At B = 0, the LIF intensity was larger than that with magnetic field because spin polarization of atoms was not conserved. With increasing external magnetic field, the LIF intensity decreased due to the increase in spin polarization. When the RF frequency is in resonance with Zeeman splittings, the spin polarization is decreased and then LIF intensity was increased. In Fig. 2, we can see the RF resonance of the 85Rb Zeeman transitions in He II. These results reveal that the produced spin polarization using pulsed laser was sufficient to observe RF resonance clearly. In the case of using pulsed lasers under 10 mW at 1 to 3 kHz repetition rate, we could produce comparable spin polarization to the CW laser experiment5 and observe RF resonance.

In the future, we plan to use the pulsed Ti: Sa laser for optical pumping of atomic species that have not yet been spin-polarized and develop a technique to produce spin polarization of various atoms. The excitation wavelength of In atoms is 370 nm in He II6. We expect to produce spin polarization of In atoms using a second harmonic generation of the pulsed Ti: Sa laser.

References
3) K. Muramatsu.: Master Dissertation, Nagoya University (2011)
Microwave system development of enlarged spin-polarized proton target for RI beam experiments


A spin-polarized proton target provides opportunities to observe spin-dependent interactions in unstable nuclei. The center for Nuclear Study, University of Tokyo and RIKEN groups have developed a spin-polarized proton target system that is applicable to RI beam experiments.1) The method of generating spin polarization employed in the target system is based on the cross-polarization technique,2) where the polarization of an electron system is transferred to protons in the presence of a rotating magnetic field. The rotating field is generated as a standing electromagnetic wave using a microwave resonator.

Recently, the target system was upgraded to accommodate a target sample with a larger diameter (24 mm) compared with the diameter before (14 mm). This upgrade was carried out to increase the fraction of beam particles accepted by the target and to decrease the rate of background events from the target holder. One of the problems expected with this upgrade is that the standing electromagnetic wave in a large resonator is generally weaker than that in a small one, which might prevent us from producing a sufficiently strong field required for achieving optimal polarization conditions and attaining a high spin polarization.

To facilitate polarization transfer using the cross-polarization technique, electron and proton systems have to be coupled in order for spin-exchange interaction to occur. The coupling condition $\hbar \omega_c = \hbar \omega_1$ is known as the “Hartmann–Hahn condition”3). Here, $\omega_c$ is the electron effective Larmor frequency in an external microwave magnetic field $H_1$, and $\omega_1$ is the proton Larmor frequency. The electron effective Larmor frequency is proportional to the amplitude of $H_1$, $\omega_c \propto H_1$, and therefore $\omega_c$ can be adjusted to match the proton Larmor frequency. In the experiment, $\omega_c$ is tuned by changing the $H_1$ field amplitude, which in turn is proportional to the square root of the input power supplied to the system, $H_1 \propto \sqrt{P_{MW}}$.

In the test we performed previously,4) it was found that the amplitude of the oscillating magnetic field was not sufficiently high to fulfill the Hartmann–Hahn condition. To address this problem, a redesign of the loop-gap resonator (LGR) has been attempted. LGR is the device responsible for generating a microwave field with power $P_{MW}$ provided from an RF amplifier. It is made of a sheet of CuFlon material, which consists of a copper metal clad on both sides of a thin Teflon sheet. The CuFlon sheet is rolled around a holder to form a cylindrical resonator.5) Our estimation shows that there is a possibility to increase the efficiency of the resonator by increasing the thickness of its copper plates from 4.4 to 36 $\mu$m, as thicker plates better suppress radiation losses due to the skin effect.

In Fig. 1, the closed triangles represent results of the present test carried out with LGR whose copper plates are 36 $\mu$m thick. It can be seen that saturation is reached at approximately $2.0 \sqrt{W}$ of input power where the polarization stops increasing despite the increasing input power. The presence of saturation indicates that the Hartmann–Hahn condition was fulfilled, i.e., the polarization of electrons was fully transferred to the protons. In Fig. 1 the hollow circles indicate the results of the test carried out using LGR whose copper plates are 4.4 $\mu$m thick. Here, the signal intensity rises across the entire region of powers applied, which means that the condition was satisfied only partially.

In summary, we designed LGR with thicker copper plates and performed test with it. The results of the test are promising – the Hartmann–Hahn condition is satisfied at reasonable microwave powers, which means that the newly constructed LGR should be suitable for application with enlarged target samples.

References
The off-line adjustment of the parasitic production of low-energy RI-beam system for installation in BigRIPS

T. Sonoda,*1 M. Wada,*1 I. Katayama,*1 N. Fukuda,*1 H. Iimura,*2 N. Inabe,*1 T. Kubo,*1 K. Kusaka,*1 H. Takeda,*1 H. Suzuki,*1 M. Reponen,*1 M. Wakasugi,*1 K. Yoshida*1 and SLOWRI collaborations

The construction of a low-energy RI-beam facility SLOWRI(1) began in 2013. The parasitic low-energy RI-beam production system (PALIS)(2) in SLOWRI was successfully manufactured in 2014. The preliminary installation of PALIS in the second focal plane chamber (F2) in BigRIPS was demonstrated. The performance evaluation of PALIS by off-line experiments is in progress.

We will restore unused RI-beams by installing a small gas cell in the F2 chamber in BigRIPS. This will provide parasitic low-energy RI-beams for various precision experiments whenever BigRIPS experiments are in operation. In order to realize the parasitic beam production, there should be no interference from PALIS in terms of BigRIPS beam tuning, detector operation and replacement, vacuum level, etc. This year we confirmed the following items whether there is no mechanical interference due to the installation of PALIS in the F2 chamber. The first item was the fitting check between the F2 chamber and PALIS which is integrated with the F2 chamber’s roof(3). Position reproducibility was ensured by using locating guide pins equipped in PALIS. PALIS, whose weights approximately 1100 kg, was carefully moved by a floor-operated crane and placed on the F2 chamber within <1.0 mm reproducibility without any trouble. The second item was the applicability for the replacement of detectors used for BigRIPS beam tuning without taking PALIS away. There are three detectors, i.e., two PPACs and one plastic scintillator inside the F2 chamber, they need to be occasionally replaced for maintenance. By using two maintenance windows equipped in PALIS, we confirmed that these detectors were able to be put in or out. The third item was the vacuum level for the F2 chamber together with PALIS. After several hours of pumping, the pressure in the F2 chamber was 10^{-4} Pa, the same as in conventional operation. Fig. 1 shows the photographs during the installation test of PALIS in the F2 chamber in BigRIPS.

The off-line experiment was started for the performance evaluation of PALIS. A new differential pumping method was implemented in PALIS from the result of a prototype system(4). The differential pumping region is divided into four sections. The capability of differential pumping was verified; a pressure difference from approximately 10^{5} Pa argon or helium in the gas cell down to 10^{-3} Pa in the final section was achieved, while using a 2 mm diameter gas cell exit hole.

Fig. 1. The upper photo shows the entire PALIS integrated with the F2 chamber’s roof. The lower photo is the gas cell part in PALIS.

Fig. 2. Capability of differential pumping in PALIS.

We plan to start on-line commissioning experiments in 2015.

References
3) T. Sonoda et al. ARIS2014 proceedings to be published.

*1 RIKEN Nishina Center
*2 Japan Atomic Energy Agency
Current status of the gas cell ion beam cooler-buncher at SLOWRI

Y. Ito,*1 F. Arai,*1,†2 I. Katayama,*1 M. Reponen,*1 P. Schury,*1 T. Sonoda,*1 M. Wada,*1 and H. Wollnik*1,†3

Conversion of a continuous ion beam to a pulsed ion beam will be an essential process for various precision experiments at the SLOWRI facility1). Continuous ion beams from SLOWRI gas cells can be stopped and provided as low-emittance pulsed ion beams with a gas cell ion beam cooler-buncher (GCCB)2). The GCCB consists of a gas cell with an RF carpet (RFC), an RF quadrupole ion guide, and a flat trap3). Ion beams of energy as high as 30 keV will be injected into a low-pressure He gas cell, and then decelerated and thermalized solely by gas collisions. The ions will then be efficiently transported by the RFC and the RFQ ion guide to the flat trap, and then bunched and cooled.

In this process, there was a concern regarding the performance of the RF carpet at such unusually low pressure – as low as 2 mbar. Simulations indicated that a rough-pitch RFC could transport ions more efficiently than a fine-pitch RFC that a rough-pitch RFC could transport ions more efficiently than a fine-pitch RFC. The transport and extraction efficiency was investigated experimentally using an RFC with a pitch of 0.32 mm and an exit hole area and 10 mm with ~10 mm diameter, respectively. The ranges for both windows were calculated by the SRIM code as shown in Fig. 2. In both cases, the ranges at 30 keV for the elements as heavy as Cs are larger than the minimum thicknesses, indicating that ions can penetrate the windows. Because the residual ion energy after the window will be much lower than the windowless case, the size of the gas cell can be much smaller, i.e., total length of <100 mm.

Another concern was the injection of a 30 keV beam into the gas cell. The gas cell has no window to transport the low-energy ion beam, and thus all elements can be injected into the gas cell. However the incoming beam might be scattered due to the leak gas around the entrance. As a complementary idea, we are considering using nm-thick windows for the entrance. One option is a SiN membrane and the other is a Acetylcellulose membrane. The minimum thicknesses of SiN and Acetylcellulose membranes are 10 mm with 5 × 5 mm² area and 10 nm with ~10 nm diameter, respectively. The ranges for both windows were calculated by the SRIM code as shown in Fig. 2. In both cases, the ranges at 30 keV for the elements as heavy as Cs are larger than the minimum thicknesses, indicating that ions can penetrate the windows. Because the residual ion energy after the window will be much lower than the windowless case, the size of the gas cell can be much smaller, i.e., total length of <100 mm.

Fig. 1. Transport and extraction efficiency as a function of the He gas pressure for several $E_{\text{push}}$ values.

As shown in Fig. 1, at He gas pressures higher than 2 mbar, efficiencies of ≈100% were obtained for a wide range of push electric field strengths. For an even lower gas pressure, such as 1 mbar, the efficiency slightly decreased; efficiencies of more than 60% were achieved even with the highest push electric field strengths. Compared to the efficiency of 22% seen with a fine-pitch RFC at 5 mbar, a rougher pitch can be expected to make the GCCB highly efficient.

A performance test of these windows, i.e., a stress test for the pressure difference and the heat cycle between the room temperature and cryogenic temperature, will be performed soon. Using a 30 keV ion beam of stable nuclei, the overall efficiency of the GCCB with and without a window will be evaluated in FY2015.

References
2) Y. Ito et al., JPS Conf. Proc. 6 (2015) (in press)
4) Y. Ito et al., RIKEN Accl. Prog. Rep. 47, 205 (2013)
SCRIT luminosity monitor


A luminosity monitor has been newly constructed and installed at the SCRIT electron scattering facility[1,2]. This monitor measures the number of bremsstrahlung photons produced by collisions between an electron beam and the target short-lived nuclei trapped in the SCRIT device. Using known a bremsstrahlung cross section, one can determine the collision luminosity on-line.

The monitor consists of a position detector and a calorimeter as shown in Fig. 1. The position detector measures the spatial distribution of the bremsstrahlung photons, and the calorimeter measures their energies. The position detector consists of two identical X- and Y-detectors, each of which has 16 optically isolated scintillating fibers of 3×3 mm² cross section. The scintillating fibers are coupled to a 4×4 multi-anode photomultiplier. The calorimeter consists of seven optically isolated pure-CsI crystals, each of which is 20 cm long with a hexagonal cross section with 4 cm sides.

In order to define the angular acceptance of the detector for the bremsstrahlung process, a large Pb block, 300 (h) x 300 (w) x 50 (t) mm³, with a hole of 50 mm φ is placed in front of the monitor for collimation of bremsstrahlung photons. Note that the bremsstrahlung photons enters the center crystal of the calorimeter. The luminosity monitor is placed ~670 cm downstream from the center of the SCRIT device.

Figure 2 shows the spatial distributions of bremsstrahlung photons, whose energy is larger than 50 MeV. The stored electron beam energies were 150 and 300 MeV, and typical stored currents were 250 mA for both energies.

Fig. 1. Bremsstrahlung Luminosity Monitor.

Fig. 2. X and Y distributions for E_e = 150 and 300 MeV

During the luminosity measurements mentioned above, elastically scattered electrons from the trapped residual gases were measured simultaneously using a newly installed high-resolution large-acceptance magnetic spectrometer, WiSES (Window-frame Spectrometer for Electron Scattering)[3]. As the elastic scattering cross section for oxygen is also well known, the collision luminosity will be independently determined from the elastic scattering events soon, and the results should be compared with that determined by the luminosity monitor.

References
4) K. Tsukada et al., in this report.

*1 RIKEN Nishina Center
*2 ELPH, Tohoku University
*3 Department of Physics, Rikkyo University
*4 Department of Electrical Engineering, Nagaoa University of Technology
Study of the performance of the SCRIT rear drift chamber

S. Matsuo,*1,*2 A. Enokizono,*1,*2 K. Kurita,*1,*2 Y. Moriya,*2,*3 T. Suda,*2,*3 T. Tamae,*2,*3 K. Tsukada,*2,*3 T. Tsuru,*2,*3 and S. Yoneyama*2,*3

The SCRIT electron spectrometer called WiSES (Window-frame Spectrometer for Electron Scattering) consists of a dipole magnet, front and rear drift chambers (FDC and RDC, respectively), a helium bag to reduce multiple scattering and plastic scintillators for event triggering. To obtain charge density distributions of unstable nuclei, the angular distributions of differential cross sections have to be precisely measured using elastic electron scattering. Thus, the WiSES differential cross sections have to be precisely measured using a tungsten wire target experiment in December 2014.*3

In this article, we report performances of the RDC and RAINERs, which were examined using a tungsten wire target experiment in December 2014.*3

Since the RDC and RAINERs are installed very close to the RF power source for the electron storage ring, the background noise effect must be carefully investigated. Although the RF noise test has been performed using a small prototype DC with RP1212 (an old version of RAINER) which showed a good performance,*4 the actual RF effect on the RDC is still uncertain. Therefore, we repeated the same RF noise test using the RDC and RAINERs prior to the wire target experiment. As shown in Fig. 1 (a), the noise level was found to be slightly larger than that observed in the previous report but still less than ~800 mV in the worse case. Fig. 1 (b) shows the comparison of noise counts between the RF off and on cases as a function of the threshold voltage (Vth) for the ASD chip in RAINER. There is basically no difference in the noise rate for the RF on/off conditions at Vth > 800 mV, and the rate reduces to zero for Vth > 2200 mV. For the wire target experiment, Vth is set to 1500 mV, where the noise rate is still much smaller than the event rate (a few hundred hertz) and such a low-rate random background could be eliminated in the tracking.

The RDC consists of 10 layers as VV’UU’XX’VV’UU’ and the tracking is performed using the following iterative algorithm. First, the U and V planes are determined using the hit position information for every four layers. Here, the initial hit position in each cell is calculated using TDC and a roughly estimated x − t (space-time) calibration parameter. Second, a track is determined by combining the V/U planes and the hit positions in the remaining two X layers by minimizing χ²/ndf. Then, the residual distributions between the initial hit positions and the track intersection on the layer planes and the x − t calibration parameters are re-evaluated for each layer. The procedure is iterated (typically 4-5 times) until the widths of the residual distributions converge to the minima. The position resolution and efficiency per layer of the RDC were determined from the wire-target experimental data. Fig. 2 shows the converged residual distribution for a given V layer without the hit information of the layer. The rms was found to be ~200 µm.

In summary, we conducted a wire target experiment for SCRIT WiSES and obtained calibration parameters for the RDC. Some efforts to improve the tracking algorithm are underway by tuning the calibration parameters to obtain a better position resolution.

References
2) A. Enokizono et al.: in this progress report.
3) K. Tsukada et al.: in this progress report.
Current status of RI beam production at electron-beam-driven RI separator for SCRIT (ERIS)

T. Ohnishi,*1 S. Ichikawa,*1 M. Togasaki,*1,*2 K. Kurita,*1,*2 and M. Wakasugi*1

ERIS (electron-beam-driven RI separator for SCRIT 1) consists of an RI generator, a FEBIAD-type ion source, and an RI separator. The photofission of uranium driven by an electron beam is used for RI production in ERIS. Details of ERIS were reported in Ref. 2. During the present year, we improved the release efficiency including the efficiency of release from the production target and that of transport from the target to the ionization chamber. In this paper, we report improvements and the present status of ERIS.

One of the improvements is the stable supply of a 1-mm uranium carbide target disk. Using a 1-mm target disk, the efficiency of release from the production target is expected to increase, because the total surface area of target disks becomes larger than in the case of 2-mm target disks used in the previous test3). Uranium carbide is obtained by the carbothermal reduction of uranium oxide in presence of carbon. Details of constructing the target were presented in Ref. 3. In order to construct a thin disk, the careful selection of the graphite grain size is required for the process of constructing a disk from graphite powder. Furthermore, the uranium-oxide-coated graphite powder is also needed to construct a disk without a binder. These requirements are aimed at reducing the vacancy inside the disk and the crack at the edge of the disk. The obtained disk was approximately 1 mm in thickness and 18 mm in a diameter. In total, 23 disks were prepared. The total amount of uranium was about 15 g, and the average mass concentration of uranium in the disk was estimated as 3.4 g/cm³.

Another improvement involved strengthening the heat shield. In particular, the heat shield of the transfer tube located between the target and the ionization chamber was increased in order to ensure no cold spots were present.

After these improvements, the uranium-carbide disks were irradiated with an electron beam accelerated to 150 MeV. The electron beam power was nearly 10 W. Tantalum disks with a thickness of 5 mm and a diameter of 20 mm were inserted in front of the production target to increase the production of γ rays. The temperature of the target and the transfer tube was approximately 2000 °C. The produced RIs were accelerated to 20 kV and mass-separated by the analyzing magnet. They were identified by the measurement of γ rays corresponding to the decay of the RIs using a Ge detector.

Figure 1 shows the rate of Sn and Xe isotopes at the particle identification detector at ERIS. The electron beam power was almost 10 W. Total amount of uranium is 15g.

Table 1. Summary of rate and efficiency with 10-W beam

<table>
<thead>
<tr>
<th></th>
<th>137Xe</th>
<th>132Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed rate (atoms/s)</td>
<td>6.4×10⁷</td>
<td>2.6×10⁷</td>
</tr>
<tr>
<td>Expected rate (atoms/s)</td>
<td>7.5×10⁷</td>
<td>1.3×10⁷</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>8.4%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Overall efficiency of stable xenon</td>
<td>14%</td>
<td>15%</td>
</tr>
<tr>
<td>Release efficiency</td>
<td>61%</td>
<td>14%</td>
</tr>
</tbody>
</table>

References

*1 RIKEN Nishina Center
*2 Department of Physics, Rikkyo University
Development of the readout system for SCRIT WiSES

A. Enokizono,*1,2 H. Baba,*2 Y. Haki,*3 K. Kurita,*1,2 S. Matsuo,*1,2 Y. Moriya,*2,4 T. Tamae,*2,4 K. Tsukada,*2,4 S. Matsuo,*1,2 Y. Moriya,*2,4 T. Suda,*2,4 T. Tsuru,*2,4 K. Tsukada,*2,4 T. Tsuru,*2,4 and S. Yoneyama*2,4

WiSES (Window-frame Spectrometer for Electron Scattering) has been developed for SCRIT experiments in order to achieve the world’s first measurement of the detailed structures of unstable nuclei using electron elastic scattering. A detailed description of the WiSES apparatus is reported elsewhere. One of the key components of WiSES is the Rear Drift Chamber (RDC) and the readout module (RAINER). In December 2014, all WiSES components including RDC and RAINERs have been installed for a wire target experiment, and the performance has been measured. In this report, the setup of RDC and the WiSES readout system for the wire target experiment is described.

RDC has a volume of 274 cm x 36 cm x 78 cm and consists of 10 layers as UU′VV′XX′UU′VV′ made out of 1002 sense wires (20 µm Au-W) and 3026 field wires (80 µm Au-Al). Each drift cell has a hexagonal shape with each side measuring 1 cm, and He + CH4 (50:50) gas is used with an operation voltage of 2.95 kV. During the performance measurement and burn-in test for a year, 2 field wires of the U and V layers had a high current problem and have been replaced. We have found no hot/dead channel and experienced no HV trip throughout the wire target experiment.

Figure 1 shows RAINER which is a general multi-purpose readout card (15 cm x 20 cm) manufactured by REPIC and is capable of processing ADC and TDC for 64 independent channels. TDC is counted by FPGA with the timing resolution of ~1 ns with an 8 µs ring buffer. One of the advantages of using RAINER is the reduction of analog background noises by digitizing the signal at FPGA and the data is sent on TCP. This is beneficial for RDC which is installed near SCRIT SR2’s RF power source. An RF noise test has been performed and reported elsewhere. 16 cards are mounted on RDC to read all 1002 channels and the data is sent to a DAQ PC via Ethernet cables with a Gigabit switching hub. It has two data write modes, i.e. RAW mode and zero suppression mode to help in speeding up the DAQ rate.

As shown in Figure 2, two plastic scintillators are installed for triggering events and veto scintillators are also placed to remove cosmic events and background from the SR2 ring. TDC data for FDC are obtained with AMT-VME and the data is sent to the same DAQ PC as one for RAINERs. RIBFDAQ (Babirl and ANAROOT) are used as the DAQ and online monitoring softwares. 16 RAINER data and VME data are taken by independent 17 processes using only one DAQ PC including the event builder. The DAQ performance test shows that there is no event loss up to a few kHz in the zero suppression mode. This is sufficient considering our trigger rate which is typically a few hundreds Hz including backgrounds.

In summary, SCRIT WiSES and the readout system have been developed and operated smoothly for the wire target experiment, except for a few minor issues. More studies and improvements of the DAQ system are underway toward the first electron-132Sn scattering experiment at SCRIT in 2015.

References
3) K. Tsukada et al.: in this progress report.
4) S. Matsuo et al.: in this progress report.
New fast-kicker system for Rare RI Ring

Y. Yamaguchi,*1 H. Miura,*1,2 Y. Abe,*1,3 and M. Wakasugi*1

We are developing a new fast-kicker system for Rare RI Ring. Figure 1 shows the block diagram of the new fast-kicker system. It primarily consists of a thyratron switch, a charger coupled with a pulse forming network (PFN), a kicker magnet, a matching resistor, and a control section of the discharge trigger. The thyratron is a deuterium-filled three-gap ceramic CX1171, which was assembled by e2v technologies. The kicker magnet is a distributed constant type magnet with a characteristic impedance of 12.5 Ω. We use a new substrate of the thyratron grid pulser on the basis of a previous feasibility study1 to shorten the response time. In addition, we adopt a fast-charger named the hybrid charging system2 to reduce the recharging time.

The new substrate of the thyratron grid pulser is mainly composed of four FET drivers, four MOSFETs, and four pulse transformers (PTs). Here, the response time refers to the interval between the time of input of the discharge trigger signal and the time of 10 % of the thyratron current output. The response time steadies at around 250 ns when the charging voltage becomes 25 kV or more.

The hybrid charging system, which consists of a main charging part and a sub-charging part, is indispensable for extracting a particle from the ring in 700 μs using the same kicker magnet. The main charge (90 %) is achieved in about 0.1 ms using a double forward converter composed of IGBTs and a PT. After the main charging process is completed, the sub-charging process is immediately started. The sub-charge is completed within 0.1 ms using a high-frequency (500 kHz) resonant circuit and a PT. In addition, a high-precision voltage divider, which connects to the sub-part coupled with a comparator, can be maintained at a constant charging voltage level within the range of fluctuation of less than ±1 %. Figure 2 indicates an example of the PFN charging waveform for injection/extraction.

We fabricated a prototype twin kicker magnet to investigate the magnetic field by using a single-turn long search coil. Figure 3 shows the waveform of the magnetic field. Owing to the faster response time, the propagation time from a trigger signal input to the power supply until the flat-top center of the kicker magnetic field is about 465 ns. On the other hand, the shape of the flat-top part and the tail-part of the waveform does not satisfy our requirements. The fluctuation of the flat-top, which is defined as ±80 ns of the flat-top center, should be maintained at less than ±3 %, and we want to restrict it to less than 0 ±1 % for the region after 355 ns (for 200 MeV/u) from the flat-top center. Therefore, we are trying to reduce the disturbance of the waveform.

References
Status of the resonant Schottky pick-up for the Rare RI Ring project

F. Suzuki,∗1,∗2 Y. Abe,∗1,∗3 S. Naimi,∗1 A. Ozawa,∗3 T. Suzuki,∗2 T. Uesaka,∗1 M. Wakasugi,∗1 K. Yamada,∗1 T. Yamaguchi,∗2 Y. Yamaguchi,∗1 J. Zenihiro,∗1 and Rare-RI Ring collaboration

Precise mass measurements of rare RI make a substantial contribution to the study of nucleosynthesis and nuclear structure. Rare RI Ring is an isochronous storage ring for precision mass measurements of rare RI\(^\text{1,2}\). The Rare RI Ring allows us to determine masses with a precision of \(10^{-6}\). For such high precision measurement, it is essential to maintain the isochronous condition at \(10^{-6}\). We are interested in neutron-rich nuclei that have short lifetimes and low production rates. To measure such nuclei, we adopted the individual injection technique, in which a single particle is injected to the ring and stored.

Resonant Schottky pick-up is a beam diagnostic device which can detect non-destructively the signal from a particle passing through the resonant cavity at the resonance frequency, \(f_{\text{res}}\). With the resonant Schottky pick-up we acquire revolution frequencies of nuclei circulating in the ring. The distribution of the revolution frequency corresponds to the distribution of the momentum of nuclei. We adopted the resonant Schottky pick-up as a monitor for tuning the isochronous field in the ring. Similar resonant Schottky pick-ups have been used for the same purpose at GSI\(^3\) in Germany and IMP\(^4\) in China.

We performed the offline performance test of the resonant cavity with a network analyzer\(^5\). From the measurements, \(f_{\text{res}} = 171.43\ \text{MHz}\), shunt impedance \(R_{\text{sh}} = 161\ \text{k}\Omega\), unloaded quality factor \(Q_0 = 1880\), and \(R_{\text{sh}}/Q_0 = 86\ \Omega\) were obtained. With results of the offline test, the output signal power corresponding to a single ion with charge \(q\) at resonance\(^3\) is estimated to be \(P = q^2 \times 2.7 \times 10^{-21}\ \text{W}\) and the power of thermal noise \(P_{\text{noise}}\) is estimated to be \(7.1 \times 10^{-19}\ \text{W}\). For \(q \geq 17\), the signal from a single particle could be detected by the present Schottky pick-up.

We have started new offline test to investigate the sensitivity of the resonant Schottky pick-up. We developed a test system using the electron beam generated by an electron gun. Figure 1 shows the schematic view of the setup. We used a Ta filament cathode. A grid is connected to a function generator. With the output coupler, we detect the induced electromagnetic wave inside the resonant cavity at the resonance frequency. Usually, we obtain a DC electron beam when thermal electrons are accelerated. However, the DC electron beam does not induce the alternative electromagnetic field in the resonant cavity. Therefore, we add a frequency modulation at the desired frequency and amplitude into the grid. The modulated frequency is set to the resonance frequency. This simulates the ion circulation in the storage ring at the frequency. Changing the amplitude of the modulation controls the ion beam current. Therefore, we quantitatively evaluate the sensitivity of the resonant Schottky pick-up. The results of the test will be reported in coming publications.

Fig. 1. Schematic view of the offline test using an electron beam. To induce an alternative electromagnetic field inside the resonant cavity, we use the grid to modulate the DC electron beam at the resonance frequency. Therefore alternative electromagnetic fields are induced by electrons passing through the resonant cavity. We detect the induced signals with a real time spectrum analyzer (RSA).

References

\(\text{∗1} \) RIKEN Nishina Center
\(\text{∗2} \) Department of Physics, Saitama University
\(\text{∗3} \) Institute of Physics, University of Tsukuba
Extraction of multi-nucleon transfer reaction products in $^{136}$Xe and $^{198}$Pt systems


We have developed the KEK Isotope Separation System (KISS) to study the β-decay properties of the neutron-rich isotopes with neutron numbers around $N = 126$ for astrophysics research1−3. In the KISS, a gas cell filled with argon gas at a pressure of 50 kPa, in which nuclei produced by multi-nucleon transfer reactions are to be stopped and collected, is essential equipment for selectively extracting the isotope of interest by using a resonant ionization technique. Using the elastic events of $^{199}$Pt in the $^{136}$Xe beam and $^{198}$Pt target system, we evaluated the absolute extraction efficiency and beam purity of the KISS gas cell system. We successfully measured the lifetime of the unstable nucleus of $^{199}$Pt extracted from the KISS.

We performed on-line tests using the $^{136}$Xe beam with an energy of 10.75 MeV/nucleon and a maximum intensity of 20 pnA. The $^{136}$Xe beam was directed onto the $^{198}$Pt target placed in the gas cell, and was stopped at a tungsten beam dumper after passing through the gas cell. The thermalized and neutralized $^{198,199}$Pt atoms of the reaction products were re-ionized in the gas cell, and the ions were extracted and detected after mass separation by using a Channeltron detector for ion counting. The lifetime of $^{199}$Pt was measured by using β-ray telescopes newly installed at the E3 experimental hall4.

We successfully extracted laser-ionized $^{198}$Pt atoms emitted from the target by elastic scattering. However, the $^{199}$Pt ions formed molecular ions such as $^{198}$PtH$_2$, $^{198}$PtH$_2$O, and $^{198}$PtAr$_2$ with the intensity ratio of 1, 1, and 6, respectively, relative to the intensity of $^{198}$Pt ions. Figure 1 shows the measured extraction efficiency of the $^{198}$PtAr$_2$ molecular ions ($A = 278$) as a function of the primary beam intensity. The extraction efficiency was defined as a ratio of the number of $^{198}$PtAr$_2$ ions detected to the number of $^{198}$Pt atoms emitted from the target by elastic scattering (17 barn). The measured efficiency of about 0.20% was observed to be independent of the primary beam intensity, as shown in Fig. 1, owing to the bend structure of the gas cell. The obtained beam purity was > 99.7% at the maximum primary beam intensity of 20 pnA.

After the extraction of $^{198}$Pt, we extracted laser-ionized $^{199}$Pt ($t_{1/2} = 30.8(2)$ min) atoms that mainly formed $^{199}$PtAr$_2$ molecular ions like $^{198}$Pt did. Figure 2 shows the measured lifetime when $^{199}$PtAr$_2$ molecular ions are used. The measured lifetime $t_{1/2} = 33(4)$ min was in good agreement with the reported value. Thus, the molecular formation does not affect the lifetime measurement of unstable nuclei.

Considering the production rates of nuclei around $N = 126$ calculated by the GRAZING code3), we can measure 12 new lifetimes with an efficiency of 0.1%, beam purity of > 99.7%, and a primary beam intensity of 20 pnA. To extend this study to more neutron-rich nuclei, we have been developing a new sextupole ion guide with a large angular acceptance for increasing the extraction efficiency.

Fig. 1. Extraction efficiency of $^{198}$PtAr$_2$ molecular ions measured as a function of the $^{136}$Xe beam intensity.

Fig. 2. Lifetime measurement of $^{199}$Pt.

References
Detector system for
the KEK isotope separation system

S. Kimura,*1 H. Ishiyama,*1 H. Miyatake,*2 Y. Hirayama,*2 Y.X. Watanabe,*2 M. Oyaizu,*2 M. Mukai,*1 Y.H. Kim,*4 and A. Ozawa*1

The KISS has been developed to study the β-decay properties of neutron-rich nuclei around neutron number \(N = 126\) which determine the r-process path and form the third peak of the elemental abundance \((A \sim 195)\).\(^1\)\(^2\) The detector system of the KISS requires high detection efficiency for low-energy β-rays because the nuclei of interest have small Q-value around 2 MeV. In addition, the system should be operated in a low-background environment because of the low production rates of these nuclei. Although the tolerable count rate of the background depends on the production rates, our ultimate goal is to set around several tens of counts per day, allowing access to these nuclei.

The detector system of the KISS consists of β-ray telescopes, Ge detectors, and a tape transport system. A schematic view of the detector system is shown in Fig. 1. For particle identification, three Ge detectors are employed to detect K-X rays emitted from the nuclei of interest. To efficiently count low-energy β-rays with low background, the β-ray telescopes are composed of three double-layered thin plastic scintillators; the thicknesses of the first and second layers are 0.5 mm and 1 mm, respectively. The solid angle of the β-ray telescopes is 90% of \(4\pi\).

The β-ray telescopes worked as designed. The energy spectra of the scintillators were in good agreement with Geant4 simulations. A comparison of energy deposit in the first layer between the simulation and the measured result is shown in Fig. 2. The measured efficiency of the β-ray telescopes for low-energy β-rays emitted from a \(^{90}\)Sr/\(^{90}\)Y source was 55.4(15)% with an energy threshold of 20 keVee for the first layer and 30 keVee for the second layer.

The background rate of the β-ray telescopes was measured to be 5 cps. The origins of the background were considered to be cosmic rays and electrons scattered by γ-rays from natural activities. Initially, to reduce the cosmic rays, a veto counter system was installed, which consisted of plastic scintillators. The configuration of the plastic scintillators was designed based on the Geant4 simulation, and the designed value of the veto efficiency was 92% for 1 GeV muon. The veto counter reduced the previous background rate by 1.1 cps. In addition, to reduce the room background of γ-rays from natural activities, we installed shields with low-activity Pb blocks and reduced the background rate by 2.4 cps. Finally, by raising the energy threshold of the second layer to 70 keVee without significant sacrifice of the detection efficiency for β-rays of interest, we reduced the background rate by 0.3 cps. In total, we reduced the background rate to 1.2 cps from 5 cps.

The main component of this background rate is environmental γ-rays and accidental coincidence rate in an extra active area of the scintillators. We will replace the present telescopes with new ones consisting of gas counters and thin plastic scintillators. Gas counters will be constructed with a small amount of materials to reduce the Compton scattering of γ-rays.

References
2) Y. Hirayama et al.: In this report.
Q-value resolution improvements in the spectroscopy of deeply bound pionic atoms using BigRIPS

T. Nishi,1,2 D. Ahn,2,3 G.P.A. Berg,2,4,5 M. Dozono,2,3 D. Etoh,2,4,5 H. Fujioka,2,4,5 N. Fukuda,2,3 N. Fukushima,2,3 H. Geissel,2,4,6 E. Haettner,2,4,6 T. Hashimoto,2,3 R.S. Hayano,1,2 S. Hirenzaki,2,3,7 H. Horii,1,2,8 N. Ikeno,4,8 N. Inabe,2,9 K. Itahashi,2,9 M. Iwasaki,2,9 D. Kameda,2,9 S. Kawase,9 K. Kisamori,2,9 Y. Kiyokawa,9 T. Kubo,2,3 K. Kusaka,2,9 M. Matsushita,9 S. Michimasu,9 G. Mishima,1,2 H. Miya,2,3 D. Murai,2,3 H. Nagahiro,7 M. Niikura,1,2,8 S. Ota,9 N. Sakamoto,2,9 K. Sekiguchi,2,9,4 H. Suzuki,2,3,10 M. Takaki,9 H. Takeda,4,2 Y.K. Tanaka,2,4,5 T. Uesaka,2,3 Y. Wada,2,4,5 Y.N. Watanabe,1,2 H. Weick,2,4,5 H. Yamakami,2,4,5 Y. Yanagisawa2 and K. Yoshida2

In June 2014, we performed missing-mass spectroscopy on the deeply bound pionic atoms to measure their binding energies and widths.1,2) The Q values of the 122,127Sn(d,3He) reactions were measured using BigRIPS near the π− emission threshold. We succeeded in accumulating a sufficient number of events and achieved the best Q-value resolution in the spectroscopy of the Sn(d,3He) reaction thus far. In this paper, we report how we achieved the resolution.

We improved two aspects. First, the emittance and momentum spread of the primary beam were reduced by optimizing accelerator parameters. Second, the optics of the beam-transfer line was adjusted to realize optimum dispersion matching. Here, the “beam-transfer line” indicates the beam line from the exit of SRC to the F0 focal plane in BigRIPS.

The emittance and momentum spread were monitored using the beam position and angle at the achromatic focal plane F3 and the dispersive focal plane F5 in BigRIPS. According to these measurements, the voltage and phase of the flat top cavity of SRC, the phase of the RF of RRC, and the voltage of the rebuncher were optimized. We also optimized the phase slit inside and the double slits downstream of the AVF cyclotron. After optimization, we achieved an emittance of 0.2 × 2.0 πmm-mrad (horizontal) and a momentum spread of 0.027% (σ), which are dramatic improvements from those achieved in the pilot experiment: an emittance of 0.7 × 3.0 πmm-mrad and momentum spread of 0.04% (σ).

To adjust the dispersion at F0, a new method was developed using position information at the F3 and F5 focal planes. In our experiment, we developed new ion optics with finite dispersion at F0 to realize the dispersion-matching condition.3) However, there are no high-precision position/angle detectors in the beam-transfer line to tune the optics. In the new method, the momentum deviation of the particle and the position at F0 can be deduced through position measurements at F3 and F5 using the following equations:

\[ x_0 = x_3/(x|x)_0, \]
\[ \delta = (x_5 - (x|x)_3x_3)/(x|x)_5. \]

Here, \( x_0, x_3, \) and \( x_5 \) are the positions at the F0, F3, and F5 focal planes in BigRIPS, respectively. \( (x|x)_0 \) and \( (x|x)_3 \) are the magnifications from F0 to F3 and from F3 to F5, respectively. \( (x|x) \) represents dispersion. Because of achromatic transport from F0 to F3, \( (x|x)_0 \) is assumed to be 0. These transfer matrix elements of BigRIPS were measured in advance by setting the optics of the beam-transfer line to the standard mode, in which the F0 focal plane was achromatic. Figure 1 shows the 2D plot of the deduced \( \delta \) and \( x_0 \). By using this method, we could measure and improve the new optics in the beam-transfer line.

As a result, we succeeded in improving the Q-value resolution. The peaks in the online spectrum of the present experiment were clearly narrower than those of similar past experiments. The precise analysis is in progress.

Fig. 1. Scatter plot of \( x_0 \) versus \( \delta \) deduced from \( x_3 \) and \( x_5 \).

The slope corresponds to the dispersion at F0.

References
Development of D$_2$ gas-filled drift chamber for spectroscopy measurements of pionic atoms in inverse kinematics

Y. N. Watanabe,*1,*2 H. Fujioka,*1,*3 R. S. Hayano,*2 K. Itahashi,*1 T. Nishi∗1,*2 and Y. K. Tanaka∗1,*2

We report the development of a D$_2$ gas-filled drift chamber for spectroscopy measurements of pionic atoms. We plan to perform missing-mass spectroscopy measurements of deeply bound pionic atoms in inverse kinematics of the (d,$^3$He) reaction. We will employ a D$_2$ gas-filled multi-wire drift chamber (MWDC) as an active target in a magnetic field of ~ 1 T. A heavy ion beam is injected into the chamber inside which the reaction occurs. The reaction angle and the energy of forward scattered $^3$He are measured using the MWDC and silicon strip detectors, which are installed inside the MWDC. The energy of the $^4$He is approximately 60 MeV. The feasibility of the measurements was investigated through simulations in a previous study.$^1$ According to the results of the simulations, a position resolution of 500 $\mu$m and enough gain to measure 60 MeV $^3$He are required for the MWDC.

To check the performance of the D$_2$ gas-filled MWDC, we fabricated a prototype of the detector. For the MWDC, hexagonal wire geometry, in which a sense wire is surrounded by six potential wires, is adopted. The side length of the hexagon is 6 mm. The MWDC consists of 10 planes, five of which are tilted (two U planes at -18° and three V planes at -18° as shown in Fig. 1) to measure the vertical position of charged particles. The outer cells serve as guard wires against chamber walls to eliminate field deformation.

Figure 2 shows the measurement setup. Inside the MWDC, an $\alpha$ source (241Am, 4.3 kBq) was placed and a silicon strip detector (12 strips, 37.5 × 50 mm$^2$, 300 $\mu$m thick) was installed on the opposite side. The trigger was initiated by the signal of the silicon detector and the timing of the MWDC signal was recorded using a TDC. In this measurement, the chamber was filled with 1 atm H$_2$ gas instead of D$_2$ gas as the first step.

Tracking analysis was performed and position resolution was evaluated when a HV of -1420 V was applied to the potential wires. The $\alpha$-ray detection efficiency was higher than 99% for all planes except for the first one. Figure 1 shows a typical event display. The drift length in each cell is expressed as a circle and the hit strip in the silicon strip detector is painted black. The track was successfully reconstructed as indicated by the red line in Fig. 1. The position resolution of the planes with vertical and tilted wires was evaluated to be 100 – 150 $\mu$m and 100 – 250 $\mu$m. The resolution is sufficient for the experiment if the magnetic field does not deteriorate the resolution considerably.

Fig. 1. An example of an event display. There are potential wires on the vertices and sense wires at the center of the hexagons. The circles represent the drift length for each wire and the straight line is the deduced track.

Fig. 2. A schematic drawing of the measurement setup. An $\alpha$ source was placed in front of the first plane and a silicon detector was placed on the opposite side.

In the measurement, we observed the position dependence, i.e., the plane dependence of gas gain. In the fifth – eighth planes, facing blank regions, the gas gain was more than five times larger than that in the other planes when HV was -1420 V. This was due to the geometrical configuration of the wires, and it was qualitatively confirmed through Garfield$^2$ calculations that the electric field strength in these planes was effectively 5% higher. Geiger-mode behavior in these planes caused a rapid increase of current and made it difficult to apply higher voltage. We found that extra guard wires were needed facing the blank regions. Under the current condition, the detection efficiency for 60 MeV $^3$He in the low-gain planes was estimated to be less than 20%.

As the next step, we will improve gain uniformity by applying discrete voltage to each plane.

References
2) R. Veenhof: Garfield, (http://garfield.web.cern.ch/garfield)

*1 RIKEN Nishina Center
*2 Department of Physics, University of Tokyo
*3 Department of Physics, Kyoto University
Radiation monitoring in the RIBF using ionization chamber

M. Nakamura,* 1 K. Yamada,* 1 A. Uchiyama,* 1 H. Okuno,* 1 and M. Kase* 1

In recent years, we have attempted to monitor radiation due to beam loss in the RIBF by using self-made ionization chambers (ICs) 1,2,3). However, in the course of RIBF operations, a part of 238U 36+ ion beam accelerated at 345 MeV/nucleon struck the septum electrode of the electrostatic deflection channel (EDC) of RRC and the septum was damaged in December 2012. To avoid such serious damages, the part of septum where the ion beams can easily irradiate was cut off and molded to the "V-shaped" edge and many thermocouples (TCs) were set at the surface of the septum. Before the septum was damaged by the irradiation of ion beams and the consequent rise in temperature, these signals are input to BIS. However, the response time of these TCs are estimated in the order of few seconds. Furthermore, such results showed that the septum was damaged only when a part of the 238U 36+ beam hit the septum within 10 -3 to 1 s. Hence, a faster signal for BIS with a response time of at least of the order of 10 -3 s is required. On the other hand, the response time of IC can be estimated to the order of 10 -1 ms. The response time of the whole BIS is about 1 max. 25 ms. Accordingly, we can obtain the response time to the order of 10 -1 s when the alarm signal from IC is used for BIS. Hence, we investigated to introduce the alarm signal from IC around the EDC of RRC into BIS in the case of 238U 36+ ion beam acceleration.

Usually, we input the alarm signal from IC near the EDC of SRC to BIS after the "calibration experiments" 1,2). In these experiments, the ion beams were attenuated from 1/100 to 1/10 and irradiated to the EDC for a fairly short time and IC voltages were measured. From these results, we can estimate the alarm levels of IC to BIS. However, it can be very dangerous to irradiate heavy-ion beams to the EDC of RRC because of a sudden increase in the temperature of the septum. Therefore, we can consider the alarm levels of IC from the signals of TCs set at the septum. When the temperature difference between the TC set at the upper part of the septum with the TC set at the beam-exit side of the septum (defined as "the maximum value of septum temperature rising") becomes 10°C, the alarm signal is input to BIS. Hence, we have compared the maximum value of septum temperature rising with the signal of IC set near the EDC of RRC in the machine time of the 238U 36+ beam. The result is shown in fig. 1. The data showed little dispersion and the calibration curve in fig. 1 can be drawn. From this curve, we can recognize that the voltage of IC became about 1.4 V when the maximum temperature rising of EDC reached 10°C, shown as red dotted line in fig. 1. Then we can decide the alarm level of IC for BIS for the 238U 36+ ion beam.

Fig. 1 Correlation of IC voltage and maximum value of septum temperature rising

We have input the alarm signal to BIS from April 28 to May 12 and from October 16 to November 14, 2014 when the 238U 36+ ion was accelerated at 345 MeV/nucleon. On May 5, the BIS by the alarm signal from IC acted and stopped the operations of RIBF. Fig. 2 shows the IC signal from May 5, 0:00 to 9:00. At 5:45, the signal suddenly rose up to 6.4 V and the alarm signal was sent to BIS. We could confirm that this signal reached BIS faster than the alarm signals from TCs set at EDC. After this signal, any alarm from IC did not reach BIS in the machine time of the 238U 36+ beam in 2014. The cause of this unusual signal shown in fig. 2 is unknown. In any case, as described above, we could confirm that the faster alarm signal to BIS can be input from the IC near the EDC of RRC. Thus, we investigated to input the alarm signal from IC in RRC to BIS each time heavy ions are accelerated, such as 238U 36+.

Fig. 2 Signal from the IC near EDC of RRC

References
Measurement of activation around the He gas stripper at RIBF

A. Akashio,*1 K. Tanaka,*1 and H. Imao*1

The activation of the He gas stripper setup caused by a uranium beam was evaluated. There are several types of gas and solid stripper setup in RIBF, and a stripper setup is selected for the beam nuclide, such as uranium, xenon, and calcium. The He gas stripper setup has been developed for uranium beam acceleration at RIBF.1) The stripper setups are often exchanged with other types to change the beam nuclide of the RIBF accelerator. The radiation exposure caused by the residual dose during the exchange and maintenance works is a serious issue. Thus, evaluating the residual dose and studying the origin of the dose are important to improve future setups. This evaluation is also applicable for the shielding design of future facilities.

In this study, the activation method was applied for the He gas stripper irradiated by a uranium beam. During the machine operation in the autumn of 2014, the samples were placed both inside and outside the stripper chamber. After uranium beam irradiation, the γ rays emitted from the samples were measured using a Ge detector.

The energy of the uranium beam on the stripper was 10.75 A MeV and the beam intensity in operation was 1200 particle nA. The beam irradiated for one month. The He gas pressure was 7 kPa, and the gas thickness was approximately 50 cm which corresponds to 0.7 mg/cm². The sample materials were aluminum and bismuth. The aluminum sample is made of the same material as the gas stripper chamber. Bismuth is a useful element for neutron measurement. Radioactive isotopes of bismuth are generated by neutron irradiation, and the generated isotope nuclides depend on the neutron energy because of the threshold energy of the reactions, as listed in table 1.

Some of the aluminum samples were set in the gas stripper chamber where the He gas pressure was highest. The distance between the nearest sample and the uranium beam was 47.25 mm. The samples placed inside the stripper chamber were hit by the nuclei of the fission products of the uranium beam. The other aluminum samples set outside the stripper chamber are sensitive to the neutron only because the fission products stop in the chamber wall and do not reach outside. Thus, the aluminum samples are the benchmark of the neutron activation of aluminum chamber itself. The bismuth samples are set with the aluminum samples outside the chamber to obtain the neutron energy on the aluminum samples.

Figure 1 shows the measured γ-ray spectrum obtained from the aluminum sample set inside the chamber after cooling for 13.5 days. Table 2 lists the identified nuclides with short half lives. Typical nuclides of the fission products from the 238U beam were observed. γ rays peaks from long-lived nuclides were not observed yet in the spectrum owing to the high background γ rays from the short-lived nuclides. γ-ray peaks of aluminum itself, such as 24Na with a 15 hour half life, were not found.

Table 1 lists the observed bismuth isotopes in the natural 209Bi samples that were set outside the stripper chamber. The result suggests that the energy of irradiated neutrons on the bismuth samples was up to 22.55 MeV, since γ rays from the 209Bi nucleus, which have a threshold energy of 28.6 MeV, were not detected.

After cooling the samples for a long time and background levels become low, γ rays from the long-lived nuclides will be detected. The result will be compared with a Monte Carlo simulation result to evaluate radiation issues in the future.

Table 1. Threshold of neutron energy corresponding to the production of radioactive bismuth isotopes observed in this study.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half life</th>
<th>Reaction</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>207Bi</td>
<td>31.6 year</td>
<td>209Bi(n,3n)207Bi</td>
<td>14.12</td>
</tr>
<tr>
<td>206Bi</td>
<td>6.4 day</td>
<td>209Bi(n,4n)206Bi</td>
<td>22.55</td>
</tr>
</tbody>
</table>

Table 2. Typical radioactive nuclei observed in the aluminum sample inside the stripper chamber.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half life</th>
<th>Nuclide</th>
<th>Half life</th>
</tr>
</thead>
<tbody>
<tr>
<td>90Zr</td>
<td>64 day</td>
<td>138Cs</td>
<td>13 day</td>
</tr>
<tr>
<td>96Nb</td>
<td>35 day</td>
<td>140Ba</td>
<td>13 day</td>
</tr>
<tr>
<td>99Mo</td>
<td>2.8 day</td>
<td>140La</td>
<td>1.7 day</td>
</tr>
<tr>
<td>199mIr</td>
<td>6.0 hour</td>
<td>141Ce</td>
<td>32.6 day</td>
</tr>
<tr>
<td>103Ru</td>
<td>39 day</td>
<td>147Nd</td>
<td>11 day</td>
</tr>
</tbody>
</table>

References

*1 RIKEN Nishina Center
Beam preparation for fee-based utilization of a 70-MeV/A Kr-beam

T. Kambara*1 and A. Yoshida*1

In October 2014, RIKEN provided a 70 MeV/A Kr beam from the RIKEN Ring Cyclotron (RRC) to private companies as the first fee-based utilization.1) Since the customers required irradiations in an atmosphere with a uniform flux distribution over a large area and specified linear energy transfer (LET), we developed the following system at the E5A beam line and successfully delivered desired beams to the customers.

The uniform beam-flux distribution was achieved with wobbler magnets and a scatterer foil. A pair of 60-Hz wobbler magnets deflected the beam from the RRC vertically and horizontally so that the beam center traced a circle. At about 68 cm downstream, the beam passed through a scatterer (48-µm thick Au foil), where multiple scattering brought about a lateral velocity distribution. At about 392 cm downstream from the scatterer, the beam passed to the atmosphere through an 8-cm diameter and 75-µm thick polyimide (Kapton) vacuum-separation window.

In the atmosphere part of the beam path, we used an energy degrader and several detectors to control the LET and measure the beam characteristics. Figure 1 shows the configuration. After the window, there were an ionization chamber (IC: Applied Engineering Inc., AE-1341S) and a 0.5-mm thick plastic scintillator for measuring the total beam intensity. The IC had a 5-cm diameter window that determined the beam size downstream. An adjustable energy degrader (Wood-Bell Co. Ltd.) followed to control the LET, where the beam energy was adjusted by inserting up to eight Al foils with 8-cm diameter and thicknesses of 12.8, 23.8, 48.6, 100.2, 100.8, 196.4, 486.0, and 975.4 µm. We can insert any combination of the foils by using a remote-control pneumatic system to set the LET almost continuously. After the degrader, two sets of ∆E + E Si-detector stacks were mounted on a motor-driven linear slider; the detectors can be not only placed at the center of the beam path but also horizontally moved across the beam for measuring the beam-flux distribution. The customer samples were placed at about 10 cm downstream from the Si detectors.

Beam scanning with the Si detectors revealed that the beam flux was uniform within ±1.8 % over a diameter of about 35 mm. Another measurement with a GAFCHROMIC-film irradiation showed that the local deviation of the dose was within ±5 %.

For the beam-intensity measurements, the scintillator counted the ions from nearly-zero intensity to about 2.5 × 10^6 ions/s and the IC was available from 400 to 2.5 × 10^9 ions/s.

We adjusted and verified the LET at the sample in the following way: Increasing the thicknesses of the degrader foils, we measured the beam energy by using the Si detectors until the beam was totally stopped. Then we compared the thickness-energy relation to SRIM calculations2) and obtained the stopping power in the sample as a function of the degrader thickness, with a correction for the energy loss in the atmosphere between the Si detector and the sample. We considered the stopping power as the LET.

Figure 2 shows the relation between the LETs of ⁴⁰Ar, ⁸⁴Kr, and ¹³²Xe ions at the surface of Si and their ranges in the material. The 70-MeV/A ⁸⁴Kr beam from the RRC has the maximum energy of 43 MeV/A at the irradiation position, which corresponds to anLET between 13.2 and 40.9 MeV/(mg/cm²); the solid line in Fig. 2 indicates this region. In addition, if we use 95-MeV/A ⁴⁰Ar and 26-MeV/A ¹³²Xe beams accelerated by the RRC, an LET from 2.3 to 69 MeV/(mg/cm²) is available at the same beam line.

References
1) A. Yoshida et al.: In this report.

Fig. 1. Setup of Kr-beam irradiation after the window.

Fig. 2. LETs of ⁴⁰Ar, ⁸⁴Kr, and ¹³²Xe ions at the surface of Si as functions of their ranges. The solid lines correspond to the ions accelerated by the RRC and extracted to the atmosphere.
Implantation of $^7$Be and $^{22}$Na beams for wear diagnostics application

A. Yoshida,*1 T. Kambara,*1 H. Takeichi,*1 H. Yamaguchi,*2 T. Nakao,*2 D. Kahl,*2 R. Uemoto,*3 and N. Takahashi*4

To develop a method for wear diagnostics of industrial material using RI beams, intense beams of $^7$Be ($T_{1/2} = 53$ days) and $^{22}$Na ($T_{1/2} = 2.6$ years) provided by CRIB were implanted in the surface of machine parts. Here we describe the generation and characterization of the RI beams.

The $^7$Be beam was produced via $H(^7Li,^7Be)n$ reaction. A beam of 5.7 MeV/A $^7Li^{2+}$ with an average intensity of 1.7 particle $\mu A$ ($pA$) was introduced to CRIB and passed through a cryogenic $H_2$ gas target at a pressure of 760 Torr and cooled by liquid $N_2$ to 90 K. The produced $^7Be^{4+}$ beam was introduced to a dedicated vacuum chamber at the F2 focal plane. A position-sensitive Si detector (PSD, Hamamatsu S378-02), an energy degrader, and a rotating irradiation sample holder were installed in the chamber. The energy and profile of the RI beam were measured using the PSD. The energy of the $^7Be$ beam was 4.16 MeV/A, and the beam spot size was $4.8 \times 8.1$ mm in FWHM when the momentum spread was set to $\pm 3.1$ %. The relatively large beam-spot size seems related to a halo of the beam spot at the gas target. The implantation rate of the $^7Be$ beam was approximately 60 kBq/h, according to a gamma-ray measurement after the implantation.

The $^{22}$Na beam was produced via the $H(^{22}Ne,^{22}Na)n$ reaction. A 6.1 MeV/A $^{22}Ne^{7+}$ beam with an average intensity of 0.25 $pA$ was introduced to CRIB and passed through a cryogenic $H_2$ gas target at 400 Torr and 90 K. The energy and size of the $^{22}Na^{11+}$ beam at F2 was 3.67 MeV/A and $4.7 \times 4.3$ mm in FWHM, respectively, with a momentum spread of $\pm 3.1$ %. The implantation rate was approximately 0.3 kBq/h.

For wear-loss diagnostics, the depth profile of implanted RI should be controlled and characterized accurately. The depth profile was controlled using a rotating energy degrader that had eight foils of different thicknesses. The foils were circularly placed on a wheel of diameter 14 cm rotating at 12 rpm so that they cross the RI beam path one by one. An additional degrader foil can be mounted on a beam collimator with a diameter of 10 mm placed downstream of the wheel.

To study the implantation-depth profile, we first irradiated a stack of 2-$\mu$m-thick Al foils with the RI beams, and measured the radioactivity of each foil with a Ge detector. Then we obtained the beam-energy spectra by the PSD, and calculated the range distribution of the ions in Al with the SRIM code3). Figure 1 shows a case of a $^{22}$Na beam with a narrow momentum distribution of $\pm 1$ % implanted to the stack after the rotating degrader with a blank and seven Al foils with thicknesses of 4.9, 7.6, 11.9, 16.9, 23.8, 27.4, and 31.7 $\mu$m. The depth profile with the stacked-foil is shown by black circles as relative intensities of the radioactivity in the foils. The horizontal and vertical error bars indicate the thickness and the statistical error for each foil. The dotted line shows the SRIM calculation of the range distribution from the energy spectrum. Below a depth of 5 $\mu$m, the corresponding energy spectrum could not be measured as it was below the detector threshold. The triangles indicate normalized fractions of the foils obtained by re-binning the range spectrum according to the stack-foil thicknesses. We multiplied a factor of 0.97 to the stopping power of the SRIM calculation for optimum agreement between the stacked-foil measurement and the calculation.

The conventional stacked-foil method is reliable because it directly measures the implanted RI, but its depth resolution is limited because assembling many thin foils as a stack is hard work. On the other hand, the energy measurement with a Si detector is simpler, but the accuracy of the implantation-depth distribution depends on the range calculation. Here, we combined the two methods with a correction factor for the SRIM calculation results and obtained a continuous implantation-depth profile.

![Fig. 1. Implantation-depth profile of $^{22}$Na beam in stacked Al foils.](image)

References
1) A. Yoshida et al.: “Operation report of industrial cooperation team”, in this report.
The main aim of the J-PARC E16 experiment is to measure the mass modification of $\phi$ mesons in nuclear matter at J-PARC in order to study the origin of hadron mass. The details of this experiment are presented in another article of this report\(^1\).

We employed a tracking detector using the Gas Electron Multiplier (GEM)\(^2\), and have been developing it to be a position-sensitive detector in a magnetic field with a magnitude of 1.8 T at the center of the magnet. Our requirement for this detector is a position resolution of 100 $\mu$m up to an incident angle of 30° in a high counting rate environment of up to 5 kHz/mm\(^2\). Our GEM tracker consists of a drift cathode, triple-GEM stack, and readout strip board. We chose a strip pitch of 350 $\mu$m to achieve the required position resolution.

For inclined tracks, a hit position of a GEM tracker is determined with a technique called “timing method”, where the spatial distribution of a charge cluster generated by a charged track in the drift gap is reconstructed using the arrival timing information of signals from readout strips. As shown in Fig. 1, the distance from ionization electrons to each strip ($z$) can be calculated by $v_d \times t$, where $t$ is the arrival time and $v_d$ is the drift velocity. After calculating each $z$, we fit a straight line to these points and determine the intersection point of the line with the center of drift gap. In the experiment, a drift gap of 3 mm is desirable to reduce the signal pile-up; however the test experiment was performed using a wider gap. Thus, additional analysis is performed to evaluate performance for a 3 mm gap. The analysis only uses signals that have smaller drift times corresponding to the 3 mm gap.

Results of this analysis are shown in Fig. 2 and Fig. 3. We tested four types of chambers, which are summarized in Table 1. We have achieved a position resolution better than 100 $\mu$m and an efficiency of 90% up to an incident angle of 30° for all sizes of GTRs.

### Table 1. The summary of tested chambers.

<table>
<thead>
<tr>
<th>Size</th>
<th>Drift gap</th>
<th>Legend in Fig. 2 &amp; 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm</td>
<td>7 mm</td>
<td>GTR100 A</td>
</tr>
<tr>
<td>100 mm</td>
<td>5 mm</td>
<td>GTR100 B</td>
</tr>
<tr>
<td>200 mm</td>
<td>7 mm</td>
<td>GTR200</td>
</tr>
<tr>
<td>300 mm</td>
<td>7 mm</td>
<td>GTR300</td>
</tr>
</tbody>
</table>

![Fig. 1. Positions where ionization electrons are generated can be reconstructed by $v_d \times t$.](image1)

![Fig. 2. The result of 3 mm gap equivalent analysis. Standard deviations of residual as functions of incident angle.](image2)

![Fig. 3. Detection efficiencies as functions of incident angle.](image3)

**References**

1) S.Yokkaichi, et al, in this report
Preparation status of the J-PARC E16 experiment: measurement of spectral change of vector mesons in nuclei

S. Yokkaichi*1 for the J-PARC E16 Collaboration

We have proposed the experiment E161 to measure the vector meson decays in nuclei in order to investigate the chiral symmetry restoration in dense nuclear matter. The experiment will be performed at the J-PARC Hadron Experimental Facility. Scientific ("stage 1") approval was granted to the experiment E16 by PAC in March 2007. For the full approval, we were required to demonstrate the experimental feasibility and show the prospects of acquiring sufficient funds and of beam-line construction. Toward the full approval, the technical design report (TDR) was submitted to PAC held in May 2014, and the TDR is being revised as per the requirements provided by PAC, and the revised TDR will be submitted to the PAC held in July 2015.

The aim of the experiment is to perform a systematic study of the spectral modification of vector mesons, particularly the $\phi$ meson, in nuclei, using the $e^+e^-$ decay channel with statistics that are two orders larger in magnitude than those of the preceding E3252 experiment performed at KEK-PS. In other words, the aim is to accumulate $1 \times 10^5$ to $2 \times 10^5$ events for each nuclear target (H, C, Cu, and Pb) and to deduce the dependence of the modification on the matter size, and the meson momentum. At the same time, the $e^+e^-$ decays of the $\rho$, $\omega$, and $J/\psi$ mesons can be measured, while the yields depend on the trigger condition required to suppress the background $e^+e^-$ pairs.

For the experiment, we plan to use a $10^{10}$-pps, 30-GeV proton beam in the high-momentum beam line, which is being constructed at J-PARC. In order to increase the statistics by a factor of 100, we will construct a large-acceptance spectrometer that can be operated under $10^7$ Hz nuclear interactions at the target. In order to cope with such a high-interaction rate, GEM has been adopted for constructing new tracking and PID detectors.

The construction of the high-momentum beam line, where we perform the experiment, has been on-going since 2013 by KEK. The first beam is scheduled around the end of JFY 2016; it was delayed by a year because of the beam stoppage due to the radiation accident at J-PARC in May 2013. The schedule of the spectrometer magnet reconstruction is also delayed, and it is expected to be completed by July 2015. After the completion of the magnet reconstruction, we can begin installing the detectors in the magnet. The target day of the construction is March 2016. Our spectrometer has 26 modules. Owing to the budget limitations, our first goal of the staged construction plan is to construct eight modules, which correspond to approximately one third of the full installation.

The development of the detectors has almost completed, and we are moving to the production phase. For the GEM Tracker (GTR)3, the production of GEM has been underway since 2013. Six modules (out of eight, as mentioned above) are currently under construction. The production of frames made of CFRP, which is used to install the GEM chambers in the spectrometer, started in 2014. For the HBD4, which is one of our electron ID detectors, only two modules are currently under construction. The lead-glass (LG) EM Calorimeter, another electron ID detector, utilizes the recycled LG from the TOPAZ experiment. The reshaping of LG blocks, for eight modules (330 blocks), is to be completed at the KEK engineering center within JFY 2014.

The development of the read-out and trigger modules is underway. As a pre-amplifier and front-end module (FEM) of GEM detectors, an APV25 chip and SRS, both are CERN-made, are adopted. We joined the RD51 collaboration in CERN in July 2013 to co-develop GEM-related electronics. For HBD, we use the RD51-made APV25 preamp. For GTR, a more smaller preamp using the APV25 chip was fabricated by ourselves and the production started in January 2015. The first version of the FEM for the LG is tested and the revision is on-going.

For the trigger, signals from the GEM foil of GTR and HBD are used. ASICs for the amp-shaper-discriminator to generate the trigger primitive of the two detectors has been produced under the cooperation of the KEK e-sys group. For GTR, the test of the second version is to be started. The test of the first version for HBD is almost completed. To generate a global trigger signal, an FPGA board “UT3” (Belle II collaboration) is used. To transfer the trigger primitives to UT3, we developed another module called “TRG-MRG”. The first version of TRG-MRG is already delivered and will be tested at KEK. These tests will be completed by the end of JFY 2014.

References
4) K. Kanno et al.: in this report.
5) http://rd51-public.web.cern.ch/RD51-Public/
Simulation of HBD response in the J-PARC E16 experiment based on test results

K. Kanno*1,*2 for the J-PARC E16 Collaboration

A hadron blind detector (HBD) has been developed for the J-PARC E16 experiment.1) The E16 experiment aims to investigate the origin of QCD mass through the spectral change of a ϕ meson in a nucleus. The mass spectrum is reconstructed through electron-positron decays. A detector for electron identification is required. The HBD is utilized in the E16 experiment for this purpose. The HBD identifies electrons by converting Čerenkov photons emitted by an incident electron in a CF3 radiator into photoelectrons using a CsI photocathode. These photoelectrons are amplified by gas electron multiplier2) (GEM) foils and are subsequently read out as an electric signal. Other charged particles apart from the electron do not emit Čerenkov photons in the momentum region where we perform the measurement, 0.4–3 GeV/c. With this scheme, the HBD distinguishes electrons from the other charged particles.

We have constructed a prototype of the HBD and performed a test experiment using a positron beam of 1.0 GeV/c at Research Center for Electron Photon Science, Tohoku University. We successfully observed 11 photoelectrons per incident positron with the prototype3) when the incidence angle to the beam was 0°. This result was consistent with the expected result calculated based on the performance of each detector element. However, only HBD response to an electron was obtained in this beam test, and the response to a pion is also required to determine the pion rejection power for a given electron detection efficiency. We estimated the HBD response to a pion through simulation.

For this simulation, we used the HBD response to a pion that has already been obtained with another prototype. This prototype has a smaller pad readout and longer gap lengths between GEM foils. Taking into account of the differences between the prototype and another prototype, we performed the simulation to evaluate the prototype response to a pion. With this simulation, we estimated an electron detection efficiency of 85% with a pion rejection factor of 50 for 1.0 GeV/c electrons and pions at the threshold of 6.5 e when the incidence angle was 0°. In the actual J-PARC E16 experiment, charged particles including electrons and pions are emitted from a target and the incidence angle of these particles to the HBD is approximately 0–45°. Furthermore, these charged particles move along a curved line because of the magnetic field in the spectrometer used in the experiment, resulting in a larger incidence angle to the HBD.

To evaluate the electron detection efficiency in the offline analysis, we performed another simulation by including the possible momentum and incidence angle distribution of electrons from ϕ meson decays. In the simulation, ϕ mesons were generated by a 30 GeV/c proton-induced reaction using the nuclear cascade code JAM.4) These ϕ mesons decay into electrons and positrons, and then electrons move according to the magnetic field. We assumed pion samples had the same track as the electron samples. The HBD responses to an electron and a pion were estimated based on the result of the beam test and the simulation mentioned in the previous paragraph. The electron detection efficiency as a function of electron momentum with a pion rejection factor of 100 is shown in Fig. 1. The efficiency decreases in the region of 0.4–1.5 GeV/c. This fact reflects that the signal amplitude of a pion increases with decreasing momentum. A pion sample having lower momentum has a larger curvature in a magnetic field and consequently has a larger incidence angle to the HBD, namely, a larger signal amplitude. The large errors in the high-momentum region are due to availability of limited statistics. The overall efficiency is 60% with a pion rejection factor of 100 at the threshold of 7.5 e, which meets the requirement of the experiment.

As the next step, we will measure the response to a pion, which has been simulated, using a pion beam with GEM foils and the readout pad configuration for the production type of HBD.

References
1) S. Yokkaichi et al.: in this report
2) F. Sauli: Nucl. Instr. and Meth. A 386, 531 (1997)
Resistive Plate Chamber (RPC) for BGOegg Experiment\textsuperscript{t}

T. Nam,\textsuperscript{1,\textasciitilde,3} N. Tomida,\textsuperscript{2} M. Niiyama,\textsuperscript{2} H. Ohnishi,\textsuperscript{1,\textasciitilde,3} C.-Y. Hsieh,\textsuperscript{4} M.-L. Chu,\textsuperscript{1} and W.-C. Chang\textsuperscript{4}

We have developed and installed a time-of-flight system to measure the energy of charged particles, especially protons, for BGOegg experiment. The design of the chamber was based on the RPC chamber for LEPS2 experiment, which we have already reported previously in ref.\textsuperscript{1).}

BGOegg experiment using LEPS2 beamline to study hadron photoproductions is currently under operation at SPring-8 (Super Photon Ring 8 GeV). The main detector is the BGOegg calorimeter which made from 1320 Bi\textsubscript{4}Ge\textsubscript{3}O\textsubscript{12} crystals assembled in the shape of an egg (fig. 1). The BGOegg calorimeter can detect high-energy gamma ray coming out from the target in an open angle of 24 to 144 degrees; an energy resolution of 1.3\% at 1 GeV gamma energy was achieved and previously reported at ref\textsuperscript{2).}

\textbf{Figure 1: setup of the BGOegg experiment}

The RPC is placed 12.5 m downstream from the target, and covers an open-angle of 7° in the horizontal and 4° in the vertical. In BGOegg experiment, we are measuring the $\eta'$ mass modification to study the $U_A(1)$ anomaly problem using a nuclear target with the BGOegg detector system and the LEPS2 high-intensity photon beam. We are looking for the presence of the $\eta'$ meson in its decay to $\gamma\gamma$, $\pi^0\pi^0\eta$ in the nuclear medium. In addition, the momentum of a forwardly recoiled proton in the $A(\eta',\eta')$ reaction will be measured by the RPC. We use the RF signal as the start signal and the RPC signal as the stop signal, the time resolution must include the contribution of all uncertainty sources such as the amplifier, discriminator, RPC, TDC and the time reference RF.

\[ \sigma_{\text{TOF}}^2 = \sigma_{\text{RF}}^2 + \sigma_{\text{Amp}}^2 + \sigma_{\text{DIS}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{cable}}^2 + \sigma_{\text{RPC}}^2 \]

For the timing measurements, CAEN V1290A TDC modules were used. The resolution of the RF signal is about 4 ps. The electron bunch width in the SPring-8 storage ring is ~15 ps. The time resolution of V1290A is 20 ps after the integral non-linearity corrections. If we assume that the internal time resolution of RPC is 20 ps\textsuperscript{3),} then the remaining contributions come from Front-End-Electronics(FEES) and are considered to be less than 40 ps. In total, the resolution of our RPC system is expected to be 50 ps.

During the development, we have produced and tested for many aspects of the RPC such as geometry of the pad/strip read-out, width of the gap, number of gap and trigger rate.

\textsuperscript{t} This manuscript summary the results which were reported at JINST 9 C10008, 2014.
\textsuperscript{1) Research Center for Nuclear Physics, Osaka University.
\textsuperscript{2) Physics Department, Kyoto University.
\textsuperscript{3) RIKEN Nishina Center.
\textsuperscript{4) Institute of Physics, Academia Sinica

The 260 $\mu$m x 2 stacks x 5 gaps 2.5 x 100 cm$^2$ strip read-out with anode inside geometry reached a time resolution of 50 ps and an efficiency more than 99% above 10 Hz/cm\textsuperscript{21). The coverage area is 3.2 x 2 m$^2$. The wall consists of 32 RPC modules as shown in fig. 2; 2 rows with 16 modules each. The size of an RPC module is 20.75 x 100 cm$^2$ and the active area of each RPC module overlaps about 0.3 cm with each other in the horizontal and 0.5 cm in the vertical.

The custom FEES of our RPC including the amplifier, discriminator and stretcher were developed by Dr. M.-L. Chu. A method for the signal read-out to reduce the total number of TDC and ADC channels by half was applied, and this method is shown in fig. 3.

The special feature of the amplifier is that it is designed to minimize the reflection of the signal. The input impedance of the amplifier is set to 40 ohm and it matches well with the impedance of our RPC, which is about 30 - 40 ohm. The output signal of our custom discriminator has the same width as the input. This width is very narrow, typically around 2 ns. And this width is too narrow to be read by V1290A TDC. Therefore, we developed an additional stretcher to be placed after the discriminator to stretch the pulse width to 10 ns so that it can be read by V1290A TDC. For the timing measurement, we use CAEN V1290A TDC modules. For the charge measurement, we use LeCroy Fast Encoding and Readout ADCs (FERAs). The ADC information is used for developing correction parameters and a strip separation method.

BGOegg experiment started acquiring data from April 2014, and the performance of the RPC is being checked against many aspects and the calibrations are under way to ensure the reliability of the RPC’s data for physics studies in near future.

References
Quality assurance test of pixel detector ladders for VTX

T. Sumita,*1 Y. Akiba,*1 H. Asano,*1,∗2 T. Hachiya,*1 M. Kurosawa,*1 T. Moon,*1,∗3 H. Nakagomi,*1,∗4 C. Pancake,*5 H. Sako,*1 S. Sato,*1 A. Taketani,*1 and the PHENIX VTX group

A silicon vertex tracker (VTX) was installed in the PHENIX detector at the Relativistic Heavy Ion Collider. The VTX detector consists of two inner layers of silicon pixel detectors and two outer layers of silicon strip detectors. A pixel ladder is composed of a mechanical stave, four hybrid sensors1), and two readout buses. A hybrid sensor is an assembly consisting of a silicon pixel sensor and four readout chips (ALICE1LHCb2)) bump-bonded to the sensor. One ladder has 16 readout chips and one readout chip has 8,192 pixels, with a pixel size of 425 µm × 50 µm, organized in 32 columns and 256 rows.

We fabricated new spare silicon pixel ladders. In order to ensure correct operation before the assembly of the VTX detector, quality assurance (QA) test of the ladders need to be performed. This report presents the results of the QA test for the ladders.

The QA test system consists of Silicon PIxel Read-Out (SPIRO) modules, Front-End Module (FEM), and NOVEC HFE-7200.3) The SPIRO modules provide all electricity, control the readout chip of the sensor module and read out pixel data The FEM is an interface between the SPIRO modules and the data acquisition system. NOVEC HFE-7200 was used to cool the readout chips. The following tests are performed for each ladder.

1) Current consumption:
The current consumption of the analog and digital circuits of the readout chips are measured.

2) JTAG functionality:
It is confirmed whether the configuration settings in the chip can be controlled by using Joint Test Action Group (JTAG4)) protocol.

3) Minimum threshold:
For all chips, the minimum threshold in all pixels are determined.

4) Pulse test:
Pulse test is to check for dead chips and connections. The test pulse from the pulsar inside the chip is transmitted to each pixel cell.

5) Test using a β-ray source (90Sr):
Faulty bump bonds and the maximum efficiency are evaluated by β-source measurements

The ladder is biased at 10 V during the measurement.

A total of 7 ladders were tested, and correct operation of all the ladders was confirmed except for one ladder. Four chips (one hybrid sensor) of the incorrectly working ladder did not respond to the tests because of a short circuit in the readout bus. A typical result of a readout chip in the source test is shown in Fig. 1. The inefficient area at the bottom of columns 1, 9, 17, and 25 is attributed to the presence of the test pulse signal generator on the readout chips, which affected the readout circuit.

In summary, QA tests for the seven new assembled pixel ladders were performed. The results confirmed that six ladders are working properly and that a part of one ladder is not functional. One of functional ladders will be used in the 2015 run.

References
4) IEEE std 1149.1.
Fast clear technique for NEBULA data acquisition for SAMURAI17 experiment

Y. Togano,*1,*2 Y. Kubota,*2,*3 H. Baba,*2 and H. Otsu,*2 for the SAMURAI17 collaboration

A fast clear technique for NEBULA data acquisition (DAQ) was newly introduced for the $^{132}$Sn($p, n$) experiment at SAMURAI.1) The technique enabled the measurement of recoil neutrons and projectile-like neutrons in coincidence. NEBULA DAQ could not work with the main trigger for the ($p$, $n$) reaction measurement because the recoil neutrons were slow.

The incoming $^{132}$Sn beams were detected by beam tagging detectors: SBT1 and SBT2. We define the signal from SBT1 as “Beam” in this report. Recoil neutrons from the ($p$, $n$) reaction were measured using WINDS2) surrounding a liquid hydrogen target. The charged outgoing particles were analyzed by using the SAMURAI system. The outgoing neutrons from the breakup of reaction products were measured by using NEBULA. The main trigger of the experiment was a coincidence of Beam and WINDS. Because of the slow neutrons from the ($p$, $n$) reaction detected by using WINDS, the trigger decision of the experiment was $\sim 300$ ns slower than the that with the standard SAMURAI setup.3)

The main trigger for the experiment was controlled by using the GTO module.4,5) The trigger for NEBULA DAQ was a coincidence of Beam and NEBULA signals (Beam $\times$ NEBULA trigger). The analog and time information of NEBULA was obtained by using CAEN V792 QDC and V775 TDC modules, respectively. The VME module used to interrupt NEBULA DAQ was RPV-130 by REPIC. The fast clear of V792 and V775 could be performed by inputting the fast clear signal to the modules during their data conversion. The dead time of the fast clear was $600$ ns. Figure 1 shows the circuit diagram of NEBULA DAQ for the fast clear. The interrupt of NEBULA DAQ was performed by using a 10 $\mu$s delayed main trigger signal to allow time for the data conversion of QDC and TDC. If the DAQ system was interrupted when NEBULA data were empty owing to no Beam $\times$ NEBULA trigger or the dead time of fast clear, the NEBULA data were recorded as an empty event. The fast clear signal was generated by anticoincidence between Beam $\times$ NEBULA (synchronized with DAQ start/stop) and the main trigger. If the main trigger was fired to acquire data during the dead time of fast clear for NEBULA, a fast clear flag was stored by a coincidence register (coin. reg. 1). The NEBULA-accepted trigger was Beam $\times$ NEBULA vetoed by the dead time of NEBULA DAQ and the fast clear of V775/V792. A flag for Beam $\times$ NEBULA was stored by a coincidence register if it was coincident with the main trigger (coin reg. 2). NEBULA DAQ could be switched to the singles mode, in which the trigger was generated by NEBULA itself for calibrations, in B2F experimental area.

In the experiment, the typical rate of the main trigger and the Beam $\times$ NEBULA trigger were 2.4 kHz and 1.6 kHz, respectively. Owing to the dead time of the fast clear, $\sim 0.7\%$ of NEBULA data could not be collected. Fig. 2 shows the time versus crystal ID plot of NEBULA. The locus at approximately 60 ns corresponds to fast neutrons from the target region indicating that NEBULA DAQ functions effectively. This fast clear technique can be applied to other experiments by adjusting the delay for the Beam $\times$ NEBULA signal ($300$ ns in this experiment).

Fig. 1. Circuit diagram for NEBULA DAQ with fast clear.

Fig. 2. Time versus crystal ID plot of NEBULA.

References
Test of the advanced implantation detector array (AIDA) at RIBF


As each FEE card runs a separate data acquisition system (DAQ), reading data from only 64 channels, dead-time is significantly reduced compared to that in current generation detectors dealing with high pixelation. Fig. 1 shows the full AIDA assembly.

To study the response of the AIDA to implantation of heavy ions, an in-beam test was conducted at the Radioactive Ion Beam Factory (RIBF) at RIKEN. The test was conducted parasitically to the first SEASTAR campaign, placing the AIDA at the F11 focal plane. In this test configuration, AIDA comprised one DSSSD type BB18 with a thickness of 1 mm and featuring 128 strips with a 0.625 mm pitch in both the x and y directions. Our test demonstrated the capability of AIDA to detect position and energy of fast fragment beams, as shown in Fig. 2.

With promising progress being made on all fronts, the AIDA is planned for use at the RIBF throughout 2015-2016 with two focuses: β-decay half-life and decay spectroscopy measurements using the EURICA γ-ray detector, and measurements of β-delayed neutron emission probabilities as part of the BRIKEN collaboration.

Fig. 1: A photograph of the fully constructed AIDA assembly.

The advanced implantation detector array (AIDA) represents the latest generation of silicon implantation detectors for use in decay spectroscopy measurements of exotic nuclei at fragmentation beam facilities. Designed to improve upon current generation, the AIDA features high detector pixelation and fast overload recovery (~1 µs), required at modern RI facilities with increasingly high secondary beam intensity and access to isotopes with very short half-lives.

Application specific integrated circuits (ASICs) were specifically designed to meet the above requirements. One ASIC can process 16 data channels, each with two dedicated preamplifiers: one with selectable gain to cover the low and medium energy ranges of up to 1 GeV, and the other, a low-gain amplifier that covers the full dynamic range of 20 GeV. Detector signals are carried via flexible Kapton PCBs to the front end electronics (FEE) cards, which support 64 channels of instrumentation. The FEE cards contain the following: multiple analog-to-digital converters (ADCs) for use in signal processing; a field-programmable gate array (FPGA) for control, signal processing, and event building.

References

1) http://www2.ph.ed.ac.uk/td/AIDA/welcome.html
3) In this progress report
CCJ operations in 2014

S. Yokkaichi,*1 H. En’yo,*1 T. Ichihara,*1 and Y. Watanabe*1

1 Overview

The RIKEN Computing Center in Japan (CCJ)1) commenced operations in June 2000 as the largest off-site computing center for the PHENIX2) experiment being conducted at the RHIC3). Since then, the CCJ has been providing numerous services as a regional computing center in Asia. We have transferred several hundred TBs of raw data files and nDST a) files from the RHIC Computing Facility (RCF)4) to the CCJ. The transferred data files are stored in a High Performance Storage System (HPSS)5). A joint operation of the CCJ with the RIKEN Integrated Cluster of Clusters (RICC)6) is continued since July 2009. HPSS and dedicated 20 PC nodes are maintained by them.

Many analysis and simulation projects are being carried out at the CCJ, and these projects are listed on the web page http://ccjsun.riken.go.jp/ccj/proposals/. As of December 2014, CCJ has contributed 31 published papers and 40 doctoral theses.

2 Computing hardware and software

In 2014, computing hardware (nodes and RAIDs) and software (OS, batch queuing systems, database engine, and so on) were changed slightly from those described in the previous APR1). In summary, we have 28 computing nodes, two login servers, one main server (users home directory, NIS, DNS, NTP), two disk servers and HPSS machines in our machine room, and 20 computing nodes in the RICC room. In total, 524 jobs can be processed simultaneously by these computing nodes.

One database (postgresql7)) server and one AFS8) server are operated in order to share the PHENIX computing environment (the other database server retired in 2014). Sharing of the Scientific Linux9) 4 (SL4) environment was stopped in April 2014, and now only the SL5 environment is shared by the computing nodes, which have approximately 0.9 TB of library files. We have four data-transfer servers on which the grid environment10) is installed for the data transfer to/from RCF. Two servers out of the four retired in Jan. 2015.

Disk failure occurred in March 2014, during a reboot after a planned power outage. File system of an users work disk became corrupt and about 1.5 TB of data were lost in spite of adopting VxFS, a journaling file system. Another trouble, namely, power outage at the RAID due to the power failure on Wako Campus in February, is thought to be an underlying cause of the corruption of the file system. This has been the most serious accident at the CCJ so far, although it is declared that there are no backup of the disk.

Table 1 lists the numbers of malfunctioning SATA or SAS disks in the HP servers, namely, computing nodes and NFS/AFS servers.

Table 1. Number of malfunctioning HDDs in 2011-2014

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Total</th>
<th>2014</th>
<th>2013</th>
<th>2012</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>SATA</td>
<td>1 TB</td>
<td>192</td>
<td>11</td>
<td>16</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2 TB</td>
<td>120</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SAS</td>
<td>146 GB</td>
<td>35</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>500 GB</td>
<td>24</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

2.1 HPSS

The amount of data archived in the HPSS were approximately 1.73 PB (1.53 PiB) in 2.15 million files, as of December 2014, not so changed in 2014. No new data file has been transferred in 2014, and therefore, the data list in the previous APR1) is still effective.

RICC will be upgraded to the “HOKUSAI” system, a new RIKEN computing cluster launched in April 2015, and HPSS will retire around August 2015. Data migration to the new archiving system was performed in Jan. 19 - Mar. 16 2015. The 863 TB (785 TiB) of data in 1.66 million files out of 1.73 PB were migrated to the new archiving system, because the raw data of PHENIX, which were transferred for DST production and already served out, were not migrated.

3 Prospect

The replacement of the main RAID and server is on-going, and should be completed in May 2015. The batteries of the four UPSs have expired and should be replaced in 2015. Regarding to the upgrade from RICC to HOKUSAI, configuration changes in the network and job submitting environment are planned in the first half of 2015.

References

2) http://www.phenix.bnl.gov/
3) http://www.bnl.gov/rhic/
4) https://www.racf.bnl.gov/
5) http://www.hpss-collaboration.org/
6) http://acc.riken.jp/ricc/
7) http://www.postgresql.org/
8) http://www.openafs.org/
9) http://www.scientificlinux.org/

*1 RIKEN Nishina Center

a) term for a type of summary data files in PHENIX
Computing and network environment at the RIKEN Nishina Center

T. Ichihara,*¹ Y. Watanabe,*¹ and H. Baba*¹

We are operating the Linux/Unix NIS/NFS cluster systems¹,² at the RIKEN Nishina Center (RNC).

Figure 1 shows the current configuration of the Linux/Unix servers at the RNC. We have adopted Scientific Linux (SL), which is a clone of Red Hat Enterprise Linux (RHEL), as the operation system.

The host RIBF.RIKEN.JP is used as the mail server, NFS server of the user home directory /rarf/u/, and the NIS master server. This is the core server for the RNC Linux/Unix cluster with approximately 600 registered user accounts. The hosts RIBF00/RIBF01 are used as SSH login servers to provide access to external users, and as general-purpose computational servers, printer servers, and gateways to the RIBF intranet.

An HP PIIoniant DL-585 server was installed in 2006 as RIBF00 and this was replaced by DL-320e GS in January 2015. At the same time, the OS of RIBF00 was upgraded from SL 5.11 to SL 6.6.

An anonymous ftp server, FTP.RIKEN.JP, is managed and operated at the RNC. Major Linux distributions, including Scientific Linux, Ubuntu, Debian, CentOS etc., are mirrored daily at the ftp server for the convenience of their users and for facilitating high-speed access. A new 72 TB RAID, which is capable of performing 1.3 M IO per second (IOPS), was installed in August 2014 to replace previous RAID to ensure the high performance and high reliability of the operation.

The data servers RIBFDATA02/03 and analysis servers RIBFANA01/02/03 are mostly used to store and analyze experimental data at RIBF. We have a 156 TB RAID system to store the experimental data as /rarf/w and /rarf/d/, which is connected to RIBFDATA02/03. A 52 TB SAS-FC RAID was added to RIBFANA02 for data analysis for the SAMURAI experiment in October 2014.

A new Web server RIBFWEB1 was installed in April 2014 as the official Web server of RNC WWW.NISHINA.RIKEN.JP to replace the old Web server RARFWWW, which was installed in 2005. The RIBFWEB1 also serves another Web service with using a virtual host function of the Apache http server³.

The data servers RIBFDATA02/03 and analysis servers RIBFANA01/02/03 are mostly used to store and analyze experimental data at RIBF. We have a 156 TB RAID system to store the experimental data as /rarf/w and /rarf/d/, which is connected to RIBFDATA02/03. A 52 TB SAS-FC RAID was added to RIBFANA02 for data analysis for the SAMURAI experiment in October 2014.

A new Web server RIBFWEB1 was installed in April 2014 as the official Web server of RNC WWW.NISHINA.RIKEN.JP to replace the old Web server RARFWWW, which was installed in 2005. The RIBFWEB1 also serves another Web service with using a virtual host function of the Apache http server³.

References
1) http://ribf.ribf.riken.jp/comp/
3) http://httpd.apache.org/docs/2.2/en/vhosts/
III. RESEARCH ACTIVITIES II
(Material Science and Biology)
1. Atomic and Solid State Physics (Ion)
Hyperfine structure measurement of $^{133}$Cs atoms in superfluid helium

K. Imamura,*1,2  T. Furukawa,*3  X. F. Yang,*4  Y. Mitsuya,*2  T. Fujita,*5  M. Hayasaka,*6  T. Kobayashi,*7  A. Hatakeyama,*8  H. Ueno,*1  H. Odashima,*2  and Y. Matsuo*9

The study of nuclear structure via laser spectroscopy techniques has contributed to significant progress in nuclear physics1). To extend the applicability of laser spectroscopy techniques for the study of low-yield exotic nuclei whose production rate is less than 100 pps, we have been developing OROCHI (Optical RI-atom Observation in Condensed Helium as Ion-catcher)2,3). OROCHI is based on a combination of superfluid helium (He II) as an effective stopper for high-energetic ion beams and in situ laser spectroscopy of atoms. In OROCHI, an energetic ion beam produced at an accelerator facility is directly injected into He II. The injected ions are neutralized during the stopping process and are trapped as isolated atoms. The trapped atoms are subjected to a circularly polarized laser light and driven to the spin polarized state. The Zeeman/hyperfine splittings (ZMS/HFS) of atoms are measured using a laser-RF/MW (radio-frequency/microwave) double resonance method to deduce nuclear spins and moments. So far, a series of experiments using the $^{84-87}$Rb ion beam have been performed at the RIKEN Nishina Center. The feasibility of the principle of OROCHI has been successfully demonstrated by measuring the ZMS of $^{84-87}$Rb4). For further development of OROCHI, it is indispensable to ensure the applicability of OROCHI for the measurement of HFS of atoms in He II. In particular, the following two issues have to be confirmed i) How the He II environment affects the HFS of an introduced atom, and ii) What is the highest level of measurement accuracy that can be achieved. To investigate the above mentioned issues, we conducted an experiment using $^{133}$Cs atoms that are introduced into He II using the laser ablation technique.

The experimental setup is similar to the one in ref.[4]. An open-topped quartz cubic cell (70 $\times$ 70 $\times$ 70 mm$^3$) filled with He II liquid was placed inside the cryostat. A solid CsCl was placed approximately 1 cm above the liquid surface. In this experiment, Cs atoms were introduced into He II using two pulsed lasers4). The introduced Cs atoms were pumped into the spin polarized state using circularly polarized laser tuned to the D1 transition line of Cs atoms in He II (876 nm)5). In this experiment, several gauss of static magnetic field was applied to the trapped atoms using a pair of Helmholtz coils to maintain spin polarization. To observe HFS resonance of Cs atoms, MW was irradiated to the spin polarized Cs atoms and its frequency was scanned. The emitted laser induced fluorescence (LIF) during the scanning of MW frequencies was detected using a photomultiplier tube. To suppress stray light from the laser beam, the wavelength of LIF (892 nm)5) was selected using a monochromator. Figure 1 shows the obtained spectra in this experiment. We can clearly observe the resonance peaks in the figure. Since the resonance frequencies are shifted by ZMS owing to the applied magnetic field, the resonance frequencies are measured for both cases i.e., using $\sigma^+$ and $\sigma^-$ polarized lasers. The HFS of Cs atoms in He II is calculated by averaging the two measured resonance frequencies. We obtain the preliminary value of 9.250.58(2) MHz as the HFS of Cs atoms in He II. This result shows that the HFS of Cs atoms in He II is approximately 0.63(2) % larger than that in vacuum owing to the effect of the surrounding helium. The achieved measurement accuracy is 6 digits in the current system. Since the accuracy of the HFS of Cs atoms in He II is limited owing to the fluctuation in the intensity of the applied magnetic field, it can be improved by one or two orders of magnitude by installing stabilized power supply for the magnetic field. In the near feature, we will conduct systematic measurement of HFS using $^{84-87}$Rb to demonstrate the feasibility of OROCHI for the study of low-yield exotic nuclei.

Fig. 1. Observed spectra in this experiment. (a) when using the $\sigma^+$ pumping laser. (b) when using the $\sigma^-$ pumping laser.

References

*1 RIKEN Nishina Center
*2 Department of Physics, Meiji University
*3 Department of Physics, Tokyo Metropolitan University
*4 School of Physics, Peking University
*5 Department of Physics, Osaka University
*6 Department of Physics, Tokyo Gakugei University
*7 RIKEN Center for Advanced Photonics
*8 Department of Applied Physics, Tokyo University of Agriculture and technology
*9 Department of Advanced Sciences, Hosei University
Lattice location and density distribution of hydrogen in $\beta_1\text{-}V_2\text{H}$

E. Yagi,*1,2 T. Hayashi,*1 T. Yoshida,*2 S. Koike,*3 N. Higami,*2 K. Hirabayashi,*2 A. Takebayashi,*2 H. Matsuba,*2 and K. Ogiwara*1

On the atomistic state of hydrogen in $V_2\text{H}$, it has been reported that hydrogen atoms are distributed randomly at tetrahedral ($T$) sites in the $\alpha$-phase with a bec crystal structure at high temperatures above about 470 K, whereas in the low-temperature $\beta_1$-phase below about 450 K, they occupy specific octahedral ($O$) sites with an ordered arrangement. The $\beta_1\text{-}V_2\text{H}$ has two different crystal structures, a body-centred tetragonal (bct) structure, and a body-centred monoclinic one (bcm) with slight inclination of the c-axis ($\alpha_0=90.3\text{-}91^\circ$) (a pseudo-tetragonal structure), both of which have an axial ratio between a- and c-axes $c_0/a_0=1.1$, depending on the condition for crystal growth. When tensile stress is applied along the [001] axis during transformation from the $\alpha$ to $\beta_1$-phases, the $V_2\text{H}$ crystallizes into the bct structure, while without tensile stress it crystallizes into the bcm structure. The $O_x$ sites are octahedral ($O$) sites between two adjacent V atoms aligned along the c-axis (z-axis) (Fig.1). The change of hydrogen site from $T$ to $O_x$ sites implies that the $O_x$-site occupancy is stabilized by elongation of the c-axis, which, conversely, has been induced by forces exerted by hydrogen atoms on neighbouring V atoms. The mechanism of occurrence of the bcm structure and the $O_x$-site occupancy in the $\beta_1$-phase was theoretically studied for the uniform elongation of the c-axis under the condition of constant volume, and it was proposed that the elongation of the c-axis is effective for the $O_x$-site occupancy. Therefore, to examine this effectiveness, in the present study, the site occupancy of hydrogen in both tetragonal $\beta_1\text{-}V_2\text{H}$ and monoclinic $\beta_1\text{-}V_2\text{H}$ is to be investigated in detail.

Another fundamental problem on hydrogen is the density distribution of hydrogen around its occupation site. This problem is related to the extent of wave function of hydrogen. Experimental values hitherto reported by a neutron diffraction method for the tetragonal $\beta_1\text{-}V_2\text{H}$ are larger than the theoretically calculated values and, therefore, there has been a large discrepancy between them.

In order to clarify the site occupancy and the spatial density distribution of hydrogen, the channelling method is very useful. In the present study, the channelling method utilizing a nuclear reaction $^1\text{H}(^1\text{B}, \alpha\text{a})^3\text{He}$ with a $^1\text{B}$ beam of energy of about 2 MeV, which had been developed to locate hydrogen dissolved in Ta and V, is applied.

The lattice location of hydrogen and its density distribution in the tetragonal $\beta_1\text{-}V_2\text{H}$ single crystal prepared under tensile stress and the monoclinic $\beta_1\text{-}V_2\text{H}_{1.1}$ single crystal prepared without tensile stress have been studied at room temperature. The following results have been obtained. In these crystals, H atoms are located at octahedral ($O$) sites with different distributions over $O_x$, $O_y$, and $O_z$ sites. In the tetragonal $\beta_1\text{-}V_2\text{H}$, about 80% of the H atoms are located at $O_x$ sites, about 10% of them at $O_y$ sites and about 10% of them at $O_z$ sites. In the monoclinic $\beta_1\text{-}V_2\text{H}_{1.1}$, about 65% of the H atoms are located at $O_x$ sites, about 20% of them at $O_y$ sites and about 15% of them at $O_z$ sites. These results support the theoretical prediction that hydrogen preferentially occupies $O_x$ sites under tensile stress along the z-axis (c-axis).

In both crystals, the HWHM of the density distribution of hydrogen is about 0.35 Å in the [100] direction, whereas it is less than 0.13 Å in the [001] direction on the assumption of the Gaussian distribution. The HWHM in the [110] direction has been measured only in the tetragonal crystal to be about 0.35 Å. These values are much smaller than those hitherto obtained by the neutron diffraction method, and close to the values theoretically calculated for the ground state (~0.28 Å for the [100] direction and ~0.093 Å for the [001] direction).

References

*1 RIKEN Nishina Centre
*2 School of Science and Engineering, Waseda University
*3 Department of Physics II, Tokyo University of Science
**Observation of the FFLO-like nodal planes in the Au layer of Nb/Au/Fe trilayers by neutron reflectivity measurements**

H. Yamazaki,*1 M. Kubota,*2 N. Miyata,*3 and M. Takeda*2

From the study of Nb/Au/Fe and Nb/Au/Co trilayers,1,2 it was suggested that the superconducting order parameter Δ shows an FFLO-like oscillation with a period of Δ~2.1 nm in the Au layer probably due to the existence of strong spin-orbit coupling. In order to observe the oscillation in Δ, we carried out neutron reflectivity measurements on a trilayer of Nb(28.8nm)/Au(10.4nm)/Fe(12.6nm) with a cap of Au(4.4nm). For a review on the FFLO (or LOFF) states, please see ref. 3. The Nb layer shows superconductivity below \( T_c \sim 8.0 \) K, whereas the Fe layer is ferromagnetic. Below \( T_c \), the Au layer is supposed to be in a superconducting state due to a proximity effect of the Nb layer. For the observation of possible FFLO-like nodal planes, where paramagnetic moments will appear when a magnetic field is applied perpendicular to the planes,4,5 neutron reflectivity measurements were performed for 0.07<\( Q < 0.4 \) nm\(^{-1}\) at BL17 (Sharaku) in J-PARC/MLF. Measurements were first carried out at [10 K, 0 kOe], and then the sample was cooled to 2.3 K under zero magnetic field ([\( H=0 \) 0.1 Oe] to achieve a superconducting state. Measurements were carried out in sequence as shown in Fig. 1: [2.3 K, 0 kOe]→[2.3 K, 2 kOe]→[10 K, 2 kOe]. The data were obtained under four different conditions: (\( N, H=0 \)) a normal state without field, (\( S, H=0 \)) a superconducting state without field, (\( S, H\neq 0 \)) a superconducting state with an applied field, and (\( N, H\neq 0 \)) a normal state with an applied field. The reflectivity obtained as a function of \( Q \) was in excellent agreement with previous results (Project No. 2012B0139). In the present experiment, we were particularly interested in the reflectivity at high \( Q \)'s. To improve the S/N ratio, the signal was accumulated for a larger number of counts than in the previous measurements.

In order to clearly show the changes in reflectivity when measurement conditions were changed, the reflectivity ratios \( \log(R_1/R_2) \) were plotted as a function of \( Q \) in Fig. 2: [\( R(2.3 \text{ K }, 2 \text{ kOe})/R(2.3 \text{ K }, 0 \text{ kOe}) \}], [\( R(2.3 \text{ K }, 2 \text{ kOe})/R(10 \text{ K }, 2 \text{ kOe}) \}], [\( R(2.3 \text{ K }, 0 \text{ kOe})/R(10 \text{ K }, 0 \text{ kOe}) \)], and [\( R(10 \text{ K }, 2 \text{ kOe})/R(10 \text{ K }, 0 \text{ kOe}) \)] for (1) (\( S, H=0 \))→(\( S, H\neq 0 \)), (2) (\( S, H\neq 0 \))→(\( N, H=0 \)), (3) (\( S, H=0 \))→(\( N, H=0 \)), and (4) (\( N, H\neq 0 \))→(\( N, H=0 \)), respectively. The base lines are shifted arbitrarily for clarity of comparison. The variations in \( \log(R_1/R_2) \) are qualitatively the same as those obtained in the previous measurements.

At high \( Q \)'s in Fig. 2, regular and periodic peaks are observed particularly for (1) and (2) with an interval of 0.4 nm\(^{-1}\) (shown as broken lines). This interval corresponds to a period of 15.7 nm in real space. Low-noise data acquired in this experiment allow for the resolution of these peaks. At present, the origin of the 15.7 nm period is not clear. The thickness of the Fe layer is 12.6 nm, and we can observe a peak at 0.5 nm\(^{-1}\) that corresponds to a thickness of 12.57 nm, reflecting a magnetic change in the Fe layer. For more elaborate analysis, we have to carry out reflectivity simulation based on an appropriate multilayer model, including magnetic components not only in Fe but also in Au. The intense peak at 3.2 nm\(^{-1}\) for (1) and (2), however, may prove the existence of the FFLO-like nodal planes in the Au layer.

![Fig. 1. Conditions for the measurements.](image1)

![Fig. 2. Changes in neutron reflectivity.](image2)

**References**

Response of polyimide films to U ion beams as etched-track detectors


The polyimide Kapton retains its excellent physical, electrical, and mechanical properties over a wide temperature range between 4 and 673 K, and hence, it is considered an attractive candidate for a nuclear track membrane. Size-controllable nuclear pores on the sub-micron scale have been fabricated in the polyimide films by chemical etching, subsequent to irradiation with heavy ions.1-3) Such nuclear membranes have been used in films by chemical etching, subsequent to irradiation with sub-micron scale have been fabricated in the polyimide membrane. Size-controllable nuclear pores on the considered an attractive candidate for a nuclear track temperature range between 4 and 673 K, and hence, it is electrical, and mechanical properties over a wide

The polyimide Kapton retains its excellent physical, electrical, and mechanical properties over a wide temperature range between 4 and 673 K, and hence, it is considered an attractive candidate for a nuclear track membrane. Size-controllable nuclear pores on the sub-micron scale have been fabricated in the polyimide films by chemical etching, subsequent to irradiation with heavy ions.1-3) Such nuclear membranes have been used in films by chemical etching, subsequent to irradiation with sub-micron scale have been fabricated in the polyimide membrane. Size-controllable nuclear pores on the considered an attractive candidate for a nuclear track temperature range between 4 and 673 K, and hence, it is electrical, and mechanical properties over a wide

Figure 1 shows typical growth curves of etch pit radius $r$ against the thickness of layer removed $G$ for U ions and other indicating heavy ions. During the etching, the films were reduced in thickness by 2G. With increasing energy of U ions, the fitted slope for each data set decreases. The observed linear relation allowed us to use the conical assumption in evaluating the etch rate ratio $V$, which is the ratio of the track etch rate $V_i$ to the bulk etch rate $V_b$.7) The etch rate ratio was assessed by the following relation:

$$V = \frac{1 + (dr/dG)^2}{1 - (dr/dG)^2}$$

where $(dr/dG)$ is the slope of the fitted line. The sensitivity of etch pit formation is defined as $V^{-1}$. Figure 2 indicates the sensitivity of U ions, as well as other heavy ions, as a function of the stopping power. The threshold of U ions for etch pit formation is 3,439 keV/µm, which is higher than that of other heavy ions. The threshold is also observed in the growth curve (Fig. 1), as the intersect of the fitted line for 337.6 MeV/n U ions with a depth of 1.88 µm.

Fig. 1. Etch pit growth curves for U ions (14.7, 17.1 and 337.6 MeV/n), Xe ions (2.3 MeV/n), Kr ions (2.5 MeV/n), Si ions (3.5 MeV/n), and Al ions (3.7 MeV/n). Each energy for other indicating ions is close to that of the Bragg peaks.

Fig. 2. Sensitivity of Kapton for U ions and other heavy ions against the stopping power.

References
High-density $n$-type doping of diamond by nitrogen beam implantation

H. Ueno,*1 R. Kato,*2 H.M. Yamamoto,*2,∗3 A. Yoshimi,*1,∗4 K. Morimoto,*1 Y. Ichikawa,*1 Y. Ishibashi,*1,∗5 Y. Ohtomo,*1,∗6 and T. Suzuki*1,∗6

After the discovery of the superconductivity of boron-doped ($p$-type) diamond in 2004(1), studies have been extensively conducted to raise the $T_c$ of diamond superconductivity. These studies have indicated that a high doping concentration of boron is favorable for increasing the $T_c$ of superconductivity. High doping concentration can be introduced by the chemical-vapor-deposition (CVD) method(2,3). Based on this technique, $T_c$ has so far reached 11.4 K(4) at doping concentration $\rho=8.4 \times 10^{21}$ cm$^{-3}$. Theoretically, it has been predicted that a very high critical temperature $T_c \geq 100$ K is possible for doped diamond(5), because the high phonon frequency of diamond is favorable for increasing the $T_c$ of superconductivity.

Unfortunately, the doping concentration achievable by CVD is limited to less than $\rho=10^{22}$ cm$^{-3}$ for boron and, more seriously, $\rho=10^{20}$ cm$^{-3}$ for phosphorus ($n$-type). With higher concentration, the dopants are known to form dimers, causing localization of the doped carriers, and thus cannot be used for electric conduction. In view of electronic applications, both $p$-type and $n$-type dopings are necessary. From an analogy to other superconductors such as high-$T_c$ cuprates, it is natural to expect $n$-type superconductivity in diamond. To date, however, high-density doping of $n$-type carrier has not been achieved.

A new approach expected to realize high-density doping is heavy-ion implantation, because i) a sharp fall-off at the distal edge in the stopping range (i.e., Bragg peak), which becomes remarkable for heavy-ion beams, is favorable for the purpose of high doping concentration, and ii) dopant dimerization should not occur very frequently because of the high randomness of the implanted atoms. Taking these advantages, we have been conducting doped-diamond studies in order to realize an $n$-type diamond superconductivity with $T_c$ as high as possible. Furthermore, it is also important to reproduce the increase in $T_c$ in boron-doped $p$-type region, in particular, outside the CVD limit, under the scheme of heavy-ion implantation utilizing the high beam current of various heavy ions available at the RIBF facility. In parallel, the optimization of conditions for heavy-ion implantation including an annealing process to make the diamond lattice as clean as possible should be also investigated.

In the present work, we report on the first nitrogen-ion implantation experiment at RIBF(6) to investigate a possible onset of $n$-type superconductivity of diamond. A beam of $^{14}$N$^{3+}$ delivered at energy $E/A = 450$ keV from the RILAC accelerator at RIBF was implanted into (100)-faceted single crystals of type Ib diamond(7). This beam energy was set to be much lower than the Coulomb barrier to avoid the radioactive ion of samples. The crystals were prepared in the form of 4 mm x 4 mm x 0.3 mm(t), and mounted on a Cu ladder placed in the center of the GARIS target chamber. The implantation was carried out at room temperature at beam current $I = 3 \sim 10$ mA.

The density $\rho(14N)$ of the implanted $^{14}$N particles was simply calculated by

$$\rho(14N) = \frac{I \cdot T}{q \cdot S \cdot \Delta R},$$

where $I$ is the beam current, $T$ is the irradiation time, $q = 3^+$ is the charge state of the beam, $S \approx \pi \times 4$ mm x 6.5 mm is the beam spot size, and $\Delta R$ is the stopping-range distribution of the beam in the crystal. Taking a value of $\Delta R \simeq 0.2$ μm at the mean stopping range $R \simeq 2.5$ μm, calculated with the simulation code SRIM(7), we determined $\rho(14N)$ of five nitrogen-implanted diamond crystals, ranging from $\rho = 7.8 \times 10^{20}$ to $1.9 \times 10^{22}$ cm$^{-3}$. These densities are approximately the same as the reported CVD-doped boron densities at which superconductivity of diamond has been observed(1,4,8). Offline resistivity measurements of the obtained nitrogen-doped crystals as a function of temperature are in progress.

References

*1 RIKEN Nishina Center
*2 Condensed Molecular Materials Laboratory, RIKEN
*3 Research Center of Integrative Molecular Systems (CIMoS), Institute for Molecular Science
*4 Research Core for Extreme Quantum World, Okayama University
*5 Institute of Physics, University of Tsukuba
*6 Department of Physics, Tokyo Institute of Technology

---

* The experiment was performed under the Experimental Program ML1006-LINAC29.
2. Atomic and Solid State Physics (Muon)
μSR study of the magnetism and superconductivity in the multi-layered Bi-2223 high-$T_c$ superconductor

T. Adachi,*1,∗2 M. A. Baqya,*3 K. M. Suzuki,*1,∗4 K. Tsutsumi,*4 M. Fujita,*1,∗4 S. Adachi,*5 T. Watanabe,*5 I. Watanabe,*1 and Y. Koike*1,∗3

In the research of high-$T_c$ cuprate superconductors, the relationship between the magnetism and superconductivity has been a central issue. Nuclear-magnetic-resonance (NMR) experiments in the so-called multi-layered Hg-based cuprate Hg-1245 with 5 CuO$_2$ planes in the unit cell have revealed that the hole concentration per Cu, $p$, in the CuO$_2$ plane is larger in the outer planes (OP’s) than in the inner planes (IP’s) due to the difference in the coordination number of Cu between OP’s and IP’s. Moreover, it has been suggested that both antiferromagnetic (AF) order and superconductivity coexist homogeneously in a CuO$_2$ plane with a small $p$ value. In the optimally doped Hg-1245 cuprate, it has been reported from zero-field (ZF) μSR measurements that a muon-spin precession is observed at low temperatures, suggesting the coexistence of AF order and superconductivity.

Fujii et al. have succeeded in growing sizable single-crystals of a tri-layered Bi-based cuprate Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+δ}$ (Bi-2223) with $T_c = 110$ K. Recently, we have performed ZF-μSR measurements of the underdoped Bi-2223 single-crystals with $T_c = 87$ K, obtained through the reduction annealing. It has been found that the depolarization rate of muon spins, $\lambda$, increases with decreasing temperature and exhibits a local maximum at 10 K, followed by an increase below 5 K. This suggests the existence of two distinct Cu-spin correlations in a crystal probably originating from IP and OP’s. However, the development of the Cu-spin correlation is weak even at 0.3 K, preventing us from investigating the detailed magnetic state in Bi-2223 cuprates. Based on the results, we have performed μSR measurements of Bi-2223 in the heavily underdoped (HUD) regime with $T_c = 40 - 60$ K, obtained through the further reduction-annealing. The ZF and longitudinal-field μSR measurements were carried out using a fly-past HELIOX cryostat at temperatures down to 0.3 K at RIKEN-RAL.

Figure 1 shows ZF spectra of the HUD Bi-2223. At 250 K, the spectrum shows a slow depolarization of muon spins, indicating that Cu spins fluctuate fast beyond the μSR frequency range. With decreasing temperature, it is found that the depolarization becomes fast gradually and an exponential-like depolarization is observed at 0.3 K, indicating the development of the Cu-spin correlation. The $\lambda$ at 0.3 K is more significant than that observed in the underdoped crystals at 0.3 K. Moreover, the temperature dependence of $\lambda$ exhibits local maxima at 40 K and 1 K probably corresponding to the development of the Cu-spin correlation in IP and OP’s, respectively. The temperatures are higher than those observed in the underdoped crystals, respectively. These results suggest that the Cu-spin correlation is more developed in the HUD crystals than in the underdoped crystals, although no muon-spin precession due to the formation of a magnetic order is observed even at 0.3 K. Accordingly, the $p$ value of IP in the HUD Bi-2223 cuprate may reside in the vicinity of the boundary between the AF and superconducting (SC) phases in the phase diagram.

In summary, we have found two distinct developments of the Cu-spin correlations probably originating from IP and OP’s in the HUD Bi-2223 crystals. The $p$ value of IP probably resides in the vicinity of the boundary between the AF and SC phases in the phase diagram, suggesting that the Bi-2223 crystals with $T_c$ lower than ~40 K exhibit an AF ground state.

References
µSR study of the Al-induced magnetic order in La$_{2-x}$Sr$_x$Cu$_{1-y}$Al$_y$O$_4$

K. M. Suzuki,*1,*2 T. Adachi,*1,*3 M. A. Baqiyah,*4 M. Abdel-Jawad,*1 S. Yoon,*1 I. Watanabe,*1 and Y. Koike*1,*4

The so-called stripe correlation of spins and holes has been studied intensively in order to clarify its relationship with the appearance of superconductivity in the high-$T_c$ cuprates. Nevertheless, the details of the stripes have not yet been clarified to date. One of the reasons is that the frequencies of the dynamical stripes are faster than the µSR frequency range in a wide range of the hole-concentration per Cu, $p$, where the superconductivity appears. For this reason, impurity substitution is one of crucial ways to study the stripe correlation, because substituted impurities tend to slow down the spin fluctuations, leading to the formation of the static stripe order. Formerly, we have found from the zero-field (ZF) µSR that the magnetic impurity Fe$^{3+}$ tends to stabilize a magnetic order in the whole superconducting regime of La$_{2-x}$Sr$_x$Cu$_{1-y}$Fe$_y$O$_4$ (LSCFO). Intriguing is that double successive magnetic transitions are observed in the overdoped regime of LSCFO, indicating that the stripe order induced by the Fe substitution persists up to $p \sim 0.30$ and terminates there. As for effects of non-magnetic Zn$^{2+}$ substitution, weakness of the development of the Cu-spin correlation by the Zn substitution prevents us from understanding the nature of the Cu-spin correlation especially in the overdoped regime. Recently, we have observed unexpected behavior in non-magnetic Al$^{3+}$-substituted La$_{2-x}$Sr$_x$Cu$_{1-y}$Al$_y$O$_4$ (LSCAO) by the µSR measurements, namely, a static magnetic state is induced by 3% Al-substitution in the overdoped regime. It is expected that effects of non-magnetic impurities on the Cu-spin correlation will be clarified even in the overdoped regime.

Therefore, in order to investigate the magnetism induced by the Al substitution, we have performed ZF-µSR experiments for LSCAO with $x = 0.11 - 0.30$ and $y = 0.03$. The polycrystalline samples were prepared by the ordinary solid-state reaction method. ZF-µSR measurements were carried out using a Variox, a Heliox and a Janis cryostats at temperatures down to 0.3 K at RIKEN-RAL.

Figure 1(a) shows the ZF-µSR time spectra of LSCAO with $x = 0.30$ and $y = 0.03$. At 5.0 K, the spectrum shows the Gaussian-type relaxation due to the randomly-oriented nuclear dipole field, indicating electron spins fluctuate fast beyond the µSR time window. With decreasing temperature, the muon-spin depolarization becomes fast progressively down to 0.8 K and finally a nearly-static magnetic order is formed at 0.3 K, suggesting a remarkable effect of the Al-substitution on the development of the Cu-spin correlation even in the heavily-doped regime. Figure 1(b) shows the $p$ dependence of the magnetic transition temperature, $T_N$, defined as the midpoint of the change in the initial asymmetry of the magnetic component in an analytical function. It is found that $T_N$ decreases monotonously with increasing $p$, suggesting that the stripe order is induced also in the overdoped regime. Moreover, $T_N$ disappears at $p \sim 0.30$ as observed in LSCFO$^{2}$ and LSCZO.$^3$ Therefore, it has been concluded that, regardless of the type of impurities, the development of the stripe correlation is observed up to $p \sim 0.30$, suggesting an intimate relationship between the stripe correlation and the appearance of the high-$T_c$ superconductivity. Considering the difference between the results of Fe$^{3+}$, Zn$^{2+}$ and Al$^{3+}$, charge disorder as well as large magnetic moments may play an important role in the stabilization of the stripe correlation.

![Image](image.png)

**Fig. 1.** (a) Zero-field µSR time spectra of La$_{2-x}$Sr$_x$Cu$_{1-y}$Al$_y$O$_4$ (LSCAO) with $x = 0.30$ and $y = 0.03$. (b) Temperature dependence of the magnetic transition temperature, $T_N$, of LSCAO with $y = 0.03$.

References
2) K. M. Suzuki et al., in preparation.
$\mu$SR study of cluster-glass state in Sr$_{1-x}$La$_x$RuO$_3$

I. Kawasaki,$^{*1,*2}$ M. Yokoyama,$^{*3}$ K. Fujimura,$^{*3}$ and I. Watanabe$^{*2}$

Strontium ruthenate shows various types of physical properties attributed to the itinerant feature of Ru 4$d$ electrons and the strong mixing between Ru 4$d$ and O 2$p$ electrons.$^{1,3}$ SrRuO$_3$ crystallizes into a distorted perovskite structure and is a ferromagnet with a Curie temperature of about 160 K.$^5$ Photoemission experiments showed that the density of states at Fermi level is dominated by the Ru 4$d$ states.$^{6}$ Therefore, itinerant Ru 4$d$ electrons are considered to be responsible for the magnetic properties. It is also argued that the development of the incoherent component in the density of states reflects the electronic correlation effects. In addition, this system shows a “bad metal” behavior in transport at high temperatures: the electrical resistivity continues to increase with increasing temperature, even though the Boltzmann mean free path becomes smaller than the lattice constants, indicating that the itinerant quasi-particle description is no longer available in the high temperature range.$^5$ These experimental findings suggest that the physical properties are strongly influenced by the correlation of the Ru 4$d$ electrons, and the Ru 4$d$ states have a duality of itinerant and localized natures.

We have studied the Sr site-substituted system Sr$_{1-x}$La$_x$RuO$_3$.$^6$ Substituting La for Sr suppresses the Ferromagnetism.$^7$ In addition, the Ru-O distance increases with increasing $x$, suggesting that doping La may enhance the role of the electronic interaction. Recent our studies suggest that for $x \geq 0.3$, disorder plays an important role and this system shows a short range ferromagnetic ordering (cluster formation), and with further decreasing temperature these clusters freeze into a cluster-glass state.

In the present study, we performed $\mu$SR experiments on polycrystalline sample of Sr$_{1-x}$La$_x$RuO$_3$ to further investigate the cluster-glass state of this system. The $\mu$SR experiments were carried out at the RIKEN RAL Muon Facility in the UK, where an intense pulsed muon beam is available.

Figure 1 shows the zero-field spectra for $x = 0.4$ measured at various temperatures. Below 30 K, the relaxation rate develops and a loss of initial asymmetry is observed, indicating a development of magnetic clusters. The ZF-spectra are well fitted by the following function, which assumes a presence of two components:

\[
P(t) = A_1 \left[ \frac{1}{3} e^{-\lambda_1 t} + \frac{2}{3} (1 - \Delta_1 t) e^{-\Delta_1 t} \right] + A_2 \left[ \frac{1}{3} e^{-\lambda_2 t} + \frac{2}{3} (1 - \Delta_2 t) e^{-\Delta_2 t} \right],
\]

where $A_1$ and $A_2$ represent the paramagnetic and ordered volume fractions respectively.

References
Investigation of magnetic ground states in mixed kagome systems \((\text{Rb}_{1-x}\text{Cs}_x)\text{Cu}_3\text{SnF}_{12}\) by \(\mu\)SR

T. Suzuki,*1,*4 K. Katayama,*2 H. Tanaka,*2 T. Goto,*3 and I. Watanabe*4

The Heisenberg kagome antiferromagnet (HKAF) has attracted much attention in magnetism, because several frustration and quantum effects have been indicated by theories. For example, in the classical spin model case for HKAF, the \(q = 0 \) or \(\sqrt{3} \times \sqrt{3}\) magnetic structure is stabilized when the next-nearest-neighbor interaction is considered. In the case of \(S = 1/2\) kagome lattice, exotic magnetic ground states have been theoretically predicted. For example, numerical calculations revealed that the ground state is a magnetically disordered spin liquid. In the ground state, triplet excitations are gapped, and there exists the continuum of low-lying singlet states below the triplet gap. Valence-bond crystal by a periodic arrangement of singlet dimers has also been proposed as the magnetic ground state of \(S = 1/2\) HKAF. Experimentally, many kinds of HKAF have been investigated as the candidate for the ideal kagome spin lattice material.

Another new candidate for the ideal kagome lattice with an exotic magnetic ground state was reported by Ono et al. The cupric compound \(A_2\text{Cu}_3\text{SnF}_{12}\) \((A = \text{Cs}, \text{Rb})\), which is the subject of this study, is a newly synthesized family of \(S = 1/2\) HKAF. For \(\text{Cs}_2\text{Cu}_3\text{SnF}_{12}\), the weak-ferromagnetic behavior is observed below \(T_N = 20\) K, and it is suggested that the antiferromagnetic ordered state appears. On the other hand, for \(\text{Rb}_2\text{Cu}_3\text{SnF}_{12}\), the first realization of the "pinwheel" valence bond solid (VBS) ground state in the \(S = 1/2\) HKAF are confirmed by inelastic neutron measurements. Quite recently, mixed kagome systems \((\text{Rb}_{1-x}\text{Cs}_x)\text{Cu}_3\text{SnF}_{12}\) have been prepared. By magnetic susceptibility and specific heat measurements on single crystals, they reported a phase diagram, which shows the existence of the quantum phase transition from the VBS to the AF phase at \(x_c = 0.53\). In this concentration, the spin gap vanishes and the ordered state disappears from the view point of magnetization results.

We carried out \(\mu\)SR measurements in \(x = 0.53\) single crystal to investigate dynamical magnetic properties microscopically. Figure 1 (a) shows \(\mu\)SR time spectra in 200 gauss at various temperatures. It is emphasized that no disappearance of the initial asymmetry is observed. Below 3 K, time spectra are well fitted by the two component function as follows: \(A(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t)\). Here, \(A_1 = 0.58, A_2 = 0.42\). As shown in Fig. 1 (b), \(\lambda_1\) increases with decreasing temperature. \(\mu\)SR-time spectra at 0.27 K is shown in Fig. 1 (c), and \(\mu\)SR dependence of the muon spin relaxation rate at 0.27 K.

Fig. 1. (a) Temperature dependence of the time spectra in the LF of 200 gauss. (b) Temperature dependence of the muon spin relaxation rate in LF 200 gauss. (c) LF-\(\mu\)SR time spectra above 200 gauss up to 3000 gauss at 0.27 K. (d) LF dependence of the muon spin relaxation rate at 0.27 K.

References
6) K. Katayama et al.: arXive:1412.5770v1 [cond-matt.str-el].

*1 College of Engineering, Shibaura Institute of Technology
*2 Department of Physics, Tokyo Institute of Technology
*3 Department of Physics, Sophia University
*4 RIKEN Nishina Center
High pressure $\mu$SR study of quantum phase transition in CeNiAsO

H. Guo, Y. Luo, I. Watanabe, and Z. Xu

The discovery of superconductivity in LaFeAsO$_{1-y}$F$_y$ systems\textsuperscript{1} triggers not only a new search of the iron-based superconductors, but also studies of the Kondo effect when La is replaced by magnetic ions such as Ce. The Fe 3d electrons in such systems usually undergo a spin-density-wave (SDW) transition at about 140 K on top of the much lower temperature where the 4f electrons become magnetically ordered.\textsuperscript{2} In order to study the 4f electronic properties, we therefore focused on a Ni-based compound, namely, CeONiAs, instead of Fe-based compounds since the Ni ions are not long-ranged magnetically ordered in these compounds, as observed by experiments and theoretical calculations.\textsuperscript{3}

Our previous studies including magnetic susceptibility, transport, and thermal dynamic measurements show that CeONiAs undergoes two successive magnetic transitions at $T_1 = 9.3$ K and $T_2 = 7.3$ K, respectively, and these two transitions can be suppressed both by hydrostatic and chemical pressures ($P$). When $P > 4$ kbar, $T_1$ can be hardly seen, while $T_2$ is continuously suppressed with a critical value of $P_c \sim 6.3$ kbar. Resistivity measurements indicate that there is a quantum phase transition at $P_c$. In order to reveal the role of magnetic correlations around the quantum critical point (QCP), and the evolution of magnetic structure with pressure, we have performed $\mu$SR experiments with gas pressures up to 6.1 kbar on CeONiAs$_{0.99}$P$_{0.11}$, where the substitution of As by P is expected to reduce $P_c$.

During the high pressure $\mu$SR measurement, most of the muons are stopped at the pressure cell made of Cu, and therefore, muon spin precession is hardly observed even when magnetic ordering appears in the sample, which limits our analyses of the evolution of the magnetic structure with pressure from the observation of muon spin precession in the zero field (ZF) measurement. Alternatively, we performed transverse field (TF) measurements and the spectra were fitted using the following function:

$$A(t) = A_\text{ini} \cos(\gamma \mu B t + \varphi) \exp(-\lambda t) \quad (1)$$

where $A_\text{ini}$ is the initial asymmetry, $\gamma \mu$ is the muon gyromagnetic ratio, $B$ is the magnetic field, and $\lambda$ is the muon spin relaxation rate.

Figure 1(a) shows the temperature dependence of the initial asymmetry, $A_\text{ini}$ at ambient pressure (A.P.) and $P = 6.1$ kbar. At A.P., $A_\text{ini}$ is nearly temperature independent at high temperatures, and decreases sharply below approximately 10 K. No further significant change is observed below 10 K due to the low signal-to-background ratio. The transition temperature is suppressed to approximately 6 K when $P = 6.1$ kbar. Fig. 1(b) shows the temperature dependence of the muon spin relaxation rate $\lambda$. The substantial increase of $\lambda$ below about 10 K and 6 K, respectively, at A.P. and $P = 6.1$ kbar is consistent with the results of the temperature dependence of $A_\text{ini}$. The appearance of the internal field will increase the internal field distribution width at the muon site, thus enhancing the muon spin relaxation rate. Owing to the usage of a pulsed muon source, the increase in muon spin relaxation rate will usually lead to a decrease in the initial asymmetry. Thus, our current results confirm the magnetic ordering from the microscopic viewpoint. The application of high pressures up to 6.1 kbar also confirms that the magnetic ordering is suppressed by pressure. Unfortunately, valuable information about the evolution of the internal field with the pressure cannot be obtained since we cannot observe the muon spin precession directly as mentioned above.

References

*1 Department of Physics, Zhejiang University
*2 RIKEN Nishina Center
Investigation of hydrogen dynamics in hydroxyl salts $\text{Co}_2(\text{OD})_3\text{Cl}$

X.L. Xu,*1 X.G. Zheng,*1 H.J. Guo,*2 and I. Watanabe*2

Hydroxyl salts of the type $M_2$(OH)$_3X$ (X = Cl, Br, or I) have been known for a long time. These compounds containing magnetic ions are magnetic materials. However, only in recent years their magnetic properties have been clarified as a result of our research 1,2) and they are known as “frustrated magnets”. Our latest finding is universal strong magnetic--dielectric--lattice coupling in all such compounds. Measurements of dielectric constants and lattice parameters revealed simultaneous changes at the respective $T_N$ for all hydroxyl salts, which indicate strong magnetic--dielectric--lattice coupling. Moreover, we found that for $\text{Co}_2$(OH)$_3\text{Cl}$ and $\text{Co}_2$(OH)$_3\text{Br}$, which have the highest crystal symmetry in the hydroxyl salt series shown in Fig. 1, the corresponding deuterated compounds $\text{Co}_2$(OD)$_3\text{Cl}$ [Br] clearly exhibited a ferroelectric response at exceptionally high temperatures. Sharp peaks were observed at 229 K in both dielectric constants measured at 100 kHz for $\text{Co}_2$(OD)$_3\text{Cl}$.3) Similar behaviors were observed in $\text{Co}_2$(OD)$_3\text{Br}$ ($T_E = 224$ K at 100 kHz).

Therefore, we performed $\mu$SR experiments on $\text{Co}_2$(OD)$_3\text{Cl}$ to reveal the mechanism of this unconventional ferroelectric response, using the muon facilities at RIKEN-RAL. We observed a change in the dynamics of D atoms in $\text{Co}_2$(OD)$_3\text{Cl}$ through the nuclear dipolar field of D (Fig. 2).

The asymmetry $a(t)$ of muon-spin-relaxation can be approximately expressed by a combination of the dynamic Kubo-Toyabe function and an exponential function.

The dynamic Kubo-Toyabe function represents the contribution from the nuclear dipolar field of D atoms, and the exponential one accounts for magnetic relaxation.

![Fig. 1. High crystal symmetry of $\text{Co}_2$(OD)$_3\text{Cl}$](image1)

![Fig. 2. Muon-spin-relaxation spectra indicating a change in the dynamics of D atoms in $\text{Co}_2$(OD)$_3\text{Cl}$](image2)

![Fig. 3. The analyzed fluctuation rate of the nuclear dipolar field of the D atoms in $\text{Co}_2$(OD)$_3\text{Cl}$](image3)

References
Partial magnetic order in the quantum spin system NH₄CuCl₃


The ground states of boson systems with randomness have been a puzzle for a long time. In a uniform system consisting of mobile bosons, the ground state is the Bose-Einstein condensed fluid. When the mobility of particles is reduced by introducing randomness or frustration, the system becomes solid-like, that is, the Bose glass or the Wigner crystal, details of which, however, are still unknown. For studying the property of the boson system, NH₄CuCl₃ is suitable model compound, where both the density and mobility of the field-induced magnons can be tuned by the magnitude of applied field and the state of non-centrosymmetric NH₄ molecules, respectively.

The quantum spin magnet NH₄CuCl₃ is an S =1/2 three-dimensional dimer system with the crystal structure isomorphic to TiCuCl₃, which is a spin-gapped system and is known for the Bose-Einstein condensation of field-induced magnons. The ground state of NH₄CuCl₃, however, is different from that of TiCuCl₃, that is, gapless in zero field, showing a magnetic order at TN = 1.25 K. When a high magnetic field is applied, two-step magnetization plateaus are observed. The mechanism of the two-step plateaus attracts much interest, for it is related to the fundamental property of the field-induced magnons.

One of the models proposed so far is the localized three sublattice dimer model that claims an existence of the three inequivalent dimers A, B and C with different critical fields Hc, one of which i.e. HcA is zero. This model elegantly explains the two-step plateaus: the two plateaus appear in the field regions where the dimer A and B saturates, and the net magnetization saturates when all three saturate. According to this model, only dimer A magnetically orders at zero field, indicating the partial magnetic order.

The elastic neutron scattering experiment confirms the doubling of the unit cell along c, one of which is known for the Bose-Einstein condensation of doubling of the unit cell along c. However, recent high-field NMR observation disproves three inequivalent dimers in an elongated unit cell.

Fig. 1. Muon spin depolarization curves at various temperatures below and above TN=1.25 K. Solid curves are fitted function with three components G_{k}(Δ,τ)(A_1e^{−Δ^2/2τ}+A_2e^{−Δ^2/2τ}cosΩτ+A_3e^{−Δ^2/2τ}cos2Ωτ) to fit the data below TN. Above TN, the depolarization curves simply consist of one component, that is, the first term in the above function. Figure 1 shows the typical depolarization curves with the fitted function at various temperatures. The two hyperfine fields ωh/γ and ωe/γ increased monotonically below TN and reached 150 and 90 Oe. The volume fraction of each component for A1, A2 and A3 were 25, 70 and 5 % at 0.3 K.

Although the observed data clearly demonstrate that the ordered state consists of three different parts, the fraction of each part is not in accord with the model, which declares that A1, A2 and A3 should be in the ratio 1:2:1. For further quantitative comparison of this result with the three-sublattice model, the detailed knowledge of the muon stopping site in the unit cell is indispensable.

References

*1 Department of Physics, Sophia University
*2 Department of Physics, Shibaura institute of Technology
*3 Department of Physics, Tokyo Institute of Technology
*4 RIKEN Nishina Center
Zn-substitution effects on distorted tetrahedral spin-chain system Cu₃Mo₂O₉

H. Kuroe,*¹,² T. Sekine,*¹ I. Kawasaki,*¹ I. Watanabe,*² and M. Hase*³

The Zn-substitution effects on Cu₃Mo₂O₉ were studied. This compound has a quasi one-dimensional distorted tetrahedral spin system made of S = 1/2 Cu²⁺ ions.¹ The multiferroic properties below the Néel temperature Tₙₑₑ = 8 K has been reported based on macroscopic measurements.² The substituted Zn ions cut the magnetic chain directly and reduce the magnetic order. We have reported a novel magnetic ground state based on some macroscopic measurements for the heavily (5.0%) Zn-substituted sample.³ To obtain a microscopic viewpoint of the Zn-substitution effects on Cu₃Mo₂O₉, we measured muon spin rotation/relaxation spectra in (Cu,Zn)₃Mo₂O₉ with ARGUS spectrometer at Port 2. We prepared single crystals of lightly (0.5%) and heavily (5.0%) Zn substituted Cu₃Mo₂O₉ through continuous solid-state crystallization.⁴ The signals from the muons stopping at the Ag foil on the implanted muons are stopped at the crystal. Working on the muon stopping site(s). We measured the backward-forward asymmetry spectrum A_BF(t) defined as

\[ A_{BF}(t) = \frac{[A_B(t) - \alpha A_F(t)]}{[A_B(t) + \alpha A_F(t)]} \, , \quad (1) \]

where A_B(t) and A_F(t) are the signal from the backward and the forward counters, respectively. A parameter \( \alpha \sim 1 \) is introduced to correct the small misalignment of the system. The signals from the muons stopping at the Ag foil on the crystals are removed using the comparison of A_BF(t) under the transverse magnetic field of 20 G at temperatures below and above Tₙₑₑ. We found that approximately 75% of the implanted muons are stopped at the crystal.

![Fig. 1. Normalized asymmetry spectra at 0.3 K in (Cu,Zn)₃Mo₂O₉ in (a) and their fast Fourier transformation in (b). The upper scale in (b) denotes the internal field working on the muon stopping site(s).](image)

Figures 1(a) and 1(b) show the µSR time spectra and their fast Fourier transformations, respectively. In pure Cu₃Mo₂O₉ and the Zn-0.5% sample, the signals are very similar, indicating the same magnetic ground states. The oscillation frequencies of the µSR time spectra in Fig. 1(a) correspond to the dominating components in the frequency-domain spectra of Fig. 1(b) due to the muon precession around the internal field of 650 G. The beat on the oscillating spectrum at approximately 0.7 µs in Fig. 1(a) and the weak peak at 750 G in Fig. 1(b) indicate the two kinds of internal magnetic fields. In the Zn-5.0% sample, the rapidly decaying oscillation in the time-domain spectrum and the widely distributed frequency-domain spectrum were observed as shown in Figs. 1(a) and 1(b), respectively. We conclude that the magnetic ground state of the Zn-5.0% sample is different from the ones in pure Cu₃Mo₂O₉ and the Zn-0.5% sample.

In Fig. 2, we show the normalized amplitudes of the dominating internal field in Cu₃Mo₂O₉ and the Zn-0.5% sample and that of the averaged internal field in the Zn-5.0% sample as functions of temperature normalized by Tₙₑₑ. These normalized amplitudes have similar temperature dependences with the normalized magnetization because of the weak ferromagnetic component of the spin moment in pure Cu₃Mo₂O₉ and as well as the temperature variation of the saturation magnetization in a ferromagnet calculated based on the Brillouin function. These facts indicate that the order parameter of this multiferroic phase transition is the sublattice magnetization.

References

Magnetic ground state of Cu$_8$O$_8$MCl (M = Y, Pb) with a caged structure

K. Kawashima,*1,2* H. Takeda,*1 S. Yasuda,*1 S. Igarashi,*1 W. Ito,*1 I. Kawasaki,*2 I. Watanabe,*2 and J. Akimitsu*1

Cu$_8$O$_8$MCl (M=cation) compound has a Cu$_8$O$_8$ cage which forms a three-dimensional Cu-O network by connecting their faces in its crystal structure 1). The formal Cu valence in the Cu$_6$O$_8$ cage is +2.15 for M = Pb$^{4+}$ and +2.33 for M = Y$^{3+}$, suggesting the existence of Cu$^+$ (3$d^{10}$), Cu$^{2+}$ (3$d^9$) with $S = 1/2$ spin, and Cu$^{3+}$ (3$d^8$) 2). If there is partial existence of $S = 1/2$ spins on the Cu site in the Cu$_8$O$_8$ cage, the static magnetic ordered state is expected in the square-lattice and the dynamical spin fluctuation in the triangular-lattice i.e., the magnetic competition state is expected in the magnetic ground state of Cu$_8$O$_8$MCl. To elucidate the detailed physical properties of Cu$_6$O$_8$MCl, we focused on clarifying the magnetic ground states of Cu$_6$O$_8$PbCl, which is the semiconducting material, and compared the observed data with the based material of Cu$_6$O$_8$YCl, which is the metallic compound with paramagnetic behavior.

μSR experiments were performed at the RIKEN-RAL Muon facility at the Rutherford-Appleton Laboratory, UK. Fig. 1 shows the zero field (ZF) μSR spectra of Cu$_6$O$_8$MCl (M = Y, Pb) at various temperatures. With the decrease in the temperature, the initial asymmetry of Cu$_6$O$_8$PbCl rapidly decreased below 20 K (Fig. 1(b)). On the other hand, clear decreasing behavior of the initial asymmetry was not observed in the ZF-μSR spectra of Cu$_6$O$_8$YCl down to 0.3 K, indicating that there is no magnetic ordered state in this system (Fig. 1(a)). The ZF-μSR spectra in Fig. 1 were analyzed using the following function,

$$P(t) = A \exp(-\lambda t)G_{Kr}(\Delta t + \Delta B)$$

where $A$ is the initial asymmetry at $t = 0$, $\lambda$ is relaxation ratio of the muon spin, and $\Delta B$ is the background signal. $G_{Kr}(\Delta t)$ is the static Kubo-Toyabe function with a half-width of $\Delta$, describing the distribution of the nuclear-dipole field at the muon site 3). Results of the best-fit of eq. 1 are indicated by the solid line in Fig. 1, and the observed adjusted parameters $A$, $\lambda$, and $\Delta$ of Cu$_6$O$_8$MCl (M = Y, Pb) as functions of temperature are shown in Fig. 2. $\Delta$ ($\alpha$-relaxing) of Cu$_6$O$_8$YCl slightly decreases with the decrease in the temperature (Fig. 2), whereas $\lambda$ and $\Delta$ of Cu$_6$O$_8$PbCl are almost constant, being temperature independent. These facts indicate that there is no change of spin dynamic and long range magnetic ordered state in Cu$_6$O$_8$YCl, which is a metallic compound with paramagnetic behavior. For Cu$_6$O$_8$PbCl, the temperature dependence of $\alpha$-relaxing, $\lambda$, and $\Delta$ change below 20 K, indicating the change in the magnetic spin state (Fig. 2). However, clear precession signal is not confirmed in the ZF-μSR spectra below 20 K. The Cu$_8$O$_8$ cage has a square-lattice and triangular-lattice on its surface, and the Cu sites in the Cu$_8$O$_8$ cage are occupied by various valences of Cu$^+$, Cu$^{2+}$, and Cu$^{3+}$ 2). These conditions encumber the formation of the completely static magnetic ordered state in Cu$_6$O$_8$PbCl. The observed behavior of ZF-μSR spectra and Fig. 2 data of Cu$_6$O$_8$PbCl indicate the growth of the short-range magnetic interaction between $S = 1/2$ spins below 20 K. Consequently, the magnetic ground state of Cu$_6$O$_8$PbCl does not have a static long range magnetic ordered state such as an antiferromagnetic state in high-$T_c$ cuprate. There is possibility that the short range interaction of Cu$_6$O$_8$PbCl forms the spin glass state below 20 K like under-doping material in high-$T_c$ cuprate. The magnetic ground state of Cu$_6$O$_8$MCl compound depends on the valence state of the M site ion.

References


*1 Department of Physics and Mathematics, Aoyama Gakuin University.
*2 RIKEN-RAL, Nishina Center
μSR studies on antiferromagnet RRU$_2$Al$_{10}$ (R = Sm, Gd)

I. Watanabe and Z. Xu

The Kondo semiconductor CeT$_2$Al$_{10}$ (T = Ru, Os) with an orthorhombic-type structure shows a unique antiferromagnetic (AFM) order at $T_0 \sim 30$ K.\textsuperscript{1,2} This compound exhibits numerous unusual electronic properties that can be ascribed to the strong electron correlation between conduction and localized 4$f$ electrons, namely, the $c-f$ hybridization effect, by which a renormalized quasi-particle state with heavy effective electron mass is formed in the case of many Ce- or Yb-based intermetallic compounds. However, in the class of materials known as the Kondo semiconductors or insulators, a temperature-dependent energy gap is formed instead. One of the most salient features of this system is magnetic anisotropy in the AFM ordered state. Since the magnetic susceptibility shows a large anisotropy of $\chi_a \gg \chi_c \gg \chi_b$, an AFM ordered moment ($m_{AF}$) is expected to be parallel to the $a$-axis in the AFM ordered state. However, $m_{AF} \parallel c$ is realized, as was revealed by neutron scattering and $^{27}$Al NMR/NQR studies.\textsuperscript{3-5} The AFM structure is not robust and is easily tuned by magnetic field,\textsuperscript{6} pressure,\textsuperscript{7} or chemical doping.\textsuperscript{8,9} This indicates that magnetic exchange interactions are not a key parameter for this magnetic ordering, but there could be an unknown parameter related to the strong $c-f$ hybridization effect, which must be related to the extraordinary high transition temperature of $T_0 \sim 30$ K.

We previously performed μSR experiments on the above undoped and Rh-doped CeRu$_2$Al$_{10}$. The results have been published elsewhere.\textsuperscript{9} One of the residual problems is the serious inconsistency in the temperature dependence of internal fields ($H_{int}$) between two muon sites, that is, one component shows a usual mean-field behavior, while the other does not. To address this problem, we planned to perform zero-field μSR on related antiferromagnets with more localized 4$f$-electron character, RRU$_2$Al$_{10}$ (R = Nd, Sm, and Gd). These compounds are worthy of investigation for their AFM ordered state; for instance, in the sample R = Gd, $m_{AF}$ is suggested to be parallel to the [011] direction, although a simple dipole-field calculation suggests that $m_{AF}$ prefers the $a$-axis direction.\textsuperscript{10} In ref. 9, a possible origin of this discrepancy was suggested to be the zig-zag chain structure of Gd sites along the $c$-axis direction.

Figure 1 shows the zero-field time spectra of GdRu$_2$Al$_{10}$ at $T = 20$ K and 15 K under double-pulse-beam condition.

GdRu$_2$Al$_{10}$ at $T = 20$ K and 15 K; the data were recorded under double-pulse-beam condition. We found that the initial asymmetry is reduced when the temperature is lowered below the AFM transition temperature of $T_N = 17$ K. This is clear evidence for magnetic ordering. Since $H_{int}$ is expected to be large because of the large magnetic moment of Gd-4$f$ electrons, we should use single-pulse condition with much greater time resolution than that of the double-pulse condition. However, we had to use the double-pulse condition within our beam time because we could not break the extrinsic noise resulting from the kicker operation. Within the present resolution, we could not identify any muon-spin precession behavior, and thus, from the zero field measurement, we could not obtain quantitative information on $H_{int}$.

References
Determination of muon sites on metal-organic hybrids of (C₆H₅CH₂CH₂NH₃)₂CuCl₄ and (C₂H₅NH₃)₂CuCl₄†

E. Suprayoga,*¹,² A. A. Nugroho,*² A. O. Polyakov,*³ T. T. M. Palstra,*³ and I. Watanabe*¹

Hybrid materials consisting of metal and organic components have recently attracted considerable attention because they have lots of possibilities for tailoring their functionalities and physical properties by adjusting their metal and/or organic building blocks [1]. The organic component can be used not only to bind the metal components but also to control the connectivity between the metal components and to manipulate their dimensionality [2]. One of the interesting type of hybrid materials is the magnetic hybrid with perovskite-type transition metal salt with a chemical formula such as (C₂H₅NH₃)₂CuCl₄ (EA) and (C₆H₅CH₂CH₂NH₃)₂CuCl₄ (PEA) [3]. We have carried out μSR measurements on both materials at the RIKENRAL muon facilities. The results revealed the appearance of clear muon spin precession under the zero-field condition in magnetically ordered states. This observation provided evidence of the formation of long-range magnetic ordering of Cu spins. The internal field at the muon site was determined from the muon-spin precession frequency to be approximately 200 G at 4 K in both systems. In the case of PEA, a fast-depolarized component in an earlier time region was observed from room temperature down to 4 K. This fast depolarized component was not decoupled even in fields of a couple of Tesla, showing the existence of a possible muon state that is strongly coupled with the surrounding electrons via radical formation. Such a state was not observed in EA. The dipole-dipole interaction is too weak to trigger the 3D magnetic ordered state because of the large distance between the CuCl₄ layers.

In order to gain an understanding of the magnetic properties of EA and PEA, we are now attempting to reveal the muon positions. We determine the spin alignment by comparing the experimental results with the muon positions estimated using the computational techniques on the basis of the assumption that internal fields at the muon site are caused by dipole fields from surrounding magnetic moments. We present the results of the first trial to apply density functional theory (DFT) method [4] to EA and PEA in order to reveal the minimum energy positions that could facilitate muon injection. The estimation of the potential minimum positions was carried within the DFT framework as implemented in the Vienna ab-initio simulation package (VASP) [5] using the RICC supercomputer.

Fig. 2. Crystal structure (left) and DFT calculation results on PEA. The isosurfaces of the electrostatic potentials for 425 meV (center) and 1.025 meV (right) show possible muon sites.

We found six potential minimum positions around CuCl₄ in EA as well as in PEA, as shown in Figs. 1 and 2. Four of them (A1 - A4) were around the apical Cl⁻ ions and two of them (B1 and 2) were in between in-plane Cl⁻ ions on the CuCl₄ plane. These muon positions can be candidates to show muon-spin precession behavior under the zero-field condition in magnetically ordered states in both EA and PEA. Two more minimum potential positions (C1 and 2) were found in PEA in and on the phenyl ring of the organic part, causing possible muon states bound with the surrounding electrons via radical formation with large hyperfine fields.

References
Investigation of muon sites in YBa$_2$Cu$_3$O$_x$ using density functional theory†

S.S. Mohd-Tajudin, *1,*2 S.N.A. Ahmad,*1 D.F. Hasan-Basri,*1 E. Suprayoga,*2,*3 N. Adam,*1,*2 A.F. Rozlan,*1 S. Sulaiman,*1 M.I. Mohamed-Ibrahim,*1 and I. Watanabe*2

Since the discovery of the Cu-based high-$T_c$ superconducting oxides, both theoretical and experimental investigations have been carried out to understand their magnetism, electronic properties, and superconducting mechanism. But the mechanism of high-$T_c$ superconductivity is still unclear and further investigations are required. The Muon Spin Relaxation (µSR) technique is one of the effective approaches for these investigations. The µSR technique can give us valuable information on high-$T_c$ superconductivity, electronic states, spin structures, and hyperfine fields. Additional information on muon sites can also give us more options to quantitatively discuss these properties. Unfortunately, successful determination of muon sites from µSR experimental data has been possible only for few cases in the past. Thus, we have been trying to establish a way to estimate muon sites from a computational view point by using the density functional theory (DFT). We have already tested our method on La$_2$CuO$_4$ (LCO) because this system has been well investigated by µSR. There are a lot of experimental data related to the antiferromagnetically ordered state in LCO and we can compare the data with our calculation results to successfully obtain new results in terms of muon sites in LCO.† The similar antiferromagnetically ordered state has also been reported in YBa$_2$Cu$_3$O$_6$ (YBCO) and we can apply our computational method to the YBa$_2$Cu$_3$O$_x$ as well as the case of LCO.2–4

The hole concentration of YBCO can be controlled by changing the oxygen content, $x$, from 0 to 1. The system changes from antiferromagnetic state ($x = 0$) to superconducting state ($x = 1$).2–4 The anti-ferromagnetic transition temperature, $T_N$, is approximately $350 \, K$ at $x = 0$. Several components of muon–spin precession have been clearly observed below $T_N$. This indicates that there are some muon sites in YBCO.5 In order to optimize the exchange correlation function, we first calculated the density of the state of each electronic orbital of YBa$_2$Cu$_3$O$_x$. After optimizing the electronic correlation function, we calculated the electrostatic potential as implemented in Vienna Ab-initio Simulation Package (VASP) by using RIKEN Integrated Cluster of Clusters (RICC) and found six local minimum potential positions. These minimum potential positions can be regarded as initial stopping positions of the injected muons. Three are close to the apical oxygen of the CuO$_4$ tetrahedra (marked as M1-M3) and one is close to the planar oxygen (marked as M4).2–6 The M5 site is close to the Cu(I) site in the Cu-O chain, while the M6 site is between the CuO$_2$ planes. M5 and M6 are new and different from view point of the well-known argument on the muon-binding state with oxygen because muons prefer to associate with oxygen to form the hydrogen binding state that lowers its potential energy.5 According to the following procedure, we estimate the final state of the muon. We put $\mu^+$ on the minimum potential position and recalculate the $\mu^+$ position in the 3x3x3 supercell taking into account the relaxations of the muon and all atomic positions so as to minimize the total energy of the supercell.

Figure 1. Crystal structure of YBCO with $x = 0$. Cu(II) in the CuO$_2$ plane is surrounded by five oxygen atoms and has a spin half. The Cu(II) rules the antiferromagnetically ordered state, while the Cu(I) which is in the Cu-O chain is non-magnetic with a zero spin. We found six local minimum potential positions (M1 to M6) from the calculation by the DFT method. The positions were drawn by the isosurfaces in different colors.

We will carry out precise µSR measurement on YBCO with $x = 0$ to verify our method for the estimation of muon sites. Then, we will compare the electronic structures, hyperfine fields, and spin structures with the experimental results in terms of insulating YBCO.

References

---

1 Condensed from the article in Physics Procedia 30 109-112 (2012)
*1 School of Distance Education, Universiti Sains Malaysia
*2 RIKEN Nishina Center
*1 Physics Department, Institut Teknologi Bandung
Muon sites in Ce(Ru, Rh)2Al10 investigated using Density Functional Theory from the perspective of electronic potential


CeRu2Al10 has the orthorhombic YbFe2Al10-type structure with space group Cmcm.1 Ce atoms control the magnetism of this system and are surrounded by Al atoms forming a cage-like structure which is suggested to form a two-dimensional plane structure stacking along the b-axis.2,3 Despite having the nearest neighbour distance, approximately 5.2 Å between Ce ions, CeRu2Al10 exhibits an antiferromagnetic transition at T0 = 27.3 K which cannot be explained by taking only RKKY interaction into account.4 The magnetic susceptibility is largely anisotropic whereas the direction of magnetic moment is along the c-axis and is expected to flip to the a-axis when a small concentration of Ru atoms are substituted by Rh atoms.5 In addition, from the µSR results of a Rh-doped system, Guo et al. reported drastic changes in internal fields at muon sites which were related to the spin-flop caused by doping of 3% Rh atoms in CeRu2Al10.6,7

A number of investigations of muon sites in Ce-based Kondo semiconductors, CeRu2Al10 and Ce(Ru, Rh)2Al10 were carried out by using Density Functional Theory (DFT) to understand the magnetic properties. From the calculation of electrostatic potential, we found all muon sites previously suggested by Kambe et al.7 and Khalyavin et al.8 as shown in Figure 1. Because they were not crystallographically identical, muon sites in CeRu2Al10 are still undefined and the hyperfine interactions cannot be discussed in detail.

![Fig. 1. Muon sites in CeRu2Al10 suggested by Kambe et al. and Khalyavin et al.](image)

![Fig. 2. Three planes that differentiate CeRu2Al10 (a) and Ce(Ru, Rh)2Al10 (b). Planes (1) and (3) contain the muon sites suggested by Kambe et al., whereas the plane (2) contains the muon sites suggested by Khalyavin et al. In plane (3), one Ru atom is substituted by one Rh atom.](image)

![Fig. 3. Potential differences between non-doped and doped systems in planes (1), (2) and (3). The purple and yellow points on the planes indicate the positions of suggested muon sites.](image)

The potential energies calculated for the plane in the non-doped system were subtracted from those of corresponding plane in the doped system to investigate the potential differences. Large differences are seen in plane (3) where a Ru atom was substituted by a Rh atom. Because of this change at the Rh atom in plane (3), the potential energy in plane (2) is also slightly deformed around the position underneath the Rh atom. The large potential difference at the substituted Rh atom in plane (3) may have been because of the difference in valence configuration from that of Ru atom.

However, the potential energy at the suggested muon sites did not exhibit much difference even though the Rh doping concentration in the CeRu2Al10 was increased to 12.5%.

References
μSR study of the density wave state in α-(BEDT-TTF)₂MHg(SCN)₄ (M=K, Rb)

K. Ichimura, K. Katono, and I. Watanabe

Charge density wave (CDW) and spin density wave (SDW) are well-known ground states in low-dimensional conductors and are based on different interactions. The former is due to electron-phonon interaction and the latter is due to on-site Coulomb interaction. Although manifests of CDW and SDW have been discussed separately, the coexistence of CDW and SDW is still an open problem.

In terms of the mixture of CDW and SDW, we focus on the low-dimensional organic conductor α-(BEDT-TTF)₂MHg(SCN)₄ (M=K, Rb). The compounds undergo the density wave state at \( T_{DW} = 8 \) and 12 K for K and Rb-salt, respectively, as a consequence of the nesting of Fermi surfaces. Commonly, organic conductors have too little carrier density to screen the Coulomb interaction. SDW was suggested by anisotropy of the magnetic susceptibility\(^{11}\). On the other hand, CDW was suggested by NMR\(^{2}\), in which no magnetic order was observed. Accordingly, no clear evidence for the ground state of α-(BEDT-TTF)₂MHg(SCN)₄ has been obtained as yet. We believe that this lack of evidence comes from the coexistence of CDW and SDW. Such a mixture of CDW and SDW forms a new ground state in low-dimensional conductors and are based on different interactions. The former is due to electron-phonon interaction and the latter is due to on-site Coulomb interaction. Although manifests of CDW and SDW have been discussed separately, the coexistence of CDW and SDW is still an open problem.

For K-salt, Pratt et al.\(^{4}\) performed a zero-field μSR measurement at a temperature range from 5 to 16 K. They reported SDW ordering with an amplitude of \( 3 \times 10^{-3} \mu_B \). However, this suggested value of the magnetic moment is extremely smaller than that of conventional SDW, for which the amplitude is in the order of 0.1 \( \mu_B \). In order to re-examine the density wave state in α-(BEDT-TTF)₂MHg(SCN)₄, we performed a μSR experiment at a lower temperature with higher statistics.

Small flakes of single crystals of α-(BEDT-TTF)₂MHg(SCN)₄ (M=K, Rb) were grown by a standard electrochemical method with deuterated BEDT-TTF molecules to eliminate the nuclear spin of protons. In this experiment, we concentrated on Rb-salt, which has a higher \( T_{DW} \) than K-salt. The transition temperature was determined as \( T_{DW} = 12 \) K based on the temperature dependence of the static magnetic susceptibility. The powdered sample was mounted as a fly-past setup for a \(^{3}\)He refrigerator. The μSR measurement was performed down to 0.3 K.

\(^{1}\) RIKEN Nishina Center
\(^{2}\) Department of Applied Physics, Hokkaido University

Figure 1 shows the temperature dependence of the muon-spin precession component along the longitudinal-field (LF) of 20 G applied along the initial spin-polarization of the injected muon. This component reflects the existence of a static component obtained from internal fields at the muon site in deuterated α-(BEDT-TTF)₂RbHg(SCN)₄. No drastic change was observed in the local field at \( T_{DW} = 12 \) K. This tendency is qualitatively consistent with that obtained by Pratt et al.\(^{4}\). At present, data accuracy is not considerably higher than that of Pratt et al. with large error bars. We will try to improve the accuracy by collecting more muon events in the next trial. This is expected to reduce the upper limit of the expected magnetic moment which has been suggested by Pratt et al. to be \( 3 \times 10^{-3} \mu_B \) following the same logic\(^{4}\). On the other hand, we found an unusual increase in the asymmetry below 2 K. This might be an indication of some degree of freedom or subphases\(^{5}\) in the density wave phase.

References

Study of coupling between electron conduction and spin fluctuation in novel organic charge transfer complexes with TANC

M. Enomoto,*1 Y. Furuya,*1 K. Isoda,*1 M. Tadokoro,*1 and I. Watanabe*2

We have succeeded to synthesize organic conductors with a novel electron acceptor, 5,6,11,12-tetraazanaphthacene (TANC; see Figure 1). The TANC molecule forms highly conductive compounds in various combinations with metal ions. In particular, several Cu-TANC systems are highly attractive complexes in terms of formation of both π-electron conductive bands and coordinating structure between the acceptor molecule and copper spin sites. Employing these properties is an important approach to construct π-d interaction systems, such as the (DCNQI)₂Cu system,1 where DCNQI denotes N,N’-dicynanoquinodimine.

In the case of [Cu¹.₅⁺(TANC)](NO₃)₀.₅, Cu ions and TANC radicals are alternately linked through coordinate interaction between Cu-N atoms along the b-axis, as shown in Fig. 2(a). These flat-ribbon structures stack with each other to form 2D layers in the ab-plane, while NO₃ anion layers are segregated from each Cu-TANC layers (see Figs. 1(b) and (c)). While the conductivity of this complex shows semiconducting behavior, the single crystal exhibits a high conductivity of 50 S cm⁻¹ at 300 K along the a-axis, which is the stacking direction of the TANC molecules. Moreover, conductivity shows highly anisotropic behavior, that is, σ∥ / σ⊥ ~ 8.3, which corresponds to the segregated stacked structure of Cu-TANC 2D layers. Interestingly, X-ray photoelectron spectroscopy results indicate the coexistence of Cu⁺ and the Cu^{2+} at a 1:1 ratio in the Cu-TANC layers. Moreover, the infrared reflectivity measurement reveals that electrons fluctuate between these two valence states at copper ion sites in both the directions of stacking (a-axis) and flat-ribbon (b-axis) structures.

On the other hand, the TANC complex family, Ag(TANC), also forms a similar conductive layer without a counter anion layer, such as the NO₃ layer in [Cu¹.₅⁺(TANC)](NO₃)₀.₅. The anisotropic conductivity measurement for the Ag complex at room temperature shows that σ∥ / σ⊥ ~ 13, which reflects the low-dimensional character of the Ag complex compared with the Cu one. Infrared reflectivity study supports this observation. The reflectivity component, which is normal to the stacking direction, is negligible, while the parallel component can be observed similar to that in the Cu complex.

To understand how electron conduction occurs in the TANC complexes, we carried out μSR measurements on [Cu¹.₅⁺(TANC)](NO₃)₀.₅. We found that the depolarization rate at 300 K is proportional to H⁻¹/₂, which suggests the existence of the 1D diffusion behavior of spin-excited states (the solid line in Fig. 2) rather than 2D diffusion (the broken line in Fig. 2). This behavior was also observed at 200 and 100 K. Since we have predicted from our previous light experiments that electrons are conductive in these high-temperature regions, the present μSR results support our prediction. At this moment, we are not sure whether this 1D diffusion behavior occurs in the line of the Cu⁺ and Cu^{2+} connection or in the direction of TANC stacking. Comparison between the μSR data of the Cu and Ag complexes will answer this question.

References
Study of charge carrier transport in active layer P3HT:ZnO:PCBM hybrid solar cells measured by muon spin relaxation†

L. Safriani,*1 Risdiana,*1 A. Bahtiar,*1 A. Aprilia,*1 and I. Watanabe*2

Recently, many researchers have been making an effort to obtain high performance of solar cells by modifying the active material of the solar cell. Conjugated polymers are promising active materials. Much attention has been paid to polythiophene and its derivatives owing to their chemical and thermal stability in addition to their potential to absorb the solar spectrum in solar cells. Poly(3-hexylthiophene) (P3HT), a derivative of poly(3-alkylthiophene), presents the highest hole mobility,1) thus attracting researchers’ attention. Hybrid solar cells that combine organic and inorganic materials have been developed to increase the performance of solar cells. P3HT having the highest hole mobility, when combined with inorganic materials with the highest electron mobility, shows promise for better performance. Zinc oxide (ZnO) is an inorganic material that has high electron mobility, shows promise for better performance. In bulk heterojunction systems of solar cells, ZnO behaves as an electron acceptor to dissociate excitons formed in P3HT. For practical systems of solar cells, ZnO behaves as an electron acceptor material for polymer solar cells owing to their properties of ZnO nanoparticles that facilitate electron transport using LF-μSR measurements were performed on samples of P3HT4) and P3HT:ZnO.5) For both the samples, it was found that charge carrier transport changes from intra-chain to inter-chain diffusion. For P3HT:ZnO, one-dimensional intra-chain diffusion was observed at low temperatures, while three-dimensional inter-chain diffusion was observed at high temperatures.6) The addition of PCBM into the P3HT:ZnO blend increased the charge transfer from P3HT to ZnO and also reduced the aggregation of ZnO nanoparticles.

To clarify the charge carrier dynamics in a bulk ternary system of hybrid materials, we measured charge carrier transport using LF-μSR in the P3HT:ZnO blend by adding a fullerene derivative (PCBM). Figure 1 shows the LF dependence of the raw asymmetry at 15 K and 25 K. The initial asymmetry increases with increasing LF field owing to the repolarization of the muonium state.6) The raw asymmetries at 15 K and 25 K show a clear dependence on field and temperature.

Fig. 1. The asymmetry data of P3HT:ZnO:PCBM at 15 K and 25 K for various longitudinal magnetic fields.

Figure 2 shows the LF dependence of $\lambda_1$ in P3HT:ZnO:PCBM, where $\lambda_1$ is the depolarization rate associated with the fast component. At 15K, the relationship $\lambda \sim H^{0.5}$ is observed clearly, which indicate that one-dimensional intra-chain diffusion occurs in this system. Compared with the μSR data for P3HT that show a dimensional crossover at 25K,3) the data for P3HT:ZnO:PCBM show the dimensional crossover from one-dimensional to three-dimensional apparently at a lower temperature. We cannot explain the experimental results immediately, but they are likely related to the advantageous properties of ZnO nanoparticles that facilitate electron transfer.

Fig. 2. The longitudinal-field dependence of the relaxation rate $\lambda_1$ of P3HT:ZnO:PCBM at 15 K and 25 K.

With increasing temperature, the charge carrier transfer changes from intra-chain to inter-chain diffusion. One-dimensional intra-chain diffusion is observed in the samples at temperatures below 15K, while three-dimensional inter-chain diffusion is observed at temperatures above 25 K.

References

† Condensed from the article submitted to Materials Science Forum
*1 Department of Physics, Padjadjaran University
*2 RIKEN Nishina Center
\mu\text{SR} study on antiferromagnetism in K-Rb alloy and Rb clusters in sodalite

T. Nakano,*1,*2 K. Tanibe,*1 L. M. Kien,*1 S. Yoon,*2,*3 M. Abdel-Jawad,*2 F. L. Pratt,*4 I. Watanabe,*2 and Y. Nozue*1

Porous crystals of zeolites make it possible to generate periodically arrayed alkali-metal nanoclusters. Various kinds of magnetically ordered states have been observed in these systems, although they do not contain any magnetic elements. Sodalite is a kind of aluminosilicate zeolites where the \beta cages with an inner diameter of \( \approx 7 \) \( \text{Å} \) are arrayed in a bcc structure as shown in Fig. 1 (a). The chemical formula is given by \( \text{A}_3\text{Al}_5\text{Si}_5\text{O}_{12} \) per \( \beta \) cage where \( \text{A} \) indicates an alkali cation. By the loading of guest alkali atoms into dehydrated sodalite, an \( \text{A}^{3+} \) cluster is formed in the \( \beta \) cage as schematically shown in Fig. 1 (b), where an s-electron is shared by four \( \text{A}^{3+} \) ions and is confined in the cage. When \( \text{Na}^{3+} \) clusters are formed in all the \( \beta \) cages, antiferromagnetic (AFM) ordering occurs below the Ne\öel temperature of \( T_N = 48 \text{K} \) because of the exchange coupling between the adjacent clusters. The material is assigned to a Mott insulator. When heavier alkali cations are substituted for \( \text{Na}^{3+} \), \( T_N \) systematically increases: 72, 80, and 90-100 K for clusters with average chemical compositions of \( \text{K}_4^{3+}, (\text{K}_4\text{Rb})^{3+}, \) and \( (\text{K}_3\text{Rb}_2)_3^{3+} \), respectively.4,5) However, a recent work has revealed that \( \text{Rb}_4^{3+} \) does not show AFM ordering and shows metallic behavior. In the present work, we investigate in detail the magnetic properties of this system in the vicinity of the insulator-to-metal (I-M) transition by utilizing \mu\text{SR}. The experiments were performed at the RIKEN-RAL Muon Facility using the CHRONUS spectrometer.

Figure 2 (a) shows the zero-field \mu\text{SR} spectra of K-Rb alloy clusters ((\text{K}_1.7\text{Rb}_{2.3})^{3+}). At 5 K, a muon-spin precession signal with a large amplitude is clearly observed. This result indicates that the AFM order is robust in the major volume of the sample even just before the I-M transition. The internal field at the muon site is estimated to be 166 Oe. This is stronger than that in \( \text{Na}_4^{3+} \) (92 Oe), \( \text{K}_4^{3+} \) (142 Oe), and \( (\text{K}_3\text{Rb})^{3+} \) (155 Oe). A systematic increase in the size of the s-electron wave function in the heavier alkali metals, which is the origin of the enhancement of AFM exchange interaction, is expected to provide a stronger Fermi contact between muon and s-electron. \( T_N \) is estimated to be \( \approx 90 \) K from the temperature dependence of the internal field. In contrast, the pure Rb clusters (\( \text{Rb}_4^{3+} \)) only show very slow relaxation even at 2 K as shown in Fig. 2 (b). This result confirms that a non-magnetic state is realized in the metallic phase after the I-M transition.

Fig. 1. Schematic illustrations of (a) the crystal structure of sodalite and (b) the A

Fig. 2. Zero-field \mu\text{SR} spectra of (a) K-Rb alloy clusters and (b) Rb clusters in sodalite.

References

*1 Department of Physics, Osaka University
*2 RIKEN Nishina Center
*3 Department of Physics, The Catholic University of Korea
*4 ISIS, Rutherford Appleton Laboratory
Li-ion diffusion in Li$_x$FePO$_4$ with $x = 0, 0.25$ and 0.5


Lithium iron phosphate, LiFePO$_4$, is used as a cathode material in Li-ion batteries. A comparison with the conventional cathode materials such as LiCoO$_2$, LiNiO$_2$, and LiMn$_2$O$_4$ showed that LiFePO$_4$ has a special advantage over because of its high stability during the lithium extraction/intercalation reaction at medium temperatures (around 400 K).

Based on electrochemical and structural analyses, the lithium extraction reaction from LiFePO$_4$ is represented as follows: LiFePO$_4$ - $x$Li $\rightarrow$ (1 - $x$)LiFePO$_4$ + $x$FePO$_4$. Both LiFePO$_4$ and FePO$_4$ phases coexist in Li$_x$FePO$_4$, and single phase samples of Li$_x$FePO$_4$ have not been obtained so far. Following upon the $\mu^+$SR work on LiFePO$_4$, we have measured $\mu^+$SR spectra on Li$_x$FePO$_4$ ($x = 0, 0.25$, and 0.5) in order to understand the diffusive property shown in Li$_x$FePO$_4$ sample consisting of the two phases.

Powder samples of Li$_x$FePO$_4$ were prepared from LiFePO$_4$ by reacting it with NO$_2$BF$_3$ in acetonitrile. Then, the Li-deficient powder sample was sealed into a titanium cell with a gold o-ring. The window of the cell was made of a Kapton film of 50 $\mu$m thickness. The cell was mounted onto the Cu plate of a liquid-H$_2$ flow-type cryostat in the temperature range between 10 and 400 K.

Figure 1 shows the temperature dependence of zero field (ZF-) and longitudinal field (LF-) $\mu^+$SR spectra for FePO$_4$. Since there is no crucial change with temperature, the implanted muons are static up to 250 K. In fact, the spectra were fitted by a combination of a dynamic Kubo-Toyabe (KT) signal and a time-independent background signal from a powder cell. The field distribution width ($\Delta$) and the field fluctuation ($\nu$) were found to be independent of temperature; $\Delta_{\text{FePO}_4} = 7.1 \times 10^{-4}$ s$^{-1}$ and $\nu_{\text{FePO}_4} = 2.6 \times 10^{-4}$ s$^{-1}$.

On the other hand, dynamic behavior was clearly observed for Li$_{0.25}$FePO$_4$ and Li$_{0.5}$FePO$_4$. The $\mu^+$SR spectra were well fitted by a combination of two KT signals and a background signal. The two KT signals came from the muons stopped in the FePO$_4$ phase and those in the FePO$_4$ phase. Therefore, we used the same values of $\Delta_{\text{FePO}_4}$ and $\nu_{\text{FePO}_4}$ for the KT signal from the FePO$_4$ phase. Figure 2 shows the temperature dependence of $\Delta$ and $\nu$ for the three samples. As expected, the result is very consistent with that obtained for LiFePO$_4$. Assuming that the Li-ion jump to interstitial sites, we obtained the diffusion coefficient as: $D_{\text{Li}} = 5.8 \times 10^{-11}$ cm$^2$/s at 200 K for Li$_{0.5}$FePO$_4$ and $D_{\text{Li}} = 1.3 \times 10^{-11}$ cm$^2$/s for Li$_{0.25}$FePO$_4$. These values are smaller than $D_{\text{Li}}$ for LiFePO$_4$, implying the effect of Li-ion diffusion between the LiFePO$_4$ and FePO$_4$ phases. Such interphase diffusion is believed to be the most interesting process shown in the LiFePO$_4$ cathode. In order to understand the interphase Li-ion diffusion, however, we need to study the relationship between $D_{\text{Li}}$ and $x$ in Li$_x$FePO$_4$ in more detail.

References
Investigations of defects in TiO$_2$ rutile crystal by muon and muonium

H. Ariga,*¹ ² K. Asakura,*¹ K. Shimomura,*³ K. Ishida,*² F. Platt,*⁴ W. Higemoto,*⁵ E. Torikai,*⁶ A. D. Pant,*⁶ K. Yokoyama,*⁷ B. Ohtani,*¹ and K. Nagamine*⁸

Metal oxides play a key role in the field of environmental science, heterogeneous catalysis, electrochemistry, biology, chemical sensors, magnetism, and other chemical processes. It is well known that the existence of defect sites drastically changes the chemical and physical properties of metal oxides. TiO$_2$ is the one of the most studied material among metal oxides. The defect sites in TiO$_2$ affect the catalytic and photocatalytic properties. The structure of defect site on surface is well known by scanning probe microscope (STM, AFM and so on) observations. The major defect on the surface is oxygen vacancy. However, the microscopic insight of bulk defect sites has not been established yet. Although oxygen vacancy is believed to be a typical defect site in TiO$_2$, no direct evidence has been reported to characterize the defect structure, and its properties have not been revealed because of the difficulty in detecting defects directly. In order to establish a charge balance, Ti$^{3+}$ is assumed in the nearest neighbor of the bulk oxygen vacancy. Thus, oxygen vacancy has been discussed by measuring Ti$^{3+}$ species, which have one d electron and are characterized with ESR or NMR techniques. However, since Ti$^{3+}$ species do not only exist next to the oxygen vacancies but also at other sites such as interstitial Ti, planar defects, CS planes and so on, it is necessary to obtain information including the adjacent morphology of Ti$^{3+}$. It is suggested that hydrogen stabilizes at an oxygen vacancy as hydrid (H$^-$) in TiO$_2$ through density functional calculations. As Muon is regarded as an isotope of hydrogen, μSR has potential to be the probe of oxygen vacancy.

Our recent preliminary TF μSR measurements at the RIKEN-RAL suggested the existence of a large fraction of a diamagnetic component (μ$^+$ or Mu$^-$) and some normal muonium at room temperature in TiO$_2$ with an oxygen vacancy. The purpose of the present work is to clarify whether negative muonium ions exist in TiO$_2$ with an oxygen vacancy by laser irradiation and also to determine a further detailed state of μ$^+$. We have performed both zero-field (ZF) measurements and “Pump and probe” measurements by laser irradiation at various temperatures. The μSR measurements were performed at the RIKEN-RAL Muon Facility. The mirror-polished rutile TiO$_2$ single crystals (25 x 25 x 0.5 mm$^3$, Crystal Base, Japan) oriented to the (110) plane were used. The sample was calcined at 1073 K for 6 h in air followed by reduction at 1173 K for 2 h under an ultra-high vacuum environment (0.5 x 10$^{-8}$ Pa). The color of sample became blue after the reduction procedure. Laser was irradiated from the opposite side of muon through a quartz glass by utilizing the sample cell developed by Prof. Torikai’s group.

The ZF muon spin relaxation spectra with and without oxygen vacancies are obtained at various temperatures from 15 K to room temperature. The difference between two samples are observed at a temperature lower than 50 K. The spectra at 15 K are shown in Fig. 1. The relaxation of spectra without an oxygen vacancy is predictable to be derived from nuclear spins of Ti ($^{47}$Ti and $^{49}$Ti) because of the absence of electronic spin. We expected a Gaussian field profile and fitted the plot with a Kubo-Toyabe relaxation function. The spectra without the oxygen vacancy was well fitted with $\Delta = 0.30$ MHz (Gaussian distribution: 0.71 mT), which is a typical value for nuclear spins. The Kubo-Toyabe relaxation function for a Lorentzian field distribution was added for fitting the relaxation of spectra with the oxygen vacancy. The $\Delta$ value and the Lorentzian distribution were 0.38 MHz and 1.9 mT, respectively.

We have also preformed pump and probe measurements to examine the existence of Mu$^-$. The “pump” laser irradiation is intended to remove one electron from the negative muonium ion, which makes the ion detectable by a transverse-field measurement. However, we could not detect obvious differences in the results obtained with and without laser irradiation. The remaining issue is to simulate the dynamics of Mu$^-$ by laser irradiation and determine an approach to detect Mu$^-$. 

---

*¹ Catalysis Research Center, Hokkaido University  
*² RIKEN Nishina Center  
*³ Institute of Material Structure Science, KEK  
*⁴ ISIS Science and Technology Facilities Council, Rutherford Appleton Laboratory  
*⁵ Advanced Science Research Center, Japan Atomic Energy Agency  
*⁶ Department of Research Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi  
*⁷ ISIS/Queen Mary University  
*⁸ UC-Riverside

Fig. 1. Zero field μSR spectrum of rutile TiO$_2$ (a) with and (b) without oxygen vacancy at 15 K.
Response of muonium to oxygen contents in hemoglobin and other biological aqueous solutions for cancer research


Hypoxia, or low oxygenation, is known as an important factor in tumor biology; in cancer patients, an accurate measurement of O2 concentration (c(O2)) or partial pressure in specific regions is critical1) therefore, improved methods for detecting O2 are required. Several trials that employ PET, MRI and EPR have been conducted1).

We have proposed the use of μ as a new sensitive method to probe the existence of paramagnetic O2 in cancer tumors in the human body. The μ in water is known to take the states of diamagnetic μ such as μ'OH (60%), paramagnetic muonium (Mu, μ' + e−) (20%), and a missing fraction (20%). In Mu, 50% fraction becomes an ortho state with spin 1, providing a spin rotation signal with a prescession pattern (1.39 MHz/G) that is 100 times faster than that of diamagnetic μ'. Some experimental studies have been conducted on the oxygen-dissolving effects of the spin relaxation rate (λMu) of paramagnetic Mu in pure water due to electron spin exchange interactions with paramagnetic O2 in water; the rate change of λMu against c(O2) is (1.8 ± 0.1) × 10^{10} (L/mol/s)2). A problem that remains to be solved is the effect of other magnetic molecules, which is the objective of the present study.

Experiment was conducted at Port 2 of RIKEN-RAL using 60 MeV/c decay μ. Spin rotation and relaxation were detected under 2.2 G transverse fields at room temperature.

The biological samples used were as follows: 1) Albumin; Bovin serum (plasma) albumin 2) Serum; Donor horse serum 3) Hemoglobin (Hb); Polymerized hemoglobin of bovine origin in a lactated Ringer’s solution at 13% concentration in the form of deoxy-Hb.

Before measuring the O2 dependence of λMu, its dependence on the concentration of each biological molecule was systematically measured. The increasing rates of λMu were obtained as 25 μs^{-1}(g/L) for albumin, 1 μs^{-1}(vol.%) for serum and 3.1 μs^{-1}(g/L) for Hb.

Then, by determining the relevant concentration for each molecule, the O2 dependence of λMu was measured. In these biological aqueous solutions, the O2 dependence of λMu showed an almost similar change in relaxation against increasing O2 concentration as that for pure water.

For higher Hb concentrations, by introducing O2, a part of deoxy-Hb (magnetic) becomes oxy-Hb (non-magnetic) so that the O2 dependence of λMu becomes non-linear.

Measurements were made up to 2.0 g/L c(Hb) and 20% c(O2) (Fig. 1). The O2 dependence of λMu at higher Hb concentrations was predicted by assuming the following relation3): λMu = RO2(Mu) + RO2(Hb). There, RO2(Mu) is the relaxation rate due to the amount of deoxy-Hb obtained by solving the Hill’s equation for the total Hb amount and c(O2)4), while RO2(Hb) is the relaxation rate due to the free molecular O2 in solution obtained by the O2 dependence data of the pure water and by the amount of free O2 which is estimated by subtracting the O2 amount used for oxy-Hb formation obtained by the Hill’s equation. As summarized in Fig. 1, λMu increases with increasing Hb at any fixed c(O2), slower increasing rate at Hb higher than 1 g/L due to oxy-Hb formation. The λMu becomes undetectably large (≥ 10 μs^{-1}) at c(O2) lower than 6% at higher c(Hb) of 100 g/L expected for human body.

Before carrying out the clinical application of the proposed method to studies on hypoxia, it is important to conduct further systematic studies on the behavior of O2 in various other biological aqueous systems, especially with high-concentration Hb. Significant features of the present muon method can be summarized as follows: a) non-invasive nature, b) no need of a high magnetic field and c) sub-mm probing region confinement by the advanced beam method.3)

Fig. 1 Summary of dependence on O2 concentration of muonium relaxation rates in Hb aqueous solution; experimental data up to 2.0 g/L and predictions up to 150 g/L by the method described in the text.

References
Development of gas system for MuSEUM experiment

K. S. Tanaka*1,*2 on behalf of J-PARC MuSEUM Collaboration

We are planning to measure the energy of ground state hyperfine structure (HFS) of muonium at J-PARC/MLF. Muonium is a hydrogen-like bound state that consists only leptons, and its HFS is a good probe for testing the QED theory. The latest experiment at LAMPF obtained the following value:1)

\[ \Delta HFS_{\text{Mu}} = 4.463302765(53) \text{ GHz (12 ppb)} . \] (1)

The total uncertainties were determined using the statistical uncertainties. We will achieve an accuracy more than 10 times greater than that of the latest experiment by using the H-line at J-PARC.

Muons polarized in the reverse direction of momentum enter the bore of a large superconducting solenoid magnet from the J-PARC/MLF muon beamline. A RF cavity is located at the center of the magnet containing pure Kr gas. Muons stop by collisions in the gas, and polarized muoniums are formed by the electron capture process.

In a magnetic field the ground state splits into four substates, \( \nu_{12} \) and \( \nu_{34} \) are obtained by the microwave magnetic resonance technique. High-momentum decay positrons are emitted preferentially in the direction of the muon spin. By driving the transitions with an applied microwave magnetic field perpendicular to the static magnetic field, the muon spin can be reversed and the angular distribution of high-momentum positrons changes from predominantly upstream to downstream with respect to the beam direction. The cavity was designed to be resonant simultaneously in the TM110 mode at the \( \nu_{12} \) transition frequency and in the TM210 mode at the \( \nu_{34} \) frequency2). The muonium HFS (\( \Delta \nu \)) is obtained by summing \( \nu_{12} \) and \( \nu_{34} \).

A gas chamber surrounds the RF cavity to seal in the Kr gas. The chamber consists of only aluminum and its upstream foil is thin enough (100 \( \mu \)m) for muons to pass through. We performed gas introduction tests in the chamber. The gas pressure is monitored at the 0.02 % level by a silicon pressure transducer. The gas in this system is sampled regularly by small cylinders. Since spin-exchange collisions occur between muonium and paramagnetic contaminant particular oxygen, we intend to determine the purity of a gas at the parts per million level using Q-mass. We studied the performance of the gas panel without gas sampling and precise gas pressure monitoring on November 2014 (Fig. 1). In this test, we measured muonium distributions under several gas pressures (Fig. 2). The gas pressure in the chamber maintain a steady at sub Torr level during this measurement.

References

*1 RIKEN Nishina Center
*2 Graduate School of Arts and Sciences, University of Tokyo
Development of online muon beam profile monitor for the MuSEUM experiment

S. Kanda\textsuperscript{*1,*2} for the MuSEUM Collaboration

Muonium is the bound state of a positive muon and an electron. Because neither muon nor electron has an internal structure, muonium ground state hyperfine splitting (MuHFS) can be the most precise probe for the test of the bound state QED and for the determination of muon mass via the ratio of magnetic moments of a muon and a proton. At J-PARC, we plan to perform a precision measurement of the MuHFS by microwave spectroscopy of muonium. Spectroscopy of the energy states is performed by measurement of positron asymmetry from muonium decays. Our goal is to improve the precision by an order of magnitude compared with that of the most recent experiment. In order to achieve the goal, we utilize J-PARC’s highest-intensity pulsed muon beam\textsuperscript{2),} highly segmented positron detector with Silicon PhotoMultiplier(SiPM)\textsuperscript{3),} and an online/offline muon beam profile monitor.

The online muon beam profile monitor analyses the muon beam from the aspect of beam shape and relative intensity. Requirements for the beam profile monitor are minimum destruction and high reconfigurability of the beam. We utilize thin plastic scintillation fiber and SiPM. Figure 1 shows the conceptual design of the muon beam profile monitor. The detector consists of an one dimensional array of thin plastic scintillation fiber with a 100 \(\mu\)m diameter. The fibers are bound into a bundle and connected to a SiPM. For a front-end electronics, EASIROC front-end chip\textsuperscript{4) was utilized as an ASD (amplifier, shaper, and discriminator). The pulse height is digitized by an external peak holding ADC.

Figure 2 shows the developed prototype and its cross-sectional view. The fibers were arrayed on a polyimide film of 25 \(\mu\)m thickness and bonded by epoxy resin. Forty fibers were bound into one band of 4 mm width. Two bands were arrayed with a 2 mm gap. In November 2014, a beam test was performed at J-PARC MLF MUSE D2 beam line. Figure 3 shows the measured photon yield as a function of total muon beam intensity. Saturation in higher intensity region is caused by the limited number of SiPM pixels (in case of this prototype, number of pixels was 667). The beam intensity was controlled by movable slits and measured by an offline beam profile monitor\textsuperscript{5),} which consists of a gated image intensifier and a cooled CCD. The movable slits only change beam density and keep beam profile unchanged. Based on the result of the beam test, the design of a full-scale detector is in progress. SiPM with narrower pixel pitch will be used and process of fiber bonding will be optimized for uniform thickness.

Fig. 1. Conceptual design of the online muon beam profile monitor

Fig. 2. Developed prototype of the online muon beam profile monitor

Fig. 3. Measured photon yield

References
4) S. Callier \textit{et al.}: Physics Procedia \textbf{37} (2012) 1569
5) T. U. Ito \textit{et al.}: NIM A \textbf{754} (2014)
3. Radiochemistry and Nuclear Chemistry
Reversed-phase extraction behavior of the 105th element, Db, with tributyl phosphate

M. Murakami,*1,∗2 S. Tsuto,*1 K. Ooe,*1 S. Goto,*1 D. Sato,*1 N. Goto,*1 T. Koyama,*1 T. Nagaoka,*1 R. Motoyama,*1 H. Haba,*2 Y. Komori,*2 A. Toyoshima,*3 A. Mitsukai,*3,∗4 Y. Kitayama,*5 Y. Fukuda,*5 and H. Kudo∗1

Our group has investigated the extraction behavior of Nb and Ta, homologs of the 105th element Db, from HF solutions with tributyl phosphate (TBP) by the batchwise and on-line column chromatographic methods.1,2 In the on-line column experiment with a 62 wt% TBP resin,2 the obtained distribution coefficients (Kd) of Ta were in agreement with those obtained in a batch experiment, indicating that the studied system can be applicable to the column chromatographic experiment with the short-lived 262Db (T1/2 = 33.8 s). In this work, the extraction behavior of Db was studied to discuss the chemical form of Db in HF media by comparing the behavior of Nb and Ta.

The isotopes 262Db and 170Ta (T1/2 = 6.76 min) were simultaneously produced in the bombardment of a 19F beam on the mixed 248Cm/natGd target. The 19F beam was delivered from the AVF cyclotron, and its energy was 105.3 MeV at the center of the target. The typical beam intensity was 700 particle-nA. The reaction products were transported with a He/KCl gas-jet system to a chemistry laboratory and were deposited on a collection site in Automated Rapid Chemistry Apparatus (ARCA3) for 80 s. Then, the products were dissolved in 140 µL of 1.0 M HF and were loaded onto a column (1.6 mm i.d. × 7.0 mm height) filled with the 62 wt% TBP resin. The flow rate of the eluent was 1.0 mL/min. The effluent was collected in a Ta dish as Fraction 1. The remaining products in the column were stripped with 140 µL of 10 M HF at a flow rate of 1.0 mL/min, and the effluent was collected in another Ta dish as Fraction 2. Both effluent fractions in the Ta dishes were evaporated to dryness and subjected to α spectrometry using an automated rapid α/SF detection system.4 The α-particle measurement was started at 43 s and 57 s after the collection of the products for Fractions 1 and 2, respectively. The counting duration was 259 s and 248 s for Fractions 1 and 2, respectively. After the α-particle measurement, every third or fifth pair of Ta dishes was subjected to γ-ray spectrometry to monitor the behavior of 170Ta and its chemical yield.

In total, 820 cycles of chromatographic separation were conducted. In the α energy region (Eα = 8.42–8.74 MeV) for 262Db and its α-decay daughter 258Lr (T1/2 = 3.9 s), 16 and 2 events were observed in Fractions 1 and 2, respectively, including one time-correlated α pair in Fraction 1. The chemical yield of 170Ta, including deposition and dissolution efficiencies of the aerosols, was 44 ± 13%.

Percent extraction (%Ext) values were evaluated using the equation

\[
\%\text{Ext} = \frac{100 \times A_2}{A_1 + A_2},
\]

where A1 and A2 are the radioactivities in Fractions 1 and 2, respectively. The correction for the radioactive decay was considered for A1 and A2. In Fig. 1, the obtained %Ext values of 262Db and 170Ta are shown as closed symbols, together with those of 90Nb and 178Ta (open symbols) obtained in the separate experiment,2 as a function of the initial HF concentration, [HF]ini. Because of the small number of the 262Db events in Fraction 2, an upper-limit %Ext value of ≤ 25% was evaluated for 262Db. The evaluated %Ext value for 170Ta was 93 ± 5%, which was in agreement with the previous result for 178Ta (%Ext = 94 ± 4%).2 This suggests that Db would not form a Ta-like fluoride complex [DbF6]− in 1.0 M HF, where Ta forms an extractable species, [HTaF6(TBP)3].5

References
2) M. Murakami et al.: In this report.

Fig. 1. Dependence of %Ext values of Nb, Ta, and Db on [HF]ini.
Solid-liquid extraction of 261Rf from hydrochloric acid with Aliquat 336 resin

T. Yokokita,∗1,∗2 Y. Kasamatsu,∗2 Y. Shigekawa,∗1,∗2 Y. Yasuda,∗1,∗2 K. Nakamura,∗1,∗2 H. Haba,∗1 Y. Komori,∗1 M. Murakami,∗1 and A. Shinohara∗1,∗2

The chemical properties of transactinide elements (atomic numbers Z ≥ 104) are considered to differ from those of its homologues because of the increasingly strong relativistic effects on the valence shell electrons of heavy atoms. The transactinide nuclei are produced at accelerators using heavy-ion-induced nuclear reactions. These nuclei have low production rates and short half-lives (T1/2 ≤ 4 h). Therefore, the chemical experiments of transactinides must be carried out rapidly on one-atom-at-a-time basis using nuclear reaction products transported from the target chamber by a He/KCl gas-jet system. The chemical properties of transactinides have so far been investigated mainly by a partition method based on a comparison of their chemical behavior with those of lighter homologous elements.

Solution chemistry experiments have been often conducted on element 104, rutherfordium (Rf). Anion- and cation-exchange experiments of Rf in HF and HF/HNO3 were successfully performed under conditions such that the distribution behaviors in equilibria were observed for the homologues of Rf. Clearly different behavior of Rf from its homologues Zr and Hf was reported.1) On the other hand, in the cation exchange in H2SO4/HNO3, the Kd values of Hf in the online experiment were in good agreement with those in the offline batch experiment, whereas the Kd values of Zr in the online experiment were not.2) Therefore, it is important to investigate the time dependence of the distribution behaviors of transactinides to obtain their equilibrated data because the time required to reach distribution equilibrium would be different among homologues. Thus, we developed a batch-type solid-liquid extraction apparatus to evaluate the time dependence of the distribution behavior of Rf and to obtain the equilibrated Kd values.3) To determine the experimental condition and obtain comparison data for Rf, we also performed solid-liquid extraction of Zr and Hf and Th (pseudo homologue) with a quaternary ammonium chloride, Aliquat 336, from HCl.4) In this work, we performed an online solid-liquid extraction experiment on 261Rf and 169Hf using the developed apparatus at RIKEN.

The 260Rf (T1/2 = 68 s) and 169Hf (T1/2 = 3.25 min) nuclides were produced in the 244Cm(18O,5n)260Rf and 151Gd(18O,xn)169Hf reactions, respectively, by the RIKEN K70 AVF cyclotron. The nuclear reaction products that recoiled out from the target were caught by KCl aerosols in He gas and were transported by the gas-jet system to the chemistry laboratory. In the solid-liquid extraction experiments, the reaction products in the gas-jet were deposited on a collection site on a dissolution apparatus.

Then, the deposited sample was dissolved in about 0.25 mL of 7.9 and 9.0 M HCl. The solution sample entered the chemical reaction container containing the 28 wt% Aliquat 336 resin (1.11–1.62 mg). After shaking the container with a vortex mixer for 10–60 s, only the solution phase was pushed out of the container by compressed air and collected on the Ta dish. Then the solution sample was evaporated to dryness with hot He gas and a halogen lamp to prepare a sample for α-spectrometry. Subsequently, the Ta dish was transferred to a Si PIN photodiode detector, and α-particle measurement was performed. After the measurement, the γ-ray activity of 169Hf was monitored using a Ge detector to determine its Kd value and chemical yield.

In Fig. 1, the Kd values of Zr, Hf, and Th with the 28 wt% Aliquat 336 resin5) are shown as a function of the HCl concentration. The Kd values of Hf in this work were consistent with those in the offline batch experiment (≥ 24 h of shaking), indicating that the Kd values of Hf in equilibria could be obtained using batch-type solid-liquid extraction apparatus. The 24 and 3 α events were observed in the experiments at 7.9 M HCl (38 extractions, chemical yield: 56%) and at 9.0 M HCl (68 extractions, chemical yield: 47%), respectively, in the α energy region of 260Rf and its daughter 257No. The detected α counts for eluent clearly decreased with an increase in the HCl concentration. This suggests that Rf forms anionic chloride complexes with Cl− ions, similar to the case of Zr and Hf and different from the case of Th. The present results are consistent with the previous report.5) We will report the Kd values of Rf in the present experiment in the future.

Fig. 1. The Kd values of Zr, Hf, and Th as a function of the HCl concentration with 28 wt% Aliquat 336 resin.

References
Extraction behavior of rutherfordium as a cationic fluoride complex with a 2-thenoyltrifluoroacetone chelate extractant from HF/HNO₃ acidic solutions

Y. Kitayama,¹ Y. Fukuda,¹ H. Haba,² K. Tsukada,³ A. Toyoshima,³ H. Kikunaga,⁴ M. Murakami,² Y. Komori,² M. H. Huang,⁵ T. Taniguchi,¹ S. Ueno,⁶ K. Hayashi,⁷ Y. Yatsu,⁷ I. Chiyonishio,⁷ K. Murakami,⁶ and A. Yokoyama⁶

Recently, we developed a reversed-phase-chromatography technique with 2-thenoyltrifluoroacetone (TTA) as a chelate extractant to clarify chemical properties of a cationic fluoride complex of a superheavy element, rutherfordium (Rf). The resin containing a TTA n-octanol solution has been prepared for that purpose [1]. In this study, we have investigated chromatographic behavior of Rf with this technique in various HF/HNO₃ solutions.

Both of batch and on-line experiments were performed with Zr and Hf to determine experimental conditions suitable for Rf. For batch experiments, non-carrier tracers of Zr and Hf were used to examine distribution coefficient (Kd) values. As for on-line experiments, reversed-phase chromatography of the short-lived nuclides ⁸⁹ᵐ, ⁸⁵ᵐ²⁴⁷ and ¹⁶⁹ᵐ²⁴⁷ was performed with a micro-column in the same way as Rf experiment to obtain elution curves and percent adsorption values (%ads) as defined below.

In Rf experiments, nuclides of ²⁶¹Rf with a half-life of 68 s and ¹⁶⁹ᵐ²⁴⁷Hf were simultaneously produced in the ²⁴⁸Cm(¹⁸⁷⁰, ⁵n)²⁶¹Rf and ²⁴⁸Gd(¹⁸⁵⁰, ⁵n)¹⁶⁹ᵐ²⁴⁷Hf reactions, respectively, with ¹⁰⁹.₃ MeV ¹⁸⁵⁰ Be and ¹³⁰n beams to the RIKEN K70 AVF cyclotron. The reaction products were rapidly transported with a KCl/He gas-jet system to the chemistry laboratory and were deposited on the collection site of the on-line Automated Rapid Chemistry-Apparatus (ARCA) for chromatography experiments. The products were dissolved in HF/0.01 M HNO₃ solutions and were fed onto the micro-column (1.6 mmφ×7 mm) of ARCA at a flow rate of 0.1 mL/min. The resin containing 25 wt.% of TTA was filled in the column. The effluent from the column was collected on a Ta-disk as fraction 1. The remaining products in the column were then stripped with a 0.1 M HF/0.1 M HNO₃ solution and were collected on another Ta disk as fraction 2. These disks were then separately evaporated to dryness with a halogen heat lamp and heated He gas. The samples were assayed with a rapid γ/SF detection system for studying the aqueous chemistry of superheavy elements at RIKEN.¹

The Kd values of Zr and Hf in the batch and on-line experiments were determined and compared in the wide range of F⁻ equilibrium concentration ([F⁻]ₘ) as shown in Fig. 1. The values of both Zr and Hf show sudden decreases in the range of [F⁻]ₘ > 4×10⁻⁵ M in both the batch and on-line experiments. This indicates that fluoride complexation of Zr and Hf consecutively proceeds to form neutral or anionic species from cationic ones with the increase in [F⁻]ₘ. Therefore, differences in the formation of fluoride species between Rf and its homologues can be observed in these [F⁻]ₘ.

As a preliminary result, 160 α events including 21 time-correlated α-particle pairs (8.00-8.40 MeV) from ²⁶¹Rf and its daughter nuclide ²⁵⁷No were observed in 1001 cycles of the chromatography experiment. The %ads values of Rf were evaluated by using the following equation:

\[
\%\text{ads} = \frac{100 \times Fr2}{Fr1 + Fr2}
\]

where Fr1 and Fr2 are the radioactivities observed in the fractions 1 and 2, respectively. The %ads values of Rf were constant at around 60% in the [F⁻]ₘ range up to 5×10⁻⁴ M and then steeply decreased at [F⁻]ₘ = 9×10⁻⁴ M to those of Hf decreased significantly from 100% to a few percent around [F⁻]ₘ = 1×10⁻⁴ M. The latter data reproduces the results for Hf for the on-line experiments. This suggests that the cationic fluoride complexes of Rf exist more stably than those of Hf at [F⁻]ₘ > 1×10⁻⁷ M.

Fig. 1 Distribution coefficients, Kd, of Zr and Hf plotted as a function of [F⁻]ₘ assayed by batch (solid lines) and on-line (closed symbols) experiments.

References
Thermal stability of the group 6 hexacarbonyl complexes

I. Usoltsev,*1 2 M. Asai,*3 H. Brand,*4 A. Di Nitto,*5 Ch.E. Düllmann,*6,5,7 R. Eichler,*1,7 J. Even,*5 F. Fangli,*7 H. Haba,*8 W. Hartmann,*4 M. Huang,*4 E. Jäger,*4 D. Kaji,*8 J. Kanaya,*8 Y. Kaneya,*8 J. Khuyagbaatar,*5 B. Kindler,*4 J.V. Kratz,*6 J.Krier,*4 Y. Kurou,*4 B. Lommel,*4 S. Miyashita,*8 K. Morimoto,*9 K. Morita,*9,10 M. Murakami,*6,7 Y. Nagane,*4 H. Nitsche,*12,13 K. Ooe,*11 T.K. Sato,*3 M. Schädel,*1 J. Stein,*5 P. Steinegger,*1,2 T. Sumita,*9 M. Takeyama,*9 K. Tanaka,*9 A. Toyoshima,*3 K. Tsukada,*3 A. Türler,*5,12 Y. Wakabayashi,*8 Y. Wang,*7 N. Wiehl,*5,6 S. Yamaki,*8,*1,4 A. Yakushev,*4 Q. Zhi*7

Recently, the on-line production of Sg(CO)6 was achieved.1) The Sg-CO bond in the Sg(CO)6 complex was predicted to be slightly more stable than the corresponding bond in the complex of its lighter homolog W(CO)6. 2) In this work, we aim to design the experimental setup to verify this prediction. Alpha-decaying isotopes 163W and 164W were produced in fusion-evaporation reactions 144Sm(24Mg,xn)163-164W at RIKEN Linear Accelerator (RILAC). Therefore, a 144Sm target was bombarded with a 0.66 µA 24Mg beam, at a center-of-target energy of 136 MeV. The Gas-filled Recoil Ion Separator (GARIS) allowed for efficient separation of the desired evaporation residues from the beam and from multinucleon transfer products. The separated isotopes were thermalized in a gas mixture of CO and He 1:1 by volume. The formed 163-164W(CO)6 complexes were transported to the decomposition setup through PFA Teflon capillaries. The decomposition setup consisted of a decomposition column3), covered inside by silver foil, and a bypass column of the same size made of PFA Teflon. Because of the high inertness toward carbon complexes the Teflon bypass was implemented to quantify the actual production yield of the carbonyl complexes. The yields of the carbonyl complex able to pass this decomposition setup were determined by means of total trapping of the volatile products in the cryo online thermochromatography detector array COMPACT.1) The primary result of a complete decomposition experiment is given in a form of a decomposition curve, which pictures the survival probability for a complex as a function of decomposition temperature. The results of the model experiments with 104Mo obtained from the 252Cf spontaneous fission source “Miss Piggy” at the University of Bern3) are presented together with the current results obtained for 163,164W in Fig.

1. The difference of 23 kJ/mol in (FBDEs) of Mo(CO)6 (169 kJ/mol) and W(CO)6 (192 kJ/mol) leads to a decomposition temperature shift of about 100°C. The figure suggests that the experiment can be sensitive to a small difference in FBDE i.e., 10 kJ/mol.

---

11 University of Bern
12 Paul Scherrer Institute
13 Advanced Science Research Center
14 GSI Helmholtzzentrum für Schwerionenforschung
15 Helmholtz-Institut Mainz
16 Johannes Gutenberg-Universität Mainz
17 Institute of Modern Physics Lanzhou
18 Nishina Center for Accelerator-Based Science
19 Hiroshima University
20 Kyushu University
21 Niigata University
22 University of California
23 Lawrence Berkeley National Laboratory
24 Saitama University

Fig. 1: 104Mo(CO)6 and 163-164W(CO)6 experimental decomposition curves (symbols) and simulated curves (dashed lines) for describing the heterogeneous decomposition process. This model successfully reproduced the experimental results for Mo(CO)6 and W(CO)6 (Fig. 1, red interval of FBDE= 197±8 kJ/mol) and could be used for designing and evaluating data of the future decomposition experiments with Sg(CO)6 (Fig. 1, red interval of FBDE= 189-205 kJ/mol).

To conclude, we successfully tested a fast and efficient approach for assessing the thermal stability of group 6 carbonyl complexes. The dissociation energy of the Sg-CO bond can be therefore experimentally investigated and directly compared with the related properties of lighter homologs.

References
Recently, we began to study the aqueous chemistry of a group-6 transactinide element, Sg. At present, we focus on the formation of anionic sulfate complexes of Mo and W, which are lighter homologs of Sg, by means of amine-extraction in H₂SO₄ as a preparatory experiment for Sg. Previously, we have found that the group-4 transactinide, Rf, has a weaker preference to form a sulfate complex than its lighter homologs, Zr and Hf.¹ This is consistent with its predicted, larger ionic radius compared to the measured radii of Zr and Hf; moreover, this is in good agreement with a theoretical prediction² that the stability of Rf complexes is lower because of the smaller ionic contribution to the chemical bond. The investigation of sulfate complex formation of Sg is, therefore, expected to provide valuable information on its ionic radius and chemical bonding.

This paper reports on the extraction behavior of the carrier-free radioisotopes ⁹³ᵐMo and ¹⁸¹W from aqueous H₂SO₄ solution using an amine extractant, Aliquat336, by a batch method to ensure that the chemical behavior of mononuclear complexes of these homologs is retained. First, the extraction kinetics of these radioisotopes in ⁰.¹, ⁴.³ and ⁸.⁶ M H₂SO₄ with ⁰.² M Aliquat336 were studied. Then, extraction probabilities were investigated as a function of H₂SO₄ concentration, [H₂SO₄].

In the experiments of Mo, ⁹³ᵐMo was produced in the ⁴⁰Zr(α, xn)⁴⁰T₉ reaction at the RIKEN K70 AVF cyclotron. Nuclear reaction products transported by a KCl/He gas-jet at a flow rate of 2.5 L/min were deposited on a small piece of plastic (Naflon®, ~2 cm × 1.5 cm) for 3 min. KCl aerosols were produced by sublimation at 640°C. Then, the deposited products were dissolved win 100 µL of ⁰.¹ – ⁸.⁶ M H₂SO₄ solution. The solution was then added to ⁶⁰0 µL of H₂SO₄ solution with the same concentration in a plastic vial. Subsequently, ⁷⁰0 µL of the toluene solution of Aliquat336 was added. After shaking with a Vortex mixer for ⁳⁶⁰ s, the mixed sample was centrifuged for ³⁰ s. From both the phases, ³⁰⁰ µL solutions were collected separately in ² vials. These ² samples were then subjected to γ-ray spectrometry with a Ge detector. The distribution ratio, D, was evaluated with the equation, D = Aorg / (Vorg / Aaq / Vaq), where Aorg and Aaq are the radioactivities in organic and aqueous phases, respectively, and Vorg and Vaq are the volumes of the organic and aqueous phases, respectively.

In the experiments of W, ¹⁸¹W was produced in the ¹⁸¹Ta(d, xn)¹⁸¹W reaction at the RIKEN K70 AVF cyclotron. After the chemical separation of ¹⁸¹W from a Ta target material through an ion-exchange, carrier-free ¹⁸¹W was stocked in H₂SO₄ solutions. The procedure of the subsequent batch experiment was the same as that for ⁹³ᵐMo described above.

Results of kinetics experiments showed that the extraction equilibrium of ⁹³ᵐMo was reached within ⁵ s in the range of ⁰.¹ M < [H₂SO₄] < ⁸.⁶ M, while that of W was dependent on [H₂SO₄]: the equilibrium was attained within ⁴⁰ s at [H₂SO₄] < ¹ M and within ⁲ min at ¹ M < [H₂SO₄] < ⁸.⁶ M. In Fig. ¹, the D values of Mo and W under equilibrated conditions are shown as a function of [H₂SO₄]. The D values of Mo and W decrease up to ³ M and ² M, respectively, with increasing [H₂SO₄]. This is probably due to protonation reactions of hydrolyzed Mo and W species. On the other hand, when [H₂SO₄] > ³ M and > ⁴ M, the D values of W and Mo, respectively, show a sharp increase. This clearly indicates the formation of anionic sulfate complexes of Mo and W. Sulfate complexation of Sg under the present experimental conditions will be clarified in our future experiments.

Fig. ¹. Variation of D value of Mo and W as a function of H₂SO₄ concentration, [H₂SO₄].

References

Solvent extraction of short-lived radioisotopes of Mo and W from oxalic acid solution with Aliquat 336 for chemical studies of seaborgium (Sg)

N. Goto,*1 K. Ooe,*1 A. Toyoshima,*1 M. Murakami,*1,3 Y. Komori,*3 H. Haba,*3 S. Goto,*1 and H. Kudo*4

Thus far, few studies of seaborgium (Sg) in an aqueous phase have been reported, where only a few events of Sg were detected after batch-wise cation-exchange chromatography.1,2) There have been few chemical studies of Sg owing to the experimental difficulties caused by its extremely low production yield and short half-life. To overcome the difficulties, we are developing a new rapid continuous chemistry apparatus based on the solvent extraction technique. We have been also studying solvent extraction behavior and extracted species of molybdenum (Mo) and tungsten (W), which are lighter homologs of Sg, to apply obtained results to development of the new apparatus and to compare extraction behavior among the homologs including Sg. Because it is well-known that Mo and W form polynuclear complexes, Mo and W should be extracted on a tracer scale for comparison of extraction behavior of their mononuclear complexes with that of Sg, which can exist only as single atoms. In a previous report, the solvent extraction of W from oxalic acid solution into toluene with Aliquat 336 was carried out with long-lived radiotracer, 181W (T1/2 = 121.2 d).3) In this paper, we report on the extraction behavior of Mo using short-lived radioisotope along with W. The extracted species of these two elements will be discussed.

Short-lived radiotracers 93mMo (T1/2 = 6.85 h) and 177W (T1/2 = 2.25 h) were produced in the irradiation with a 50-MeV α beam supplied from the RIKEN K70 AVF cyclotron on a metallic natZr and natHf target foils. Nuclear reaction products recoiling out of the targets were transported by a KCl/He gas-jet method at a He gas flow rate of 2.0 L/min. The transported products were deposited on a small plastic piece (Naflon®) for 1 min. Then, the deposited products were dissolved with 100 μL of 0.01 M H2C2O4 (oxalic acid)/0.1 M HCl/0.9 M LiCl solution. The solution was then pipetted to a plastic tube in which 600 μL of aqueous solution and 700 μL of Aliquat 336 in toluene had been added. After shaking with a Vortex mixer for 5 min, the mixed sample was centrifuged for 30 s. From both the phases, 500 μL of aliquots were separately taken into two vials. These two samples were then subjected to γ-ray spectrometry with a Ge detector. The distribution ratio (D) of 93mMo and 177W was calculated using the equation of $D = \frac{A_{org}}{A_{aq}} / \frac{V_{org}}{V_{aq}}$, where $A_{org}$ and $A_{aq}$ are the radioactivities in organic and aqueous phases, respectively, and $V_{org}$ and $V_{aq}$ are the volumes of organic and aqueous phases, respectively.

Dependence of the D values of 93mMo and 177W on the Aliquat 336 concentration with a 0.01 M oxalic acid/0.1 M HCl/0.9 M LiCl solution is shown in Fig. 1. Results previously obtained with 181W are also plotted in the same figure. The D values of Mo and W increase with increasing concentration of Aliquat 336. The slopes of the D value vs. [Aliquat 336] plot on logarithmic scales are evaluated to be 2.08 ± 0.03 for Mo and 1.33 ± 0.02 for W with a weighted least-squares fitting. This indicates that extracted anionic oxalate complex of Mo is associated with two molecules of Aliquat 336, while that of W is with one molecule. On a macro scale, it was reported that Mo and W are extracted as (R3NH)2MO2(C2O4)2 from oxalic acid solution, where R3N shows a trioctylamine (TOA) molecule and M shows Mo or W.4,5) The present result for Mo corresponds to the reported Mo oxalate complex. On the other hand, it seems that W forms a different complex from the Mo one. Under the present experimental condition, chloride ions of 1 M are present contrary to the experiment in the reference.5) Therefore, the extracted W complex might contain one oxalate ion and one chloride ion. To obtain further information on the extracted species of W, we need to investigate the variation in the distribution ratio as a function of the concentration of chloride ions. Based on the extraction behavior of Mo and W obtained in these studies, oxalate complex formation of Sg will be investigated.

![Fig. 1. Variation in the distribution ratio of 93mMo, 177W and 181W from 1.0 × 10^-2 M oxalic acid with 0.1 M HCl/0.9 M LiCl as a function of the concentration of Aliquat 336.](image)

References

*1 Graduate School of Science and Technology, Niigata University
*2 Advanced Science Research Center, Japan Atomic Energy Agency
*3 RIKEN Nishina Center
*4 Department of Chemistry, Faculty of Science, Niigata University
Reversed-phase chromatography of Nb and Ta with TBP for conducting a chemical experiment on the 105th element, Db

M. Murakami,*1,*2 S. Tsuto,*1 K. Ooe,*1 S. Goto,*1 D. Sato,*1 N. Goto,*1 T. Koyama,*1 T. Nagaoka,*1 R. Motoyama,*1 H. Haba,*2 Y. Komori,*2 A. Toyoshima,*3 A. Mitsukai,*3,*4 Y. Kitayama,*5 Y. Fukuda,*5 and H. Kudo*1

Detailed chemical properties of superheavy elements (SHEs) have not been elucidated owing to the difficulty in conducting chemical experiments because of their short half-lives and extremely low production rates. For investigating the chemical properties of the 105th element, Db, we studied the extraction behavior of the group-5 homolog elements Nb and Ta from HF media with tributyl phosphate (TBP), which is used in the industrial separation of Nb and Ta. In our previous study using batchwise solvent extraction,1 we observed the differences between the 95gNb and 179Ta extraction behaviors; the distribution ratios of 179Ta reach a maximum at the initial HF concentration, [HF]ini = 0.27 M, whereas those of 95gNb increase with increasing [HF]ini. To examine the applicability of this extraction system to the short-lived 262Db with T1/2 = 33.8 s, we performed an on-line reversed-phase chromatographic experiment on Nb and Ta using Automated Rapid Chemistry Apparatus (ARCA).2

The nuclides 90gNb (T1/2 = 14.6 h) and 178aTa (T1/2 = 2.45 h) were produced via the natZr(d,xn) and natHf(d,xn) reactions, respectively, with a 24-MeV deuteron beam supplied from the RIKEN AVF cyclotron. The nuclides produced were transported with a He/KCl gas-jet system and were deposited on a collection site in ARCA for 60 s. Then, the products were dissolved in 1–10 M HF solutions and were loaded onto a column (1.6 mm i.d. × 7.0 mm height) filled with a 62-wt% TBP-laden resin, which was prepared in the procedure described in Ref. 3. The flow rate of the eluent was 1.0 mL/min. The effluent fractions were consecutively collected in 7 polypropylene (PP) tubes. The remaining products in the column were stripped with 330 µL of 10 M HF at a flow rate of 1.0 mL/min, and the effluent was collected in another PP tube. Each fraction was subjected to γ-ray spectrometry with a Ge detector.

Figure 1 shows the elution curves of 90gNb and 178aTa in 1.0 M HF as an example, in which correction for a dead volume of ARCA (40 µL) was made for the effluent volume. 90gNb was eluted immediately, whereas 178aTa showed a broad peak around 770 µL with a small leakage in the first effluent (less than 5% of the total activity of 178aTa). Similar elution behavior of 90gNb was also observed at higher [HF]ini. The peak volume of the elution curves of 178aTa gradually decreased, corresponding to the decreasing distribution coefficient (Kd) of 178aTa on the TBP resin. In Fig. 1, the elution curve of 178aTa was fitted by the Glöckner formula of chromatography4 except for the first leakage fraction. The Kd values are described as Kd = v0/m1, where v0 and m1 are the peak volume and mass of dry resin (6.31 mg), respectively. The evaluated Kd values of 178aTa are shown in Fig. 2 together with those of 179Ta previously obtained by the batch experiments.1 The good agreement between the on-line and off-line results indicates that the extraction equilibrium is reached in the present column experiment. Recently, we performed an extraction experiment of Db with the studied system.5

Fig. 1. Elution curves of 90gNb and 178aTa in 1.0 M HF on the column of 62 wt% TBP resin.

Fig. 2. Variation in Kd values of 178aTa as a function of [HF]ini (closed symbols). The Kd values of 95gNb and 179Ta obtained by the batch experiment1 are also shown as open symbols.

References
5) M. Murakami et al.: In this report.

*1 Department of Chemistry, Niigata University
*2 RIKEN Nishina Center
*3 Advanced Science Research Center, Japan Atomic Energy Agency
*4 Faculty of Science, Ibaraki University
*5 Graduate School of Natural Science and Technology, Kanazawa University
Liquid-liquid extraction of Nb and Ta with Aliquat 336 from 0.27 M HF solution

D. Sato,*1,*2 M. Murakami,*1,*2 K. Ooe,*1 H. Haba,*2 H. Kikunaga,*3 S. Goto,*1 and H. Kudo*4

The elements with atomic numbers ≥ 104 are called transactinide elements. Their chemical properties are greatly interesting because it is expected that chemical behavior of these elements would deviate from that of lighter homologs by strong relativistic effects on valence electrons3). Therefore, it is very important to study the chemical behavior of transactinide elements comparing with that of lighter homologs.

Among the transactinide elements, we are interested in the chemical properties of 105th element Db, especially, for complex formation with a fluoride ion which is a strong complexing reagent for group 5 elements. Anionic fluoride complex formation of Db has been investigated through anion exchange study from HF solution 2). The result of this experiment showed that the $K_a$ value of Db in 13.9 M HF was smaller than that of Nb and Ta, which are lighter homologs of Db. However, the chemical form of Db was not yet determined in this condition. Therefore, for investigation of fluoride complex formation of Db in detail, we have been studying the liquid-liquid extraction behavior of Nb and Ta from HF solutions with quaternary ammonium salt, Aliquat 336. So far, a clear difference of the extraction behavior between Nb and Ta in 10-2-27 M HF was observed. While distribution ratios ($D$) of Nb were decreased with increasing HF concentration, those of Ta were a maximum at around 0.3 M HF3). Since linear relations with slope $\approx 1$ for both elements were observed from log $D$ vs. log [Aliquat 336] plots, it was suggested that univalent anionic fluoride complexes are extracted by Aliquat 336. Therefore, it is suggested that NbOF$_4$ and TaF$_6$ were also extracted by Aliquat 336 in 0.27 M HF along with 2.7 M and 10 M HF.

From the obtained results and reference [4-5], it is assumed that the chemical species of Nb and Ta change from NbOF$_4$ to NbOF$_5$ and from TaF$_6$ to TaF$_7$, respectively, with increasing HF concentration in the range of 0.27-10 M, expressed as following equations:

$$\text{NbOF}_4^- + F^- \leftrightarrow \text{NbOF}_5^2^- \quad (1)$$

$$\text{TaF}_6^- + F^- \leftrightarrow \text{TaF}_7^{2-} \quad (2)$$

In the near future, dependence of $D$ values of $^{95}$Nb and $^{179}$Ta on concentration of Aliquat 336 in HF solution lower than 0.27 M will be investigated for further study of fluoride complex formation of group 5 elements.

References
5) A. Agulyansky: The Chemistry of Tantalum and Niobium Fluoride Compounds, 125-134

---

*1 Graduate School of Science and Technology, Niigata University
*2 RIKEN Nishina Center
*3 Research Center for Electron Photon Science, Tohoku University
*4 Department of Chemistry, Faculty of Science, Niigata University
Coprecipitation Behaviors of Zr, Hf, and Th with Sm Hydroxide for Chemical Study of Element 104, Rf

Y. Kasamatsu,*1 K. Toyomura,*1 N. Shiohara,*1 T. Yokokita,*1 Y. Komori,*1,*2 A. Kino,*1 T. Yoshimura,*1 N. Takahashi,*1 H. Haba,*2 Y. Kudou,*2 H. Kikunaga,*2,*4 T. Mitsugashira,*5 T. Ohtsuki,*6 K. Takamiya,*6 and A. Shinohara*1

Owing to significant relativistic effects on electron orbital shells for heavy elements, the chemical properties of the superheavy elements are expected to deviate from the characteristic periodicity of the lighter homologues in the periodic table, and their chemical studies have attracted much attention. However, experimental evaluation of these species is fraught with difficulties. Because of the extremely low production rates and short half-lives (within a few min) of these heavy nuclides, chemical evaluations of the superheavy elements must be rapidly conducted on a one-atom-at-a-time basis. Thus, simple chemistry employing partition methods such as solvent extraction and ion-exchange chromatography have been utilized and the chemical separations were repeated hundreds or thousands of times under identical conditions. This approach requires a rapid chemistry apparatus. Additionally, for unambiguous identification of superheavy nuclides, it is necessary to measure the energies and lifetimes of $\alpha$ or sometimes spontaneous fission decays.

The purpose of the present study is to establish a new experimental methodology for investigating the chemical properties of superheavy elements, specifically, the coprecipitation properties of $^{261}$Rf ($T_{1/2} = 68$ s) by the formation of hydroxide and ammine complexes. Herein, we applied a simple coprecipitation method with Sm hydroxide, which facilitates $\alpha$ spectrometry with high energy resolution,13 to the investigation of the coprecipitation behaviors of the homologues of Rf: Zr, Hf, and Th. In addition, a semiautomatic apparatus for repetitive preparation of precipitate samples was developed and tested using the gas-jet transport system of nuclear products.

We used $^{88}$Zr, $^{175}$Hf, and $^{228}$Th radiotracers to prepare coprecipitated samples with Sm hydroxide. A 20 $\mu$L aliquot of the Sm standard solution (Sm 1000 ppm, 1 M HNO$_3$) was added into 220 $\mu$L of an aqueous solution (~0.4 M HCl) containing the radiotracers in a polypropylene (PP) beaker. The solution was stirred and 2 mL of the basic solution (dilute and concentrated aqueous NH$_3$ and 0.1, 1.0, 6.0, and 12.0 M NaOH solutions) was then added to produce the precipitate. After aging the precipitate for 10 s or 10 min at 25 °C, the precipitate sample was subjected to suction filtration with a PP membrane filter (eichrom, Resolve® Filters 0.1 $\mu$m). The obtained sample was dried on a heater at 100 °C, and was subjected to $\gamma$-ray and $\alpha$-particle measurements. The radioactivities of the filtrate and PP beakers used were also measured. We determined precipitation yields, $Y$, and the percent adsorption on the PP beaker, $R_{ad}$, from the radioactivities.

A computer-controlled suction filtration apparatus for the preparation of precipitated samples of heavy elements was developed. The online experiment using the apparatus was performed with relatively short-lived nuclides $^{89m,g}$Zr (4.2 min and 78.4 h) and $^{177}$Hf (23.6 h) produced using the AVF cyclotron at RCNP. These nuclides were rapidly and continuously transported from the nuclear reaction chamber to the chemistry laboratory using the He/KCl gas-jet system. Using the apparatus, the products were dissolved by 200 $\mu$L of dilute HCl and the precipitate samples were prepared at room temperature in a manner similar to that used in the above tracer experiment with stirring for 10 s.

The $R_{ad}$ values of Zr, Hf, and Th for samples aged for 10 s was generally less than 3%, which suggests that physical adsorption of these group 4 elements during coprecipitation with Sm hydroxide was small enough to be negligible in the determination of the coprecipitation yields. The $Y$ values of Zr, Hf, and Th obtained with 10-min and 10-s aging are in good agreement with each other. This suggests that the chemical reactions during coprecipitation of these elements are fast, and the present conditions are suitable for evaluating the coprecipitation behavior of $^{68}$s $^{261}$Rf. Almost complete coprecipitation of Zr and Hf with Sm hydroxide was achieved when aqueous NH$_3$ solutions and 0.1 M NaOH were used. These results are consistent with the well-known properties of these elements, i.e., hydroxide precipitation in basic solutions. With the use of more highly concentrated NaOH solutions, these yields decreased, whereas the Th yields were constant at ca. 100%. This is attributed to the fact that Zr and Hf form hydroxide complex ions in high [OH$^-$] solutions.

The $Y$ values obtained in the online experiments and their dependence on the composition of the added basic solution are consistent with those in offline experiment. This suggests that the present experimental method using the apparatus under the present conditions should be applicable to the coprecipitation experiment of Rf.

Reference
Liquid-liquid extraction of zirconium and hafnium with 2-thienyltrifluoroacetone for chemical studies of element 104, rutherfordium

A. Tanaka,† K. Ooe,‡ H. Kikunaga,§ M. Murakami,†,* Y. Komori,† H. Haba,† S. Goto,† and H. Kudo‡

Chemical studies of element 104, rutherfordium (Rf), in aqueous solutions have been carried out mainly using column chromatography. In these column chromatographic experiments, inorganic ligands such as fluoride and chloride ions were used, and inorganic complex formation of Rf was investigated. However, little has been reported regarding the complex formation of Rf with organic ligands such as a chelating agent. In the present study, liquid-liquid extraction of zirconium (Zr) and hafnium (Hf), which are lighter homologs of Rf, was performed to find suitable experimental conditions for complexation studies of Rf with organic ligands.

Radiotracers of $^{88}$Zr ($T_{1/2} = 83.4$ d) and $^{175}$Hf ($T_{1/2} = 70$ d) were produced in the $^{89}$Y(d, 3n) and $^{175}$Lu(d, 2n) reactions, respectively, using the RIKEN K70 AVF cyclotron. Metal foils of Y (150 µm thickness) and Lu (100 µm thickness) were used as targets. Incident energy of the deuteron beam was 24 MeV. The produced radiotracers were chemically separated from the target materials through the anion exchange method and stored in 3 M HNO₃ solution. Aqueous solution of 3 M HNO₃ (600 µL) containing $^{88}$Zr and $^{175}$Hf radiotracers was mixed with an equal volume of TTA in toluene solution in a polypropylene tube, and the mixture was mechanically shaken for 15 hours at 25 ºC. After equilibration, the mixture was centrifuged for 30 seconds, and a 420 µL aliquot from each phase was separately transferred into a polypropylene tube. The radioactivity of each phase was measured by a Ge detector, and the distribution ratio ($D$) was calculated by the following equation:

$$ D = A_o / A_i , \quad (1) $$

where $A_o$ and $A_i$ denote the radioactivities of either of $^{88}$Zr and $^{175}$Hf in aqueous and organic phases, respectively.

Figure 1 shows the dependence of $D$ values of $^{88}$Zr and $^{175}$Hf from 3 M HNO₃ on the TTA concentration in toluene. The $D$ value of $^{88}$Zr was approximately 10 times that of $^{175}$Hf. It is well-known that the chemical behavior of Zr is remarkably similar to that of Hf and mutual separation between these two elements is very difficult. Therefore, the present result shows that TTA has extraction selectivity for Zr, and it is very interesting to investigate extraction behavior of Rf with TTA.

In the extraction of tetravalent metal ions (M⁴⁺) with TTA, the extraction reaction is usually described by the following equation:

$$ M^{⁴⁺} + 4HTTA_{(o)} \rightleftharpoons M(TTA)_4^{(o)} + 4H^{⁺} . \quad (2) $$

From eq. (2), it is expected that the log $D$ vs. log [TTA] plot shows linear relation with the slope of 4 and the value of the slope indicates the number of TTA molecules involved in the extraction reaction. A least-squares fit to the present data showed a straight line with a slope of 3.8 for $^{88}$Zr and 3.9 for $^{175}$Hf. Therefore, this result suggests that the main extracted species of Zr and Hf would be Zr(TTA)₄ and Hf(TTA)₄ from 3 M HNO₃. The slope value of the log $D$ vs. log [TTA] plot was closer to 3 for both Zr and Hf, in not greater than 2 M HNO₃. This might be caused by the effect of hydrolysis of Zr and Hf: formation of ZrOH³⁻ and HfOH³⁻. Thus, an experimental condition suitable for extraction of Rf(TTA)₄ is determined to be 3 M HNO₃ solution.

In the future, liquid-liquid extraction experiments of Zr and Hf with a rapid extraction apparatus using flow injection analysis (FIA) technique will be performed for the Rf experiment.

References
Production of platinum radiotracer for Gamma-Ray Emission Imaging

S. Komoto,1 M. Munekane,1 T. Fukuchi,2 H. Haba,3 K. Higashikawa,4 M. Ueda,5 S. Motomura,2 and S. Enomoto1,*

Platinum drugs such as cis-diammine dichloro platinum (II) (cisplatin) have been used for a long time as a first-choice drug for several types of tumors. The efficacy of these types of drugs has been certainly approved however the disadvantages are the strong toxic side effects including nephrotoxicity, nausea, and neurotoxicity. These side effects are considered as dose-limitation factors. Further, in treatment, the tumor gradually develops resistance to these drugs. There are some mechanisms of resistance such as “Decreased uptake” and “Increased efflux.” 1)

To investigate potential side effects and drug efficacy, we are developing noninvasive and quantitative distribution analysis methods that can determine the concentration of platinum drugs in normal tissues/organs and tumors. We have propose using a new nuclear medicine imaging technology called GREI (Gamma-Ray Emission Imaging), to visualize the distribution of platinum drugs labeled with platinum radionuclides. GREI comprises a Compton camera composed of two planar germanium (Ge) detectors developed in our laboratory.2) GREI has a wide detectable energy range (200-2000 keV) which is different from the conventional imaging modalities, namely single photon emission computed tomography (SPECT) and positron emission tomography (PET). Next, a variety of nuclides that were difficult to image can now be used because of GREI.

For the GREI experiment, platinum radionuclides with optimum half-lives and emitting γ-rays are required. Some useful radionuclides for the GREI are listed in Table 1. In this study, we investigated the production of radio-platinum nuclides that are suitable for GREI experiments via the natOs(α,n) reactions.

For the radio-platinum production, we used metallic natOs powder (chemical purity: 99.99 %) as the target material. Approximately 500 mg of osmium powder was pressed by 3 t at 1 min, and molded into a pellet (φ 15 mm). The pellet was covered with a 10-μm Al foil (chemical purity: 99.999%). The osmium target was irradiated by the 30-MeV α-beam supplied by RIKEN AVF cyclotron for 1.5 h. The beam intensity was 1 particle μA. The γ-ray spectrum of the irradiated target is shown in Fig. 1. This spectrum shows that 189Pt and 191Pt were produced, and fewer quantities of other impurities such as radio-osmium and radio-iridium were produced. After the irradiation, the following separation steps were performed to remove the target osmium from the radio-platinum as reported by M. Bonardi, et al.3) First, for removing osmium, the irradiated target was dissolved in 10 mL conc. HNO3 and heated at the 200 °C.

In this step, osmium was distilled and trapped in 4.7 N NaOH. After almost all of the liquid was evaporated, another 10 mL of conc. HNO3 was added and heated until dryness was achieved. After this step, the process of adding 5 mL of conc. HCl and drying up was repeated thrice. The reaction vessel was washed with 5 mL of 3 M HCl and the solution containing radio-platinum was transferred to a vial. After the chemical separation, the radioactivities of 189Pt and 191Pt were 0.48 and 1.0 MBq, respectively, and the chemical yield was over 90 %.

GREI can detect γ-rays of various energies that are emitted from 189Pt and 191Pt. This allows us to use both of these radio-platinum as radio tracers for imaging. In future, we will synthesize cisplatin with radio-platinum, administer it to a tumor-bearing mouse, and perform imaging experiments.

Table 1. Useful platinum radionuclides for GREI.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-Life</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>189Pt</td>
<td>10.2 h</td>
<td>187.6 (10.0)</td>
</tr>
<tr>
<td></td>
<td>155.1 (15.6)</td>
<td>381.4 (7.5)</td>
</tr>
<tr>
<td></td>
<td>423.3 (4.4)</td>
<td>140.4 (2.3)</td>
</tr>
<tr>
<td>191Pt</td>
<td>10.9 h</td>
<td>721.4 (9.3)</td>
</tr>
<tr>
<td></td>
<td>94.3 (7.5)</td>
<td>563.6 (7.1)</td>
</tr>
<tr>
<td></td>
<td>249.4 (7.5)</td>
<td>544.9 (5.8)</td>
</tr>
<tr>
<td>192Pt</td>
<td>2.8 d</td>
<td>538.9 (13.7)</td>
</tr>
<tr>
<td></td>
<td>409.4 (8.8)</td>
<td>399.9 (6.6)</td>
</tr>
<tr>
<td></td>
<td>802.4 (4.9)</td>
<td>372.2 (3.5)</td>
</tr>
</tbody>
</table>

Fig. 1. Gamma-ray spectrum of produced nuclides in irradiated target.

References
Production of $^{88}$Y for gamma-ray emission imaging

K. Higashikawa,*1,2 A. Morioka,*1 H. Haba,*3 M. Ueda,*1 T. Fukushima,*4 and S. Enomoto*1,*4

Radioimmunotherapy (RIT) is an internal radiation therapy that uses radiolabeled drugs, in particular particularly in monoclonal antibodies (mAbs) or peptides. $^{90}$Y emits highly cytotoxic $\beta^-$ ray and is thus a promising radionuclide for use in RIT. However, $^{90}$Y cannot be readily imaged by nuclear medicine imaging modalities, because $^{90}$Y is a pure $\beta^+$ emitter.1 On the other hand, $^{86}$Y emits $\beta^-$ rays, which can be detected by PET.1–3 In addition, $^{86}$Y-labeled drugs (mAbs or peptides) display identical biodistributions to $^{90}$Y-labeled drugs because $^{86}$Y is chemically identical to $^{90}$Y.1 Therefore, in recent years, $^{86}$Y has attracted attention as an attractive surrogate for studying $^{90}$Y-labeled drugs. However, the physical half-life of $^{86}$Y ($T_{1/2} = 14.7\ h$) is shorter compared to that of $^{90}$Y ($T_{1/2} = 64.1\ h$), and thus, it is not suitable as a surrogate for investigating serial biodistribution of RIT drugs with long biological half-lives, such as mAb, which remain circulating in vivo for weeks.4 A chemically identical surrogate with a longer half-life is desirable for development phases of $^{90}$Y-labeled drugs.

$^{88}$Y is chemically identical to $^{90}$Y and has a long half-life of $T_{1/2} = 106.6\ d$. Moreover, $^{88}$Y emits $\gamma$ rays with energies of 898 and 1836 keV, which can be detected using semiconductor Compton cameras through gamma-ray emission imaging (GREI).5 Therefore, the imaging of $^{88}$Y-labeled drugs with GREI has the potential ability to investigate the serial biodistribution of $^{90}$Y-labeled drugs with a long biological half-life, in particular, in preclinical studies. The final purpose of our study is to develop an imaging method for $^{88}$Y-labeled drugs through GREI. In this study, we produced $^{88}$Y for the GREI experiment. $^{88}$Y was produced by the $^{90}$Sr(d,x)$^{88}$Y reactions. To prepare a $^{88}$SrO pellet target with a diameter of 10 mm, approximately 400 mg of $^{88}$SrCO$_3$ (Wako Pure Chemical Industries, Ltd., chemical purity: 99.99%) was heated for 2 h at 1000°C and pressed at 1.6 t. The pellet was covered with a 10-μm Al foil (chemical purity: 99.999%). The target was irradiated with a 24-MeV deuteron beam supplied from the RIKEN AVF cyclotron. The irradiation was performed for 5 h at a beam current of approximately 1.5 particle μA.

Thirty-nine days after the irradiations, $^{88}$Y was chemically isolated from the $^{90}$SrO target by extraction chromatography using Ln-resin (Eichrom Technologies, Inc., particle size: 50-100 μm) filled in a Muromac column (Muromachi Technos Co., Ltd., internal diameter: 5 mm, height: 50 mm). The Ln-resin column was washed in advance with 3 mL of water, 10 mL of 10 M HNO$_3$, and then 4 mL of water, and was pre-equilibrated with 2 mL of 1 M HNO$_3$. The irradiated $^{88}$SrO target was dissolved in 1 M HCl and evaporated to dryness on a hot plate and under a heat lamp. The residue was dissolved in 5 mL of 1 M HNO$_3$, and was evaporated to dryness. Subsequently, the residue was dissolved in 5 mL of water and 2 mL of 1 M HNO$_3$, and was evaporated to dryness. Then, the residue was dissolved in 2 mL of 1 M HNO$_3$ and loaded onto the Ln-resin column. The resin was then washed with 16 mL of 1 M HNO$_3$. $^{88}$Y was eluted from the resin with 10 mL of 10 M HNO$_3$. The eluted solution was heated to dryness, and 2 M HCl was added to the residue.

The $\gamma$-ray spectrum of the final purified product is shown in Fig. 1. Approximately 10 MBq of $^{88}$Y was obtained. The radiochemical yield of $^{88}$Y in the chemical isolation process was approximately 80%. In the next experiment, we plan to synthesize $^{88}$Y-labeled drugs and try to visualize their biodistribution using GREI.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{gamma_spectrum.png}
\caption{Gamma-ray spectrum of $^{88}$Y after the chemical isolation.}
\end{figure}

References

---

*1 Department of Pharmaceutical Analytical Chemistry, Graduate school of Medicine, Dentistry, and Pharmaceutical Sciences, Okayama University
*2 Japan Society for the Promotion of Science
*3 RIKEN Nishina Center
*4 Next-Generation Imaging Team, RIKEN
Sodium-ion batteries have attracted considerable attention recently, because of their potential for large-scale applications: higher power and less expensive batteries compared to Li-ion batteries can be realized by utilizing abundant and polarizable sodium ion as a mobile charge carrier. One of the main obstacles to realizing high performance sodium-ion batteries is the low specific capacity of the electrode materials. Thus, it is particularly important to develop novel Na-ion cathode materials with a high capacity as well as a high operating potential.

Our group has recently reported the electrochemical properties of Na excess transition metal oxide Na[Na1/3Ru2/3]O2, where the cation arrangement in the [Na1/3Ru2/3] layer is controlled between the ordered and disordered states by synthetic conditions. Importantly, the ordered and disordered Na[Na1/3Ru2/3]O2 exhibit significant differences in the electrochemical properties. In this work, we conducted Ru Mössbauer spectroscopy for the ordered and disordered Na[Na1/3Ru2/3]O2 to clarify the valence states of Ru ions during desodiation/sodiation.

The source nuclide, 99Rh (T1/2=15.0 d) for 99Ru Mössbauer spectroscopy was produced via the 99Ru (p,n) 99Rh reaction. The 96% enriched 99Ru metal powder was irradiated by protons with $E = 12$ MeV and $I = 10$ $\mu$A at the AVF Cyclotron. The 99Ru metal powder was packed into an Al holder, which was tightly fixed to the irradiation equipment for cooling by He gas flow and water flow during the irradiation. After irradiation for about 24 hours, the target was used as a 99Rh Mössbauer source without being subjected to annealing or chemical treatment.

99Ru absorption Mössbauer spectra of Na[Na1/3Ru2/3]O2 samples were obtained using a conventional Mössbauer spectrometer. Owing to the relatively high energy of the Mössbauer $\gamma$-ray (89.8 keV), both the source and the absorbers were maintained at liquid-helium temperature in a cryostat.

The obtained spectra are shown in Fig. 1 and 2. The Mössbauer spectrum for the disordered Na[Na1/3Ru2/3]O2 (Fig. 1 (a)) shows a broad singlet with isomer shift ($\delta$) of $-0.30$ mm/s and linewidth ($\Gamma$) of 0.95 mm/s. The $\delta$ value is typical of Ru$^{IV}$, although the large linewidth suggests structural disorder around Ru. The Mössbauer spectrum for the ordered Na[Na1/3Ru2/3]O2 (Fig. 1 (b)) shows a singlet with $\delta = -0.27$ mm/s and $\Gamma = 0.63$ mm/s, indicating Ru$^{IV}$. Thus, regardless of the synthetic conditions, the valence states of Ru in both compounds are the same. However, the linewidth for the ordered compound is much smaller than that of the disordered one, most likely due to the ordered honeycomb arrangement of Na and Ru in the [Na1/3Ru2/3] layer.

On charging the ordered compound, the Mössbauer spectrum, as shown in Fig. 2, cannot determine the electronic structure accurately, in part due to the small amounts of the obtained sample. However, a preliminary result indicates oxidation of Ru from tetravalent to pentavalent, from the obtained $\delta$ value of +0.21 mm/s with a small quadrupole splitting of 0.60 mm/s. Further experiments with a larger amount of samples are now in progress to reveal the reaction mechanism of Na[Na1/3Ru2/3]O2.

Fig. 1. 99Ru Mössbauer spectra of (a) disordered and (b) ordered Na[Na1/3Ru2/3]O2 at 4.2 K.

Fig. 2. 99Ru Mössbauer spectra at 4.2 K of the ordered Na[Na1/3Ru2/3]O2 after electric charge.

References
Production of $^{262,263}$Db in the $^{248}$Cm($^{19}$F,$xn$)$^{267-x}$Db reactions at $E_{\text{lab}} = 96$ MeV

M. Murakami,*1,*2 S. Goto,*1 K. Ooe,*1 D. Sato,*1 S. Tsuto,*1 N. Goto,*1 T. Koyama,*1 R. Aono,*1 H. Haba,*2 M. Huang,*2 and H. Kudo*1

The isotope $^{262}$Db ($T_{1/2} = 33.8$ s) is often used in the chemical studies of element 105, Db. At RIKEN, the decay properties of $^{262}$Db produced in the $^{248}$Cm($^{19}$F,5n)$^{262}$Db reaction were recently studied with a gas-jet transport system coupled to the gas-filled recoil ion separator GARIS.1 In this study, however, $^{263}$Db produced in the 4n channel was not observed at 97.4 MeV and 103.1 MeV. The upper-limit cross sections of $^{263}$Db were rather smaller than those predicted by the HIVAP code, which reproduced the 5n channel fairly well. Therefore, in this work, we investigated the production of Db isotopes at a lower energy of 96 MeV, at which the predicted excitation function for $^{263}$Db exhibits the maximum.

A $^{248}$CmO$_2$ target of 460 $\mu$g/cm$^2$ thickness was prepared by electrodeposition onto a Be backing foil of 1.8-mg/cm$^2$ thickness. $^{nat}$Gd$_2$O$_3$ of 23-$\mu$g/cm$^2$ thickness was admixed with the target material to simultaneously produce $^{170}$Ta ($T_{1/2} = 6.76$ min) via the $^{nat}$Gd($^{19}$F,$xn$)$^{170}$Ta reaction. A 19$^{+}$F$^{-}$ beam was supplied by the AVF cyclotron. The beam energy at the middle of the target was 96.2 MeV, and the energy degradation in the target was estimated to be 1.0 MeV. The average beam intensity was 450 pnA.

The reaction products recoiling out of the target were continuously transported by a He/KCl gas-jet system to the rotating wheel detection system MANON. The transport efficiency was estimated to be 74%. Other details of the measurement were similar to those in our previous study.2

We searched for time-correlated $\alpha$-$\alpha$ event pairs at the $\alpha$-energy range of $8.0 \leq E_\alpha \leq 9.0$ MeV. On setting the time window to 25 s, 16 $\alpha$-$\alpha$ correlations were found. Figure 1(a) shows the two-dimensional arrays of these $\alpha$-$\alpha$ correlations. In Fig. 1(a), 74 $\alpha$-$\alpha$ correlations assigned to the decay chain $^{262}$Db $\alpha \rightarrow ^{258}$Lr $\alpha$ in the previous experiments1) are compared. The $\alpha$-particle spectra of the parent and daughter nuclides are shown in Figs. 1(b) and (c), respectively. For the parent $\alpha$ spectrum, the 8.46-MeV $\alpha$ line of $^{262}$Db is seen, while the 8.68-MeV $\alpha$ line was not very clear owing to the low counting statistics. On the other hand, the $\alpha$ lines of $^{258}$Lr were clearly found in the daughter $\alpha$ spectrum.

In Fig. 1(a), a solid box indicates the gated $\alpha$-energy range of the parent $^{262}$Db (8.26–8.83 MeV) and the daughter $^{258}$Lr (8.36–8.80 MeV). Fourteen events are found in this energy region. The deduced half-life of the daughter nuclide, $T_{1/2} = 4.5\pm1.7\pm1.0$ s, is in agreement with the reported half-life of $^{258}$Lr, $T_{1/2} = 3.9$ s.1) Thus, these events are attributed to the $\alpha$ decay chain $^{262}$Db $\alpha \rightarrow ^{258}$Lr $\alpha$. The expected number of random correlations was evaluated to be 0.3 in this energy region. Regarding all 14 events as true ones, the production cross section of $^{262}$Db is derived as $\sigma = 0.25_{-0.08}^{+0.06}$ nb. This cross section is consistent with the previously reported one, $\sigma = 0.23_{-0.11}^{+0.08}$ nb at 97.4 MeV.1)

Only one $\alpha$-$\alpha$ correlation was found around the energy regions of $^{263}$Db and its $\alpha$-decay daughter $^{259}$Lr, as shown by an arrow in Fig. 1(a). Although this number of the event, one, is comparable with the expected number of random events, the deduced half-life of the daughter nucleus, $T_{1/2} = 3.1_{-1.4}^{+1.8}$ s, is consistent with the reported half-life of $^{259}$Lr ($T_{1/2} = 6.2$ s).3) If this event is regarded as a true one, the cross section of $^{263}$Db is deduced to be $\sigma = 0.03_{-0.026}^{+0.072}$ nb, which is one order of magnitude smaller than that of $^{262}$Db as well as the HIVAP predictions.1

References

*1 Department of Chemistry, Niigata University
*2 RIKEN Nishina Center

Fig. 1. (a) Two-dimensional representation of time-correlated events. (b) $\alpha$ spectrum of parent nuclei. (c) $\alpha$ spectrum of daughter nuclei.

- 292 -
Production of $^{174}$Re in the $^{nat}$Gd($^{23}$Na,$x$n) reactions for future studies on Bh chemistry using GARIS

H. Haba,*1 R. Aono,*2 D. Kaji,*1 Y. Kasamatsu,*3 H. Kikunaga,*4 Y. Komori,*1 H. Kudo,*2 K. Morimoto,*1 K. Morita,*1 M. Murakami,*1 K. Nishio,*5 A. Shinobara,*3 M. Takeyama,*1 T. Tanaka,*1 S. Tsuto,*2 Y. Wakabayashi,*1 S. Yamaki,*1 and T. Yokokita*3

We have been developing a gas-jet transport system coupled to GARIS as a novel technique for superheavy element (SHE) chemistry.1) So far, isotopes of $^{261}$Rf (atomic number $Z = 107$), $^{262}$Db ($Z = 105$), and $^{265}$Sg ($Z = 106$) have been produced in the $^{288}$Cm($^{19}$O,$5$n), $^{248}$Cm($^{18}$F,$5$n), and $^{298}$Cm($^{22}$Ne,$5$n) reactions, respectively, and the production and decay properties of these isotopes have been investigated for chemical studies.1–3) Recently, the chemical synthesis and gas-chromatographic analysis of Sg(CO)$_6$ were successfully conducted with $^{265}$Sg.4) We plan to obtain a heavier element, Bh ($Z = 107$), by investigating production conditions of $^{266,267}$Bh in the $^{248}$Cm($^{23}$Na,$5$n) reactions. In this work, as the first step, we optimized setting parameters of the GARIS gas-jet system using $^{174}$Re produced in the $^{nat}$Gd($^{23}$Na,$xn$) reactions. Since Re is a homologous element of Bh in the periodic table, the Re isotopes would be useful in fundamental experiments on Bh chemistry in the future.

The $^{nat}$Gd$_2$O$_3$ target with a thickness of 340 μg cm$^{-2}$ was prepared by electrodeposition onto a 2-μm Ti foil. The $^{23}$Na$^{2+}$ ion beam was extracted from RILAC. The beam energy was 130.6 MeV at the middle of the target, and the typical beam intensity was 1.4 particle μA. The evaporation residues (ERs) were separated by GARIS. Several magnetic rigidities were investigated ($B_p = 1.58–1.94$ Tm) at a He pressure of 33 Pa. Then, the ERs were guided into a gas-jet chamber of 100-mm depth through a 0.7-μm Mylar window. The ERs were transported by a He/KCl gas-jet to a chemistry laboratory. The He flow rate was 5 L min$^{-1}$, and the chamber pressure was 78 kPa. The KCl aerosols were then collected on a glass filter for 60 s and subjected to γ-ray spectrometry with a Ge detector after a cooling time of 60 s. A 20-μm Al foil was placed at the entrance of the gas-jet chamber to evaluate the gas-jet transport efficiency.

Figure 1 shows a typical γ-ray spectrum observed in the $^{nat}$Gd($^{23}$Na,$xn$) reactions at $B_p = 1.74$ Tm.

![Fig. 1. Typical γ-ray spectrum observed in the $^{nat}$Gd($^{23}$Na,$xn$) reactions at $B_p = 1.74$ Tm.](image)

**Fig. 1.** Typical γ-ray spectrum observed in the $^{nat}$Gd($^{23}$Na,$xn$) reactions at $B_p = 1.74$ Tm.

Figure 2 shows the variation in the yield of $^{174}$Re as a function of magnetic rigidity. The dashed curve represents the result of the least-squares fitting with the Gaussian curve with a maximum yield at $B_p = 1.74 ± 0.01$ Tm and a resolution of Δ$B_p/B_p = 10.0 ± 0.4%$. This optimum $B_p$ agrees well with that ($B_p = 1.78 ± 0.05$ Tm) deduced from our systematic trend for the low-energy recoil ions.5) The gas-jet transport efficiency was about 80%. The radioactivity of $^{174}$Re available at the chemistry laboratory is 55 ± 2 kBq μA$^{-1}$ after the 60-s aerosol collection. This yield is high enough to allow development of chemistry apparatuses and investigation of chemical systems for the study of Bh chemistry in the future.

![Fig. 2. The yield of $^{174}$Re as a function of magnetic rigidity.](image)

**Fig. 2.** The yield of $^{174}$Re as a function of magnetic rigidity.

References
5) R. B. Firestone and V. S. Shirley: *Table of Isotopes, 8th ed.*
Excitation function of the $^{\text{nat}}$Hf($\alpha$,x)$^{182g}$Ta reaction: 
Cyclotron production of a long-lived $\gamma$-ray emitter $^{182g}$Ta

M. Murakami,*1,*2 H. Haba,*1 and H. Kudo*2

We previously investigated the production of $^{179}$Ta ($T_{1/2} = 1.82$ y) in the proton- and deuteron-induced reactions on $^{\text{nat}}$Hf,1,2 for basic chemical studies of the $^{105}$ element Db, which must be conducted at a single-atom scale. Although the long half-life of $^{179}$Ta is convenient for such the chemical experiments, the decay characteristics of $^{179}$Ta are less suitable: $^{179}$Ta does not emit any $\gamma$ ray in its EC decay, and it must be traced by measuring the characteristic X rays of Hf, which are often interfered by X or $\gamma$ rays of other nuclides.

Another long-lived Ta isotope, $^{182g}$Ta ($T_{1/2} = 114.74$ d), is a $\gamma$-emitting isotope, and it has also been used as a radiotracer to explore the chemical behavior of Ta. $^{182g}$Ta is usually produced by the $^{183}$Ta($n_{th},\gamma$) reaction with a high cross section of 20.5 $\pm$ 0.5 b.3 However, the $^{182g}$Ta radiotracer produced in this way is undesirable for basic studies of Db, because it is obtained with a macro amount of the target material of Ta.

Very recently, Tárkányi et al. measured the cross sections of W, Ta, and Hf isotopes in the $^{\text{nat}}$Hf($\alpha$,x) reactions up to 40 MeV.4 As shown in Fig. 1, they reported that the excitation function for the $^{\text{nat}}$Hf($\alpha$,x)$^{182g}$Ta reaction increased with the beam energy. Because the $^{182g}$Ta tracer with high specific radioactivity can be obtained with this reaction, we further studied the production of $^{182g}$Ta in this reaction.

The excitation functions were measured by a stacked-foil activation technique. 11 pairs of thin metallic foils of $^{\text{nat}}$Hf (97% chemical purity, 23 $\mu$m thickness) and $^{\text{nat}}$Cu (99.9% chemical purity, 9 $\mu$m thickness) were stacked in an alternating sequence.

The excitation functions were measured by a stacked-foil activation technique. 11 pairs of thin metallic foils of $^{\text{nat}}$Hf (97% chemical purity, 23 $\mu$m thickness) and $^{\text{nat}}$Cu (99.9% chemical purity, 9 $\mu$m thickness) were stacked in an alternating sequence. The $^{\text{nat}}$Cu foils were used for monitoring the beam current and energy by measuring the well-established $^{\text{nat}}$Cu($\alpha$,x)$^{67}$Ga excitation function.5) The size of the all foils was $15 \times 15$ mm$^2$. The stack was bombarded by a 50-MeV $\alpha$ beam supplied by the AVF cyclotron for 31 min. The beam was collimated within 9 mm in diameter and the average beam current was 0.23 $\mu$A. After the bombardment and the proper cooling duration, each foil was subjected to $\gamma$-ray spectrometry with a Ge detector.

The production cross sections were derived by the well-known activation formula. The beam energies in the individual target foils were calculated with the SRIM-2008 program.7) The experimental cross sections were compared with the calculated ones by the TALYS-1.6 code.8)

In this work, independent cross sections were obtained for the $^{\text{nat}}$Hf($\alpha$,x)$^{176,177,178}$W, $^{178,183}$Ta, $^{179n2,183}$Hf reactions, while cumulative ones were obtained for $^{\text{nat}}$Hf($\alpha$,x)$^{175,176,177,182g}$Ta, $^{175}$Hf. The measured cross sections of the $^{\text{nat}}$Hf($\alpha$,x)$^{182g}$Ta reaction are shown in Fig. 1 along with the calculated ones. The cross sections in the energy range of 41–50 MeV were measured for the first time. The excitation function exhibits the maximum cross section of 8.3 $\pm$ 0.3 mb at 41.5 $\pm$ 1.2 MeV. The data of Tárkányi et al.4) are consistent with the present data at $\geq$30.7 MeV, while that at 27.6 $\pm$ 0.7 MeV (0.2 $\pm$ 0.3 mb) is much smaller than the present one of 1.60 $\pm$ 0.08 mb at 27.2 $\pm$ 1.6 MeV. The cross sections calculated by the TALYS-1.6 code8) show systematically lower values with a similar shape of the excitation function.

The physical thick-target yield was deduced from the measured cross sections and the calculated stopping power by the SRIM-2008 program.7) The deduced yield of $^{182g}$Ta was 5.2 kBq/$\mu$Ah at 50 MeV.

Fig. 1. Excitation function of the $^{\text{nat}}$Hf($\alpha$,x)$^{182g}$Ta reaction. Dashed curves indicate the individual reaction channels evaluated by the TALYS-1.6 code.8)

References

*1 RIKEN Nishina Center
*2 Department of Chemistry, Niigata University
Production cross sections of \((d,x)\) reactions on natural ytterbium†

M. U. Khandaker*1, *2 and H. Haba*2

The method for obtaining accurate information of light-charged-particle-induced reaction cross sections has generated significant interest in the nuclear data community because these reactions are being increasingly used in nuclear medicine, accelerator and nuclear technology, and the testing of nuclear reaction theories. Recently, we investigated deuteron-induced reaction cross sections from various target elements because measured data of the \((d,x)\) processes are limited compared to those of \((p,x)\) processes. A survey of literature shows that several investigations have been conducted for the \(^{171}\)Lu \((n,x)\) reactions leading to various applications. As an example, the production of the \(^{177}\)Lu radionuclide via the \(^{171}\)Yb \((d,x)\) reaction finds applications in internal radiotherapy and imaging procedures 1,2). Its half-life is long enough to allow sophisticated preparation (e.g., shipping, labelling, purification etc.) for use without any significant loss of activity. \(^{177}\)Lu can be produced in principle in several ways. Currently, a large scale production of \(^{177}\)Lu is in practice by using only the high flux nuclear reactor via the direct \(^{176}\)Yb \((n,\gamma)\) \(^{177}\)Lu or indirect \(^{170}\)Yb \((n,\gamma)\) \(^{177}\)Yb \(\rightarrow\) \(^{177}\)Lu routes followed by a complex separation procedure of \(^{177}\)Lu from the Yb isotopes 3). On the other hand, the carrier-free \(^{171}\)Lu is available in the charged-particle irradiations on various targets, though its activity is relatively lower than those in the reactor productions. However, it may be possible to overcome this deficiency with recent high-power accelerator technologies, which enable large scale and on-site productions of \(^{177}\)Lu leading to its various practical applications.

The objective of the present study was to report the latest cross sections of the \(^{171}\)Yb \((d,x)\) \(^{169,170,171,172,173,174,176,177}\)Lu and \(^{169,175,177}\)Yb reactions that were measured with a high precision over the energy range of 2–24 MeV using the AVF cyclotron facility of the RIKEN RI Beam Factory, Wako, Japan. Details on the irradiation technique, radioactivity determination, and data evaluation procedures are available in Ref.5). Owing to the space limitation of this report, we present only the \(^{171}\)Yb \((d,x)\) \(^{177}\)Lu cross sections and the deduced yield in Figs. 1 and 2, respectively. Measured cross sections with an overall uncertainty of about 12.8% are listed in Ref.4). The deduced thick-target yields indicate that a low amount of no-carrier-added radioactivity of \(^{177}\)Lu (2.4 MBq/μA-h) could be obtained by irradiating an enriched \(^{176}\)Yb target with 11-MeV deuteron energy from a cyclotron.

Fig. 1. Excitation function of the \(^{171}\)Yb \((d,x)\) \(^{177}\)Lu reaction.

Fig. 2. Physical thick target yields for the \(^{169}\)Yb \(\rightarrow\) \(^{177}\)Lu and \(^{175}\)Yb \(\rightarrow\) \(^{177}\)Lu radionuclides.

References

* Condensed from the article in Nucl. Inst. Meths. B. 335, 8 (2014).
*1 Department of Physics, University of Malaya
*2 RIKEN Nishina Center
Measurement of production cross sections of Tc isotopes in the natMo(d,x) reactions

Y. Komori,*1 M. Murakami,*1 and H. Haba*1

Chemical characterization of superheavy elements is one of the important and challenging subjects in the field of nuclear chemistry. We plan to conduct model experiments for chemical studies of element 107, Bh using radiotracers of its homologous, Tc and Re. Relatively long-lived isotopes, $^{95m}$Tc ($T_{1/2} = 61$ d) and $^{184g}$Re ($T_{1/2} = 35.4$ d) are useful for tracer experiments. In the field of nuclear medicine, the isotope $^{99m}$Tc, the daughter nuclide of $^{99}$Mo, is the most widely used for diagnostic imaging. Recently, the direct production of $^{99}$Mo/$^{99m}$Tc using an accelerator has attracted much attention. In this work, production cross sections of deuteron-induced nuclear reactions on natMo (nat: natural isotopic abundance) have been measured up to 24 MeV for the quantitative production of Tc isotopes. The results are discussed by referring to previously reported data and the theoretical model code TALYS.1)

The production cross sections were measured using a stacked-foil technique. Seventeen natMo foils (99.95% purity, 20.9 mg/cm² thickness), sixteen natTi foils (99.5% purity, 9.2 mg/cm² thickness), and sixteen natTa foils (99.95% purity, 16.1 mg/cm² thickness) were stacked in the order of Mo/Ti/Ta. The Ti foils were used to calibrate the beam current and the incident energy via the monitor reaction natTi(d,x)⁴⁸V.2) The Ta foils were used to attenuate the beam energy. The size of all foils was 15 × 15 mm². The target stack of the Mo/Ti/Ta foils was irradiated for 1 h with a 24-MeV deuteron beam supplied from the RIKEN AFV cyclotron. The average beam current was 0.17 μA. After the irradiation, each foil was subjected to γ-ray spectrometry with a Ge detector.

The excitation functions were measured for the natMo(d,x)$^{93m}$Tc, $^{93}$Mo,$^{90}$Nb, and $^{89}$Zr reactions. Figure 1 shows the excitation function of the natMo(d,x)$^{99m}$Tc reaction. Our results are in good agreement with the previously reported data.3–5) It can be seen that the TALYS code (TENDL-2013) underestimates the cross sections at deuteron energies exceeding 10 MeV. For the other reactions, most of our results are in good agreement with those of previous studies. We measured the production cross section of $^{99m}$Tc ($T_{1/2} = 91$ d) in the deuteron energy range of 14–24 MeV for the first time. It was found that the TALYS code qualitatively reproduces the shape of these excitation functions, though there is little agreement between the experimental cross sections and the theoretical values.

Thick-target yields for all the investigated Tc, Mo, Nb, and Zr isotopes were deduced from the measured production cross sections. Figure 2 shows the thick-target yields of the Tc isotopes as a function of the deuteron energy. The deduced yield of $^{95m}$Tc at 23.7 MeV is 0.36 MBq/μA h. For $^{99}$Mo and $^{99m}$Tc, the deduced yields at 23.7 MeV are 9.6 and 40 MBq/μA h, respectively. To increase the production yields of $^{99}$Mo/$^{99m}$Tc and to reduce radioactivities from by-reaction products, the use of enriched $^{98}$Mo and $^{100}$Mo targets is favorable. Based on the present results, we will produce $^{95m}$Tc for the model experiments on Bh chemistry. We will also develop a simple and efficient chemical separation scheme to obtain no-carrier-added Tc tracer from the Mo target.

References

*1 RIKEN Nishina Center
Measurements of alpha-induced cross section for $^{48}$Cr and $^{49}$Cr up to 50 MeV

H. Kikunaga,*1 M. Muralami,*2 Y. Komori,*2 and H. Haba*2

Chromium is one of the essential trace elements in some animals but also can be toxic in high concentrations. Understanding the behavior of chromium in animals, plants, and the environment is important and influential on the various fields such as biological sciences.

The radioactive tracer technique has been widely recognized as a powerful tool for behavior analysis of elements in trace amounts. The isotopes $^{48}$Cr ($T_{1/2} = 21.6$ h), $^{49}$Cr ($T_{1/2} = 42.3$ m), and $^{51}$Cr ($T_{1/2} = 27.7$ d) have potential as tracers because of their suitable half-lives. In this work, the cross sections for the reactions $^{nat}$Ti($\alpha$, X)$^{48}$Cr and $^{nat}$Ti($\alpha$, X)$^{49}$Cr up to 50 MeV were measured to produce these isotopes efficiently.

The excitation functions of these reactions were measured by the stacked-foil technique. The target stack containing 20 natural Ti foils (99.5% pure) with thickness of 20 and 40 $\mu$m were irradiated with a $\alpha$-particle beam delivered from the RIKEN K70 AVF Cyclotron for 30 min. The cyclotron was operated at a beam energy of 50.4 MeV, which was confirmed by TOF measurement, with a mean current of around 0.4 $\mu$A.

After the irradiation, the target foils were enclosed in a polyethylene film separately and were subjected to $\gamma$-ray spectrometry using a high-purity germanium detector. The incident beam energy and flux were determined by activation of the monitor foil technique using the $^{nat}$Ti($\alpha$, X)$^{49}$Cr reaction. The reference data were obtained from the IAEA Reference Data1). The energy loss in each foil was calculated using the TRIM code3).

A $\gamma$-ray spectrum of a Ti foil sample at an effective energy of around 50 MeV is shown in Fig. 1. The $\gamma$-peaks of scandium, vanadium, and chromium are observed in the spectrum. During the tracer preparation, it is necessary to separate chromium from titanium and the other elements.

The cross sections for the $^{nat}$Ti($\alpha$, X)$^{48}$Cr and $^{nat}$Ti($\alpha$, X)$^{49}$Cr reaction obtained in this work are shown in Fig. 2. For comparison, the earlier experimental data3–6) of the $^{nat}$Ti($\alpha$, X)$^{48}$Cr reaction and the values calculated using the Talys 1.6 code7) with default parameters are included in Fig. 1. The cross sections of $^{48}$Cr obtained in this work is in good agreement with the earlier experimental data. The calculated values with the Talys code reproduce the experimental values of $^{48}$Cr and $^{49}$Cr with a reasonable accuracy although each peak position of the excitation functions is deviated slightly.

Fig. 1. A $\gamma$-ray spectrum of a Ti foil sample at an effective energy of around 50 MeV.

Fig. 2. Cross sections for the $^{nat}$Ti($\alpha$, X)$^{48}$Cr and $^{nat}$Ti($\alpha$, X)$^{49}$Cr reactions.

References

*1 Research Center for Electron Photon Science, Tohoku University
*2 RIKEN Nishina Center
*3 Graduate School of Science and Technology, Niigata University
Improvement in the chemical yield of purified $^{109}\text{Cd}$ for fee-based distribution at the RIKEN AVF cyclotron

Y. Wakitani,*1 S. Yano,*1 T. Yamada,*1 H. Haba,*2 S. Shibata,*2 and K. Takahashi*2

Since October 2007, we have distributed fee-based $^{109}\text{Cd}$ ($T_{1/2} = 469.4\text{d}$) produced via the $^{109}\text{Ag}(d, 2n)^{109}\text{Cd}$ reaction using the RIKEN AVF cyclotron, to the general public.1) After irradiation, $^{109}\text{Cd}$ was chemically separated from the Ag target and reaction byproducts. We have employed a separation method involving AgCl precipitate and anion exchange in HBr without AgCl precipitation for the chemical separation of $^{109}\text{Cd}$ from the irradiated target in the present work.

Cadmium-109 was produced by irradiating a silver plate in the Ag target according to the procedure shown in Fig. 1. After the irradiation, $^{109}\text{Cd}$ was chemically separated from the Ag target according to the procedure shown in Fig. 1. The Ag target was dissolved in 5 mL of concentrated nitric acid, 5 mL of water, and three drops of hydrogen peroxide solution. The solution was evaporated to dryness. The residue was dissolved in 10 mL of c. HBr. This solution was also evaporated to dryness. The residue was dissolved in 90 mL of 7 M HBr. This 7 M HBr solution was passed through an anion-exchange column ($ø7 \text{mm} \times 40 \text{mm height}$) packed with Dowex 1X8 (100–200 mesh, Cl– form). $^{109}\text{Cd}$ was adsorbed on the resin, and Ag was eluted. Then the column was washed with 7 M HBr and 0.02 M HCl. $^{109}\text{Cd}$ was adsorbed on the resin and the unwanted $^{65}\text{Zn}$ was also evaporated to dryness. The residue was dissolved in 10 mL of c. HBr. This solution was also evaporated to dryness. The residue was dissolved in 90 mL of 7 M HBr. This 7 M HBr solution was passed through the anion-exchange column ($ø7 \text{mm} \times 40 \text{mm height}$) packed with Dowex 1X8 (100–200 mesh, Cl– form). $^{109}\text{Cd}$ was adsorbed on the resin, and Ag was eluted. Then the column was washed with 7 M HBr and 0.02 M HCl. $^{109}\text{Cd}$ was adsorbed on the resin and the unwanted $^{65}\text{Zn}$ was eluted. Finally, $^{109}\text{Cd}$ was eluted with 3 M HNO$_3$ and H$_2$O.

The present results are shown in Table 1, together with those obtained in our previous study. The specific radioactivity and radionuclidic purity were measured by $\gamma$-ray spectrometry using a Ge detector. The chemical impurity was also estimated by ICP-MS for a control sample treated using the same chemical process as the irradiated Ag target. Chemical impurities were found to be 57 ppm for S and 87 ppm for Ca. The others were below 10 ppm. As shown in Table 1, the chemical yield obtained in the present work was significantly improved from 80% to 98%.

Table 1. Comparison of the results of the $^{109}\text{Cd}$ purification between our previous2) and the present work.

<table>
<thead>
<tr>
<th></th>
<th>Our previous work</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical yield (%)</td>
<td>80</td>
<td>98</td>
</tr>
<tr>
<td>Specific radioactivity*1</td>
<td>94</td>
<td>93</td>
</tr>
<tr>
<td>(MBq/$\mu$g)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decontamination factor of Ag</td>
<td>$3 \times 10^6$</td>
<td>$7.6 \times 10^6$</td>
</tr>
<tr>
<td>Radionuclidic purity</td>
<td>$&gt;99.9%$</td>
<td>$&gt;99.9%$</td>
</tr>
</tbody>
</table>

*1 (Beam intensity :10 $\mu$A, irradiation time: 48 h)

References
Preparation of no-carrier-added $^{85}\text{Sr}$ using the $\text{natRb}(d,x)^{85}\text{Sr}$ reaction

S. Yano,*1,*2 Y. Wakitani,*1 T. Yamada,*1 H. Haba*2, S. Shibata,*2 and K. Takahashi*2

Since 2007, we have distributed purified radioisotopes such as $^{65}\text{Zn}$, $^{88}\text{Y}$, and $^{109}\text{Cd}$ produced at the RIKEN AVF cyclotron to the general public.1) After the Fukushima Dai-ichi Nuclear Power Plant accident in 2011, distribution of $^{85}\text{Sr}$ solutions having high specific radioactivity was required to develop analysis techniques for discharged radio-strontium. In response to these demands, we intended to produce $^{85}\text{Sr}$ via the $\text{natRb}(d,x)^{85}\text{Sr}$ reaction using a 24-MeV deuteron beam from the RIKEN AVF cyclotron. We also studied a chemical separation procedure to obtain a purified $^{85}\text{Sr}$ solution using a no-carrier-added technique. In the previous study,2) we successfully produced a $^{85}\text{Sr}$ solution having high radionuclidic purity. To estimate specific radioactivity, however, chemical purity should be estimated carefully. In the present study, we therefore evaluated chemical impurities in the prepared solution and assessed the applicability of the $\text{natRb}(d,x)^{85}\text{Sr}$ reaction and the no-carrier-added technique to the large-scale production of the $^{85}\text{Sr}$ solution for distribution.

The $^{85}\text{Sr}$ isotope used in this work was produced by irradiating a RbCl disk (Sigma-Aldrich; chemical purity: > 99.99%; thickness: 500 mg cm$^{-2}$) of natural isotopic abundance with 24-MeV deuterons. The average beam intensity was 159 nA. The irradiation time was 17 min. $^{85}\text{Sr}$ was chemically separated in accordance with the scheme using a two-step chromatographic separation technique that we had reported.2) The chemical impurities in 5.0 mL of this purified solution was evaluated using ICP-MS (Agilent Technologies; Model 7700) for a control sample, which was treated using the same procedure as that for the irradiated sample.

The production yield of $^{85}\text{Sr}$ was estimated to be approximately 3.90 MBq·μA$^{-1}$·h$^{-1}$ under the present experimental condition. The chemical yield reached as high as 94%. As shown in Table 1, the Rb target material was successfully removed and the decontamination factor of Rb reached 10$^6$. The strontium content required for the purification process was chemically separated in accordance with the scheme.

Table 1. Measured principal chemical impurities in the $^{85}\text{Sr}$ solution after the purification process.

<table>
<thead>
<tr>
<th>Element</th>
<th>Na</th>
<th>Al</th>
<th>Si</th>
<th>S</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (ppm)</td>
<td>12.8</td>
<td>4.6</td>
<td>19.5</td>
<td>110.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

The amount of Sr impurities from irradiation to be 346 ng under 3μA irradiation for 24 h. The amount of Sr isotopes produced by the nuclear reaction depends on the deuteron beam dose. To apply the present technique to a larger-scale production, we estimated the expected specific radioactivity for the distribution shown in Fig. 2. According to the present result, the purified $^{85}\text{Sr}$ solution having a high specific radioactivity of 124 MBq μg$^{-1}$ could be produced under 3μA irradiation for 24 h using the present chemical separation scheme. We are planning to launch the purified $^{85}\text{Sr}$ solution with a high specific radioactivity prepared using these studied techniques in response to customers' request.

Fig 1. Cross sections for $^{85}\text{Sr}$ and other stable Sr isotopes calculated using the TALYS code.

Fig 2. Calculated specific radioactivity for distribution of the purified $^{85}\text{Sr}$ solution as a function of the deuteron beam dose.

References
2) S. Yano et al.: In this report.

---

1) Japan Radioisotope Association
2) RIKEN Nishina Center
4. Radiation Chemistry and Biology
Localization of Rad51 and phosphorylated DNA-PKcs after heavy-ion irradiation in mammalian cells

M. Izumi*1 and T. Abe*1

Accelerated heavy-ion particles with high linear energy transfer (LET) induce complex clustered DNA damage, which is considered an obstacle to efficient repair and causes different biological effects compared with low-LET radiation such as X-ray. However, the biological effects of heavy-ion irradiation are not fully understood at the molecular level. To analyze the repair mechanism for DNA double-strand breaks (DSBs) caused by heavy ions, we have investigated cell sensitivity to heavy ions using the wild-type CHO-AA8 cells and two CHO mutant lines deficient in homologous recombination (HR)1) or non-homologous end-joining (NHEJ)2) in a previous study3) and found that HR, but not NHEJ, is primarily involved in the repair pathway induced by high-LET ionizing radiation.

In this study, we investigated the localization of Rad51 and the phosphorylated form of the catalytic subunit of the DNA-dependent kinase (DNA-PKcs) in CHO cells after X-ray or heavy-ion irradiation with immunofluorescence staining. Rad51 is essential for HR and is involved in strand transfer during homologous pairing,4) whereas DNA-PKcs is involved in NHEJ and phosphorylated upon DNA damage on threonin-2609.5)

One hour after X-ray irradiation, hundreds of Rad51 or phosphorylated DNA-PKcs foci were observed in nuclei (Fig. 1A), although they were not colocalized with each other. The number of foci started to decrease 4 h after irradiation and fractions of Rad51 and phosphorylated DNA-PKcs foci were colocalized. A small fraction of DSBs was not repaired within 24 h (data not shown), and the foci remaining at 16 h after irradiation contained both Rad51 and phosphorylated DNA-PKcs, suggesting that irreparable DSBs recruit repair proteins of the NHEJ and HR pathways.

On the other hand, large fractions of Rad51 and phosphorylated DNA-PKcs foci were colocalized 1 h after iron-ion irradiation (LET = 1000 keV/µm) (Fig. 1B), suggesting that the majority of DSBs have different structures in nature. Although our previous results suggest that NHEJ is not involved in the repair pathway after heavy-ion irradiation,6) we observed that phosphorylated DNA-PKcs was recruited to DSBs. These results suggest that repair proteins of both pathways are recruited to DSBs induced by heavy ions, and finally HR is selected for damage repair.

Currently, we are investigating how the cell cycle and LET affect the repair kinetics and colocalization of Rad51 and phosphorylated DNA-PKcs. We are also planning to examine the localization of 53BP1 and Rif1 after heavy-ion irradiation, which are involved in the selection of repair pathways for DSB repair.6,7)

Fig. 1 Representative images of CHO nuclei (blue) with Rad51 (green) and phosphorylated DNA-PKcs (red) foci. The cells were irradiated with 5 Gy of X-ray (A) or iron ions (B) and fixed with 4% paraformaldehyde at indicated time points after irradiation. Foci formation of Rad51 and phosphorylated DNA-PKcs was detected by immunofluorescence staining.

References
4) A. Shinoara et al: 69, 457 (1992)

*1 RIKEN Nishina Center
Low-dose high-LET heavy ion-induced bystander signaling

M. Tomita,*1,∗2 T. Tsukada,*1 and M. Izumi*1

The radiation-induced bystander response (RIBR) is a cellular response induced in nonirradiated cells that receive bystander signals from directly irradiated cells within an irradiated cell population. The RIBR induced by low doses of high-LET radiations is an important issue concerning the health of astronauts and in heavy-ion radiation cancer therapy. Here, we investigated the molecular mechanisms underlying and biological implications of the RIBR induced by such low doses of high-LET radiations.

Figure 1 shows the clonogenic survival curve of normal human fibroblast WI-38 cells irradiated with Fe ions (1000 keV/µm). Cells were harvested from the cell culture flask immediately (0 h) or 16–24 h after irradiation, and the surviving fraction was determined by using a colony formation assay. At doses below 0.2 Gy, the surviving fractions of the cells harvested 16–24 h after exposure to Fe ions were much lower than those extrapolated from higher doses above 0.1 Gy using the linear-quadratic model (LQ model). On the other hand, the cells harvested immediately after exposure did not show such a high cell killing effect at lower doses. These results suggest that an adequate incubation period is necessary for the bystander signal induction and transfer.

Previously, we have reported that reactive oxygen species (ROS), gap-junction intercellular communication (GJIC), and cyclooxygenase-2 (COX-2) protein as well as nitric oxide (NO) may be involved in high-LET radiation-induced bystander signal transfer. Here, we show the progress of results reflecting new data [Fig. 2]. Lindane and NS-398 (an inhibitor of GJIC and COX-2, respectively) were dissolved in DMSO (a scavenger of ROS). DMSO did not significantly suppress the bystander cell killing effect. In contrast, lindane, NS-398, and c-PTIO (a scavenger of NO) significantly suppressed cell death to similar levels. Cells pretreated with both c-PTIO and lindane did not show significantly higher surviving fraction than those pretreated with lindane or c-PTIO alone. These results suggest that bystander signaling through GJIC and the cell culture medium induces the bystander cell killing effect in a coordinated manner.

Currently, we are examining the role of the NF-κB/Cox-2/prostaglandin E2 and NF-κB/iNOS/NO pathways, which may be activated in bystander cells.

References

*1 RIKEN Nishina Center
*2 Radiation Safety Research Center, Central Research Institute of Electric Power Industry
Effect of days after irradiation on lethal rate of F3 progeny in the fruit fly mutation isolation system

K. Tsuneizumi*1 and T. Abe*1

Heavy-ion beam mutagenesis is generally recognized as an effective method for mutation breeding[1,2]. Although this method was greatly successful with a plant, its application is still limited for animals. We therefore plan to acquire more basic data to set up optimal conditions for the irradiation system by heavy-ion beam using Drosophila melanogaster (fruit fly) as a useful model.

In a previous study, we have developed and improved a stable mutant isolation system using fruit flies by employing carbon-ion beam irradiation. In the system, we prepared a useful genetic tool, called balancer chromosome, to prevent genomic recombination. We also prepared small commercial cuvettes with a plane surface to apply heavy-ion beam equally to overcome unstable results[3]. Then, we could observe a linear correlation between a number of F1 progeny and an irradiation dose when the males were irradiated with a carbon-ion beam[3].

In this report, we introduced a new machine to improve the mutant isolation system [Fig. 1a]. If fruit flies are put in empty cuvettes for irradiation, they die because of dryness. So, it is necessary to put fly foods in the cuvettes to avoid dryness. However, it was difficult to prepare many samples without polluting the irradiated surface because the food was stuffed manually. The machine made it possible to dispense fly foods to many cuvettes without polluting the side surface of the cuvettes.

We prepared powdered fly foods for the machine, because it is easy to use and is commercially available. We considered using a needle tip for dispensing viscous fly foods to many cuvettes continuously [Fig. 1b]. Then we optimized the water-to-powder ratio for injection. Next, we set parameters for the dispensing machine using a program, such that the surface of fly foods was slanted in a cuvette [Fig. 1c]. As a result of these examinations, we were able to prepare more than 300 cuvettes in 2 hours.

To optimize the conditions for the mutant isolation system, we estimated the suitable state of F1 progeny that includes a possibility of chromosome damages. Various developmental cells are intermingled in testis of irradiated fruit fly. The repair mechanism to DNA damages and the sensitivity to irradiation are different in each cell[4]. So, it is important to know when flies with high probability of DNA damage are born. Because DNA damages to important genes for survival can be judged by the homozygotes born in F3 progeny, we measured a frequency of lethal rate of F3 progeny [Fig. 2]. The progeny being born 4 days after irradiation at 10 Gy dose levels recorded the maximum frequency of lethal rate [Fig. 2]. These data will be helpful for optimizing the irradiation system in the future.

References
Extra-early-flowering wheat mutants produced by heavy-ion-beam mutagenesis†

A. Nishiura,*1 Y. Kazama,*2 T. Abe,*2 N. Mizuno,*3 S. Nasuda,*3 and K. Murai*1

To avoid harvesting in the rainy season, early flowering or early heading is one of the most important characteristics for bread wheat (Triticum aestivum) in East Asia, including Japan. A detailed understanding of the flowering mechanism in wheat plants is of value not only for wheat breeding but also for basic scientific research. From the large scale mutant panel of diploid einkorn wheat (Triticum monococcum) strain KU104-1 developed by heavy-ion-beam irradiation†, we identified four extra early-flowering mutants, named extra-early-flowering1 (exe1), exe2, exe3, and exe4. The four exe mutants fell into two groups, namely Type I (moderately extra-early-flowering type; exe1 and exe3) and Type II (extremely extra-early-flowering type; exe2 and exe4), based on a field experiment.

In a growth chamber, leaf-emergence timing in wild-type (WT) and exe mutant plants was examined under long-day (LD) or short-day (SD) conditions. Under LD conditions, WT plants averaged about 180 days from sowing to flag-leaf unfolding. In contrast, Type I exe mutants took about 65 days and Type II about 50 days. WT plants transited from the vegetative to reproductive growth phase at the 9-leaf stage, while exe mutants showed earlier phase transition: at the 5-leaf stage for exe1 and exe3 (Type I) and the 4-leaf stage for exe2 and exe4 (Type II). In WT plants, the flag leaf occurred at the 18-leaf stage, while in exe1, exe2, exe3, and exe4, the flag leaf appeared at the 9-leaf, 8-leaf, 9-leaf, and 7-leaf stages, respectively. Under SD conditions, WT plants transited from the vegetative to reproductive growth phase at the 13-leaf stage. In contrast, exe1 and exe3 mutants (Type I) transited at the 8-leaf stage, while exe2 and exe4 mutants (Type II) transited at the 4-leaf stage. Interestingly, the phase transition was early (at the 4-leaf stage) in Type II exe mutants under both SD and LD conditions. Comparing Type I exe mutants between SD and LD conditions indicates that these mutants retained photoperiodic sensitivity. However, Type II exe mutants had lost almost all photoperiodic sensitivity.

In wheat, it was found that three genes mainly control the flowering, namely VERNALIZATION 1 (VRN1), VRN2 and VRN3. The analysis of VRN1, a flowering-promoter gene, showed that it was more highly expressed in seedlings at the early developmental stages in Type II mutants than in Type I mutants. The up-regulation of VRN1 expression in exe mutants was associated with earliness in flowering under LD conditions. The extremely extra-early flowering in Type II mutants was associated with a more rapid up-regulation of VRN1 expression than in Type I mutants. It is notable that a similar level of VRN1 expression was observed at the phase transition in each exe mutant: at the 5-leaf stage for Type I mutants and at the 4-leaf stage for Type II mutants. This finding suggests that the level of VRN1 expression is correlated with the phase transition from vegetative to reproductive growth and may act as a threshold for flowering competency in wheat plants.

The original KU104-1 is an einkorn wheat strain that carries a null allele of the VRN2 gene, a repressor of flowering. Thus, our results indicate that the level of VRN1 expression controls earliness in flowering in exe mutants independently of VRN2. In bread wheat, it has been known that winter cultivars quantitatively requires prolonged cold temperature to yield vernalization saturation. Some winter cultivars require 2-4 weeks of low temperature to reach the maximum vernalization effect on heading, and others require more than 4 weeks. Positional cloning of the gene was performed for the duration required for vernalization, and the results demonstrated that this trait is controlled by the recessive VRN1 gene on the A genome at the protein level2. A previous study also revealed that the binding ability of the VRN1 protein to TaHox1 was associated with the requirement of low-temperature duration to reach vernalization saturation. These findings, together with the present exe study, support our model of gene network for flowering: VRN1 plays a central role in the flowering pathway†.

References

Fig. 1. Extra-early-flowering (exe) mutant plants grown in the field.

† Condensed from the article in Breeding Science 64, 213 (2014)
*1 Department of Bioscience, Fukui Prefectural University
*2 RIKEN Nishina Center
*3 Graduate School of Agriculture, Kyoto University
Hereditary analysis of radiation induced semidwarf mutants in Tartary buckwheat (*Fagopyrum tataricum* Gaertn.)

T. Morishita,*1*  Y. Hayashi,*2* and T. Abe*2*

Recently, heavy-ion beams have been regarded as a good mutagen for plant breeding, and as such various varieties have been developed by using heavy-ion beams. We previously reported the biological effects and mutation induction by ion beams in Tartary buckwheat*1* *2). We obtained semidwarf mutants named IRBFT-45, 63, 67 and 77. The semidwarf type is important for improving the lodging resistance and yielding ability in buckwheat breeding. These semidwarf mutants were obtained by irradiating dry seeds of Tartary buckwheat (var. Rotundatum) with 40 Gy of carbon (25 keV/μm, 12C6+), 100 Gy of carbon (39 keV/μm, 12C6+), 30 Gy of iron (624 keV/μm, 56Fe24+) and 20 Gy of argon (280 keV/μm, 40Ar77) ions*3). On the other hand, we obtained similar semidwarf lines named IRBFT-6 and 20 by irradiating dry seeds with 50 and 500 Gy of gamma rays (60Co, 44.4TBq) at the Institute of Radiation Breeding, and IRBFT-38 by irradiating dry seeds with 40 Gy of helium ions (46 keV/μm, 4He2+) at JAEA. The plant height of all of these semidwarf lines was 50-60% of the original varieties. We performed heredity analysis on these semidwarf mutants.

All of the F1 plants obtained by crossing among IRBFT-6, 20, 45 and their original varieties showed wild type like phenotype. The phenotypes in the populations of F2 were segregated into wild type like and semidwarf, and the appropriate segregation ratio was found to be 3:1 by a chi square test (Table 1). This suggests that the trait of semidwarf in IRBFT-6, 20, and 45 was controlled by a nuclear single recessive gene.

To classify these semidwarf lines, a half diallel cross was performed (Fig. 1). When F1 plants showed a semidwarf phenotype, the causal gene of the parents was considered to be the same. When F1 plants showed wild-type like phenotype, the causal genes of the parents were considered to be different. From the phenotype in F1, it was estimated that these 7 lines were classified into 2 groups. One consisted of IRBFT-6, 20, and 45, which had a common semidwarf gene termed *sdA*. The other consisted of IRBFT-38, 63, 67 and 77, which had another semidwarf gene termed *sdB*.

Because a crossing test with original varieties was not performed in *sdB* lines (IRBFT-38, 63, 67 and 77), the number of *sdB* gene(s) was not determined. Instead, we investigated the segregation ratios in the F2 plants generated by crossing *sdB* lines with IRBFT-20 (sdA) (Table 2). The phenotypes in the populations of F2 were segregated into wild type like and semidwarf. Their segregation ratios were then fitted to the two recessive gene model (Table 2). These results indicated that *sdB* was controlled by a single recessive gene different from *sdA*.

Table 1. Segregation patterns of plant type crossing between semidwarf lines and the original variety in the F2 population

<table>
<thead>
<tr>
<th>Cross combination</th>
<th>No. of plants</th>
<th>χ²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wild type</td>
<td>Semidwarf</td>
<td>3:1</td>
</tr>
<tr>
<td>Pontivy×IRBFT-6</td>
<td>21</td>
<td>9</td>
<td>0.4</td>
</tr>
<tr>
<td>Hokkaid T8×IRBFT-20</td>
<td>54</td>
<td>17</td>
<td>0.04</td>
</tr>
<tr>
<td>Rotundatum×IRBFT-45</td>
<td>60</td>
<td>13</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Fig. 1. Phenotypes of F1 plants by a half diallel cross. SD means semidwarf type, and WT means wild-type like. Numbers in parentheses are the numbers of research plants.

Table 2. Segregation patterns of plant type crossing between semidwarf lines in the F2 population

<table>
<thead>
<tr>
<th>Cross combination</th>
<th>No. of plants</th>
<th>χ²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wild type</td>
<td>Semidwarf</td>
<td>9:7</td>
</tr>
<tr>
<td>IRBFT-20×IRBFT-38</td>
<td>109</td>
<td>85</td>
<td>0.01</td>
</tr>
<tr>
<td>IRBFT-20×IRBFT-63</td>
<td>64</td>
<td>56</td>
<td>0.41</td>
</tr>
<tr>
<td>IRBFT-20×IRBFT-67</td>
<td>137</td>
<td>103</td>
<td>0.07</td>
</tr>
<tr>
<td>IRBFT-20×IRBFT-77</td>
<td>130</td>
<td>109</td>
<td>0.33</td>
</tr>
</tbody>
</table>

References

---

*1* NARO Hokkaido Agricultural Research Center  
*2* RIKEN Nishina Center
Effects of Ar-ion beam irradiation on inducing mutations in chrysanthemum and sweetpotato

Y. Tanokashira,*1 J. Nagai,*1 S. Nagayoshi,*1 and T. Abe*2

It is expected that heavy-ion beam irradiation will be useful in inducing mutations for plant breeding in agriculture1,2. However, effects of Ar-ion beam irradiation on many plant species remain unexplained. Therefore, effects of Ar-ion beam irradiation on chrysanthemum and sweetpotato, which are major crops in Kagoshima Prefecture, was investigated and compared with C-ion beams in this study.

At first, we investigated effects of Ar-ion beam irradiation on regeneration of chrysanthemum. Leaf blades of the spray-mum cultivar “Southern Chelsea”, which was developed in Kagoshima Prefecture, were irradiated by Ar-ion beams (LET: 280 keV/μm) at doses of 0.1, 0.3, 0.5, 1, 2, and 3 Gy, and C-ion beams (LET: 23 keV/μm) at doses of 0.1, 1, 2, and 3 Gy. After irradiation, these tissues were cultured in vitro, and the number of directly regenerated plants from adventitious shoots13 were counted. The relative regeneration rates of Ar ions were lower than that of C ions at the same dose, and the proportion between relative regeneration rates of Ar ions and C ions (Ar/C) became lower according to increasing of irradiation doses (Fig. 1). In addition, the relative regeneration rate of Ar ions became higher according to decreasing of irradiation doses; 37.8%, 65.9%, and 90.9% at doses of 1, 0.5, and 0.3 Gy, respectively (Fig. 1). From past findings, the optimal dose for inducing mutations in chrysanthemum will be at the dose when the relative regeneration rate has declined considerably, and this optimal dose of C ions will be 2 Gy3. Consequently, the optimal dose of Ar ions is estimated to be 0.5 Gy assuming that the relative regeneration rate of Ar ions for optimal dose is at the same level with C ions.

![Fig. 1](image-url)  
Fig. 1. Comparison of the relative regeneration rate by the Ar-ion and C-ion beam irradiation in “Southern Chelsea”. The relative regeneration rate means the rate of regenerated shoots after ion beam irradiation to radiationless regenerated shoots, which were directly developed from adventitious shoots13.

Next, we investigated the effects of Ar-ion beam irradiation on inducing mutations for sweetpotato. Axillary shoots of in vitro-grown stems of cultivar “Konamizuki” were irradiated by Ar-ion beams (LET: 280 keV/μm) at doses of 1, 2, and 3 Gy, and C-ion beams (LET: 23 keV/μm) at doses of 10 and 15 Gy. After irradiation, these tissues were cultured for about 10 weeks, and the growth and morphological mutations of in vitro plants were observed. In Fig. 2, mortality rate, stunting rate, and mutation rate mean the rate of samples that died without germination, samples whose stem lengths were less than 2 cm, and samples whose leaves have one or more incisions, respectively, to investigated samples. The original leaf of cultivar “Konamizuki” is cordate. Under the experimental condition used in this study, the mortality rates of both Ar ions and C ions were relatively low (Fig. 2). In contrast, the stunting rate at 3 Gy Ar ions was about 4.7 times and about 1.8 times higher than those at 10 Gy and 15 Gy C ions, respectively (Fig. 2). This fact suggests that the dose of Ar ions that strongly influences the growth of sweetpotato will be lower than that of C ions. Furthermore, the morphological mutation rate at 2 Gy Ar ions was 25.7% (Fig. 2). This rate was highest under all irradiation conditions. Because many morphological mutations can be detected at the mature stage, the reason that the mutation rate at 2 Gy Ar ions is higher than that at 3 Gy Ar ions could be the high stunting rate at 3 Gy Ar ions. Moreover, some of the mutations leading to the incision of leaves were the results of spontaneous mutation; however, the mutation rate under heavy-ion beam irradiation was clearly higher than that observed under non-irradiation. These morphological mutants are chimera plants generated from multicellular tissues. Therefore, we tried to separate mutation sites by cutting out mutation tissues. On the basis of these results, it is supposed that a low dose of Ar-ion beams strongly affects on the growth and morphological mutation of sweetpotato.

![Fig. 2](image-url)  
Fig. 2. Effects of heavy-ion beam irradiation on sweetpotato cultivar “Konamizuki”. The period and times of irradiation and the number of samples (from 96 to 187) were different based on the line class and doses.

References

*1 Kagoshima Prefectural Institute for Agricultural Development
*2 RIKEN Nishina Center
Rapid screening of heavy-ion-induced large deletion mutants by using quantitative real-time PCR in *Arabidopsis thaliana*


In heavy-ion irradiation, the size of deletions can be varied according to different values of linear energy transfer (LET). In irradiation experiments on *Arabidopsis thaliana*, we previously found that beams with LET of 30 keV/μm induced small deletions (1 to 51 bp) with high frequency, and this size is appropriate for disrupting a single gene.1 Thus, 30-keV/μm beams are suitable for use in mutation breeding as well as in reverse genetics to find single gene disruption lines in conjunction with SNP detection systems. On the other hand, beams with LET of 290 keV/μm caused larger deletions (1 kbp to several hundred kbp).2 Such high-LET beams can be used for generating mutants lacking tandemly arrayed genes (TAGs) that have functions similar to one another, allowing us to investigate the function of TAGs. Thus, we are now developing a deletion-mutant correction by screening them from M1 generations after being irradiated with 100-, 200-, or 290-keV/μm beams. The screening is performed using array-CGH designed for all TAGs of *A. thaliana*. Researchers will be able to screen deletion mutants of interest from our stock of over 10,000 of 290-keV/μm irradiated M1 lines.

However, screening deletion mutants is time-consuming. Conventionally, it was performed by PCR in the M1 generation, in which only homozygous deletions (HomDels) could be detected unless primers were designed to have deletions placed between them (Table 1). In case that the HomDel mutant of interest is lethal, no candidate would be obtained. By contrast, heterozygous deletions (HetDels) can be inherited over generations, and are found in the M2 generation with about two times frequency compared with HomDels (Fig.1). If a HetDel is easily detected in the M2 generation (See Fig. 1), the screening pool size can be reduced. Herein, we tested the quantitative real time PCR (qPCR) for detection of a HetDel.

For our test, we selected an *Arabidopsis* line (C200-84-N2) from our stock induced by carbon-ion beam irradiation (135 MeV/nucleon, 200 keV/μm) at a dose of 75 Gy. This line has a 3.5-kbp deletion at the 2762232-2765771 position on chromosome 4. The 3.5-kbp deletion is harbored as a HetDel in the M2 generation. Thus, four individual progenies of the M3 plants of C200-84-N2 were used for qPCR, since some of them would have a 3.5-kbp deletion as the HetDel.

qPCR was performed by using LightCycler and the Universal Probe Library detection format (Roche Diagnostics, Penzberg, Germany). Relative amplification ratios between the 3.5-kbp deleted and non-deleted regions were calculated by using the ΔΔCp method. Sample A showed the same relative amplification ratio as wild-type (Fig. 2). Samples B and C showed about half-level of the ratio as compared to wild-type, indicating that they contain HetDels. Sample D showed no amplification. These results indicate that large deletions can be detected even if they are heterozygous. Our irradiated M2 seed stocks in conjunction with this method will prove a powerful tool for analyzing the functions of TAGs.

References
LET-dependent effect on mutation induction DNA repair-deficient background in Arabidopsis thaliana

K. Ishii,*1 Y. Kazama,*1 Y. Shirakawa,*1 S. Ohbu,*1 and T. Abe*1

A previous study on the effect of LET on inducing mutation revealed that the most effective value of LET (LETmax) on dried seeds of Arabidopsis thaliana was 30.0 keVμm−1, within a range 22.5 to 640 keVμm−1.1) LET is therefore an important factor in mutation induction. In the mutagenesis process, the DNA double-strand break (DSB) repair system is concerned with the production of mutations. There are two major DSB repair pathways: non-homologous end joining (NHEJ) and homologous recombination repair (HRR) function in eukaryotic cells.2) NHEJ and HRR are independent pathways. HRR is a relatively error-free pathway because it utilizes the homologous region of a sister chromatid to repair the damaged strand, whereas the NHEJ pathway is relatively error-prone.

To determine whether DSB repair pathways are involved in the LET-dependent effect on mutation induction, we intended to investigate the effect of LET in the DSB repair-deficient background. We planned to measure the mutation rates after heavy-ion beam irradiation with LET values 22.5 and 30 keVμm−1 in the three mutant lines: 1) the HRR pathway-deficient mutant line, 2) the NHEJ pathway-deficient mutant line, and 3) both HRR and NHEJ pathway-deficient mutant line. Here, we report the mutation rates of the rad54-deficient mutant as the HRR pathway-deficient mutant line.

Seeds of the APG3(+/-) mutant (CS16118) and the AtRad54(+/-) mutant (SALK_038057) were obtained from the Arabidopsis Biological Resource Center (ABRC, Ohio State University) and the European Arabidopsis Stock Centre (NASC, the University of Nottingham), respectively. The APG3(+/-) mutant carries BASTA-resistance at the APG3-disrupted allele, and a uniformly heterozygous population can be selected as photosynthetic and BASTA-resistant seedlings.3) The uniformly heterozygous population facilitates investigation of the mutation frequency in the irradiated (M1) generation by calculating the proportion of the number of plants with white sectors on true leaves to that of total plants with true leaves (Fig. 1). The AtRad54(+/-) mutant carries a kanamycin resistance. The APG3(+/-) plants were crossed with the AtRad54(+/-) plants. The F1 seeds were germinated in the presence of BASTA (2 μg/mL) and kanamycin (50 μg/mL), and the germinated plants were replanted to pots. F2 seeds were collected from the self-pollinated F1 plants. In the F2 generation, the photosynthetic and both BASTA- and kanamycin-resistant plants were screened. The second screening of the APG3(+/-)/AtRad54(+/-) plants were conducted by PCR. A sufficient number of seeds were collected from progenies of the identified APG3(+/-)/AtRad54(+/-) plants.

Heavy-ion beam irradiation was conducted as previously described3) with some modifications. The seeds of the APG3(+/-)/AtRad54(+/-) and APG3(+/-)/AtRad54(+/-) plants were irradiated with 12C6+ ions with LETs of 22.5 or 30.0 keVμm−1 at a dose of 300 Gy.

The mutation frequencies were obtained as previously described.3) The mutation frequencies of AtRad54(+/-) plants were 3.0 and 6.6% when the LET values were 22.5 and 30.0 keVμm−1, respectively, and they are significantly different (Table 1; p<0.05 with chi-square test). The mutation frequency of 22.5 keVμm−1-irradiated AtRad54(+/-) plants was 5.6%, which was at the same level as that of 30.0-keVμm−1 irradiated control (p≥0.05). It is assumed that because the HRR pathway is disabled, the error-prone NHEJ pathway mainly functioned to repair DSB. The mutation frequency of 30.0-keVμm−1 irradiated AtRad54(+/-) plants, however, was still 6.8%, which was at the same level as that of the control (p≥0.05). This result proposed a hypothesis: in the case of the 30.0-keVμm−1 irradiation, DSBs occur beyond the capacity of the HRR pathway functions and are repaired mainly by the NHEJ pathway, leading to a high mutation frequency. Further analysis on other DNA repair gene-deficient mutants is in progress.

Fig. 1. Sector mutation caused by heavy-ion beam irradiation on the APG3(+/-) mutant. (A) A plant showing sector mutation. The leaf exhibiting mutation is indicated by the white arrow head. (B) A plant not showing abnormal phenotype. Bars = 2 mm.

Table 1. LET-dependent effect on inducing mutation.

<table>
<thead>
<tr>
<th>LET (keVμm−1)</th>
<th>Mutation frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AtRad54(+/-)</td>
</tr>
<tr>
<td>22.5</td>
<td>5.6 (916)</td>
</tr>
<tr>
<td>30.0</td>
<td>6.8 (857)</td>
</tr>
</tbody>
</table>

Numbers in parentheses indicate numbers of samples. *Kazama et al. (2012).

References
Characterization of isolates derived from heavy-ion-beam irradiated cells in the unicellular green alga Parachlorella kessleri

T. Yamazaki,*1,2 Y. Yamashita,*1 S. Ota,*1,2 T. Takeshita,*1 Y. Kazama,*3 T. Abe,*3 and S. Kawano*1,2

Parachlorella kessleri is a unicellular microalga related to the Chlorella species that belong to the class of Trebouxiophyceae in the Chlorophyta and accumulates starch followed by lipids after suffering sulfur-starvation. 1) A P. kessleri strain (NIES-2152) exhibits the highest biomass productivity under continuous high-light conditions among the strains that are relative algal species. 2) The properties of P. kessleri such as the ability to produce biomaterials including starch and lipids, and high biomass productivity qualify this strain as the most desired candidate in industrial production.

To improve the productivity of biomass or biomaterials in algal cells, we have been developing a breeding system for microalgae using P. kessleri as a model case. Our previous report demonstrated that the isolates from heavy-ion-beam irradiated P. kessleri cells exhibit a broad spectrum of phenotypes, which are different from the wild type strain. 3) Another case study demonstrated that the heavy-ion-beam irradiation could disrupt gene(s) responsible for a metabolic pathway to assimilate extracellular nitrates by transporting and oxidizing them to ammonium. 4) These findings suggest that the breeding system based on the heavy-ion-beam will modify a specific metabolic pathway to produce biomaterials.

Wild type P. kessleri cells were grown in the wells of a 384-well plate using a tris-acetate-phosphate (TAP) medium containing inorganic nutrients sufficient for healthy growth under continuous-light conditions. Optical density at 595 nm (OD595) and the emission of a lipophilic fluorescence stain, Nile Red, in each well were measured as an index of cell density and accumulation of neutral lipids in cells, respectively (Fig. 1). The median of OD595 for wild type P. kessleri cells reached to approximately 1.11 at 12th day of culture after inoculation into a fresh TAP medium. Although the individual values were scattered, they exhibited a constant range of scatter in replications. The wild type cells were grown in nutrient-limited media (dSTAP for sulfur starvation; dNTAP for nitrogen starvation; dPTAP for phosphorus starvation). Among the three conditions, nitrogen starvation suppressed the increase of OD595 after inoculation most effectively. In addition, the values in individual wells exhibited also a constant range of scatter. The Nile Red fluorescence values for the three nutrient-limited culture media were almost the same, and they were higher than that for the TAP-medium, suggesting that the neutral lipids accumulate in those cells in high and isolates using this method should consider the scatter between wells.

The P. kessleri cells were irradiated by heavy-ion beams of different doses and nuclear species (Fe and Ar ions at 25 Gy and 50 Gy). These cells were grown on plates containing a solid TAP medium, and the obtained colonies were defined as isolates. The individual isolates were inoculated in the wells of 384-well plates containing a fresh TAP medium. Four thousand six hundred and eight isolates were grown for 12 days. OD595 values and Nile Red emissions for these wells were measured at the 12th day of culture after inoculation (Fig. 1). The distribution of OD595 values differed from the expected pattern with the constant range of the scatter spreading around the median calculated for the wild type replications. Although the exact scatter of individual isolates was unclear because the value was measured only once, this result indicates that the population contains heterogeneous isolates with different genetic backgrounds. Under sulfur and phosphorus starvations, the scatter were consistent with that for the wild type replications; however, under nitrogen starvation the median was lower than that for the in the case of wild type. These inconsistencies with the expected result were observed in the constant range of scatter for Nile Red emission except in the case of sulfur starvation. These data suggest that a certain group of isolates from heavy-ion-beam irradiated algal cells alters the genetic background responsible for cell proliferation and metabolism.

This study was supported by JST, CREST (to SK).

References
3) Ota et al. : Bioreasur Technol. 149, 432-438 (2013)
**Effects of Ar-ion beam irradiation on survival rate of *Aurantiochytrium* sp.**

K. Ikeda,*¹  R. Kose,*¹  T. Okuda,*¹  Y. Sakakura,*¹  K. Kaya,*¹  Y. Kazama,*²  and T. Abe*²

The organisms that belong to the *Aurantiochytrium* sp. are heterotrophic marine thauroctonids with a high growth rate. They produce many bioactive compounds such as squalene, docosahexanoic acid (DHA, C₂₂:₆n-₃) and odd-numbered fatty acids, and they are being improved in terms of their cellular cell functions for industrial utilization¹,².

To introduce novel cell functions, irradiation with a swift, heavy-ion beam to induce mutations is an effective method³. At RIKEN RI Beam Factory (RIBF), microbial cells and plant seeds are irradiated with heavy-ion beams such as of carbon and argon (Ar).

In this study, *Aurantiochytrium* spp. NB6-3 and SYLR6#3 were selected because of their short lag times and industrial usage. The strains were exposed to accelerated Ar ions with a dose range of 20 Gy to 80 Gy. After irradiation, cells were cultured on GTY medium (2% glucose, 1% Tryptone, 0.5% yeast extract and 1.8% Red Sea Salt)-containing agar plates (φ90 mm) at 25°C for 48 h. The colonies were counted using the colony forming unit (CFU) to estimate their survival rates and were isolated for mutant screening. Survival rates were expressed as averages of duplicate CFU experiments. Survival rate was obtained using the formula:

\[
\text{Survival rate (\%)} = \frac{\text{(number of colonies)}}{\text{(cell number before irradiation)}} \times 100
\]

The survival rates of both strains rapidly decreased with a dose of 20 Gy (Fig.1). The colony-forming cells were isolated from the agar plates and suspended in the sterilized GTY medium. The cell suspension was transferred to the cell-culture plates with 96 wells for primary screening. Cell density was measured using the iMark Microplate Reader (BIO RAD) at 650 nm. During the primary screening, based on the colony color and a higher growth rate, mutant cells were selected and transferred to test tubes for secondary screening. The colonies of *Aurantiochytrium* with high lipid contents showed cells also show orange to brown color. Therefore, to select mutants with high lipid contents, dark orange to brown colonies were picked out from the various mutated colonies.

During the secondary screening, the selected cells were cultured in test tubes with reciprocal shaking at 25°C for 48 h. The cell growth rate was measured using packed cell volume (PCV, %) and was converted to cell number.

Growth rate was calculated using the following equation:

\[
\text{Growth rate (hour}⁻¹\text{)} = \frac{\ln(X_t / X_0)}{(t_1 - t_0)}
\]

where \(X_t\) and \(X_0\) are cell densities (cells/mL) at times \(t_1\) and \(t_0\), respectively. During the primary screening, 22 and 12 mutants were selected from the SYLR6#3 and NB6-3 strains, respectively. However, the characteristic features of the selected mutants in terms of their colors and high growth rates completely disappeared.

The effects of other heavy-ion beams on cells are being investigated.

![Fig.1 Survival curves of *Aurantiochytrium* sp.](image1)

![Fig.2 Growth rates of isolated strains estimated during the secondary screening](image2)

**References**


¹ Sea Act Co. Ltd.
² RIKEN Nishina Center
Analysis of DNA breakpoint detected from rice exome sequencing data

R. Morita,*1 K. Ishii,*1 S. Kogure,*1 K. Ichinose,*1 Y. Hayashi,*1 and T. Abe*1

We have performed exome sequencing analysis to reveal mutations induced by heavy-ion beams in rice. We used three software packages, GATK, Pindel, and BEDTools, to detect mutations from exome sequencing data. Among them, Pindel finds DNA breakpoints, decides the types of mutations such as deletion, insertion, and tandem duplication1). When Pindel cannot determine types of mutations, the mutation is called an "unassigned breakpoint". We found homozygous mutations called unassigned breakpoints from the rice mutant (Mutant-1) induced by Ne-ion beam irradiation. This mutant possessed three unassigned breakpoints. Two of these were located in the same chromosome, suggesting that they were breakpoints derived from an inversion.

We confirmed the candidate inversion by polymerase chain reaction (PCR) analysis. First, we estimated the position of two breakpoints, namely, breakpoint A and breakpoint B by using Integrative Genomic viewer2). Then, we designed primer F1 having the sequences in the upstream region of the breakpoint A (Fig. 1). We created primer R1 corresponding to the downstream region of this breakpoint. Similarly, primers F2 and R2 were synthesized on both sides of the breakpoint B. When PCR was carried out with primer sets F1R1 or F2R2 using wild-type genomic DNA as the template, DNA amplification was observed (Fig. 1). On the other hand, when PCR was carried out using Mutant-1 DNA as the template, no amplification of these DNA fragments should be observed (Fig. 1). When we attempted to amplify a DNA fragment with primer sets F1F2 and R1R2 using Mutant-1 DNA, DNA amplification should be observed (Fig. 1).

We investigated the existence of the inversion from DNA amplification pattern in this way.

In the PCR experiment, DNA amplification was observed when we used primer sets F1F2 or R1R2 using mutant 1 genomic DNA as the template (Fig. 2). No amplification of these DNA fragments was observed when we used wild-type DNA as the template (Fig. 2). These results demonstrated that homozygous inversion existed in the Mutant-1 plant as we expected. Sequencing analysis using PCR products of the Mutant-1 plant revealed that 2-bp deletion occurred at breakpoint A and 5-bp deletion occurred at breakpoint B (Fig. 3). The distance from breakpoint A to B was 298.6 kb, and we found a new mutant gene disrupted by breakpoint B (Fig. 3). Our findings suggest that we can identify new mutated gene from a mutation that is called an "unassigned breakpoint" by using Pindel. PCR analysis of "unassigned breakpoint" mutations generated in other mutants is in progress.

Fig. 2. Detecting an inversion generated in mutant-1. DNA amplification is detected by MCE-202 MultiNA (Shimadzu). The names of the genomic DNAs and primers are displayed above the gel image. DNA size markers are shown on the left side.

Fig. 3. Structure of inversion determined in this study. Thin arrows indicate the direction of the DNA. The gene disrupted by the inversion is shown as the yellow box.

References

*1 RIKEN Nishina Center

Fig. 1. Experimental design for detecting an inversion by PCR. Bold arrows indicate the annealing site of each primer. Thin arrows indicate the direction of the DNA. Boxes indicate chromosome.
Establishment of rice transformation systems to study gene functions

R. Morita,*1 K. Ichinose,*1 Y. Shirakawa,*1 and T. Abe*1

We have screened a large number of rice mutants induced by heavy-ion beam. To identify the causal gene for each mutant, a complementation test is needed. The complementation test is the experiment used to determine whether a gene is a causal gene for a mutant. The Recovery of a specific phenotype of a mutant is observed when an intact causal gene is introduced to a mutant (Fig. 1). To clarify the causal gene for the rice mutant of interest, we used a reliable Agrobacterium-mediated transformation system. In the Agrobacterium-mediated method, a DNA region termed "T-DNA" transfers from a circular DNA in Agrobacterium into plant chromosomes (Fig. 2). We introduce both the gene of interest and the marker gene for a selection reagent, such as antibiotics or herbicides, into the T-DNA region. Plant cells that have accepted T-DNA will only survive on a medium containing a selection reagent. The Agrobacterium-mediated method is a good means to obtain a transgenic plant with high efficiency and a low copy number.

For a pilot experiment, we introduced the hygromycin phosphotransferase (HPT) gene in rice. The HPT gene confers hygromycin-resistance to rice cells and is one of the most frequently used marker gene in transformation experiments of rice. We obtained more than 20 plantlets from the calluses induced from 100 rice seeds (Fig. 3).

The transformation efficiency of our experiment (over 20%) was equivalent to the efficiency reported by Toki et al. (2006). Using this technique, we will determine the causal gene for a rice mutant exhibiting an interesting phenotype.

Fig. 1. Complementation test performed in the study of a rice virescent mutant. The virescent mutant generates white leaves when they are grown at 20 °C (left). Mutant plants that contain T-DNA including the intact causal gene show green leaves under the same condition (right). Rice plants are grown in the Murashige and Skoog medium. Bar = 1 cm.

Fig. 2. Schematic representation of the Agrobacterium-mediated plant transformation system.

Fig. 3. Regenerated plant from the hygromycin-resistant callus. Bar = 1 cm.

References
Functional analysis of a new *virescent* mutant in rice induced by heavy-ion beam irradiation

H. Abe,*1 R. Morita,*1 S. Kogure,*1 K. Ichinose,*1 Y. Hayashi,*1 and T. Abe*1

It is evident that heavy-ion beam irradiation effectively produced many phenotypic mutants in rice (*Oryza sativa* L. cv. Nipponbare)1, 2; thus, the method has been applied to rice breeding as a new technology. Although many rice mutants have been isolated to date, the functions of a number of their causative genes have not been completely elucidated. One such mutant, 22-4Y in rice, has been obtained as a *virescent* mutant by irradiating seeds with a carbon-ion beam (20 Gy, LET: 22.5 keV/µm)3. *virescent* is a chlorotic mutant of higher plants that reduces the chlorophyll content in young leaves, but the chlorophyll content of the leaves recover as the plants grow4). Certain chlorophyll mutants in young leaves, but the chlorophyll content in young leaves, but the chlorophyll content of the leaves recover as the plants grow4). Certain classes of the *virescent* mutants are low-temperature conditional5; the 22-4Y mutant also shows chlorotic leaves phenotype when grown at 20 °C but not at 30 °C during the early growth stages5). As the 22-4Y functions are related with chlorophyll synthesis and/or chloroplast development, both of which are important for crop production, we decided to investigate the 22-4Y gene and to analyze its functions.

Genetic analysis of the 22-4Y mutant revealed that gene LOC_Os05g34040 on the long arm of chromosome 5 showed a deletion of 13095 bp3). Morita et al.3 confirmed by using a genetic complementation test that the causative gene of 22-4Y is LOC_Os05g34040.

In order to know the gene functions, in many cases, it is most important and necessary to reveal the functions of the protein encoding to the corresponding gene. BLAST searches of the complete *Oryza sativa* sequence revealed that only one copy of the 22-4Y gene is present in the nuclear genome, which encodes a putative polypeptide of 720 amino acids with a calculated molecular mass of 78.2 kDa (Fig.1, the upper line). Pfam search predicted that the 22-4Y protein had a putative conserved FAD/NAD(P)-binding motif (GXGXXG) (Fig.1, red bars) and a homology to pyridine nucleotide-disulfide oxidoreductase family enzymes (Fig1, green region). This means that 22-4Y is a new class of VIRECENT protein among so far identified6 (V1, chloroplast-localized RNA-binding protein; V2, guanylate kinase; V3, large subunit of ribonucleotide reductase). TargetP program predicted that the N-terminal 57 amino acids sequence of the 22-4Y protein was a chloroplast transit peptide. Actually, when the N-terminal 76 amino acids sequence of the 22-4Y protein was fused to cyan fluorescent protein (CFP) and transiently expressed in an onion epidermal cell, the fusion protein was localized to chloroplast. Thus, the N-terminal sequence of the 22-4Y protein was functional as a chloroplast targeting peptide. Electron microscopic observation revealed that chloroplast development was arrested when 22-4Y mutant was grown at 20 °C but not at 30 °C during the early growth stages. These results suggest that the 22-4Y protein was functional in chloroplast and had some important regulatory functions in chloroplast development.

To further reveal and analyze the protein function of 22-4Y, we decided to purify some recombinant proteins of 22-4Y by using an *E. coli* expression system (Fig. 1). It is important to demonstrate the enzymatic activity of the 22-4Y protein, as well as to identify the target (substrate) protein(s) to reveal the regulatory functions of the 22-4Y protein during chloroplast development.

Fig. 1. Schematic representation of the 22-4Y protein and its fragments expressed in *E. coli*.

The predicted 22-4Y protein (the upper line) has 720 amino acids (M1-Y720) with a calculated molecular mass of 78.2 kDa. Each fragment of 22-4Y(C58-Y720), (C58-R417), (D418-Y720), (C58-P239) and (R240-R417) is shown. Positions of the FAD/NAD(P)-binding motif (GXGXXG) are shown in red bars. A region with homology to pyridine nucleotide-disulfide oxidoreductase family enzymes is shown in green. The predicted chloroplast transit peptide is shown in dark blue.

References

*RIKEN Nishina Center*
Tracking alleles linked with Fusarium head blight resistance QTLs in wheat (Triticum aestivum) released in Kyushu region

S. Niwa,*1,*2 Y. Kazama,*1,*2 M. Alagu,*2 T. Abe,*1 and T. Ban*2

Fusarium head blight (FHB) is a plant disease occurring in small grains such as wheat, barley and maize. In Japan, the FHB of wheat is one of the most destructive diseases because of its coincidence with the flowering to grain-filling period of wheat which provides a fungus-favorable condition. In addition, FHB decreases the yield and the quality of wheat.

The Kyushu region is one of the main wheat production areas in Japan. After the FHB epidemics in 1963, an intensive breeding program for FHB resistance has been conducted in Kyushu as a national breeding program. Similar to the general breeding program, FHB resistance breeding has been performed by crossing a cultivar of interest with another resistant cultivar. Then, progenies having appropriate traits are selected. Through this process, feasible alleles (feasible one of a number of alternative forms of the same gene) would be selected, which implies that the alleles linked to loci related to an unfavorable agronomic trait may also be excluded. Because of the annual variation in rainfall, FHB disease pressure fluctuates, causing rendering the evaluation of FHB resistance lines laborious and uncertain. By investigating the alleles related to the FHB resistance through the breeding lineage, information on alleles contributing to the FHB resistance in the breeding program can be obtained.

As a first step, thirteen representative cultivars bred from 1920s to 2010s were selected. The seeds of the cultivars were sown on petri dishes and refrigerated at 4°C for four days; subsequently, they were germinated in a 25°C chamber. The germinated plantlets were transplanted to pots and grown in a glasshouse at 25°C. Leaves were harvested 18 days after sowing and used for DNA extraction. Of the 21 wheat chromosomes, DNA markers linked to the alleles related to FHB resistance were reported in the short arm of chromosomes 2D (2DS), long arm of 2D (2DL), 3BS, 5AS, and 6BS.1-4) By conducting PCR using these markers, types of alleles related to FHB resistance (resistant, susceptible, or other) in individual cultivars were determined. The fragment, after amplification with a DNA marker UMN10 at 3BS was analyzed by sequencing. The PCR products of the other markers were electrophoresed using MultiNA (Shimadzu, Kyoto, Japan).

The results are listed in Table 1. Resistant alleles on 3BS and 5AS were retained after ‘Shinchunaga’ was bred. The resistant allele on 2DL was fixed in the lineage after ‘AsakazeKomugi’ was bred. In contrast, resistant alleles on 2DS and 6BS were excluded from the lineage for cultivars released after the 1940s released cultivars, when ‘Shinchunaga’ had contributed as their frequent crossing parent. Interestingly, the susceptible alleles from ‘Shinchunaga’ had been selected for 2DS, and the resistance alleles on 6BS were selected alternatively from the counter parents of ‘Shinchunaga.’ It can be expected that some alleles responsible for unfavorable agronomic trait(s) on 6BS from ‘Shinchunaga’ may be linked to these regions. ‘Shinchunaga’ has favorable allele(s) such as rht8 that determines plant height and was selected even linked with the susceptible allele for FHB. In the same manner, other alleles detected in modern cultivars might contribute to FHB resistance rather than the ones detected in old cultivars as new linkage disequilibrium. Further investigation of the alleles related to FHB resistance in every generation of lineages is in progress.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Types of FHB resistance-related alleles in Kyushu lineages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release</td>
<td>Cultivar</td>
</tr>
<tr>
<td>year</td>
<td></td>
</tr>
<tr>
<td>1923</td>
<td>Eshimashinriki</td>
</tr>
<tr>
<td>1931</td>
<td>Norin 5</td>
</tr>
<tr>
<td>1933</td>
<td>Shinchunaga</td>
</tr>
<tr>
<td>1936</td>
<td>Norin 20</td>
</tr>
<tr>
<td>1943</td>
<td>Norin 52</td>
</tr>
<tr>
<td>1956</td>
<td>Shirasagikomugi</td>
</tr>
<tr>
<td>1957</td>
<td>Junreikomugi</td>
</tr>
<tr>
<td>1978</td>
<td>AsakazeKomugi</td>
</tr>
<tr>
<td>1986</td>
<td>Wheat Norin PL-4</td>
</tr>
<tr>
<td>1986</td>
<td>Sakai 165</td>
</tr>
<tr>
<td>1994</td>
<td>Chikugoizumi</td>
</tr>
<tr>
<td>2006</td>
<td>Towaizumi</td>
</tr>
<tr>
<td>2011</td>
<td>Wheat Norin PL-9</td>
</tr>
</tbody>
</table>

R: resistant allele, S: susceptible allele, o: other allele (resistant type unknown), nd: not determined

References
Ion track observation in cell nucleus irradiated by 3 MeV He ion microbeams produced with glass capillaries

T. Ikeda,*1 M. Izumi,*1 V. Mäckel,*2 T. Kobayashi,*2 R. J. Bereczky,*1 T. Hirano,*1 Y. Yamazaki,*2 and T. Abe*1

Microbeam irradiation of cultured single cells using tapered glass capillaries with outlet diameters of the order of 1 μm has been performed employing RIKEN Pelletron accelerator. Apparatus with a 3-μm outlet diameter is reported in elsewhere1). Microbeam is a unique scheme that can actively select an irradiation volume of ~μm³. When a microbeam of He ions of a few MeV hits a target, e.g., a biological cell, the ions will stop at the depth corresponding to their range (10–20 μm). Any other parts downstream of the stopping volume will not be damaged. This is one of advantages of employing beams of a few MeV. The glass capillaries with thin end-windows play an important role in delivering the ions directly to the cells in solution.

At RIKEN, we have developed a unique technology for mutation breeding using high-energy heavy-ion beams from RIKEN Ring Cyclotron. Such high linear energy transfer (LET) ions produce clustered DNA damage that cannot be repaired by the cell itself, leading to cell death, or can only be repaired incompletely by the cell, which induces mutations. In order to investigate both the lethality and the effectiveness of mutation induction, the position selectivity of the microbeam will be needed because hitting of different parts may cause unwanted effect. Here we demonstrate the DNA damages along ion tracks in a cell nucleus using a microbeam with relatively high LET.

A 3-MeV He ion microbeam was used for the irradiation of the nucleus of human cells (HeLa cells) because it is known that there is a similarity in the radiation response between plant and animal cells. The ions were generated by the Pelletron and transported to the cell irradiation port1). A 5-cm-long glass capillary optics with a 4-μm-thick end-window whose diameter was 3 μm and with an inlet diameter of 0.8 mm was installed at the beam port with an angle of 45° with respect to the horizontal plane so that widely-used petri dish filled with liquid solution can be exposed. The LET of a 3-MeV He ion is 150 keV/μm in water. The range of the ions is only 12 μm in water after the end-window. In order to adjust the dose of the irradiation to each cell, a beam chopper consisting of an electrostatic beam deflector was employed so that a few to ten ions were included in a short pulse of 0.8 μs. The pulse was repeated 100-1000 times according to the number of the required ions to the target.

It took approximately 12 min to irradiate about 40 cells in one dish, and totally 168 cells in 4 dishes were irradiated. After the irradiation, the Double Strand Breaks (DSBs) at DNAs were fluorescent-labeled as follows. The time for the repair process based on an enzymatic reaction was 20 min after the irradiation, and then the cells were washed three times with ice-cold phosphate-buffered saline (PBS) and fixed with 4% formaldehyde in PBS at 4°C for 20 min. Then, the cells were permeabilized with 0.5% Nonidet P-40 in PBS at 4°C for 5 min, and phosphorylated histone H2AX was detected by using rabbit antibody (Millipore) and an Alexa488-conjugated donkey anti-rabbit IgG (Jackson ImmunoResearch Laboratories).

Figures 1(a) and (b) are the cross-sectional and bottom views of the irradiated cells, respectively, reconstructed from the photos taken by changing the focus position along the z-axis (vertical axis). Cell nuclei are identified as bean-shaped blue regions with a width of ~15 μm and have fluorescence from a stain DAPI binding to A-T rich regions in DNA. The outlines of the cells are not seen. The DSBs are detected as bright points with green color from Alexa488. Even without irradiation, DSBs can take place as an activity of a living cell. However, the concentration of DSB bright points along a line is an evidence of artificial lesion. The ion track with the angle of 45° is clearly seen as a fluorescent line in Fig. 1(a). We succeeded in observation of a visible track for MeV ions inside a cell nucleus. It is confirmed that MeV-ion irradiation made DSB lesions in the DNA, which may cause gene defects. Further experiments considering other conditions, e.g., LET, control of cell cycle, and so on are needed as well as the number of ions necessary to form a track.

Fig. 1. Fluorescent lines corresponding to the ion track in a human cell nucleus. (a) Cross-sectional view of the irradiated cells at the horizontal line in the bottom view. (b) Bottom view of the cell.

References

*1 RIKEN Nishina Center
*2 Atomic Physics Laboratory, RIKEN
Estimation method of microbeam divergence from glass capillaries for biological use

R.J. Bereczky,*1 T. Ikeda,*1 T. Kobayashi,*2 M. Utsugi,*3,1 T. Hirano,*4,1 Y. Sakai,*1 and T. Abe*1

Ion microbeams can be used in various fields such as basic research, or for many different technical applications such as in radiobiology. When an ion beam with energy on the order of megaelectron volts is transmitted through a tapered glass microcapillary, the extracted beam can be used as an ion microbeam for cell irradiation. Moreover, the ions can be directly guided to the cell using a capillary with a thin-end window. At RIKEN, we have developed a unique technology for mutation breeding using high-energy heavy-ion beams. Heavy-ion beams at relatively low doses induce mutations at a high rate without severely inhibiting growth. Densely ionizing radiation produces clusters of DNA damage that cannot be repaired by the cell, leading to cell death, or can only be repaired incompletely by the cell, which induces mutations. The effects of heavy-ion beams on both the lethality and effectiveness of mutation induction should be investigated in more detail in future studies. An ion microbeam is a useful tool for DNA damage or repair process research. The regions relevant to mutations in a living cell are not distributed uniformly, but concentrated into a small region. A well-defined microbeam is required to irradiate these small regions.

The purpose of our work is the development of microbeam irradiation for human cells, in which it is easy to observe DNA damages. Through these investigations, we provide an estimation method to define the beam divergence in a tapered glass capillary. Our studies have been performed both experimentally and theoretically. In the case of thinner capillaries, i.e., on the order of 1 micron, the divergence of the transmitted beam has been investigated, and similar experiments with a 200 μm diameter capillary without a thin end-window were also reported3). No study has yet reported on capillaries with outlet diameters in the 10 μm range and with thin end-windows, a size at which the application for cell irradiation is not obvious anymore.

The result of our first SRIM simulations2) showed discrepancy from the experimental ones (see procedure below). When we changed the divergence of the beam inside the capillary from 0 to a nonzero value, i.e., 2.5°, the results of the simulation and the experiment were in good agreement (Fig. 1).

We measured the beam distribution extracted in air as a function of the distance between the exit of the capillary and a piece of CR-39, using He ions with the energy of 4.5 MeV produced by the RIKEN pelletron accelerator.

The ions were transmitted through a tapered glass capillary (pulled from injection needle), set at the end of the beam line.

The inlet diameter of the capillary was 800 μm, the outlet diameter was 4 μm, and it had a thin end-window made of plastic with a thickness of 8 μm9). The length of the capillary was ~ 65 mm. The profile of the extracted beam was measured with CR-39 (Fig. 2). The average rate of the ions was 14 counts/s during the measurement. To avoid the overlap of the ion tracks on the CR-39 surface, the number of transmitted ions was chosen once as 200, and as 600 in the other cases.

Further systematic studies will be performed in the near future that will contribute to the development of microbeam irradiation of human cells.

Fig.1. Comparison of the beam profile of the experiments (black) and SRIM simulations (orange). The horizontal axis shows the distance of the ion tracks from the center of the beam. The values of the beam divergence inside the capillary are shown in each figures. The distance between the exit of the capillary and the CR-39 was 6 mm.

Fig.2. Profile of the extracted beam, when the distance between the exit of the capillary and the CR-39 was 2 mm. The scale corresponds to 50 μm.

References
2) SRIM-2013: http://www.srim.org/.
Fricke nanocomposite gel dosimeter for heavy ion beam irradiation

T. Maeyama,*1 N. Fukunishi,*1 K. L. Ishikawa,*1,2 K. Fukasaku,*3,4 and S. Fukuda*5

In advanced radiotherapy with energetic heavy ions such as pencil beam scanning treatment, a very complex dose distribution is applied to a desired target volume. A real 3D verification dosimeter is needed. Gel dosimetry has been proposed as a possible method for the 3D verification dosimeter in radiotherapy. One drawback of gel dosimetry is the decrease in radiation detection sensitivity with the increase in linear energy transfer (LET), which hinders absolute dose determination when used for ion beams. Thus, we have started developing new nanocomposite gel dosimeters based on the liquid radiation chemical dosimeter and diffusion suppression technique using adsorption properties of nano-clay. In our previous report, we presented the nanocomposite dichromate gel dosimeter with radiation-induced reduction reactions, which showed sensitivity degradation with increase in LET. On the other hand, nanocomposite Fricke gel (NC-FG) with radiation-induced oxidation reactions exhibited the response almost independent of LET. These observations indicated a different LET dependence from that of the liquid radiation chemistry study, and therefore, more detail investigations were required. In this study, detailed radiological properties of NC-FG under various preparation conditions were investigated under argon and carbon beam irradiation covering an LET range from 10 to 3000 eV/nm. Details of the chemical compositions of gel dosimeters are summarized in Table 1. Irradiations were performed with 290 MeV/nucleon $^{12}$C$^{6+}$ or 500 MeV/nucleon $^{40}$Ar$^{18+}$ ion beams accelerated by the HIMAC. Measurements of the relaxation rates ($R_1 = 1/T_1$) were performed using a 1.5-T MRI (Philips).

Figures 1(a) and 1(b) show the $R_1$ ($1/T_1$) distributions measured for the normal NC-FG sample (composition was 1 wt% Laponite, 3 wt% gelatin, 1 mM ammonium iron (II) sulfate, and 50 mM perchloric acid, as shown in our previous report) irradiated with 290 MeV/nucleon carbon ion beams and 500 MeV/nucleon argon ion beams, respectively. The dose dependence of $R_1$ near the entrance surface (square symbol, 5 mm depth) and near the Bragg Peak (circle symbol, 79 mm for carbon beam, 105 mm for argon beam) was shown in Figs. 1(c) and 1(d). Although the peak positions of each irradiated sample was adjusted within 1 pixel of the MRI resolution (0.78 mm) to ensure overlapping, a good linearity was confirmed at every position. The rate of $R_1$ incensement per unit of entrance surface dose was calculated and is plotted in Figs. 1(e) and 1(f) to compare it with the dose distribution obtained by the ionization chamber (right vertical axis in Fig. 1). The $\delta R_1$ distribution of NC-FG faithfully reproduces the dose distribution including the peak of argon ion beam. Surprisingly, the radiation sensitivity of NC-FG does not change even at very high LET (3000 eV/nm) at the Bragg peak region of argon ion beam. This is a unique property because all gel and solid type dosimeters such as film, scintillation, and semiconductor dosimeters have LET dependence.

By varying the concentration of the nano-clay, Fe$^{2+}$ and perchloric acid from the standard composition described in our previous report, we have obtained the following features.

1. NC-FG works not only in an acidic, but also in a neutral condition.
2. The concentration of ferrous ions affects radiation sensitivity.
3. Radiation sensitivity is lost at nano-clay concentration below 0.1 wt%.

The first two features were completely different from those of conventional Fricke gel dosimeters. The third feature suggested that nano-clay in NC-FG is essential for radiation induced reactions, and that ferrous ions oxidize by a new mechanism that completely different from the previous one.

Table 1 Chemical composition.

<table>
<thead>
<tr>
<th>Gelatin</th>
<th>Laponite</th>
<th>HClO$_4$</th>
<th>Fe$^{2+}$</th>
<th>Degassing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 wt%</td>
<td>0.1 – 1 wt%</td>
<td>0 - 150 mM</td>
<td>0.2 - 5 mM</td>
<td>Ar</td>
</tr>
</tbody>
</table>

Fig. 1. Dose dependence of $R_1$ distribution with different ion beam irradiation.

References

*1 RIKEN Nishina Center
*2 Dept. of Nucl. Eng. & Management, Grad. Sch. Eng., Univ. of Tokyo
*3 RIKEN Advanced Center for Computing and Communication
*4 Dept. of neurosurgery, Himon'ya Hospital
*5 NIRS Research Center for Charged Particle Therapy
IV. OPERATION RECORDS
Program Advisory Committee meetings for nuclear physics and for material and life science


The Program Advisory Committees (PAC) is in charge of reviewing scientific proposals submitted for use of the accelerator facility of RIKEN Nishina Center (RNC). In Fiscal Year 2014, three PAC meetings were held; two for proposals of nuclear physics (NP-PAC), and one for proposals of material and life science (ML-PAC). The NP-PAC meetings were co-organized by RNC and the Center for Nuclear Study (CNS), the University of Tokyo. The NP-PAC reviewed experimental proposals at RIBF, whereas the ML-PAC reviewed proposals at Rutherford Appleton Laboratory (RAL) and RIBF.

NP-PAC

The 14th and 15th NP-PAC meetings were held on June 27 and 28, 2014, and December 12 and 13, 2014, respectively1). In the 14th (15th) NP-PAC meeting, 23 (20) proposals were reviewed, and 11 (14) proposals were approved as grade S or A. The outcome of these NP-PAC meetings is summarized in Table 1.

Before the 14th NP-PAC meeting, one of the PAC members resigned, and no new member was added. Consequently, the number of the PAC members became sixteen.

The PAC members of the 14th and 15th NP-PAC meetings are as follows:
M.N. Harakeh (KVI, the chair), R.F. Casten (Yale Univ.), H. Emling (GSI), H. Iwasaki (Michigan State Univ.), W. Loveland (Oregon State Univ.), S. Nakamura (Tohoku Univ.), T. Nakatsukasa (RNC), T. Nilsson (Chalmers Univ. of Technology), C. Scheidenberger (GSI), B. Sherrill (FRIB Lab.), O. Sorlin (GANIL), A. Tamii (RCNP, Osaka Univ.), F.-K. Thielemann (Univ. of Basel), Y. Utsuno (JAEA), M. Yahiro (Kyushu Univ.), and Y. Ye (Peking Univ.).

ML-PAC

The 11th ML-PAC meeting was held on January 8 and 9, 20152). In this meeting, 31 RAL proposals and 8 RIBF proposals were reviewed. The summary of the outcome of the meeting is given in Table 2.

The 11th ML-PAC members are as follows:
J.-M. Poutissou (TRIUMF, the chair), A. Amato (PSI), T. Azuma (RIKEN), A. Hiller (ISIS, RAL), R. Kadono (KEK), A. Kawamoto (Hokkaido Univ.), N. Kojima (Univ. of Tokyo), H. Yamase (NIMS), S. Yoshida (Thera Projects Associates), and X.G. Zheng (Saga Univ.).

Table 1. Summary of the outcome of the 14th and 15th NP-PAC meetings. The proposals ranked with S and A are treated as the "approved" proposals.

<table>
<thead>
<tr>
<th></th>
<th>requested proposals (days)</th>
<th>approved proposals (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14th NP-PAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GARIS (RILAC)</td>
<td>1 (26)</td>
<td>1 (26)</td>
</tr>
<tr>
<td>CRIB (AVF)</td>
<td>3 (37)</td>
<td>1 (18)</td>
</tr>
<tr>
<td>RIPS (RRC)</td>
<td>3 (38)</td>
<td>3 (16.5)</td>
</tr>
<tr>
<td>BigRIPS/ZDS</td>
<td>9 (88)</td>
<td>3 (20.5)</td>
</tr>
<tr>
<td>SHARAQ</td>
<td>1 (5.5)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>SAMURAI</td>
<td>6 (50.5)</td>
<td>3 (21)</td>
</tr>
<tr>
<td>Construction</td>
<td>0 (-)</td>
<td>0 (-)</td>
</tr>
<tr>
<td>Total</td>
<td>23 (245)</td>
<td>11 (102)</td>
</tr>
<tr>
<td>15th NP-PAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GARIS (RILAC)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>CRIB (AVF)</td>
<td>3 (19.333)</td>
<td>3 (19.333)</td>
</tr>
<tr>
<td>RIPS (RRC)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>BigRIPS/ZDS</td>
<td>12 (91.5)</td>
<td>7 (34)</td>
</tr>
<tr>
<td>SHARAQ</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>SAMURAI</td>
<td>5 (40.5)</td>
<td>4 (12.5)</td>
</tr>
<tr>
<td>Construction</td>
<td>0 (-)</td>
<td>0 (-)</td>
</tr>
<tr>
<td>Total</td>
<td>20 (151.333)</td>
<td>14 (65.833)</td>
</tr>
</tbody>
</table>

Table 2. Summary of the outcome of the 11th ML-PAC meeting.

<table>
<thead>
<tr>
<th></th>
<th>requested proposals (days)</th>
<th>approved proposals (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11th ML-PAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAL</td>
<td>31 (208)</td>
<td>30 (123)</td>
</tr>
<tr>
<td>RIBF</td>
<td>8 (66)</td>
<td>7 (50)</td>
</tr>
<tr>
<td>Total</td>
<td>39 (274)</td>
<td>37 (173)</td>
</tr>
</tbody>
</table>

References
1) http://www.nishina.riken.jp/RIBF/NP-PAC/index.html
2) http://www.nishina.riken.jp/RIBF/ML-PAC/index.html

*1 RIKEN Nishina Center
*2 Center for Nuclear Study, the University of Tokyo


(RAL) and RIBF.

ML-PAC

The 11th ML-PAC meeting was held on January 8 and 9, 20152). In this meeting, 31 RAL proposals and 8 RIBF proposals were reviewed. The summary of the outcome of the meeting is given in Table 2.

The 11th ML-PAC members are as follows:
J.-M. Poutissou (TRIUMF, the chair), A. Amato (PSI), T. Azuma (RIKEN), A. Hiller (ISIS, RAL), R. Kadono (KEK), A. Kawamoto (Hokkaido Univ.), N. Kojima (Univ. of Tokyo), H. Yamase (NIMS), S. Yoshida (Thera Projects Associates), and X.G. Zheng (Saga Univ.).

References
1) http://www.nishina.riken.jp/RIBF/NP-PAC/index.html
2) http://www.nishina.riken.jp/RIBF/ML-PAC/index.html

(RAL) and RIBF.

ML-PAC

The 11th ML-PAC meeting was held on January 8 and 9, 20152). In this meeting, 31 RAL proposals and 8 RIBF proposals were reviewed. The summary of the outcome of the meeting is given in Table 2.

The 11th ML-PAC members are as follows:
J.-M. Poutissou (TRIUMF, the chair), A. Amato (PSI), T. Azuma (RIKEN), A. Hiller (ISIS, RAL), R. Kadono (KEK), A. Kawamoto (Hokkaido Univ.), N. Kojima (Univ. of Tokyo), H. Yamase (NIMS), S. Yoshida (Thera Projects Associates), and X.G. Zheng (Saga Univ.).

References
1) http://www.nishina.riken.jp/RIBF/NP-PAC/index.html
2) http://www.nishina.riken.jp/RIBF/ML-PAC/index.html

(RAL) and RIBF.

ML-PAC

The 11th ML-PAC meeting was held on January 8 and 9, 20152). In this meeting, 31 RAL proposals and 8 RIBF proposals were reviewed. The summary of the outcome of the meeting is given in Table 2.

The 11th ML-PAC members are as follows:
J.-M. Poutissou (TRIUMF, the chair), A. Amato (PSI), T. Azuma (RIKEN), A. Hiller (ISIS, RAL), R. Kadono (KEK), A. Kawamoto (Hokkaido Univ.), N. Kojima (Univ. of Tokyo), H. Yamase (NIMS), S. Yoshida (Thera Projects Associates), and X.G. Zheng (Saga Univ.).

References
1) http://www.nishina.riken.jp/RIBF/NP-PAC/index.html
2) http://www.nishina.riken.jp/RIBF/ML-PAC/index.html
This report describes the statistics of the beam times (BTs) at the RIBF facility in Fiscal Year (FY) 2014. In the following, the BTs are categorized into two groups: high-energy-mode and low-energy-mode BTs. In the former mode, the beams were delivered in the acceleration scheme of AVF, RILAC, or RILAC2 → RRC → (fRC → IRC →) SRC, where the accelerators in parentheses can be skipped in the cascade acceleration, depending on the beam species used. In the latter mode, the acceleration scheme is AVF or RILAC (→ RRC).

BTs in the high-energy mode were scheduled from April to July, from October to December 2014, and in the latter half of March 2015, considering the restriction of utility-power use, budgetary constraints, maintenance schedule of the accelerator system and co-generation system, as well as other constraints. In the series of experiments in spring, the primary beams of $^{238}\text{U}$, $^{70}\text{Zn}$, $^{2}\text{H}$, and $^{16}\text{O}$ were provided to users, and in the autumn series, the primary beams of $^{238}\text{U}$ and $^{48}\text{Ca}$ were provided. The beam time in March 2015 was used only for the nuclear transmutation program which was carried out as a Nishina Center mission program, i.e. as an experiment other than what the RIBF Program Advisory Committees$^1$ (PAC) was approved. 13 experiments approved by the PAC with the approved beam time of 70.4 days were conducted in total. 7.3 days were used for the facility development programs, defined as machine study (MS) experiments. Other than these, three new isotope search experiments and two transmutation experiments were conducted as the Nishina Center mission programs.

The data summary of the high-energy-mode BTs in FY2014 is given in Fig. 1 as a bar chart. Compared to the beam time in FY2013, the user time increased, as the beam time operation in FY2013 was in spring only. Including the Nishina Center mission beam time, the total amount of beam time available in FY2014 was recovered to the level of FY2012.

The data summary for the low-energy mode is shown in Fig. 2. Here the BTs are classified by the accelerator operation modes, AVF, RILAC, and RRC. In FY2014, most of the low-energy-mode experiments after December had to be cancelled, due to the restriction of the operation budget. Despite of this cancellation, the total amount was almost the same as in FY2013. The fraction of the RILAC stand-alone beam time increased, as a long experiment approved as the S grade was conducted.

References

$^1$ RIKEN Nishina Center
Operation report of the industrial cooperation team

A. Yoshida,∗1 T. Kambara,∗1 H. Takeichi,∗1 H. Haba,∗1 S. Shibata,∗1 K. Takahashi,∗1 S. Yanou,∗2 and Y. Wakitani∗2

In 2014, the industrial cooperation team was engaged in collaboration research for industrial application of RI beam, fee-based utilization of heavy-ion beams to industry, and fee-based distribution of radioisotopes. These activities are summarized below.

Under a collaborative research agreement entitled “Development and application of wear diagnosis method with RI beams” between RIKEN, University of Tokyo, and two private companies, we develop a method for wear diagnostics of industrial materials using RI beams as tracers. Compared with conventional methods where tracer RIs are produced in the materials by ion-beam irradiations, our method employs RI beam implantation for the materials, which results in less radiation damage in the materials. We had two beamtimes, IC13-01-01 in February and IC13-01-02 in March 2014, at E7A beamline of the AVF cyclotron. Beams of RI nuclei 7Be (T1/2 = 53 days) with intensities up to 10⁸ ions/s and 22Na (T1/2 = 2.6 years) with intensities up to 10⁷ ions/s were provided by CNS RI beam separator (CRIB) and implanted near the surface of metallic machine parts, whose wear-loss was evaluated through radioactivity measurements. Another article in this report describes technical details on the preparation and characterization of the RI beams. 13 Concerning this research, two patents have been applied for.2)

RIKEN Nishina Center opened the AVF cyclotron, RILAC, and RIKEN Ring Cyclotron (RRC) for industrial utilisations.3) The first proposal of fee-based utilization was submitted by private companies in June and was reviewed and approved by the Industrial Program Advisory Committee (InPAC) in August (proposal number IC14-01). The beamtime was performed in October with a 70-MeV/A 84Kr beam at the E5A beamline of the RIKEN Ring Cyclotron. Another article in this report describes technical details of the beam preparation and characterization according to the customers’ requests.4)

Since 2007, RIKEN distributes radioisotopes (RIs) produced at RIBF to users in Japan for a fee in collaboration with the Japan Radioisotope Association5) (JRIA). According to a material transfer agreement (MTA) drawn between JRIA and RIKEN, JRIA mediates the transaction of the RIs and distributes them to users. The distributed RIs are 65Zn (T1/2 = 244 days), 109Cd (T1/2 = 463 days), and 88Y (T1/2 = 107 days). The RIs are produced by the RI Applications Team at the AVF cyclotron. 65Zn, 109Cd, and 88Y are produced with a 24-MeV deuteron beam through 64Cu(d,2n)65Zn, 109Ag(d,2n)109Cd, and 238U(d,xn)88Y reactions, respectively.

In 2014, we delivered three shipments of 109Cd with a total activity of 22 MBq, seven shipments of 65Zn with a total activity of 44 MBq, and one shipment of 88Y with an activity of 1 MBq. The final recipients of the RIs were five universities, one research institute, and two hospitals. Figure 1 shows the yearly trends in the number of orders and the amounts of the distributed RIs.

Fig. 1. Number of orders (left) and amount (right) of the RIs distributed yearly from 2007 to 2014. The distribution of 88Y started in 2010.

Information on the RIs can be obtained from JRIA through their dedicated website (https://www.j-ram.net/jram/DispatchTopPage.do; in Japanese) or FAX (03-5395-8055).

References
1) A. Yoshida et al.: in this report.
4) T. Kambara et al.: in this report.
5) http://www.jrias.or.jp/ (Japanese),
   http://www.jrias.or.jp/e/ (English).

∗1 RIKEN Nishina Center
∗2 Japan Radioisotope Association
Electric power condition of Wako campus in 2014

E. Ikezawa, *1 M. Kato, *1 H. Yamazawa, *1 and M. Kase*1

The monthly electrical power consumption data for RIKEN Wako campus (Wako) and RIKEN Nishina Center (RNC), and the energy supply by the cogeneration systems (CGSs) are shown in Fig. 1. The hourly average electrical power consumption at RNC for each day in 2014 is shown in Fig. 2. The annual data of electrical power consumption and energy supply in 2014 is listed in Table 1. The total electrical power consumption of Wako in 2014 was 157,943 MWh, which was 10% higher than that in 2013. On the other hand, the total electrical power consumption of RNC in 2014 was 72,724 MWh, which was 30% higher than that in 2013. When the RI Beam Factory (RIBF) experiments using the uranium (238U) beam were conducted, the maximum electrical power supply to Wako from Tokyo electric power corporation (TEPCO) reached 22.0 MW with a CGS output of 3.5 MW on April 9, 2014, whereas the maximum electrical power consumption of RNC reached 17.1 MW on October 21, 2014.

A complete overhaul of the gas turbine of the CGS #1 after 8,000 h of operation was carried out in September 2014. We experienced the following problems during the reporting period. The CGS #1 stopped on May 25, 2014, and again, on October 21, 2014, because of control equipment failure. We had an interruption in power supply on February 15, 2014, due to a snow storm. Earth leakages also occurred 9 times. However, the origin of most of those leakages were unexplained.

Table 1 Annual data of electrical power consumption and energy supply in 2014.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Unit</th>
<th>Note</th>
<th>% of 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wako purchase</td>
<td>139,851</td>
<td>MWh</td>
<td>Total electrical power supply to Wako from TEPCO</td>
<td>111%</td>
</tr>
<tr>
<td>Wako consumption</td>
<td>157,943</td>
<td>MWh</td>
<td>Wako electrical power consumption (CGSs + TEPCO)</td>
<td>110%</td>
</tr>
<tr>
<td>RNC purchase</td>
<td>59,319</td>
<td>MWh</td>
<td>Total electrical power supply to RNC from TEPCO</td>
<td>137%</td>
</tr>
<tr>
<td>CGS #1</td>
<td>13,405</td>
<td>MWh</td>
<td>CGS #1 total electrical power output</td>
<td>107%</td>
</tr>
<tr>
<td>RNC consumption</td>
<td>72,724</td>
<td>MWh</td>
<td>RNC total electrical power consumption</td>
<td>130%</td>
</tr>
</tbody>
</table>

*1 RIKEN Nishina Center
Radiation safety management at RIBF

K. Tanaka,*1 Y. Uwamino,*1 H. Sakamoto,*1 R. Hirunuma-Higurashi,*1 H. Mukai,*2 A. Akashio,*1 T. Okayasu,*1 R. Suzuki,*3 M. Takekoshi,*3 Y. Yamauchi,*3 S. Fujita,*1 H. Aiso,*1 K. Igarashi,*1 S. Iizuka,*1 and N. Usudate*1

Residual radioactivity at the cyclotron deflectors was measured just before maintenance works were carried out in the summer of 2014. The same measurement has been performed regularly since 1986, and the variations in the dose rates are shown in Fig. 1. Considering that the dose rate depends on the beam intensity and the cooling time, the trend has not changed considerably since 2006, when RIBF operation started.

The residual radioactivity was measured along the beam lines after almost every experiment. Points 1–26, marked with solid circles in Fig. 2, are locations where high-residual dose rates were usually observed. Table 1 lists these dose rates and the measurement dates, beam conditions, and the decay periods after the end of operation. The conditions for the data are chosen to be maximum doses among the measured data at each points. The maximum dose rate was found to be 17 mSv/h at point 13, which is the neighbor of the G01 Faraday cup.

We continuously monitor the radiation in and around the RIBF facility by using neutron and gamma area monitors. In 2014, the annual dose at the site boundary were less than the detection limit of the monitors after background correction. The neutron dose had been lower than the detection limit of 2 µSv/y and the γ-ray dose had been lower than the detection limit of 8 µSv/y. Therefore, the annual total dose in 2014 was less than 10 µSv/y, which was considerably lower than the legal limit of 1 mSv/y.

Fig. 1. Dose rates of residual radioactivity at the deflectors of five cyclotrons.

Fig. 2. Layout of beam lines at RIBF. Locations listed in Table 1 are indicated. G01, the target, and D1 magnet are also shown.

*1 RIKEN Nishina Center
*2 Japan Environment Research Corporation
*3 Daiwa Atomic Engineering Corporation
The dose rates at the radiation-controlled area in 2014 have been monitored. Three monitors are placed at the boundary of the radiation-controlled area. One is in the computer room of the Nishina building, and the other two are on the roofs of the IRC and BigRIPS. The highest observed value was 142 $\mu$Sv/y at the IRC roof as a result of beam loss at the transport line between SRC and BigRIPS. Figure 3 shows the annual neutron dose at these locations since 1999. These were considerably lower than the legal limit of 1.3 mSv/3 month. The dose on the BigRIPS roof was below the detection limit of 3 $\mu$Sv/y for neutrons.

The water in closed cooling systems at BigRIPS was sampled after the 2014 operation of RIBF. A 345-MeV/u 20 particle nA, on average, $^{238}$U beam was provided during April and May, and during October and November. A $^{70}$Zn 75 particle nA was provided in May and June. A 400 particle nA $^{48}$Ca beam was in November and December. Radionuclide concentrations were measured by using a liquid-scintillation counter and a Ge detector to compare them with the legal limit. The results are shown in Table 2. After operation with the intense $^{48}$Ca beam, the summation of the ratios of the concentrations to the legal limits for the drain water of all the radionuclides at the BigRIPS became approximately 1/4, and the water was transferred into the drain tank before the next operation. This is to prevent contamination of the room in case of a water leakage. The water in the drain tank, which contains drain water from other places, is released after the concentration of radionuclides is confirmed to be lower than the legal limit. This water circulates in the closed system with ion exchange resins. Thus, the nuclides in waters listed in Table 2, with the exception of tritium, are already filtered values. However, tritium accumulates in the water because the nuclide has a long half life of 12.3 year and is difficult to remove with filters. At the measurement before beam irradiation in 2014, the concentration of tritium in water in all systems was approximately 3 Bq/cm$^3$.

In 2014, the primary beam mode was newly mounted on the safety management system of RIBF by considering the high radiation dose risk due to the intense beam. The target intensity of the primary beam in RIBF is $6 \times 10^{12}$ particle/second on the production target of BigRIPS. Then, a secondary beam of low intensity is generated via a nuclear reaction and separation through BigRIPS. However, in the experimental rooms located downward from BigRIPS, the permitted beam intensity is $10^7$ particle/second both for primary and secondary beams. In RIBF operation, faint primary beams are sometimes derived to the experimental rooms directly. If intense primary beams more than the permission derived to the experimental rooms owing to accelerator trouble etc., the interlock system work in a moment and stop the beam automatically. However, a delay of few seconds is necessary before a beam is stopped by the interlock system operation. There may be a serious risk of radiation exposure to workers even in the neighbor rooms that are outside the irradiated area. Therefore, the safety...
management system was improved to inhibit the unexpected radiation exposure.

The primary beam mode in the radiation control system affects the restriction area, accelerator operation, and beam transport operation. When the primary beam mode is started, the entry-forbidden area is first expanded to the neighbor experimental rooms of the beam delivered area. Secondly, a combination of the attenuation devices of the accelerator, which control the beam intensity, is limited to regulate the beam intensity less than permitted limit. Additionally, while the primary beam mode is off, the magnetic field of the D1 magnet of BigRIPS, which determines whether the primary or secondary beam is transported to the experimental rooms, is always monitored. Moreover, if the value corresponds to a primary beam transportation, the safety management system does not permit beam irradiation until the primary beam mode is on, which means no-entry allowed to the neighbor experimental rooms. With these improvements, radiation exposure risk due to unexpected intense beams is mitigated.

<table>
<thead>
<tr>
<th>Cooling water</th>
<th>Nuclide</th>
<th>Concentration[a] (Bq/cm³)</th>
<th>Limit[b] (Bq/cm³)</th>
<th>Ratio to limit [a/b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BigRIPS F0 target</td>
<td>H-3</td>
<td>14</td>
<td>60</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Be-7</td>
<td>1.5e-3</td>
<td>30</td>
<td>4.9e-3</td>
</tr>
<tr>
<td></td>
<td>Co-58</td>
<td>8.2e-4</td>
<td>1</td>
<td>8.2e-4</td>
</tr>
<tr>
<td></td>
<td>Mn-54</td>
<td>6.4e-4</td>
<td>1</td>
<td>6.4e-4</td>
</tr>
<tr>
<td>summation</td>
<td></td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>BigRIPS exit beam dump</td>
<td>H-3</td>
<td>12</td>
<td>60</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Be-7</td>
<td>1.7e-2</td>
<td>30</td>
<td>5.7e-4</td>
</tr>
<tr>
<td></td>
<td>Co-57</td>
<td>1.2e-3</td>
<td>4</td>
<td>2.9e-4</td>
</tr>
<tr>
<td></td>
<td>Co-58</td>
<td>3.7e-3</td>
<td>1</td>
<td>3.7e-3</td>
</tr>
<tr>
<td></td>
<td>Mn-54</td>
<td>9.7e-4</td>
<td>1</td>
<td>9.7e-4</td>
</tr>
<tr>
<td>summation</td>
<td></td>
<td></td>
<td></td>
<td>0.21</td>
</tr>
<tr>
<td>BigRIPS side-wall beam dump</td>
<td>H-3</td>
<td>11</td>
<td>60</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Be-7</td>
<td>0.14</td>
<td>30</td>
<td>4.7e-3</td>
</tr>
<tr>
<td></td>
<td>Co-58</td>
<td>1.3e-3</td>
<td>1</td>
<td>1.3e-3</td>
</tr>
<tr>
<td>summation</td>
<td></td>
<td></td>
<td></td>
<td>0.19</td>
</tr>
</tbody>
</table>

1) read as 4.9×10⁻³
The RIKEN heavy-ion linac (RILAC) has operated steadily throughout the reporting period and has supplied various ion beams for different experiments. Some statistics regarding the RILAC operation from January 1 to December 31, 2014, are given in Table 1. The total beam service time of the RILAC accounted for 84.5% of its operation time. The two operation modes of the RILAC, the standalone mode and the injection mode, in which the beam is injected into the RIKEN Ring Cyclotron (RRC), accounted for 53.1% and 46.9% of the total beam service time of the RILAC, respectively. For beam experiments and machine study of the RI Beam Factory (RIBF), a 2.650-MeV/nucleon $^{70}$Zn-ion beam and a 2.675-MeV/nucleon $^{48}$Ca-ion beam accelerated by the RILAC were injected into the RRC from May 12 to June 7 and from November 12 to December 11 2014, respectively.

Table 2 lists the beam service times in the standalone mode of the RILAC allotted to each beam course in the RILAC target rooms in 2014. The e2 beam course in target room no. 1 was used in experiments using the GARIS2. The e3 beam course in target room no. 1 was used in experiments using the GARIS. The e6 beam course in target room no. 2 was used in the analysis of trace elements. Table 3 lists the operation time of the 18-GHz ECR ion source (18G-ECRIS) in 2014.

We carried out the following improvements and overhauls during the reporting period.
1) In the RF systems, the DC high-voltage power supplies were subjected to annual inspection. The major components of mechanical parts were subjected to simple inspection. The contact fingers for the trimmer of CSM cavities were replaced with new ones.
2) Two water pumps were overhauled. The other water pumps were subjected to simple inspection. All cooling towers were subjected to monthly inspection and annual cleaning.
3) All the turbomolecular pumps were subjected to annual inspection. Cryogenic pumps used for the no. 1 and no. 2 cavities of RILAC and the A5 and A6 cavities of CSM were overhauled. A compressor unit of the cryogenic pump used for the no. 5 RILAC cavity was repaired.

We faced the following mechanical problems during the reporting period.
1) A section of the cooling pipe of an earth ring for the lower stem in the FC-RFQ cavity had a vacuum leak. We repaired the pipes with a repair material as a stopgap measure.
2) Water was found to have splashed in the rf power feeder of the no.1 RILAC cavity because of leakage from a cooling pipe for the coaxial conductor. We replaced it with new ones.
3) Water was found to have splashed in the CSM A4 cavity because of leakage from a cooling pipe of the end drift tube. We replaced the pipes with a repair material as a stopgap measure.
AVF operations in 2014

N. Tsukiori,*2 M. Fujimaki,*1 T. Fujinawa,*1 N. Fukunishi,*1 S. Fukuzawa,*2 M. Hamanaka,*2 H. Hasebe,*1 Y. Higurashi,*1 E. Ikezawa,*1 H. Imao,*1 S. Ishikawa,*2 T. Kageyama,*1 O. Kamigaito,*1 M. Kase,*1 M. Kidera,*1 K. Kobayashi,*2 M. Komiyama,*1 Y. Kotaka,*3 R. Koyama,*2 H. Kuboki,*1 K. Kumagai,*1 T. Maie,*1 M. Nagase,*1 T. Nagatomo,*1 T. Nakagawa,*1 M. Nakamura,*1 T. Nakamura,*2 M. Nishida,*2 M. Nishimura,*2 J. Ohnishi,*1 Y. Ohshiro,*3 H. Okuno,*1 K. Ozeki,*1 N. Sakamoto,*1 J. Shibata,*2 K. Suda,*1 A. Uchiyama,*1 T. Watanabe,*1 Y. Watanabe,*1 K. Yadomi,*2 K. Yamada,*1 and S. Yamaka*3

In 2014, the total annual operation time of the K70 AVF cyclotron (denoted as AVF hereafter) was 2942 hours as shown in Table 1. This was increased by 311 hours compared with that in 2013. In this duration, the time for beam tuning was 1240 hours, which was 274 hours longer than that in 2013. Most of the increased time (311 hours) was spent on beam tuning because the time for beam tuning for “Injection to RRC-SRC” was increased to two to three times longer than usual, and it took considerable time to recover from problems. On the other hand, the total beam supply time was 1702 hours, which was classified into three categories: “Injection to RRC”, “Injection to RRC-SRC”, and “AVF standalone”. The operation times for these three categories are listed in Table 1.

All of the beams accelerated by the AVF in 2014 are listed in Table 2. In this table, the following beams were accelerated for the first time in 2014: 16O (4.9 MeV/u), 84Kr (3.97 MeV/u), 12C (5.0 MeV/u), 13B (5.0 MeV/u), and 13C (5.0 MeV/u). The supplied courses were as follows (in order of the supplied time): RI production, RRC-SRC, CRIB, RRC-E5, Student Ex., and E7B.

Table 1. AVF operation statistics in 2014.

<table>
<thead>
<tr>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total operation time (hr)</td>
<td>2631</td>
</tr>
<tr>
<td>Beam tuning</td>
<td>966</td>
</tr>
<tr>
<td>Injection to RRC</td>
<td>738</td>
</tr>
<tr>
<td>Injection to RRC-SRC</td>
<td>118</td>
</tr>
<tr>
<td>AVF standalone</td>
<td>809</td>
</tr>
<tr>
<td>Beam course (AVF standalone) (hr)</td>
<td></td>
</tr>
<tr>
<td>E7A</td>
<td>480</td>
</tr>
<tr>
<td>E7B</td>
<td>18</td>
</tr>
<tr>
<td>C03</td>
<td>311</td>
</tr>
</tbody>
</table>

The total fault time was 118 hours. The main faults are listed in Table 3, in descending order of time spent on restoration, and details are indicated below.

Table 2. AVF beam list in 2014.

<table>
<thead>
<tr>
<th>Particle</th>
<th>E (MeV/u)</th>
<th>Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>12.0</td>
<td>RI production</td>
</tr>
<tr>
<td>d</td>
<td>12.0</td>
<td>RI production</td>
</tr>
<tr>
<td>d</td>
<td>4.9</td>
<td>RRC-SRC</td>
</tr>
<tr>
<td>α</td>
<td>6.5</td>
<td>Student Ex.</td>
</tr>
<tr>
<td>α</td>
<td>7.5</td>
<td>RI production</td>
</tr>
<tr>
<td>α</td>
<td>12.5</td>
<td>RI production</td>
</tr>
<tr>
<td>6Li</td>
<td>11.2</td>
<td>CRIB</td>
</tr>
<tr>
<td>7Li</td>
<td>5.6</td>
<td>CRIB</td>
</tr>
<tr>
<td>7Li</td>
<td>8.6</td>
<td>E7B</td>
</tr>
<tr>
<td>11B</td>
<td>5.0</td>
<td>CRIB</td>
</tr>
<tr>
<td>12C</td>
<td>7.0</td>
<td>RRC-E5</td>
</tr>
<tr>
<td>16O</td>
<td>4.9</td>
<td>RRC-SRC</td>
</tr>
<tr>
<td>18O</td>
<td>6.07</td>
<td>RI production</td>
</tr>
<tr>
<td>19F</td>
<td>6.08</td>
<td>RI production</td>
</tr>
<tr>
<td>19F</td>
<td>6.768</td>
<td>RI production</td>
</tr>
<tr>
<td>22Ne</td>
<td>6.1</td>
<td>CRIB</td>
</tr>
<tr>
<td>40Ar</td>
<td>5.2</td>
<td>RRC-E5</td>
</tr>
<tr>
<td>56Fe</td>
<td>5.0</td>
<td>RRC-E5</td>
</tr>
<tr>
<td>84Kr</td>
<td>3.97</td>
<td>RRC-E5</td>
</tr>
</tbody>
</table>

(1) During 40Ar beam tuning, the beam stopped unexpectedly at RRC. This was due to an incorrect arrangement of the readout-cable of baffle slits, which cut across the beam trajectory in the chamber of the RRC.

(2) During 6Li beam supply, the beam current decreased at the ion source. To investigate the cause, the ion source was disassembled. Consequently, some contaminations were observed and lack of 6Li metal was found.

(3) During 12C beam tuning, one of the hollow conductors from the magnetic channel of the AVF cracked and cooling water sprayed out from that crack. The crack was temporarily caulked by putty because it was difficult to close the crack by weld. The beam tuning was restarted without any problems.

Table 3. Main faults in 2014. See text for details.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time for restoration (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 6th September</td>
<td>22</td>
</tr>
<tr>
<td>(2) 13th May</td>
<td>18</td>
</tr>
<tr>
<td>(3) 16th September</td>
<td>17</td>
</tr>
</tbody>
</table>

*1 RIKEN Nishina Center
*2 SHI Accelerator Service Ltd.
*3 Center for Nuclear Study, the university of Tokyo
The liquid-helium supply and recovery system\textsuperscript{1)}, which can produce liquid helium at a liquefaction rate of 200 L/h from pure helium gas, has been under stable operation since the beginning of April 2001. The volumes of liquid helium supplied each year from 2001 to 2013 are shown in Fig. 1. The volume gradually increased from 2001 to 2008 but sharply increased in 2010, before decreasing sharply in 2011, and again sharply increasing in 2012.

We improved our recovery system in 2014. A new recovery line was connected to the existing line of the Nanoscience Joint Laboratory at the Emergent Matter Research Facilities. The purity of helium gas recovered from laboratories gradually improved once the construction of the system was completed. Currently, the impurity concentration in the recovered gas rarely exceeds 200 ppm. The volume of helium gas recovered from each building in the Wako campus and the volume transported to the liquid helium supply and recovery system were measured. The recovery efficiency, which is defined as the ratio of the amount of recovered helium gas to the amount of supplied liquid helium, was calculated. The recovery efficiency for the buildings on the south side of the Wako campus, such as the Cooperation Center building of the Advanced Device Laboratory, the Chemistry and Material Physics building, and the Nanoscience Joint Laboratory building, increased to more than 90%.

However, the system experienced malfunctioning at the end of September 2014. The motor of helium compressor failed and we could not supply liquid helium for a period of two and a half months. One cause of motor failure was deterioration due to age. We updated the inverter of the helium compressor in March 2014.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Volumes of liquid helium supplied to laboratories for each fiscal year from 2001 to 2013}
\end{figure}

References
Operation of the superconducting ring cyclotron cryogenic system

H. Okuno,*1 T. Dantsuka,*1 M. Ohshima,*2 H. Shiraki,*2 H. Hazama,*2 A. Mikami,*2 H. Miura,*2 H. Shiba,*2 M. Kubota,*2 H. Hirai,*2 and M Haneda*2

The SRC (Superconducting Ring Cyclotron) cryogenic system, which consists of three compressors, a He refrigerator, and four He buffer tanks for cooling the 240-MJ superconducting magnets used for the SRC, has a cooling capacity of approximately 1 kW at 4.5 K and an inventory of 5000 L of liquid He. The cooling system was operated for approximately nine months in 2014, with a three-month maintenance shutdown in summer (July–August) and a shutdown to conserve electrical power in January.

We experienced some problems with in the operations, some of which required us to stop the operation of the He refrigerator and the compressor. The problems are listed in Table 1. We stopped the operation of the helium compressor during the He purification process on February 19, 2014 because heavy snow on that day stopped the fan in the cooling tower for cooling water. Some improvements were carried out to prevent the fans from stopping due to heavy snow. A temperature sensor in the He refrigerator also demonstrated unusual, and we presume that this was because the attachment between the pipe and sensor became loose. Unfortunately this sensor plays a role in the interlock logic, but we let it go because we had to open the cold box to improve the attachment. On October 29 the second and third turbines tripped suddenly due to the high speed of the third turbine. However, we could find no sign of their high speed from the trend graph. We suspect that this was caused by the noise of the control system. We will check the rotation speed monitor system using a signal generator during the next summer maintenance.

During the operation from April to June, the helium flow rate of the cooling channel for a small power lead gradually degraded. This suggests trapping of some impurity that decreased the flow rate. On November 22 the interlock system for the superconducting magneto required that the power supply of all the superconducting trim coils be shut down. We could find no signs of an increase in temperature. Thus we suspect that this comes from the noise of the control system. On December 25, the flow rate of the cooling channel for one small power lead suddenly increased: we suspect that the impurity dropped or a control valve in the line. We believe that we need to monitor the impurity and aging of the control system regularly.

Table 1. Lists of problems that occurred in the He cooling system in 2014.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Date</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>He compressor</td>
<td>February 19</td>
<td>Fans in the cooling stopped working due to heavy snow</td>
</tr>
<tr>
<td>He refrigerator</td>
<td>April – June</td>
<td>A temperature sensor behaved unusually</td>
</tr>
<tr>
<td></td>
<td>October 12</td>
<td>Mishandling of the pre-cooling valve (warm gas injection)</td>
</tr>
<tr>
<td></td>
<td>October 29</td>
<td>Trip of the second and third turbines.</td>
</tr>
<tr>
<td>Sc. magnet</td>
<td>April – June</td>
<td>Gradual decrease of the flow rate for small current power leads</td>
</tr>
<tr>
<td></td>
<td>November 22</td>
<td>Discharge of the superconducting trim coils</td>
</tr>
<tr>
<td></td>
<td>October 29</td>
<td>Sudden increase of the flow rate for a small current power lead</td>
</tr>
</tbody>
</table>

*1 RIKEN Nishina Center
*2 Nippon Kucho Service Co., Ltd
Present status of the BigRIPS cryogenic plant


In addition to periodic calibration of pressure and temperature sensors, maintaining the oil-removal module in the helium compressor unit is crucial to ensure long-term continuous operations of BigRIPS1). The oil-removal module comprises an oil vessel with a demister (1SP), three coalescer vessels (2SP, 3SP, and, 3.5SP), and two adsorbent vessels (4SP and 5SP). We replaced the activated charcoal and molecular sieves in 4SP every year and the activated charcoal in 5SP every 2 years to ensure low oil contamination in helium gas at the exit of the oil-removal module.

Before the adsorbent vessels, oil in the helium gas is separated by coalescer filters in three coalescer vessels. The drain oil separated from the helium gas is sent to the compressor via a drain line with solenoid valves, depending on the oil level in the coalesce vessel. By measuring the operation interval of the solenoid valves, the oil contamination level of the helium gas at the entrance of the second and the third coalesce vessel can be evaluated. The expected oil contamination levels at the entrance of the coalescer vessels are 15-50 and 0.75-1.25 wt. ppm for 3SP and 3.5SP, respectively. The oil contamination level can also be easily measured with an oil check kit2).

Each coalescer vessel contains four coalescer filters, manufactured by Domnick Hunter3), and all the filters were replaced every 2 years, since 2008. However, the filters used for 6 years were discontinued and replaced with the successive product of Domnick Hunter in 2014.

Figure 1 shows an estimate of the oil contamination level at the entrance of 3SP as a function of the coalescer filter operation time from the oil drain from the 3SP. The navy blue, green, and, yellow diamonds represent the estimates for the 2008-2009, 2010-2011, and 2012-2013 operations, respectively. The estimate for the 2014 operation with new coalescer filters is shown as pink diamonds. The estimates increase to 50-75 wt. ppm up to an operation time of 2000 hours for the period of 2008-2009 and 2010-2011 and then stays constant. The estimate for the 2014 operation shows similar behavior. On the other hand, the estimate for the period of 2012-2013 scatters largely and shows monotonous increasing tendency. The oil check kit values are also shown as open symbols in Fig. 1. The open triangles, squares, circles, and diamonds represent results for the 2008-2009, 2010-2011, 2012-2013, and 2014 operations, respectively.

In Fig. 2, we show a similar analysis of the oil contamination at the entrance of 3.5SP. Symbols and colors used in Fig. 2 are same as those in Fig. 1. A gradual increasing tendency of the oil contamination is seen in all operation periods. Following the large oil contamination at the entrance of the 3SP, the results for the period of 2012-2013 are approximately twice of that for the other period. Since the solenoid valve of 3.5SP was operated only once since Sept. 2014, only one pink symbol is plotted in Fig. 2. Although the performance efficiency of the new filter elements seem to be similar to that of discontinued ones, we shall continue observations and investigate oil-removal modules carefully in the coming maintenance period.

References
3) http://www.parker.com/
The operation of ring-cyclotrons (RRC, fRC, IRC, and SRC) in the RIBF accelerator complex in 2014 is reported. Table 1 summarizes the accelerated beams provided for users. The scheduled beam service time was 3192.3 h. The delivered beam service time was 2967.1 h. Note that 82% of the beam service time was distributed to the experiments in which the beams extracted from SRC are used by the users. Beam availability, which is the most important parameter indicating the stability of operation, was 92.9%.

In March 2014, the campaign-type experiments utilizing the 238U 345 MeV/u beam were performed. In the beginning of the beam tuning procedure, we experienced a hardware fault related to the main differential probe (MDP) of the fRC twice, which resulted in 4.5-day delay of the beam start time. Once the beam service started on March 27, five experiment programs were performed without any issue with accelerators. After an 8.3-day break of the IRC and fRC twice, which resulted in 4.5-day delay of the beam start time. After the problem was fixed, the beam was stably delivered until June 7. Owing to the beam current upgrade in the interruption in total.

From May 16, we started a beam service of a 345-MeV/u 70Zn beam. During the beam service, a hardware fault was obtained. This corresponds to the beam power of 8.8 kW which is the power record of the beams obtained in RIBF.

In addition to the biological experiments at E5B, the beam services of 48Ca for RIPS (E6) and 136Xe for KISS (E2B) were performed.

Table 1. Summary of the accelerated beams in 2014

<table>
<thead>
<tr>
<th>Ions</th>
<th>Energy (MeV/u)</th>
<th>Accelerators</th>
<th>Beam Course</th>
<th>BeamCurrent/particle nA requested</th>
<th>Max</th>
<th>BeamCurrent/particle nA Delivered</th>
<th>Down time (h)**</th>
<th>Downtime (h)**</th>
<th>Total time (h)***</th>
<th>Availability (%)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C</td>
<td>135</td>
<td>AVF-RRC</td>
<td>E2B(KEK+MS)</td>
<td>1 393</td>
<td>71</td>
<td>71</td>
<td>0</td>
<td>71</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>24Na</td>
<td>95</td>
<td>RILAC-RRC</td>
<td>E2B(KEK)</td>
<td>1 91.2</td>
<td>32</td>
<td>32</td>
<td>0</td>
<td>32</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>27Al</td>
<td>60</td>
<td>RILAC-RRC</td>
<td>E2B(KEK)</td>
<td>1 2.8</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>40Ca</td>
<td>63</td>
<td>RILAC-RRC</td>
<td>SHARAQ(CNS)</td>
<td>200 235.3</td>
<td>108</td>
<td>108.1</td>
<td>1.2</td>
<td>104.3</td>
<td>95.4</td>
<td></td>
</tr>
<tr>
<td>44Ti</td>
<td>70</td>
<td>RILAC-RRC</td>
<td>fRC</td>
<td>1 0.1</td>
<td>85</td>
<td>72.9</td>
<td>9.8</td>
<td>82.8</td>
<td>85.8</td>
<td></td>
</tr>
<tr>
<td>50Cr</td>
<td>10.75</td>
<td>RILAC-RRC</td>
<td>EURICA</td>
<td>10 405</td>
<td>96</td>
<td>100.5</td>
<td>2.8</td>
<td>103.4</td>
<td>104.7</td>
<td></td>
</tr>
<tr>
<td>238U</td>
<td>10.75</td>
<td>RILAC-RRC</td>
<td>EURICA</td>
<td>N/A 1428</td>
<td>121</td>
<td>121</td>
<td>0</td>
<td>121</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>270Zr</td>
<td>10</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>N/A 123</td>
<td>15</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>238U</td>
<td>50</td>
<td>RILAC-RRC-RC</td>
<td>fRC</td>
<td>N/A 123</td>
<td>15</td>
<td>15</td>
<td>0</td>
<td>15</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>48Ca</td>
<td>250</td>
<td>AVF-RRC</td>
<td>SHARAQ(CNS)</td>
<td>10 510</td>
<td>252</td>
<td>268.1</td>
<td>42.7</td>
<td>310.8</td>
<td>106.4</td>
<td></td>
</tr>
<tr>
<td>50Ca</td>
<td>250</td>
<td>RILAC-RRC</td>
<td>EURICA</td>
<td>10 41.8</td>
<td>108</td>
<td>125.4</td>
<td>18.6</td>
<td>144</td>
<td>116.1</td>
<td></td>
</tr>
<tr>
<td>64Zn</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>500 530</td>
<td>492.2</td>
<td>474.1</td>
<td>18.1</td>
<td>492.2</td>
<td>96.3</td>
<td></td>
</tr>
<tr>
<td>76Se</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>75 123</td>
<td>216</td>
<td>202.2</td>
<td>39.1</td>
<td>239.3</td>
<td>92.9</td>
<td></td>
</tr>
<tr>
<td>35S</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>75 116.6</td>
<td>96</td>
<td>93.1</td>
<td>2.9</td>
<td>96</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>35S(1st)</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>10 22.1</td>
<td>540</td>
<td>384.4</td>
<td>159.6</td>
<td>544.1</td>
<td>71.2</td>
<td></td>
</tr>
<tr>
<td>35S(2nd)</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>10 25</td>
<td>408</td>
<td>385.2</td>
<td>94.8</td>
<td>480.1</td>
<td>94.4</td>
<td></td>
</tr>
<tr>
<td>35S(3rd)</td>
<td>345</td>
<td>RILAC-RRC-RC</td>
<td>EURICA</td>
<td>15 27.9</td>
<td>532.1</td>
<td>501</td>
<td>31.1</td>
<td>532.1</td>
<td>94.2</td>
<td></td>
</tr>
</tbody>
</table>

*Delivered time = Supply time for Beam users.

**Down time = Supply stop time caused by accelerator issues.

***Availability =Delivered time/scheduled time.
V. EVENTS
ARIS2014 - 2nd Conference on Advances in Radioactive Isotope Science

T. Motobayashi∗

The second conference on Advances in Radioactive Isotope Science (ARIS 2014) was held at the Ito International Research Center in Tokyo on June 1-6, 2014. It was jointly organized by the RIKEN Nishina Center and CNS, the University of Tokyo, sponsored by IUPAP (International Union of Pure and Applied Physics), and supported by several Japanese institutions and societies. The first ARIS conference was held in 2011 in Leuven, Belgium, by merging the two meetings, ENAM (International Conference on Exotic Nuclei and Atomic Masses) and RNB (International Conference on Radioactive Nuclear Beam). In a joint assembly of the advisory committees of the two meetings, the ultimate goal of ARIS was set to create the “flagship conference” series on the science of radioactive isotopes, including the physics of exotic nuclei and studies with RI beams. Since the Nishina Center and the CNS have extensively studied on radioactive isotopes with excellent RI-beam facilities and their significant contributions in the near future are foreseen, the second conference in Japan was very well-timed.

The scientific scope of ARIS 2014 was of the following subjects, taking over the ones of the first conference with some modifications: 1) nuclear structure, 2) nuclear astrophysics, 3) fundamental symmetries and interactions, 4) nuclear reactions and responses, 5) nuclear properties including atomic masses and fundamental constants, nuclear moments and radii, rare decay modes, and nuclei at the driplines, 6) nuclear EOS and its implications, 7) heaviest elements and fission, 8) radioactive isotope production and developments of experimental devices, 9) computational developments, 10) applications, and 11) other related issues.

On Sunday June 1, public lectures attracted a large audience of about 300 people including high school students. The conference started on Monday with the welcome address by the Conference Chair, Hideto En’yo. In the first scientific session chaired by the Conference Co-chair, Takaharu Otsuka, Robert Janssens gave the keynote talk addressing “big” questions in the field and providing an overview of the new and important developments after the first conference.

The number of registrants turned out to be 407 from 27 countries. Thus the highly optimistic goal set by the organizers was reached, reflecting the considerable interest and amount of work done in the research field. The conference photo shown below (Fig. 1) delivers the lively atmosphere of the conference.

There were 48 plenary talks and 82 oral presentations in three parallel sessions held on June 3 and 6 afternoons. Recent highlights from RIBF, the new neutron magic number 34 experimentally confirmed for the neutron-rich nucleus $^{54}$Ca and first lifetime measurements for a number of nuclei in the r-process path, for example, attracted much attention as well as new results from world facilities. Among 239 papers presented in poster sessions, seven posters presented by young scientists were selected as “Best Posters”, and the awarding ceremony took place in the closing session. Angela Bracco summarized the conference by selecting major aspects from numerous presentations and emphasizing the bright future of the field.

The conference proceedings will be published electronically in the JPS Conference Proceedings Volume 6 (2015). The next ARIS conference will be jointly hosted by NSCL and TRIUMF.

Fig. 1. Conference photo taken in the session hall.

∗1 Scientific Secretary of ARIS2014, RIKEN Nishina Center
The 8th Nishina School

T. Kishida*1 and H. Ueno*1

The RIKEN Nishina Center (RNC) has commenced Nishina School to enhance international research relationship in the Asian Region through human-resource development in the field of nuclear physics. In this program, undergraduate students are being accepted by the RNC from Peking University since 2008 and from Seoul National University since 2012 for two weeks every summer. Both the programs have been merged since 2013.

The 8th Nishina School was held from July 28 to August 8, 2014. The curriculum of the School was designed to introduce the pleasure of nuclear physics into the undergraduate students from Peking University (5 students) and Seoul National University (5 students). The first week, program consisted of lectures and basic experimental trainings. In the second week they performed a real-beam experiment using the RIKEN Pelletron accelerator, starting from its planning and followed by the analyses and the discussions. On the last day of the School, the presentation session by the students was held. The program timetable in 2014 is shown in Fig. 1.

In response to a request for improving the management of the Nishina School proposed by the people in charge of the Nishina School held in the last year, the RNC director convened a preparatory meeting on December 25, 2013, to discuss the development of an organizational management system of the Nishina School and the improvement of transparency in the decision-making process. For this purpose, it was determined at the meeting to newly set up the Nishina School Steering Committee. The Committee is composed of Ueno (Chair), En’yo, Sakurai, and Sakai. The Committee Meetings were held four times on March 3, April 23, May 26, and July 15, 2014. Kishida, principle of the Nishina School, also attended all these Meetings as an observer. Their meeting minutes were reported at the second, fourth, and fifth RNC Coordination Committee Meetings held in 2014.

In order to enhance the experimental training, the Committee determined to incorporate accelerator experimental training into the curriculum. In this year, cross-section measurements were conducted for the $^{12}$C($p,\gamma$)$^{13}$N reaction utilizing a proton beam at $E_p = 1600-1850$ keV delivered from the RIKEN Pelletron accelerator. Technical instructions of the experimental training were provided by Research Scientists in Nuclear Spectroscopy Lab., Spin Isospin Lab., and RI Physics Lab. They were technically assisted by IPA and JRA researchers of these laboratories.

The Committee also considered that enhancement of working-level dialogue among the persons in charge of, e.g., the entire program, experimental trainings, and office procedures is an important subject. This year, three working-level meetings, including an on-site meeting at the Pelletron, were held on July 4, 10, and 18. Despite such a gradual improvement, the situation can be further improved.

All the students had a good experience and enjoyed the School and life at the RNC. Figure 2 shows a photograph taken at the opening ceremony on July 28.

---

*1 RIKEN Nishina Center
The 27th World Conference of the International Nuclear Target Development Society (INTDS2014)

H. Okuno,*1 H. Hasebe,*1 H. Kuboki,*1 H. Imao,*1 A. Yoshida,*1 K. Morimoto,*1 D. Kaji,*1 K. Yoshida,*1 and K. Sakuma*1

The 27th World Conference of the International Nuclear Target Development Society (INTDS 2014) was held from August 31th to September 5th, 2014 at the National Museum of Emerging Science and Innovation (Miraikan) in Odaiba Tokyo, Japan with special emphasis on targets for accelerator-based research. INTDS 2012 was organized by the RIKEN Nishina Center for Accelerator-based Science, Saitama.

The series of INTDS conferences dates back to 1963 when the "First Symposium on Research Materials for Nuclear Measurements" was held sponsored by the Central Bureau for Nuclear Measurements (CBNM; recently, IRMM, -Institute for Reference Materials and Measurements) in Belgium. Since then, researchers involved in target preparation shared their experience and discussed related problems during biennial conferences hosted alternatively in Europe, North America, and Asia (www.intds.org). The 23rd INTDS conference was held in Tsukuba, Japan in 2006. It was delightful to meet again in Japan on the occasion of the 27th International INTDS conference.

More than 77 participating scientists from 17 countries (Belgium, Canada, China, France, Germany, India, Italy, Japan, Korea, Pakistan, Poland, Romania, Russia, South Africa, Switzerland, UK, USA), met in Tokyo to present over 67 scientific contributions covering the wide field of "State-of-the-art Technologies for Nuclear Target and Charge Stripper". A laboratory tour of the RIKEN RI Beam Factory was included in the scientific program to introduce the institution and laboratories. The conference comprised eleven different sessions titled, "Targets and strippers for RIBF", "Classical accelerator targets", "RI beams", "Gas strippers", "Liquid strippers", "Production targets", "Medical and industrial applications", "Radioactive targets", "Target characterization", "Liquid and gas targets", "Radioactive targets", and "Laser-related targets". The sessions included many activities such as the discussion of exciting new developments or methods, reports on improvements of established techniques, presentation of scientific results by young scientists, and the introduction of new groups and laboratories in the society.

Fig. 1: Photo of conference attendees

*1 RIKEN Nishina Center for Accelerator-Based Science
The 6th International Conference on Trapped Charged Particles and Fundamental Physics

M. Wada,*1 P. Schury,*1 Y. Ichikawa,*1 and Y. Ito*1

The 6th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2014) was held from 1st to 5th December, 2014 at the Takamatsu International Conference Hall. Prior to the conference, a preschool (TCP school) for young researchers was organized from 28th to 29th November at the Nishina Hall of RIKEN where inspiring lectures were given by S. Ulmer, R. Thompson, R. Hayano, H. Katori, V. Dzuba, Yu. Litvinov, W. Nörtershäuser. About 60 participants enrolled in the school and half of them went to Takamatsu.

During the conference, a variety of scientific programs using stored particles were actively discussed. Anti-Hydrogens are routinely synthesized and precision spectroscopy of them is being actively pursued. Multi-reflection time-of-flight (MRTOF) mass spectographs were put online at three different laboratories at almost the same time at ISOLDE, RIKEN and GSI, and are also under preparation at TRIUMF, MSU, ANL, and IBS in Korea. Advanced resonance detection methods in Penning trap mass spectrometers were discussed. Several fundamental symmetry studies using molecular ions, neutral atoms and highly charged ions (HCl) were discussed. The highlight of the conference was a sympathetically cooled HCl crystal in a linear Paul trap by Heidelberg-Aarhus collaboration. It can be a next-generation frequency standard, but also provides a platform for research in physics beyond the standard model such as time variation of the fine structure constant. An Australian theorist suggests that C166+ is the best candidate for such research at present.

A total of 107 registered participants attended and 63% of them were from abroad. We invited 47 speakers. Of them, 45 accepted the invitation, 2 of whom later cancelled. We accepted 23 oral presentations and 26 posters; additionally, 3 oral contributions included posters.

An international workshop, NNP2014, was held at the same time and location, hence joint sessions and social events were held.

In the international organization committee meeting, it was decided that TCP2018 will be held in USA and organized by G. Bollen of MSU.

Fig. 1 Participants of TCP2014 in Takamatsu

Fig. 2 An attraction during the banquet.

*1 RIKEN Nishina Center
The 6th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2014) was held from 1st to 5th December, 2014 at the Takamatsu International Conference Hall. Prior to the conference, a preschool (TCP school) for young researchers was organized from 28th to 29th November at the Nishina Hall of RIKEN where inspiring lectures were given by S. Ulmer, R. Thompson, R. Hayano, H. Katori, V. Dzuba, Yu. Litvinov, W. Nörtershäuser. About 60 participants enrolled in the school and half of them went to Takamatsu.

During the conference, a variety of scientific programs using stored particles were actively discussed. Anti-Hydrogens are routinely synthesized and precision spectroscopy of them is being actively pursued.

Multi-reflection time-of-flight (MRTOF) mass spectrographs were put online at three different laboratories at almost the same time at ISOLDE, RIKEN and GSI, and are also under preparation at TRIUMF, MSU, ANL, and IBS in Korea. Advanced resonance detection methods in Penning trap mass spectrometers were discussed. Several fundamental symmetry studies using molecular ions, neutral atoms and highly charged ions (HCI) were discussed. The highlight of the conference was a sympathetically cooled HCI crystal in a linear Paul trap by Heidelberg-Aarhus collaboration. It can be a next-generation frequency standard, but also provides a platform for research in physics beyond the standard model such as time variation of the fine structure constant. An Australian theorist suggests that Cf16+ is the best candidate for such research at present.

A total of 107 registered participants attended and 63% of them were from abroad. We invited 47 speakers. Of them, 45 accepted the invitation, 2 of whom later cancelled. We accepted 23 oral presentations and 26 posters; additionally, 3 oral contributions included posters.

An international workshop, NNP2014, was held at the same time and location, hence joint sessions and social events were held.

In the international organization committee meeting, it was decided that TCP2018 will be held in USA and organized by G. Bollen of MSU.

VI. ORGANIZATION AND ACTIVITIES OF RIKEN NISHINA CENTER
(Activities and Members)
1. Organization

1.1 Organization Chart as of March 31, 2015

[Diagram of organizational chart with various departments and research groups represented by nodes connected with edges]
1.2 Topics in FY2014

In fiscal year 2014, RNC launched several interdisciplinary innovation programs as yet another new challenge for its researchers. One such example is RNC’s participation in the ImPACT program which aims to significantly reduce and resource recycle high-level radioactive waste. To achieve this goal, the organizational structure required to develop key technology for effective nuclear transmutation has been revised so that the nuclear reaction data of the long-life fission products can be obtained. RNC also participates in the Strategic Innovation Program (SIP) in cooperation with eighteen other institutes in Japan to undertake the task of building a system for strategic omics breeding technology.

With President’s Discretionary Fund providing the financial support of 450 million yen for international research collaboration, RNC was able to execute approximately five months of RIBF operation in total. Accordingly, user time also reached its record-high 2597 hours.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 1, 2014</td>
<td>Start of Nuclear Transmutation Data Research Group associated with following three teams: Fast RI Data Team, Slow RI Data Team, Muon Data Team</td>
</tr>
<tr>
<td>Mar. 31, 2015</td>
<td>End of Mathematical Physics Laboratory</td>
</tr>
</tbody>
</table>

2. Finances

As mentioned in “I. Administrative Topic in FY2014”, RNC executed approximately five months of RIBF operation. Breakdown expenses of the RNC FY2014 budget and a transition for the past five years are shown in following graphs.

[Correction: In the 2013 edition, the FY2014 budget was shown erroneously instead of that of FY2013. The budget of FY 2014 has been reprinted with the revised external funding.]
3. Staffing

At the start of FY 2014, April 1, 2014, there were 246 personnel affiliated with RNC and 347 researchers visiting RNC for research purpose. The following graphs show a breakdown of personnel into seven categories as of April 2014, and a transition of the number of each category. In the transition graph, researchers associated with the BNL collaboration in 2014 are counted as Contract Researcher.

4. Research publication

Research results published in 2014 are roughly split into two categories, i.e., papers published in journals and oral presentations. A transition of the number of the past five years is shown in the following graph.
5. Management

Headed by the RNC Director Hideto En'yo, the RIKEN Nishina Center for Accelerator-Based Science (RNC) consists of:

- 10 Laboratories
- 1 Research unit
- 9 Groups with 25 Teams
- 2 overseas research center with 3 Groups

as of the latter half of FY2014. There are also three 'Partner Institutes' which conduct research in the laboratories set up in RNC.

RNC is managed by its Director who takes into consideration the majority decision of the RNC Coordination Committee. The Nishina Center Planning Office under the auspices of President of RIKEN is responsible for administrative matters of RNC.

The management of RNC is supported by the following committees:

- Scientific Policy Committee
- Program Advisory Committee
- Safety Review Committee
- RIBF Machine Time Committee
- Public Relations Committee

There are also committees to support the President of RIKEN and/or the Director of RNC such as:

- RBRC Management Steering Committee (MSC) and Nishina Center Advisory Council with two subcommittees,
- RBRC Management Steering Committee (MSC) and
- Nishina Center Advisory Council with two subcommittees,
- RBRC Scientific Review Committee (SRC) and
- Advisory Committee for the RIKEN-RAL Muon Facility

Nishina Center for Accelerator-based Science

Executive Members (as of March 31, 2015)

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hideto EN'YO</td>
<td>Director, RNC; Chief Scientist, Director of Radiation Laboratory</td>
</tr>
<tr>
<td>Tetsuo HATSUDA</td>
<td>Deputy Director (Theoretical Research), RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory</td>
</tr>
<tr>
<td>Hiroyoshi SAKURAI</td>
<td>Deputy Director (RIBF Research), RNC; Chief Scientist, Director of Radioactive Isotope Physics Laboratory; Group Director, Nuclear Transmutation Data Research Group</td>
</tr>
<tr>
<td>Tohru MOTOBAYASHI</td>
<td>RIBF Synergetic-Use Coordinator</td>
</tr>
<tr>
<td>Walter F. HENNING</td>
<td>Senior Advisor</td>
</tr>
<tr>
<td>Yasushige YANO</td>
<td>Senior Advisor</td>
</tr>
<tr>
<td>Minami IMANISHI</td>
<td>Assistant</td>
</tr>
</tbody>
</table>

RNC Coordination Committee

The following subjects relevant to the RNC management are deliberated under the chairmanship of the RNC Director:

- Establishment of the new organization or reorganization in RNC
- Personnel management of RNC researchers
- Research themes and research budget
- Approval of the Partner Institutes
- Evaluation of the management of RNC and the response to the recommendations by external evaluation

The RNC Coordination Committee is held monthly.

Members (as of March 31, 2015)

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hideto EN'YO</td>
<td>Director, RNC; Chief Scientist, Director of Radiation Laboratory</td>
</tr>
<tr>
<td>Hiroyoshi SAKURAI</td>
<td>Deputy Director, RNC; Chief Scientist, Director of Radioactive Isotope Physics Laboratory; Group Director, Nuclear Transmutation Data Research Group</td>
</tr>
<tr>
<td>Tetsuo HATSUDA</td>
<td>Deputy Director, RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory</td>
</tr>
<tr>
<td>Tohru MOTOBAYASHI</td>
<td>RIBF Synergetic-Use Coordinator</td>
</tr>
<tr>
<td>Walter F. HENNING</td>
<td>Senior Advisor</td>
</tr>
<tr>
<td>Yasushige YANO</td>
<td>Senior Advisor</td>
</tr>
<tr>
<td>Masahiko IWASAKI</td>
<td>Chief Scientist, Director of Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td>Tomohiro UESAKA</td>
<td>Chief Scientist, Director of Spin isospin Laboratory</td>
</tr>
<tr>
<td>Hideki UENO</td>
<td>Chief Scientist, Director of Nuclear Spectroscopy Laboratory; Deputy Group Director, User Liaison and Industrial Cooperation Group</td>
</tr>
<tr>
<td>Toru TAMAGAWA</td>
<td>Associate Chief Scientist, Director of High Energy Astrophysics Laboratory</td>
</tr>
<tr>
<td>Takashi NAKATSUKASA</td>
<td>Associate Chief Scientist, Director of Theoretical Nuclear Physics Laboratory</td>
</tr>
<tr>
<td>Emiko HIYAMA</td>
<td>Associate Chief Scientist, Director of Strangeness Nuclear Physics Laboratory</td>
</tr>
<tr>
<td>Koji HASHIMOTO</td>
<td>Associate Chief Scientist, Director of Mathematical Physics Laboratory</td>
</tr>
<tr>
<td>Kosuke MORITA</td>
<td>Group Director, Research Group for Superheavy Element; Team Leader, Superheavy Element Production Team</td>
</tr>
<tr>
<td>Osamu KAMIGAITO</td>
<td>Group Director, Accelerator Group; Group Director, High-Intensity Accelerator E&amp;D Group</td>
</tr>
</tbody>
</table>
Nishina Center Planning Office

The Nishina Center Planning Office is responsible for the following:

- Planning and coordination of RNC’s research program and system
- Planning and management of RNC’s use of budget
- Public relations activities

Members (as of March 31, 2015)

- Hiroshi TSUBOI: Executive Director; Director, Head of Nishina Center Planning Office
- Mitsuru KISHIMOTO: Deputy Director, Nishina Center Planning Office; Administration Manager, RBRC; Administration Manager, RIKEN Facility Office at RAL
- Kazumori MABUCHI: Deputy Manager, Nishina Center Planning Office
- Yasutaka AKAI: Administrative Officer of Nishina Center Planning Office; Deputy Administration Manager, RBRC
- Yukari ONISHI: Chief, Nishina Center Planning Office
- Kumiko SUGITA: Special Administrative Employee
- Yoko OKADA: Task-Specific Employee
- Yukiko SATO: Task-Specific Employee
- Kyoji YAMADA: Special Temporary Employee
- Yoshio OKUZUMI: Temporary Employee
- Masatoshi MORIZAM: Consultant for Advisory Committee, Research Review, etc.
- Rie KUWANA: Temporary Staff

Scientific Policy Committee

The Scientific Policy Committee deliberates on the following:

- Research measures and policies of RNC
- Administration of research facilities under RNC’s management

The Committee members are selected among professionals within and outside RNC. The members were not chosen nor the Committee held in FY2014.

Program Advisory Committee

The Program Advisory Committee reviews experimental proposals submitted by researchers and reports the approval/disapproval of the proposals to the RNC Director. The Committee also reports to the RNC Director the available days of operation at RIBF or the Muon Facility at RAL allocated to researchers.

The Committee is divided into three categories according to the research field.

1. Nuclear Physics Experiments at RIBF (NP-PAC): academic research in nuclear physics
(2) Materials and Life Science Researches at RNC (ML-PAC): academic research in materials science and life science
(3) Industrial Program Advisory Committee (In-PAC): non-academic research

Program Advisory Committee for Nuclear Physics Experiments at RI Beam Factory (NP-PAC)

Members (as of March 31, 2015)

Muhsin N. HARAKEH (Chair) Prof., KVI (Kernfysisch Versneller Instituut), University of Groningen, Netherlands
Yanlin YE Prof., State Key Lab. of Nucl. Phys. and Tech., School of Physics, Peking University, China
Christoph SCHIEDENBERGER Head, NuSTAR/ENNA Department, GSI, Germany
Friedrich-K. THIELEMANN Prof., Department of Physics, University of Basel, Switzerland
Rick F. CASTEN Prof., Department of Physics, Yale University, USA
Christopher J. (KIM) LISTER Prof., Department of Physics and Applied Physics, University of Massachusetts, Lowell, USA
Hans EMLING Prof. Dr., GSI, Germany
Hironori IWASAKI Assistant Prof., National Superconducting Cyclotron Laboratory, Michigan State University, USA
Walter D. LOVELAND Full Prof., Department of Chemistry, Oregon State University, USA
Thomas NILSSON Prof., Chalmers Univ. of Technology, Sweden; Chair of BFC (Board of FAIR Collaborations)
Bradley. M. SHERRILL FRIB Associate Laboratory Director for Users, Michigan State University, USA
Oliver SORLIN GANIL (Grand Accélérateur National d’Ions Lourds), France
Satoshi N. NAKAMURA Prof. Nuclear Experiment Group, Faculty of Science, Tohoku University, Japan
Takashi NAKATSUKASA Associate Chief Scientist, Theoretical Nuclear Physics Laboratory, RNC, Japan

Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)

Members (as of March 31, 2015)

Jean-Michel POUTISSOU (Chair) Senior research scientist Emeritus, TRIUMF, Canada
Alex AMATO Bulk μSR Group Head, GPS Scientist, Laboratory for Muon Spin Spectroscopy, PSI, Switzerland
Douglas E. MACLAUGHLIN Prof., Emeritus, University of California, Riverside, USA
Sadamichi MAEKAWA Director General, Advanced Science Research Center, JAEA, Japan
Kenya KUBO Prof., Department of Material Science, International Christian University, Japan
Adrian HILLIER ISIS, RAL, UK
Philippe MENDELS Prof., Laboratoire de Physique des Solides, Universite Paris-SUD, France
Xu-Guang ZHENG Prof., Department of Physics Faculty of Science and Engineering, Saga University, Japan
Hirooyuki YAMASE Senior Researcher, National Institute for Materials Science, Japan
Ryouses KADONO Prof., Division Head, Muon Science Laboratory, Institute of Materials Structure Science, KEK, Japan
Norimichi KOJIMA Prof., Department of Basic Science, Graduate School of Arts and Sciences, University of Tokyo, Japan
Toshiyuki AZUMA Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN, Japan
Atsushi KAWAMOTO Prof., Graduate School of Science, Hokkaido University, Japan
Shigeo YOSHIDA Research Consultant, RIKEN Center for Sustainable Resource Science, RIKEN, Japan

Industrial Program Advisory Committee (In-PAC)

Members (as of March 31, 2015)

Akihiro IWASE (Chair) Prof., Graduate School of Engineering, Osaka Prefecture University, Japan
Kenya KUBO Prof., The College of Liberal Arts, International Christian University, Japan
Hitoshi NAKAGAWA Auditor, Japan International Research Center for Agricultural Sciences, Japan
Nobuhiko NISHIDA Full time research fellow, Toyota Physical and Chemical Research Institute, Japan
Toshimori MITSUMOTO Chief Engineer, Quantum Equipment Division, Sumitomo Heavy Industries, Ltd, Japan
Toshiyuki AZUMA Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN, Japan

Safety Review Committee

The Safety Review Committee is composed of two sub committees, the Safety Review Committee for Accelerator Experiments and the Hot-Lab Safety Review Committee. These Committees review the safety regarding the usage of radiation generating equipment based on the proposal submitted to RNC Director from the spokesperson of the approved experiment.

Safety Review Committee for Accelerator Experiments

Members (as of March 31, 2015)

Takashii KISHIDA (Chair) Senior Research Scientist, Radioactive Isotope Physics Laboratory
Kouji MORIMOTO Team Leader, Superheavy Element Device Development Team
Eiji IKEZAWA Team Leader, RILAC Team
Hiromitsu HABA Team Leader, RI Applications Team
Shinichiro MICHIMASA Assistant Prof., Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI Lecturer, Center for Nuclear Study, University of Tokyo
Hiroshi WATANABE Lecturer, Radioactive Nuclear Beam Group, IPNS, KEK
RIBF Machine Time Committee

Upon request of the RNC Director, the RIBF Machine Time Committee deliberates on the machine time schedule of RIBF, and reports the results to him.

Members (as of March 31, 2015)

- Hideyuki SAKAI (Chair) - Group Director, User Liaison and Industrial Cooperation Group
- Tomoko ABE - Group Director, Accelerator Applications Research Group
- Nobuhisa FUKUNISHI - Deputy Group Director, Accelerator Group
- Osamu KAMIGAITO - Group Director, Accelerator Group
- Masayuki KASE - Deputy Group Director, Accelerator Group
- Toshiyuki KUBO - Group Director, Research Instruments Group
- Kouji MORIMOTO - Team Leader, Superheavy Element Research Device Development Team
- Hiroki OKUNO - Deputy Group Director, Accelerator Group
- Hiroyoshi SAKURAI - Chief Scientist, Radioactive Isotope Physics Laboratory
- Hideki UENO - Chief Scientist, Nuclear Spectroscopy Laboratory
- Tomohiro UESAKA - Chief Scientist, Spin isospin Laboratory
- Yoshitomo UWAMINO - Group Director, Safety Management Group
- Masanori WAKASUGI - Group Director, Instrumentation Development Group
- Ken-ichiro YONEDA - Team Leader, User Support Office
- Susumu SHIMOURA - Professor, Center for Nuclear Study, University of Tokyo
- Hiroo MIYATAKE - Professor, Radioactive Nuclear Beam Group, IPNS, KEK

Observers (as of March 31, 2015)

- Hideto EN’YO - Director, RNC
- Nobuaki IMAI - Chair, RIBF-UEC, Associate Prof. Center for Nuclear Study, University of Tokyo
- Hiromitsu HABA - Team Leader, RI Applications Team
- Kosuke MORITA - Group Director, Research Group for Superheavy Element
- Tohru MOTOBAYASHI - RIBF Synergetic-Use Coordinator
- Koichi YOSHIDA - Team Leader, BigRIPS Team; Team Leader, Slow RI Data Team
- Kanenobu TANAKA - Deputy Group Director, Safety Management Group
- Mitsuru KISHIMOTO - Deputy Director, Nishina Center Planning Office

Public Relations Committee

Upon request of the RNC Director, the Public Relations Committee deliberates and coordinates the following matters:

1. Creating public relations system for the RNC
2. Prioritization of the public relations activities for the RNC
3. Other general and important matters concerning the public relations of RNC

Members (as of March 31, 2015)

- Hiroshi TSUBOI - Executive Director; Director, Head of Nishina Center Planning Office
- Hiroyoshi SAKURAI - Deputy Director, RNC; Chief Scientist, Radioactive Isotope Physics Laboratory
- Tetsuo HATSUDA - Deputy Director, RNC; Chief Scientist, Quantum Hadron Physics Laboratory
- Tohru MOTOBAYASHI - RIBF Synergetic-use coordinator
- Walter F. HENNING - Senior Advisor
- Yasushige YANO - Senior Advisor
RBRC Management Steering Committee (MSC)

RBRC MSC is set up according to the Memorandum of Understanding between RIKEN and BNL concerning the collaboration on the Spin Physics Program at the Relativistic Heavy Ion Collider (RHIC).

Members (as of March 31, 2015)
- Maki KAWAI: Executive Director, RIKEN
- Shoji NAGAMIYA: Science Advisor, RIKEN
- Hideto EN’YO: Director, RNC
- Berndt MUELLER: Associate Laboratory Director for Nuclear and Particle Physics, BNL
- David LISSAUER: Deputy Chair, Physics Department, BNL
- Satoshi OZAKI: Senior Advisor, BNL

Nishina Center Advisory Council

The agenda to be deliberated by NCAC are set by the Terms of Reference presented by the RNC Director on the fundamental issues regarding research activities and administrative matters. NCAC submits its report to the President of RIKEN, and to the Director of Nishina Center if necessary. The members of NCAC are recommended by the Director of the Nishina Center to the President of RIKEN and selected from among highly knowledgeable individuals and experts worldwide. NCAC has two sub-councils for the RBRC and the RAL Muon Facility, respectively.

Members (as of March 31, 2015)
- Robert TRIBBLE (Chair): Deputy Director for Science and Technology, BNL, USA
- Hirokazu TAMURA: Prof., Department of Physics, Graduate School of Science, Tohoku University, Japan
- Muhsin N. HARAKEH: Prof., Emeritus, KVI (Kernfysisch Versneller Instituut), University of Groningen, Netherlands; Chair, NP-PAC
- Jean-Michel POUTISSOU: Senior research scientist Emeritus, TRIUMF, Canada; Chair, ML-PAC
- Richard MILNER: Prof., Director, Laboratory for Nuclear Science, MIT, USA; Chair, RBRC-SRC
- Andrew TAYLOR: Executive Director, STFC National Laboratories, UK; Chair, RAL-IAC
- Juha ÄYSTÖ: Director of Helsinki Institute of Physics, Finland
- Angela BRACCO: Prof., Department of Physics, the University of Milan, Italy
- Masaki FUKUSHIMA: Prof., Institute for Cosmic Ray Research, University of Tokyo, Japan
- Ken’ichi IMAI: Group Leader, Research Group for Hadron Physics, Advanced Science Research Center, JAEA, Japan
- Marek LEWITOWICZ: Deputy Director, GANIL (Grand Accélérateur National d’lons Lourds), France
- Martin MERKING: Head, Accelerator Division, TRIUMF, Canada
- Witold NAZAREWICZ: Prof., Department of Physics and Astronomy, the University of Tennessee, USA
- Susumu SHIMOURA: Prof., Center for Nuclear Study (CNS), University of Tokyo, Japan
- Matthias SCHÄDEL: Group Leader, Research Group for Superheavy Elements, Advanced Science Research Center, JAEA, Japan
- Jun SUGIYAMA: Principal Research Scientist, Toyota Central R&D Labs., INC, Japan
- Wolfgang WEISE: Director, European Center for Theoretical Studies in Nuclear Physics and Related Areas, Italy
- GuoQing XIAO: Director, Institute of Modern Physics, Chinese Academy of Sciences, China
- Akira YAMAMOTO: Head, Linear Collider Project Office, Department of Advanced Accelerator Technologies, KEK, Japan

RBRC Scientific Review Committee (SRC)

Members (as of March 31, 2015)
- Richard MILNER (Chair): Prof., Director, Laboratory for Nuclear Science, MIT, USA
- Shin’ya AOKI: Prof., Yukawa Institute for Theoretical Physics, Kyoto University, Japan
- Ken’ichi IMAI: Group Leader, Research Group for Hadron Physics, Advanced Science Research Center, JAEA, Japan
- Tetsuo MATSUI: Prof., Department of Basic Science, Graduate School of Arts and Sciences, Komaba, University of Tokyo, Japan
- Alfred MUELLER: Prof., Department of Physics, Columbia University, USA
- Peter Braun-MUNZINGER: Prof., Dr. GSI Helmholtzzentrum für Schwerionenforschung, Germany
- Charles PRESCOTT: Prof., Stanford Linear Accelerator Center, USA
- Akira UKAWA: Prof., Graduate School of Pure and Applied Science, University of Tsukuba, Japan
### 6. International Collaboration

<table>
<thead>
<tr>
<th>Country</th>
<th>Partner Institute</th>
<th>Objects</th>
<th>RNC contact person</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>Stefan Meyer Institute for Subatomic Physics</td>
<td>Experimental and theoretical hadron physics, especially in exotic hadronic atoms and meson and baryon nuclear bound states</td>
<td>Masahiko IWASAKI, Chief Scientist, Director of Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td>Belgium</td>
<td>Katholieke Universiteit Leuven</td>
<td>Framework</td>
<td>Michiharu WADA, Team Leader, SLOWRI Team</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>The Institute for Nuclear Research and Nuclear Energy (INRNE)</td>
<td>Framework</td>
<td>Hedeki UENO, Chief Scientist, Nuclear Spectroscopy Laboratory</td>
</tr>
<tr>
<td>Canada</td>
<td>TRIUMF</td>
<td>Accelerator-based Science</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td>China</td>
<td>China Nuclear Physics Society</td>
<td>Creation of the council for China-Japan research collaboration on nuclear physics</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>Peking University</td>
<td>Nuclear Science</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>Shanghai Jiao Tong University</td>
<td>International Joint Graduate School Program</td>
<td>Takashi NAKATSUKASA, Associate chief scientist, Theoretical Nuclear Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>ZHEJIANG University</td>
<td>International Joint Graduate School Program</td>
<td>Yasa WATANABE, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td></td>
<td>Institute of Modern Physics, Chinese Academy of Science</td>
<td>Physics of heavy ions</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>School of Nuclear Science and Technology, Lanzhou University</td>
<td>Framework</td>
<td>Yur MA, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td></td>
<td>School of Physics, Nanjing University</td>
<td>Framework</td>
<td>Emiko HIYAMA, Associate chief scientist, Strangeness Nuclear Physics Laboratory</td>
</tr>
<tr>
<td>EU</td>
<td>European Gamma-Ray Spectroscopy Pool Owners Committee</td>
<td>The use of Euroball detector at RIKEN</td>
<td>Shunji NISHIMURA, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*)</td>
<td>Theoretical physics</td>
<td>Tetsuo HATSUDA, Deputy Director, Chief Scientist, Quantum Hadron Physics Laboratory</td>
</tr>
<tr>
<td>CERN</td>
<td></td>
<td>Framework</td>
<td>Satoshi YOKKAICHI, Senior Research Scientist, Radiation Laboratory</td>
</tr>
<tr>
<td></td>
<td>ALICE Collaboration</td>
<td>RD-51:R&amp;D programme for micro-pattern gas detectors (MPGD)</td>
<td>Satoshi YOKKAICHI, Senior Research Scientist, Radiation Laboratory</td>
</tr>
<tr>
<td></td>
<td>GSI &amp; Reaction with Relativistic Radioactive Beams (R3B) Collaboration</td>
<td>To unravel structure of nuclei in the vicinity of and beyond the neutron dripline through experiments with the NeuLAND detector combined with the SAMURAI magnetic spectrometer at the RIBF</td>
<td>Tomohiro UESAKA, Chief Scientist, Spin Isopin Laboratory</td>
</tr>
<tr>
<td>Finland</td>
<td>University of Jyvaskyla</td>
<td>Basic nuclear physics and related instrumentation</td>
<td>Michiharu WADA, Team Leader, SLOWRI Team</td>
</tr>
<tr>
<td>France</td>
<td>National Institute of Nuclear Physics and Particle Physics (IN2P3)</td>
<td>Physics of heavy ions</td>
<td>Tohru MOTOBAYASHI, RIBF synergetic-use coordinator</td>
</tr>
<tr>
<td></td>
<td>CNRS, CEA, GANIL, Université Paris Sud, etc.</td>
<td>Creation of an International Associated Laboratory (ILIA)</td>
<td>Tohru MOTOBAYASHI, RIBF synergetic-use coordinator</td>
</tr>
<tr>
<td></td>
<td>IRFU/CEA-Saclay DSM/IRFU, IPNO CNRS IN2P3, GANIL</td>
<td>French-Japanese International Associated Laboratory for Nuclear Structure Problems</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>CEA-DSM</td>
<td>The use of MINOS device at RIKEN</td>
<td>Tomohiro UESAKA, Chief Scientist, Spin Isopin Laboratory</td>
</tr>
<tr>
<td></td>
<td>SIMEM Graduate School, Department of Physics, Caen University</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spin Isopin Laboratory</td>
</tr>
<tr>
<td></td>
<td>Université de Caen Basse Normandie</td>
<td>International Joint Graduate School Program</td>
<td>Tomohiro UESAKA, Chief Scientist, Spin Isopin Laboratory</td>
</tr>
<tr>
<td>Country</td>
<td>Partner Institute</td>
<td>Objects</td>
<td>RNC contact person</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------</td>
<td>---------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Germany</td>
<td>Technische Universität München</td>
<td>Nuclear physics, hadron physics, nuclear astrophysics</td>
<td>Emiko HIYAMA, Associate chief scientist,Strange Nuclear Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>Max-Planck Gesellschaft</td>
<td>Comprehensive agreement</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>GSI</td>
<td>Physics of heavy ions and accelerator</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td>Hungary</td>
<td>The Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI)</td>
<td>Nuclear physics, Atomic Physics</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>ITB, UNPAD, ITS, UGM</td>
<td>Material science using muons at the RIKEN-RAL muon facility</td>
<td>Isao WATANABE, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td></td>
<td>UNPAD</td>
<td>International Joint Graduate School Program</td>
<td>Isao WATANABE, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td></td>
<td>Institut Technologi Bandung (ITB)</td>
<td>International Joint Graduate School Program</td>
<td>Isao WATANABE, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td></td>
<td>Universitas Hasanuddin</td>
<td>Agriculture and the related fields involving heavy-ion beam mutagenesis using Indonesian crops</td>
<td>Tomohiro UESAKA, Group Director, Accelerator Applications Research Group</td>
</tr>
<tr>
<td>Italy</td>
<td>National Institute of Nuclear Physics (INFN)</td>
<td>Physics of heavy ions</td>
<td>Tohru MOTOBAYASHI, RIBF synergetic-use coordinator</td>
</tr>
<tr>
<td>Korea</td>
<td>Seoul National University</td>
<td>Nishina School</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>Institute of Basic Science, Rare Isotope Science Project</td>
<td>Rare ion accelerator and related fields</td>
<td>Hiroyoshi SAKURAI, Shunsuke NISHIMURA</td>
</tr>
<tr>
<td></td>
<td>Department of Physics, Kyungpook National University</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>College of Natural Sciences of Kyungpook National University</td>
<td>International Joint Graduate School Program</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>College of Science, Yonsei University</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>Department of Physics, Yonsei University</td>
<td>International Joint Graduate School Program</td>
<td>Yasuyuki AKIBA, Radiation Laboratory</td>
</tr>
<tr>
<td></td>
<td>Department of Physics, Korea University</td>
<td>Framework</td>
<td>Yuji GOTO, Radiation Laboratory</td>
</tr>
<tr>
<td></td>
<td>College of Natural Science, Ewha Women’s University</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Universiti Sains Malaysia</td>
<td>Framework on Muon Science</td>
<td>Isao WATANABE, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td>Poland</td>
<td>the Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences (IFJ PAN)</td>
<td>Framework</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td>Romania</td>
<td>“Horia Hulubei” National Institute of Physics and Nuclear Engineering Bucharest-Magurele, Romania</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td>Russia</td>
<td>Joint Institute for Nuclear Research (JINR)</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>Russian Research Center “Kurchatov Institute”</td>
<td>Framework</td>
<td>Hiroyoshi SAKURAI, Tomohiro UESAKA, Osamu KAMIGAITO, Masanori WAKASUGI</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Paul Scherrer Institute</td>
<td>Improve the performance and reliability of accelerator systems</td>
<td>Osamu KAMIGAITO, Director, Chief Scientist, Accelerator Group</td>
</tr>
<tr>
<td>UK</td>
<td>The Science and Technology Facilities Council</td>
<td>Muon science using the ISIS Facility at the Rutherford Appleton Laboratory</td>
<td>Philip KING, Director of RIKEN-RAL muon facility</td>
</tr>
<tr>
<td></td>
<td>University of Liverpool</td>
<td>International Joint Graduate School Program</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td>USA</td>
<td>BNL</td>
<td>The Spin Physics Program at the Relativistic Heavy Ion Collider(RHIC)</td>
<td>Hideto EN’YO, Director of RNC</td>
</tr>
<tr>
<td></td>
<td>Columbia University</td>
<td>The development of QCDCQ</td>
<td>Taku IZUBUCHI, Group Leader, Computing Group, RRBC</td>
</tr>
<tr>
<td></td>
<td>Michigan State University</td>
<td>Framework</td>
<td>Tomohiro UESAKA, Chief Scientist, Spins Isospin Laboratory</td>
</tr>
<tr>
<td></td>
<td>TPC(Time Projection Chamber)</td>
<td></td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory &amp; Tadaaki ISOBE, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Vietnam Atomic Energy Commission</td>
<td>Framework</td>
<td>Tohru MOTOBAYASHI, RIBF synergetic-use coordinator</td>
</tr>
<tr>
<td></td>
<td>Hanoi University of Science</td>
<td>International Joint Graduate School Program</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
<tr>
<td></td>
<td>Institute of Physics, Vietnam Academy of Science and Technology</td>
<td>Framework</td>
<td>Hiroyoshi SAKURAI, Deputy Director, Chief Scientist, Radioactive Isotope Physics Laboratory</td>
</tr>
</tbody>
</table>
7. Awards

<table>
<thead>
<tr>
<th>Awardee, Laboratory / Team</th>
<th>Award</th>
<th>Organization</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetsuo HATSUDA, Quantum Hadron Physics Laboratory</td>
<td>The Prizes for Science and Technology in Research Category, in the FY2015 Commendation for Science and Technology</td>
<td>The Minister of Education, culture, Sports, Science and Technology (MEXT)</td>
<td>Apr. 15</td>
</tr>
<tr>
<td>Shinya AOKI (Visiting Scientist), Quantum Hadron Physics Laboratory Noriyoshi ISHII (Visiting Scientist), Radiation Laboratory</td>
<td>The Outstanding Presentation Award for their research at the 125th Meeting of the Japanese Society of Breeding</td>
<td>Japanese Society of Breeding</td>
<td>May 14</td>
</tr>
<tr>
<td>Tomonari HIRANO, Ion Beam Breeding Team Yusuke KAZAMA, Ion Beam Breeding Team Kotaro ISHII, Ion Beam Breeding Team Sumir OHBU, Ion Beam Breeding Team Yuki SHIRAKAWA, Ion Beam Breeding Team Tomoko ABE, Ion Beam Breeding Team</td>
<td>Young Scientist Award</td>
<td>The 5th Asia Pacific Symposium on Radiation Chemistry (APSRC2014)</td>
<td>Sep. 11</td>
</tr>
<tr>
<td>Tetsuo HATSUDA, Quantum Hadron Physics Laboratory Shinya AOKI (Visiting Scientist), Quantum Hadron Physics Laboratory Noriyoshi ISHII (Visiting Scientist), Radiation Laboratory</td>
<td>The Prizes for Science and Technology in Research Category, in the FY2015 Commendation for Science and Technology</td>
<td>The Minister of Education, culture, Sports, Science and Technology (MEXT)</td>
<td>Apr. 15</td>
</tr>
<tr>
<td>Tomonari HIRANO, Ion Beam Breeding Team Yusuke KAZAMA, Ion Beam Breeding Team Kotaro ISHII, Ion Beam Breeding Team Sumir OHBU, Ion Beam Breeding Team Yuki SHIRAKAWA, Ion Beam Breeding Team Tomoko ABE, Ion Beam Breeding Team</td>
<td>The Outstanding Presentation Award for their research at the 125th Meeting of the Japanese Society of Breeding</td>
<td>Japanese Society of Breeding</td>
<td>May 14</td>
</tr>
<tr>
<td>Tomonari HIRANO, Ion Beam Breeding Team Yusuke KAZAMA, Ion Beam Breeding Team Kotaro ISHII, Ion Beam Breeding Team Sumir OHBU, Ion Beam Breeding Team Yuki SHIRAKAWA, Ion Beam Breeding Team Tomoko ABE, Ion Beam Breeding Team</td>
<td>Young Scientist Award</td>
<td>The 5th Asia Pacific Symposium on Radiation Chemistry (APSRC2014)</td>
<td>Sep. 11</td>
</tr>
<tr>
<td>Macayama TAKUYA, Beam Dynamics &amp; Diagnostics Team</td>
<td>The silver prize of the 2nd Yuasa Prize</td>
<td>Ochanomizu University</td>
<td>Dec. 24</td>
</tr>
<tr>
<td>Yuko MOTIZUKI, the Astro-Glaciology Research Unit</td>
<td>niceSTEP Award</td>
<td>National Institute of Science and Technology Policy</td>
<td>Dec. 19</td>
</tr>
<tr>
<td>Kimiko SEKIGUCHI (Visiting Scientist), Spin Isospin Laboratory</td>
<td>The 20th Best Paper Award</td>
<td>The Physical Society of Japan</td>
<td>Mar. 23</td>
</tr>
<tr>
<td>Yoichi IKEDA, Quantum Hadron Physics Laboratory Toru SATO (Visiting Scientist), Strangeness Nuclear Physics Laboratory</td>
<td>The 9th Young Scientist Award in the field of experimental nuclear physics</td>
<td>The Physical Society of Japan</td>
<td>Mar. 21</td>
</tr>
<tr>
<td>Aiko TAKAMINE (Visiting Scientist), SLOWRI Team</td>
<td>Appointment as an APS Fellow</td>
<td>The American Physical Society</td>
<td>Mar. 13</td>
</tr>
</tbody>
</table>

8. Brief overview of the RI Beam Factory

Intensity of Primary Beams

Achieved beam intensities (as of March 2015)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Intensity</th>
<th>Energy</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>28 pA</td>
<td>(345 MeV/u, Oct. 2014)</td>
<td></td>
</tr>
<tr>
<td>$^{124}\text{Xe}$</td>
<td>38 pA</td>
<td>(345 MeV/u, Jun. 2013)</td>
<td></td>
</tr>
<tr>
<td>$^{86}\text{Kr}$</td>
<td>30 pA</td>
<td>(345 MeV/u, Nov. 2007)</td>
<td></td>
</tr>
<tr>
<td>$^{70}\text{Zn}$</td>
<td>123 pA</td>
<td>(345 MeV/u, Jun. 2014)</td>
<td></td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>530 pA</td>
<td>(345 MeV/u, Nov. 2014)</td>
<td></td>
</tr>
<tr>
<td>$^{18}\text{O}$</td>
<td>1,000 pA</td>
<td>(345 MeV/u, Jun. 2010)</td>
<td></td>
</tr>
<tr>
<td>$^{14}\text{N}$</td>
<td>400 pA</td>
<td>(250 MeV/u, Oct. 2010)</td>
<td></td>
</tr>
<tr>
<td>$^{4}\text{He}$</td>
<td>1,000 pA</td>
<td>(250 MeV/u, Oct. 2009)</td>
<td></td>
</tr>
<tr>
<td>$\text{d}$</td>
<td>1,000 pA</td>
<td>(250 MeV/u, Oct. 2010)</td>
<td></td>
</tr>
<tr>
<td>$\text{pol. d}$</td>
<td>1,000 pA</td>
<td>(250 MeV/u, Apr. 2009)</td>
<td></td>
</tr>
</tbody>
</table>
Total beam time for experiments
VI. RNC ACTIVITIES


Total beam time allocated to BigRIPS experiments
1. Abstract

Atomic nuclei are made of protons and neutrons bound by the exchange of Yukawa's pion and other mesons. Also, protons and neutrons are made of quarks bound by the exchange of gluons. These strong interactions are governed by the non-Abelian gauge theory called the quantum chromodynamics (QCD). On the basis of theoretical and numerical analyses of QCD, we study the interactions between the nucleons, properties of the dense quark matter realized at the center of neutron stars, and properties of the hot quark-gluon plasma realized in the early Universe. Strong correlations common in QCD and cold atoms are also studied theoretically to unravel the universal features of the strongly interacting many-body systems. Developing perturbative and non-perturbative techniques in quantum field theory and string theory are of great importance not only to solve gauge theories such as QED and QCD, but also to find the theories beyond the standard model of elementary particles. Various theoretical approaches along this line have been attempted.

2. Major Research Subjects

(1) Improving the tenth-order QED contribution to the electron g−2
(2) Physics of particles with resonant interactions
(3) String duality and Sine-Square Deformation of Conformal Field Theory
(4) Theory of spontaneous symmetry breaking
(5) QCD under extreme conditions
(6) Lattice baryon forces

3. Summary of Research Activity

(1) Improving the tenth-order QED contribution to the electron g−2

The preliminary value of the tenth-order of the perturbation theory of QED contribution to the electron anomalous magnetic moment (g−2) was reported by us in 2012. Since then, we have been involved in improving and establishing its accuracy. To carry out it, we reevaluated the most difficult and large set of the Feynman diagrams by using the advanced technique of numerical calculation especially suitable to RIKEN's supercomputer. As a result, we have obtained more reliable and more precise values for the eighth- and tenth-order terms. Together with the Harvard experiment of the electron g−2, it leads to the world-best value of the fine-structure constant α that will be used to determine a next CODATA recommended value of α.

(2) Physics of particles with resonant interactions

Some particles, such as nucleons, can only weakly or nearly bind by pair. As a result, their pairwise interaction is resonant. Resonant interactions induce universal few-body phenomena, such as the Efimov effect. These phenomena lead to the existence of universal three-body bound states, that can be easily investigated with ultra-cold atoms. After analysing these experiments and clarifying these few-body phenomena for the past few years, we have now started to explore their consequences at the many-body level, by first looking at mixtures of resonantly interacting heavy and light particles. The near-resonant interaction induces a phase made of trimers of two heavy and one light particles. We have characterized this phase by carrying out for the first time a six-body calculation of the effective interaction between two universal trimers.

(3) String duality and Sine-Square Deformation of Conformal Field Theory

String duality is the concept that has been leading us to better understandings of the dynamics of string theory. One of such dualities is the open-closed duality, which suggests relation between gauge theories and the theory of gravity, thus could be behind another duality, AdS/CFT correspondence. Since the difference between open string and closed string is the difference of the boundary condition of the worldsheet of string, of particular interest is the recently found phenomenon called Sine-Square Deformation (SSD) in which certain quantum systems exhibit the change from the closed-boundary vacuums to open-boundary ones through the spatial modulation of the couplings. We investigated SSD in the context of Conformal Field Theory (CFT) in particular and found continuous Virasoro algebra, suggesting that CFT would acquire a continuous energy spectrum under SSD.

(4) Theory of spontaneous symmetry breaking

(4-1) Dispersion relations of Nambu-Goldstone modes at finite temperature and density

We discussed the dispersion relations of Nambu-Goldstone (NG) modes associated with spontaneous breaking of internal symmetries at finite temperature and/or density. We showed that the dispersion relations of type-A (I) and type-B (II) NG modes are linear and quadratic in momentum, whose imaginary parts are quadratic and quartic, respectively. In both cases, the real parts of the dispersion relations are larger than the imaginary parts when the momentum is small, so that the NG modes can propagate far away. We derived the gap formula for NG modes in the presence of a small explicit breaking term. We also discussed the gapped partners of type-B NG modes, when type-A and type-B NG modes coexisted.

(4-2) Effective field theory for spacetime symmetry breaking

We discussed the effective field theory for spacetime symmetry breaking from the local symmetry point of view. By gauging spacetime symmetries, the identification of Nambu-Goldstone (NG) fields and the construction of the effective action were performed based on the breaking pattern of diffeomorphism, local Lorentz, and (an)isotropic Weyl symmetries as well as the internal symmetries including possible central extensions in nonrelativistic systems. Such a local picture distinguishes, e.g., whether the symmetry breaking condensations have spins and provides a correct identification of the physical NG fields, while the standard coset construction based on global symmetry breaking does not. We illustrated that the local picture becomes important in particular when we took into account
massive modes associated with symmetry breaking, whose masses were not necessarily high. We also revisited the coset construction for spacetime symmetry breaking. Based on the relation between the Maurer-Cartan one form and connections for spacetime symmetries, we classified the physical meanings of the inverse Higgs constraints by the coordinate dimension of broken symmetries. Inverse Higgs constraints for spacetime symmetries with a higher dimension remove the redundant NG fields, whereas those for dimensionless symmetries can be further classified by the local symmetry breaking pattern.

(5) QCD under extreme conditions

(5-1) Production and Elliptic Flow of Dileptons and Photons in the semi-Quark Gluon Plasma

We considered the thermal production of dileptons and photons at temperatures above the critical temperature in QCD. We used a model where color excitations are suppressed by a small value of the Polyakov loop, the semi Quark-Gluon Plasma (QGP). Comparing the semi-QGP to the perturbative QGP, we found a mild enhancement of thermal dileptons. In contrast, to leading logarithmic order in weak coupling there are far fewer hard photons from the semi-QGP than the usual QGP. To illustrate the possible effects on photon and dileptons production in heavy ion collisions, we integrated the rate with a realistic hydrodynamic simulation. Dileptons uniformly exhibit a small flow, but the strong suppression of photons in the semi-QGP tends to bias the elliptical flow of photons to that generated in the hadronic phase.

(5-2) Relativistic hydrodynamics from quantum field theory on the basis of the generalized Gibbs ensemble method

We derived relativistic hydrodynamics from quantum field theories by assuming that the density operator is given by a local Gibbs distribution at initial time. We decomposed the energy-momentum tensor and particle current into nondissipative and dissipative parts, and analyzed their time-evolution in detail. Performing the path-integral formulation of the local Gibbs distribution, we microscopically derived the generating functional for the nondissipative hydrodynamics. We also constructed a basis to study dissipative corrections. In particular, we derived the first-order dissipative hydrodynamic equations without choice of frame such as the Landau-Lifshitz or Eckart frame.

(6) Lattice baryon forces

One of the most important subjects in nuclear physics is to determine nuclear forces and hyperon forces, or generalized baryon forces, directly based on the fundamental theory, QCD. In HAL QCD Collaboration, we have been developing a novel lattice QCD formulation and performing first-principles numerical simulations to determine baryon forces. Spin-orbit forces have been calculated for the first time, and attraction in 3P2 channel is observed, which is related to the P-wave neutron pairing in neutron stars. The calculation of the N-Omega interaction shows that the system is bound in SS2 channel. Three-nucleon forces have been calculated at several heavy quark masses, and quark mass dependence is found to be small. The lattice calculations are extended to the the exotic tetraquark systems as Tc and Tcs, and the phenomenological diquark picture in these systems is studied as well. As an application, properties of medium-heavy nuclei have been calculated based on lattice nuclear forces, and so-called "mass-formula" is obtained.

Members

Chief Scientist (Lab. Head)
Tetsuo HATSUDA (Deputy Director, RNC)

Vice Chief Scientist
Tsukasa TADA

Research & Technical Scientists
Takumi DOI (Senior Research Scientist)
Yoshimasa HIDAKA (Senior Research Scientist)

Nishina Center Research Scientist
Makiko NIO

Special Postdoctoral Researchers
Arata YAMAMOTO (~ Mar. 31, 2014)
Kanabu NAWA (~ Mar. 31, 2015)
Yuji SAKAI (~ Apr. 30, 2014)

Foreign Postdoctoral Researchers
Gergely Peter FEJOES
Vojtech KREJCIRIK (Apr. 1, 2014 ~)

Postdoctoral Researchers
Yoichi IKEDA
Keich HATTORI (Feb. 1, 2014 ~)
Taichi KAWANAI (~ Sep. 30, 2014)

Junior Research Associate
Masaru HONGO (Univ. of Tokyo)
International Program Associate
Robert Friedrich LANG (~ Feb. 12, 2012)

Visiting Scientists
Noriyoshi ISHII (Osaka Univ.)
Yoshitaka HATTA (Kyoto Univ.)
Motoki TACHIBANA (Saga Univ.)
Masashi HAYAKAWA (Nagoya Univ.)
Toichiro KINOSHITA (Cornell Univ.)
Kenji SAKAI (Univ. of Tsukuba)
Shinya AOKI (Kyoto Univ.)
Hiroshi SUZUKI (Kyushu Univ.)
Keiko MURANO (Osaka Univ.)
Daisuke KADOH (KEK)
Yuji HIRONO (Univ. of Tokyo)
Tatsuuyuki TAKATSUKA (Iwate Univ.)
Hong MAO (Hangzhou Normal Univ.)
Arata YAMAMOTO (Univ. of Tokyo)

Student Trainees
Bruno CHARRON (Univ. of Tokyo)
Shimpei ENDO (Univ. of Tokyo)
Yusuke HAMA (Univ. of Tokyo)
Takao TACHIBANA (Univ. of Tokyo)
Tomoya HAYATA (Univ. of Tokyo)
Koichi MURASE (Univ. of Tokyo)
Yuya TANIZAKI (Univ. of Tokyo)

Part-time Workers
Theoretical Research Division
Theoretical Nuclear Physics Laboratory

1. Abstract

Nuclei are finite many-particle systems composed of protons and neutrons. They are self-bound in femto-scale (10^{-15}m) by the strong interaction (nuclear force) whose study was pioneered by Hideki Yukawa. Uncommon properties of the nuclear force (repulsive core, spin-isospin dependence, tensor force, etc.) prevent complete microscopic studies of nuclear structure. There exist number of unsolved problems even at present. In addition, radioactive beam facilities reveal novel aspects of unstable nuclei. We are tackling these old problems and new issues in theoretical nuclear physics, developing new models and pursuing large-scale calculations of quantum many-body systems. We are also strongly involved in research on other quantum many-body systems, to resolve mysteries in the quantum physics.

2. Major Research Subjects

(1) Nuclear structure and quantum reaction theories
(2) First-principle calculations with the density functional theory for many Fermion systems
(3) Computational nuclear physics

3. Summary of Research Activity

(1) Systematic calculation of $T = 1$ triplets with proton-neutron-mixed energy density functionals

We have performed a systematic calculation for the $T = 1$ isobaric analog states (IAs) based on the Skyrme energy density functionals (EDFs) including protons-neutron ($p-n$) mixing. The IAs are calculated using the isocranking method. First we performed a systematic calculation for the energies of the $T = 1$ triplets in the $A = 10 \sim 66$ region with several Skyrme parameter sets. We used the isoscalar $p-n$ mixed Skyrme EDFs, which are invariant under rotation in the isospin space, together with the Coulomb energy functional. The calculated results show a systematic underestimation from the experimental data, which may be related to violation of the charge symmetry and the charge independence of the nucleon-nucleon interaction and may imply that we need to further extend the energy functionals including isospin breaking terms. Recently, we have started a calculation including the isospin breaking interactions.

(2) Three dimensional mesh calculations for covariant density functional theory

The covariant density functional theory has some numerical difficulties, such as variational collapse and the fermion doubling. Because of these problems, the three-dimensional (3D) mesh calculation was impossible for a long time. In order to realize such calculations for the first time, we proposed a novel and practical method to solve Dirac equations in the 3D coordinate space. The variational collapse is prevented by employing a method based on the variational principle for the inverse of a single-particle Hamiltonian, while for the fermion doubling, we have extended the method of Wilson fermion, which has been widely employed in lattice QCD calculations.

Using $^{16}$O as an example, we have confirmed that our strategy provides accurate solutions for self-consistent mean-field calculations without the influence of the negative-energy spectrum and the spurious solutions of a discretized Dirac equation. We have also shown with $^{24}$Mg and $^{28}$Si that this method is applicable to deformed solutions in the $(\beta, \gamma)$ deformation plane. This development enables us, e.g., i) to study any complicated structure of nuclei with a single numerical code, ii) to compare directly the results of the relativistic models to those of 3D mesh calculations with the non-relativistic models, and iii) to provide reliable theoretical predictions with the relativistic models for unknown nuclei allowing symmetry-breaking solutions. It also allows a straightforward extension of the finite amplitude method within the relativistic framework for a study of nuclear excitations in deformed nuclei.

(3) Microscopic description of fusion hindrance in heavy systems

We investigate fusion hindrance in heavy systems, where the fusion probability is strongly hindered compared with that in light- and medium-mass systems, to understand the origin of the fusion hindrance from a microscopic point of view. We employ microscopic time-dependent Hartree-Fock (TDHF) model for the analysis. In TDHF simulations, we reasonably reproduce the extra-push energies estimated from experimental data for heavy systems. Then, we extract nucleus-nucleus potential and energy dissipation by combining TDHF simulations for fusion reactions with Newton equation including a dissipation term. Extracted potentials in heavy systems show monotonic increase as the relative distance of two nuclei decreases and the disappearance of an ordinary barrier structure, which are different from lighter systems. Using these properties, we analyze the origin of the extra-push energy and find that the contribution to extra-push energy from the increase in potential is larger than that from dissipated energy in most systems. We conclude from our analysis that the main origin of the fusion hindrance is dynamical increase in potential.

(4) Hidden pseudo-spin and spin symmetries and their origins in atomic nuclei

Pseudo-spin symmetry (PSS) was introduced to explain the near degeneracy between pairs of nuclear single-particle states with the quantum numbers $(n-1, l+1/2, j=\pm 1/2)$ and $(n, l, j=l+1/2)$. We have written a review article [arXiv:1411.6774, Phys. Rep. in press], and intended to provide a comprehensive overview on the recent progress of pseudo-spin and spin symmetries in a systematic way. These symmetries were discussed in various systems and potentials: from stable nuclei to exotic nuclei, from non-confining to confining potentials, from local to non-local potentials, from central to tensor potentials, from bound states to resonant states, from nucleon spectra to...
anti-nucleon spectra, from nucleon spectra to hyperon spectra, from spherical nuclei to deformed nuclei.

Furthermore, three of the open issues in this field were selected and discussed in detail, i.e., the perturbative nature of PSS, the puzzle of intruder states, and the supersymmetric (SU(4)) representation of PSS. For the perturbative nature of PSS, we emphasized that whether or not the symmetry breaking behaves perturbatively depends on whether an appropriate symmetry limit is chosen and an appropriate symmetry-breaking term is identified. As long as an appropriate symmetry limit is chosen, the nature of PSS is indeed perturbative. For the puzzle of intruder states, we showed several different features about this puzzle. By doing that a number of “contradicting” results in the literature for the spin (pseudo-spin) partners have been clarified in an explicit way. For the SU(4) representation of PSS, we pointed out one of the promising ways for understanding the PSS and its symmetry breaking, by combining the similarity renormalization group, the SUSY quantum mechanics, and the perturbation theory. Meanwhile, how to apply the SUSY technique directly to the Dirac equations, which have non-trivial scalar and vector potentials, remains an interesting and open question.

(5) "Hybrid Kurotama model" for total reaction cross sections

We have developed a new general-purpose-total-reaction-cross-section model/subroutine called ‘Hybrid Kurotama’. The model has been tested and compared with available data for $p^\uparrow\text{He}$, $p^n\text{nucleus}$, and $nucleus+nucleus$ total reaction cross sections. The overall agreement has been found better than former published models. This model is therefore very suitable to be used in any deterministic or Monte Carlo particle and heavy ion transport code.

(6) Improved parametrization of the transparency parameter in Kox and Shen models of total reaction cross sections

The total reaction cross section is an essential quantity in particle and heavy-ion transport codes when determining the mean-free path of a transported particle. Many transport codes determine the distance a particle is transported before it collides with the target or is stopped in the target material, with the Monte Carlo (MC) method using semiempirical parametrization models for the total reaction cross sections. In order to improve the well-known Kox and Shen models of total reaction cross sections and allow the models to be used at energies below 30 MeV/nucleon, we have proposed a modified parametrization of the transparency parameter. We have also reported that the Kox and Shen models have a projectile-target asymmetry and should be used so that the lighter nucleus is always treated as the projectile.

(7) Energy and mass number dependence of total reaction cross sections of nuclei

We have systematically analyzed nuclear reaction data that are sensitive to nuclear size, namely, proton-nucleus total reaction cross sections and differential elastic cross sections, using a phenomenological black-sphere approximation of nuclei that we are developing. In this framework, the radius of the black sphere is found to be a useful length scale that simultaneously accounts for the observed proton-nucleus total reaction cross section and first diffraction peak in the proton elastic differential cross section. This framework is expected to be applicable to any kind of projectile that is strongly attenuated in the nucleus. On the basis of a cross-section formula constructed within this framework, we find that a less familiar $A^{1/6}$ dependence plays a crucial role in describing the energy dependence of proton-nucleus total reaction cross sections.

(8) Probing the critical behavior in the evolution of GDR width at very low temperatures in $A \sim 100$ mass region

The influence of giant dipole resonance (GDR) induced quadrupole moment on GDR width at low temperatures is investigated experimentally by measuring the GDR width systematically in the unexplored temperature range $T = 0.8-1.5$ MeV, for the first time, in $A \sim 100$ mass region. The measured GDR width, using alpha induced fusion reaction, for $^{97}$Tc confirms that the GDR width remains constant at the ground state value up to a critical temperature and increases sharply thereafter with the increase in $T$. The data have been compared with the adiabatic thermal shape fluctuation model (TSFM), phenomenological critical temperature fluctuation model (CTFM) and microscopic phonon damping model (PDM). Interestingly, the CTFM and PDM give the similar results and agree with the data, whereas the TSFM differs significantly even after incorporating the shell effects indicating towards the inclusion of GDR-GQR coupling in the TSFM.

(9) Giant dipole resonance in highly excited nuclei

The evolution of the giant dipole resonance’s (GDR) width and shape at finite temperature $T$ and angular momentum $J$ is described within the framework of the phonon damping model (PDM). The PDM description is compared with the established experimental systematics obtained from heavy-ion fusion and inelastic scattering of light particles on heavy target nuclei, as well as with predictions by other theoretical approaches. Extended to include the effect of angular momentum $J$, its strength functions have been averaged over the probability distributions of $T$ and $J$ for the heavy-ion fusion evaporation reaction, which forms the compound nucleus $^{98}$Mo at high $T$ and $J$. The results of theoretical predictions are found in excellent agreement with the experimental data. The predictions by PDM and the heavy-ion fusion data are also employed to predict the viscosity of hot medium and heavy nuclei.

We also explore an approach that includes temperature-dependent shell effects and fluctuations of the pairing field in the thermal shape fluctuation model (TSFM). We apply this approach to study the width of GDR in $^{120}$Sn, $^{179}$Au and $^{208}$Pb. Our results demonstrate that the TSFM that includes pairing fluctuations can explain the recently observed quenching in the GDR width.

(10) Reentrance phenomenon of superfluid pairing in hot rotating nuclei

When a nucleus rotates (total angular momentum $J$ and/or rotational frequency $\omega$ are not zero), the nucleon (proton and neutron) pairs located around the Fermi surface will scatter to the empty levels nearby and lead to the decreasing of pairing correlation. When the $J$ or $\omega$ is sufficiently high, i.e., equal to the critical value $J_c$ or $\omega_c$, the scattered nucleons completely block the single-particle levels around the Fermi surface. Consequently, pairing correlation disappears. However, when $J$ is slightly higher than $J_c$ (or $\omega > \omega_c$), the increase of temperature $T$ will relax the particles scattered around the Fermi surface and causes some levels become partially unoccupied, making them available for scattered pairs. As a result, the pairing correlation reappears at some critical value $T_1$. As $T$ goes higher, e.g., at $T_2 > T_1$, the newly created pairs will be eventually broken down again. This phenomenon is called the pairing reentrance. The recently developed
FTBCS1 theory that includes the effect due to quasiparticle-number fluctuations in the pairing field and angular momentum $z$ projection at $T \neq 0$ has predicted the pairing reentrance effect in some realistic nuclei. The shell-model Monte Carlo calculations have suggested that the pairing reentrance effect can be observed in the nuclear level density in a form of a local maximum at low $T$ (or excitation energy $E'$) and high $J$ (or $\omega$). Recently, an enhancement of level density of $^{104}$Pd at low $E'$ and high $J$ has been experimentally reported. This work demonstrates that the enhancement observed in the extracted level density of $^{104}$Pd is the first evidence of pairing reentrance phenomenon in atomic nuclei.

Members

Associate Chief Scientist (Lab. Head)
Takashi NAKATSUKASA

Research & Technical Scientist
Akihisa KOHAMA (Senior Research Scientist)

Nishina Center Research Scientist
Dang Dinh NGUYEN

Special Postdoctoral Researchers
Koichi SATO

Foreign Postdoctoral Researcher
Haozhao LIANG (Mar. 31, 2015 –)

Research Consultants
Akitsu IKEDA
Kenichi MATSUYANAGI

Visiting Scientists
Kazuhiro OYAMATSU (Aichi Shukutoku Univ.)
Kei IIDA (Kochi Univ.)
Yasuyuki SUZUKI (Niigata Univ.)
Nguyen Quang HUNG (Tan Tao Univ.)
Kazuyuki OGATA (Osaka Univ.)

Takashi ABE (Univ. of Tokyo)
Naoyuki ITAGAKI (Kyoto Univ.)
Kazuko TANABE (Osotuma Women's Univ.)
Kaori KAKI (Shizuoka Univ.)
Kiyomi IKEDA (Niigata Univ.)

Part-time Workers
Kiyomi ARAI
Noriko OKAYASU
Tsuneo SUZUKI
Miki KANOU

Yoko OZAWA (Mar. 31, 2014 –)
Kahori SHIMADA (Sep. 30, 2014 –)
Mie DOI (Oct. 1, 2014 –)
Naomi MURAKAMI (Jan. 1, 2015 –)
1. Abstract

We proposed an accurate calculation method called ‘Gaussian Expansion Method using infinitesimally shifted Gaussian lobe basis function’. When one proceeds to four-body systems, calculation of the Hamiltonian matrix elements becomes much laborious. In order to make the four-body calculation tractable even for complicated interactions, the infinitesimally-shifted Gaussian lobe basis function has been proposed. The GEM with the technique of infinitesimally-shifted Gaussians has been applied to various three-, four- and five-body calculations in hypernuclei, the four-nucleon systems, and cold-atom systems. As results, we succeeded in extracting new understandings in various fields.

2. Major Research Subjects

(1) Hypernuclear structure from the viewpoint of few-body problem
(2) Structure of exotic hadron system
(3) Baryon-baryon interaction based on lattice QCD
(4) Structure of three- and four-body $^4$He atom systems

3. Summary of Research Activity

(1) Recently, we observed of neutron-rich system $nn\Lambda$ as a bound state. To investigate this system, we performed $nn\Lambda+Nn\Sigma$ three-body coupled channel calculation. Using $YN$ interaction to reproduce observed binding energies for $^4\Lambda H$, $^4\Lambda He$, and $^3\Lambda H$, we do not find any bound state for $nn\Lambda$ system which is inconsistent with the data. Now, we propose the experimentalists to perform a search experiment of $nn\Lambda$ system again.

(2) It is interesting to study the structure of Ar isotope, since we have some superdeformed states (SD) in this isotope. Within the framework of AMD method, we investigate the structure of SD states. In addition, we study the structure of Ar $\Lambda$ hypernuclei. Then, we found that $\Lambda$-separation energy was dependent on the degree of deformation of core nuclei.

(3) Using several realistic $^4$He atomic potential, we calculate Efimov spectra of trimer and tetramer systems of $^4$He. Our result shows an extension of the universality in Efimov trimers that the appearance of the repulsive barrier at the three-body hyperradius $R_3 \approx 2 W_{vd}$ makes the critical scattering lengths independent of the short-range details of the interactions as reported in the literature and also in the present work for the $^4$He trimer with the realistic potentials.

Members

Associate Chief Scientist (Lab. Head)
Emiko HIYAMA

Contract Researcher
Yasuro FUNAKI

Research Scientists
Hiroya SUNO (Research Scientist, concurrent: Strangeness Nuclear Physics Laboratory, Main: Field Theory Research Team)

Special Postdoctoral Researcher
Masahiro ISAKA

Foreign Postdoctoral Researcher
Philipp GUBLER (– Oct. 31, 2014)

Postdoctoral Researcher
Hajime TOGASHI (Apr. 1, 2014 –)

Research Consultants
Yoshikazu FUJIWARA (Apr. 1, 2014 –)

Junior Research Associates
Tetsuya YOSHIDA (Apr. 1, 2014 –)  Saori MAEDA (Apr. 1, 2014 –)
Shota OHNISHI
1. Abstract
We proposed a method called 'Gaussian Expansion Method using infinitesimally shifted Gaussian lobe basis function'. When one proceeds to four-body systems, calculation of the Hamiltonian matrix elements becomes much laborious. In order to make the four-body calculation tractable even for complicated interactions, the infinitesimally-shifted Gaussian lobe basis function has been proposed. The GEM with the technique of infinitesimally-shifted Gaussians has been applied to various three-, four- and five-body calculations in hypernuclei, the four-nucleon systems, and cold-atom systems. As results, we succeeded in extracting new understandings in various fields.

2. Major Research Subjects
(1) Hypernuclear structure from the view point of few-body problem
(2) Structure of exotic hadron system
(3) Baryon-baryon interaction based on lattice QCD
(4) Structure of three- and four-body $^4$He atom systems

3. Summary of Research Activity
(1) Recently, we observed of neutron-rich system $nn\Lambda$ as a bound state. To investigate this system, we performed $nn\Lambda+Nn$ three-body coupled channel calculation. Using $YN$ interaction to reproduce observed binding energies for $4\Lambda H$, $4\Lambda He$, and $3\Lambda H$, we do not find any bound state for $nn\Lambda$ system which is inconsistent with the data. Now, we propose the experimentalists to perform a search experiment of $nn\Lambda$ system again.
(2) It is interesting to study the structure of Ar isotope, since we have some superdeformed states (SD) in this isotope. Within the framework of AMD method, we investigate the structure of SD states. In addition, we study the structure of Ar $\Lambda$ hypernuclei. Then, we found that $\Lambda$-separation energy was dependent on the degree of deformation of core nuclei.
(3) Using several realistic $^4$He atomic potential, we calculate Efimov spectra of trimer and tetramer systems of $^4$He. Our result shows an extension of the universality in Efimov trimers that the appearance of the repulsive barrier at the three-body hyperradius $R_3 \approx 2 W_r v_d$ makes the critical scattering lengths independent of the short-range details of the interactions as reported in the literature and also in the present work for the $^4$He trimer with the realistic potentials.
1. Abstract

The aim of mathematical physics laboratory is to apply mathematical scheme to resolve long-standing issues in various subjects of physics. Mathematics, in particular that originates in superstring theory, has universal feature which is common to wide range of physics. This covers elementary particle physics, hadron physics, nuclear physics, cosmology, general relativity and condensed matter physics. We apply mathematical scheme such as superstring theory, D-branes, AdS/CFT correspondence, solitons, statistical mechanics and integrable systems. Topics which the laboratory covers currently include non-perturbative analysis of quantum chromo-dynamics, superstrings, and models beyond the standard model of particle physics, and soliton physics.

2. Major Research Subjects

(1) Application of Superstring Theory
(2) Non-perturbative analyses of strongly-coupled gauge theories
(3) Physics of Black Holes and Cosmology
(4) Solitons physics
(5) Mathematical physics
(6) Lattice gauge theory

3. Summary of Research Activity

Interplay between mathematics and physics is indispensable, as any physics law is described in terms of mathematics. However, the present status of various theoretical physics does not fully appreciate the usefulness of mathematics, as each topics goes into details and has less interaction with other subjects even nearby. We integrate various subjects of physics, by applying recent development of mathematics and mathematical physics, to solve long-standing issues in physics. In particular, mathematical methods in superstring theory has been developed and is mature enough to be applied to other physics. We put efforts on the application as described below, in addition to some other mathematical techniques such as numerical simulations, solitons and integrable systems.

(1) Application of superstring theory
1) Magnetic instability in AdS/CFT : Schwinger effect and Euler-Heisenberg Lagrangian of Super-symmetric QCD

To reveal the Schwinger effect for quarks, i.e., pair creation process of quarks and antiquarks, we derive the vacuum decay rate at strong coupling using AdS/CFT correspondence. Magnetic fields, in addition to the electric field responsible for the pair creation, causes prominent effects on the rate, and is important also in experiments such as RHIC/LHC heavy ion collisions. In this paper, through the gravity dual we obtain the full Euler-Heisenberg Lagrangian of N=2 supersymmetric QCD and study the Schwinger mechanism with not only a constant electric field but also a constant magnetic field as external fields. We determine the quark mass and temperature dependence of the Lagrangian. In sharp contrast with the zero magnetic field case, we find that the imaginary part, and thus the vacuum decay rate, diverges in the massless zero-temperature limit. This may be related to a strong instability of the QCD vacuum in strong magnetic fields. The real part of the Lagrangian serves as a generating function for non-linear electro-magnetic responses, and is found such that the Cotton-Mouton effect vanishes. Interestingly, our results of the Schwinger / Cotton-Mouton effects coincide precisely with those of N=2 supersymmetric QED.

2) Electric Field Quench in AdS/CFT

An electric field quench, a suddenly applied electric field, can induce nontrivial dynamics in confining systems which may lead to thermalization as well as a deconfinement transition. In order to analyze this nonequilibrium transitions,we use the AdS/CFT correspondence for N=2 supersymmetric QCD that has a confining meson sector. We find that the electric field quench causes the deconfinement transition even when the magnitude of the applied electric field is smaller than the critical value for the static case (which is the QCD Schwinger limit for quark-antiquark pair creation). The time dependence is crucial for this phenomenon, and the gravity dual explains it as an oscillation of a D-brane in the bulk AdS spacetime. Interestingly, the deconfinement time takes only discrete values as a function of the magnitude of the electric field. We advocate that the new deconfinement phenomenon is analogous to the exciton Mott transition.

3) Entropic destruction of heavy quarkonium in non-Abelian plasma from holography

Lattice QCD indicates a large amount of entropy associated with the heavy quark-antiquark pair immersed in the quark-gluon plasma. This entropy grows as a function of the inter-quark distance giving rise to an entropic force that can be very effective in dissociating the bound quarkonium states. In addition, the lattice data show a very sharp peak in the heavy quark-antiquark entropy at the deconfinement transition. Since the quark-gluon plasma around the deconfinement transition is strongly coupled, we employ the holographic correspondence to study the entropy associated with the heavy quark-antiquark pair in two theories: i) N=4 supersymmetric Yang-Mills and ii) a confining Yang-Mills theory obtained by compactification on a Kaluza-Klein circle. In both cases we find the entropy growing with the inter-quark distance and evaluate the effect of the corresponding entropic forces. In the
2) Cosmology
   1) Dynamical breaking of shift-symmetry in supergravity-based inflation
      Shift-symmetry is essential to protect the flatness of the potential, even beyond the super-Planckian vacuum expectation value (VEV) for an inflaton field. The breaking of the shift-symmetry can yield potentials suitable for super-Planckian excursion of the inflaton. The aim of this paper is to illustrate that it is indeed possible to break the shift-symmetry dynamically within 4-dimensional supergravity prior to a long phase of inflation. Thanks to the shift-symmetry, the leading contribution to the inflaton potential is free from the dangerous exponential factor even after its breaking, which is the main obstacle to realizing the super-Planckian inflation in supergravity. But, in our simple model, the resulting inflaton potential is a cosine type potential rather than the power-law one and it is difficult to realize a super-Planckian breaking scale unfortunately.

2) Effective gravitational interactions of dark matter axions
   We investigate the structure of gravitational self-interactions of coherently oscillating axions in the general relativistic framework. A generic action for a massive scalar field in the Friedmann-Robertson-Walker background is first introduced based on the effective field theory approach to cosmological perturbations. Using the obtained setup, we evaluate the effective gravitational interaction of the massive scalar field, i.e. scalar quartic interactions mediated by metric perturbations. Applying the results to the system of dark matter axions, we estimate their self-interaction rate and discuss its implications for the axion Bose-Einstein condensate dark matter scenario. Leading contributions for the gravitational interactions of axions are given by the process mediated by the dynamical graviton field, which is essentially the Newtonian potential induced by fluctuations of the background fluids. We find that it leads to the same order of magnitude for the interaction rate of dark matter axions in the condensed regime, compared with the results of previous studies using the Newtonian approximation.

3) Condensed matter physics
   1) Current Reflection and Transmission at Conformal Defects: Applying BCFT to Transport Process
      We study reflection/transmission process at conformal defects by introducing new transport coefficients for conserved currents. These coefficients are defined by using BCFT techniques thanks to the folding trick, which turns the conformal defect into the boundary. With this definition, exact computations are demonstrated to describe reflection/transmission process for a class of conformal defects. We also compute the boundary entropy based on the boundary state.

2) Bulk angular momentum and Hall viscosity in chiral superconductors
   We establish the Berry-phase formulas for the angular momentum (AM) and the Hall viscosity (HV) to investigate chiral superconductors (SCs) in two and three dimensions. The AM is defined by the temporal integral of the anti-symmetric momentum current induced by an adiabatic deforming motion, while the HV is defined by the symmetric momentum current induced by the symmetric torsional electric field. Without suffering from the system size or geometry, we obtain the macroscopic AM $L_z = (h/2\pi) m N_0/2$ at zero temperature in full-gap chiral SCs, where $m$ is the magnetic quantum number and $N_0$ is the total number of electrons. We also find that the HV is equal to half the AM at zero temperature not only in full-gap chiral SCs as is well-known but also in nodal ones, but its behavior at finite temperature is different in the two cases.

4) Mathematical physics
   1) Duality and integrability of supermatrix model with external source
      We study the Hermitian supermatrix model involving an external source. We derive the determinant formula for the supermatrix partition function, and also for the expectation value of the characteristic polynomial ratio, which yields the duality between the characteristic polynomial and the external source with an arbitrary matrix potential function. We also show that the supermatrix integral satisfies the one and two dimensional Toda lattice equations as well as the ordinary matrix model.

2) Laplace operators on Sasaki-Einstein manifolds
   We decompose the de Rham Laplacian on Sasaki-Einstein manifolds as a sum over mostly positive definite terms. An immediate consequence are lower bounds on its spectrum. These bounds constitute a supergravity equivalent of the unitarity bounds in dual superconformal field theories. The proof uses a generalization of Kahler identities to the Sasaki-Einstein case.

3) Non-Lagrangian Theories from Brane Junctions
   We use 5-brane junctions to study the 5D TN SCFTs corresponding to the 5D N=1 uplift of the 4D N=2 strongly coupled gauge theories, which are obtained by compactifying N M5 branes on a sphere with three full punctures. Even though these theories have no Lagrangian description, by using the 5-brane junctions proposed by Benini, Benvenuti and Tachikawa, we are able to derive their Seiberg-Witten curves and Nekrasov partition functions. We cross-check our results with the 5D superconformal index proposed by Kim, Kim and Lee. Through the AGTW correspondence, we discuss the relations between 5D superconformal indices and n-point functions of the q-deformed WN Toda theories.

4) From the Berkovits formulation to the Witten formulation in open superstring field theory
   The Berkovits formulation of open superstring field theory is based on the large Hilbert space of the superconformal ghost sector. We discuss its relation to the Witten formulation based on the small Hilbert space. We introduce a one-parameter family of conditions...
for partial gauge fixing of the Berkovits formulation such that the cubic interaction of the theory under the partial gauge fixing reduces to that of the Witten formulation in a singular limit. The local picture-changing operator at the open-string midpoint in the Witten formulation is regularized in our approach, and the divergence in on-shell four-point amplitudes coming from collision of picture-changing operators is resolved. The quartic interaction inherited from the Berkovits formulation plays a role of adjusting different behaviors of the picture-changing operators in the s channel and in the t channel of Feynman diagrams with two cubic vertices, and correct amplitudes in the world-sheet theory are reproduced. While gauge invariance at the second order in the coupling constant is obscured in the Witten formulation by collision of picture-changing operators, it is well defined in our approach and is recovered by including the quartic interaction inherited from the Berkovits formulation.

5) Duality of topological branes

We show a duality of branes in the topological B-model by inserting two kinds of the non-compact branes simultaneously. We explicitly derive the integral formula for the matrix model partition function describing this situation, which correspondingly includes both of the characteristic polynomial and the external source. We show that these two descriptions are dual to each other through the Fourier transformation, and the brane partition function satisfies integrable equations in one and two dimensions.

Members

Associate Chief Scientist (Lab. Head)
Koji HASHIMOTO

Contract Researcher
Shunji MATSUURA (Sep. 1, 2014 – )

Special Postdoctoral Researchers
Masato TAKI ( – Apr. 30, 2014)
Shingo TORII ( – Mar. 31, 2015)

Toshifumi NOUMI ( – Mar. 31, 2015)

Postdoctoral Researchers
Yuki MINAMI ( – Mar. 31, 2014)

Yasahiro YAMAGUCHI (Apr. 1, 2014 –)

Visiting Researcher
Taro KIMURA (JSPS Fellow, – Mar. 31, 2015)

Senior Visiting Scientist
Koichi YAZAKI (Univ. of Tokyo)

Visiting Scientists
Yoshiyuki YAMAGUCHI (Univ. of Tokyo)
Shoichi MIDORIKAWA (Aomori Univ.)
Keiji IGI (Univ. of Tokyo)
Hiroshi ITOYAMA (Osaka City Univ.)
Yuuyichiro SHIBUSA (Nagasaki Inst. of Applied Sci.)
Nobuyuki ISHIBASHI (Univ. of Tsukuba)
Asato TSUCHIYA (Shizuoka Univ.)
Tatsuumi AOYAMA (Nagoya Univ.)
Kazutoshi OHTA (Meiji Gakuin Univ.)

Takeo INAMI (Chuo Univ.)
Masanori HANADA(KEK)
Yu MAEZAWA(Univ. Bielefeld)
Minoru ETO (Yamagata Univ.)
Norisuke SAKAI (Tokyo Women's Christian Univ.)
Makoto SAKAGUCHI (Ibaraki Univ.)
Tetsutaroh HIGAKI (KEK)
Keisuke HIDAKA (Tokyo Gakugei Univ.)
Kazuo FUJIKAWA (Univ. of Tokyo)
1. Abstract

Nucleons, such as protons and neutrons, are a bound state of constituent quarks glued together with gluons. The detail structure of nucleons, however, is not well understood yet. Especially the mechanism to build up the spin of proton, which is 1/2, is a major problem in physics of the strong force. The research goal of Radiation Laboratory is to solve this fundamental question using the world first polarized-proton collider, realized at RHIC in Brookhaven National Laboratory (BNL) in USA. RHIC stands for Relativistic Heavy Ion Collider, aiming also to create Quark Gluon Plasma, the state of Universe just after the Big Bang. RIKEN-BNL Research Center (RBRC) directed by S. Aronson carries our core team at BNL for those exciting researches using the PHENIX detector. We have found that the proton spin carried by gluons is indeed small. We also identified W bosons in the electron/positron decay channel and in the muon decay channel, with which we are about to conclude how much anti-quarks carry the proton spin. Other than the activities at RHIC we are preparing new experiments at J-PARC and Fermilab to study the nature of hadron. We are also performing technical developments such as novel ion sources, fine-pitch silicon pixel detectors and high-performance trigger electronics.

2. Major Research Subjects
1) Spin physics with relativistic polarized-proton collisions at RHIC
2) Study of nuclear matter at high temperature and/or at high density
3) Technical developments on radiation detectors and accelerators

3. Summary of Research Activity
(1) Experimental study of spin structure of proton using RHIC polarized proton collider
[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

In 2014 we have reached a major milestone in determining the gluon spin contribution to the total spin of the nucleon. After initially measuring small asymmetries statistically consistent with zero, we have succeeded to determine non-zero gluon polarization in the recent high statistics runs at 510 GeV. With the valence quark spin contribution already reasonably well known, the contributions from sea quarks and orbital angular momenta remain to be understood. PHENIX has collected data to access the sea quark polarizations via leptonic decays of W bosons. Preliminary results have been obtained using all the data taken so far. While orbital angular momentum cannot be directly accessed at RHIC, several transverse spin phenomena are being accumulated to study the orbital angular momentum and the overall three-dimensional structure of the nucleon.

To further investigate these effects the PHENIX experiment proposes substantial detector upgrades to go along the expected accelerator improvements. The proposed upgrade replaces the present magnet with a solenoid, so that we are considering to build an open-geometry forward spectrometer which can measure hadrons, photons, electrons, muons and jets in the forward rapidity region. Especially the Drell-Yan (quark-antiquark annihilation into lepton pairs) transverse single spin asymmetries are the main goal of these upgrades. As a pilot measurement, some of us are participating in the Fermilab SeaQuest experiment which has been collecting muon pairs using a 120-GeV unpolarized proton at Fermilab. By measuring the unpolarized Drell-Yan process, we can study quark spin-orbit effects which supplement what can be learned in the polarized Drell-Yan process.

(2) Experimental study of quark-gluon plasma using RHIC heavy ion collider
[See also RIKEN-BNL Research Center Experimental Group for the activities at BNL]

We have completed several key measurements in the study of quark-gluon plasma at RHIC. As the top of them, we lead the analysis of the first thermal photon measurement in heavy ion collisions. The measurement indicates that the initial temperature reached in the central Au+Au collision at 200 GeV is about 350MeV, far above the expected transition temperature Tc~170MeV, from hadronic phase to quark-gluon plasma. This work was rewarded by Nishina Memorial Prize in 2011. Using the same “virtual photon” method used in the thermal photon measurement, we measured direct photons in d+Au collisions. The results show that there is little cold nuclear effects in direct photons. This supports that the large enhancement of direct photons observed in Au+Au is indeed due to hot quark-gluon plasma formed in Au+Au collisions.

We also measured the elliptic flow strength, v2, of direct photons in Au+Au collisions. The results show surprisingly large v2, which means the source of those photons expands elliptically. This is one of the most interesting results from RHIC in the last three years. One of the JRA students of Radiation Laboratory led this important analysis. Also, the most recent measurements of high p_T π0 suppression in Au+Au collisions show that the suppression reduces at very high pT (pT~20GeV).

We lead measurement of heavy quark (charm and bottom) using VTX, a 4 layer silicon vertex tracker which we jointly constructed with US DOE. The detector was installed in PHENIX in 2011. Analysis of heavy quark using the silicon vertex detector is ongoing. The first preliminary results from the 2011 Au+Au run and 2012 p+p run was reported in the Quark Matter 2012 conference. We are now finalizing the results for publication. Analysis of the 2014 Au+Au run is also in progress and we expect the first preliminary results from the 2014 run in this year (2015).

In Wako we are operating a cluster computer system specialized to analyze huge data sets taken with the PHENIX detector. It consists
of 28 nodes (18 old nodes and 10 new nodes) each of which has two CPUs and 10 sets of local disk for data repository (old node: quad-core CPU, 1TB disk, new node: six-core CPU, 2TB disk). There are 264 CPU cores and 380 TB disks in total. This configuration ensures the fastest disk I/O when the jobs are assigned to the nodes where the required data sets are stored. It is also important that this scheme doesn't require an expensive RAID system and network. Through this development we have established a fast and cost-effective solution in analyzing massive data.

We have about 1.7 PB of data produced by the PHENIX experiment. They are stored in the archive system (HPSS) operated by the Advanced Center for Computing and Communication (ACCC). Since ACCC decided to replace HPSS, we have started to transfer the data into the new archive system.

(3) Study of properties of mesons and exotic hadrons with domestic accelerators

Preparation of the experiment E16 at J-PARC 50-GeV PS is underway with the Grant-in-Aid for Scientific Research on Innovative Areas (MEXT). This experiment aims to perform a systematic study of the mass modification of low-mass vector mesons in nuclei to explore the chiral symmetry breaking in dense nuclear matter, namely, the mechanism proposed by Nambu to generate the major part of hadron mass.

Gas Electron Multiplier (GEM) technology is adopted for the two key detectors, GEM Tracker (GTR) and Hadron-blind Cherenkov detector (HBD). With a cooperation with Japanese industries, GEM foils with a world-largest size (30cm x 30cm) are newly developed. Through the beam tests at ELPH, J-PARC, LEPS, and RIKEN RIBF, the followings are achieved and proven: 1) required position resolution of 0.1 mm, and 2) stable operation under the hadron-background environment, typically 30 times higher rate than that expected in the J-PARC experimental area. The design parameters of the GTR and HBD were finalized and the mass-production of GTR GEM started. HBD GEM is under the final tuning to achieve the required stability, efficiency and pion-rejection power.

For the readout electronics of GEM, a preamp using the APV25 ASIC chip is developed and tested. For the digitization and the data transfer, the SRS system developed by CERN is also tested and adopted. Another preamp-ASIC for the trigger signal from GEM foils is also developed and tested. Trigger logic boards, which are developed by Belle II, are tested with the firmware customized for this experiment.

The development phase of the detectors is just over and we are moving to the production phase. For the readout electronics, the mass production will start in a year after some remained tests. The construction of the beam line is finally funded in KEK and started at J-PARC in 2013. It will be completed by March 2016. The spectrometer construction at the beam line is planned to start in March 2015 and the commissioning with a primary beam will be performed in early 2016.

(4) Detector development for PHENIX experiment

After 7 years of hard work, we installed the silicon vertex tracker (VTX) into the PHENIX detector at RHIC in December 2010. VTX is a 4-layer silicon tracker to measure heavy quark (charm and bottom) production in p+p and heavy ion collisions at RHIC. The detector was funded by RIKEN and the US DOE. We and RIKEN BNL Research Center are responsible for construction and operation of the inner two pixel detectors. The VTX was successfully commissioned during the 500 GeV p+p run in 2011. Subsequently, we collected 5 billion Au+Au collision events with VTX. This dataset is effectively more than 10 times of that of 2011 data. We expect definitive results on heavy quark measurements from the 2014 run.

Sea quark polarization measurement via W-boson production is one of the highlight of PHENIX spin program. In order to detect high momentum muons from W-decay, we developed the momentum-sensitive trigger system for the PHENIX forward muon arms with collaborators from KEK, Kyoto and Rikkyo University. Together with new hadron absorber, W-boson measurement was successfully carried out using the new high momentum trigger. We accumulated high-integrated luminosity of about 250 pb⁻¹ in Run13 and almost achieved our goal. The intensive analysis is underway towards the publication. Preliminary results were released in October 2014 and the analysis is at the final stage towards the publication. Besides W detection, the trigger system has been also operated for heavy flavor meson detection in conjunction with a forward vertex (FVTX) detector.

(5) Development of beam source

Under the collaboration with Brookhaven National Laboratory, we are developing various techniques for a laser ion source (LIS) to provide high quality heavy-ion beams to the accelerators at present or in the future. In 2014, we installed a new LIS which provides various species of singly charged ions to the RHIC-AGS complex. The commissioning was very successful and we have delivered C, Al, Ti, Si, Ta and Au ions. We also demonstrated fast switching of ion species within one second. At this moment, we are upgrading this LIS to provide gold beam and other lighter ion beams simultaneously. Once this upgrade is completed, all the ion beams except proton and uranium will be supplied by the LIS at the RHIC-AGS complex with much enhanced versatility. Besides, we are studying the highly charged ionization and magnetic field confinement of laser ablation plasma, and testing a linear accelerator model which selectively accelerates charge states.
and Au ions. We also demonstrated fast switching of ion species within one second. At this moment, we are upgrading this LIS to provide detection in conjunction with a forward vertex (FVTX) detector.

Species of singly charged ions to the RHIC-AGS complex. The commissioning was very successful and we have delivered C, Al, Ti, Si, Ta doesn’t require an expensive RAID system and network. Through this development we have established a fast and cost-effective solution in CPU, 1TB disk, new node: six-core CPU, 2TB disk). There are 264 CPU cores and 380 TB disks in total. This configuration ensures the

Study of properties of mesons and exotic hadrons with domestic accelerators

Advanced Center for Computing and Communication (ACCC). Since ACCC decided to replace HPSS, we have started to transfer the data into the new archive system.

Areas (MEXT). This experiment aims to perform a systematic study of the mass modification of low-mass vector mesons in nuclei to

in 2013. It will be completed by March 2016. The spectrometer construction at the beam line is planned to start in March 2015 and the

was funded by RIKEN and the US DOE. We and RIKEN BNL Research Center are responsible for construction and operation of the inner

collaborators from KEK, Kyoto and Rikkyo University. Together with new hadron absorber, W-boson measurement was successfully carried out using the new high momentum trigger. We accumulated high-integrated luminosity of about 250pb⁻¹ in Run13 and almost

momentum muons from W-decay, we developed the momentum-sensitive trigger system for the PHENIX forward muon arms with

2014 run is a major heavy quark run of RHIC and the VTX detector worked very well during the run. PHENIX recorded about 20 billion


During the 2011 run, part of the pixel detector was damaged due to thermal stress on the detector. We repaired the damaged pixel

Maki Kurosawa (~ Sep. 30, 2014)
Yuki ARAMAKI (~ Mar. 31, 2014) Takayuki SUMITA
Yuhei MORINO (~ Jul. 31, 2014) Yoshimasa IKEDA (~ Mar. 31, 2014)
Tomonori TAKAHASHI (~ Mar. 31, 2014)

Yusuke KOMATSU (Univ. of Tokyo, ~ Mar. 31, 2014) Tomoya HOSHINO (Hiroshima Univ.)
Shinichi HAYASHI (Univ. of Tokyo, ~Mar. 31, 2015) Shinusuke Ikeda (Tokyo Tech.)
Yuko SEKIGUCHI (Univ. of Tokyo) Masafumi KUMAKI (Waseda Univ.)
Koki KANNO (Univ. of Tokyo) Hiroshi NAKAGOMI (Univ. of Tsukuba)
Wataru NAKAI (Univ. of Tokyo) Yasuhiro FUWA (Kyoto Univ., ~ Mar. 31, 2015)
Megumi SEKINE (Tokyo Tech., ~ Mar. 31, 2014) Satoshi YANO (Hiroshima Univ.)
Sanshiro MIZUNO (Univ. of Tsukuba, ~ Mar. 31, 2015) Daisuke WATANABE (Univ. of Tsukuba)
Tomoya TSUIJI (Univ. of Tokyo, ~ Mar. 31, 2015) Kohei TERASAKI (Univ. of Tokyo)

Sanghwa PARK (Seoul Nat’l Univ., ~ Feb. 26, 2015) Taebong MOON (Yonsei Univ.)
Inseok YOON (Seoul Nat’l Univ.) Chong KIM (Korea Univ., ~ Dec. 9, 2014)
Minjung KIM (Seoul Nat’l Univ.) Se Young HAN (Ewha Womans Univ., Oct. 1, 2014 ~)

Daisuke KAWAMA (JSPS Fellow, ~ Mar. 31, 2015)

Senior Visiting Scientists
Toshiaki SHIBATA (Tokyo Tech.) Takashi NAKANO (Osaka Univ.)

Visiting Scientists
Kyoichiro OZAWA (KEK) Maya SHIMOMURA (Iowa State Univ.)
Noriyoshi ISHII (Univ. of Tsukuba) Noriyosu HAYASHIZAKI (Tokyo Tech.)
Susumu SATO (JAEA) Yuhei MORINO (KEK)
Megumi NARUKI (KEK) Kenji FUKUSHIMA (Keio Univ.)
Akiyoshi ENOKIZONO (Rikkyo Univ.) Atsushi NAKAMURA (Hiroshima Univ.)
Yoshinori FUKAO (KEK) Ryo ICHIMIYA (KEK)
Mikiko SEKIMOTO (KEK) Tomohiro NISHITANI (Nagoya Univ.)
Kiyoshi TANIDA (Seoul Nat’l Univ.) Tomonori TAKAHASHI (Osaka Univ.)
Hirotugu KASHIWAGI (JAEA) Tsutomu MIBE (KEK)
Taku GUNJI (Univ. of Tokyo) Makoto KUWAHARA (Nagoya Univ.)
Junpei TAKANO (KEK) Masahiro OKAMURA (BNL)
Kazuya AOKI (KEK) Shunzo KUMANO (KEK)
Masashi KANETA (Tohoku Univ.) Bentz WOLFGANG (Tokai Univ.)
Munehisa OHTANI (Kyorin Univ.) Alexander BAZILEVSKY (BNL)
Yoritomo YAMAGUCHI (Univ. of Tokyo) Shin-ya SAWADA (KEK)
Youngil KWON (Yonsei Univ.) Ryotaro MUTU (KEK)
Kenichi NAKANO (Tokyo Tech.) Masanori HIRAI (Tokyo Univ. of Sci.)

Members

Chief Scientist (Lab. Head)
Hideto EN’YO (Director, RNC)

Vice Chief Scientist
Yasuuki AKIBA

Research & Technical Scientists
Yasushi WATANABE (Senior Research Scientist) Ralf SEIDL (Senior Research Scientist)
Yuji GOTO (Senior Research Scientist) Hiroaki ONISHI (Senior Research Scientist, concurrent; Advanced Meson Science Lab.)
Itaru NAKAGAWA (Senior Research Scientist)
Satoshi YOKKAICHI (Senior Research Scientist)

Contract Researchers

Postdoctoral Researchers

Junior Research Associates

International Program Associates

Visiting Researcher

Senior Visiting Scientists
Toshiaki SHIBATA (Tokyo Tech.) Takashi NAKANO (Osaka Univ.)
Student Trainees
Yusuke KOMATSU (Univ. of Tokyo)  Kazuya NAGASHIMA (Hiroshima Univ.)
Shoichiro NISHIMURA (Univ. of Tokyo)  Hikari MURAKAMI (Univ. of Tokyo)
Takuya SHIBUKAWA (Univ. of Tokyo)  Yusuke UEDA (Hiroshima Univ.)
Yuki OBARA (Univ. of Tokyo)  Key NAGAI (Tokyo Tech.)
Yusuke OYA (Hiroshima Univ.)

Interns
Hidemitsu ASANO (Kyoto Univ.)  Kotoko SHUKUTANI (Rikkyo Univ.)
Chong KIM (Korea Univ.)  Yomei FUKUSHIMA (Rikkyo Univ.)
Sarah CAUSSIN  Junsang PARK (Seoul Nat'l Univ.)

Part-time Workers
Kimiaki HASHIMOTO (Rikkyo Univ., – Mar. 31, 2014)  Toru NAGASHIMA
Ryoji AKIMOTO (Univ. of Tokyo, – Mar. 31, 2014)  Hikari MURAKAMI (Univ. of Tokyo)
Takeru IGURI (Rikkyo Univ., – Mar. 31, 2014)

Assistants
Keiko SUZUKI  Mitsue YAMAMOTO
Ⅵ. RNC ACTIVITIES

Sub Nuclear System Research Division
Advanced Meson Science Laboratory

1. Abstract

Particles like muons, pions, and kaons have finite life times, so they do not exist in natural nuclei or matters. By implanting these particles into nuclei/matters, exotic phenomena in various objects can be studied from new point of view.

Kaon is the second lightest meson having “strange”-quark as a constituent quark, which also does not exist in natural nuclei. It is expected that if one embed mesons into nuclei, the sizes of the nuclei become smaller and one can form a high density object beyond the normal nuclear density. Study of this object could lead to better understanding of the origin of the mass of the matter, and may reveal the quark degree of freedom beyond the quark-confinement. The other example is the weak interaction in nuclear matter. It can only be studied by the weak decay of hypernuclei, which have Lambda particle in the nuclei.

Muon provides even wider scope of studies, covering condensed matter physics as well as nuclear and atomic physics, and we are trying to extend the application field further into chemical and biological studies. For instance, stopping positively charged muon in a material, we obtain information on the magnetic properties or the local field at the muon trapped site (µSR). Injecting negatively charged muon to hydrogen gas, muonic hydrogen atom (µp) is formed. We are planning to measure µp hyperfine splitting energy to measure proton magnetic radius, which is complementary quantity to the proton charge radius and its puzzle lately attracts strong interest. We are also interested in precision measurement of muon property itself, such as muon anomalous magnetic moment (g-2) to study physics beyond the standard model.

In our research, we introduce different kind of impurities into nuclei / matters, and study new states of matter, new phenomena, or the object properties.

2. Major Research Subjects

(1) Study of meson property and interaction in nuclei
(2) Origin of matter mass / quark degree of freedom in nuclei
(3) Condensed matter and material studies with muon
(4) Nuclear and particle physics studies via muonic hydrogen
(5) Development of ultra cold muon beam, and its application from material science to particle physics

3. Summary of Research Activity

(1) Hadron physics at J-PARC, RIKEN-RIBF, GSI and SPring-8

Kaon and pion will shed a new insight to the nuclear physics. The discovery of deeply bound pionic atom enables us to investigate the properties of mesons in nuclear matter. At RIKEN-RIBF, we are preparing precise experimental study of the pionic atom. We have also started next generation kaon experiments (E15 and E31) at J-PARC. In these experiments, we are aiming at precise determination of the KpN interaction, and clarify the nature of kaon in nuclei and the nature of Λ(1405), which could be Kp bound state. At Spring-8 and at GSI, we are also aiming to study omega and η’ nuclei. By these experiments, we aim to be a world-leading scientific research group using these light meta-stable particles.

(1-A) Deeply bound kaonic nuclei

We have performed experimental exploration of theoretically predicted deeply bound kaonic nuclear states, such as the <Kpp> bound state. One of the most interesting features of the kaonic nucleus is the strong attraction of the KpN interaction. Because of this strong attraction, the kaon in nucleus will attract surrounding nucleons, resulting in extremely high-density object, which is several times larger than normal nuclear density. Measurement of the kaon properties at such high energy density will provide precious information on the origin of hadron masses and the chiral symmetry breaking and its partial restoration.

The experiment J-PARC E15 aims to identify the nature of the <Kpp> bound state by the in-flight 3He(K-, n) reaction, which allows us to investigate such state both in the formation via the missing-mass spectroscopy using the emitted neutron, and in its decay via the invariant-mass spectroscopy by detecting decay particles from <Kpp>. For the experiment, we constructed a dedicated spectrometer system at the secondary beam-line, K1.8BR, in the hadron hall of J-PARC.

The first physics data-taking was carried out in March and May, 2013 with 6x10⁹ kaons on ³He target, corresponding to a ~1% of the approved proposal. We successfully obtained semi-inclusive ³He(K-, n) X missing-mass spectrum, and found a tail structure just below the mass threshold of (K + p + p) which cannot be explained by well-known processes and backgrounds. We also demonstrated an exclusive analysis by reconstructing ³He(K-, Ap) n events. To derive more information on the KpN interaction by the exclusive measurement, we are planning to perform the second physics-run, in which 10 times more data will be accumulated.

(1-B) Precision X-ray measurement of kaonic atom

Simultaneously, with the above experiment (1), we have performed an X-ray spectroscopy of atomic 3d→2p transition of negatively charged K mesons captured by helium atoms (J-PARC E17). However, the energy resolution of the conventional semiconductor spectrometers is insufficient to see the K⁻ nucleus potential observed by atomic levels at zero energy. This is closely related to the problem on the existence of deeply bound kaonic states in nuclei, well below the atomic levels, and this is one of the biggest problems in strangeness
nuclear physics. Aiming to provide a breakthrough from atomic level observation, we will perform high-resolution X-ray spectroscopy of kaonic atoms at a J-PARC hadron beam line using a novel cryogenic X-ray spectrometer: an array of superconducting transition-edge-sensor (TES) micro-calorimeters. The spectrometer offers unprecedented energy resolution, which is about two orders of magnitude better than that of conventional semiconductor detectors. A spectrometer array of 240 pixels will have an effective area of about 20 mm². Very recently, we have performed a proof-of-principle experiment by measuring pionic-atom X rays with a TES array at the PiM1 beam line at the Paul Scherrer Institut (PSI), and successfully demonstrated the feasibility of TES-based exotic-atom x-ray spectroscopy in a hadron-beam environment. Based on the results, we are preparing for the kaonic-atom experiment at J-PARC.

Another important X-ray measurement of kaonic atom would be 2p→1s transition of kaonic deuteron. We have measured same transition of kaonic hydrogen, but the width and shift from electro-magnetic (EM) value reflect only isospin average of the K²N interaction. We can resolve isospin dependence of the strong interaction by the measurement. We submitted a proposal to J-PARC PAC to measure kaonic deuteron X-ray and got stage-one approval.

(1-C) Deeply bound pionic atoms and η’ mesic nuclei

We have been working on precision spectroscopy of pionic atoms systematically, that leads to understanding of the origin of hadron mass. The precision data set stringent constraints on the chiral condensate at nuclear medium. We are presently preparing for the precision measurement at RIBF. The first measurement is aiming at 121Sn as the first step for the systematic spectroscopy. A pilot experiment was performed in 2010, and showed a very good performance of the system. We have been analyzing the data to improve experimental setup of the pionic atom spectroscopy at the RIBF in RIKEN. We expect to achieve better experimental resolution with much reduced systematic errors.

We are also working on spectroscopy of η’ mesic nuclei in GSI/FAIR. Theoretically, peculiarly large mass of η’ is attributed to UA(1) symmetry and chiral symmetry breaking. As a result, large binding energy is expected for η’ meson bound states in nuclei (η’-mesic nuclei). From this measurement, we can access information about partial restoration of chiral symmetry in nuclear media via the binding energy and decay width of η’-nuclear bound state.

(1-D) Hadron physics at SPring-8/LEPS2

Photo-production of meson in nuclei is known to be a powerful tool to investigate property of the hadron in nuclear media. For this study, we started a new experimental project named LEPS2 (Laser Electron Photon at SPring-8 II) in this RIKEN Mid-term. The experimental hutch for LEPS2 at SPring-8 was constructed in March 2011, lead by RIKEN. The Large solenoid spectrometer magnet (2.96 m inner diameter x 2.22 m length) was successfully transported from BNL (US) to SPring-8 and installed into LEPS2 hutch in 2011.

One of the first physics programs is photo-production of η’ in nuclei. Especially (γ, p) is most important reaction channel, where we can perform missing mass spectroscopy by detecting forward going proton. One of the big advantage of photo-production reaction is that the initial reaction is expected to be much cleaner than the hadron channel.

Detector construction for the first physics program is in progress. The 4π Electro-Magnetic calorimeter has been constructed and proton counter to detect forward going proton produced via (γ, p) reaction was installed in November 2013. Engineering run for the first experiment was performed in December 2013 to confirm performance of our detector system. Full set of the detector will be installed by mid April 2014 and we are planning to perform first physics data taking run starting from mid April 2014 to end of July 2014.

(2) Muon science at RIKEN-RAL branch

The research area ranges over particle physics, condensed matter studies, chemistry and life science. Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford-Appleton Laboratory (UK), which provides intense pulsed-muon beams. We have variety of important research activities such as particle / nuclear physics studies with muon's spin and condensed matter physics by muon spin rotation / relaxation / resonance (µSR).

(2-A) Condensed matter/materials studies with µSR

We have opened the new µSR spectrometer named CHRONUS to collaborative experiments from the May-June cycle in 2014. To have higher affinity on µSR studies with the ISIS muon facility, common data acquisition (DAQ) system with the ISIS standard DAQ (DAEIII) and the front-end control system (SECI) have been installed and optimized along with other equipment in Port-4. The same DAQ and control systems will be installed in Port-2 as well. Thus, we can perform two independent µSR experiments in Port-2 and 4 at the same time, switching double-pulse to share beam between the two.

Among our scientific activities on µSR studies from year 2012 to 2014, following five subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

1. A static ordering of small Ir moments in the pyrochlore iridate, Nd2Ir2O7, was examined. We found that this system is located close to the quantum critical point.

2. A static ordering of Yb moment in pyrochlore structure of Yb2Ti2O7 crystal has been confirmed. This ordering can be explained by the Higgs mechanism.

3. Spontaneous small static internal fields in the superconducting state of URu2Si2 have been measured. From the data and its crystal structure, we obtained a scenario to explain superconducting mechanism of this system.

4. The universality class of the Mott transition in EtMe3P[Pd(dmit)2]: has been confirmed by pressure dependences of transport properties.

5. A novel coexisting state between Fe spin-glass and Cu stripe ordered states have been found in the overdoped regime of La2−xSrxCu1−yFeO4.
(2-B) Nuclear and particle physics studies via ultra cold muon beam and muonic atoms

If we can improve muon beam-emittance, beam-timing and energy-dispersion (so-called “ultra-slow muon”), then the capability of μSR study will be drastically improved. The ultra-slow muon beam can be stopped in thin foil, multi-layered materials and artificial lattices and we can apply the μSR techniques to surface and interface science. The development of ultra-slow muon beam is also very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon g-2 measurement. Therefore, we have been working on R&D study.

We had been working on the “ultra-slow muon” generation based on the following technique, namely, positive muon beam with thermal energy has been produced by laser ionization of muoniums in vacuum (bound system of μ+ and electron) emitted from the hot tungsten surface by stopping “surface muon beam” at Port-3. However, the muon yield and obtained emittance was far from satisfactory, and remained to be far from any kind of realistic application.

Therefore, in this mid-term, we are developing two key components first, namely high efficiency muonium generator at room temperature and high intensity ionization laser. The study of muonium generator has been done in collaboration with TRIUMF. In 2013, we demonstrated tremendous increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. We also developed a high power Lyman-α laser in collaboration with laser group at RIKEN. In this laser development, we succeeded to synthesize novel laser crystal Nd:YAG, which has an ideal wave-length property for laser amplification to generate Lyman-α by four wave mixing in Kr gas cell. The developed new laser will ionize muoniums 100 times more efficiently for slow muon beam generation. In order to fully apply these new developments to slow muon generation, we designed and manufactured a new beam line based on microscope optics. Its installation and beam test is planned in the first half of 2015.

Concerning the muonic atom, we are planning a new precise measurement of proton radius. A large discrepancy was found recently in the proton charge radius between the new precise value from muonic hydrogen atom and those from normal hydrogen spectroscopy and e-p scattering. We propose a precise measurement of Zemach radius (with charge and magnetic distributions combined) using the laser spectroscopy of hyperfine splitting energy in the muonic hydrogen atom. Preparation of the hydrogen target, mid-infrared laser and muon spin polarization detectors is in progress.

Members

Chief Scientist (Lab. Head)
Masahiko IWASAKI

Vice Chief Scientist
Katsuhiko ISHIDA

Research & Technical Scientists
Isao WATANABE (Senior Research Scientist)
Kenta ITAHASHI (Senior Research Scientist)
Haruhiko OUTA (Senior Research Scientist)

Hiroaki OHNISHI (Senior Research Scientist)
Fuminori SAKUMA (Senior Research Scientist)
Yue MA (Research Scientist)

Contract Researchers
Yu OISHI
Shinji OKADA
Masaharu SATO

Majed ABEDL JAWAD (– Sep. 30, 2014)
Teiichiro MATSUZAKI (Main; Team Leader, Muon Data Team, Dec. 1, 2014 - )

Special Postdoctoral Researchers
Tadashi HASHIMOTO (Apr. 1, 2014 - )

Special Temporary Employees
Teiichiro MATSUZAKI (~ Nov. 30, 2014)

Research Consultants
Yoshinori AKAISHI
Hironari MIYAZAWA

Masayasu KAMIMURA

Junior Research Associates
Kazuo TANAKA (Univ. of Tokyo) (Apr. 1, 2014- )
Yuki NOZAWA (Kyoto Univ) (~ Mar. 31, 2015)
Sohtaro KANDA (Univ. of Tokyo) (~ Mar. 31, 2014)

Takuya SHIBUKAWA (Univ. of Tokyo) (Apr. 1, 2014- )
Hirotono HAMANO (Osaka Univ.)
Nam TRAN (Osaka Univ.) (Apr. 1, 2014- )

International Program Associates
Edi SUPRAYOGA (Bandung Inst. Tech.)
Zhang Qi (Lanzhou Univ.)

Noraina ADAM (USM, Feb. 15, 2014 – )
Sungwon YOON (Catholic Univ. of Korea, Nov. 25, 2014 – )
Senior Visiting Scientist
Kazuhiro TANAKA (KEK)

Visiting Scientists
Toshimitu YAMAZAKI (Univ. of Tokyo)
Mototsugu MIHARA (Osaka Univ.)
Donald George FLEMING (Univ. of British Columbia/TRIUMF)
Yasuo NOZUE (Osaka Univ.)
Takehito NAKANO (Osaka Univ.)
Tadashi ADACHI (Tohoku Univ.)
Zyun Francis EZAWA (Tohoku Univ.)
Jin NAKAMURA (Univ. of Elec.-Com.)
Yasuyuki ISHII (Tokyo Med. Univ.)
Johann ZMESKAL (SMI)
Risdiana (UNPAD)
Norimichi KOJIMA (Univ. of Tokyo)
Satoshi TSUTSUI (JASRI)
Takao SUZUKI (Shibaura Inst. of Tech.)
Masami IIO (KEK)
Georg Peter BERG (Univ. of Notre Dame)
Takayuki GOTO (Sophia Univ.)
Masaya ENOMOTO (Tokyo Univ. of Sci.)
Hiroyuki FUJIOKA (Kyoto Univ.)
Takayuki KAWAMATA (Tohoku Univ.)
Lee CHOW (UCF)
Helmut WEICK (GSI)
Harry W. K. TOM (UC Riverside)
Agustinus NUGROHO (ITB)
Kawakami Kenji ROLAND (Univ. of California, Riverside)
Ichiro SHIRAKI (Univ. of Yamanashi)
Kensuke SUZUKI (Tohoku Univ.)
Kyoosuke ISODA (Tokyo Univ. of Sci.)
Ken SUZUKI (SMI)
Irwan DHARMAWAN (UNPAD)
Keiji YOKOYAMA (Queen Mary Univ.)
Kazuki UENO (KEK)
Tobat Parasian Irianto SARAGI (Univ. of Kassel)
Katsuhiko NISHIMURA (Univ. of Toyama)
Kenji MATSUDA (Univ. of Toyama)
Hexi SHI (Univ. of Tokyo)
Mohamed Ismail MOHAMED IBRAHIM (USM)
Shukri SULAIMAN (USM)
Kenji KAWASHIMA (Aoyama Gakuin Univ.)
Ayi BAHTIAR (UNPAD)
Yasuyuki ISHII (Tokyo Med. Univ.)
Yoichi IGARASHI (KEK)
Takayuki GOTO (Sophia Univ.)
Jun MIYAZAKI (Nihon Univ.)
Kouichirou SHIMOMURA (KEK)
Eiko TORIKAI (Univ. of Yamanashi)
Wataru HIGEMOTO (JAEA)
Yoji KOIKE (Tohoku Univ.)
Masahiro SATO (Saitama Univ.)
Kazuhiko SATO (Saitama Univ.)
Daichi TOMONO (Kyoto Univ.)
Kazuki OHISHI (Comprehensive Res. Org. for Sci. and Soc.)
Yasuhiro MIYAKE (KEK)
Prasad TARA DAS (SUNY)
Yasuhiro YAMADA (Tokyo Univ. of Sci.)
Jun MIYAZAKI (Nihon Univ.)
Kenya KUBO (ICU)
Tsutomu MIBE (KEK)
Satoru HIRENZAKI (Nara Women's Univ.)
Kenji KAWASHIMA (Aoyama Gakuin Univ.)
Dita PUSPITA SARI (Inst. Teknologi Sepuluh Nopember)
Retno ASIH (Insti. Teknologi Sepuluh Nopember)

Visiting Technicians
Yuya FUJIWARA (Univ. of Tokyo)
Kazuo OKEYAMA (JOHO com.)
Dita PUSPITA SARI (Inst. Teknologi Sepuluh Nopember)

Research Fellows
Yuta SADA (Kyoto Univ.)
Shun ENOMOTO (Osaka Univ.)

Student Trainees
Kensuke SUZUKI (Tohoku Univ.)
Takahiro NISHI (Univ. of Tokyo)
Natsuki TOMIDA (Kyoto Univ.)
Ryo SHIMIZU (Tokyo Univ. of Sci.)
Sohtaro KANDA (Univ. of Tokyo) (Apr. 1, 2014- )
Kentarō INOUE (Osaka Univ.)
Yoshiki TANAKA (Univ. of Tokyo)
Yohji MURAKAMI (Univ. of Tokyo)
Hirokazu YAMADA (Univ. of Tokyo)
Ryo MIYATANI (Tokyo Univ. of Sci.)
Shingo KAWASAKI (Osaka Univ.)
Sajjad MARI (IUT)
Ryo KITAMURA (Univ. of Tokyo)
Shingo YASADA (Aoyama Gakuin Univ.)

Student Trainees
Kensuke SUZUKI (Tohoku Univ.) (-Mar. 31, 2014)
Yukiko SATO (Univ. of Elec.-Com.)
Daiki NATORI (Kyoto Univ.)
Shota TANABE (Tokyo Univ. of Sci.)
Yuki SATO (Univ. of Elec.-Com.)
Kensuke SUZUKI (Tohoku Univ.)
Daiki NATORI (Kyoto Univ.)
Kenichi KAWASHIMA (Aoyama Gakuin Univ.)
Kenji FUJIMURA (Ibaraki Univ.)

Part-time Workers

Makoto TOKUDA (Tokyo Tech.)
Abdel Jawad MAJED (Oct. 1, 2014 - )

Assistants

Yuri TSUBURA(- Apr. 30, 2014)
Mitsue YAMAMOTO (May 1, 2014- )

Kazuhiro KATONO (Hokkaido Univ.)
Shu AIKAWA (Tokyo Tech.)
Takumi YAMAGA (Osaka Univ.)
Hiroshi HORII (Univ. of Tokyo)
Kenji TANIBE (Osaka Univ.)
Kien LUU (Osaka Univ.)
Kazuya KATAYAMA (Tokyo Tech.)
Koshi KURASHIMA (Tohoku Univ.)
1. Abstract

The RIKEN BNL Research Center was established in April 1997 at Brookhaven National Laboratory with Professor T. D. Lee of Columbia University as its initial Director. It is funded by the Rikagaku Kenkyusho (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD and RHIC physics through the nurturing of a new generation of young physicists. Professor Lee was succeed by BNL Distinguished Scientist, N. P. Samios, who served until 2013. The current director is Dr. S. H. Aronson. Support for RBRC was initially for five years and has been renewed three times, and presently extends to 2018. The Center is located in the Physics Department. The RBRC Theory Group activities are closely and intimately related to those of the Nuclear Theory, High Energy Theory, and Lattice Gauge Theory Groups at BNL. The RBRC Experimental Group works closely with the DOE RHIC Spin Group, the RIKEN Spin Group at BNL, and the PHENIX heavy ion groups. BNL provides office space, management, and administrative support. In addition, the Computer Science Center (CS) and Information Technology Division (ITD) at BNL provides support for computing, particularly the operation and technical support for the RBRC 400 Teraflop QCDCQ (QCD Chiral Quark) lattice gauge theory computer. The Deputy Director of RBRC is R. Pisarski (BNL). L. McLerran (BNL) is leader of the Theory Group. Y. Akiba (RIKEN) is Experimental Group leader with A. Deshpande (Stony Brook) deputy. T. Izubuchi (BNL) is Computing Group leader.

2. Major Research Subjects

Major research subjects of the theory group are:
1. Heavy Ion Collision
2. Perturbative QCD
3. Phenomenological QCD

Major research subjects of the computing group are:
1. Search for new law of physics through tests for Standard Model of particle and nuclear physics
2. Dynamics of QCD and related theories
3. Theoretical and algorithmic development for lattice field theories, QCD machine design

Major research subject of the experimental group are:
1. Experimental Studies of the Spin Structure of the Nucleon
2. Study of Quark-Gluon Plasma at RHIC
3. PHENIX detector upgrades

3. Summary of Research Activity

Summary of Research Activities of the three groups of the Center are given in the sections of each group.

Members

Director
Samuel H. ARONSON

Deputy Director
Robert PISARSKI

Administrative Staff
Mituru KISHIMOTO (Administration Manager, Nishina Center Planning Office)
Kazunori MABUCHI (Deputy Administration Manager, Nishina Center Planning Office, – Dec. 31, 2014)
Yasutaka AKAI (Deputy Administration Manager, Nishina Center Planning Office, Jan. 1, 2015 –)
Colleen MICHAEL (Administrative Assistant)
Pamela ESPOSITO (Administrative Assistant)
Taeko ITO (Administrative Assistant)
Sub Nuclear System Research Division
RIKEN-BNL Research Center
Theory Group

1. Abstract
The efforts of the RBRC theory group are concentrated on the major topics of interest in High Energy Nuclear Physics. This includes: understanding of the Quark-Gluon Plasma; the nature of dense quark matter; the initial state in high energy collisions, the Color Glass Condensate; its evolution through a Glasma; spin physics, as is relevant for polarized hadronic collisions; physics relevant to electron-hadron collisions.

Theory Group hosted many joint tenure track positions with universities in U.S. and Japan.

2. Major Research Subjects
(1) Heavy Ion Collision
(2) Perturbative QCD
(3) Phenomenological QCD

3. Summary of Research Activity
(1) Spin Physics
The experimental program at RBRC is strongly focused on determining the origin of spin in the proton and neutron. To extract the spin content of nucleon requires both precise data and precise computation. Dr. Jianwei Qiu of the Nuclear Theory group is one of the world’s leading theorists in perturbative QCD, and leading the effort at BNL in spin physics. Their effort will continue to concentrate on computing perturbative QCD effects to sufficient precision that one can reliably extract information from the evolving experimental program. In addition they are developing ideas which might be tested in an electron-hadron collider, such as the one proposed to be built by adding an electron ring to RHIC.

(2) Matter at High Energy Density
The RHIC experimental heavy ion program is designed to study the properties of matter at energy densities much greater than that of atomic nuclei. This includes the initial state of nucleus-nucleus collisions, the Color Glass Condensate, the intermediate state to which it evolves, the Glasma, and lastly the thermal state to which it evolves, the Quark-Gluon Plasma. Theorists at the RBRC have made important contributions to all of these subjects.

Matter at high temperature has been studied by a variety of techniques involving both numerical and analytic methods. Much of the high precision work on numerical simulations of lattice QCD at nonzero temperature and density such matter have been done by members of the Lattice Gauge Theory Group at BNL, including Frithjof Karsch, Peter Petreczky, Swagato Mukherjee, and postdoctoral assistants. These groups, along with collaborators at Columbia University, the University of Bielefeld, and other groups, have computed numerous properties of QCD in thermodynamic equilibrium. This includes the equation of state for physical quark masses, susceptibilities with respect to quark chemical potentials, and transport coefficients.

Phenomenological theories of the Quark-Gluon Plasma, based upon results from lattice simulations, have been developed by R. Pisarski of the Nuclear Theory Group, in collaboration with Dr. Y. Hidaka (previously of RBRC/BNL, and now a permanent member at RIKEN in Waco), Shu Lin, Daisuke Sato, and other postdoctoral research assistants at RBRC/BNL.

The theory of the Color Glass Condensate and Glasma was largely developed by RBRC scientists. This theory has been successfully applied to a wide variety of experimental results involving high energy collisions of hadrons, electrons and nuclei. There is recent data on heavy ion collisions that are naturally explained by such matter, including data on proton (or deuteron) nucleus collisions. Much of the effort here will be aimed towards excluding or verifying the Color Glass Condensate and Glasma hypothesis in RHIC and LHC experiments.

Thermal matter at high temperature and baryon density has been traditionally conjectured to be of two phases: confined and deconfined, with a direct correlation between deconfinement and the restoration of chiral symmetry. RBRC scientists have recently conjectured a third phase, of quarkyonic matter. This is baryonic matter at energy densities very high compared to the QCD scale. It has a pressure and energy density typical of quarks, yet it is confined. The name arises because it shares properties of confined baryonic matter with unconfined quark matter. This hypothesis is new and predicts new classes of phenomena that might be observed in collisions of nuclei of relatively low energy at RHIC. There are a number of first principle theoretical issues also to be understood.

Efforts on RHIC phenomenology proceed on a broad front. Recent efforts include improving hydrodynamic computations using state of the art equations of state derived from lattice gauge theory. Understanding the nature of matter at high baryon number density has generated the idea of Quarkyonic Matter, that may have implications for an upcoming low energy run at RHIC and eventual experiments in the future at FAIR and NICA. An issue being studied is the nature of mass generation and the breaking of translational invariance. A central focus of work at RBRC, the Color Glass Condensate and the Glasma, matter that controls the high energy limit of QCD, is being realized in experiments at RHIC. Much activity focuses on the relation between observations at LHC and the implications made at RHIC.
Members

Group Leader (Lab. Head)
Larry McLERRAN

Deputy Group Leader
Robert PISARSKI (concurrent: Deputy Director, RBRC)

RHIC Physics Fellows
Fedor BEZRUKOV
Jinfeng LIAO
Ho-Ung YEE

Research Associates
Adam BZDAK (~ Apr. 30, 2014)
Daniel PITONYAK

Special Postdoctoral Researchers
Kouji KASHIWA (~ Mar. 31, 2014)
Akihiko MONNAI

Foreign Postdoctoral Researchers
Shu LIN
Sergey SYRITSYN

Visiting Scientists
Testufumi HIRANO (Univ. of Tokyo)
Feng YUAN (LBNL)
Edward SHURYAK (State Univ. New York, Stony Brook)
Miklos GYULASSY (Columbia Univ.)
Robert L. JAFFE (MIT)
Thomas BLUM (Univ. of Connecticut)
Taku IZUBUCHI (concurrent; Computing Gr.)
1. Abstract

The computing group founded in 2011 as a part of the RIKEN BNL Research Center established at Brookhaven National Laboratory in New York, USA, and dedicated to conduct researches and developments for large scale physics computations important for particles and nuclear physics. The group was forked from the RBRC Theory Group.

The main mission of the group is to provide important numerical information that is indispensable for theoretical interpretation of experimental data using the theories of particle and nuclear physics. Their primary area of research is lattice quantum chromodynamics (QCD), which describes the sub-atomic structures of hadrons, which allow us the ab-initio investigation for strongly interacting quantum field theories beyond perturbative analysis.

The RBRC group and its collaborators have emphasized the necessity and importance of precision calculations, which will precisely check the current understandings of nature, and will have a potential to find physics beyond the current standard model of fundamental physics. We have therefore adopted techniques that aim to control and reduce any systematic errors. This approach has yielded many reliable results.

The areas of the major activities are R&D for high performance computers, developments for computing algorithms, and researches of particle, nuclear, and lattice theories. Since the inception of RBRC, many breakthroughs and pioneering works has carried out in computational forefronts. These are the use of the domain-wall fermions, which preserve chiral symmetry, a key symmetry for understanding nature of particle nuclear physics, the three generations of QCD devoted supercomputers, pioneering works for QCD calculation for Cabibbo-Kobayashi-Maskawa theory, QCD+QED simulation for isospin breaking, novel algorithm for error reduction in general lattice calculation. Now the chiral quark simulation is performed at the physical up, down quark mass, the precision for many basic quantities reached to accuracy of sub-percent, and the group is aiming for further important and challenging calculations, such as the full and complete calculation for $K\to\pi\pi$ decay, $\epsilon'/\epsilon$, or hadronic contributions go muon’s anomalous magnetic moment, or Nucleon’s shape and structures.

2. Major Research Subjects

(1) Search for new law of physics through tests for Standard Model of particle and nuclear physics, especially in the framework of the Cabibbo–Kobayashi–Maskawa (CKM), hadronic contributions to the muon's anomalous magnetic moment (g-2).

(2) Dynamics of QCD and related theories, including study for the structures of nucleons

(3) Theoretical and algorithmic development for lattice field theories, QCD machine design

3. Summary of Research Activity

In 2011, QCD with Chiral Quarks (QCDCQ), a third-generation lattice QCD computer that is a pre-commercial version of IBM’s Blue Gene/Q, was installed as an in-house computing resource at the RBRC. The computer was developed by collaboration among RBRC, Columbia University, the University of Edinburgh, and IBM. Two racks of QCDCQ having a peak computing power of $2 \times 200$ TFLOPS are in operation at the RBRC. In addition to the RBRC machine, one rack of QCDCQ is owned by BNL for wider use for scientific computing. In 2013, 1/2 rack of Blue Gene/Q is also installed by US-wide lattice QCD collaboration, USQCD. The group has also used the IBM Blue Gene supercomputers located at Argonne National Laboratory and BNL (NY Blue), and RICC, the cluster computers at RIKEN (Japan), Fermi National Accelerator Laboratory, the Jefferson Lab, and others.

Such computing power enables the group to perform precise calculations using up, down, and strange quark flavors with proper handling of the important symmetry, called chiral symmetry, that quarks have. Several projects are ongoing: flavor physics in the framework of the CMK theory for kaons and B mesons; the electromagnetic properties of hadrons; hadronic contributions to the muon’s anomalous magnetic moment; the proton’s and neutron’s electric dipole moments; proton decay; nucleon form factors, which are related to the proton spin problem; and QCD thermodynamics in finite temperature/density systems such as those produced in heavy-ion collisions at the Relativistic Heavy Ion Collider. Major breakthroughs on important problems such as the direct CP violation process ($K\to\pi\pi$, $\epsilon'/\epsilon$) will be attempted using this computer.

The RBRC group and its collaborators have emphasized the necessity and importance of precision calculations, which will precisely check the current understandings of nature, and will have a potential to find physics beyond the current standard model of fundamental physics. We have therefore adopted techniques that aim to control and reduce any systematic errors. This approach has yielded many reliable results.

The group also delivers an algorithmic breakthrough, which speed up generic lattice gauge theory computation typically by a factor of 20 or more. In this novel technique called All Mode Averaging (AMA), the whole calculation is divided into frequent approximated calculations, and infrequent expensive and accurate calculation using lattice symmetries.
Members

Group Leader (Lab. Head)
Taku IZUBUCHI

RIKEN BNL Fellow
Tomomi ISHIKAWA (concurrent; Visiting Scientist, Univ. of Connecticut)

RHIC Physics Fellows
Brian TIBURZI
Ethan NEIL

RHIC Physics Fellows
Stefan MEINEL

Foreign Postdoctoral Researcher
Christopher KELLY

Visiting Senior Scientist
Robert MAWHINNEY (Columbia Univ.)

Visiting Scientists
Shigemi OHTA (KEK)
Yasumichi AOKI (Nagoya Univ.)
Thomas BLUM (Univ. of Connecticut)
Chulwoo JUNG (BNL)
Christoph LEHNER (BNL)

Meifeng LIN (Yale Univ.)
Eigo SHINTANI (Inst. für Kernphysik Johannes Gutenberg-Univ. at Mainz)
Takeshi YAMAZAKI (Nagoya Univ.)
Hyung-Jin KIM (BNL)

Fig. The rack, motherboard, and chips of QCDCQ
1. Abstract

RIKEN BNL Research Center (RBRC) Experimental Group studies the strong interactions (QCD) using RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized p+p collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment at RHIC. We study the spin structure of the proton using the polarized proton-proton collisions at RHIC. This program has been promoted by RIKEN’s leadership. The first focus of the research is to measure the gluon spin contribution to the proton spin. Our recent data analysis has shown that the proton spin carried by the gluons is small, which is a very striking finding beyond our expectations. The aim of Heavy ion physics at RHIC is to re-create Quark Gluon Plasma (QGP), the state of Universe just after the Big Bang. Two important discoveries, jet quenching effect and strong elliptic flows, have established that new state of dense matter is indeed produced in heavy ion collisions at RHIC. We are now studying the property of the matter. Recently, we have measured direct photons in Au+Au collisions for 1<p_T<3 GeV/c, where thermal radiation from hot QGP is expected to dominate. The comparison between the data and theory calculations indicates that the initial temperature of 300 MeV to 600 MeV is achieved. These values are well above the transition temperature to QGP, which is calculated to be approximately 160 MeV by lattice QCD calculations.

We have major roles in detector upgrades of PHENIX experiment, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. Both of the upgrade is now complete. VTX detector was installed in PHENIX in 2011 and we are taking data since then. Muon trigger was complete and it was essential for W→μ measurement in 2013.

2. Major Research Subjects

(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) PHENIX detector upgrades

3. Summary of Research Activity

We study the strong interactions (QCD) using the RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized p+p collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment.

(1) Experimental study of spin structure of proton using RHIC polarized proton collider

How is the spin of proton formed with 3 quarks and gluons? This is a very fundamental question in Quantum Chromodynamics (QCD), the theory of the strong nuclear forces. The RHIC Spin Project has been established as an international collaboration between RIKEN and Brookhaven National Laboratory (BNL) to solve this problem by colliding two polarized protons for the first time in history. This project also has extended the physics capabilities of RHIC.

The first goal of the Spin Physics program at RHIC is to determine the gluon contribution to proton spin. It is known that the spin of quark accounts for only 25% of proton spin. The remaining 75% should be carried either by the spin of gluons or the orbital angular momentum of quarks and gluons. One of the main goals of the RHIC spin program has been to determine the gluon spin contribution. Before the start of RHIC, there was little experimental constraint on the gluon polarization, ΔG.

PHENIX measures the double helicity asymmetry (A_{LL}) of π^0 production to determine the gluon polarization. Our publication from 2006 run has shown that the gluon polarization in the proton is small and only about half of proton spin can be accounted by gluon spin in the measured region of gluon momentum in proton. Figure 1 shows our most recent results of A_{LL} measurement, which has just submitted to Physical Review D. The figure shows the combined results of RUN5, RUN6, and RUN9. The new data give even stronger constraint on the gluon spin. RBRC exp. G led the gluon spin analysis in PHENIX. K. Bolye, a fellow of RBRC experimental group has a major role in this paper.

RHIC achieved polarized p+p collisions at 500 GeV in 2009. The collision energy increased to 510 GeV in 2012 and 2013. We have recorded The main goal of these high energy p+p run is to measure anti-quark polarization via single spin asymmetry AL of the W boson production. We have published the first results on W→e measurement at mid-rapidity from 2009 dataset in 2011. We upgraded the muon trigger system to measure W→π decays in the forward direction. With the measurement of W→e and W→μ, we can cover a wide kinematic range in anti-quark polarization measurement. The 2013 run is the main spin run at 510 GeV. PHENIX has recorded more than 150/pb of data in the run. Combined with the datasets in 2009 (8.6/pb), 2011(18/pb), and 2012(~30/pb), we will have a definite measurement of anti-quark spin.
The goal of high energy heavy ion physics at RHIC is study of QCD in extreme conditions i.e. at very high temperature and at very high energy density. Experimental results from RHIC have established that dense partonic matter is formed in Au+Au collisions at RHIC. The matter is very dense and opaque, and it has almost no viscosity and behaves like a perfect fluid. These conclusions are primarily based on the following two discoveries:

- Strong suppression of high transverse momentum hadrons in central Au+Au collisions (jet quenching)
- Strong elliptic flow

These results are summarized in PHENIX White paper, which has over 1900 citations to date.

The focus of the research in heavy ion physics at RHIC is now to investigate the properties of the matter. RBRC have played the leading roles in some of the most important results from PHENIX in the study of the matter properties. These include (1) measurements of heavy quark production from the single electrons from heavy flavor decay (2) measurements of J/Psi production (3) measurements of di-electron continuum and (4) measurements of direct photons.

The most important recent result is the measurement of direct photons for 1<p_T<5 GeV/c in p+p and Au+Au through their internal conversion to e+e- pairs. If the dense partonic matter formed at RHIC is thermalized, it should emit thermal photons. Observation of thermal photon is direct evidence of early thermalization, and we can determine the initial temperature of the matter. It is predicted that thermal photons from QGP phase is the dominant source of direct photons for 1<p_T<3 GeV/c at the RHIC energy. We measured the direct photon in this p_T region from measurements of quasi-real virtual photons that decays into low-mass e+e-pairs. Strong enhancement of direct photon yield in Au+Au over the scaled p+p data has been observed. Several hydrodynamical models can reproduce the central Au+Au data within a factor of two. These models assume formation of a hot system with initial temperature of Tinit = 300 MeV to 600 MeV. This is the first measurement of initial temperature of quark gluon plasma formed at RHIC. These results are recently published in Physical Review Letters. Y. Akiba is the leading person of the analysis and the main author of the paper. He received 2011 Nishina memorial Prize mainly based on this work.

(3) PHENIX detector upgrade

The group has major roles in several PHENIX detector upgrades, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. VTX is a high precision charged particle tracker made of 4 layers of silicon detectors. It is jointly funded by RIKEN and the US DOE. The inner two layers are silicon pixel detectors and the outer two layers are silicon strip detectors. Y. Akiba is the project manager and A. Deshpande is the strip system manager. The VTX detector was completed in November 2010 and subsequently installed in PHENIX. The detector started taking data in the 2011 run. With the new detector, we are measuring heavy quark (charm and bottom) production in p+p, A+A collisions to study the properties of quark-gluon plasma. We have recorded 20 billion Au+Au collisions in the 2014 run. The large dataset will produce definitive results on heavy quark production at RHIC.

Muon trigger upgrades are needed for W→μ measurement at 500 GeV. New trigger electronics (Muon Trigger FEE) and new Muon...
trigger detectors using RPC technology were installed in PHENIX muon arms. Additional hadron absorbers were installed in front of the muon arms to reduce the background. These upgrades were essential for the high statistic W→μ measurement in 2013 run. Over 150 pb of data was recorded in the run. I. Nakagawa is the leading person of the installation of the Muon Trigger FEE, and R. Seidl have major role in the RPC project. He is also leading the W→μ analysis.

(4) Other data analysis in PHENIX

PHENIX experiment has a very good capability of low mass electron pair measurement. Recently we used this capability for search for “dark photon”, a hypothetical particle in Beyond Standard Model theories. Many experiments looked for this particle since it can provide a simultaneous explanation of the 3.6σ deviation of the measured value of muon anomalous magnetic moment (g-2) from its theoretically calculated value and the positron excess observed by PAMELLA, FERMI, and AMS-2 experiments. If dark photon exists, it decays into an electron-positron pair, and thus it can be observed as a narrow peak in e^+e^- mass spectrum. We looked for this signal of dark photon in a large sample of electron pairs measured by PHENIX experiment. We observed no significant signal of dark photon and then set the upper limit of the dark photon – ordinary photon mixing parameter as function of mass. The result is shown in Fig. 3 below. Combined with other experimental limits, the parameter space of dark photon as the explanation of muon g-2 anomaly was almost completely ruled out.

Figure 3 90% CL limit of photon-dark photon mixing parameter as a function of mass. The shaded band show the parameter space favored by the muon g-2 anomaly. Accepted in Physical Review C.

Members

Group Leader (Lab. Head)
Yasuyuki AKIBA (Deputy Chief Scientist)
Deputy Group Leader
Abhay DESHPANDE

RIKEN Spin Program Researchers
Yasushi WATANABE (concurrent: Radiation Lab.)
Yuji GOTO (concurrent: Radiation Lab.)
Itaru NAKAGAWA (concurrent: Radiation Lab.)
Takashi ICHIHARA (concurrent: RI Physics Lab.)

Atsushi TAKETANI (concurrent: Neutron Beam Technology Team, Advanced Photonics Technology development Group, RAP)
Satoshi YOKKAICHI (concurrent: Radiation Lab.)

RIKEN BNL Fellows
Josef SEELE (- Feb. 7, 2014)
Kieran BOYLE

RHIC Physics Fellows
Xiaorong WANG
Stefan BATHE (- Jan. 31, 2015)

Special Postdoctoral Researcher
Maki KUROSAWA (- Mar. 31, 2014)

Research Associates
Chin-Hao CHEN (- Aug. 29, 2014)

RBRC Collaborating Scientists
Rachid NOUCER
Ady HERSHCOVITCH (BNL)

Visiting Scientists
Akio OGAWA (BNL)
Zheng LI
Masahiro OKAMURA (concurrent: BNL)
1. Abstract
Our core activities are based on the RIKEN-RAL Muon Facility located at the Rutherford Appleton Laboratory (UK), which provides intense pulsed-muon beams. Muons have their own spins with 100% polarization, and can detect very precisely local magnetic fields and their fluctuations at muon stopping sites. The method to study characteristic of materials by observing time-dependent changes of muon spin polarization is called "Muon Spin Rotation, Relaxation and Resonance (μSR) method", and is applied to studies of electro-magnetic properties of insulating, metallic, magnetic, superconducting systems. Muons reveal static and dynamic properties of electronic state of materials in the zero-field condition, which is the ideal magnetic condition for researches on the magnetism. μSR is applied to those systems. As one example of those researches, we have carried out μSR investigations on frustrated pyrochlore systems, which have variety of exotic ground state of magnetic spins. We are approaching to achieve the first evidence of the appearance of a quasi-monopole state in the pyrochlore system.

We have been working on producing ultra-slow muon beam, which has a momentum spread as small as thermal energy. Our method of the beam generation is based on the laser ionization of muoniums (bound system of μ and electron), which emitted from hot tungsten surface by stopping low-momentum muon beam at Port-3. The ultra-slow muon beam can be stopped in thin foils, multi-layered materials and artificial lattices and we can apply the μSR techniques to surface and interface science. The development of ultra-slow muon beam is also very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon g-2/EDM measurement. We have been developing muonium generators to create more muoniums in vacuum even at room temperature. Very recently, we demonstrated tremendous increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. We also developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. The new laser will ionize muoniums 100 times more efficiently for slow muon beam generation.

2. Major Research Subjects
(1) Materials science by muon-spin-relaxation method
(2) Hyperfine interactions at muon sites studied by the computation science
(3) Nuclear and particle physics studies via muonic atoms and ultra-cold muon beam

3. Summary of Research Activity
(1) Material Science at the RIKEN-RAL Muon Facility
Muons with their own spin polarization enable us to conduct (1) material studies under external zero-field condition, (2) magnetism studies with samples without nuclear spins, and (3) measurements of muon spin relaxation changes at wide temperature range with same detection sensitivity. The detection time range of local field fluctuations by μSR is 10⁻⁶ to 10⁻¹¹ second, which is an intermediate region between neutron scattering method (10⁻¹⁰-10⁻¹² second) and Nuclear Magnetic Resonance (NMR) (longer than 10⁻⁶ second). At Port-2 and 4 of the RIKEN-RAL Muon Facility, we have been performing μSR researches on newly fabricated strong correlated-electron systems, organic molecules and biological samples to study electron structures, superconductivity, magnetism, molecular structures and crystal structures.

In the period from 2012 to 2014, we have obtained excellent results, and the highlights are listed in the following,
1) A static ordering of small Ir moments in the pyrochlore iridate; Nd₂Ir₅O₁₀ is close to a quantum critical point.
2) A static ordering of Yb moment on the corner of the pyrochlore structure of Yb₂Ti₃O₇ can be explained by the Higgs mechanism.
3) Spontaneous formation of small static internal fields in the superconducting state of URu₂Si₂ was observed, which indicate appearance of an exotic superconducting state in this material.
4) Universality class of the Mott transition is confirmed in EtMe₃P[Pd(dmit)₂]₂.
5) Finding new muon sites in La₂Cu₃O₆, which can only be explained by taking into account the spatial distribution of Cu spin.
6) A novel coexisting state between Fe spin-glass and Cu stripe ordered states in the over-doped regime of La₂₋ₓSrₓCu₁₋ₓFe₂O₅.
7) International collaborations to organize new μSR experiments and to develop a group to work on muon-site calculations by using computational technique.

Solid observations of a statically ordered state of corner-shared magnetic moments on pyrochlore systems gave us new interpretation to understand exotic phenomena, like the quantum criticality of magnetic moments and a quasi-magnetic monopole state (result-1 and 2). We measured an increase of static internal fields at the muon site in the zero-field condition just below the superconducting transition temperature of URu₂Si₂. This could shed a light on the mechanism of the superconductivity, which has been a long-standing problem of this system (result-3). We have been developing gas-pressureized high-pressure apparatus, which can be used not only for μSR but also for other purposes. We have applied this pressure system to EtMe₃P[Pd(dmit)₂]₂ and have found that pressure dependent resistivity and thermoelectric coefficient measurements have shown that the Mott transition belongs to the Ising universality
class even in two-dimensional states (result-4). Well-known and deeply investigated $\text{La}_2\text{CuO}_4$ has opened a new scheme of the Cu spin. Taking into account the effect of the spatial distribution of Cu spin, we have succeeded to explain newly found muon sites and hyperfine fields at those sites (result-5). Fe spins form a spin glass state through the RKKY interaction in the over-doped regime in $\text{La}_2\text{Sr}_x\text{Cu}_{1-x}\text{Fe}_y\text{O}_4$. This spin glass state is expected to co-exist with the stripe ordered state at lower temperatures (result-6).

We have been very keen to develop muon activities in Asian countries. We have formed MOU with Universiti Sains Malaysia (USM) in order to develop activities on the muon-site calculation. We have newly started to collaborate in µSR experiments on strongly correlated systems with researchers from Taiwan and Korea including graduate students (result-7).

A new µSR spectrometer “Chorus” which has finely multi-segmented forward and backward µ-ε counter arrays (304 counters each) is now used for real µSR experiments in Port-4 in parallel with ARGUS in Port-2. Software systems, which control the data acquisition and experimental conditions, are renewed based on the ISIS frontend so as to have common data format with the other ISIS muon facilities (DAE with SECI), so as to have more affinity with the ISIS facility and its analysis platform.

(2) Ultra Slow (low energy) Muon Beam Generation and Applications

We are performing R&D to realize efficient generation of ultra-slow muon beam having energy dispersion below thermal energy utilizing laser ionization of muoniums at Port-3. To study magnetism at surface and interface, and to realize new high-precision muon g-2/EDM measurement, it is essential to increase the slow muon beam production efficiency by more than 100 times. There are three key techniques in ultra-slow muon generation: production of thermal muonium, high intensity Lyman-alpha laser and the ultra-slow muon beam line.

In the period from 2011 to 2014, we developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at RIKEN. The new laser will ionize muoniums 100 times more efficiently for slow muon beam generation. This development was funded mostly by the Grant-in-Aid for Scientific Research on Innovative Areas “Frontier in Materials, Life and Particle Science Explored by Ultra Slow Muon Microscope”. This Grant-in-Aid research group is a complex of research institutions from universities together with J-PARC muon group and RIKEN. The new laser system was installed to J-PARC slow muon beam line and is being tested. In this development, we succeeded to synthesize novel ceramic-based Nd:YGAG crystal, and this crystal can also be applicable to the flash-lamp based Lyman-alpha laser system of RIKEN-RAL to realize substantial improvement of the laser power at a much reduced cost based on the experiences.

Another plan in 2011-2014 was to realize drastic improvements on the ultra-slow muon source with much reduced emittance. We have been developing muonium generators to create more muoniums in vacuum even at room temperature. In 2013, we demonstrated tremendous increase of the muonium emission efficiency by fabricating fine laser drill-holes on the surface of silica aerogel. The measurement was carried out at TRIUMF in collaboration with J-PARC muon g-2/EDM group. We believe that the better efficiency and beam quality can be achieved in ultra-slow muon generation by using this new muonium source.

Based on these two new key components, we are planning to feed these new techniques to RIKEN-RAL ultra-slow muon beam line to realize further development of ultra-slow muon technology. The present muonium production target section, which had been designed with hot tungsten, was rebuilt to use advantage of the new room temperature target, such as no need of thermal shielding etc. Also, we adopted an all-cylindrical beam-translate design, because of its simpler optics and better manufacture precision, which will contribute to the ultimate cold muon source required for muon g-2/EDM. We plan the testing with the muon beam to be started in middle 2015.

(3) Other topics

Muon catalyzed fusion has been one of the main subject of studies since the start of the RIKEN-RAL Muon Facility. It has produced many new results by using the advantage of the high-intensity pulsed muon beam and the advanced tritium handling facility as was reported in previous RIKEN-RAL IACs. Even though, huge increase of the catalysis rate that is enough for energy production is yet difficult to achieve. Considering the limited budget and human resources maintaining the tritium facility, we had discussions with RAL on the safe closure of the tritium facility. The decommissioning was completed in March 2015.

New demand is emerging on utilizing the muon beam for electronics chips radiation effect studies. Recent progress of semiconductor devices has produced electronics chips with very fine structure. It is concerned that the single memory upset by the ionization effect of single muon may result in malfunction or errors of advanced electronics. Muon is the main component of the cosmic ray in our ordinal life and difficult to be removed. We have started measurement at RIKEN-RAL in 2013 to measure such an error rate and observed an effect that is correlated with the muon energy deposit rate. Further measurements were performed in 2014.

A new proposal was submitted to measure the proton radius by using the hyperfine splitting of the 1S states of muonic hydrogen. This is in contrast to the recent measurement at PSI using energy splitting between 2S-2P levels. The hyperfine transition measurement needs a high intensity laser so it needs to be matched with pulsed muon beam. A new laser system was designed in collaboration with RIKEN's advanced photonics group based on their experience on the commissioning of a laser of similar type. We are also preparing the target chamber and detectors for this measurement.
chamber and detectors for this measurement. The advanced photonics group based on their experience on the commissioning of a laser of similar type. We are also preparing the target high intensity laser so it needs to be matched with pulsed muon beam. A new laser system was designed in collaboration with RIKEN's is in contrast to the recent measurement at PSI using energy splitting between 2S-2P levels. The hyperfine transition measurement needs a is correlated with the muon energy deposit rate. Further measurements were performed in 2014.

The safe closure of the tritium facility. The decommissioning was completed in March 2015. The ultimate cold muon source required for muon g-2/EDM. We plan the testing with the muon beam to be started in middle 2015.

Taking into account the effect of the spatial distribution of Cu spin, we have succeeded to explain newly found muon sites and hyperfine class even in two-dimensional states (result-5). Fe spins form a spin glass state through the RKKY interaction in the over-doped regime in

Well-known and deeply investigated La2CuO4 has opened a new scheme of the Cu spin. The safe closure of the tritium facility. The decommissioning was completed in March 2015. The ultimate cold muon source required for muon g-2/EDM. We plan the testing with the muon beam to be started in middle 2015.

We have been very keen to develop muon activities in Asian countries. We have formed MOU with Universiti Sains Malaysia (USM) for the temporary tritium transportation. Other topics

Once the target at the beam line was rebuild, we can also realize further development of ultra-slow muon technology. The present muonium production target section, which had been designed

In 2013, we demonstrated reported in previous RIKEN-RAL IACs. Even though, huge increase of the catalysis rate that is enough for energy production is yet

It is concerned that the single memory upset by the ionization effect of

The ultimate cold muon source required for muon g-2/EDM. We plan the testing with the muon beam to be started in middle 2015.

Considering the limited budget and human resources maintaining the tritium facility, we had discussions with RAL on

Many new results by using the advantage of the high-intensity pulsed muon beam and the advanced tritium handling facility as was

A new proposal was submitted to measure the proton radius by using the hyperfine splitting of the 1S states of muonic hydrogen. This

New demand is emerging on utilizing the muon beam for electronics chips radiation effect studies. Recent progress of semiconductor

Muon catalyzed fusion has been one of the main subject of studies since the start of the RIKEN-RAL Muon Facility. It has produced

Based on these two new key components, we are planning to feed these new techniques to RIKEN-RAL ultra-slow muon beam line to

Another plan in 2010-2014 was to realize drastic improvements on the ultra-slow muon source with much reduced emittance. We have

In the period from 2011 to 2014, we developed a high power Lyman-alpha laser in collaboration with the Advanced Photonics group at

Another plan in 2010-2014 was to realize drastic improvements on the ultra-slow muon source with much reduced emittance. We have

We are performing R&D to realize efficient generation of ultra-slow muon beam having energy dispersion below thermal energy

µSR spectrometer "Chronus" which has finely multi-segmented forward and backward

µSR experiments in Port-4 in parallel with ARGUS in Port-2. Software systems, which control the data acquisition and

µ now used for real
1. Abstract

This laboratory explores exotic nuclear structures and dynamics in exotic nuclei that have never been investigated before, such as those with largely imbalanced proton and neutron numbers. Our aim is to develop new experimental techniques utilizing fast RI beams to discover new phenomena and properties in exotic nuclei. Another important subject is the equation-of-state in asymmetric nuclear matter, and its association with the origin of elements and with neutron stars. For instance, we are making attempts to the better understand underlying mechanism for exotic stability-enhancements of very neutron-rich fluorine isotopes, the large deformation of the nucleus Mg-34 with N=22 in spite of its vicinity to the N=20 magic neutron number and anomalous collectivity in Ca-46. We are further extending these studies to medium- and heavy-mass regions by developing facilities, detectors and unique methods at RIBF, thereby leading on the challenging task to find new exotic phenomena. We also perform numerical simulations of nucleosynthesis under the environment of core-collapse supernovae, and moreover quest for footprints of supernovae and solar activities in the past, embedded in Antarctic ice core.

2. Major Research Subjects

1. Study of structure and dynamics of exotic nuclei through developments of new tools in terms of reaction- and technique-based methodology
2. Research on EOS in asymmetric nuclear matter via heavy-ion induced reactions
3. Detector developments for spectroscopy and reaction studies

3. Summary of Research Activity

1. In-beam gamma spectroscopy

In the medium and heavy mass region explored at RIBF, collective natures of nuclei are one of important subjects, which are obtained through production and observation of high excited and high spin states. To populate such states, heavy-ion induced reactions such as fragmentation, fission are useful. So far, we have developed two-step fragmentation method as an efficient method to identify and populate excited states, and lifetime measurements to deduce transition strength.

Devices utilized for the in-beam gamma spectroscopy are ZeroDegree Spectrometer (ZDS) and a NaI array DALI2. Since the end of 2008, the first spectroscopy on nuclei island-of-inversion region was performed, we have explored step-by-step new and unknown regions in the nuclear chart. The second campaign in 2009 was organized to study background components originating from atomic processes in a heavy target. Neutron-rich nuclei at N=20 to 28 were studied in 2010. In 2011-2013, we conducted experiment programs for Ca-54, Ni-78, neutron-rich nuclei at N=82 and neutron-deficient nuclei at Z=50.

A multitude of data obtained with inelastic, nucleon knock-out, fragmentation channels have been analyzed and published. In 2011-2013, collective natures of Mg-36, 38 and Si-42 were both published in PRL. Excited states firstly observed in Ca-54 were reported in Nature to demonstrate a new nuclear magic number of 34. Fragmentation reaction has been found efficient for nuclei with A>100 and low-lying excited state in Pd-126 has been successfully observed and reported in PRC.

To further strengthen the in-beam gamma spectroscopy at RIBF, we have proposed a new setup of MINOS + DALI2 to search for the 1st excited states in even-even neutron-rich nuclei with Z=20 to 40. The program was submitted to the PAC 2013 as a new category "proposal for scientific program" and was S-ranked. A dedicated collaboration “SEASTAR” has been established as a subset of in-beam gamma collaboration “SUNFLOWER”. The two campaigns were organized in 2014 and 2015 to study very neutron-rich isotopes.

Concerning a next generation detector, a construction proposal of a LaBr3 array “SHOGUN”, was submitted to the PAC 2009, and an international workshop was organized in Feb. 2011 to form the SHOGUN collaboration. A technical development with small sized crystals is now in progress.

2. Decay spectroscopy

Beta- and isomer-spectroscopy is an efficient method for studying nuclear structure, especially for non-yrast levels. We had accumulated experimental techniques at the RIPS facility to investigate nuclear structure in light mass region via beta-gamma and beta-p coincidence. Concerning the medium and heavy mass region available at RIBF, we have developed two position-sensitive active-stoppers, strip-silicon detectors and a cylindrical active stopper called CAITEN, to achieve a low-background measurement by taking correlation between heavy ion stop position and beta-ray emission position. A site of decay-spectroscopy at the new facility of RIBF is the final focal plane of ZDS, where high precision of TOF in particle identification is obtained due to a long flight path from BigRIPS to ZDS.

At the end of 2009, the first decay spectroscopy was organized with a minimum setup of four clover gamma detectors and silicon strip detectors, to study neutron-rich nuclei with A=110. The first campaign was found successful and efficient to publish four letter articles in 2011, two PRL’s and two PLB’s. One of the PRL papers is associated to the r-process path where half-lives for 18 neutron-rich nuclei were determined for the first time. The other PRL paper reported a finding of deformed magic number 64 in the Zr isotopes.

The success of the first decay-spectroscopy campaign stimulated to form a new large-scale collaboration “EURICA”, where a twelve Euroball cluster array is coupled with the silicon-strip detectors to enhance gamma efficiency by a factor of 10. A construction proposal of “EURICA” was approved in the PAC 2011, and the commissioning was successfully organized in spring 2012. Since then, physics runs have been conducted for programs approved to survey nuclei of interest as many as possible, such as Ni-78, Pd-128, Sn-100. So far, 10 papers including 7 PRL’s were published. One of the highlights is discovery of a seniority isomer in Pd-128, of which cascade gamma decay gives the energy of 1st excited state and robustness of N=82 magic number.

Beta-delayed neutron emission probability of medium and heavy neutron-rich nuclei is important to understand nuclear structure and the r-process path. In 2013, a new collaboration “BRIKEN” has been established to form a He-3 detector array. A present design of the
array has neutron efficiency as high as 70% up to 3 MeV. The array will be coupled with the AIDA silicon strip system. A construction proposal was approved at the PAC 2013 and two physics proposals have been approved at PAC 2014.

The CAITEN detector was successfully tested with fragments produced with a Ca-48 beam in 2010.

(3) **Equation-of-state via heavy-ion central collisions**

Equation-of-state in asymmetric nuclear matter is one of major subjects in physics of exotic nuclei. Pi-plus and pi-minus yields in central heavy ion collisions at the RIBF energy are considered as one of EOS sensitive observables at the RIBF energy. To observe charged pions, a TPC for the SAMURAI spectrometer is being constructed under an international collaboration “SrRIT”. Construction proposal was submitted at the PAC 2012, and physics proposals were approved at the PAC 2012 and 2013. Physics runs are scheduled in 2016.

An international symposium “NuSYM” on nuclear symmetry energy was organized at RIKEN July 2010 to invite researchers in three sub-fields, nuclear structure, nuclear reaction and nuclear astrophysics, and to discuss nuclear symmetry energy together. Since then, the symposium series have been held every year and been useful to encourage theoretical works and to strengthen the collaboration.

(4) **Nucleon correlation and cluster in nuclei**

Nucleon correlation and cluster in nuclei are matters of central focus in a “beyond-mean-field” picture. The relevant programs with in-beam gamma and missing-mass techniques are to depict nucleon condensations and correlations in nuclear media as a function of density as well as temperature. Neutron-halo and $\pi$-skin nuclei are objects to study dilute neutron matter at the surface. By changing excitation energies in neutron-rich nuclei, clustering phenomena and role of neutrons are to be investigated.

In 2013, two programs were conducted at the SAMURAI spectrometer. One is related to proton-neutron correlation in the C-12 nucleus via p-n knockout reaction with a carbon target. The other is to search for a cluster state in C-16, which was populated via inelastic alpha scattering. The data is being analyzed.

(5) **Nuclear data for nuclear waste of long-lived fission products**

The nuclear waste problem is an inevitable subject in nuclear physics and nuclear engineering communities. Since the Chicago Pile was established in 1942, nuclear energy has become one of major sources of energy. However, nowadays the nuclear waste produced at nuclear power plants has caused social problems. Minor actinide components of the waste have been studied well as a fuel in fast breeder reactors or ADS. Long-lived fission products in waste, on the other hand, have not been studied extensively. A deep geological disposal has been a policy of several governments, but it is difficult to find out location of the disposal station in terms of security, sociology and politics. To solve the social problem, a scientific effort is necessary for nuclear physics community to find out efficient methods for reduction of nuclear waste radioactivity.

In 2013, we have started up a new project to take nuclear data for transmutation of long-lived fission products to obtain cross section data needed for designing a nuclear waste treatment system. In 2014, we made the first attempt to obtain fragmentation reaction data with Cs-137 and Sr-90 beams at 200A MeV.

Since 2014, this activity has been intensively organized as one of the ImPACT projects by the Nuclear Transmutation Data Research Group.
Consultant
Takeaki TORII (– May 2014)

International Program Associates
Xiaofei YANG (Peking Univ.)
Hongna LIU (Peking Univ.)
Jin WU (Peking Univ.)

Junior Research Associates
Shintaro GO (Univ. of Tokyo)
Yoshiaki SHIGA (Rikkyo Univ.)

Part-time Worker
Zhengyu XU (Univ. of Tokyo, – Mar. 31, 2014)

Visiting Researchers
Gabor KISS (JSPS)
David STEPPENBECK (JSPS)

Senior Visiting Scientists
Kengo OGAWA (Chiba Univ.)

Visiting Scientists
Toshiyuki SUMIKAMA (Tohoku Univ.)
Hooi Jing ONG (RCNP)
Megumi NIKURA (Univ. of Tokyo)
Silvio CHERUBINI (Univ. of Catania)
Hyo Soon JUNG (Univ. of Notre Dame)
Daiki NISHIMURA (Tokyo Univ. of Sci.)
Nobuyuki KOBAYASHI (Univ. of Tokyo)
Naohiko OTSKU (Intl. Atomic Energy Agency, Austria)
Giuseppe LORUSSO (National Physics Lab., UK)
Hiu Ching LEE (Univ. of Hong Kong)
Indranil MAZUMDAR (OSI)
Alessia Pietro DI (INFN Catania)
Pierpaolo FIGUERA (INFN Catania)
Byungsik HONG (Korea Univ.)

Visiting Technicians
Ivan KOJOUGHAROV (OSI)

Student Trainees
Kenta YOSHINAGA (Tokyo Univ. of Sci.)
Masayuki NAGASHIMA (Niigata Univ.)
Jongwon HWANG (Seoul Nat’l Univ.)
Sunji KIM (Seoul Nat’l Univ.)
Zhengyu XU (Tokyo Univ.)
Yosuke MITSUYA (Meiji Univ.)
Yusuke MORITA (Osaka Univ.)
Junichi OHNO (Osaka Univ.)
Yasuto KAMISHOU (Osaka Univ.)
Hiromi NISHIBATA (Osaka Univ.)
Yifan ZHU (Tokyo Univ. of Sci.)
Hisayuki HIRATA (Tohoku Univ.)
Kotomi MUTO (Tohoku Univ.)
Tetsuya YAMAMOTO (Osaka Univ.)
Noritsugu NAKATSUKA (Kyoto Univ.)
Ayumi YAGI (Osaka Univ.)
Kazuma KOBAYASHI (Rikkyo Univ.)
Ryo YANO (Univ. of Tokyo)
Tomomi FUJITA (Osaka Univ.)
Takamaru YOSHIDA (Rikkyo Univ.)
Takumi USUKURA (Rikkyo Univ.)
Shunpei KINNO (Tokyo Univ. of Sci.)
Daisuke WATANABE (Univ. of Tsukuba)
Yifan FANG (Osaka Univ.)
Jin-hee CHANG (Korea Univ.)

Tomoki ISHIGAKI (Osaka Univ.)
Rie DAIDO (Osaka Univ.)
Shouta MORIMOTO (Osaka Univ.)
Keisuke TASHIRO (Niigata Univ.)
Akira HOMMA (Niigata Univ.)
Daiki MIROOKA (Niigata Univ.)
Akhiro KOJIMA (Tohoku Univ.)
Ippei NISHIZUKA (Tohoku Univ.)
Takuya MIYAZAKI (Univ. of Tokyo)
Satoru MOMICHI (Univ. of Tokyo)
Mana TANAKA (Osaka Univ.)
Shintaro YAMAMOTO (Osaka Univ.)
Kouta WATANABE (Osaka Univ.)
Justin Brian ESTEE (MSU)
Masanori KANEKO (Kyoto Univ.)
Hideyuki MITSUZAWA (Rikkyo Univ.)
Schrödinger PHILIPP (TU Darmstadt)
Hirotaka SUZUKI (Osaka Univ.)
Suwat TANGWANCHAROEN (MSU)
JungWoo LEE (Korea Univ.)
Takashi ANDO (Univ. of Tokyo)
Yuki YAMAGUCHI (Rikkyo Univ.)
Hiroyasu NAGAKURA (Rikkyo Univ.)
### VI. RNC ACTIVITIES

| Hang DU (Osaka Univ.) | Junya NAGUMO (Tokyo Univ. of Sci.) |
| Yutaro TANAKA (Osaka Univ.) | Matthew CHAPMAN (Texas A&M Univ.) |
| Jiro SHIMAYA (Osaka Univ.) | Rensheng WANG (Tsinghua Univ.) |
| Jonathan BARNEY (MSU) | Phong VI (Hanoi Univ. of Sci.) |
| Hiroyuki OIKAWA (Tokyo Univ. of Sci.) | Jiajian LIU (Univ. of Hong Kong) |
| Yoshimasa TAGUCHI (Tokyo Univ. of Sci.) | Joachim TSCHUESCHNER (TU Darmstadt) |
| Naoya KAMBARA (Tokyo Univ. of Sci.) | Shinnosuke YOSHIDA (Osaka Univ.) |
| Toshiki YOSHINOBU (Tokyo Univ. of Sci.) | Hiroshi KANAOKA (Osaka Univ.) |
| Atsushi MIZUKAMI (Tokyo Univ. of Sci.) | Shoichiro MASUOKA (Rikkyo Univ.) |
| Yuki KANKE (Tokyo Univ. of Sci.) | Yan ZHANG (Tsinghua Univ.) |

**Interns**

| Ilias AROUEL (Universite Paris Sud XI) | Jonathan BARNEY (MSU) |
| Yuito AWATAGUCHI (Tokyo Met. College of Ind. Tech.) | |

- 385 -
1. Abstract
The Spin Isospin Laboratory pursues research activities putting primary focus on interplay of spin and isospin in exotic nuclei. Investigations on isospin dependences of nuclear equation of state, spin-isospin responses of exotic nuclei, occurrence of various correlations at low-densities, evolution of spin-orbit coupling are main subjects along the line. One of our goals is to elucidate a variety of nuclear phenomena in terms of interplay of spin and isospin.

Establishment of storage-ring science in Japan is another big goal of our laboratory. We are leading, in collaboration with the Wakasugi group, the Rare RI Ring project to achieve precision mass measurement of r-process nuclei.

2. Major Research Subjects
(1) Direct reaction studies of neutron-matter equation of state
(2) Study of spin-isospin responses with RI-beams
(3) Production of spin polarized protons and its application to RI-beam experiments
(4) R-process nucleosynthesis study with heavy-ion storage ring
(5) Development of special targets for RI-beam experiments

3. Summary of Research Activity
(1) Direct reaction studies of neutron matter equation of state
   - Direct reactions induced by light-ions serve as powerful tools to investigate various aspects of nuclei. We are advancing experimental programs to explore equation of state of neutron matter, via light-ion induced reactions with RI-beams.
   - Determination of a neutron skin thickness by proton elastic scattering
     - A neutron skin thickness is known to have strong relevance to asymmetry terms of nuclear equation of state, especially to a term proportional to density. The ESPRI project aims at determining density distributions in exotic nuclei precisely by proton elastic scattering at 200–300 MeV/nucleon. An experiment for $^{132}$Sn that is a flagship in this project is planned to be performed in 2015. Prior to the $^{132}$Sn experiment, we have applied the ESPRI setup that consists of a solid hydrogen target and recoil proton detectors to $^{16}$C in 2012.
   - Asymmetry terms in nuclear incompressibility
     - Nuclear incompressibility represents stiffness of nuclear matter. Incompressibility of symmetric nuclear matter is determined to be $\pm 20$ MeV, but its isospin dependence still has a large uncertainty at present. A direct approach to the incompressibility of asymmetric nuclear matter is an experimental determination of energies of isoscalar giant monopole resonances (GMR) in heavy nuclei. We have developed, in close collaboration with Center for Nuclear Study (CNS) of University of Tokyo, an active gas target for deuteron inelastic scattering experiments to determine GMR energies. The active gas target has been already tested with oxygen and xenon beams at HIMAC and will be applied to a $^{132}$Sn experiment in 2015.
   - Multi-neutron and alpha-cluster correlations at low densities
     - Occurrences of multi-neutron and/or-cluster correlations are other interesting aspects of nuclear matter and define its low-density behavior. The multi-neutron and/or-cluster correlations can be investigated with the large-acceptance SAMURAI spectrometer. The SAMURAI has been already applied to experiments to explore light neutron-rich nuclei close to the dripline. We plan to reinforce experimental capabilities of the SAMURAI by introducing advanced devices such as MINOS (Saclay) and NeuLAND (GSI).
   - Fission barrier heights in neutron-rich heavy nuclei
     - The symmetry energy has a strong influence on fission barrier heights in neutron-rich nuclei. Knowledge on the fission barrier heights, which is quite poor at present, is quite important for our proper understanding on termination of the r-process. We are planning to perform, in collaboration with the TU Munich group, $(p,2p)$-delayed fission experiments at the SAMURAI to determine the fission barrier heights in neutron-rich nuclei in Pb region.
(2) Study of spin-isospin responses with RI-beams
   - The study of spin-isospin responses in nuclei forms one of the important cores of nuclear physics. A variety of collective states, for example isovector giant dipole resonances, isobaric analogue states, Gamow-Teller resonances, have been extensively studied by use of electromagnetic and hadronic reactions from stable targets.
   - The research opportunities can be largely enhanced with light of availabilities of radioactive isotope (RI) beams and of physics of unstable nuclei. There are three possible directions to proceed. The first direction is studies of spin-isospin responses of unstable nuclei via inverse-kinematics charge exchange reactions. A neutron-detector array WINDS has been constructed, under a collaboration of CNS, Tokyo and RIKEN, for inverse kinematics $(p,n)$ experiments at the RI Beam Factory. We have already applied WINDS to the $(p,n)$ experiments for $^{12}$Be, $^{132}$Sn and plan to extend this kind of study to other exotic nuclei.
   - The second direction is studies with RI-beam induced charge exchange reaction. RI-beam induced reactions have unique properties which are missing in stable-beam induced reactions and can be used to reach the yet-to-be-discovered states. We have constructed the SHARAQ spectrometer and the high-resolution beam-line at the RI Beam Factory to pursue the capabilities of RI-beam induced reactions as new probes to nuclei. One of the highlights is an observation of $\beta^+ \!$ isovector spin monopole resonances (IVSMR) in $^{208}$Pb and $^{90}$Zr via the $(t,^3\!He)$ reaction at 300 MeV/nucleon.
   - The third direction is studies of neutron- and proton-rich nuclei via stable-beam induced charge exchange reactions, which is conducted under collaboration with Research Center for Nuclear Physics (RCNP), Osaka University. We have performed the double charge exchange $^{12}$C$(^{16}O,^{18}Ne)^{12}$Be reaction at 80 MeV/nucleon to investigate structure of a neutron-rich $^{12}$Be nucleus. Peaks corresponding to...
ground and excited levels in $^{12}$Be have been clearly observed.

(3) Production of spin-polarized protons and its application to RI-beam experiments

Recent experimental and theoretical studies have revealed that spin degrees of freedom play a vital role in exotic nuclei. Tensor force effects on the evolution of shell and possible occurrence of p-n pairing in the proton-rich region are good examples of manifestations of spin degrees of freedom.

In exploring the spin effects in exotic nuclei, scattering with polarized protons should be a powerful tool. We have constructed a novel polarized proton solid target aiming to shed light of polarization on the physics of exotic nuclei. A distinguished feature of the target system is that it works under a low magnetic field of 0.1 T and temperature higher than 100 K, which exhibits a striking contrast to standard DNP targets working in extreme conditions of several Tesla and sub-Kelvin. It should be noted that we have recently achieved a proton polarization of 40% at room temperature in a pentacene-d14 doped p-terphenyl crystal.

The polarized proton target was applied, for the first time, to measurement of vector analyzing power in the proton elastic scattering of neutron-rich $^{6,8}$He nuclei at 71 MeV/nucleon at RIPS, RIKEN. At RI Beam Factory, a hole-state spectroscopy via the $(p, 2p)$ knockout reaction from unstable oxygen isotopes was performed with the polarization target.

(4) R-process nucleosynthesis study with heavy-ion storage ring

Most of the r-process nuclei become within reach of experimental studies for the first time at RI Beam Factory at RIKEN. The Rare RI Ring at RIBF is the unique facility with which we can perform mass measurements of r-process nuclei. Construction of the Rare RI Ring started in FY2012 in collaboration with Tsukuba and Saitama Universities. A major part of the ring has been completed and the commissioning run is planned in FY2014.

We are planning to start precise mass measurements of r-process nuclei in 2015. A series of experiments will start with nuclei in the A=80 region and will be extended to heavier region.

(5) Development of special targets for RI-beam experiments

For the research activities shown above, we are developing and hosting special targets for RI-beam experiments listed below:

a) Polarized proton target
b) Thin solid hydrogen target
c) MINOS (developed at Saclay and hosted by the Spin Isospin Laboratory)

Members

Chief Scientist (Lab. Head)
Tomohiro UESAKA

Research & Technical Scientists
Ken-ichiro YONEDA (Senior Research Scientist, concurrent; Team Leader, User Support Office)
Masaki SASANO (Research Scientist)

Juzo ZENIHIRO (Research Scientist)
Sarah NAIMI (Research Scientist, Apr. 1, 2014 –)

Contract Researcher
Daisuke NAGAE (Jan. 1, 2015 –)

Special Postdoctoral Researchers
Masami SAKO
Yuma KIKUCHI

Postdoctoral Researchers
Masanori DOZONO (– Mar. 31, 2014)
Kenichiro TATEISHI (Apr. 1, 2014 –)

Valerii PANIN

Research Associate
Kenichiro TATEISHI (– Mar. 31, 2014)

Junior Research Associates
CheongSoo LEE (Univ. of Tokyo)
Fumi SUZAKI (Saitama Univ.)

Keiichi KISAMORI (Univ. of Tokyo)
Yuki KUBOTA (Univ. of Tokyo)

International Program Associates
Chao WEN (Peking Univ.)

Clementine Angleique Marie SANTAMARIA (Univ. Paris Sud XI, – Sep. 30, 2014)
Sebastian Benedict REICHERT (TUM, Aug. 1, 2014 – Nov 10, 2014)
Dahee KIM (Ewha Womans Univ., Oct. 1, 2014 –)

Part-time Worker
Tomomi KAWAHARA (– Jul. 31, 2014)

Research Consultant
Harutaka SAKAGUCHI
Visiting Researchers
Alexandre OBERTELLI (CEA Saclay, – May 1, 2014)
Dennis MUECHER (JSPS Fellow, Apr. 1, 2014 – Jun. 6, 2014)

Senior Visiting Scientists
Didier BEAUMEL (IPN)

Visiting Scientists
Didier BEAUMEL (IPN)
Yosuke KONDO (Tokyo Tech.)
Elekes ZOLTAN (Atomki)
Hidetoshi AKIMUNE (Konan Univ.)
Yohei MATSUDA (Osaka Univ.)
Yasuhiro TOGANO (Tokyo Tech.)
Satoshi SAKAGUCHI (Kyusyu Univ.)
Kenjiro MIKI (Osaka Univ.)
Valerie LAPOUX (CEA Saclay)
Alexandre OBERTELLI (CEA Saclay)
Alain GILLIBERT (CEA Saclay)
Emanuel POLLACCO (CEA Saclay)
Anna CORSI (CEA Saclay)
Dennis MUECHER (TUM)
Yury LITVINOV (GSI)
Yuhu ZHANG (CAS)
Igor GASPARIC (Ruder Boskovic Inst. Zagreb Croatia)
Hans Toslihide TOERNQVIST (TU Darmstadt)
Christoph CAESAR (GSI)
Haik SIMON (GSI)
Matthias HOLL (TU Darmstadt)
Takayuki YAMAGUCHI (Saitama Univ.)
Takashi NAKAMURA (Tokyo Tech.)
Atsushi TAMII (Osaka Univ.)
Atrila KRASZNAROKAY (ATOMKI)
Takashi WAKUI (Tohoku Univ.)
Kimiko SAKAGUCHI (Tohoku Univ.)

Visiting Technicians
Tomomi KAWAHARA (Toho Univ.)
Gilles AUTHELET (CEA Saclay)
Jean-Marc GHELLER (CEA Saclay)
Cedric PERON (CEA Saclay)
Jean-Yves ROUSSE (CEA Saclay)
Denis CALVET (CEA Saclay)
Alan PEYAUD (CEA Saclay)
Alain DELBART (CEA Saclay)
Frederic CHATEAU (CEA Saclay)
Caroline LAHONDE-HAMDOUN (CEA Saclay)
Arnaud GIGANON (CEA Saclay)
Daniel KOERPER (GSI)

Student Trainees
Shota FUKUOKA (Univ. of Tsukuba)
Zhengyang TIAN (Peking Univ.)
Ryogo MINAKATA (Tokyo Tech.)
Yasunori WADA (Toho Univ.)
Takahiro TAGUCHI (Toho Univ.)
Shun OGOSHI (Tokyo Tech.)
Tatsuya FURUNO (Kyoto Univ.)
Tatsuo BABA (Kyoto Univ.)
Mihio TSUMURA (Kyoto Univ.)
Jumpei YASUDA (Kyushu Univ.)
Taku FUKUNAGA (Kyushu Univ.)
Hiroshi MIURA (Saitama Univ.)
Takuma NISHIMURA (Saitama Univ.)
Motoki MURATA (Kyoto Univ.)
Kazuki SAWAHA (Tokyo Tech.)
Clementine Angelique Marie SANTAMARIA (Univ.Paris Sud XI)
Syunsuke KAWAKAMI (Miyazaki Univ.)
Daigoro ETO (Tohoku Univ.)
Junki TANAKA (Osaka Univ.)
Sebastian Benedikt REICHERT (TU Munchen)
Tomoyuki OZAKI (Tokyo Tech.)
Atsumi SAITO (Tokyo Tech.)
Yasutaka NISHIO (Kyushu Univ.)
Yusuke SHINDO (Kyushu Univ.)
Munemichi TABATA (Kyushu Univ.)
Yusuke MIYAMOTO (Kyushu Univ.)
Satoshi MATSUNAGA (Saitama Univ.)
Yuki ISHI (Kyoto Univ.)
Takato KANEA (Toho Univ.)
Yuki CHIKA (Kyushu Univ.)
Manabu SATO (Kyushu Univ.)
Yukina CHIKA (Univ. of Tsukuba)
Xiangcheng CHEN (Univ. of Heidelberg)
Masahiro YAMA (Toho Univ.)
Tomoaki KANEKO (Toho Univ.)
Julian KAHLBOW (TU Darmstadt)
Robert KISSEL (TU Darmstadt)
Gregor DENTINGER (TU Darmstadt)
Taras LOKOTKO (Univ. of Hong Kong)

Interns
Raphael SASEAU (Univ. Paris Sud XI)
Zhuang GE (IMP, CAS)

Assistants
Emiko ISOGAI
Yu NAYA
RIBF Research Division
Nuclear Spectroscopy Laboratory

1. Abstract

The research group has conducted nuclear-physics studies utilizing stopped/slowed-down radioactive-isotope (RI) beams mainly at the RIBF facility. These studies are based on the technique of nuclear spectroscopy such as β-ray-detected NMR, γ-PAD (Perturbed Angular Distribution), laser, and Mössbauer among other methods that takes advantage of intrinsic nuclear properties such as nuclear spins, electromagnetic moments, and decay modes. In particular, techniques and devices for the production of spin-controlled RI beams have been developed and combined to the spectroscopic studies, which enable high-sensitivity measurements of spin precessions/resonances through a change in the angular distribution of radiations. Anomalous nuclear structures and properties of far unstable nuclei are investigated from thus determined spin-related observables. The group also aim to apply such techniques to interdisciplinary fields such as fundamental physics and materials science by exploiting nuclear probes.

2. Major Research Subjects

(1) Nuclear spectroscopy with stopped/slowed-down RI beams
(2) R&D studies on the production of spin-oriented RI beam
(3) Application of RI probes
(4) Fundamental physics: Study of symmetry

3. Summary of Research Activity

(1) Nuclear spectroscopy with stopped/slowed-down RI beams

Measurements of static electromagnetic nuclear moments over a substantial region of the nuclear chart have been conducted for structure studies on the nuclei far from the β-decay stability. Utilizing nuclear spin orientation phenomena of RIs created in the projectile-fragmentation reaction, ground- and excited-state nuclear moments of nuclei far from the stability have been determined by means of the β-ray-detected nuclear magnetic resonance (β-NMR) and the γ-ray time differential perturbed angular distribution (γ-TDPAD) methods. To extend these observations to extremely rare RIs, a new method has been developed based on the laser spectroscopy which makes use of characteristic atomic properties of RIs surrounded by liquid helium.

(2) R&D studies on the production of spin-oriented RI beams

A new method has been developed for controlling spin in a system of rare RIs, taking advantage of the mechanism of the two-step projectile fragmentation reaction combined with the momentum-dispersion matching technique. This success allows us to utilize spin-controlled world's highest intensity rare RIBs delivered from BigRIPS for researches on the nuclear structure of species situated outside the traditional region of the nuclear chart. In parallel with this work, the development of a new apparatus to produce highly spin-polarized RI beams will be conducted by extending the atomic beam resonance method to fragmentation-based RI beams.

(3) Application of RI probes

The application of RI and heavy ion beams as a probe for condensed matter studies is also conducted by the group. The microscopic material dynamics and properties have been investigated through the deduced internal local fields and the spin relaxation of RI probes based on various spectroscopies utilizing RI probes such as the β-NMR/nuclear quadrupole resonance (NQR) methods, in-beam Mössbauer spectroscopy and the γ-ray time differential perturbed angular correlation (γ-TDPAC) spectroscopy.

(4) Fundamental physics: Study of symmetry

The nuclear spins of stable and unstable isotopes sometimes play important roles in fundamental physics research. New experimental methods and devices have been developed for studies of the violation of time reversal symmetry (T-violation) using spin-polarized nuclei. These experiments aim to detect the small frequency shift in the spin precession arising from new mechanisms beyond the Standard Model.

Members

Chief Scientist (Lab. Head)
Hideki UENO

Research & Technical Scientists
Aiko NAKAO (Senior Research Scientist)
Hiroki YAMAZAKI (Senior Research Scientist)
Yuichi ICHIKAWA (Research Scientist)

Research Consultant
Takuya OKADA

Junior Research Associates
Yoko ISHIBASHI (Univ. of Tsukuba, – Mar. 31, 2014)
Kei IMAMURA (Meiji Univ.)
Yuichi OHTOMO (TIT, – Feb. 28, 2015)

Part-time Worker
Yoko ISHIBASHI (Univ. of Tsukuba, Sep. 1, 2014 –)

Senior Visiting Scientist
Yukari MATSUO (Hosei Univ.)

Visiting Scientists
Wataru SATO (Kanazawa Univ.)
Kensaku MATSUTA (Osaka Univ.)
Jin NAKAMURA (Univ. of Elec.-Com.)
Atsushi HATAKEYAMA (Tokyo Univ. of Agric. and Tech.)
Takeshi FURUKAWA (Tokyo Met. Univ.)
Satoshi TSUTSUI (JASRI)
Takamasa MOMOSE (Kyoto Univ.)
Jean-Michel DAUGAS (CEA)
Yukari MATSUO (Hosei Univ.)
Xiaolong WANG (Kyoto Univ.)

Student Trainees
Yoko ISHIBASHI (Univ. of Tsukuba)
Masato TSUCHIYA (Tokyo Tech.)
Hazuki SHIRAI (Tokyo Tech.)
Miki HAYASAKA (Tokyo Gakugei Univ.)
Ryo MIYATANI (Tokyo Univ. of Sci.)
Kazuma SHIGA (Tokyo Univ. of Sci.)
Tomomi FUJITA (Osaka Univ.)
Yuichi OHTOMO (Tokyo Tech)
Takahiro SUZUKI (Tokyo Tech)
Masami TANAKA (Osaka Univ.)
Ryosuke KANBE (Osaka Univ.)
Yu SAKAMOTO (Tokyo Tech.)
Daiki NATORI (Osaka Univ.)
Kenichi TANABE (Tokyo Univ. of Sci.)
Takafumi TABATA (Tokyo Univ. of Sci.)
Tsukasa SAGAYAMA (Tokyo Gakugei Univ.)

Interns
ZheWei YIN (Peking Univ.)
Hoi Io KONG (Peking Univ.)
Jing MA (Peking Univ.)
Zong Hao LI (Peking Univ.)
Bo WANG (Peking Univ.)

- 390 -
1. Abstract

In the immediate aftermath of the Big Bang, the beginning of our universe, only hydrogen and helium existed. However, nuclear fusion in the interior of stars and the explosion of supernovae in the universe over the course of 13.8 billion years led to the evolution of a world brimming with the many different elements we have today. By using man-made satellites to observe X-rays and gamma-rays emitted from celestial objects, we are observing the synthesis of the elements at their actual source. Our goal is to comprehensively elucidate the scenarios for the formation of the elements in the universe, together with our research on sub-atomic physics through the use of an accelerator.

2. Major Research Subjects

(1) Nucleosynthesis in Stars and Supernovae
(2) Particle Acceleration Mechanism in Astronomical Objects
(3) Physics in Extremely Strong Magnetism and Gravity
(4) Research and Development of Innovative X-ray and Gamma-ray detectors

3. Summary of Research Activity

High Energy Astrophysics Laboratory started on April 2010. The goal of our research is to reveal the mechanism of nucleosynthesis in the universe, and to observe exotic physical phenomena in extremely strong magnetic and/or gravitational field. We have observed supernova remnants, strongly magnetized neutron stars, pulsars, black holes and galaxies with X-ray astronomical satellites.

We showed that the expansion of ejecta in Tycho's supernova remnant was consistent with a spherically symmetric shell, based on Suzaku (Japanese X-ray observatory) measurements of the Doppler broadened X-ray emission lines. This is the first direct measurement of the expansion velocity of the elements produced in the thermonuclear expansion supernova. This information tells us the stratified structure of the elements, implying that the heavier elements such as Fe are produced deeper interior of the explosion.

We discovered the emission line of aluminum in supernova remnant G344.7-0.1 for the first time. Aluminum is produced in the neutron rich environment of supernova explosions. We also found manganese, which is enriched in the environment of neutron excess, in some supernova remnants. A systematic study of those lines emitted from the neutron rich elements will be a good tool to explore the nucleosynthesis in the interior of star explosions.

High-energy X-rays from radioactive Ti-44, which is a direct tracer of the supernova blast, was first imaged with the focusing telescope, NuSTAR. The map of Ti-44 in Cassiopeia A does not show spherical or axial symmetry, but asymmetry, supporting a mildly asymmetric explosion model with low-mode convection. This is the first astronomical image with nuclear gamma-rays and new observational evidence to understand the mechanism of supernova explosion and nucleosynthesis.

Gamma-ray emission up to 10 MeV was detected from thundercloud, suggesting that the detected gamma-rays were produced by relativistic electrons via bremsstrahlung. Those relativistic electrons are probably accelerated through an electrical potential difference in the thundercloud. This observation gives us a hint of the particle acceleration probably occurred near the neutron stars.

We continue to construct the Gravity and Extreme Magnetism Small Explorer (GEMS) under the collaboration with NASA Goddard Space Flight Center (USA). GEMS is the first dedicated satellite for the X-ray polarimetry, which is opening a new field in Astrophysics and Astronomy. The construction of an engineering model and basic performance studies of an X-ray polarimeter were carried out in FY2010, and the semiflight model of the detector was built in FY2012 and tested in FY2013. Unfortunately, NASA stops the GEMS project due to an expected cost overrun in 2012, but we will repropose the mission in 2014 with some modification. RIKEN will become a co-principal investigator institute and takes more responsibility on the X-ray polarimeter system and science.

Members

Associate Chief Scientist (Lab. Head)
Toru TAMAGAWA

Contract Researcher
Goro SATO (– Mar. 31, 2014) Yuki OKURA (Jun. 1, 2014 –)

Special Postdoctoral Researchers
Asami HAYATO Kami ISHIKAWA

Postdoctoral Researcher
Takao KITAGUCHI

Part-time Workers
Fumi ASAMI (– Jul. 31, 2014) Rie YOSHII
### Visiting Researchers
- Megu KUBOTA
- Shigeru ENDO (– Feb. 28, 2014)
- Wataru IWAKIRI (JSPS Fellow, Saitama Univ.)
- Tenuki ENOTO (JSPS Fellow, Stanford Univ.)

### Visiting Scientists
- Yukikatsu TERADA (Saitama Univ.)
- Toru MISAWA (Shinshu Univ.)
- Yuijin NAKAGAWA (Waseda Univ.)
- Hiroya YAMAGUCHI (Harvard Univ.)
- Masaki WAKABAYASHI (Jakulin Commercial Company LC)
- Satoru KATSUDA (JAXA)
- Aya BAMBA (JAXA)
- Shin'ya YAMADA (Tokyo Met. Univ.)
- Naohisa INADA (Univ. of Tokyo)
- Takao KITAGUCHI (Hiroshima Univ.)
- Rohta TAKAHASHI (Tomakomai Nat'l College of Tech.)
- Harufumi TSUCHIYA (JAEA)

### Student Trainees
- Rie YOSHII (Tokyo Univ. of Sci.)
- Kenta KANEKO (Kogakuin Univ.)
- Fumi ASAMI (Tokyo Univ. of Sci.)
- Megu KUBOTA (Tokyo Univ. of Sci.)
- Akifumi YOSHICAWA (Tokyo Univ. of Sci.)
- Kazuki NISHIDA (Tokyo Univ. of Sci.)
- Yoko TAKEUCHI (Tokyo Univ. of Sci.)
- Kenta KANEKO (Kogakuin Univ.)
- Megu KUBOTA (Tokyo Univ. of Sci.)
- Kazuki NISHIDA (Tokyo Univ. of Sci.)

- 392 -
Our Astro-Glaciology Research Unit promotes both theoretical and experimental studies to open up a new interdisciplinary research field between astrophysics and glaciology. On the theoretical side, we numerically simulate:

1. Changes in the chemical composition of the stratosphere induced by high-energy photons and/or particles emitted from explosive astronomical phenomena, such as solar proton events and galactic supernovae, and

2. The explosive nucleosynthesis, including the rapid neutron capture process (the r-process) for the creation of the elements heavier than iron, arising in the environment of core-collapse supernova explosions.

Subjects (1) and (2) themselves are very important in solar–terrestrial research and nuclear astrophysics, respectively; furthermore, the items (1) and (2) are intended to be coupled with experimental studies described below.

On the experimental side, we analyze ice cores drilled at the Dome Fuji station in Antarctica in collaboration with National Institute of Polar Research, Tokyo. These ice cores correspond to time capsules of the past. In particular, the ice cores obtained at Dome Fuji are known to be unique because they contain much more information on conditions in the stratosphere than any other ice cores recovered from other locations in either hemisphere. This means that the Dome Fuji ice cores may have an original advantage to study astronomical phenomena of the past, since gamma-rays and high-energy protons emitted from astronomical events affect the chemical and isotopic compositions in the stratosphere and not those in the troposphere. Accordingly, we measure:

3. Variations in the nitrate ion (NO$_3^-$) concentrations in the ice cores, in order to seek the proxy of past solar activity and the footprints of supernovae in our galaxy,

4. Variations in the water isotopes ($^{18}$O and $^2$H) in the ice cores, in order to reconstruct past temperature changes on the earth, and

5. Variations in the nitrate isotope ($^{15}$N) in the ice cores, in order to investigate the possibility of this isotope becoming a new and a more stable proxy for solar activity and/or galactic supernovae.

Items (3), (4), and (5) have been analyzed with Dome Fuji ice cores with a temporal resolution of about 1 year. By comparing the results for items (3) and (4), we aim to understand the correlation between solar activity and climate changes in the past on the millennium scale. The basis for item (4) is already established in glaciology. Item (5) will be the one of very first measurements taken in ice cores. The theoretical studies related to items (1) and (2) will provide a background for distinguishing the characteristics of the astronomical events from meteorological noise that usually appears in the ice core data. Finally, we note that the supernova rate in our galaxy is crucial to understand the r-process nucleosynthesis but yet remains unknown. Our item (3) is also intended to diagnose the galactic supernova rate ultimately.

Members

**Research Unit Leader (Lab. Head)**
Yuko MOTIZUKI

**Research & Technical Scientists**
Kazuya TAKAHASHI ( Concurrent: Senior Research Scientist)  
Yoichi NAKAI ( Concurrent: Senior Research Scientist)

**Postdoctoral Researcher**
Sachiko OKAMOTO

**Part-time Workers**
Ai SHIMADA (TANEICHI) (– May 31, 2014)  
Keiko FUKUSHIMA (WATANABE) (– Nov. 30, 2014)  
Manami MARUYAMA  
Yuma HASEBE (Saitama Univ., Nov. 1, 2014 –)

**Visiting Scientists**
Akira HORI (Kitami Inst. of Tech.)  
Hideharu AKIYOSHI (Nat’l Inst. for Environ. Studies)  
Hideki MADOKORO (Mitsubishi Heavy Ind., Ltd.)

**Student Trainees**
Yuma HASEBE (Saitama Univ.)
1. Abstract

The elements with their atomic number $Z>103$ are called as trans-actinide or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Those elements do not exist in nature. Therefore, they must be produced by artificially for the scientific study of those elements. In our laboratory, we have been studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN and various methods of efficient production of the superheavy elements.

2. Major Research Subjects

(1) Search for new superheavy elements
(2) Decay spectroscopy of the heaviest nuclei
(3) Study of the chemical properties of the heaviest elements
(4) Study of the reaction mechanism of the fusion process (theory)

3. Summary of Research Activity

(1) Searching for new elements
To expand the periodic table of elements and the nuclear chart, we will search for new elements.

(2) Spectroscopic study of the nucleus of heavy elements
Using the high sensitivity system for detecting the heaviest element, we plan to perform a spectroscopic study of nuclei of the heavy elements.

(3) Chemistry of superheavy elements
Study of chemistry of the trans-actinide (superheavy element) has just started world-wide, making it a new frontier in the field of chemistry. Relativistic effects in chemical property are predicted by many theoretical studies. We will try to develop this new field.

(4) Study of a reaction mechanism for fusion process
Superheavy elements have been produced by complete fusion reaction of two heavy nuclei. However, the reaction mechanism of the fusion process is still not well understood theoretically. When we design an experiment to synthesize nuclei of the superheavy elements, we need to determine a beam-target combination and the most appropriate reaction energy. This is when the theory becomes important. We will try to develop a reaction theory useful in designing an experiment by collaborating with the theorists.

(5) Research Highlight
The discovery of a new element is one of the exciting topics both for nuclear physicists and nuclear chemists. The elements with their atomic number $Z>103$ are called as trans-actinides or superheavy elements. The chemical properties of those elements have not yet been studied in detail. Since those elements do not exist in nature, they must be produced by artificially, by using nuclear reactions for the study of those elements. Because the production rate of atoms of those elements is extremely small, an efficient production and collection are key issues of the superheavy research. In our laboratory, we have been trying to produce new elements, studying the physical and chemical properties of the superheavy elements utilizing the accelerators in RIKEN.

Although the Research Group for Superheavy element has started at April 2013, the Group is a renewal of the Superheavy Element Laboratory started at April 2006, based on a research group which belonged to the RIKEN accelerator research facility (RARF), and had studied the productions of the heaviest elements. The main experimental apparatus is a gas-filled recoil ion separator GARIS. The heaviest elements with their atomic numbers, 107 (Bohrium), 108 (Hassium), 109 (Meitnerium), 110 (Darmstadtium), 111 (Roentgenium), and 112 (not yet named) were discovered as new elements at Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Germany by using $^{209}$Pb or $^{209}$Bi based complete fusion reactions, so called “cold fusion” reactions. We have made independent confirmations of the productions of isotopes of 108$^{\text{th}}$, 110$^{\text{th}}$, 111$^{\text{th}}$, and 112$^{\text{th}}$ elements by using the same reactions performed at GSI. After these work, we observed an isotope of the 113$^{\text{th}}$ element, $^{278}$Hs, in July 2004, in April, 2005, and in August 2012. The isotope, $^{278}$Hs, has both the largest atomic number, ($Z = 113$) and atomic mass number ($A = 278$) which have determined experimentally among the isotopes which have been produced by cold fusion reactions. We could show the world highest sensitivity for production and detection of the superheavy elements by these observations.

We decided to make one more recoil separator GARIS-II, which has an acceptance twice as large as existing GARIS, in order to realize higher sensitivity. The design of GARIS-II has finished in 2008. All fabrication of the separator will be finished at the end of fiscal year 2008. It will be ready for operation in fiscal year 2009 after some commissioning works.

Preparatory work for the study of the chemical properties of the superheavy elements has started by using the gas-jet transport system coupled to GARIS. The experiment was quite successful. The background radioactivity of unwanted reaction products has been highly suppressed. Without using the recoil separator upstream the gas-jet transport system, large amount of unwanted radioactivity strongly prevents the unique identification of the event of our interest. This new technique makes clean and clear studies of chemistry of the heaviest elements promising.

The spectroscopic study of the heaviest elements has started by using alpha spectrometry. New isotope, $^{263}$Hs ($Z=108$), which has the smallest atomic mass number ever observed among the Hassium isotopes, had discovered in the study. New spectroscopic information for $^{264}$Hs and its daughters have obtained also. The spectroscopic study of Rutherfordium isotope $^{264}$Rf ($Z=104$) has done and 1.9-s isomeric state has directly produced for the first time.

Preparatory works for the study of the new superheavy elements with atomic number 119 and 120 have started in 2013. We measured the reaction products of the $^{248}$Cm$^{48}$Ca, xn$^{296}$Lv($Z=116$) previously studied by Frelow Laboratory of Nuclear Reaction, Russia, and GSI.
We observed 5 isotopes in total which tentatively assigned to $^{293}$Lv, and $^{292}$Lv.

**Members**

**Group Director**
Kosuke MORITA

**International Program Associate**
Christian BERNER (TUM, Aug. 1, 2014 – Nov. 10, 2014)

**Visiting Scientist**
Kunihiro FUJITA (Kyushu Univ.)

**Student Trainees**
Shoya YAMAMOTO (Kyushu Univ.)
Taiki TANAKA (Kyushu Univ.)
Yoshihiro NARIKIYO (Kyushu Univ.)
Rei KAKU (Kyushu Univ.)
RIBF Research Division  
Research Group for Superheavy Element  
Superheavy Element Production Team

For this year, see the section of Research Group for Superheavy Element.

Members

*Team Leader*
Kosuke MORITA (concurrent; Group Director, Research Group for Superheavy Element)

*Research & Technical Scientist*
Kouji MORIMOTO (Senior Research Scientist, concurrent; Team Leader, Superheavy Element Device Development Team)

*Nishina Center Technical Scientists*
Akira YONEDA
Daiya KAJI (concurrent; Superheavy Element Device Development Team)

*Special Postdoctoral Researcher*
Yasuo WAKABAYASHI (Univ. of Tokyo)

*Research Consultant*
Kenji KATORI

*Junior Research Associate*
Mirei TAKEYAMA (Yamagata Univ.)

*Part-time Worker*
Kengo TANAKA (Tokyo Univ. of Sci.)

*Visiting Scientists*
Hiroyuki KOURA (JAEA)
Benoit Jean-Paul GALL (Strasbourg Univ.)
Marc ASFARI (Institut Pluridisciplinaire Hubert Curien)

*Student Trainees*
Yukiko KOMORI (Osaka Univ.)
Takuya YOKOKITA (Osaka Univ.)
Kengo TANAKA (Tokyo Univ. of Sci.)
1. Abstract

A gas-filled recoil ion separator has been used as a main experimental device for the study of superheavy elements. This team is in charge of maintain, improve, develop and operate the separators and rated devices. There are two gas-filled recoil ion separators installed at RILAC experimental hall. One is GARIS that is designed for symmetric reaction such as cold-fusion reaction, and the other is newly developed GARIS-II that is designed for asymmetric reaction such as hot-fusion reaction. New element 278113 were produced by $^{70}$Zn + $^{208}$Bi reaction using GARIS. Further the new element search Z > 118 are preparing by using GARIS-II.

2. Major Research Subjects

(1) Maintenance of GARIS and development of new gas-filled recoil ion separator GARIS-II.
(2) Maintenance and development of detector and DAQ system for GARIS and GARIS-II.
(3) Maintenance and development of target system for GARIS and GARIS-II.

3. Summary of Research Activity

The GARIS-II is newly developed which has an acceptance twice as large as existing GARIS, in order to realize higher sensitivity. It will be ready for operation in fiscal year 2014 after some commissioning works. We will also offer user-support if a researcher wishes to use the devices for his/her own research program.
1. Abstract
The disposal of high-level radioactive wastes from nuclear power plants is a problem considered to be one of the most important issues at both national and international levels. As a fundamental solution to the problem, the establishment of nuclear transmutation technology where long-lived nuclides can be changed to short-lived or stable ones will be vital. Progress in R & D in the transmutation of long-lived fission products (LLFP) in the nuclear wastes however, has been slow. Our group aims to obtain reaction data of LLFP at RIBF and other facilities which may lead to a new discovery and invention for peaceful use of nuclear power and the welfare of humanity.

2. Major Research Subjects
The Group is formed by three research teams. The first two Teams, “Fast RI Data Team” and “Slow RI Data Team”, are in charge of proton- and deuteron-induced reaction data of LLFP in inverse kinematics at RIBF. The third Team “Muon Data Team” is to obtain muon capture data of LLFP at muon facilities. All of the teams are focusing to obtain high-quality data which are essentially necessary to establish reliable reaction models. Each team has its own subjects and promotes LLFP reaction programs based on their large experiences, techniques and skills.

3. Summary of Research Activity
In 2014, all the teams polished up experimental strategies, formed collaboration and prepared experiments.

Members

Group Director
Hiroyoshi SAKURAI (concurrent: Chief Scientist, RI Physics Lab.)
1. Abstract

Fast RI team aims at obtaining and accumulating the cross section data for long lived fission products (LLFPs) in order to explore the possibility of using accelerator for nuclear transmutation.

LLFPs as nuclear waste have been generated continuously in nuclear power plants for wealth for human lives, while people noticed the way of disposal has not necessarily been established, especially after the Fukushima Daiichi power plant disaster. One of the ways to reduce the amount of LLFP or to recover them as recycled resources is nuclear transmutation technique.

RIBF facility has a property to generate such LLFP as a secondary beam and the beam species are identified by event by event. Utilizing the property, absolute values of the cross section of various reactions on LLFPs are measured and accumulated as database.

2. Major Research Subjects

1) Measurement of reaction products by the interaction of LLFPs with proton, deuteron, and photon to explore candidate reactions for transmutation of LLFPs.
2) Evaluation of the cross section data for the neutron induced reactions from the obtained data.

3. Summary of Research Activity

1) Acting as collaboration hub on many groups which plan to take data using fast RI beam in RIBF facility.
2) Concentrating on take data for proton and deuteron induced spallation reactions with inverse kinematics.
3) Accumulating the cross section data and evaluating them as evaluated nuclear data.
4) Evaluating cross section of neutron induced reaction on LLFP by collaborating with the nuclear model calculation and evaluation group.

Members

Team Leader
Hideaki OTSU (Oct. 1, 2014−, concurrent: Team Leader, SAMURAI Team)

Technical Staff I
Nobuyuki CHIGA (Jan. 1, 2015−)

Student Trainees
Shouhei ARAKI (Kyushu Univ.)
Tatsuya YAMAMOTO (Miyazaki Univ.)
1. Abstract
This team is in charge of the development of low-energy RI beams of long-lived fission fragments (LLFP) from the $^{238}$U by means of degrading the energy of beams produced by the BigRIPS fragment separator.

2. Major Research Subjects
Studies of the energy degradation and purification of RI beams are the main subjects of the team. Developments of devices used for the energy degradation of RI beams are also an important subject.

3. Summary of Research Activity
1) Study and development of the energy degradation methods for LLFP.
2) Development of the devices used for the energy degradation.
3) Operation of the BigRIPS separator and supply the low energy LLFP beam to the experiment in which the cross sections of LLFP are measured at the low energy.

Members

Team Leader
Koichi YOSHIDA (concurrent: BigRIPS Team)
1. Abstract
Dr. Yoshiro Nishina observed muons in cosmic rays in 1937. The muon is an elementary particle belonging to electron group, and is 207 times as heavy as electron. The muon has positive or negative electric charge, and the lifetime is 2.2 μsec. The negative muon is caught by a nucleus (atomic number: Z) in materials to form a muonic atom, and is then captured by the nucleus. The negative muon is combined with a proton to form a neutron and a neutrino to create an excited state of the nucleus with the atomic number of Z-1, followed by emissions of neutrons and gamma rays. The muon nuclear capture reaction produces the isotopes of the (Z-1) nucleus. However, the reaction mechanism is not yet well clarified. The research team aims at obtaining the experimental data to understand the mechanism of muon nuclear capture reactions as well as at establishing the reaction theory.

2. Major Research Subjects
(1) Experimental clarification on reaction mechanism of nuclear muon-capture
(2) Establishment of reaction theory on nuclear muon-capture
(3) Interdisciplinary applications of nuclear muon-capture reactions

3. Summary of Research Activity

Members

Team Leader
Teiichiro MATSUZAKI (Dec. 1, 2014 –)
1. Abstract
The R&D group, consisting of two teams, develops elemental technology of high-power accelerators and high-power targets, aiming at future applications to nuclear transmutations of long-lived fission product into short-lived nuclides. The research subjects are superconducting rf cavities for low-velocity ions, design of high-power accelerators, high-power target systems and related technologies.

2. Major Research Subjects
(1) R&D of elemental technology of high-power accelerators and high-power targets

3. Summary of Research Activity
(1) Based on the discussion with other research groups, R&D study of various accelerator components and elements is under progress.

Members

Group Director
Osamu KAMIGAITO (concurrent: Chief Scientist, Group Director, Accelerator Gr.)
RIBF Research Division
High-Intensity Accelerator R&D Group
High-Gradient Cavity R&D Team

Members

Team Leader
Naruhiko SAKAMOTO (concurrent: Cyclotron Team)

Research & Technical Scientists
Kazunari YAMADA (Senior Technical Scientist, concurrent: Beam Dynamics & Diagnostics Team)
Kazutaka OHZEKI (Technical Scientist, concurrent: Cyclotron Team)
RIBF Research Division
High-Intensity Accelerator R&D Group
High-Power Target R&D Team

Members

Team Leader
Hiroki OKUNO (concurrent: Deputy Group Director, Accelerator Gr.)
1. Abstract

The accelerator group, consisting of seven teams, pursues various upgrade programs of the world-leading heavy-ion accelerator facility, RI-Beam Factory (RIBF), to enhance the accelerator performance and operation efficiency. The programs include the R&D of superconducting ECR ion source, charge stripping systems, beam diagnostic devices, radiofrequency systems, control systems, and beam simulation studies. We are also maintaining the large infrastructure to realize effective operation of the RIBF, and are actively promoting the applications of the facility to a variety of research fields.

Our primary mission is to supply intense, stable heavy-ion beams for the users through effective operation, maintenance, and upgrade of the RIBF accelerators and related infrastructure. The director members shown below govern the development programs that are not dealt with by a single group, such as intensity upgrade and effective operation. We also promote the future plans of the RIBF accelerators along with other laboratories belonging to the RIBF research division.

2. Major Research Subjects

(1) Intensity upgrade of RIBF accelerators (Okuno)
(2) Effective and stable operation of RIBF accelerators (Fukunishi)
(3) Operation and maintenance of infrastructures for RIBF (Kase)
(4) Promotion of the future plan (Kamigaito, Fukunishi, Okuno)

3. Summary of Activity

(1) The maximum intensity of the calcium beam reached 530 pnA at 345 MeV/u, which corresponds to 8.8 kW.
(2) The maximum intensity of the uranium beam reached 28 pnA at 345 MeV/u.
(3) The overall beam availability for the RIBF experiments in 2014 reached 92 %.
(4) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.
(5) An intensity-upgrade plan of the RIBF has been further investigated, mainly on the design of a new superconducting linac.

Members

Group Director
Osamu KAMIGAITO

Deputy Group Directors
Hiroki OKUNO (Intensity upgrade)
Nobuhisa FUKUNISHI (Stable and efficient operation)
Masayuki KASE (Energy-efficiency management)

Research Consultant
Tadashi FUJINAWA (– Mar. 31, 2015)

International Program Associate
Vasileios TZOGANIS (Univ. of Liverpool)

Visiting Researchers
Akira GOTO (Yamagata Univ.)
Toshiyuki HATTORI (Tokyo Tech.)

Assistant
Karen SAKUMA
1. Abstract

We are developing the key hardware in upgrading the RIBF accelerator complex. Our primary focus and research is charge stripper which plays an essential role in the RIBF accelerator complex. Charge strippers remove many electrons in ions and realize efficient acceleration of heavy ions by greatly enhancing charge state. The intensity of uranium beams is limited by the lifetime of the carbon foil stripper conventionally installed in the acceleration chain. The improvement of stripper lifetimes is essential to increase beam power towards the final goal of RIBF in the future. We are developing the low-Z gas stripper. In general gas stripper is free from the lifetime related problems but gives low equilibrium charge state because of the lack of density effect. Low-Z gas stripper, however, can give as high equilibrium charge state as that in carbon foil because of the suppression of the electron capture process. Another our focus is the upgrade of the world's first superconducting ring cyclotron.

2. Major Research Subjects

(1) Development of charge strippers for high power beams (foil, low-Z gas)
(2) Upgrade of the superconducting ring cyclotron
(3) Maintenance and R&D of the electrostatic deflection/inflection channels for the beam extraction/injection

3. Summary of Research Activity

(1) Development of charge strippers for high power beams (foil, low-Z gas)
   (Hasebe, H., Imao, H. Okuno., H.)
   We are developing the charge strippers for high intensity heavy ion beams. We are focusing on the developments on carbon or berrilium foils and gas strippers including He gas stripper.
(2) Upgrade of the superconducting ring cyclotron
   (Ohnishi, J., Okuno, H.)
   We are focusing on the upgrade of the superconducting ring cyclotron.
(3) Maintenance and R&D of the electrostatic deflection/inflection channels for the beam extraction/injection
   (Ohnishi, J., Okuno, H.)
   We are developing high-performance electrostatic channels for high power beam injection and extraction.

Members

Team Leader
Hiroki OKUNO (concurrent: Deputy Group Director, Accelerator Gr.)

Research & Technical Scientists
Hiroshi IMAO (Senior Research Scientist) 
Jun-ichi OHNISHI (Senior Technical Scientist)

Nishina Center Technical Scientist
Hiroo HASEBE

Special Postdoctoral Researcher
Hironori KUBOKI (~ Mar. 31, 2013)

Visiting Scientists
Andreas ADELMANN (PSI) 
Noriyosu HAYASHIZAKI (Tokyo Tech.)

Hironori KUBOKI (KEK)
1. Abstract

Our aim is to operate and develop the ECR ion sources for the accelerator-complex system of the RI Beam Factory. We focus on further upgrading the performance of the RI Beam Factory through the design and fabrication of a superconducting ECR ion source for production of high-intensity uranium ions.

2. Major Research Subjects

(1) Operation and development of the ECR ion sources
(2) Development of a superconducting ECR heavy-ion source for production of high-intensity uranium ion beams

3. Summary of Research Activity

(1) Operation and development of ECR ion sources
   (T. Nakagawa, M. Kidera, Y. Higurashi, K. Ozeki, T. Nagatomo, H. Haba, and T. Kageyama)
   We routinely produce and supply various kinds of heavy ions such as zinc and calcium ions for the super-heavy element search experiment as well as uranium ions for RIBF experiments. We also perform R&D’s to meet the requirements for stable supply of high-intensity heavy ion beams.

(2) Development of a superconducting ECR ion source for use in production of a high-intensity uranium ion beam
   (T. Nakagawa, J. Ohnishi, M. Kidera, Y. Higurashi, K. Ozeki and T. Nagatomo)
   The RIBF is required to supply uranium ion beams with very high intensity so as to produce RI’s. We have designed and are fabricating an ECR ion source with high magnetic field and high microwave-frequency, since the existing ECR ion sources have their limits in beam intensity. The coils of this ion source are designed to be superconducting for the production of high magnetic field. We are also designing the low-energy beam transport line of the superconducting ECR ion source.

Members

Team Leader
Takahide NAKAGAWA

Research & Technical Scientist
Takashi NAGATOMO (Technical Scientist)

Nishina Center Research Scientists
Masanori KIDERA
Yoshihide HIGURASHI

Contract Researcher
Kazutaka OHZEKI (~ Sept. 30, 2014)

Special Postdoctoral Researcher
Tatsuya URABE (Apr. 1, 2014 ~)

Postdoctoral Researcher
Tatsuya URABE (~ Mar. 31, 2014)

Research Consultant
Tadashi KAGEYAMA (Apr. 1, 2014 ~)

Temporary Employee
Tadashi KAGEYAMA (~ Mar. 31, 2014)

Part-time Worker
Yumi KURAMITSU
1. Abstract
The operation and maintenance of the RIKEN Heavy-ion Linac (RILAC) have been carried out. There are two operation modes: one is the stand-alone mode operation and the other is the injection mode operation. The RILAC has been used especially as an injector for the RIKEN RI-Beam Factory accelerator complex. The RILAC is composed of the ECR ion source, the frequency-variable RFQ linac, six frequency-variable main linac cavities, and six energy booster cavities (CSM).

2. Major Research Subjects
(1) The long term high stability of the RILAC operation.
(2) Improvement of high efficiency of the RILAC operation.

3. Summary of Research Activity
The RILAC was started to supply ion beams for experiments in 1981. Thousands hours are spent in a year for delivering many kinds of heavy-ion beams to various experiments.

The RILAC has two operation modes: one is the stand-alone mode operation delivering low-energy beams directly to experiments and the other is the injection mode operation injecting beams into the RRC. In the first mode, the RILAC supplies a very important beam to the nuclear physics experiment of “the research of super heavy elements”. In the second mode, the RILAC plays a very important role as upstream end of the RIBF accelerator complex.

The maintenance of these devices is extremely important in order to keep the log-term high stability and high efficiency of the RILAC beams. Therefore, improvements are always carried out for the purpose of more stable and more efficient operation.

Members

Team Leader
Eiji IKEZAWA

Research & Technical Scientist
Yutaka WATANABE (Senior Technical Scientist)

Research Consultants
Masatake HEMMI
Toshiya CHIBA
1. Abstract
Together with other teams of Nishina Center accelerator division, maintaining and improving the RIBF cyclotron complex. The accelerator provides high intensity heavy ions. Our mission is to have stable operation of cyclotrons for high power beam operation. Recently stabilization of the rf system is a key issue to provide 10 kW heavy ion beam.

2. Major Research Subjects
(1) RF technology for Cyclotrons
(2) Operation of RIBF cyclotron complex
(3) Maintenance and improvement of RIBF cyclotrons
(4) Single turn operation for polarized deuteron beams
(5) Development of superconducting cavity

3. Summary of Research Activity
Development of the rf system for a reliable operation
Development of highly stabilized low level rf system
Development of superconducting cavity
Development of the intermediate-energy polarized deuteron beams.

Members
Team Leader
Naruhiko SAKAMOTO

Research & Technical Scientist
Kazutaka OHZEKI (Technical Scientist)

Nishina Center Research Scientist
Kenji SUDA

Research Consultant
Yoshiaki CHIBA

Visiting Technician
Yan CONG (IMP, CAS)
1. Abstract

The cascaded cyclotrons used in RIKEN RI Beam Factory (RIBF) requires not only strict matching of operation parameters but also high stability of all the accelerator components in order to establish stable operation of the world’s most intense heavy-ion beams. Beam Dynamics and Diagnostics Team is responsible for power supplies, beam instrumentation, computer control and beam dynamic of the RIBF accelerator complex and strongly contributes to the performance upgrade of the RIBF.

2. Major Research Subjects

(1) Seeking the best operation method of the RIBF accelerator complex based on the beam dynamics study.
(2) Maintenance and development of the beam instrumentation, especially non-destructive monitors.
(3) Upgrade of the computer control system of the RIBF accelerator complex.
(4) Maintenance and improvements of the magnets and power supplies.
(5) Developments of beam interlock system suited to high-power cyclotron complex.

3. Summary of Research Activity

(1) The world-first beam current monitor with a high-Tc current sensor and SQUID has been developed.
(2) The bending power of the fixed-frequency Ring Cyclotron has been upgraded to 700 MeV. It enables us to accelerate $^{238}$U$^{64+}$ ions obtained by the helium gas stripper and contributes to stable and high-intensity operation of RIBF.
(3) An EPICS-based control system and a homemade beam interlock system have been stably working. Replacement of the existing legacy control system used in the old half of our facility is ongoing. Construction of the new control system for the new injector RILAC2 was successfully completed, where the embedded EPICS system running on F3RP61-2L CPU module, developed by KEK and RIKEN control group, was used.
(4) We replaced some dated power supplies of RIKEN Ring Cyclotron by new ones, which have better long-term stability than the old ones. The other existing power supplies (~900) are stably operated owing to elaborate maintenance work.
(5) We have contributed to RILAC2 construction, especially in its beam diagnosis, control system, magnet power supplies, vacuum system, high-energy beam transport system etc.

Members

Team Leader
Nobuhisa FUKUNISHI (concurrent; Deputy Group Director, Accelerator Gr.)

Research & Technical Scientists
Masaki FUJIMAKI (Senior Technical Scientist)  
Keiko KUMAGAI (Senior Technical Scientist)  
Tamaki WATANABE (Senior Technical Scientist)  
Kazunari YAMADA (Senior Technical Scientist)

Nishina Center Technical Scientists
Misaki KOMIYAMA  
Akito UCHIYAMA

Special Postdoctoral Researcher
Takuya MAEYAMA

Temporary Employee

Part-time Workers
Yuki SHIRAISHI  
Makoto NAGASE

Visiting Scientists
Kenichi ISHIKAWA (Univ. of Tokyo)  
Shin-ichiro Hayashi (Hiroshima Int’l Univ.)  
Hiromichi RYUTO (Kyoto Univ.)

Visiting Technician
Jun-ichi ODAGIRI (KEK)
1. Abstract

We are operating the cryogenic system for the superconducting ring cyclotron in RIBF. We are operating the helium cryogenic system in the south area of RIKEN Wako campus and delivering the liquid helium to users in RIKEN. We are trying to collect efficiently gas helium after usage of liquid helium.

2. Major Research Subjects

(1) Operation of the cryogenic system for the superconducting ring cyclotron in RIBF
(2) Operation of the helium cryogenic plant in the south area of Wako campus and delivering the liquid helium to users in Wako campus.

3. Summary of Research Activity

(1) Operation of the cryogenic system for the superconducting ring cyclotron in RIBF
   (Okuno, H., Dantsuka, T., Nakamura, M., Maie, T.)
(2) Operation of the helium cryogenic plant in the south area of Wako campus and delivering the liquid helium to users in Wako campus.
   (Dantsuka, T., Tsuruma, S., Okuno, H.).

Members

**Team Leader**
Hiroki OKUNO (concurrent: Deputy Group Director, Accelerator Gr.)

**Research & Technical Scientist**
Masato NAKAMURA (Senior Technical Scientist)

**Nishina Center Technical Scientist**
Takeshi MAIE

**Technical Staff I**
Tomoyuki DANTSUKA

**Temporary Employee**
Kumio IKEGAMI (~ Mar. 31, 2014)

**Research Consultant**
Kumio IKEGAMI (Apr. 1, 2014 ~)

**Part-time Worker**
Shizuho TSURUMA
1. Abstract

The RIBF facility is consisting of many accelerators and its infrastructure is very important in order to make an efficient operation of RIBF project. We are maintaining the infrastructure of the whole system and to support the accelerator operation with high performance. We are also concerning the contracts of gas- and electricity-supply companies according to the annual operation plan. The contracts should be reasonable and also flexible against a possible change of operations. And we are searching the sources of inefficiency in the operation and trying to solve them for the high-stable machine operation.

2. Major Research Subjects

(1) Operation and maintenance of infrastructure for RIBF accelerators.
(2) Renewal of the old equipment for the efficient operation.
(3) Support of accelerator operations.

Members

Team Leader
Masayuki KASE (concurrent; Deputy Group Director, Accelerator Gr.)

Research & Technical Scientists
Shu WATANABE (Senior Technical Scientist) Hideyuki YAMASAWA (Manager)

Temporary Employee
Tadashi FUJINAWA (~ Mar. 31, 2014)

Research Consultant
Shin-ichi WATANABE

Visiting Scientist
Hideshi MUTO (Tokyo Univ. of Sci. Suwa)
1. Abstract

This group develops core experimental installations at the RIBF facility. Experimental installations currently under setting up include common elements enabling multiple-use (SLOWRI), as well as others that are highly program specific (SCRIT and Rare-RI Ring). All were designed to maximize the research potential of the world's most intense RI beams, made possible by the exclusive equipment available at the RIBF facility. Beam manipulation techniques, such as a beam accumulation and a beam cooling, will be able to provide opportunities of new experimental challenges and the foundation for future developments of RIBF.

2. Major Research Subjects

(1) SCRIT Project
(2) SLOWRI Project
(3) Rare RI Ring Project

3. Summary of Research Activity

We are developing beam manipulation technology in carrying out above listed project. They are the high-quality slow RI beam production (SCRIT and SLOWRI), the beam cooling and stopping (SCRIT and SLOWRI), and the beam accumulation technology (Rare RI Ring). The technological knowhow accumulated in our projects will play a significant role in the next generation RIBF. Status and future plan for each project is described in subsections. SCRIT is now under finalizing the experimental setup for electron scattering off unstable nuclei, and the comprehensive test will be soon. The first experiment will be planed in 2015. Rare RI Ring construction has been almost completed. Test experiments using alpha particle for evaluating the ring performance were successfully performed, and the isochronism in the order of $10^{-5}$ was confirmed in ten-turns circulation. The first commissioning experiment is planned in June 2015. Construction of the SLOWRI system was completed in 2014, and it is now under setting up for the first commissioning in 2015.

Members

**Group Director**
Masanori WAKASUGI

**Senior Visiting Scientist**
Akira OZAWA (Univ. of Tsukuba)

**Student Trainees**
Mamoru TOGASAKI (Rikkyo Univ.)
Yohei SUMI (Rikkyo Univ.)
Saki MATSUO (Rikkyo Univ.)
Kohei YAMADA (Rikkyo Univ.)
1. Abstract

Construction of a next-generation stopped and low-energy radioactive ion beam facility (SLOWRI) which will provide low-energy, high-purity and small emittance ion beams of all elements has been started in FY2013 as one of the principal facilities at the RIKEN RI-beam factory (RIBF). High-energy radioactive ion beams from the projectile fragment separator BigRIPS are thermalized in a large He gas catcher cell (RFC cell) or in a small Ar gas catcher cell (PALIS cell). In the RFC cell, thermalized ions in buffer gas are guided and extracted to a vacuum environment by a combination of dc electric fields and inhomogeneous rf fields (rf carpet ion guide). The PALIS cell will be placed in the vicinity of the second focal plane slits of BigRIPS and can be used continuously during other experiments. From these gas cells, the low-energy ion beams will be delivered via mass separators and switchyards to various devices: such as an ion trap, a collinear fast beam apparatus, and a multi-reflection time of flight mass spectrometer. In the R&D works at the present ring cyclotron facility, an extraction efficiency of 33% for a 100A MeV $^7$Li ion beam from the projectile fragment separator RIPS was achieved and the dependence of the efficiency on the ion beam intensity was investigated.

First spectroscopy experiment at the prototype SLOWI was performed on Be isotopes. Energetic ions of $^{7,10,11}$Be from the RIPS were trapped and laser cooled in a linear rf trap and precision spectroscopy was performed. The evaluated ion temperature of <10 mK demonstrates that a reduction of more than 15 orders of magnitude for the kinetic energy of radioactive Be was achieved online. The ground state hyperfine constants of all Be isotopes have been measured precisely by laser and microwave. These precision measurements will be used to confirm the anomalous mean radius of the valence neutron of the so called neutron halo nucleus. Other laser spectroscopy experiments using the slow RI-beams are also under progress in off-line setups. A collinear fast beam apparatus for nuclear charge-radii measurements was build and tested with stable Ar$^+$ ion beams.

A multi-reflection time-of-flight mass spectograph (MRTOF) has been developed and tested online for radioactive lithium isotope, $^3$Li. A high mass resolving power of 170,000 has been obtained for an isobaric doublet of $^{40}$K and $^{40}$Ca with a very short flight time of 2 ms. This performance allowed accurate mass determination of $<10^{-7}$ accuracy by a single isobaric reference. Two mass measurement projects using MRTOF mass spectographs have been started: one is for trans uranium elements at the GARIS facility and the other is for r-process nuclides at SLOWRI facility.

Resonance ionization spectroscopy has been tested during the offline development of PALIS gas cell. Stable isotopes of Co, Cu, Fe, Ni, Ti, Nb, Sn, In, and Pd were resonantly ionized by excimer pumped dye lasers or Nd:YAG laser pumped Ti:Sapphire lasers with the prototype gas cell setup. The resonance spectra are in many cases sufficient to resolve the hyperfine structures. Nuclear spins and magnetic moments will be determined for various isotopes obtained during other experiments.

2. Major Research Subjects

1. Construction of stopped and low-energy RI-beam facility, SLOWRI.
2. Laser spectroscopy of trapped radioactive Beryllium isotopes.
5. Development of ion-surfing gas cell.

3. Summary of Research Activity

1. Construction of stopped and low-energy RI-beam facility (SLOWRI)

(WADA, Michiharu, SONODA, Tetsu, KATAYAMA, Ichiro, SCHURY, Peter, ITO, Yuta, ARAI, Fumiya, ARAI, Shigeaki, KUSAKA, Kensuke, FUJINAWA Tadashi, MAIE Takeshi, YAMASAWA Hideyuki, WOLLNIK, Hermann.)

Installation of SLOWRI has been started in FY2013. It consists of two gas catchers (RF Carpet gas cell and PALIS gas cell), mass separators a 50-m beam transport line, a beam cooler-buncher, an isobar separator, and a laser system. The RFCarpet gas cell will be installed at the exit of the D5 dipole magnet of BigRIPS. The gas catcher contains a large cryogenic He gas cell with a large traveling wave rf-carpet. It will convert main beams of BigRIPS to low-energy, low-emittance beams without any restrictions on the chemical properties of the elements. The PALIS gas cell will be installed in the vicinity of the second focal plane slit of BigRIPS. It will provide parasitic RI-beams from those ions lost in the slits during other experiments. In this gas catcher, thermalized RI ions quickly become neutral and will be re-ionized by resonant laser radiations. These gas catchers will be tested off-line in FY2014. The 50 m beam transport line consists of four dipole magnets (SD1 to SD4), two focal plane chambers, 62 electrostatic quadrupole singlets, 11 electrostatic quadrupole quartets (EQ1 to EQ11) and 7 beam profile monitors (BPM). SD1 and SD2, located right after the gas catchers will be used for isotope separation. After eliminating contaminant ions at the focal plane chamber, the low energy beam will be transported by FODO lattice structure with phase space matching using EQs. The EQs have multipole elements made of 16 rods on which various potentials can be applied to produce 6-pole and 8 pole fields, simultaneously, for compensation of ion optical aberrations. This multipole element can also produce dipole fields for steering and scanning the beam. The BPM have a classical cross-wire beam monitor as well as a channel electron multiplier with a pinhole collimator. Combining the scanning capability of the EQs and the pinhole detector, we can observe a beam profile even for a very low-intensity RI-beams. Off- and on-line commissioning will take place in FY2014 and the low-energy RI-beams will be provided for users in FY2015.
(2) Laser spectroscopy of trapped radioactive beryllium isotope ions
(WADA, Michiharu, SCHURY Peter, SONODA Tetsu, OKADA, Kunihiro, KANAI, Yasuyuki, YOSHIDA, Atsushi, KUBO, Toshiyuki, WOLLNIK, Hermann, SCHUESSLER, Hans, Shunsuke, KATAYAMA Ichiro)

As a first application of the prototype SLOWRI setup, we applied hyperfine structure spectroscopy to the beryllium isotopes to determine in particular the anomalous radius of the valence neutron of the neutron halo nucleus $^{11}$Be, and to determine the charge radii of these beryllium isotopes through laser-laser double resonance spectroscopy of laser-cooled ions. Laser cooling is an essential prerequisite for these planned experiments. The first laser spectroscopy experiments for beryllium isotopes were performed to measure the resonance frequencies of $2^3S_{1/2} - 2^3P_{1/2}$ transition of $^{7}$Be$^+$, $^{9}$Be$^+$, $^{10}$Be$^+$ and $^{11}$Be$^+$ ions and the nuclear charge radii of these isotopes were determined. The hyperfine structures of $^{11}$Be$^+$ and $^{9}$Be$^+$ ions using the laser-microwave double resonance spectroscopy were also performed and the magnetic hyperfine constants of $^{9}$Be$^+$ and $^{11}$Be$^+$ ions were determined with accuracies of better than $10^{-7}$.

(3) Development of a multi-reflection TOF mass spectrometer for short-lived nuclei
(WADA, Michiharu, SCHURY Peter, ITO, Yuta, ARAI Fumiya, SONODA Tetsu, WOLLNIK, Hermann, MORIMOTO, Koji, KAJI, Daiya, HABA, Hiromitsu, KOURA, Hiroyuki)

The atomic mass is one of the most important quantities of a nucleus and has been studied in various methods since the early days of physics. Among many methods we chose a multi-reflection time-of-flight (MR-TOF) mass spectrometer. Slow RI beams extracted from the RF ion-guide are bunch injected into the spectrometer with a repetition rate of ~100 Hz. The spectrometer consists of two electrostatic mirrors between which the ions travel back and forth repeatedly. These mirrors are designed such that energy-isochronicity in the flight time is guaranteed during the multiple reflections while the flight time varies with the masses of ions. A mass-resolving power of 170,000 has been obtained with a 2 ms flight time for 40K and 40Ca isobaric doublet. This mass-resolving power should allow us to determine ion masses with an accuracy of $10^{-5}$. An online mass measurement for radioactive lithium isotope has been carried out at the prototype SLOWRI setup.

The MR-TOF mass spectograph has been placed under the GARIS-II separator aiming at direct mass measurements of trans-uranium elements. A small cryogenic gas catcher cell will be placed at the focal plane box of GARIS-II and a bunched low-energy heavy ion beam can be transported to the trap of MR-TOF. An online commissioning experiment is planned in FY2014.

(4) Development of collinear fast beam apparatus for nuclear charge radii measurements
(WADA, Michiharu, SCHUESSLER, Hans, IIMURA, Hideki, SONODA, Tetsu, SCHURY, Peter, TAKAMINE, Aiko, OKADA, Kunihiro, WOLLNIK, Hermann)

The root-mean-square charge radii of unstable nuclei have been determined exclusively by isotope shift measurements of the optical transitions of singly-charged ions or neutral atoms by laser spectroscopy. Many isotopes of alkaline, alkaline-earth, noble-gases and several other elements have been measured by collinear laser spectroscopy since these ions have all good optical transitions and are available at conventional ISOL facilities. However, isotopes of other elements especially refractory and short-lived ones have not been investigated so far.

In SLOWRI, isotopes of all atomic elements will be provided as well collimated mono-energetic beams. This should expand the range of applicable nuclides of laser spectroscopy. In the first years of the RIBF project, Ni and its vicinities, such as Ni, Co, Fe, Cr, Cu, Ga, Ge are planned to be investigated. They all have possible optical transitions in the ground states of neutral atoms with presently available laser systems. Some of them have so called recycle transitions which enhance the detection probabilities noticeably. Also the multistep resonance ionization (RIS) method can be applied to the isotopes of Ni as well as those of some other elements. The required minimum intensity for this method can be as low as 10 atoms per second.

We have built an off-line mass separator and a collinear fast beam apparatus with a large solid-angle fluorescence detector. A 617 nm transition of the metastable Ar$^+$ ion at 20 keV was measured with both collinear and anti-collinear geometry that allowed us to determine the absolute resonant frequency of the transition at rest with more than $10^{-8}$ accuracy. Such high accuracy measurements for Ti and Ni isotopes are in progress.

(5) Development of parasitic slow RI-beam production scheme using resonance laser ionization
(SONODA Tetsu, IIMURA Hideki, WADA Michiharu, KATAYAMA Ichiro, ADACHI Yoshitaka, NOTO Takuma, TAKATSUKA Takaaki, TOMITA Hideki, WENDT Klaus, ARAI Fumiya, ITOU Yuta, SCHURY Peter, FUKUDA Naoki, INABE Naohito, KUBO Toshiyuki, KUSAKA Kensuke, TAKEDA Hiroyuki, SUZUKI H., WAKASUGI Masanori, YOSHIDA Koichi)

More than 99.9% of RI ions produced in projectile fission or fragmentation are simply dumped in the first dipole magnet and the slits. A new scheme, named PALIS, to rescue such dumped precious RI using a compact gas catcher cell and resonance laser ionization was proposed as a part of SLOWRI. The thermalized RI ions in a cell filled with Ar gas can be quickly neutralized and transported to the exit of the cell by gas flow. Irradiation of resonance lasers at the exit ionizes neutral RI atoms efficiently and selectively. The ionized RI ions can be further selected by a magnetic mass separator and transported to SLOWRI experimental area for various experiments. The resonance ionization scheme itself can also be a useful method to perform hyperfine structure spectroscopy of RI of many elements.

A prototype setup has been tested for resonance ionization scheme of several elements, extraction from the cell, and transport to a high vacuum chamber. An online setup, which will be placed at the second focal plane (F2) of BigRIPS, has been fabricated in FY2013 and commissioning is scheduled in FY2014.
Members

Team Leader
Michiharu WADA

Research & Technical Scientist
Hideyuki YAMASAWA (concurrent; Infrastructure Management Team)

Nishina Center Research Scientists
Tetsu SONODA
Kensuke KUSAKA (concurrent; BigRIPS Team)

Nishina Center Technical Scientist
Takeshi MAIE (concurrent; Cryogenic Technology Team)

Contract Researcher
Peter Henry SCHURY

Special Postdoctoral Researcher
Yuta ITO (Apr. 1, 2014 –)

Research Associate
Yuta ITO (– Mar. 31, 2014)

Temporary Employee
Tadashi FUJINAWA (concurrent; – Mar. 30, 2014)

Part-time Workers
Shigeaki ARAI
Ichiro KATAYAMA

Research Consultant
Hirokane KAWAKAMI

Visiting Researcher
Mikael REPONEN (JSPS, Aug. 4, 2014 –)

Visiting Scientists
Hans A SCHUESSLER (Texas A&M Univ.)
Hermann WOLLNIK (Univ. of Giessen)
Aiko TAKAMINE (Aoyama Gakuin Univ.)
Hideki IIMURA (JAEA)

Student Trainees
Takuma NOTO (Nagoya Univ.)
Takaaki TAKATSUKA (Nagoya Univ.)
Fumiya ARAI (Univ. of Tsukuba)

Yoshitaka ADACHI (Nagoya Univ.)
Takahide TAKAMATSU (Nagoya Univ.)
1. Abstract

Mass measurement is one of the most important contributions to a nuclear property research especially for short-lived unstable nuclei far from the beta-stability line. In particular, a high-precision mass measurement for nuclei located around the r-process pass (r-RIs) is required in nucleosynthesis point of view. We chose a method of isochronous mass spectrometry (IMS) to make a measurement time shorter than 1 ms. Heavy-ion storage ring named “Rare-RI Ring (R3)” has been constructed until end of 2013 and is now under preparation for the first commissioning experiment. Our target performance in the mass determination is to achieve accuracy of the order of 10⁻⁶ (~100 keV) even if we get only one event. Since an isochronism in R3 is established over a wide range of the momentum, r-RIs with a large momentum spread, Δp/p=±0.5 %, are acceptable. Another significant feature of the R3 system is an individual injection scheme in which a produced rare-RI itself triggers the injection kicker. Design study for R3 has been continued from more than ten years ago, and it was constructed in 2012 and 2013. In 2014, we demonstrated the R3 performances in test experiments using alpha particle. We are now setting up and testing all equipments including the power supplies, the control system, the vacuum system, and so on, toward the first commissioning planed in 2015.

2. Major Research Subjects

Developments of isochronous storage ring to measure mass of rare RI.

3. Summary of Research Activity

Since the lattice design of R3 is based on the cyclotron motion, it can provide an isochronism in a wide range of the momentum. We expect a great improvement in mass resolution in IMS as long as the isochronous field is precisely formed in R3. Therefore, IMS using R3 is capable of both a high-precision measurement and a fast measurement. All the devices in R3 was designed under the assumption that an incoming beam has an energy of 200 MeV/u and a charge to mass ratio, m/q, of less than 3. The ring structure was designed with a similar concept of a separate-sector ring cyclotron. It consists of six sectors and 4.02-m straight sections, and each sector consists of four rectangular bending magnets. A radially homogeneous magnetic field is produced in the magnet, and a magnetic rigidity is 6.5 Tm at maximum. Main coils of all the bending magnets are connected in series, and the current of 3000 A is required for rare-RIs, for instance, ⁷⁷Ni with the magnetic rigidity of 5.96 Tm. Two magnets at both ends of each sector are additionally equipped with ten trim coils to form a precise isochronous magnetic field. For Δp=0 particle, the circumference is 60.35 m and the betatron tunes are vₓ=1.21 and vᵧ=0.84 in horizontal and vertical directions, respectively. The momentum acceptance is Δp/p=±0.5 %, and the transverse acceptances are 20π mm·mrad and 10π mm·mrad in horizontal and vertical directions, respectively. Although the transverse acceptances of the R3 itself are actually larger than these values, they are limited by that of the injection beam line. Of special note is that the isochronism is precisely fulfilled in a wide range of momentum (full width 1 %) due to a cyclotron-motion based lattice design.

Another performance required for R3 is to efficiently seize hold of an opportunity of the measurement for rare-RIs produced unpredictably. We adopted an individual injection scheme in which the produced rare-RI itself triggers the injection kicker magnets. Full activation of the kicker magnetic field have to be completed within the flight time of the rare-RI from an originating point (F3 focal point in BigRIPS) of the trigger signal to the kicker position in R3. Development of an ultra-fast response kicker system is a key issue for establishing the individual injection scheme. Performances required for the kicker system are an ultra-fast response, a fast charging, and a full-time charging.

We provided ordinary beam diagnostic devices such as a screen monitor and a beam position monitor based on triangle pickup electrodes. Although five sets of these monitors distributed along the orbit in R3 are useful in a machine tuning process using a high-intensity primary beam. They, however, are incapable for rare-RIs because of the poor sensitivity. Therefore, we inserted high-sensitive monitors, which are applicable even for a single particle circulation. One of them is a cavity type of Schottky pick-up. A resonance frequency is designed to be 171 MHz, which corresponds to the harmonic number of 56, and a measured quality factor is about 1900 and shunt impedance is 170 kΩ. We can detect single ion circulation of ⁷⁷Ni²⁸⁺ with only a few ms measurement. Another is a timing monitor, which detects secondary electrons emitted from thin carbon foil placed on the accumulation orbit. The thickness of the foil will be 50 µg/cm². The rare-RI with the energy of 200 MeV/u survives only for first 1000 turns because of an energy loss at the foil.

In test experiments using alpha particles emitted from an⁶⁴⁴Am source performed in 2014, we succeeded in the individual injection of the single particle, beam accumulation and the beam extraction. We successfully measured the TOF for 1~10 turns circulation of alpha particles, and the isochronism in R3 in the order of 10⁻⁶ was confirmed. R2 is now under preparation for the first commissioning experiment using heavy ion beam from accelerators.
Members

Team Leader
Masanori WAKASUGI (concurrent; Group Director, Instrumentations Development Gr.)

Research & Technical Scientists
Yoshiyuki YANAGISAWA (Senior Research Scientist, concurrent; BigRIPS Team)
Tamaki WATANABE (Senior Technical Scientist, concurrent; Beam Dynamics and Diagnostics Team)
Yutaka WATANABE (Senior Technical Scientist, concurrent; RILAC team)
Naohito INABE (Senior Technical Scientist, concurrent; BigRIPS Team)
Hideyuki YAMASAWA (concurrent; Infrastructure Management Team)

Nishina Center Research Scientist
Yoshitaka YAMAGUCHI

Nishina Center Technical Scientists
Takeshi MAIE (concurrent; Cryogenic Technology Team)
Misaki KOMIYAMA (concurrent; Beam Dynamics and Diagnostics Team)

Research Consultant
Akira NODA (~ Mar. 31, 2014)

Junior Research Associate
Yasushi ABE (Univ. of Tsukuba)

Temporary Employee
Tadashi FUJINAWA (concurrent, ~ Mar. 30, 2014)

Visiting Scientist
Daisuke NAGAE (Univ. of Tsukuba)

Student Trainees
Yuta SAITO (Univ. of Tsukuba)
Shunsuke OKADA (Univ. of Tsukuba)
Ayano ENOMOTO (Saitama Univ.)
1. Abstract

The SCRIT Electron Scattering Facility is now under construction at RIKEN RIBF. This aims at investigation of internal nuclear structure for short-lived unstable nuclei by means of electron scattering. SCRIT (Self-Confining RI Ion Target) is a novel method to form internal targets in an electron storage ring. This technique has made electron scattering experiments for unstable nuclei possible. Construction of the facility has been started in 2009. This facility consists of an electron accelerator (RTM), a SCRIT-equipped electron storage ring (SR2), an electron-beam-driven RI separator (ERIS), and a detector system for scattered electrons. Operation of accelerators, RTM and SR2, was started in 2010, performance test of the SCRIT system using stable isotopes, $^{133}$Cs and $^{132}$Xe, was successfully done in 2011 and 2012. Construction of ERIS was started in 2011 and it was commissioned in 2012. The first RI beams from ERIS were supplied in 2013, and the extraction efficiency was improved by a factor more than ten in 2014. The detector system consisting of a high-resolution magnetic spectrometer, drift chambers, trigger scintillators, and luminosity monitors were installed. The commissioning using tungsten wire target resulted the energy resolution of $10^{-3}$. We are going to perform the first experiment of electron scattering from unstable nuclei within a fiscal year 2015.

2. Major Research Subjects

Development of SCRIT electron scattering technique and construction of the SCRIT electron scattering facility.

3. Summary of Research Activity

Development of an electron scattering experimental system for short-lived unstable nuclei using a novel internal target of unstable nuclei (SCRIT).

SCRIT is novel technique to form internal target in an electron storage ring. Positive ions are confined in the electron beam axis by transverse focusing force given by the circulating electron beam. This is well known "ion trapping" phenomenon. The created ion cloud in which RI ions injected from outside are confined works as a target of electron scattering.

In 2010, we successfully commissioned electron accelerators RTM and SR2. Current of electron beams stored in SR2 and its storage lifetime have been reached to 300 mA and 2 hours, respectively, in the energy range of 150-300 MeV that is required in electron scattering experiments. In test experiments of the SCRIT system performed in 2011 and 2012, we used stable isotopes, $^{133}$Cs and $^{132}$Xe, and revealed many details of the SCRIT performance. The luminosity of $10^{27}$/(cm$^2$s) was obtained in case of the number of injected ions of $10^9$. The lifetime of the ion confinement was obtained to be over 1 s. They are performances satisfactory to the electron scattering experiment. In fact, we succeeded in measurements of angular distributions of scattered electrons from the target ions trapped in the SCRIT device.

Development of ERIS is one of the most important issue in the facility construction. RIs are generated by photo-fission process of $^{238}$U, which is driven by the 150-MeV electron beams from RTM. ERIS consists of a target ion source including UCx targets and a mass separation system. ERIS was constructed in 2011 and performances such as the extraction efficiency of 21 % and the mass resolving power of 1660 were obtained in the commissioning in 2011. We developed production method of UCx targets by ourselves. The first RI production was succeeded in last year, and $^{126-132}$Sn and $^{138-141}$Xe isotopes were extracted. The extraction efficiency was improved in 2014, and the overall efficiencies for $^{137}$Xe and $^{132}$Sn reached to 14% and 2%, respectively. The yield of $^{137}$Xe isotopes exceeded $10^8$ pps with 10-W driver power. A cooler buncher system based on a RFQ linear trap connected to the ERIS beam line is indispensable, because the continuous beam from ERIS has to be converted to pulsed beam for ion injection to the SCRIT device. The offline test experiments resulted more than 10% bunching efficiency for heavy ion beam, and the cooler buncher was installed in the ion beam line from ERIS.

The new detector system consists of a high-resolution magnetic spectrometer, a beam tracking system using drift chambers, trigger scintillators, and a luminosity monitor. This has a solid angle of 100 msr, energy resolution of $10^{-3}$, and the scattering angle coverage of 30-60 degrees. A wide range of momentum transfer, 80-300 MeV/c, is covered by changing the electron beam energy from 150 to 300 MeV. In last year, the new detector system was successfully commissioned by means of electron scattering from a tungsten wire target.

Members

**Team Leader**
Masanori WAKASUGI (concurrent; Group Director, Instrumentations Development Gr.)

**Research & Technical Scientists**
Masamitsu WATANABE (Senior Research Scientist) Tetsuya OHNISHI (Senior Technical Scientist)

**Research Consultants**
Senior Visiting Scientist
Toshitada HORI (Hiroshima Univ.)

Visiting Scientists
Shuo WANG (Tohoku Univ.)
Kyo TSUKADA (Tohoku Univ.)
Toshimi SUDA (Tohoku Univ.)

Part-time Worker
Shunpei YONEYAMA

Student Trainees
Takaya MIYAMOTO (Tohoku Univ.)
Yuto SHIMAKURA (Rikkyo Univ.)
Yuji HARAGUCHI (Nagaoka Univ. of Tech.)
Shunpei YONEYAMA (Tohoku Univ.)
Teruaki TSURU (Tohoku Univ.)
Yosuke MORIYA (Tohoku Univ.)

Intern
Ryota TOBA (Nagaoka Univ. of Tech.)
RIBF Research Division
Research Instruments Group

1. Abstract
The research instruments group is the driving force at RI Beam Factory (RIBF) for continuous enhancement of activities and competitiveness of experimental research. Consisting of four teams, we are in charge of the construction, operation and improvement of the core research instruments at RIBF, such as BigRIPS in-flight separator, ZeroDegree spectrometer and SAMURAI spectrometer, and the related infrastructure and equipment. We are also in charge of the production and delivery of RI beams using the BigRIPS separator. The group also conducts related experimental research as well as R&D studies on the research instruments.

2. Major Research Subjects
Design, construction, operation and improvement of the core research instruments at RIBF and related R&D studies. Experimental studies on exotic nuclei.

3. Summary of Research Activity
The current research subjects are summarized as follows:
(1) Production and delivery of RI beams and related research
(2) Design, construction, operation and improvement of the core research instruments at RIBF and their related infrastructure and equipment
(3) R&D studies on the core research instruments and their related equipment at RIBF
(4) Experimental research on exotic nuclei using the core research instruments at RIBF

Members

Group Director
Toshiyuki KUBO

Junior Research Associates
Daichi MURA (Rikkyo Univ.)
Momo MUKAI (Tsukuba Univ.)

Part-time Worker
Meiko UESAKA

Senior Visiting Scientist
Toshio KOBAYASHI (Tohoku Univ.)
1. Abstract

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator and its related research instruments at RI beam factory (RIBF). They are employed not only for the production of RI beams but also the experimental studies using RI beams.

2. Major Research Subjects

Design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments

3. Summary of Research Activity

This team is in charge of design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer at RI beam factory (RIBF). They are employed not only for the production of RI beams but also various kinds of experimental studies using RI beams. The research subjects may be summarized as follows:

(1) General studies on RI-beam production using in-flight scheme.
(2) Studies on ion-optics of in-flight separators, including particle identification of RI beams
(3) Simulation and optimization of RI-beam production.
(4) Development of beam-line detectors and their data acquisition system.
(5) Experimental studies on production reactions and unstable nuclei.
(6) Experimental studies of the limits of nuclear binding.
(7) Development of superconducting magnets and their helium cryogenic systems.
(8) Development of a high-power production target system.
(9) Development of a high-power beam dump system.
(10) Development of a remote maintenance and remote handling systems.
(11) Operation, maintenance and improvement of BigRIPS separator system, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer and so on.
(12) Experimental research using RI beams.

Members

**Team Leader**
Koichi YOSHIDA

**Research & Technical Scientists**
Yoshiyuki YANAGISAWA (Senior Research Scientist)  
Naohito INABE (Senior Technical Scientist)  
Masao OHTAKE (Senior Technical Scientist)  
Kanenobu TANAKA (Technical Scientist, concurrent; Deputy Group Director, Safety Management Gr.)

**Nishina Center Research Scientists**
Hiroyuki TAKEDA  
Kensuke KUSAKA  
Naoki FUKUDA

**Contract Researcher**
Daisuke KAMEDA (~ Aug. 31, 2014)

**Postdoctoral Researchers**
Hiroshi SUZUKI  
Deuk Soon AHN

**Part-time Worker**
Hidekazu KUMAGAI (~ Mar. 31, 2014)

**Research Consultant**
Hidekazu KUMAGAI (Apr. 1, 2014 ~)
1. Abstract
This team is in charge of design, construction, development and operation of BigRIPS in-flight separator and its related research instruments at RI beam factory (RIBF). They are employed not only for the production of RI beams but also the experimental studies using RI beams.

2. Major Research Subjects
Design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments.

3. Summary of Research Activity
This team is in charge of design, construction, development and operation of BigRIPS in-flight separator, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer at RI beam factory (RIBF). They are employed not only for the production of RI beams but also various kinds of experimental studies using RI beams.

The research subjects may be summarized as follows:

1. General studies on RI-beam production using in-flight scheme.
2. Studies on ion-optics of in-flight separators, including particle identification of RI beams.
3. Simulation and optimization of RI-beam production.
4. Development of beam-line detectors and their data acquisition system.
5. Experimental studies on production reactions and unstable nuclei.
6. Experimental studies of the limits of nuclear binding.
7. Development of superconducting magnets and their helium cryogenic systems.
8. Development of a high-power production target system.
9. Development of a high-power beam dump system.
10. Development of a remote maintenance and remote handling systems.
11. Operation, maintenance and improvement of BigRIPS separator system, RI-beam transport lines, and their related research instruments such as ZeroDegree spectrometer and so on.
12. Experimental research using RI beams.

Members

Team Leader
Koichi YOSHIDA

Research & Technical Scientists
Yoshiyuki YANAGISAWA (Senior Research Scientist)
Naohito INABE (Senior Technical Scientist)
Masao OHTAKE (Senior Technical Scientist)
Kanenobu TANAKA (Technical Scientist, concurrent; Deputy Group Director, Safety Management Gr.)

Nishina Center Research Scientists
Hiroyuki TAKEDA
Kensuke KUSAKA
Naoki FUKUDA

Contract Researcher
Daisuke KAMEDA (– Aug. 31, 2014)

Postdoctoral Researchers
Hiroshi SUZUKI
Deuk Soon AHN

Part-time Worker
Hidekazu KUMAGAI (– Mar. 31, 2014)

Research Consultant
Hidekazu KUMAGAI (Apr. 1, 2014 –)

Senior Visiting Scientist
Jerry NOLEN (Argonne National Lab.)

Visiting Scientists
Daisuke KAMEDA (TOSHIBA Corp.)
Michael A. FAMIANO (Western Michigan Univ.)
Daniel Pierre BAZIN (NSCL, MSU)
Oleg Borisovich TARASOV (NSCL, MSU)
Hans GEISSEL (GSI)
David Joseph MORRISSEY (NSCL, MSU)
Bradley Marc SHERRILL (NSCL, MSU)
Martin Alfred WINKLER (GSI)
Mauricio PORTILLO (NSCL, MSU)
Dogyun KIM (IBS)
Eunhee KIM (IBS)
Alan Matthew AMTHOR (Bucknell Univ.)
Yutaka MIZOI (Osaka Elec.-Com. Univ.)
Naohito IWASA (Tohoku Univ.)
Sadao MOMOTA (Kochi Univ. of Tech.)
Kazuo IEKI (Rikkyo Univ.)

Student Trainees
Yohei OHKODA (Tohoku Univ.)
Kousei ASADA (Tohoku Univ.)
1. Abstract
   In collaboration with research groups in and outside RIKEN, the team designs, develops and constructs the SAMURAI spectrometer and relevant equipment that are and will be used for reaction experiments using RI beams at RI Beam Factory. The SAMURAI spectrometer consists of a large superconducting dipole magnet and a variety of detectors to measure charged particles and neutrons. After the commissioning experiment in March 2012, the team prepared and conducted, in collaboration with researchers in individual experimental groups, the first series of experiments with SAMURAI in May 2012. Then, several numbers of experiments were well performed until now utilizing the property of SAMURAI. The team also provides basis for research activities by, for example, organizing collaboration workshops by researchers who are interested in studies or plan to perform experiments with the SAMURAI spectrometer.

2. Major Research Subjects
   Design, operation, maintenance and improvement of the SAMURAI spectrometer and its related research instruments. Help and management for SAMURAI-based research programs.

3. Summary of Research Activity
   The current research subjects are summarized as follows:
   (1) Operation, maintenance and improvement of a large superconducting dipole magnet that is the main component of the SAMURAI spectrometer.
   (2) Design, development and construction of various detectors that are used for nuclear reaction experiments using the SAMURAI spectrometer.
   (3) Preparation for planning experiments using SAMURAI spectrometer.
   (4) Maintenance and improvement of the SAMURAI beam line.
   (5) Formation of a collaboration platform called “SAMURAI collaboration”

Members

Team Leader
   Hiromi SATO (Mar. 31, 2014)
   Hideaki OTSU (Apr. 1, 2014 –)

Deputy Team Leader
   Ken-ichiro YONEDA (Mar. 31, 2014, concurrent; Team Leader, User Support Office)

Research Associate
   Yohei SHIMIZU (Dec. 31, 2014)

Visiting Scientist
   Bertis Charles RASCO (Louisiana State Univ.)

Visiting Technician
   Nobuyuki CHIGA (Tohoku Univ.)

Student Trainee
   Kunihiko HASEGAWA (Tohoku Univ.)
1. Abstract
This team is in charge of development, management and operation of the computing and network environment, mail and information servers and data acquisition system and management of the information security of the RIKEN Nishina Center.

2. Major Research Subjects
(1) Development, management and operation of the general computing servers
(2) Development, management and operation of the mail and information servers
(3) Development, management and operation of the data acquisition system
(4) Development, management and operation of the network environment
(5) Management of the information security

3. Summary of Research Activity
This team is in charge of development, management and operation of the computing and network environment, mail and information servers and data acquisition system and management of the information security. The details are described elsewhere in this progress report.

(1) Development, management and operation of the general computing servers
We are operating Linux/Unix NIS/NFS cluster system for the data analysis of the experiments and general computing. This cluster system consists of eight computing servers with 64 CPU cores and totally 200 TB RAID of highly-reliable Fibre-channel interconnection. Approximately 600 user accounts are registered on this cluster system. We are adopting the latest version of the Scientific Linux (X86_64) as the primary operating system, which is widely used in the accelerator research facilities, nuclear physics and high-energy physics communities in the world. We have added a 52 TB RAID for the data analysis in the autumn of 2014 and replaced the ssh login server (RIBF00) in the winter of 2015.

(2) Development, management and operation of the mail and information servers
We are operating RIBF.RIKEN.JP server as a mail/NFS/NIS server. This server is a core server of RIBF Linux cluster system. Postfix has been used for mail transport software and dovecot has been used for imap and pop services. These software packages enable secure and reliable mail delivery. Sophos Email Security and Control (PMX) installed on the mail front-end servers tags spam mails and isolates virus-infected mails. The probability to identify the spam is approximately 95-99%. We are operating several information servers such as Web servers, Integrated Digital Conference (INDICO) server, Wiki servers, Groupware servers, Windows Media and Quick Time streaming servers, and an anonymous FTP server (FTP.RIKEN.JP). A new Web server has been installed in April 2014 as an official Web server of RNC to replace the old Web server installed in 2005. A new 72 TB RAID was installed to replace the old RAID to the anonymous FTP server in August 2014.

(3) Development, management and operation of the data acquisition system
We have developed the standard data-acquisition system named as RIBFDAQ. This system can process up to 40 MB/s data. By using parallel readout from front-end systems, the dead time could be small. To synchronize the independent DAQ systems, the time-stamping system has been developed. The resolution and depth of the time stamp are 10 ns and 48 bit, respectively. This time-stamping system is very useful for beta decay experiments such as EURICA and BRIKEN projects. The current main task is the DAQ coupling, because detector systems with dedicated DAQ systems are transported to RIBF from foreign facilities. In case of SAMURAI Silicon (NSCL/TUM/WUSTL), the readout system is integrated into RIBFDAQ. The projects of MUST2 (GANIL), MINOS (CEA Saclay), and NeuLAND (GSI) cases, data taken by their DAQ systems are transferred to RIBFDAQ. For SPIRIT (RIKEN/GANIL/CEA Saclay/NSCL), RIBFDAQ data are sent to GET system that is a large-scale signal processing system for the time projection chamber. These cases, data are merged in online. On the other hand, EURICA (GSI) and BRIKEN (GSI/Univ. Liverpool/IFIC) projects, we adopt the time-stamping system to use individual trigger for each detector system. In this case, data are merged in offline. In addition to the development DAQ system, we are developing intelligent circuits based on FPGA. Mountable Controller (MOCO) is a very fast readout controller for VME modules. General Trigger Operator (GTO) is an intelligent triggering NIM module. Functions of “common trigger management”, “gate and delay generator”, “scaler” are successfully implemented on GTO.

(4) Development, management and operation of the network environment
We have been managing the network environment collaborating with Advanced Center for Computing and Communications (ACCC). All the Ethernet ports of the information wall sockets are capable of the Gigabit Ethernet connection (10/100/1000BT). In addition, a 10 Gbps network port has been introduced to the RIBF Experimental area in for the high speed data transfer of RIBF experiment to ACCC in near future. Approximately 60 units of wireless LAN access points have been installed to cover the almost entire area of Nishina Center.

(5) Management of the information security
It is essential to take proper information security measures for information assets.
We are managing the information security of Nishina Center collaborating with ACCC.

Members

**Team Leader**
Takashi ICHIHARA (concurrent; Vice Chief Scientist, RI Physics Lab.)

**Research & Technical Scientist**
Yasushi WATANABE (concurrent; Senior Research Scientist, Radiation Lab.)

**Nishina Center Research Scientist**
Hidetada BABA

**Student Trainee**
Ryousuke TANUMA (Rikkyo Univ.)
1. Abstract
This team is in charge of development, fabrication, and operation of various detectors used for nuclear physics experiments at RIBF. Our current main mission is maintenance and improvement of beam-line detectors which are used at BigRIPS separator and its succeeding beam lines for beam diagnosis and particle identification of RI beams. We are also engaged in research and development of new detectors that can be used for higher-intensity RI beams.

2. Major Research Subjects
Development, fabrication, and operation of various detectors for nuclear physics experiments, including beam-line detectors which are used for the production and delivery of RI beams (beam diagnosis and particle identification).

3. Summary of Research Activity
The current research subjects are summarized as follows:
(1) Maintenance and improvement of the beam-line detectors which are used at BigRIPS separator and its succeeding beam lines.
(2) Development of new beam-line detectors with radiation hardness and tolerance for higher counting rates
(3) Development of a high dynamic range preamplifier for silicon strip detectors

Members

**Team Leader**
Toshiyuki KUBO (concurrent; Group Director, Research Instruments Gr., – Mar. 31, 2014)
Hiromi SATO (Apr. 1, 2014 –)

**Special Postdoctoral Researcher**
Yuki SATO

**Research Consultant**
Hiroyuki MURAKAMI

**Visiting Scientist**
RIBF Research Division
Accelerator Applications Research Group

1. Abstract
This group promotes various applications of ion beams from RI Beam Factory (RIBF). Radiation Biology Team studies various biological effects of fast heavy ions and develops new technology to breed plants and microbials by heavy-ion irradiations. RI Applications Team studies production and application of radioisotopes for various research fields, development of trace element analysis and its application, and development of chemical materials for ECR ion sources of RIBF accelerators.

2. Major Research Subjects
Research and development in biology, chemistry and materials science utilizing heavy-ion beams from RI Beam Factory.

3. Summary of Research Activity
(1) Biological effects of fast heavy ions.
(2) Development of heavy-ion breeding.
(3) Production and application of radioisotopes.
(4) Developments of trace elements analyses.
(5) Development of chemical materials for ECR ion sources of RIBF accelerators.

Members

Group Director
Tomoko ABE
1. Abstract

Ion beam breeding team studies various biological effects of fast heavy ions. It also develops new technique to breed plants by heavy-ion irradiations. Fast heavy ions can produce dense and localized ionizations in matters along their tracks, in contrast to photons (X rays and gamma rays) which produce randomly distributed isolated ionizations. These localized and dense ionization can cause double-strand breaks of DNA which are not easily repaired and result in mutation more effectively than single-strand breaks. A unique feature of our experimental facility at the RIKEN Ring Cyclotron (RRC) is that we can irradiate living tissues in atmosphere since the delivered heavy-ion beams have energies high enough to penetrate deep in matter. This team utilizes a dedicated beam line (E5B) of the RRC to irradiate microbes, plants and animals with beams ranging from carbon to iron. Its research subjects cover physiological study of DNA repair, genome analyses of mutation, and development of mutation breeding of plants by heavy-ion irradiation. Some new cultivars have already been brought to the market.

2. Major Research Subjects

(1) Study on the biological effects by heavy-ion irradiation
(2) Studies on ion-beam breeding and genome analysis
(3) Innovative application of heavy-ion beams

3. Summary of Research Activity

We study biological effects of fast heavy ions from the RIKEN Ring Cyclotron using 135A MeV C, N, Ne ions, 95A MeV Ar ions and 90A MeV Fe ions. We also develop breeding technology of microbes and plants. Main subjects are:

(1) Study on the biological effects by heavy-ion irradiation

Heavy-ion beam deposits a concentrated amount of dose at just before stop with severely changing the LET. The peak of LET is achieved at the stopping point and known at the Bragg peak (BP). It is well know to be good for cancer therapy to adjust the BP to target malignant cells. On the other hand, a uniform dose distribution is a key to the systematic study, and thus to the improvement of the mutagenesis efficiency. Therefore plants and microbes are treated using ions with stable LET. We investigated the effect of LET ranging from 22.5 to 640 keV/μm, on mutation induction using the model plant Arabidopsis thaliana. The most effective LET (LETmax) was 30.0 keV/μm. In the case of microbe (Mesorhizobium lothi), the results showed a higher incidence of deletion mutations for Fe ions at 640 KeV/μm than for C ions at 23-40 keV/μm. Thus, the LET of ion beams seems to be an important factor affecting mutagenesis.

(2) Study on ion-beam breeding and genome analysis

In contrast to X rays and gamma rays, fast heavy ions are found to be useful for plant breeding since they only cause localized damage on DNA and can induce mutations more effectively with lower dosage. Our team utilizes beams of fast heavy ions from the RRC to develop heavy-ion breeding techniques. LETmax is effective for breeding because of its very high mutation frequency. Since most mutations are small deletions, these are sufficient to disrupt a single gene. Thus, irradiation can efficiently generate knockout mutants of a target gene, and can be applied to reverse genetics. Higher LET (> 290 keV/μm) was shown to efficiently generate large deletions ranging from several to several tens of kbp. Many genes in the Arabidopsis genome (> 10%) are composed of tandem duplicated genes that share functions. Previous studies demonstrated that large deletions were required to knockout tandem arrayed genes, and the appropriate deletion size was estimated to be approximately 5–10 kbp, based on gene density in Arabidopsis. No method is currently available to efficiently generate deletion mutants of this size. As such, higher LET irradiation is promising as a new mutagen suitable for the functional analysis of tandem duplicated genes.

(3) Innovative application of heavy-ion beams

We have formed a consortium for ion-beam breeding. It consisted of 24 groups in 1999, in 2014, it consisted of 168 groups from Japan and 18 from overseas. Breeding was performed previously using mainly flowers and ornamental plants. We have recently put a new Japanese barnyard millet cultivar with low amylose content and short culm, ‘Neharikko No. 2’ on the market. Beneficial variants have been grown for various plant species, such as high yield rice, semi-dwarf early rice, semi-dwarf buckwheat, semi-dwarf barley, hypoallergenic peanut, spineless oranges, non-flowering Eucalyptus and lipids-hyperaccumulating unicellular alga. We also successfully isolated 4 salt-resistant lines of rice from 325 progeny lines. We collaborate with Miyagi prefecture and Tohoku University to breed salt-resistant plants and microbes, such as ‘Hitomebore’ and ‘Manamusume’, that will grow normally and retain their good taste in saline paddy fields affected by the recent tsunami. The target of heavy-ion breeding is extended from flowers to crops like grains so that it will contribute to solve the global problems of food and environment.

Members

Team Leader
Tomoko ABE (concurrent: Group Director, Accelerator Applications Research Gr.)
VI. RNC ACTIVITIES

Research & Technical Scientist
Kazuhide TSUNEIZUMI (Senior Research Scientist)
Masako IZUMI (Senior Research Scientist)
Tokihiro IKEDA (Senior Research Scientist)
Teruyo TSUKADA (Senior Research Scientist)
Katsunori ICHINOSE (Senior Technical Scientist)
Hiroshi ABE (Senior Technical Scientist)
Ryouhei MORITA (Technical Scientist)

Contract Researchers
Hiroyuki ICHIDA (Feb., 1, 2015)
Yusuke KAZAMA
Tomonari HIRANO (– Nov. 30, 2014)

Postdoctoral Researcher
Koutaro ISHII

Technical Staff I
Yoriko HAYASHI
Sachiko KOGURE (– Mar. 31, 2014)
Motoko MURAKAMI (Apr. 1, 2014 –)

Technical Staff II
Sumie OHBU

Foreign Postdoctoral Researcher
Reka BERECZKY

Research Consultants
Tadashi SAITO
Masahiro MIll

Part-time Workers
Hideo TOKAIRIN
Yuki SHIRAKAWA
Sachiko KOGURE (Apr. 15, 2014 –)
Taeko WAKANA
Sayaka NIWA (May 7, 2-14 – Nov. 30, 2014)
Haruka WATANABE (Aug. 11, 2014 – Sep. 12, 2014)
Honami OOHASHI (– Sep. 5, 2014)

Visiting Scientist
Makoto FUIWARA (Univ. of Tokyo)
Masao WATANABE (Tohoku Univ.)
Hisashi TSUIJIMOTO (Tottori Univ.)
Yutaka MIYAZAWA (Tohoku Univ.)
Toshinari GODO (Botanic Gardens Toyama)
Masanori TOMITA (CRIEPI)
Toshikazu MORISHITA (Nat'l. Inst. Agric. Res.)
Hiroyuki ICHIDA (Stanford Univ.)
Koji MURAI (Fukuoka Pref. Univ.)
Hinako TAKEHISA (Nat'l. Inst. Agric. Sci.)
Akkiko HOKURA (Tokyo Denki Univ.)
Norihiro OHTSUBO (Natl. Inst. Floricult. Sci.)
Eitaro FUKATSU (Forestry and Forest Products Res. Inst.)
Tonomari HIRANO (Univ. of Miyazaki)
Yoichi SATO (Riken Food Co., Ltd.)
In-Ja SONG (Jeju Nat'l University)
Katsutomo SASAKI (Nat'l Agric. and Food Res. Org.)
Kanjo SUZUKI (Technofoora, Co., Ltd.)
Kazumitsu MIYOSHI (Fukuoka Pref. Univ.)
Makoto UBUKATA (Hokkaido Univ.)
Akihiro IWASE (Osaka Pref. Univ.)

Visiting Technicians
Takui YOSHIDA (Takii Seed Co., Ltd.)
Tomojirou KOIDE (Riken Vitamin Co., Ltd.)
Yutaka ITOH (Riken Food Co., Ltd.)

Research Fellows
Naooji WAKITA (Wadomari Cho Agr. Exp. Station)
Kyoosuke NIWA (Hyogo Pref. Res. Inst.)
Miyuki NISHI (Saga Agric. Experiment Station)
Tadahito OOTUBO (Wadomari Cho Agr. Exp. Station)
Shunsuke IMANISHI (Natl. Inst. Veg. and Tea Sci.)
Takeya ICHIKI (Wadomari Cho)
Tomihiro TAKESHITA (Wadomari Cho)
Humio SUGAMURA (Wadomari Cho)

Student Trainees
Fumitaka YAMAGISHI (Tokyo Denki Univ.)
Fumitaka TAMEZAWA (Tokyo Denki Univ.)
Kento SUZUKI (Tohoku Univ. of Sci.)
Kana MIYOSHI (Tokyo Univ. of Sci.)
Takuto TAKAHASHI (Tokyo Denki Univ.)
Hiroki KAWAMOTO (Univ. of Tokyo)
Megumi UTSUGI (Toho Univ.)
Yu IMAMURA (Tokyo Denki Univ.)
Hiroki ISHIKAWA (Sophia Univ.)
Mao SUZUKI (Sophia Univ.)
Shun SASAKI (Sophia Univ.)
1. Abstract

The RI Applications Team develops production technologies of radioisotopes (RIs) at RIKEN RI Beam Factory (RIBF) for application studies in the fields of physics, biology, medicine, engineering, and environmental sciences. We use the RIs mainly for nuclear and radiochemical studies such as RI production and superheavy element chemistry. The purified RIs such as $^{65}$Zn and $^{109}$Cd are delivered to universities and institutes through Japan Radioisotope Association. We also develop new technologies of mass spectrometry for the trace-element analyses using accelerator technology and apply them to the research fields such as cosmochemistry, environmental science, archaeology and so on. We also develop chemical materials for ECR ion sources of the RIBF accelerators.

2. Major Research Subjects

(1) Research and development of RI production technology at RIBF

(2) RI application researches

(3) Development of trace element and isotope analyses using accelerator techniques and its applications to geoscience and environmental science

(4) Development of chemical materials for ECR ion sources of RIBF accelerators

3. Summary of Research Activity

RI Applications Team utilizes RIBF heavy-ion accelerators for following research subjects:

(1) Research and development of RI production technology at RIBF and RI application studies

Due to its high sensitivity, the radioactive tracer technique has been successfully applied for investigations of the behavior of elements in the fields of chemistry, biology, medicine, engineering, and environmental sciences. We have been developing production technologies of useful radiotracers at RIBF and conducted their application studies in collaboration with many researchers in various fields. With 14-MeV proton, 24-MeV deuteron, and 50-MeV alpha beams from the AVF cyclotron, we presently produce about 30 radiotracers from $^3$He to $^{209}$Bi. Among them, $^{65}$Zn, $^{85}$Sr, $^{89}$Y, and $^{109}$Cd are delivered to Japan Radioisotope Association for fee-based distribution to the general public in Japan. On the other hand, radionuclides of a large number of elements are simultaneously produced from metallic targets such as $^{186}$Ti, $^{186}$Ag, $^{186}$Hf, and $^{197}$Au irradiated with a 135-MeV nucl.-1 $^{14}$N beam from the RIKEN Ring Cyclotron. These multitracers are also supplied to universities and institutes as collaborative researches.

In 2014, we developed production technologies of radioisotopes such as $^{20}$Mg, $^{45,63}$Cr, $^{67}$Cu, $^{95}$Tc, $^{183,184}$Re, and $^{195}$Pt which were strongly demanded but lack supply sources in Japan. We also investigated the extraction functions for the $^{nat}$Ti($x$,$x$), $^{nat}$Ge($x$,$x$), $^{nat}$Zr($x$,$x$), $^{nat}$Mo($d$,$d$), $^{nat}$Cd($x$,$x$), $^{nat}$Sm($d$,$d$), $^{nat}$Ho($x$,$x$), $^{nat}$W($d$,$d$), and $^{nat}$Pt($d$,$d$) reactions to produce useful RIs. We produced $^{65}$Zn, $^{109}$Cd, and $^{89}$Y for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2014, we have accepted 5 orders of $^{65}$Zn with a total activity of 33 MBq, 3 orders of $^{109}$Cd with 21 MBq, and 2 orders of $^{89}$Y with 2 MBq.

(2) Superheavy element chemistry

Chemical characterization of newly-discovered superheavy elements (SHEs, atomic numbers $Z \geq 104$) is an extremely interesting and challenging subject in modern nuclear and radiochemistry. We are developing SHE production systems as well as rapid single-atom chemistry apparatuses at RIBF. Using heavy-ion beams from RILAC and AVF, long-lived $^{260}$Rf ($Z = 104$), $^{262}$Db ($Z = 105$), and $^{265}$Sg ($Z = 106$) are produced in the $^{252}$Cf($^{18}$O,$n$)$^{261}$Rf, $^{254}$Cf($^{17}$F,$5n$)$^{260}$Db, and $^{258}$Cf($^{16}$Ne,$5n$)$^{265}$Sg reactions, respectively, and their chemical properties are investigated.

We have been developing a gas-jet transport system at the focal plane of the gas-filled recoil ion separator GARIS at RILAC. This system is a promising approach for exploring new frontiers in SHE chemistry: (i) the background radioactivities of unwanted reaction products are strongly suppressed, (ii) the intense beam is absent in the gas-jet chamber and hence high gas-jet efficiency is achieved, and (iii) the beam-free condition also allows for investigations of new chemical systems. In 2014, the isotope of element 107 $^{266}$Bh was produced in the $^{248}$Cm($^{23}$Na,$5n$)$^{263}$Bh reaction, and its decay properties were investigated using the rotating wheel apparatus MANON for a/$\alpha$-SF spectrometry. Toward the SHE chemistry behind GARIS, we developed a gas-chromatograph apparatus directly coupled to GARIS, which enabled in-situ complexation and gas-chromatographic separation of a large variety of volatile compounds of SHEs. Toward aqueous chemistry of the heaviest elements such as Sg and Bh, we also started to develop a new rapid chemistry apparatus which consisted of a continuous dissolution apparatus Membrane DeGasser (MDG), a flow liquid-liquid extraction apparatus, and a flow liquid scintillation detector for a/$\alpha$-SF spectrometry.

At the AVF cyclotron, the distribution coefficients ($K_d$) of $^{261}$Rf on the Aliquat 336 resin were measured in HCl with the AutoMated Batch-type solid-liquid Extraction apparatus for Repetitive experiments of transactinides (AMBER) in collaboration with Osaka Univ. The extraction behavior of $^{89m}$Zr and $^{173}$Hf in the Aliquat 336/HCl system was investigated for Rf chemistry with the flow-type liquid-liquid extraction apparatus. The reversed-phase TTA extraction chromatography of $^{261}$Rf and its homologues $^{89}$Zr and $^{109}$Cd was conducted in HF/HNO$_3$ using the Automated Rapid Chemistry Apparatus (ARCA) in collaboration with Kanazawa Univ., Niigata Univ., and JAEA. The reversed-phase extraction chromatography of $^{90}$Nb and $^{176}$Ta in Aliquat 336/HF and the anion-exchange chromatography of $^{90}$Nb and $^{178}$Ta in HF/HNO$_3$ were also conducted with ARCA for chemical studies of Db. For Sg chemistry, we investigated the extraction behavior of $^{93}$Mo and $^{177,179}$W in H$_2$SO$_4$ and H$_2$C$_2$O$_4$ solutions with Aliquat 336.
(3) Development of trace element analysis using accelerator techniques and its application to geoscience and environmental science

We developed new mass spectrometry technologies for trace element analyses as an application of accelerator technology to various fields such as cosmochemistry, environmental science, and archaeology. ECRIS-AMS is a new type of accelerator mass spectrometry at RILAC equipped with an ECR ion source. This system is available for measuring trace elements (10^{-14} to 10^{-15} level) and is expected to be especially effective for measurements of low-electron-affinity elements such as 26Al, 41Ca, and 53Mn. In 2014, we have renovated the detection system and examined the sensitivity and mass resolution power. We also attempted to develop another technology by customizing a mass spectrometer equipped with a stand-alone ECR ion source for analyses of elemental and isotopic abundances. Especially, we equipped laser-ablation system with ion source to achieve high-resolution analysis. Furthermore, we analyzed sulfur and lead isotope ratios for cinnabar samples from ancient tombs in Japan to elucidate the origin of cinnabar. In 2014, we showed that the lead isotopes in cinnabar ore exhibited clear local characteristics and the origin of the cinnabar ore could be distinguished from the lead isotope compositions.

(4) Development of chemical materials for ECR ion sources of RIBF

In 2014, we investigated production methods of 238U(C8H8)2 and metallic 50Ti powder for the ECR ion source of RIBF. We also prepared metallic 238U and 238UO2 on a regular schedule.

Members

Team Leader
Hiromitsu HABA

Research & Technical Scientist
Kazuya TAKAHASHI (Senior Research Scientist)

Postdoctoral Researchers
Minghui HUANG (~ Mar. 31, 2014) Yukiko KOMORI

Technical Staff I
Jumpei KANAYA

Research Consultant
Seiichi SHIBATA

Junior Research Associate
Masashi MURAKAMI (Niigata Univ.)

Part-time Workers
Michiko KITAGAWA Yu Vin SAHOO

Visiting Scientists
Akihiko YOKOYAMA (Kanazawa Univ.) Mayeen Uddin KHANDAKER (Univ. Malaya)
Kazuhiro AKIYAMA (Tokyo Met. Univ.) Takahiro YAMADA (Japan Rad. Assoc.)
Kazuhiro OEI (Niigata Univ.) Miho TAKAHASHI (Tokyo Univ. Marine Sci. and Tech.)
Hidetoshi KIKUNAGA (Tohoku Univ.) Hiroshi SHIMIZU (Rissho Univ.)
Masayoshi TODA (Tokyo Univ. Marine Sci. and Tech.)

Visiting Technicians
Yuichiro WAKITANI (Japan Rad. Assoc.) Shinya YANOU (Japan Rad. Assoc.)

Student Trainees
Junichi HIRATA (Tokyo Univ. Marine Sci. and Tech.) Takumi KOYAMA (Niigata Univ.)
Yuuki SHIGEYOSHI (Kanazawa Univ.) Shohei TSUTO (Niigata Univ.)
Yuuta KITAYAMA (Kanazawa Univ.) Ryuji AOIO (Niigata Univ.)
Hajime KIMURA (Kanazawa Univ.) Daizuke SATO (Niigata Univ.)
Eita MAEDA (Kanazawa Univ.) Akira TANAKA (Niigata Univ.)
Keigo TOYOMURA (Osaka Univ.) Tetuya NAGAOKA (Niigata Univ.)
Kouhei NAKAMURA (Osaka Univ.) Iori CHIYONISHIO (Kanazawa Univ.)
Yuri OBI (Tokyo Univ. Marine Sci. and Tech.) Ahmed USMAN (Univ. of Malaya)
Yoshiki FUKUDA (Kanazawa Univ.) Kento MURAKAMI (Kanazawa Univ.)
Yudai SHIGEKAWA (Osaka Univ.) Teruyoshi FUJISAWA (Kanazawa Univ.)
Shingo UENO (Kanazawa Univ.) Yukari YATSU (Kanazawa Univ.)
Kazunori HAYASHI (Kanazawa Univ.) Yuki YASUDA (Osaka Univ.)
Takumi TANIGUCHI (Kanazawa Univ.) Yoshihiko HAYASHI (Osaka Univ.)
Naoya GOTO (Niigata Univ.) Risa MOTOYAMA (Niigata Univ.)

- 432 -
RIBF Research Division
User Liaison and Industrial Cooperation Group

1. Abstract
The essential mission of the “User Liaison and Industrial Cooperation (ULIC) Group” is to maximize the research activities of RIBF by attracting users in various fields with a wide scope.

The ULIC Group consists of two teams.

The User Support Team provides various supports to visiting RIBF users through the User’s Office. The Industrial Cooperation Team supports potential users in industries who use the beams for application purposes or for accelerator related technologies other than basic research. Production of various radioisotopes by the AVF cyclotron is also one of the important mission. The produced radioisotopes are distributed to researchers in Japan for a charge through the Japan Radioisotope Association.

In addition the ULIC Group takes care of laboratory tours for RIBF visitors from public. The numbers of visitors amounts to 2,300 per year.

Members

Group Director
Hideyuki SAKAI

Deputy Group Director
Hideki UENO (concurrent: Chief Scientist, Nuclear Spectroscopy Lab.)

Research & Technical Scientist
Mieko KOGURE (Technical Assistant, – Mar. 31, 2014)

Special Temporary Employee
Tadashi KAMBARA

Senior Visiting Scientists
Ikuko HAMAMOTO (Lund Univ.)
Munetake ICHIMURA (Univ. of Tokyo)

Assistants
Katsura IWAI
Tomoko IWANAMI
Noriko KIYAMA
1. Abstract
To enhance synergetic common use of the world-class accelerator facility, the Radioisotope Beam Factory (RIBF), it is necessary to promote a broad range of applications and to maximize the facility’s importance. The facilitation and promotion of the RIBF are important missions charged to the team. Important operational activities of the team include: i) the organization of international Program Advisory Committee (PAC) meetings to review experimental proposals submitted by RIBF users, ii) RIBF beam-time operation management, and iii) promotion of facility use by hosting outside users through the RIBF Independent Users program, which is a new-user registration program begun in FY2010 at the RIKEN Nishina Center (RNC) to enhance the synergetic common use of the RIBF. The team opened the RIBF Users Office in the RIBF building in 2010, which is the main point of contact for Independent Users and provides a wide range of services and information.

2. Major Research Subjects
(1) Facilitation of the use of the RIBF
(2) Promotion of the RIBF to interested researchers

3. Summary of Research Activity
(1) Facilitation of the use of the RIBF
The RIBF Users Office, formed by the team in 2010, is a point of contact for user registration through the RIBF Independent User program. This activity includes:
- registration of users as RIBF Independent Users,
- registration of radiation workers at the RIKEN Wako Institute,
- provision of an RIBF User Card (a regular entry permit) and an optically stimulated luminescence dosimeter for each RIBF Independent User, and
- provision of safety training for new registrants regarding working around radiation, accelerator use at the RIBF facility, and information security, which must be completed before they begin RIBF research.

The RIBF Users Office is also a point of contact for users regarding RIBF beam-time-related paperwork, which includes:
- contact for beam-time scheduling and safety review of experiments by the In-House Safety Committee,
- preparation of annual Accelerator Progress Reports, and
- maintaining the above information in a beam-time record database.

In addition, the RIBF Users Office assists RIBF Independent Users with matters related to their visit, such as invitation procedures, visa applications, and the reservation of on-campus accommodation.

(2) Promotion of the RIBF to interested researchers
- The team has organized an international PAC for RIBF experiments; it consists of leading scientists worldwide and reviews proposals in the field of nuclear physics (NP) purely on the basis of their scientific merit and feasibility. The team also assists another PAC meeting for material and life sciences (ML) organized by the RNC Advanced Meson Laboratory. The NP and ML PAC meetings are organized twice a year.
- The team coordinates beam times for PAC-approved experiments and other development activities. It manages the operating schedule of the RIBF accelerator complex according to the decisions arrived at by the RIBF Machine Time Committee.
- To promote research activities at RIBF, proposals for User Liaison and Industrial Cooperation Group symposia/mini-workshops are solicited broadly both inside and outside of the RNC. The RIBF Users Office assists in the related paperwork.
- The team is the point of contact for the RIBF users’ association. It arranges meetings at RNC headquarters for the RIBF User Executive Committee of the users’ association.
- The Team conducts publicity activities, such as arranging for RIBF tours, development and improvement of the RNC official web site, and delivery of RNC news via email and the web.

Members

Team Leader
Ken-ichiro YONEDA

Deputy Team Leader
Yasushi WATANABE (concurrent: Senior Research Scientist, Radiation Lab.)

Technical Staff I
Narumasa MIYAUCHI
1. Abstract
Industrial cooperation team handles non-academic activities at RIBF corresponding to industries and to general public.

2. Major Research Subjects
(1) Fee-based distribution of radioisotopes produced at RIKEN AVF Cyclotron
(2) Support of industrial application using the RIBF accelerator beam and its related technologies including novel industrial applications.
(3) Development of real-time wear diagnostics of industrial material using RI beams

3. Summary of Research Activity
(1) Fee-based distribution of radioisotopes
This team handles fee-based distribution of radioisotopes Zn-65, Y-88 and Cd-109 from 2007, which are produced by the RI application team at the AVF cyclotron, to nonaffiliated users under a Material Transfer Agreement between Japan Radioisotope Association and RIKEN. In 2014, we delivered 3 shipments of Cd-109 with a total activity of 22 MBq, 7 shipments of Zn-65 with a total activity of 44 MBq and one shipment of Y-88 with an activity of 1 MBq. The final recipients of the RIs were five universities, one research institutes and two hospitals.

(2) Support of Industrial application using RIBF
In November 2009, RNC started a new project “Promotion of applications of high-energy heavy ions and RI beams” as a grant-in-aid program of MEXT “Sharing Advanced Facilities for Common Use Program”. In this project, RNC opens the old part of the RIBF facility, which includes the AVF cyclotron, RILAC, RIKEN Ring Cyclotron and experimental instruments like RIPS, to non-academic proposals from users including private companies. This MEXT program was terminated in September 2010, but RNC succeed and promote this facility sharing program after that. The proposals are reviewed by a program advisory committee, industrial PAC. The proposals which have been approved by the industrial PAC are allocated with beam times and the users pay RIKEN the beam time fee. The intellectual properties obtained by the use of RIBF belong to the users. In order to encourage the use of RIBF by those who are not familiar with utilization of ion beams, the first two beam times of each proposal can be assigned to trial uses which are free of beam time fee.

The fourth industrial PAC meeting held in August 2014 reviewed two fee-based proposals from private companies and approved them. The first proposal of fee-based utilization was performed in October with a 70-MeV/A 84Kr beam at the E5A beamline of the RIKEN Ring Cyclotron.

(3) Development of real-time wear diagnostics using RI beams
We are promoting a method for real-time wear diagnostics of industrial material using RI beams as tracers. For that purpose, very intense RI beams of 7Be (T1/2=52 days) at 4.1 MeV/u and 22Na (T1/2=2.6 years) at 3.7 MeV/u were produced via the (p,n) reaction at the CRIB separator using beams from the AVF cyclotron. As we can provide RI beams of different nuclides and control the implantation depth, we have developed a novel method of wear diagnostics.

Under a collaborative research agreement entitled “Development and application of wear diagnosis method with RI beams” between RIKEN, University of Tokyo and two private companies, we had two beam-times in February and in March 2014, at E7A beam-line of the AVF cyclotron. Beams of RI nuclei 7Be and 22Na were provided by CRIB and implanted near surface of metallic machine parts, whose wear-loss rate was evaluated through measurements of the radio-activities.

We are also developing a new method to determine the spatial distribution of positron-emitting RIs on periodically-moving objects in a closed system, which can be used for real-time evaluation of wear loss in a running machine. This is based on the same principle as the medical PET systems but is simpler and less expensive.

Members
Team Leader
Atsushi YOSHIDA

Research & Technical Scientist
Hiroshima TAKEUCHI (Senior Research Scientist, -Jun. 30, 2014)

Visiting Technicians
Shuhei TATEMICHI (Fuji Electric Systems) Masanori INOUE (Fuji Electric Systems)
1. Abstract
The RIKEN Nishina Center for Accelerator-Based Science possesses one of the largest accelerator facilities in the world, which consists of two heavy-ion linear accelerators and five cyclotrons. This is the only site in Japan where uranium ions are accelerated. The center also has electron accelerators of microtron and synchrotron storage ring. Our function is to keep the radiation level in and around the facility below the allowable limit and to keep the exposure of workers as low as reasonably achievable. We are also involved in the safety management of the Radioisotope Center, where many types of experiments are performed with sealed and unsealed radioisotopes.

2. Major Research Subjects
(1) Safety management at radiation facilities of Nishina Center for Accelerator-Based Science
(2) Safety management at Radioisotope Center
(3) Radiation shielding design and development of accelerator safety systems

3. Summary of Research Activity
Our most important task is to keep the personnel exposure as low as reasonably achievable, and to prevent an accident. Therefore, we daily patrol the facility, measure the ambient dose rates, maintain the survey meters, shield doors and facilities of exhaust air and wastewater, replenish the protective supplies, and manage the radioactive waste. Advice, supervision and assistance at major accelerator maintenance works are also our task.

We revised the safety interlock system of RIBF building to prevent excess exposures due to unexpected high-intensity beam transport through the BigRIPS. When the primary beam is transported through BigRIPS, rooms adjacent to and in the vicinity of the room where the beam is transported are evacuated. If the magnetic fields of the two dipole magnets before and after the BigRIPS target position were set very closely, the interlock system recognizes the primary beam is transported through the BigRIPS. The primary beam mode can be also set manually. In the primary beam mode, some attenuators of accelerators cannot be taken out not to deliver a high-intensity beam to BigRIPS by human error.

Members
Group Director
Yoshitomo UWAMINO

Deputy Group Director
Kanenobu TANAKA (Apr. 1, 2014 –)

Nishina Center Technical Scientists
Rieko HIGURASHI
Hisao SAKAMOTO

Technical Staff I
Atsuko AKASHIO

Research Consultant
Masaharu OKANO (Japan Radiation Res. Soc.)

Visiting Scientists
Hee Seock LEE (POSTECH)
Joo-Hee OH (POSTECH)
Nam-Suk JUNG (POSTECH)

Assigned Employee
Hiroki MUKAI

Temporary Staffing
Ryaji SUZUKI

Part-time Workers
Hiroshi KATO
Satoshi IIZUKA
Kimie IGARASHI
Hiroko AISU

Assistant
Tomomi OKAYASU
The Nishina Center established the research partnership system in 2008. This system permits an external institute to develop its own projects at the RIKEN Wako campus in equal partnership with the Nishina Center. At present, three institutes, Center for Nuclear Study of the University of Tokyo (CNS), Institute of Particle and Nuclear Studies of KEK (KEK), and Department of Physics, Niigata University (Niigata) are conducting research activities under the research partnership system.

CNS and the Nishina Center signed the partnership agreement in 2008. Until then, CNS had collaborated in joint programs with RIKEN under the “Research Collaboration Agreement on Heavy Ion Physics” (collaboration agreement) signed in 1998. The partnership agreement redefines procedures related to the joint programs while keeping the spirit of the collaboration agreement. The joint programs include experimental nuclear physics activities using CRIB, SHARAQ, GRAPE at RIBF, theoretical nuclear physics activities with ALPHLEET, accelerator development, and activities at RHIC PHENIX.

The partnership agreement with the Niigata University was signed in 2010. The activity includes theoretical and experimental nuclear physics, and nuclear chemistry.

KEK started low-energy nuclear physics activity at RIBF in 2011 under the research partnership system. The newly constructed isotope separator KISS will be available for the users in near future.

The activities of CNS, Niigata, and KEK are reported in the following pages.
1. Abstract

The Center for Nuclear Study (CNS) aims to elucidate the nature of nuclear system by producing the characteristic states where the Isospin, Spin and Quark degrees of freedom play central roles. These researches in CNS lead to the understanding of the matter based on common natures of many-body systems in various phases. We also aim at elucidating the explosion phenomena and the evolution of the universe by the direct measurements simulating nuclear reactions in the universe. In order to advance the nuclear science with heavy-ion reactions, we develop AVF upgrade, CRIB and SHARAQ facilities in the large-scale accelerators laboratories RIBF. We started a new project OEDO for a new energy-degrading scheme, where a RF deflector system is introduced to obtain a good quality of low-energy beam. We promote collaboration programs at RIBF as well as RHIC-PHENIX and ALICE-LHC with scientists in the world, and host international meetings and conferences. We also provide educational opportunities to young scientists in the heavy-ion science through the graduate course as a member of the department of physics in the University of Tokyo and through hosting the international summer school.

2. Major Research Subjects

(1) Accelerator Physics
(2) Nuclear Astrophysics
(3) Nuclear spectroscopy of exotic nuclei
(4) Quark physics
(5) Nuclear Theory
(6) OEDO/SHARAQ project
(7) Exotic Nuclear Reaction
(8) Active Target Development

3. Summary of Research Activity

(1) Accelerator Physics

One of the major tasks of the accelerator group is the AVF upgrade project that includes development of ion sources, upgrading the AVF cyclotron of RIKEN and the beam line to CRIB. Development of ECR heavy ion sources is to provide new HI beams, higher and stable beams of metallic ions, and to improve the control system. The Hyper ECR and the Super ECR sources provide all the beams for the AVF cyclotron and support not only CRIB experiments but also a large number of RIBF experiments. Injection beam monitoring and control are being developed and studied. Detailed study of the optics from the ion sources are expected to improve transmission and qualities of beams for the RIBF facility.

(2) Nuclear Astrophysics

The nuclear astrophysics group in CNS is working for experimental researches using the low-energy RI beam separator CRIB. The call for proposals for the NP-PAC now includes proposals for CRIB again, and 3 new proposals have been approved in the NP-PAC meetings in the fiscal year 2014. In May 2014, a measurement of the elastic scattering of $^8$B+Pb was performed in collaboration with INFN-LNL (Padova). It was made possible by the special development of intense and energy-enhanced $^6$Li beam. A unique beam of $^8$B at 50 MeV and 10$^4$ pps was produced, and the measurement was successfully completed.

(3) Nuclear structure of exotic nuclei

The NUSPEQ (NUclear SPectroscopy for Extreme Quantum system) group studies exotic structures in high-isospin and/or high-spin states in nuclei. The CNS GRAPE (Gamma-Ray detector Array with Position and Energy sensitivity) is a major apparatus for high-resolution in-beam gamma-ray spectroscopy. Missing mass spectroscopy using the SHARAQ is used for another approach on exotic nuclei. In 2014, the following progress has been made.

Experimental data taken in 2013 under the EURICA collaboration are being analyzed for studying octupole deformation in neutron-rich nuclei. Gamow-Teller transitions of $^4$He were studied by the (p,n) reaction in inverse kinematics, where a prominent sharp peak at Ex~8 MeV was found to be the Gamow-Teller resonance. Exothermic charge exchange reactions ($^4$He,$^6$Li*(1+)) on $^3$He are being analyzed for studying spin-dipole response of few-body system on the photon line. The tetra-neutron system was studied by the $^4$He($^8$He,$^8$Li)4n reaction, which shows a candidate of the ground state of the tetra neutrons just above the 4n threshold as well as continuum at higher excitation energy.

The readout system of 14 detectors of the CNS GRAPE was upgraded, where digital pulse data taken by sampling ADCs are analyzed by FPGAs on boards.

(4) Quark Physics

Main goal of the quark physics group is to understand the properties of hot and dense nuclear matter created by colliding heavy nuclei at relativistic energies. The group has been involved in the PHENIX experiment at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, and the ALICE experiment at Large Hadron Collider (LHC) at CERN.
As for PHENIX, the group has been concentrating on the physics analysis involving leptons and photons; dielectron measurement in Au+Au collisions, dark photon searches in low mass Dalitz decays, and J/ψ production in ultra-peripheral Au+Au collisions.

As for ALICE, the group has involved in the data analyses, which include the neutral pion production in Pb+Pb collisions, and measurement of low-mass lepton pairs in Pb+Pb and p+Pb collisions. The group has involved in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM). Performance evaluation of the MicroMegas + GEM systems for the upgrade is performed.

R&D of GEM and related techniques has been continuing. Development of Teflon GEM has been progressing in collaboration with the Tamagawa group of RIKEN.

(5) Nuclear Theory

The nuclear theory group has been promoting the CNS-RIKEN collaboration project on large-scale nuclear structure calculations since 2001 and maintaining its PC cluster. In order to review and promote this collaboration further, an international workshop "Progress in nuclear shell-model calculations in CNS-RIKEN collaboration" was held on Nov. 26-28, 2014. This group has revealed that the $4^+_1$ of $^{44}$Si is high-K isomer, and discussed the deformation properties of the high-spin states of neutron-rich Cr and Fe isotopes utilizing shell-model calculations. A memorandum of understanding on this collaboration has been made between CNS and RIKEN in March 2014. In parallel, this group participated in activities of HPCI Strategic Programs for Innovative Research (SPIRE) Field 5 “The origin of matter and universe” since 2011.

(6) OEDO/SHARAQ project

The OEDO/SHARAQ group has been promoting high-resolution experimental studies of RI beams by using the high-resolution beamline and SHARAQ spectrometer. The mass measurement by TOF-Bp technique was performed for very neutron-rich calcium isotopes around $N=34$. For the experiment, we introduced new detector devices into the experiment. Diamond detectors, which were developed as timing counters with extreme resolution, were installed for measuring time of flight at the first and final foci of the beam line. Clover-type Ge detectors were installed at the final focal plane of the SHARAQ spectrometer for the first time, enabling particle identification of RI beams by probing delayed gamma rays from known isomeric states of specific nuclei.

We have started ion optical development for achievement of high-quality RI beams with energies lower than 100 MeV/u. This project was named OEDO (Optimized Energy-Degrading Optics for RI beam) and the basic magnet arrangement and ion optics was discussed based on the existing high-resolution beamline and SHARAQ spectrometer.

(7) Exotic Nuclear Reaction

The Exotic Nuclear Reaction group studies various exotic reactions induced by beams of unstable nuclei. In 2014, a parity transfer probe of the ($^4$He, $^6$He(g.s.)) reaction was demonstrated on $^5$C at SHARAQ. The proton from the subsequent instant decay of $^{16}$F(g.s.) → $^{16}$F-$\beta$ was detected by a MWDC newly introduced. The kinematical reconstruction of $^{16}$F was successful. At SAMURAI, a measurement of knockout reactions from Borromean nuclei, $^{18}$Li and $^{18}$Be was performed to study the two-neutron correlation. Analysis of the $^{22,23}$O(p,2p) reaction data obtained in 2012 was almost finished and the spin-orbit splitting of proton 0p orbitals in $^{22}$O was derived.

(8) Active Target Development

In a project of active target development launched as an intergroup collaboration in 2009, two types of active target, called GEM-MSTPC and CAT, respectively, have been developed. The (a,p) reactions on $^{18}$Ne, $^{22}$Mg and $^{30}$S, and the alpha emission following the beta decay of $^{15}$N have been measured using GEM-MSTPC and data analyses are on going. The deuteron inelastic scattering off $^{132}$Xe was measured by using the CAT with $^{10}$-particles-per-spill $^{132}$Xe beam at HIMAC accelerator facility in Chiba.

Members

**Director**

Takaharu OTSUKA

**Scientific Staff**

Susumu SHIMOURA (Professor)  
Hidki HAMAGAKI (Professor)  
Kentaro YAKO (Associate Professor)  
Nobuaki IMAI (Associate Professor, June 2014 –)  
Noritaka SHIMIZU (Project Associate Professor)

**Guest Scientists**

Hiroaki UTSUNOMIYA (Guest Professor)  
Yutaka UTSUNO (Guest Associate Professor)

**Technical Staff**

Norio YAMAZAKI (–Mar. 2014)  
Hiroshi KUREI

**Technical Assistants**

Hiroshi KUREI  
Takehiko SENOO (–Mar. 2014)

Guest Scientists

Yukimitsu OHSHIRO

Technical Staff

Yukimitsu OHSHIRO

Technical Assistants

Akira YOSHINO (Jun. 2014–)
Shoichi YAMAKA
Kazuyuki YOSHIMURA
Masahiko TANAKA (Jun. 2014–)
Mamoru KATAWANAGI (Apr. 2014–)

**Project Research Associates**
Tooru YOSHIDA
Yoritaka IWATA

**Post Doctoral Associates**
Masanori DOZONO (Apr. 2014 –)
Yorito YAMAGUCHI (~ May 2014)
Taro NANAOK (~ Mar. 2014)
Reiko KOJIMA (~ Mar. 2014)
David STEPPENBECK (~ Oct. 2014)
Tomoaki TOGASHI

**Graduate Students**
David. M KAHL
Akihisa TAKAHARA (~ Mar. 2014)
Hiroyuki MIYA
Ryoji AKIMOTO (~Mar. 2014)
Hiroshi TOKIEDA
Tomoya TSUJI
Shintaro GO (~ Mar. 2014)
Shoichiro KAWASE
Shinichi HAYASHI
Keiichi KISAMORI
Motonobu TAKAI

**Administration Staff**
Hiroshi YOSHIMURA
Ikuko YAMAMOTO
Takako ENDO

Nasifumi KADOTA (Apr. 2014–)
Masafumi MATSUSHITA
Yuki ARAMAKI (~ Oct. 2014)
Yosuke WATANABE (Apr. 2014–)
Seiya HAYAKAWA (Aug. 2014–)

Tang T. LEUNG (~Mar. 2014)
Yuko SEKIGUCHI
Rin YOKOYAMA
Yuki KUBOTA
CheongSoo LEE
Kohei TERASAKI
Motoki KOBAYASHI
Kentarou YUKAWA
Yuji SAKAGUCHI
Yu KIYOKAWA

Yukino KISHI
Toshiko ITAGAKI
Yuko SOMA
1. Abstract
The Center for Radioactive Ion Beam Sciences, Niigata University, aims at uncovering the properties of atomic nuclei and heavy elements and their roles in the synthesis of elements, with use of the advanced techniques of heavy ion and radioactive ion beam experiments as well as the theoretical methods. Main research subjects include the measurements of various reaction cross sections and moments of neutron- or proton-rich nuclei, synthesis of super-heavy elements and radio-chemical studies of heavy nuclei, and theoretical studies of exotic nuclei based on quantum many-body methods and various nuclear models. In addition, we promote interdisciplinary researches related to the radioactive ion beam sciences, such as applications of radioactive isotopes and radiation techniques to material sciences, nuclear engineering and medicine. Many of them are performed in collaboration with RIKEN Nishina Center and with use of the RIBF facilities. The center emphasizes also its function of graduate education in corporation with the Graduate School of Science and Technology, Niigata University, which invites three researchers in RIKEN Nishina Center as visiting professors.

2. Major Research Subjects
(1) Reaction cross section and radii of neutron-rich nuclei
(2) Production of superheavy nuclei and radiochemistry of heavy elements
(3) Nuclear theory

3. Summary of Research Activity
(1) Reaction cross section and radii of neutron-rich nuclei
The experimental nuclear physics group has studied nuclear structure with the RI beam. One of our main interests is the interaction/reaction cross section measurements. They are good probes to investigate nuclear matter radii and nuclear matter distributions including halo or skin structure. Recently we have measured the interaction sections of Ne, Na, Mg and Al isotopes from stable region to neutron drip line with BigRIPS in RIBF. We found a large enhancement of cross section at 31Ne. It suggests that 31Ne nucleus has a neutron halo. It is consistent with the soft E1 excitation measurement. We also found an enhancement at 37Mg. For odd-Z nuclei, Na and Al, we did not find such a large enhancement from neighbor isotopes. The systematics of observed interaction/reaction cross sections shows the changing of nuclear structure from stable region to neutron drip line via island of inversion.

(2) Production of superheavy nuclei and radiochemistry of heavy elements
The nuclear chemistry group has been investigating decay properties of super-heavy nuclei, measured the excitation functions of rutherfordium isotopes, and clarified the ambiguity of the assignment of a few-second spontaneously fissioning isotope of 261Rf. The new equipment designed for measurement of short-lived alpha emitters is under development. For the chemistry research of super-heavy elements, preparatory experiments, such as solvent extraction for the group 4, 5, and 6th elements and gaseous phase chemistry for group-4 elements, have been performed using radioisotopes of corresponding homolog elements.

(4) Nuclear theory
One of the main activities of the nuclear theory group concerns with developments of the nuclear density functional theory and exploration of novel correlations and excitations in exotic nuclei. A fully selfconsistent scheme of the quasiparticle random phase approximation (QRPA) on top of the Skyrme-Hartree-Fock-Bogoliubov mean-field for deformed nuclei has been developed in the group. The versatility of this method to describe the deformation splitting of the giant resonances associated with the onset of deformation has been demonstrated for the first time by the intensive numerical calculation performed for Nd and Sm isotopes. The same method is further extended to describe the spin-isospin modes of excitation in deformed neutron-rich nuclei. A successful description of the Gamov-Teller beta-decay transition rate in the neutron-rich Zr isotopes is achieved with this method. Another correlation of interest in neutron-rich nuclei is the pair correlation, for which the spatial di-neutron correlation has been a key topic. Applying the continuum QRPA to the pairing modes of excitation in neutron-rich Sn isotopes, we predict the emergence of an anomalous pair vibration for isotopes with A>132. Furthermore the new mode is predicted to exhibits the di-neutron character. In addition to these studies, activities related to the proton-neutron pairing, the di-neutron correlation in the asymptotic tail in drip-line nuclei, the quasiparticle resonances in unbound odd-N nuclei are under way. Cluster structure and the ab initio studies of light nuclei are also important research subjects of the theory group.

Members

Director
Masayuki MATSUO (Professor)

Scientific Staff
Hisao KUDO (Professor) Shigeyoshi AOYAMA (Associate Professor)
Takashi OHTSUBO (Associate Professor) Takuji IZUMIKAWA (Associate Professor)
Shin-ichi GOTO (Associate Professor) Kenichi YOSHIDA (Assistant Professor)
Kazuhiro OOE (Assistant Professor)  
Jun GOTO (Assistant Professor)  
Maya TAKECHI (Assistant Professor)

Post Doctoral Associates  
Hirotaka SHIMOYAMA

Graduate Students  
Kazuya HIROKAWA  
Yoshikiko KOBAYASHI  
Junpei ANZAI  
Sho KANESAWA
1. Abstract

The KEK Isotope Separation System (KISS) has been constructed to experimentally study the β-decay properties of unknown neutron-rich nuclei with around neutron magic numbers N = 126 for astrophysical interest. In FY2014, first radioactive nuclear beam of 199Pt, which was produced by 136Xe + 198Pt reaction, collected by an Ar gas cell, selectively ionized by a resonant ionization technique and mass-separated, has been successfully extracted from KISS. The measured half-life of extracted 199Pt was good agreement with the reported value.

2. Major Research Subjects

(1) Radioactive isotope beam production and manipulation for nuclear experiments.
(2) Explosive nucleosynthesis (r- and p-process).
(3) Heavy-ion reaction mechanism for producing heavy neutron-rich nuclei.
(4) Single particle states of neutron-rich nuclei by isobaric analog resonances.
(5) Development of RNB probes for materials science applications.

3. Summary of Research Activity

The KISS is an element-selective isotope separator using a magnetic mass separator combined with in-gas-cell resonant laser ionization. The gas cell filled with argon gas of 50 kPa is a central component of the KISS for extracting only the element of interest as ion beam for subsequent mass separation. In the cell, the element primarily produced by low-energy heavy ion reactions is stopped (thermalization and neutralization), transported by buffer gas (argon gas-flow of ~50 kPa in the present case), and then re-ionized by laser irradiation just before the exit. The gas cell was fabricated to efficiently correct the reaction products produced by the multi-nucleon transfer reaction of 136Xe + 198Pt system. For the first extraction of the reaction products, the 136Xe beam energy and 198Pt target thickness were set at 10.8 MeV/u and 6 mg/cm², respectively. In FY2014, for the half-life measurement, β-ray telescopes were composed of three double-layered thin plastic scintillators; thickness of the first layer and second one were 0.5 and 1 mm, respectively. In order to reduce the background, they were surrounded with low-activity lead blocks and a veto counter system consisting of plastic scintillator bars. The background rate of the present β-ray telescopes was measured to be 0.7 counts per second. After the installation of the detection system, we have successfully extracted laser-ionized 199Pt which mainly formed 199PtAr²⁺ molecular ions and was transported with the mass separator as the molecular ions. The measured half-life of 199Pt was t½ = 33(4) min. which was good agreement with the reported value of 30.8(2) min.

Also, we investigated the extraction efficiency of ions from KISS, using 198Pt elastic scattered particles. The 198Pt was also extracted as 199PtAr²⁺ molecule. The extraction efficiency was measured to be about 0.2 % which was independent of the 136Xe primary beam intensities. The obtained selectivity and purity were higher than 300 and 99.7 %, respectively, at the maximum primary beam intensity of 20 pA. In order to improve the extraction efficiency, we have started to install a new sextupole ion-guide (SPIG) at the exit of the gas cell with lager angular acceptance, which is divided into two parts with different apertures of 8 and 3 mm diameters, respectively. At the off-line test for the newly installed SPIG, we have clearly observed the dissociation of molecular ions of laser-ionized iodium, by applying DC voltage between first and second parts of the SPIG. We can expect to improve the extraction efficiency, at least, by a factor of 1.5. In FY2015, we will perform the on-line test for the new SPIG to measure the improved extraction efficiency.

For measurements of half-lives of unknown neutron-rich nuclei on N = 126, the present background rate of β-rays telescopes is not low enough. We have constructed a new β-rays telescopes in which ΔE plastic scintillator would be exchanged to a smaller one. We can expect to reduce the background rate by several factors. Further, we have started to develop a gas counter as a ΔE counter to realize the background rate of our goal, several counts per hour or less.

As a continuing effort for search for effective laser ionization scheme of elements of our interest (Z <82), a reference cell was fabricated, and is currently being used to search for auto ionizing states in Ta, W, and etc...

In order to investigate the feasibility of the multi-nucleon transfer (MNT) in the reaction system of 136Xe on 198Pt for producing heavy neutron-rich isotopes around the mass number of 200 with the neutron magic number of 126, we performed the cross section measurement at GANIL in 2012 and the analysis of the data has been almost completed. The cross sections of target-like fragments around N =126 were comparable to those estimated using the GRAZING code, and they appear to be mainly contributed by the reactions with low total energy loss with the weak N/Z equilibration and particle evaporation. This suggests the promising use of the MNT reactions with a heavy projectile at the energies above the Coulomb barrier for production of the neutron-rich isotopes around N = 126.

The diffusion coefficient of lithium in solid materials used in secondary Li-ion batteries is one of key parameters that determine how fast a battery can be charged. The reported Li diffusion coefficients in solid battery materials are largely scattered over several order of magnitudes. We have developed an in-situ nanoscale diffusion measurement method using α-emitting radioactive ⁸Li tracer. In the method, while implanting a pulsed ⁸Li beam of 8 keV, the alpha particles emitted at a small angle (θ = 10 ± 1°) relative to a sample surface were detected as a function of time. We can obtain Li diffusion coefficient from the time dependent yields of the α particles, whose energy loss can be converted to nanometer-scale position information of diffusing ⁸Li. The method has been successfully applied to measure the lithium diffusion coefficients for an amorphous Li₅SiO₄ - Li₁VO₄ (LVSO) which was used as a solid electrolyte in a solid-state Li thin film battery, well
demonstrating that the present method has the sensitivity to the diffusion coefficients down to a value of $10^{-12}$ cm$^2$/s, corresponding with nanoscale Li diffusion. From FY2014, we have started to measure Li diffusion coefficients in a spinel type Li compound of LiMn$_2$O$_4$ (LMO), which is used as a positive electrode of a Li battery in an electric vehicle. We have observed a significant change on the time dependent yields of the $\alpha$ particles at the sample temperature of around 623 K and will continue the measurements to obtain temperature dependency of Li diffusion coefficients in LMO.

Members

**Group Leader**
Hiroari MIYATAKE

**Members**
Yoshikazu HIRAYAMA
Nobuaki Imai
Yutaka WATANABE
Hironobu ISHIYAMA
Sunchan JEONG

Michihiro OYAIZU
Hyo-Soon Jung
Yung-Hee KIM (PhD. Student, Seoul National Univ.)
Momo MUKAI (PhD. Student, Tsukuba Univ.)
Sota KIMURA (PhD. Student, Tsukuba Univ.)
demonstrating that the present method has the sensitivity to the diffusion coefficients down to a value of 10^{-12} \text{cm}^2/\text{s}, corresponding with nanoscale Li diffusion. From FY2014, we have started to measure Li diffusion coefficients in a spinel type Li compound of LiMn_2O_4 (LMO), which is used as a positive electrode of a Li battery in an electric vehicle. We have observed a significant change on the time dependent yields of the $\alpha$ particles at the sample temperature of around 623 K and will continue the measurements to obtain temperature dependency of Li diffusion coefficients in LMO.

Members

Group Leader
Hiroari MIYATAKE

Members
Yoshikazu HIRAYAMA
Nobuaki IMAI
Yutaka WATANABE
Hironobu ISHIYAMA
Sunchan JEONG

Michihiro OYAIZU
Hyo-Soon Jung
Yung-Hee KIM (PhD. Student, Seoul National Univ.)
Momo MUKAI (PhD. Student, Tsukuba Univ.)
Sota KIMURA (PhD. Student, Tsukuba Univ.)

Events (April 2014 - March 2015)

RIKEN

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 10 - 11</td>
<td>The 3rd EURICA Workshop</td>
</tr>
<tr>
<td>Apr. 19</td>
<td>Wako Open campus</td>
</tr>
<tr>
<td>Jun. 1 - 6</td>
<td>The 2nd Conference on &quot;Advances in Radioactive Isotope Science&quot; (ARIS2014)</td>
</tr>
<tr>
<td></td>
<td><a href="http://ribf.riken.jp/ARIS2014/">http://ribf.riken.jp/ARIS2014/</a></td>
</tr>
<tr>
<td>Jun. 27 - 28</td>
<td>The 14th NP-PAC</td>
</tr>
<tr>
<td>Jul. 1 - 3</td>
<td>Nishina Center Advisory Council</td>
</tr>
<tr>
<td>Jul. 28 - Aug. 8</td>
<td>Nishina School</td>
</tr>
<tr>
<td>Aug. 7</td>
<td>The 4th In-PAC</td>
</tr>
<tr>
<td>Aug. 31 - Sep. 5</td>
<td>The 27th International Conference of the International Nuclear Target Development Society (INTDS-2014)</td>
</tr>
<tr>
<td>Oct. 1</td>
<td>Start of Nuclear Transmutation Data Research Group associated with following three teams</td>
</tr>
<tr>
<td></td>
<td>Fast RI Data Team, Slow RI Data Team and Muon Data Team</td>
</tr>
<tr>
<td>Dec. 1-5</td>
<td>The 6th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2014)</td>
</tr>
<tr>
<td></td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1395">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1395</a></td>
</tr>
<tr>
<td>Dec. 10</td>
<td>Effect of MOU between Universitas Hasanuddin, Indonesia and RNC</td>
</tr>
<tr>
<td>Dec. 12 - 13</td>
<td>The 15th NP-PAC</td>
</tr>
<tr>
<td>Jan. 5</td>
<td>Effect of MOU between RNC and Peking University</td>
</tr>
<tr>
<td>Jan. 8 - 9</td>
<td>The 11th ML-PAC</td>
</tr>
<tr>
<td>Mar. 31</td>
<td>End of Mathematical Physics Laboratory led by associate chief scientist Koji Hashimoto</td>
</tr>
</tbody>
</table>

CNS

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 28 - Sep. 03</td>
<td>The 12th CNS international Summer School (CNSS13)</td>
</tr>
<tr>
<td></td>
<td><a href="http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=81">http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=81</a></td>
</tr>
</tbody>
</table>

Niigata Univ.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>not held in FY2014</td>
</tr>
</tbody>
</table>

KEK

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 21-28</td>
<td>KEK Summer Challenge 2014</td>
</tr>
<tr>
<td></td>
<td><a href="http://www2.kek.jp/ksc/8th_2014/index.html">http://www2.kek.jp/ksc/8th_2014/index.html</a></td>
</tr>
</tbody>
</table>
## Press Releases (April 2014 - March 2015)

<table>
<thead>
<tr>
<th>RNC</th>
<th>Elucidation of exotic structures in very neutron-rich nuclei: a unified picture for neutron-halo, magicity-loss and large deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 11</td>
<td>Joint PR: Released from Tokyo Tech.</td>
</tr>
<tr>
<td>Apr. 24</td>
<td>Hyperfine structure constant of the single neutron halo nucleus ( \text{Be}^{11+} ) has been precisely measured to be ( A = -2677.302988 \pm 0.000072 \text{ MHz} ) using laser microwave double resonance spectroscopy.</td>
</tr>
<tr>
<td>Jun. 18</td>
<td>Neutron Halo Appears in a Neutron-rich Magnesium Isotope ---Suggesting that neutron halo is a more common feature of heavier, extremely neutron-rich nuclei---</td>
</tr>
<tr>
<td>Jul. 22</td>
<td>Rewriting the history of volcanic forcing during the past 2000 years ---A year-by-year record of volcanic eruptions from a comprehensive Antarctic ice core array---</td>
</tr>
<tr>
<td>Aug. 29</td>
<td>Nickels-78 has been confirmed to be a ‘doubly magic’ isotope --- Precise beta-decay half-life measurement of ( \text{Ni}^{78} ) ---</td>
</tr>
<tr>
<td>Sep. 18</td>
<td>SUZAKU studies of the central engine in the typical Type I Seyfert NGC 3227: Detection of multiple primary X-ray continua with distinct properties</td>
</tr>
<tr>
<td>Sep. 18</td>
<td>Efficient production of muonium at room temperature--- Stringent survey of deviation from the standard model of particle physics comes closer to reality in Japan---</td>
</tr>
<tr>
<td>Sep. 19</td>
<td>Synthesis of a carbonyl complex of element 106, seaborgium (Sg) ---Sg shows chemical properties characteristic to the group-6 elements in the periodic table---</td>
</tr>
<tr>
<td>Mar. 9</td>
<td>Ensuring food safety using space technology ---technology originally designed for use in outer space to create a new system, called LANFOS, which can inexpensively and non-destructively detect radioactive cesium contamination in food---</td>
</tr>
</tbody>
</table>

---

**Joint PR: Released from Tokyo Tech.**

**Michiharu WADA (SLOWRI Team)**

**Yuko MOTIZUKI (Astro-Glaciology Research Unit)**

**Z. Y. Xu & Shunji Nishimura (Radioactive Isotope Physics Lab.)**

**Katsuhiko Ishida (Advanced Meson Science Lab.)**

**Dai Tomono & Teiichiro MATSUZAKI (Muon Data Team)**

**Hiromitsu Haba (RI Applications Team)**
VII. LIST OF PUBLICATIONS & PRESENTATIONS
RIKEN Nishina Center for Accelerator-Based Science

Publications

[Book · Proceedings]


Oral Presentations

(International Conference etc.)


Quantum Hadron Physics Laboratory

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Misumi T. and Kanazawa T.: “Adjoint QCD on $R^3 \times S^1$ with twisted fermionic boundary conditions ”, JHEP06, 181 (2014)*.

Kanazawa T. and Wettig T.: “Stressed Cooper pairing in QCD at high isospin density: effective Lagrangian and random matrix theory ”, JHEP10, 055(2014)*.


Kanazawa T. and Tanizaki Y.: “Structure of Lefschetz thimbles in simple fermionic systems”, JHEP03, 044(2015)*.


Hayata T. and Hidaka Y.: “Broken spacetime symmetries

Takizawa Y., “Graded QCD Simulation for high-dimensional nuclear physics”, Reviews of Modern Physics, 85, 1391 (2013)*


Hatsuda T.: “Zc and Tc from Lattice QCD with HAL QCD method”, KEK Flavor Factory Workshop / Belle
II Theory Interface Platform Meeting, KEK, Japan, Oct. 31 (2014).


(Homestic Conference)


研究会-」 理化学研究所, 和光,2月,(2015).
小川軌明, 橋本幸士, 山口康宏: “ホログラフィック模型による
重クォーティーウムのスペクトラムとスピン縮退”, 日本物理
学会年次大会, 早稲田大学,3月,(2015).

Ⅶ. LIST OF PUBLICATIONS

Theoretical Nuclear Physics Laboratory

Publications

[Journal]
(Original Papers)  *Subject to Peer Review


Oral Presentations

(National Conference etc.)


Dinh Dang N.: “Recent achievements in the study of highly excited nuclei: Thermal pairing and giant dipole...
Liang H.Z.: “Supersymmetry and relativistic symmetry in nuclei”, Seminar in School of Physics, (Peking University), Beijing, China, Apr. (2014).
Liang H.Z.: “Solutions of Dirac equation in 3D lattice”, Seminar in Institute of Theoretical Physics, (Chinese Academy of Sciences), Beijing, China, Apr. (2014).

(Domestic Conference)
中務孝: “原子核密度汎関数理論の概要”, サマースクール「クォークから超新星爆発まで」, (京都大学基礎物理学研究所, 計算基礎科学連携拠点, HPCI 戦略プログラム分野 5「物質と宇宙の起源と構造」), 京都, 7月 (2014).

- 453 -
Strangeness Nuclear Physics Laboratory

Publications

[Journal]
(Original Papers) *Subject to Peer Review
Hiyama E., Ohnishi S., Gibson B., Rijken T.,
“Three-body structure of the nn Λ system with AN·ΣN coupling”, Physical Review C, 89, 061302(R) (2014). *
Zhou B., Funaki Y., Tohsaki H., Horiuchi H., Ren Z.,
“The container picture with two-alpha correlation for the ground state of 12C”, Progress of Theoretical and Experimental Physics, 101D01(7pages) (2014). *
Funaki Y., Yamada T., Hiyama E., Zhou B., Ikeda K.,
“The container structure of alpha-alpha-Lambda clusters in 9-Lambda-Beryllium”, Progress of Theoretical and Experimental Physics, 113D01(16pages) (2014). *
Roepke G., Schuck P., Funaki Y., Horiuchi H., Roepke G., Schuck P., Tohsaki A., Xu C., Yamada T.,
Homma H., Isaka M., Kimura M.,
Sakumichi N., Suganuma H.,
“Perfect Abelian dominance of quark confinement in SU(3) QCD”, Physical Review D (Rapid communication), 90, 111501 (2014). *
Ikeda T.N., Sakumichi N., Polkovnikov A., Ueda M.,
“The second law of thermodynamics under unitary evolution and external operations”, Annals of Physics, 354, 338 (2015). *
Lu BN., Hiyama E., Sagawa H., Zhou SG.,
“Superdeformed Λ hypernuclei within relativistic mean field models”, Physical Review C, 89, 044307 (2014). *
Hiyama E., Kamimura M.,
“Universality in Efimov-associated tetramers in 4He”, Physical Review A, 90, 052514 (2014). *
Schulze HJ., Hiyama E.,
Hu J., Hiyama E.,Toki H.,
Suno H., Eary BD.,
Suno H., Suzuki Y., Descouvemont P.,

(Book · Proceedings)

(Others) *Subject to Peer Review
Isaka M.,

Oral Presentations

(International Conference etc.)
Hiyama E.,

Hiyama E.,
“Structure of light Lambda hypernuclei by (e, eK+) reaction”, JLab Workshop on hypernuclear physics “Perspectives of high resolution hypernuclear spectroscopy at Jlab”, Newport News, VA, USA, May (2014).

Hiyama E.,

Hiyama E.,

Hiyama E.,

Hiyama E.,

Hiyama E.,
“Structure of few-body hypernuclei”, Fourth Joint...

Hiyama E.,

Hiyama E.,

Hiyama E.,

Funaki Y.,

Funaki Y.,

Funaki Y.,

Isaka M.,

Isaka M.,
“Deformations of sd and pf shell Lambda hypernuclei with antisymmetrized molecular dynamics”, JLab Workshop on hypernuclear physics “Perspectives of high resolution hypernuclear spectroscopy at Jlab”, Newport News, VA, USA, May (2014).

Isaka M.,

Isaka M., Homma H., Kimura M.,

Isaka M.,

Isaka M.,

Isaka M., Kimura M., Hiyama E., Sagawa H.,

Isaka M.,

Isaka M.,

Ohnishi S., Ikeda Y., Hyodo T., Hiyama E., Weise W.,

Ohnishi S., Ikeda Y., Hyodo T., Hiyama E., Weise W.,

Ohnishi S., Ikeda Y., Hyodo T., Hiyama E., Weise W.,

Togashi H., Takehara Y., Yamamuro S., Nakazato K., Suzuki H., Sumiyoshi K., Takano M.,

Togashi H., Takehara Y., Yamamuro S., Nakazato K., Suzuki H., Sumiyoshi K., Takano M.,

Togashi H., Hiyama E., Takano M., Yamamoto Y.,

Togashi H., Hiyama E., Takano M., Yamamoto Y.,

Maeda S., Yokota A., Hiyama E., Oka M., Liu YR., Fukukawa K.,

Yoshida T., Oka M., Hosaka A., Hiyama E., Sadato K.,

Yoshida T., Oka M., Hosaka A., Hiyama E., Sadato K.,
"P-wave heavy baryons in the constituent quark model", Workshop "Charm Hadron and Nuclear Physics", Tokyo, Japan, Nov. (2014).

Yoshida T., Oka M., Hosaka A., Hiyama E., Sadato K.,

肥山詠美子： "変分法の一般論と無限小変位ガウスローブ底関数展開法,	
 	
 少数核子系、及び不安定核物理への応用,	
 	
 ハドロン物理への応用,	
 	
 ハイパー核物理の応用と J-PARC を視野に入れた将来の展望", 少数多体系物理の最前線, 大阪,
 11 月(2014).

肥山詠美子： "ミクロな世界の 3 体・4体問題へのいざない", 理化学研究所 科学講演会 2014,
 東京, 11 月(2014).

肥山詠美子： "厳密少数多体系計算法の確立とその展開", 第 922 回九大原子核セミナー,
 福岡, 1 月(2015).

井坂政裕: "AMD, hyper核理論	
 ~AMDによるハイパー核の構造研究~
, ストレノジネスを含む原子核に関わる研究会 	\-	
 課題と挑戦\-	
, 和光, 6 月(2014).

井坂政裕, 福川賢治,
木村真明,
肥山詠美子,
佐川弘幸,
山本安夫:
"反対称化分子動力学よるA~40 のΛハイパー核の超変形状態", ダブルストレンジネス核物理研究会,
 岐阜, 9 月(2014).

井坂政裕:
"AMD による s d p f 殻Λハイパー核の変形態の研究", "ストレンジネスを含む原子核の最近の展開", 研究会, 静岡, 9 月(2014).


吉田哲也, 岡真, 佐保淳, 肥山詠美子, 定藤克法: "P-wave heavy baryons in the constituent quark model", Hadron Spectroscopy Café（東京工業大学）, 東京, 5 月(2014).

Mathematical Physics Laboratory

Publications

[Journal] (Original Papers) *Subject to Peer Review


(Internal Conference)

Oral Presentations


Kimura T., “FQH/CFT and its deformation” University of Crete HEP seminar, (Crete Center for Theoretical Physics, University of Crete), イラクリオン, ギリシャ, Nov. (2014).
Radiation Laboratory

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Kanesue T, Fuwa Y, Kondo K, Okamura M, ”Las Ion source with solenoid field”, APPLIED PHYSICS LETTERS, 105, 193506 (2014) *


(Review) *Subject to Peer Review

Akiba Y, ”Quest for the quark-gluon plasma — hard and electromagnetic prolbles”, Progress of theoretical and experimental physics 09A105(2015), 2015/01/12 *

[Book • Proceedings]
(Original Papers)


(Review)


Oral Presentations

(International Conference etc.)
Yasuyuki Akiba, "Future plan at BNL", Hadron physics symposium (研核費新学術領域「新ハドロン」), Nagoya, Japan, 2014/4/18

Yasuyuki Akiba, "Electromagnetic probes and heavy flavor from RHIC and LHC", Hawaii 2014 (Fourth Joint Meeting of the Nuclear Physics Division of the American Physical Society and the Physical Society of Japan) (APS/JPS), Waikoloa Village, HI, USA, 2014/10/7

Ralf Seidl, "W to mu measurements at PHENIX", Conference on Deep inelastic scattering and related topics, Warsaw, Poland, 2014/05/29

Ralf Seidl, "Three-Dimensional Imaging and Spin - from Valence Quarks to the Sea", Hawaii 2014 (Fourth Joint Meeting of the Nuclear Physics Division of the American Physical Society and the Physical Society of Japan) (APS/JPS), Waikoloa Village, HI, USA, 2014/10/7

T. Kanesue, "THE COMMISSIONING OF THE LASER ION SOURCE FOR RHIC EBIS", 5th International Particle Accelerator Conference (Cockcroft Inst. and U. Liverpool), Dresden, Germany, 2014/06/15-16

Y. Fuwa, "Charge-State Selective Ion Beam Acceleration with RFQ Linac", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

T. Kanesue, "Stable operation of Laser Ion Source for low charge state ion production", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

Shunsuke Ikeda, "Control of plasma flux with pulsed solenoid for laser ion source", 5th International Particle Accelerator Conference (Cockcroft Inst. and U. Liverpool), Dresden, Germany, 2014/06/15-16

N. Munemoto, "LASER ABLATION ION SOURCE FOR THE KEK DIGITAL ACCELERATOR", 5th International Particle Accelerator Conference (Cockcroft Inst. and U. Liverpool), Dresden, Germany, 2014/06/15-20

M. Okamura, "Preliminary result of rapid solenoid for controlling heavy-ion beam parameters of laser ion source", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

Y. Fuwa, "Beam dynamics of multi charge state ions in RFQ linac", 27th Linear Accelerator Conference (CERN), Geneva, Switzerland, 2014/08/31-09/05

M. Okamura, "Low Charge Laser Ion Source for the EBIS injector", 27th Linear Accelerator Conference (CERN), Geneva, Switzerland, 2014/08/31-09/05

Shunsuke Ikeda, "Influence of solenoidal magnetic field on laser ablation plasma", 5th Euro-Asian Pulsed Power Conference (Kumamoto Univ.), Kumamoto, Japan, 2014/09/11


Satoshi Yokkaichi, "Measurement of vector mesons in nuclei at J-PARC E16 experiment", Hadrons and Hadron Interactions in QCD 2015 (YITP), Kyoto, Japan 2015/03/05

(Related Conference etc.)

Ralf Seidl, "Experimental overview: Nucleon spin structure", APS Division of Nuclear Physics (APS) Temple University, Philadelphia, PA, USA 2014/9/13,


秋葉康之, "RHIC PHENIX 実験とその将来計画", 第 1 回 GIRSE ワークショップ (筑波大学数理物質融合科学センター), 筑波大学, つくば市, 2015/3/12

Kotaro KONDO 大電流レーザーイオン源にむけた重金属標的を用いたレーザーアブレーションプラズマの価数分析日本原子力学会 2014 年秋の大会京都大学, 京都 2014/09/08-10

池田峻輔, "レーザーアブレーションプラズマに対するバルス磁場の影響", 日本物理学会第 70 回年次大会早稲田大学, 東京, 2015/3/21-24

熊木雅史" ピコ秒レーザーを用いたレーザーイオン源開発" 日本物理学会第 70 回年次大会早稲田大学, 東京 2015/3/21-24

村上ひかり, “チェレンコフ検出器用 CsI GEM の開発”, 第 11 回 MPGD 研究会 (東北大学), 東北大学, 仙台, 2014/12/20

中井 恒, “J-PARC E16 実験における GEM 検出器の開発状況”, 第 11 回 MPGD 研究会 (東北大学), 東北大学, 仙台, 2014/12/20
Advanced Meson Science Laboratory

Publications

[Journal]


Adare A., Ohnishi H. et al. (PHENIX Collaboration)

Adare A., Ohnishi H. et al. (PHENIX Collaboration)


Adler S.S., Ohnishi H. et al. (PHENIX Collaboration)


Cargnello M., Iwasaki M., SIDDHARTA collaboration, "X-ray spectroscopy of kaonic atoms at SIDDHARTA“, EPJ Web Conf. 73 (2014) 05008*


Hashimoto T. et al. (J-PARC E15 collaboration),


Ishiwatari T., Iwasaki M., Okada S. et al. (SIDDHARTA Collaboration), "New precision era of experiments on strong interaction with strangeness at DAFNE/LNF-INFN", EPJ Web Conf. 66 (2014) 05016


Nishimura K., Matsuda K., Komaki Y., Nunomura N., Wenner S., Holmeastad R., Matsuzaki T., Watanabe I., Pratt F.L., and Marioara C.D., "µSR Study of Al-0.67%
Oral Presentations

(Internal Conference etc.)


Itahashi K., "Precision measurement of deeply bound pionic Sn atoms in RIBF", EXA14, Vienna, Sep. (2014)

Itahashi K., "High precision systematic measurement of deeply bound pionic p atoms", 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, Oct. (2014)


Tanaka Y.K., "Search for η mesic nuclei with (p,d) reaction at GSI", 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, Oct. (2014)

Tanaka Y.K., "Eta’ mesic nucleus spectroscopy with (p,d) reaction at GSI", 20th Particles and Nuclei International Conference (PANIC2014), 25-29, August, 2014, Hamburg, Germany


Abdel-Jawad M.M., 渡邊功雄, 石井康之, 今野真雅, 加藤雅恒, "Universality Class Of The Mott Transition In EtMe3P[Pd(dmit)2]",International Conference on Synthetic Metals ICSM2014, Turku, インターナディアル, 2014 年 6月

足立匡, 高橋智, 鈴木謙介, Baqiya M.A., 今野巧也, 高松智寿, 加藤雅恒, 渡邊功雄, 幸田章宏, 宮崎正範, 門野良典, 小池洋二, "μSR からみた過剰 
Kμ0 中間子原子核探索の最近の進展", 日本物理学会大 96 回年次大会, 東海大学, 湘南キャンパス, 3月(2014) 


佐藤将春, 板橋健太, 岩崎雅彦, 應田治彦, 天谷健一, "La2-xSrxCu1-yAlyO4 のオーバードープ領域におけるス 

c(0.1) 単結晶における超導相, コラボレート 

田中良樹, 細田克承, 田畑吉計, "逆運動学によるパイ中間子原子分光のための重 

"J-PARC ミュオン g-2/EDM 精密測定実験のためのミュ 

でのオーバードープ領域における超 

H2 \rightarrow \text{EDM} 上の超 

J-PARC E15 の実験における K 中間子原子核探索の最近の進展", 新学術研究領域「実験と観測で解き明かす中性子 

実験における K 中間子原子核探索の最近の進展", 新学術研究領域「実験と観測で解き明かす中性子原子核」 

小池洋二: "μSR からみた過剰 Kμ0 中間子原子核探索の最近の進展", 日本物理学会第69回年次大会, 東海大学, 湘南 


佐藤将春, 板橋健太, 岩崎雅彦, 應田治彦, 天谷健一, "La2-xSrxCu1-yAlyO4 のオーバードープ領域におけるス 

が示すフェリ磁性の He, による圧力効果", 日本物理
**RBRC Theory Group**

**Publications**

<table>
<thead>
<tr>
<th>Journal</th>
<th>(Original Papers)</th>
<th>Subject to Peer Review</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liao J.: Anomalous transport effects and possible environmental symmetry violation in heavy-ion collisions&quot;, Pramana Volume 84 Issue 5 Article 901, 2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lin, S, Robert D. Pisarski, Vladimir V. Skokov: &quot;Collisional energy loss above the critical temperature in QCD&quot;, Physics Letters B Volume 730, Pages 236242, 2014/03/07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K. Kashiwa, A. Monnai: &quot;Quark contribution for center domain in heavy ion collisions&quot;, Physical Review D Rapid Communications Volume 89 Issue 1 Article 011501 Page 1-5, 2014/01/07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Monnai: &quot;$T$ Thermal photon $\nu_\beta$ with slow quark chemical equilibration&quot;, Physical Review C Rapid Communications Volume 90 Issue 2 Article 021901 Page 1-5, 2014/08/11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamberg L, Kang Z-B, Metz A, Pitonyak D, Prokudin A.: Left-right spin asymmetry in $\ell N^\tau \rightarrow hX$, Physical Review D Volume 90 Issue 7 Article 074012 Page 1-12, 2014/10/01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satow D, Yee H.-U.: &quot;Chiral Magnetic Effect at Weak Coupling with Relaxation Dynamics&quot;, Physical Review D Volume 90 Issue 1 Article 014027 Page 1-12, 2014/07/17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Books, Proceedings**

**(Books)**


**(Original Papers)**

- A. Monnai: "Effects of quark chemical equilibration on thermal photon elliptic flow", Journal of Physics: Conference Series Volume 612 Article 012026 Pages 1-4 2015/05/19

**Oral Presentations**

**(International Conference etc.)**

- Bezrukov F: "Higgs Inflation - relating particle physics
Bezrukov F: “Higgs inflation and large gravity waves – status and predictivity”, QUARKS-2014 Suzdal, Russia, 2014/06/05.
Liao, J: Condensed Matter Physics of Strong Interaction”, Six Lectures for Advanced Summer Course Physics Department, Fudan University, Shanghai, China, 2014/07/28.
Liao, J: Geometry & Physics of Jet Quenching, and What We Can Learn from Heavy Flavor”, The 1st HFT+ Meeting of STAR Collaboration UIC, Chicago, Illinois, USA, 2014/12/01.
Liao, J: Theoretical Summary on QGP at RHIC and LHC and Future”, Joint JPA/APS DNP Annual Full Meeting 2014 Big Island, Hawaii, USA, 2014/10/07.
Liao, J: Jet Tomography of Fluctuating Initial Conditions and the Opaqueness Evolution from RHIC to LHC”, Plenary Talk at ATHIC 2014 Osaka, Japan, 2014/08/06.
Lin, S: “Photon suppression and dilepton enhancement in semi-QGP”, Quark Matter 2014 Darmstadt, Germany, 2014/05/19.
A. Monnai: "Effects of quark chemical equilibration on thermal photon $v_2$", Extreme QCD 2014 Stony Brook University, New York, USA, 2014/06/21.
A. Monnai: "Quark chemical equilibration and thermal photons in heavy-ion collisions", RIKEN Symposium/iTHES Workshop "Thermal Quantum Field Theory and Their Applications" RIKEN, Wako, Japan, 2014/09/05.
Pitonyak, D: $A_N$ in proton-proton collisions and the role of twist-3 fragmentation, Transversity Workshop Cagliari, Italy, 2014/06/11.
Pitonyak, D: Transverse single-spin asymmetries in proton-proton collisions within collinear factorization, QCD Evolution Workshop Santa Fe, NM, 2014/13/05.
Pitonyak, D: Towards an understanding of transverse single-spin asymmetries in proton-proton collisions, RBRC Brain Workshop BNL, Upton, NY, 2014/13/03.
Yee, H.-U: "Chiral Magnetic and Vortical Effects at Weak Coupling", Extreme QCD (XQCD) Stony Brook University, New York, USA, 2014/06/19.
Yee, H.-U: "Interplay of QCD with Electromagnetism in Heavy-ion Collisions", QCD Long Range Plan Town
Yee, H.-U: "Aspects of Chiral Magnetic and Vortical Effects at Weak Coupling", BNL Nuclear Seminars Brookhaven National Laboratory, Upton New York, USA, 2014/10/17
RBRC Computing Group

Publications

[Journal] (Original Papers) *Subject to Peer Review

Thomas Blum, Masashi Hayakawa, and Taku Izubuchi, : "Hadronic light-by-light scattering contribution to the muon anomalous magnetic moment from lattice QCD", Physical Review Letters Volume 114 Issue 1 Article 012001, 2014/07/10 *


Ethan Neil, Alexei Bazavov et al. (Fermilab Lattice and MILC Collaborations): “Determination of |V_{us}| from a lattice-QCD calculation of the K → πν semileptonic form factor with physical quark masses”, Physical Review Letters Vol. 112, no. 11, 112001 2014/03/17 *

Ethan Neil, Thomas Appelquist et al. (LSD Collaboration): “Composite bosonic baryon dark matter on the lattice: SU(4) baryon spectrum and the effective Higgs interaction”, Physical Review D Vol. 89, no. 9, 094508 2014/05/28 *

Ethan Neil, Jon A. Bailey et al. (Fermilab Lattice and MILC Collaborations): “Update of |V_{cb}| from the B → D^{(*)}lν form factor at zero recoil with three-flavor lattice QCD”, Physical Review D Vol. 89, no. 11, 114504 2014/06/19 *


Ethan Neil, Alexei Bazavov et al. (LSD Collaboration): “Charmed and light pseudoscalar meson decay constants from four-flavor lattice QCD with physical light quarks”, Physical Review D Vol. 90, no. 7, 074509 2014/10/30 *

Ethan Neil, Thomas Appelquist et al. (LSD Collaboration): “Lattice simulations with eight flavors of domain wall fermions in SU(3) gauge theory”, Physical Review D Vol. 90, no. 11, 114502 2014/12/12 *


Tiburzi, B: "Neutron in a strong magnetic field: Finite volume effects", Physical Review D Volume 89 Issue 7 Article 074019 Page 1-22, 2014/04/08 *

Tiburzi, B: "Finite volume effects on the extraction of form factors at zero momentum", Physical Review D Volume 90 Issue 5 Article 054008 Page 1-15, 2014/09/23 *
Lee, J-W, Tiburzi, B: "Reconciling the lattice background field method with nonrelativistic QED: Spinor case", Physical Review D Volume 90 Issue 7 Article 074036 Page 1-16, 2014/10/29 *


[Book, Proceedings]

(Original Papers)


N. Christ et al. [RBC and UKQCD Collaborations], "Calculating the K_L - K_S mass difference and epsilon_K to subpercent accuracy," PoS LATTICE 2013, 397 (2014)


T. Blum et al. [RBC and UKQCD Collaborations], "Weak Decay Measurements from 2+1 flavor DWF Ensembles," PoS LATTICE 2013, 404 (2014).


Lin,M et. al: "Accelerating Ab Initio Nucleon Structure Calculations with All-Mode-Averaging on Gordon" XSEDE2014 proceedings


Ethan Neil, Alexei Bazavov et al. (Fermilab Lattice and MILC Collaborations): “The D_s, D^*, B_s and B decay constants from 2+1 flavor lattice QCD”, PoS LATTICE 2013, 394 (2014).

Ethan Neil, Elvira Ganiz et al. (Fermilab Lattice and MILC Collaborations): “Kaon semileptonic form factors with N_f = 2 + 1 + 1 HISQ fermions and physical light quark masses”, PoS LATTICE 2013, 395 (2014).


**Oral Presentations**

(Internal Conference etc.)

Blum, T: "Hadronic contributions to the muon g-2", Conference XI (St. Petersburg) St. Petersburg, Russia, 2014/09/13.

Blum, T: "Lattice calculation on the nucleon EDM", BNL HET lunch seminar BNL, USA, 2014/08/8.

Blum, T: "Lattice calculations of the Hadronic contributions to the muon g-2", 5th International Symposium on LEPTON MOMENTS Cape Cod, MA, USA, 2014/07/24.

Blum, T: "Fundamental Parameters I: Quark Masses", FLAG-Mad, Instituto de Física Teórica UAM/CSIC Madrid, Spain, 2014/05/24.

Blum, T: "Summary and Perspectives of Lattice QCD", Hadronic contributions to the muon anomalous magnetic moment: strategies for improvements of the accuracy of the theoretical prediction UTIP, Walthausen Castle, Mainz, Germany, 2014/04/05.

Christ, N: "Chiral fermions and precision lattice field theory", PPCM 2014, Boston University, May 8-10, 2014 http://blogs.bu.edu/ppcm/


Christ, N: “Computing K → &pi;pi decay and the KL KS mass difference using lattice QCD”, the University of Maryland, May 12, 2014.


Izbuchi, T: “Supercomputing Fundamental Particle & Nuclear Physics” BNL Lecture BNL, Upton, NY September 2014

Izbuchi, T: “Lattice QCD calculations for particle physics” XXVI IUPAP Conference on Computational Physics Boston University,Boston, MA 2014/08/11-14.


Izbuchi, T: "Hadronic Vacuum Polarization for muon g-2" Lattice QCD Meets Experiment 2014 Fermi National Laboratory, Batavia, IL 2014/03/08.

Christopher Kelly: "Light hadronic physics from lattice QCD at the physical point", RBRC lunch seminar BNL, Upton, NY, USA, 2014/01/31.


Lehner, C "Perspectives in lattice B physics" HET/RIKEN Lunch Seminar BNL, Upton, NY 2014/02/07

Lehner, C "Towards the large volume limit" Lattice 2014 New York, NY 2014/06/27

Lehner, C "Analytic Methods for Precise Predictions" Lattice Meets Continuum Siegen, Germany 2014/10/01

Lehner, C "Bloch’s theorem and QCD+QED simulations" HET lunch seminar BNL,Upton, NY 2014/11/21

Lin, M "Nucleon structure on the lattice: Approaching the physical limit" High Energy Theory/RIKEN Lunch Seminar BNL, Upton, NY 2014/03/28

Lin, M "Computational Issues in BSM Theories Past, Present and Future" Field Theoretic Computer Simulations for Particle Physics and Condensed Matter Boston University Center for Computational Science Boston, MA 2014/05/08

Lin, M Multigrid HMC” The Eighth International Workshop on Numerical Analysis and Lattice QFT Yale University, Yale, CT. 2014/06/20

Lin, M "Application of Adaptive Multigrid Algorithm in Hybrid Monte Carlo Simulations" The 32nd International Symposium on Lattice Field TheoryColumbia University, NY 2014/06/23

S. Meinel: "Lattice QCD and the search for new physics using beauty quarks", APS Four Corners Section Meeting, Utah Valley University, Utah, 2014/10/18.

Ethan Neil: "Bayesian Methods for Parameter Estimation from LAttice Simulations", Eighth International Workshop on Numerical Analysis and Lattice QFT, Yale University, New Haven, CT 2014/06/21

Ethan Neil: "Leptonic B and D decay constants with 2+1 flavor asqtad fermions", XXXII International Symposium on Lattice Field Theory, Columbia University, New York, NY 2014/06/25

Shintani,E "Accurate calulation of nucleon form factor in lattice QCD” the 4th Joint Meeting of the APS Division
of Nuclear Physics and the Physical Society of JapanOctober 7-11, 2014 Waikoloa, Hawaii.
Shintani, E "Symmetry on honeycomb lattice formulation", 11th Quark confinement and Hadron spectrum XI, 7-12 September 2014, St. Petersburg.
Shintani, E "Hadronic contributions to the muon anomalous magnetic moment: strategies for improvements of the accuracy of the theoretical prediction", Working group in lattice QCD, MITP workshop, 1-5 April 2014, Waldhausen Castle near Mainz.
Shintani, E "αs from the lattice", High precision fundamental constants at the TeV scale, March 10-21, 2014, JGU Campus Mainz.
Tiburzi, B: "Neutron in a strong magnetic field and effects from finite volume", Theory seminar Maryland Center for Fundamental Physics, College Park, Maryland USA 2014/03/13
Tiburzi, B: "A smaller size for the proton?", Physics department colloquium Amherst College, Amherst, Massachusetts USA 2014/04/03
Tiburzi, B: "Four lectures on effective field theories", National nuclear physics summer school College of William and Mary, Williamsburg, Virginia USA 2014/06/09
Tiburzi, B: "Towards exploring parity violation with lattice QCD", Workshop on Bound states and resonances in effective field theories and lattice QCD calculations Centro de Ciencias de Benasque Pedro Pascual, Benasque, Spain 2014/07/30
Tiburzi, B: "The prospects for two-photon physics with lattice QCD", Town Hall Meeting, American Physical Society, Division of Nuclear Physics Temple University, Philadelphia, Pennsylvania USA 2014/09/14 (Domestic Conference etc.)
Izubuchi, T: “Study of the nucleon structure by lattice QCD” Physical Society of Japan Joint symposium among experimental nuclear, theoretical nuclear, experimental particle, and theoretical particle physics, Latest results and future programs on the nucleon structure - Toward an understanding of the nucleon spin - JPS Symposium Tokai University, Kanagawa, Japan 2014/03/30

Poster Presentations
(International Conference etc.)
Shintani, E "Precise lattice calculation of nucleon form factor with all-mode-averaging", 11th Quark confinement and Hadron spectrum XI, 7-12 September 2014, St. Petersburg.
Shintani, E "Improved statistics of proton decay matrix element", the 32st International Symposium on Lattice Field Theory 23-28 June 2014, Columbia University, NY
T.Blum T. Izubuchi (for USQCD Collaboration), “All mode averaging and calculations of the muon anomalous magnetic moment, (g − 2)μ”, SciDAC PI meeting, September 2014, Washington D.C., MD
RBRC Experimental Group

Publications

[Journals]
(Original Papers) *Subject to Peer Review


Adare A., et al. PHENIX Collaboration, “Measurement of \( K_{S}^{0} \) and \( K^{\pm} \) in p+p, d+Au and Cu+Cu collisions at \( \sqrt{s_{NN}}=200 \) GeV”, Phys. Rev. C 90, 054905 (2014). *


(Review) *Subject to Peer Review

Akiba Y, ”Quest for the quark-gluon plasma — hard and electromagnetic probes”, Progress of theoretical and experimental physics 03A105(2015), 2015/01/12 *

[Book • Proceedings]

(Original Papers)


Oral Presentations


**Oral Presentations**

(International Conference etc.)

Yasuyuki Akiba, "Future plan at BNL", Hadron physics symposium (科研費新学術領域「新ハドロン」), Nagoya, Japan, 2014/4/18

Yasuyuki Akiba, "Electromagnetic probes and heavy flavor from RHIC and LHC", Hawaii 2014 (Fourth Joint Meeting of the Nuclear Physics Division of the American Physical Society and the Physical Society of Japan) (APS/JPS), Waikoloa Village, HI, USA, 2014/10/7

Ralf Seidl, "W to mu measurements at PHENIX", Conference on Deep inelastic scattering and related topics, Warsaw, Poland, 2014/05/29

T. Kanesue, "THE COMMISSIONING OF THE LASER ION SOURCE FOR RHIC EBIS", 5th International Particle Accelerator Conference (Cockcroft Inst. and U. Liverpool), Dresden, Germany, 2014/06/15-16

Y. Fuwa, "Charge-State Selective Ion Beam Acceleration with RFQ Linac", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

T. Kanesue, "Stable operation of Laser Ion Source for low charge state ion production", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

Shunsuke Ikeda, "Control of plasma flux with pulsed solenoid for laser ion source", 5th International Particle Accelerator Conference (Cockcroft Inst. and U. Liverpool), Dresden, Germany, 2014/06/15-16

M. Okamura, "Preliminary result of rapid solenoid for controlling heavy-ion beam parameters of laser ion source", 20th International Symposium on Heavy-Ion Inertial Fusion (IMP), Lanzhou, China, 2014/08/11-15

Y. Fuwa, "Beam dynamics of multi charge state ions in RFQ linac", 27th Linear Accelerator Conference (CERN), Geneva, Switzerland, 2014/08/31-09/05

M. Okamura, "Low Charge Laser Ion Source for the EBIS injector", 27th Linear Accelerator Conference (CERN), Geneva, Switzerland, 2014/09/21-09/24

Shunsuke Ikeda, "Influence of solenoidal magnetic field on laser ablation plasma", 5th Euro-Asian Pulsed Power Conference (Kumamoto Univ.), Kumamoto, Japan, 2014/09/11


(Domestic Conference etc.)

秋葉康之, "RHIC PHENIX 実験とその将来計画", 第 1 回 CiRiSE ワークショップ (筑波大学数理物質融合科学センター), 筑波大学、つくば市, 2015/3/12

池田峻輔, "レーザーアプレーションプラズマに対するバルス磁場の影響", 日本物理学会第 70 回年次大会, 早稲田大学, 東京, 2015/3/21-24

熊本雅史" ピコ秒レーザーを用いたレーザーイオン源開発" 日本物理学会第 70 回年次大会早稲田大学, 東京 2015/3/21-24
Radioactive Isotope Physics Laboratory

Publications

[Journal]

(Original Papers) *Subject to Peer Review


- 477 -


Warr N., Blazhev A. and Moschner K.: "Simulations of the SIMBA array towards the determination of Q8 values"  EPJ Web Conf. 93, 07008 (2015)


Wang H., "In-beam gamma-ray spectroscopy and cross section measurement strategy for long-lived fission products at RIBF", Proceedings of the 2014 Symposium on Nuclear Data(*Subject to Peer Review)


Oral Presentations

H. Sakurai: "Emergence of Exotic Phenomena in Unstable Nuclei “how to observe them”, International School of Nuclear Physics in Erice, Sicily, Italy, September (2014) Invited Talk


Nishimura S.: Decay spectroscopy of exotic nuclei with EURICA and RIBF", Fifteenth International


Nishimura S.: “Decay Properties of Exotic Nuclei and their Impacts to the r-process Nucleosynthesis” International Conference for Advances in Radioactive Isotope Science (ARIS2014), Tokyo, Japan, June 1-6 (2014). Invited Talk


Pieter Doornenbal: "Perspectives for In-Beam Gamma-Ray Spectroscopy at the RIBF", Invited talk at the JPS Spring Meeting, Waseda Univ., Japan, March (2015)


Pieter Doornenbal: "In-Beam Gamma-Ray Spectroscopy with Fast Beams Around the 'Island of Inversion'", Invited talk at ISPUN14, Ho Chi Minh City, Vietnam, November 3th - 8th (2014)

Pieter Doornenbal: "In-Beam Gamma-Ray Spectroscopy of Fast Exotic Beams at the RIBF", Invited talk at the 4th Joint APS-JPS Meeting, Hawaii, USA, October 7th - 11th (2014)

Pieter Doornenbal: "Overview of In-Beam Gamma-Ray Spectroscopy at the RIBF", Invited talk at CGS15, Dresden, Germany, August 25th - 29th (2014)

Pieter Doornenbal: "Overview of In-Beam Gamma-Ray Spectroscopy at the RIBF", Invited talk at the Zakopane Conference on Nuclear Physics, Poland, August 31st - September 7th (2014)


Pieter Doornenbal: "AGATA@RIBF", Oral Presentation at the 4th EGAN Workshop, Darmstadt, Germany, June 23rd - 26th (2014)


Isobe T., “SPIRIT project for the study of density dependent symmetry energy of high dense matter with Heavy RI collisions at RIBF”, 4th International Symposium on the Nuclear Symmetry Energy NuSYM14, University of Liverpool, UK, 7-9 July 2014.


Isobe T., “SPIRIT-TPC with GET readout electronics for the study of density dependent symmetry energy of high dense matter with Heavy RI collisions”, APS/DNP 4th joint meeting @HAWAII, Hawaii, USA, 7-11 Oct. 2014.


H. Sakurai, “Current Status and Future of RIBF My Very Personal Perspectives” (招待講演), RIBF Theory Forum Workshop, Wako, August (2014)

原子力システム成果報告会、東京、2015年1月

M. Kurata-Nishimura: “Status Of the SPIRIT Time Projection Chamber”


磯部忠昭, “自由自在にモノ (物質) を変えられるとしたら、何を何に変えたいですか?”, 日本科学未来館サイエンティスト・クエスト, 日本科学未来館, 27 Mar. 2015

http://www.miraikan.jst.go.jp/event/1503031418003.html


Spin Isospin Laboratory

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Sagawa, H. and Colò, G.: “Tensor interaction in mean-field and density functional theory approaches to nuclear structure”, Progress in Particle and Nuclear Physics, 76, 76-115(2014).*


Tanimura, Y. and Sagawa, H. and Horigo, K.: “Three-body model calculations for N = Z odd-odd nuclei with T=0 and T=1 pairing correlations” Progress of Theoretical and Experimental Physics, 5, 053D02(2014).*

Nuclear Spectroscopy Laboratory

Publications

[Journal]
(Original Papers) *Subject to Peer Review

[Review]

[Book • Proceedings]
(Original Papers) *Subject to Peer Review

Oral Presentations
(International Conference etc.)


Ueno H.: “Research Activities at RIBF”, Internaional Workshop on Progress in nuclear shell-model calculations in CNS-RIKEN collaboration, (Center for Nuclear Study, the University of Tokyo and RIKEN Nishina Center), Wako, Japan, Nov. (2014).


(UW Simons Center)  
(UW Simons Center)
鈴木貴大，近森正敏，彦田絵里，土屋真人，古川武，
吉見彰洋，猪野隆，上野秀樹，松尾由賀利，福山武志，旭
耕一郎： "一様磁場環境下での $^{129}$Xe/$^3$He 同時メーザー発
振", 日本物理学会第 70 回年次大会, (日本物理学会), 東京
都新宿区, 3 月 (2015).

小島修一郎，佐藤智哉，市川雄一，大友祐一，坂本雄，舟山
智歌子，平尾千佳，菅野雄輝，小峰太郎，鈴木貴大，近森
正敏，彦田絵里，土屋真人，古川武，吉見彰洋，Bidinosti
C. P., 猪野隆，上野秀樹，松尾由賀利，福山武志，旭
耕一郎： "ダブルセルにおける $^{129}$Xe/$^3$He 核スピンメー
ザーゼの周波数特性", 日本物理学会第 70 回年次大会, (日本
物理学会), 東京都新宿区, 3 月 (2015).

佐藤智哉，市川雄一，大友祐一，坂本雄，小島修一郎，舟山
智歌子，平尾千佳，菅野雄輝，小峰太郎，鈴木貴大，近森
正敏，彦田絵里，土屋真人，古川武，吉見彰洋，Bidinosti
C. P., 猪野隆，上野秀樹，松尾由賀利，福山武志，旭
耕一郎： $^3$He 共存磁力計の導入による $^{129}$Xe 原子 EDM
測定実験 IV", 日本物理学会第 70 回年次大会, (日本物理學
会), 東京都新宿区, 3 月 (2015).

西村太樹，金野峻平，田口義眞，千葉順成，藤田佳孝，阿部
康介，馬場秀成，福田茂一，木間彰，保高寿也，市川雄一
，京川健司，神戸篤輔，髙川直樹，北川淳志，小島拓実，
小島和佳，吉浦新司，劉昌，松本健策，三原基嗣，水上
淳，森田修介，室岡大樹，長島正幸，大野淳一，大坪隆，
鈴木伸司，佐藤真司，田中聖臣，田代圭佑，若林優，渡邉
大，吉永健太，朱易帆： "超許容ベータ崩壊核 $^{34}$Ar の精
密分岐比測定 III", 日本物理学会第 70 回年次大会, (日本
物理学会), 東京都新宿区, 3 月 (2015).

大友祐一，市川雄一，石橋陽子，鈴木貴大，上野秀樹，今村
慧，藤田朋美，早坂美希，富永大樹，松本未来，江上魁
，古川武，佐藤智哉，坂本雄，小島修一郎，舟山智歌子，
平尾千佳，菅野雄輝，小峰太郎，旭耕一郎： "中性子過剰
核 $^5$He 同位体の偏極度および磁気モーメント測定", 日本物理
学会第 70 回年次大会, (日本物理学会), 東京都新宿区, 3 月

今村慧，古川武，涌井崇志，藤田朋美，早坂美希，富永大樹，松本未来，
江上魁，富永大樹，小島仁司，上野秀樹，松尾由賀利:
"低収量原子核の核構造研究へ向けたレーザー・RF/MW
二重共鳴信号の高強度化", 日本物理学会第 70 回年次大会,
(日本物理学会), 東京都新宿区, 3 月 (2015).

金原慎二，仲澤和馬，上野秀樹，市川雄一，吉野純也，
KhinThanTint, MyintKyawSoe, AyeMohMohTheint, 三品旭弘，伊藤宏紀，遠藤陽子，小林秀隆： "原子核乾板
を用いた荷電粒子識別法の開発", 日本物理学会第 70 回年
次大会, (日本物理学会), 東京都新宿区, 3 月 (2015).
High Energy Astrophysics Laboratory

Publications

[Journal] (Original Papers) *Subject to Peer Review
Noda, Hirofumi; Makishima, Kazuo; Yamada, Shin’ya; Nakazawa, Kazuhiro; Sakurai, Soki; Miyake, Katsuma: “Suzaku Studies of the Central Engine in the Typical Type I Seyfert NGC 3227: Detection of Multiple Primary X-Ray Continua with Distinct Properties” The Astrophysical Journal, 794, 2 (2014). *
Asami, Fumi; Enoto, Teruki; Iwakiri, Wataru; Yamada, Shin’ya; Tamagawa, Toru; Mihara, Tatehiro; Nagase, Fumiaki: “Band-play spectroscopy of Hercules X-1 with Suzaku” Publications of the Astronomical Society of Japan, 66, 44 (2014). *
Maeda, Keiichi; Katsuda, Satoru; Bamba, Aya; Terada, Yukikatsu; Fukazawa, Yasushi; “Long-lasting X-Ray Emission from Type IIB Supernova 2011dh and Mass-loss History of the Yellow Supergiant Progenitor” The Astrophysical Journal, 785, 95 (2014). *
Serino, Motoko; Sakamoto, Takenori; Kawai, Nobuyuki; Yoshida, Atsumasa; Ohno, Masanori; Ogawa, Yuji; Nishimura, Yasunori; Fukushima, Kosuke; Higa, Masaya; Ishikawa, Kazuto; Ishikawa, Masaki; Kawai-muro, Taiki; Kimura, Masashi; Matsuoka, Masaru; Mi-hara, Tatehiro; Morii, Mikio; Nakagawa, Yujin E.; Nakahira, Satoshi; Nakajima, Motoki; Nakano, Yuki; Negoro, Hitoshi; Onodera, Takuya; Sasaki, Masayuki; Shidatsu, Megumi; Sugimoto, Juri; Sugizaki, Mutsumi;
Suwa, Fumitoshi; Suzuki, Kazuhiko; Tachibana, Yutaro; Takagi, Toshihiro; Toizumi, Takahiro; Tomida, Hiroshi; Tsuboi, Yoshihiko; Tsunemi, Hiroshi; Ueda, Yoshihiro; Ueno, Shiro; Usui, Ryoichi; Yamada, Hisaki; Yamamoto, Takaaki; Yamaoka, Kazutaka; Yamauchi, Makoto; Yoshidome, Kosho; Yoshii, Taketoshi: “MAXI observations of gamma-ray bursts” Publications of the Astronomical Society of Japan, 66, 8714 (2014).* 

Broersen, Sjors; Chiotellis, Alexandros; Vink, Jacco; Bamba, Aya: “The many sides of RCW 86: a Type Ia supernova remnant evolving in its progenitor’s wind bubble” Monthly Notices of the Royal Astronomical Society, 441, 3040 (2014).* 


Misawa, Toru; Inada, Naohisa; Oguri, Masamune; Gandhi, Poshak; Horiiuchi, Takashi; Koyamada, Suzuki; Okamoto, Rina: “Resolving the Clumpy Structure of the Outflow Winds in the Gravitationally Lensed Quasar SDSS J1029+2623” The Astrophysical Journal Letters, 794, L20 (2014). *

“Discovery of Four Doubly Imaged Quasar Lenses from the Sloan Digital Sky Survey” Inada, Naohisa; Oguri, Masamune; Rusu, Cristian E.; Kayo, Issha; Morokuma, P., Takeshi; Tashiro, Makoto; Yoshikawa, Yasushi; Kamae, Tuneoyoshi; Kokubun, Motohide; Makishima, Kazuo; Mitani, Takefumi; Mizuno, Tsunemi; Nomachi, Masaharu; Tajima, Hironosu; Takahashi, Takeshi; Tamagawa, Toru; Terada, Yukikatsu; Tashiro, Makoto; Uchiyama, Yasunobu; Yoshimitsu, Totsuo: “Sub-MeV all sky survey with a compact Si/CdTe Compton telescope” Proceedings of the SPIE, 9144, 91440J (2014). 


Oral Presentations
(International Conference etc.)


Hiroyuki Noda, “A Novel Picture of the AGN Central Engine Derived with X-ray and Optical Simultaneous Observations” COSPAR 2014, Moscow, Russia, August (2014).


(Domestic Conference)
吉川英文、山田真也、野田博文、玉川徹: “すずく”衛星を用いたブラックホール連星 Cygnus X-1のHigh/soft状態のハード成分の詳細解析” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).


勝田哲、森浩二、大谷豊、常深泰、小林勝也、内藤義之、上司文善、馬場彩、山崎了、澤田真理、塩崎義雄、Petre Robert, 玉川徹: “「チャンピオン」衛星による超新星残骸RCW 86南西端の再観測” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).


岩切歩、早藤麻美、武内隆子、川原穂、北口賢貴、樫戸輝揚、吉川英文、金子健太、篠田忠、西田和樹、Keith Gendreau: “小型かつ変速型のX線高能分散実装MatroX Source(MXS)の製作と性能評価” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).

林田清, 吉永圭, キムジュヨン, 井出憲一郎, 上司文善, 穴吹直久、常深泰、司修一、柴田善平、片桐惇、中森健之、木村大輔、三原建弘、川原裕、早藤麻美、杉本樹梨、高村裕、水野恵子、高橋弘光、谷津陽一、堂谷忠靖、藤藤芳隆、吉川英文、前川秀利、岸真賢二、岸本栄二、Keith Jahoda, Joe Hill, ほか Polaris-S-WG: “X線ガンマ線偏光観測小型衛星 PolarisS: 開発の現状 XI” 日本天文学会 2014年秋季年会, (日本天文学会), 山形, 9月 (2014).

武内隆子、川原穂、北口賢貴、早藤麻美、樫戸輝揚、岩切歩、吉川英文、金子健太、篠田忠、西田和樹: “光電子追跡型X線偏光計の製作および基礎性能評価” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).

河口賢至、深沢泰司、田中康之、伊藤亮介、川端弘治、植村誠、秋田谷洋、神田浩一、村上弘志、野田博文, かなたチーム: “かなた望遠鏡による活動銀河核の可視光・X線・ガンマ線での相関の探索” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).


篠野理、樫戸輝揚、牧島一夫、堂谷忠靖、岩井将輔: “すずく”による特異な低質量星と中性子星の連星 時間変動の観測” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).

平賀純子、深沢泰司、田中康之、伊藤亮介、川端弘治、植村誠、秋田谷洋、神田浩一、村上弘志、野田博文, かなたチーム: “かなた望遠鏡による活動銀河核の可視光・X線・ガンマ線での相関の探索” 日本天文学会 2014 年秋季年会, (日本天文学会), 山形, 9月 (2014).


篠野理、樫戸輝揚、牧島一夫、堂谷忠靖、岩井将輔: “すずく”による特異な低質量星と中性子星の連星 GRO J1744-28の観測” 日本天文学会 2014年秋季年会, (日本天文学会), 山形, 9月 (2014).

牧島一夫、樫戸輝揚、中澤知洋、平野真子、中倉俊男、篠野理、樫戸輝揚、上司文善、上田浩章: “マグネター 4U 0142+61における自転差動風の観測 II” 日本天文学会 2014年秋季年会, (日本天文学会), 山形, 9月 (2014).

安田哲也、田代信、寺田幸功、神頭知美、岩切歩、樫戸輝揚、中川俊雄、馬場彩、浦田裕次、柴田善平、牧島一夫、すずく WAM チーム: “すずく衛星搭載WAM検出器によるAXP 1E1547.0-5408の硬X線パーストの観測 (II)” 日本天文学会
北口賀雄, 寺田幸功, 之充, Joanne E. Hill, Kevin Black: "PRAXyS
ファート銀河のX 櫻井壮希, 新也, 村上浩章, 早藤麻美, 石崎欣尚
の硬エックス線観測ほか
Chiao, M. A. Leutenegger, G.V. Brown, D. McCammon, K.
渡辺誠, 線偏光観測衛星: "X ほか
早藤麻美, 窪田恵, 牧島一夫, 北口賀雄, 日本天文学会
大阪 岡本篤, 岩切渉, 馬場彩, 野田博文, 内山秀樹, 吉川瑛文
X, 中澤知洋 月
来嘉彦 年春季年会
中澤知洋, 玉川徹, 大橋隆哉, 三石郁, 小久保 花野恒, 佐藤理江
狭輝線 線分光装置 古田禄大, 诸隈智貴, 藤原康平, 本物理学会
(2014).
玉川徹, 大橋隆哉, 三石郁, 小久保 水野恒, 佐賀洋 市川崇, 西田和樹, 牀元茂
間子原子 古田輝介, 藤原康平, 本物理学会 第70回年次大会 (日本物理学会, 早稲田, 3月 (2015).
桜戸秀行, D.A. Bennett, C. Curecanu, W.B Doriese, J.W.
Fowler, J. Gard, F.P. Gustafsson, 優底六, 施陸善, M. Iliescu, 石元茂, 板橋健太, 岩崎雅彦, 桑原啓介, J.
大桐, 窪田讓二, G.C. O ’Neil, 早稲田, 池田治彦, C.D. Reintsema, 佐藤将春, D.R. Schmidt, A. Scordo,
鈴木謙, 在木隆敏, D.S. Swetz, 厚利行, J.N. Ulkum, E.
桜戸秀行, D.A. Bennett, C. Curecanu, W.B Doriese, J.W.
Fowler, J. Gard, F.P. Gustafsson, 優底六, 施陸善, M. Iliescu, 石元茂, 板橋健太, 岩崎雅彦, 桑原啓介, J.
大桐, 窪田讓二, G.C. O ’Neil, 早稲田, 池田治彦, C.D. Reintsema, 佐藤将春, D.R. Schmidt, A. Scordo,
鈴木謙, 在木隆敏, D.S. Swetz, 厚利行, J.N. Ulkum, E.
桜戸秀行, D.A. Bennett, C. Curecanu, W.B Doriese, J.W.
Fowler, J. Gard, F.P. Gustafsson, 優底六, 施陸善, M. Iliescu, 石元茂, 板橋健太, 岩崎雅彦, 桑原啓介, J.
大桐, 窪田讓二, G.C. O ’Neil, 早稲田, 池田治彦, C.D. Reintsema, 佐藤将春, D.R. Schmidt, A. Scordo,
鈴木謙, 在木隆敏, D.S. Swetz, 厚利行, J.N. Ulkum, E.
桜戸秀行, D.A. Bennett, C. Curecanu, W.B Doriese, J.W.
Fowler, J. Gard, F.P. Gustafsson, 優底六, 施陸善, M. Iliescu, 石元茂, 板橋健太, 岩崎雅彦, 桑原啓介, J.
大桐, 窪田讓二, G.C. O ’Neil, 早稲田, 池田治彦, C.D. Reintsema, 佐藤将春, D.R. Schmidt, A. Scordo,
鈴木謙, 在木隆敏, D.S. Swetz, 厚利行, J.N. Ulkum, E.
桜戸秀行, D.A. Bennett, C. Curecanu, W.B Doriese, J.W.
Fowler, J. Gard, F.P. Gustafsson, 優底六, 施陸善, M. Iliescu, 石元茂, 板橋健太, 岩崎雅彦, 桑原啓介, J.
大桐, 窪田讓二, G.C. O ’Neil, 早稲田, 池田治彦, C.D. Reintsema, 佐藤将春, D.R. Schmidt, A. Scordo,
鈴木謙, 在木隆敏, D.S. Swetz, 厚利行, J.N. Ulkum, E.
Astro-Glaciology Research Unit

Publications

[Journal]
(Original Papers) *Subject to Peer Review

Oral Presentations

(International Conference etc.)

(Domestic Conference)
Superheavy Element Production Team

Publications

[Journal]

(Original Papers) *Subject to Peer Review


D. Kaji, Morimoto, F. Tokanai


D. Kaji, "First α-γ spectroscopic study by using a Si-Ge detector array installed at the focal plane of GARIS", Tokyo, June, 2014, ARIS2014.


Yamaki S., Morimoto K., Kaji D., Wakabayashi Y., et al., "SHE experiments with GARIS-I/-II at RIKEN", (Invited talk)


Ⅶ. LIST OF PUBLICATIONS

(Original Papers) *Subject to Peer Review

K. Morita, 2nd Conference on Advances in Radioactive Isotope Science (ARISS2014), (Invited talk), June 4, 2014, Tokyo, Japan, 'Research of Superheavy Elements at RIKEN - Present Status and Perspective -'

K. Morita, Zakopane Conference on Nuclear Physics, Invited talk Sep. 3, 2014, Zakopane, Poland, 'Research on Superheavy Element at RIKEN'


D. Kaji, "The first α-γ spectroscopic study by using a Si-Ge detector array installed at the focal plane of GARIS", Tokyo, June, 2014, ARIS2014.


(Internal Conference)

加治大哉, "Flash-ADC により取得したプリアンプ波形のための解析アルゴリズムの開発", 日本物理学会第 69 回年次大会, (物理学会), 平塚市, 東海大学, 3月 2014

加治大哉, "Flash-ADC により取得したプリアンプ波形のための解析アルゴリズムの開発", 日本物理学会第 69 回年次大会, (物理学会), 平塚市, 東海大学, 3月 2014.

加治大哉, "Flash-ADC により取得したプリアンプ波形のための解析アルゴリズムの開発", 日本物理学会第 69 回年次大会, (物理学会), 平塚市, 東海大学, 3月 2014 (B) 2014年4月, RIKEN-2014

(Invited talk)

D. Kaji, NUSTAR meeting 2014, “SHE experiments with GARIS-I/-II at RIKEN”, (Invited talk)

(Invited talk)

K. Morita, 2nd Conference on Advances in Radioactive Isotope Science (ARISS2014), (Invited talk), June 4, 2014, Tokyo, Japan, ‘Research of Superheavy Elements at RIKEN - Present Status and Perspective -’

K. Morita, Zakopane Conference on Nuclear Physics, Invited talk Sep. 3, 2014, Zakopane, Poland, ‘Research on Superheavy Element at RIKEN’


D. Kaji, "Production of Black Hole and the Search for Long-lived Decay of Super Heavy Elements", ARIS2014, Tokyo, June 2014.

(Internal Conference)

D. Kaji, "Production of Black Hole and the Search for Long-lived Decay of Super Heavy Elements", ARIS2014, Tokyo, June 2014.

(Internal Conference)


D. Kaji, "The first α-γ spectroscopic study by using a Si-Ge detector array installed at the focal plane of GARIS", Tokyo, June, 2014, ARIS2014.


森本幸司：”加速器を用いた新元素探索の最前線”，第23理化学研究所里庄セミナー、岡山県、8月（2014）

一般向け講演会
森田浩介、大阪大学理学部物理学科セミナー 2014年7月25日 豊中市‘新元素の探索－現代の錬金術－’
森田浩介、日本耳鼻咽喉科学会学術講演会 2014年5月16日 福岡市‘113番元素発見への道のり’
森田浩介、福岡県高校理科部会夏季研修会講演会2014年8月20日 福岡市‘113番新元素の探索’
森田浩介、科学を語る会講演会 2014年11月8日 福岡市‘新元素の探索－現代の錬金術－’
森田浩介、理化学研究所、研究員幹事会総会講演会 2015年3月6日 和光市‘113番新元素の探索’
Superheavy Element Research Device Development Team

Publications

[Journal]

(Original Papers) *Subject to Peer Review


D. Kaji, "The first α-γ spectroscopic study by using a Si-Ge detector array installed at the focal plane of GARIS", Tokyo, June, 2014, ARIS 2014


(Short Communication)

D. Kaji, "NUSTAR meeting 2014, ‘SHE experiments with GARIS-I/II at RIKEN’, (Invited talk)"


D. Kaji, NUSTAR meeting 2014, “SHE experiments with GARIS-I/II at RIKEN”, (Invited talk)

Oral Presentations

(International Conference etc.)
Accelerator Group

Publications

[Journal] *(Original Papers) Subject to Peer Review*

[Book] *(Original Papers) Subject to Peer Review*

渡邉環, 福沢聖尚, 加瀬昌之, 稲森聡, 今康一: “HTc-SQUID ビーム電流モニターの実用化”, Proceedings of the

**Oral Presentations**

(Final International Conference etc.)


(Domestic Conference)

前山拓哉，福西暢尚，石川顕一，古田琢哉，深作和明，高木周，野田茂穂，野野崎太郎，福田茂一：“LET依存性のないナノクレイ添加フリッケゲル線量計の開発”，第 107 回日本医学物理学会学術大会，日本医学物理学会横浜，4 月 (2014)。

前山拓哉，福西暢尚，石川顕一，深作和明，古田琢哉，高木周，野田茂穂，野野崎太郎，福田茂一：“LET に依存しない三次元線量計”，第 15 回放射線プロセスシンポジウム，東京，6 月 (2014)。

前山拓哉，福西暢尚，石川顕一，深作和明，福田茂一：“LET 依存性のないゲル線量計の開発”，先端放射線化学シンポジウム，日本放射線化学会東京，3 月 (2015)。

渡邉環，福西暢尚，加瀬昌之，福西暢尚：今康一：“HTc-SQUID ビーム電流モニターの実用化”，第 11 回日本加速器学会年会，青森，8 月 (2014)。

渡邉環，石川顕一：“理研 RIBF における高温超伝導 SQUID ビーム電流モニターの実用化”，日本物理学会第 70 回年次大会，東京，3 月 (2015)。

(Others)


前山拓哉，福西暢尚，石川顕一，深作和明，古田琢哉，高木周，野田茂穂，野野崎太郎，福田茂一：“LET 依存性のないゲル線量計の開発”，平成 25 年度 HIMAC 共同利用研究成果発表会，放射線医学研究会千葉, 4 月 (2014)。

前山拓哉：“粒子線治療計画の三次元検証ツールとしてのナノコンポジットゲル線量計”，平成 26 年度第 3 回重粒子線医工学連携セミナー，群馬大学群馬, 6 月 (2014)。

前山拓哉：“粒子線治療計画の三次元検証ツールとしてのナノコンポジットゲル線量計”，理化学研究所新技術説明会，理化学研究所，埼玉, 6 月 (2014)。

前山拓哉，福西暢尚，石川顕一，深作和明，福田茂一：“ナノコンポジットフリッケゲル線量計の組成条件の検討”，第 3 回 3D ゲル線量計研究会, 名古屋, 11 月 (2014)。

渡邉環：“理研 AVF サイクロトロンのエネルギー測定”，第 10 回 AVF 会合打合せ, 高崎, 7 月 (2014)。

渡邉環：“HTc-SQUID ビーム流計”, 日新イオン機器株式会社講演会, 京都, 11 月 (2014)。
SLOWRI Team

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Oral Presentations

(International Conference etc.)


(Domestic Conference)

Rare RI-ring Team

Oral Presentations

(Intermediate Conference etc.)


Yamaguchi Y., and rare-RI ring collaboration: “Rare-RI Ring at RIKEN RI Beam Factory”, The sixth international conference on Trapped Charged Particles and Fundamental Physics (TCP2014), Takamatsu, Japan, Desember (2014).


Abe Y.: “Mass measurement of RI with Rare-RI Ring at RIKEN”, Post-TCP PMM Workshop, Wako, Japan, December (2014).


(Domestic Conference)


山口由高, 若杉昌徳, 阿部康志, 山崎ふみ, 藤岡雅, 加瀬昌之, 辻山美玲, 澤谷桂子, 鈴木健, 長江大輔, 鈴木健十三, 小沢頌, 上坂友洋, 山口貴之, 山澤秀行, 柳澤善行, 鈴木健十三, 矢野安重: “理研 RIBF における稀少 RI リングの現状”, 第 11 回日本加速器学会年会, (日本加速器学会), 青森市, 8 月 (2014).
SCRIT Team

Oral Presentations

(International Conference etc.)


Ohnishi T., and SCRIT collaboration: “The SCRIT electron scattering facility at RIKEN RI Beam Factory”, 9th International conference on Nuclear Physics at Storage Rings (STORI14), (GSI Helmholtz Centre for Heavy Ion Research), St Goar, Germany, Oct. (2014).


(Domestic Conference)

植園昭智，市川進一，栗田和好，須田利美，玉江忠明，塚田幹，水流輝明，戸ヶ崎衛，森谷洋祐，松尾咲希，米山俊平，若杉昌徳，WANG Shou: “Development of the electron spectrometer for the SCRIT experiment”, 4th Joint Meeting of the Nuclear Physics Divisions of the American Physics Society and the Physical Society of Japan, (日本物理学会, アメリカ物理学会), Hawaii, USA, 10月 (2014).

塚田幹，市川進一，栗田和好，玉江忠明，水流輝明，戸ヶ崎衛，森谷洋祐，松尾咲希，米山俊平，栗田和好，松尾咲希，戸ヶ崎衛，戸ヶ崎衛，森谷洋祐，松尾咲希，WANG Shou: “SCRIT electron scattering facility”, 4th Joint Meeting of the Nuclear Physics Divisions of the American Physics Society and the Physical Society of Japan, (日本物理学会, アメリカ物理学会), Hawaii, USA, 10月 (2014).

松尾咲希，市川進一，植園昭智，大西哲哉，栗田和好，須田利美，玉江忠明，塚田幹，水流輝明，戸ヶ崎衛，森谷洋祐，松尾咲希，米山俊平，若杉昌徳，WANG Shou: “Development of the scattered electron spectrometer for the SCRIT experiment”, 第 70 回日本物理学会年次大会, (日本物理学会), 新宿, 日本, 3月 (2015).

米山俊平，須田利美，玉江忠明，塚田幹，水流輝明，松尾咲希，森谷洋祐，栗田和好，松尾咲希，戸ヶ崎衛，森谷洋祐，大西哲哉，栗田和好，戸ヶ崎衛： "制動散乱を利用した SCRIT 実験用ルミノ


Murai D. Ieki K., Kubo T., Inabe N., Kameda D., Fukuda N., Takeda H., Suzuki H., Yoshida K., and BigRIPS collaboration: \textquoteleft Measurement of production yield for neutron-rich nuclei around Z=60 from in-flight fission of a $^{238}$U beam at 345 MeV/nucleon\textquoteright, Fourth joint meeting of the nuclear physics divisions of the American Physical Society and the Physical Society of Japan, ( The American Physical Society and the Physical Society of Japan ), Hawaii, USA, Oct. (2014). (Domestic Conference)
SAMURAI Team

Publications

[Journal]

(Original Papers) *Subject to Peer Review

N. Kobayashi, T. Nakamura, Y. Kondo, J. A. Tostevin, Y. Utsuno, N. Aoi, H. Baba, R. Barthelemy, M. A. Fami-
nano, N. Fukuda, N. Inabe, M. Ishihara, R. Kanungo, S. Kim, T. Kubo, G. S. Lee, H. S. Lee, M. Matsu-
shita, T. Motobayashi, T. Ohnishi, N. A. Orr, H. Otsu, T. Otsuka, S. Sako, H. Sakurai, Y. Satou, T. Sumi-


maguchi, K. Yoneda.


A. Obertelli, A. Delbart, S. Anvar, L. Audirac, G. Au-
thelet, H. Baba, B. Bruyneel, D. Calvet, F. Chateau, A. Corsi, P. Doornenbal, J.-M. Gheller, A. Giganon, C. Lahonde-Handoum, D. Leboeuf, D. Loiseau, A. Moh-

“MINOS: A vertex tracker coupled to a thick liquid-
hydrogen target for in-beam spectroscopy of exotic nu-

ishi, S. Shimoura, M. Tamaki, T. Kobayashi, Y. Matsu-
da, N. Endo, M. Kitayama.


launay, J. Gibelin, F. M. Marques, N. A. Orr, T. Honda, T. Kobayashi, T. Sumikama, Y. Miyashita, K. Yoshi-


R. Shane, A.B. McIntosh, T. Isebo, W.G. Lynch, H. Baba, J. Barney, Z. Chajecki, M. Chartier, J. Esteel, M. Fami-
nano, B. Hong, K. Ieki, G. Jiang, R. Lemmon, F. Lu, T. Murakami, N. Nakatsuka, M. Nishimura, R. Olsen, W. Powell, H. Sakurai, A. Taketani, S. Tangvan-
charoen, M.B. Tsang, T. Usukura, R. Wang, S.J. Yen-
nello, J. Yurkona.

“S2RIT: A time-projection chamber for symmetry-

[Book · Proceedings]

(Original Papers)


Oral Presentations

(International Conference, etc.)

Y. Kondo.: “Experimental study of neutron-rich nuclei near and beyond drip line with SAMURAI at RIBF”, 3rd International Workshop on “State of the Art in Nu-
clear Cluster Physics” (SOTANCP3), KGU Kainai Me-
dia Center, Kanto Gakuin University, Yokohama, Japan. May 26-30, 2014.

Y. Kondo.: “Invariant-mass spectroscopy of extremely neutron-rich nuclei with SAMURAI at RIBF”, Advances in Radioactive Isotope Science (ARIS2014), ITO Inter-
national Research Center, University of Tokyo, Japan, June 1-6, 2014


-503-


Y. Kondo.: “Recent experimental results on unbound oxygen isotopes beyond the drip line”, PKU-CUSTIPEN Nuclear Reaction Workshop “Reactions and Spectroscopy of Unstable Nuclei”, Peking University, Beijing, China, August 10-14, 2014.


T. Nakamura.: “Recent experimental results on unbound oxygen isotopes beyond the drip line”, PKU-CUSTIPEN Nuclear Reaction Workshop “Reactions and Spectroscopy of Unstable Nuclei”, Peking University, Beijing, China, August 10-14, 2014.


梅野 泰宏: “Symmetry energy and electric dipole response of neutron-rich nuclei”, 新学術領域研究会「中性子星核物 質」, 2015 年 3 月, 京都大学.

Computing and network Team

Publications

[Journal]
(Original Papers)  *Subject to Peer Review

Oral Presentations
(International Conference etc.)

(Domestic Conference)
Detector Team

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Oral Presentations
(International Conference etc.)


Letter to the Editor

栂野泰宏，南方亮吾，生越駿，中村隆司，磯部忠昭，稲辺尚人，
大津秀暁，亀田大輔，筒野大輝，久保敏幸，小林俊雄，
小林信之，近藤洋介，佐藤茂海，佐藤義輝，清水陽平，
鈴木宏，高橋賢人，竹田浩之，田中隆己，中嶋丈嘉，
中塚徳継，西征爾郎，福田直樹，馬場隆忠，武藤琴美，
村井大地，村上哲也，本林透，米田健一郎，N. L. Achouri，
A. G. Tuff，T. Aumann，F. Delaunay，J. Gibelin，
J. Hwangy，S. Kim，J. Lee，M. Marques，A. Navin，
N. A. Orr，P. Doornenbal，S. Leblond，M. Vandebrouck：
"19,20,22\(^{\text{C}}\) の反応断面積"，日本物理学会第 70 回年次大会，
(早稲田大学)，東京，3 月 (2015)。
Ion Beam Breeding Team

Publications

[Journal] (Original Papers) *Subject to Peer Review


(Review)


[Book・Proceedings]


Oral Presentations

(International Conference etc.)


RI Applications Team

Publications

[Journal]

(Original Papers) *Subject to Peer Review


Kandascker M. U., Haba H., Ohtuka N., and Usman A. R., “Investigation of (d,x) Nuclear Reactions on Natural Ytterbium up to 24 MeV”, Nucl. Instr. and Meth. B 335, 8 (2014).*


Murakami M., Haba H., Goto S., and Kudo H., “Production Cross Sections of Nb and Ta Isotopes in the ($p$,n) and ($d$,x) Reactions on $^{40}$Zr and $^{40}$Hf”, 17th Radiochemical Conference, (Division of Nuclear and Radiochemistry, European Association for Chemical and Molecular Sciences), Marianske Lazne, Czech Republic, May (2014).
Conference, (Division of Nuclear and Radiochemistry, European Association for Chemical and Molecular Sciences), Marianske Lazne, Czech Republic, May (2014).
Takahashi K., Obi Y., and Tanaka M., "The Lead Isotopes of Aeolian Dust Observed at Saitama Area (Japan) and Their Genetic Implications", China-Japan-Korea Symposium for Analytical Chemistry, (Research Center for Analytical Sciences, Northeastern University), Shenyang, China, Aug. (2014).
(Domestic Conference)
羽場宏光, "理研 RIBF における RI 製造応用", 第 24 回金属の関与する生体関連反応シンポジウム (SRM2014), 特別講演 (兼市民講演会), (日本薬学会 物理薬学科部会), 京都, 6 月 (2014).
加治大哉, 森本幸司, 羽場宏光, 若林泰生, 武山美眉, 山本さやか, 田中謙吾, 長谷部裕雄, M. Huang, 金谷淳平, 村上昌史, 米田晃, 吉田敦, 杉田貴之, 関井光夫, 羽場宏光, Tan Z., Ma L., Geissel H., Hofmann S., Maurer Y., 藤原觀, 成瀬義博, 田中幸義, 山本翔也, 浅井雅人, 鹿取慎一, 塚田浩二, "GARIS を用いたホットフュージョン反応 $^{258}$Cm + $^{48}$Ca $\rightarrow$ $^{258}$Lv のに関する研究", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
村上昌史, 羽場宏光, 黄明輝, "{$^{104}$Zr,d~x, {$^{14}$Hf,d~x} 反応による Nb, Ta 同位体の励起関数測定", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
笠良義宏, 豊村悟志, 横北卓也, 重河健大, 高橋成人, 羽場宏光, 小林有希子, 金谷淳平, 黄明輝, 森本幸司, 村上昌史, 森本幸司, 吉村浩明, 高宮卓, 佐藤原厚, "104 番元素 Ra の水素化ナトリウム共同挙動", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
津藤翔平, 村上昌史, 大江一弘, 後藤真一, 佐藤大輔, 後藤尚哉, 長岡哲也, 羽場宏光, 豊嶋厚史, 木野愛子, 木野愛子, 田中誠, 塚田和明, "Db の化学実験に向けた 5 つ元素 Nb, Ta のオキシライオン類似クロマトグラフィー", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
北山雄太, 福田裕芳, 塚田和明, 豊嶋厚史, 羽場宏光, 菊永英浩, 村上昌史, Huang M.H., 谷口拓海, 上野慎吾, 小川和憲, 横山明彦, "TTA 類似クロマトグラフィーによる超重元素ラファゾリウム (Rf) の吸着挙動", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
北山雄太, 木野愛子, 重河健大, 豊村悟志, 中村宏平, 笠良義宏, 高橋成人, 安田勇輝, 吉村浩明, 小林有希子, 羽場宏光, 金谷淳平, 黄明輝, 村上昌史, 塚田和明, "104 番元素 Ra の吸着挙動を用いた Zr と Hf の試料抽出", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
村上昌史, 羽場宏光, 柴田誠一, 工藤久昭, "{$^{186}$Hf(a,d) 反応の励起関数測定", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
小林有希子, 村上昌史, 羽場宏光, 柴田誠一, "{$^{Mo}$d~x} 反応による Tc 同位体の生成断面積測定", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).
後藤尚哉, 大江一弘, 村上昌史, 後藤真一, 工藤久昭, 塚田和明, 高橋成人, 浅井雅人, 佐藤浩二, 宮下直, 金谷淳平, 北山雄太, 羽場宏光, 小林有希子, "$^{14}$Sg の同位体 Ra の シュウ酸溶液からラジオアイオン抽出挙動", 2014 日本放射化学会年会・第 58 回放射化学討論会 (日本放射化学学会), 名古屋, 9 月 (2014).

脇谷雄一郎, 矢納慎也, 山田崇裕, 羽場宏光, 柴田誠一, 高橋和也, “理研AVFサイクロトロンを用いた頒布用Rfの調製(I)⁵⁹Cd”, 2014日本放射化学会年会・第58回放射化学討論会, (日本放射化学会), 名古屋市, 9月 (2014)。

矢納慎也, 腰谷雄一郎, 山田崇裕, 羽場宏光, 金谷淳平, 柴田誠一, 高橋和也, “理研AVFサイクロトロンを用いた頒布用Rfの調製(II)⁸⁵Sr”, 2014日本放射化学会年会・第58回放射化学討論会, (日本放射化学会), 名古屋市, 9月 (2014)。

羽場宏光, “理研におけるRI製造応用”, 東北大学電子光学研究センター研究会「大強度電子ビームとその応用利用」, (東北大学電子光学研究センター), 仙台市, 3月 (2015)。

横北卓也, 中村宏平, 重河優大, 安田勇輝, 笠松良崇, 高橋成人, 吉村崇, 羽場宏光, 小森有希子, 村上昌史, 篠原厚, “104番元素Rfの抽出挙動の時間依存性：バッチ型固液抽出装置を用いたRfのAliquat336/HCl系の固液抽出”, 日本化学会第95春季年会, (日本化学会), 船橋市, 3月 (2015)。

北山雄太, 福田芳樹, 羽場宏光, 塚田和明, 豊崎厚史, 菊永英寿, 小森有希子, 村上昌史, 上野慎吾, 谷口拓海, 林和憲, 谷津由香里, 千代速西尾伊織, 村上春夫, 混川明彦, “TTA逆相クロマトグラフィーによる超重元素ラザホージウム（Rf）フッ化物錯体族合成の評価”, 日本化学会第95春季年会, (日本化学会), 船橋市, 3月 (2015)。

- 514 -
Industrial Cooperation Team

Publications

[Book · Proceedings]
吉田敦、神原正、上本龍二，"RI ビーム打込み法を用いた摩耗検査法の開発"，月刊トライボロジー2014-08 No324 pg.16-18,新樹社
吉田敦、神原正，"研究室紹介 No.43 理化学研究所仁科加速器研究センター産業連携チーム"，月刊トライボロジー2015-02 No330 pg.66,新樹社

Oral Presentations
(Domestic Conference)
吉田敦：”理研 RI ビームバラエティ（産業利用まで）”，第54回放射線科学研究会(エキゾチックビームシリーズ<12>), 大阪ニューキリアサイエンス協会, 大阪, 7月(2014).
Safety Management Group

Publications

[Journal]
(Original Papers)

(Book · Proceedings)
(Original Papers)

(Others)

Oral Presentations

(International Conference etc.)

(Domestic Conference)
岡野真人, 加藤博: “スペクトロメトリー解析”, 第 51 回アイソトープ・放射線研究発表会 (日本アイソトープ協会), 東京, 7 月 (2014).
上蓑義朋, 岡野真人, 加藤博, 向井弘樹, 七沢潔, 大森淳郎: “福島原発事故直後ならびに 3 年後の環境放射能推移”, 第 51 回アイソトープ・放射線研究発表会 (日本アイソトープ協会), 東京, 7 月 (2014).
Center for Nuclear Study (CNS)
Graduate School of Science, the University of Tokyo

Publications

[Journal]
(Original Papers) *Subject to Peer Review


Abelev B.B. et al. [ALICE Collaboration]: “Measurement of visible cross sections in proton-lead collisions at √sNN = 5.02 TeV in van der Meer scans with the ALICE detector”, JINST 9, no. 11, P11003 (2014)


Abelev B.B. et al. [ALICE Collaboration]: “Transverse momentum dependence of inclusive primary charged-particle production in p-Pb collisions at √sNN =
Adare A. et al. [PHENIX Collaboration]: “Measurement of K_{S}^{0} and K^{*0} in p + p, d + Au, and Cu + Cu collisions at √s_{NN} = 200 GeV”, Phys. Rev. C 90, no. 5, 054905 (2014)
Abelev B.B. et al. [ALICE Collaboration]: “Suppression of ϒ(2S) production in p-Pb collisions at √s_{NN} = 5.02 TeV”, JHEP 1412, 073 (2014)


Oral Presentations

(Internal Conference etc.)


Takaki M. (oral); “New type of spectroscopy via Heavy-Ion Double Charge eXchange reaction”, Advances in Nuclear Structure at Extreme Conditions, Bormio, Italy, Feb. 19–22, 2014.


Dozono M. (oral) : “The $^1\text{H}(^8\text{O},^4\text{He})^6\text{Be}$ reaction as a novel probe for studying the spin-dipole excitations in nuclei”, Neutrino Nuclear Reponses for Neutrino Studies in Nuclei (NNR14), RCNP, Osaka University, Japan, Nov. 5-6, 2014

Shimoura S. (invited): “Nucleon transfer reactions at intermediate energy to exotic nuclei using inverse kinematics”, ECT* Workshop on ‘From nuclear structure to particle-transfer reactions and back II’, Trento, Italy, November 10–14, 2014


Hayashi S. on behalf of the ALICE Collaboration (poster): “Study of di-electron production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using Transition Radiation Detector triggers with the ALICE detector”, XXIV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (QM2014), Darmstadt, Germany, May 19 - 24,
Hayashi S. on behalf of the ALICE Collaboration (oral): “Dielectron measurement in p-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV with the ALICE detector”, The 5th Asian Triangle Heavy Ion Conference (ATHIC2014), Osaka, Japan, August 5-8, 2014

Hayashi S. on behalf of the ALICE Collaboration (oral): “Dielectrons production from heavy quark decays in p-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV”, High Energy Strong Interactions: A School for Young Asian Scientists, Wuhan, China, September 22-26, 2014


Yamaguchi H.(invited): “Studies on Nuclear Astrophysics and Exotic Structure at the Low-Energy RI Beam Facility CRIB”, The 2nd Conference on Advances in Radioactive Isotope Science (ARIS2014) Ito International Center, Tokyo, Japan, June 2-6, 2014

Kahl D.(poster): “\(^{30}\)S+alpha Resonant Elastic Scattering with an Active Target”, The 2nd Conference on Advances in Radioactive Isotope Science (ARIS2014) Ito International Center, Tokyo, Japan, June 2-6, 2014

Yamaguchi H.(oral): “Studies on Nuclear Astrophysics and Exotic Structure at the Low-Energy RI Beam Facility CRIB”, Sicily-East Asia Workshop for Low-energy Nuclear Physics, Catania University, Ortygia island, Siracusa, July 28–31, 2014

Kahl D.(oral): “\(^{30}\)S+alpha Resonant Elastic Scattering with an Active Target”, Sicily-East Asia Workshop for Low-energy Nuclear Physics, Catania University, Ortygia island, Siracusa, July 28–31, 2014


Otsuka T. (invited): “Shape evolution, shape coexistence and shell evolution in exotic nuclei”, 11th INT. SPRING SEMINAR ON NUCLEAR PHYSICS, Ischia, Italy, May 12-16, 2014


Shimizu N. (invited), Abe T., Honma M., Mizusaki T., Otsuka T., Togashi T., Tsumoda Y., Utsuno Y., and Yoshida T.: “Frontier of nuclear shell-model calculations and high performance computing”, Advances in Radioactive Isotope Science (ARIS2014), Univ. of Tokyo, Tokyo, Japan, Jun. 05, 2014


Iwata Y. (invited): “Present status of fission research based on TDDFT”, Symposium on Nuclear Data, Hokkaido University, Japan, Nov 2014

Iwata Y. (invited): “Nuclear matrix element of 48Ca”, NNR14, RCNP, Osaka University, Japan, Nov 2014


Iwata Y.: “Shape transition induced by rotation”, 3rd International Workshop on “State of the Art in Nuclear Cluster Physics” (SOTANC3), Yokohama, Japan, May 2014


Togashi T. (Poster), Shimizu N., Utsuno Y., Otsuka T. and Honma M.: “Shell-model calculation of high-spin states in neutron-rich Cr and Fe isotopes”, Advances in Radioactive Isotope Science (ARIS2014), Univ. of Tokyo, Tokyo, Japan, Jun. 05, 2014


Iwata Y.: “Large-scale shell model calculation project for double-beta decay”, Workshop on “Progress in nuclear shell-model calculations in CNS-RIKEN collaboration”, RIKEN, Japan, Nov. 2014


(Domestic Conference)


ヤナグチ, ほか: "重水素ガスアクティプ標的の反応粒子飛跡再構成と性能評価", JPS Spring meeting, Tokai University, Japan, Mar. 27-30, 2014
Yako K.: "Study of nuclear matrix element of the double-beta decay by charge-exchange reactions", JPS Spring meeting, Tokai University, Japan, Mar. 27-30, 2014
Gunji T. for the ALICE Collaboration, "R&D status of the ALICE GEM-TPC upgrade", JPS Spring meeting, Tokai University, Japan, Mar. 27-30, 2014
Yukawa K., Gunji T., Hamagaki H., Terasaki K., "GEM-TPCにおけるイオンバックフローの空間電荷依存性の研究", JPS Spring meeting, Tokai University, Japan, Mar. 27-30, 2014
Lee C.S., Ota S., Aramaki Y., Saiseau R., Tokieda H., and Watanabe Y.: "Development of a dual-gain multiplication in CNS Active Target for high-intensity heavy-ion beam injection", The 4th Joint Meeting of the Nuclear Physics Devisions of the APS and JPS, Hawaii, USA, October 7–11, 2014
Watanabe Y. (oral): “Measurements of di-electron production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by RHIC-PHENIX using Hadron Blind Detector”, 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, Oct. 7-11, 2014
Hayashi S. on behalf of the ALICE Collaboration (oral): “Dielectrons from Charm and Bottom meson decays in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with the ALICE detector”, Fourth Joint Meeting of the Nuclear Physics Divisions of the American Physical Society and The Physical Society of Japan, Waikoloa, Hawaii, USA, October 7-11
Hayashi S. (invited): “Review of Quark Matter 2014 (Heavy Flavor)”, Heavy Ion Pub and Heavy Ion Cafe 合同研究会, Nagoya, Japan, June 6
Hayashi S. (invited): “LHC での p-Pb 衝突における粒子相関”, Heavy Ion Pub, Osaka, Japan, December 5
Sekiguchi Y. for ALICE collaboration (oral): “Long-range correlation in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector”, 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, Oct. 7-11, 2014


Yokokita T., Kasamatsu Y., Ooe K., Yoshimura T., Takahashi N., Komori Y., and Shinohara A.: “Solvent extraction of Mo(V) and Mo(VI) from hydrochloric acid into Alquat 336 chloroform solution”, J. Radioanal. Nucl. Chem. 301, 751–756 (2014). *


[Book · Proceedings]

(Original Papers) *Subject to Peer Review


Oral Presentations

(International Conference etc.)


Yoshida K.: “Giant multi-pole resonances in rare-earth
nuclei with shape changes”, International Workshop on Nuclear Science and Simulation in fundamental and applied researches, (Ton Duc Thang University), Ho Chi Minh City, Vietnam, Oct. (2014).


Murai M., Haba H., Huang M., Goto S., and Kudo H. (Oral): “$^{nat}$Zr(d,x), $^{nat}$Hf(d,x) 反応による Nb, Ta 同位体の励起関数測定”, 第 58 回放射化学討論会, (日本放射化学学会), 名古屋大学 (東山キャンパス), 9 月 (2014).


Murai M., Haba H., Huang M., Goto S., and Kudo H. (Oral): “$^{nat}$Zr(d,x), $^{nat}$Hf(d,x) 反応による Nb, Ta 同位体の励起関数測定”, 第 58 回放射化学討論会, (日本放射化学学会), 名古屋大学 (東山キャンパス), 9 月 (2014).


Radioactive nuclear beam group
IPNS (Institute for Particle and Nuclear Studies)
KEK (High Energy Accelerator Research Organization)

Publications

[Journal] (Original Papers) *Subject to Peer Review

[Book • Proceedings]
(Original Papers) *Subject to Peer Review

- 529 -
VIII. LIST OF PREPRINTS
# List of Preprints (April 2014 - March 2015)

## RIKEN NC-NP

<table>
<thead>
<tr>
<th>Preprint Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>Systematic investigation of low-lying dipole modes using the canonical-basis time-dependent Haratree-Fock-Bogoliubov theory</td>
<td>S. Ebata, T. Nakatsukasa, T. Inakura</td>
</tr>
<tr>
<td>135</td>
<td>Mean-field analysis of ground state and low-lying electric dipole strength in 22C</td>
<td>T. Inakura, W. Horiuchi, Y. Suzuki, T. Nakatsukasa</td>
</tr>
<tr>
<td>136</td>
<td>Thermal pairing and giant dipole resonance in highly excited nuclei</td>
<td>N.D. Dang</td>
</tr>
<tr>
<td>137</td>
<td>Hidden pseudospin and spin symmetries and their origins in atomic nuclei</td>
<td>H. Liang, J. Meng et al.</td>
</tr>
<tr>
<td>138</td>
<td>Pairing effect in thermal shape fluctuation model on the width of giant dipole resonance</td>
<td>A.K. Rhine Kumar, P. Arumugam, N. Dinh Dang</td>
</tr>
<tr>
<td>139</td>
<td>Viscosity: From air to hot nuclei</td>
<td>N.D. Dang</td>
</tr>
<tr>
<td>140</td>
<td>Possible presence and properties of multi chiral pair-bands in odd-odd nuclei with the same intrinsic</td>
<td>I. Hamamoto</td>
</tr>
<tr>
<td>141</td>
<td>Oblate deformation of light neutron-rich even-even nuclei</td>
<td>I. Hamamoto</td>
</tr>
<tr>
<td>142</td>
<td>Pigmy resonance in monopole response of neutron-rich Ni isotopes ?</td>
<td>I. Hamamoto, H. Sagawa</td>
</tr>
<tr>
<td>143</td>
<td>Energy and mass-number dependence of hadron-nucleus total reaction cross sections</td>
<td>A. Kohama, K. Iida, K. Oyamatsu</td>
</tr>
<tr>
<td>144</td>
<td>Microscopic analysis of fusion hindrance in heavy systems</td>
<td>K. Washiyama</td>
</tr>
<tr>
<td>145</td>
<td>Repulsive aspects of pairing correlation in nuclear fusion reaction</td>
<td>S. Ebata, T. Nakatsukasa</td>
</tr>
<tr>
<td>146</td>
<td>Finite amplitude method in linear response TDDFT calculations</td>
<td>T. Nakatsukasa</td>
</tr>
<tr>
<td>147</td>
<td>Mean-field calculation based on proton-neutron mixed energy density functionals</td>
<td>K. Sato, J. Dobaczewski, T. Nakatsukasa, W. Satula</td>
</tr>
<tr>
<td>148</td>
<td>Multiple period states of the superfluid fermi gas in an optical lattice</td>
<td>S. Yoon, F. Dalfovo, T. Nakatsukasa, G. Watanabe</td>
</tr>
<tr>
<td>149</td>
<td>Hidden pseudospin and spin symmetries and their origins in atomic nuclei</td>
<td>H. Liang, J. Meng, S.G. Zhou</td>
</tr>
<tr>
<td>150</td>
<td>Three-dimensional mesh calculations for covariant density functional theory</td>
<td>Y. Tanimura, K. Hagino, H. Z. Liang</td>
</tr>
</tbody>
</table>

## RIKEN NC-AC

<table>
<thead>
<tr>
<th>Preprint Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not Applicable</td>
<td></td>
</tr>
</tbody>
</table>

## RIKEN MP

<table>
<thead>
<tr>
<th>Preprint Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>Entanglement Entropy of de Sitter Space $\alpha$-Vacua</td>
<td>N. Iizuka, T. Noumi, N. Ogawa</td>
</tr>
<tr>
<td>89</td>
<td>Dynamical breaking of shift-symmetry and super-Planckian inflation</td>
<td>A. Mazumdar, T. Noumi, and M. Yamaguchi</td>
</tr>
<tr>
<td>90</td>
<td>Towards U(N</td>
<td>M) knot invariant from ABJM theory</td>
</tr>
<tr>
<td>91</td>
<td>Electric field quench in QdS/CFT</td>
<td>K. Hashimoto, S. Kinoshita, K. Murata, and T. Oka</td>
</tr>
<tr>
<td>#</td>
<td>Title</td>
<td>Authors</td>
</tr>
<tr>
<td>----</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>92</td>
<td>Bulk Angular Momentum and Hall Viscosity in Chiral Superconductors</td>
<td>A. Shitade and T. Kimura</td>
</tr>
<tr>
<td>93</td>
<td>Turbulent Meson Condensation as Quark Deconfinement</td>
<td>K. Hashimoto, S. Kinoshita, K. Murata, and T. Oka</td>
</tr>
<tr>
<td>94</td>
<td>Duality and integrability of a supermatrix model with an external source</td>
<td>T. Kimura</td>
</tr>
<tr>
<td>95</td>
<td>Entropic destruction of heavy quarkonium in non-Abelian plasma from the holographic correspondence</td>
<td>K. Hashimoto, D.E. Kharzeev</td>
</tr>
<tr>
<td>96</td>
<td>Effective field theory for spacetime symmetry breaking</td>
<td>Y. Hidaka, T. Noumi, and G. Shiu</td>
</tr>
<tr>
<td>97</td>
<td>Is cosmological constant screened in Liouville gravity with matter?</td>
<td>T. Inami, Y. Koyama, Y. Nakayama, M. Suzuki</td>
</tr>
<tr>
<td>98</td>
<td>Meson turbulence at quark deconfinement from AdS/CFT</td>
<td>K. Hashimoto, S. Kinoshita, K. Murata, and T. Oka</td>
</tr>
<tr>
<td>99</td>
<td>Electromagnetic instability in holographic QCD</td>
<td>K. Hashimoto, A. Sonoda, T. Oka</td>
</tr>
<tr>
<td>100</td>
<td>Holographic heavy quark symmetry</td>
<td>K. Hashimoto, N. Ogawa, and Y. Yamaguchi</td>
</tr>
<tr>
<td>101</td>
<td>$h^0 \to c \bar{c}$ as a test case for quark flavor violation in the MSSM</td>
<td>A. Bartl, H. Eberl, E. Ginina, K. Hidaka, W. Majerotto</td>
</tr>
<tr>
<td>102</td>
<td>Higgs boson decay to charm pair at full one-loop level in the MSSM with flavour violation</td>
<td>H. Eberl, A. Bartl, E. Ginina, K. Hidaka, W. Majerotto</td>
</tr>
<tr>
<td>103</td>
<td>Ramond-Ramond Couplings of D-branes</td>
<td>K. Hashimoto, S. Sugishita, S. Terashima</td>
</tr>
<tr>
<td>104</td>
<td>Possibility of QCD ferromagnetism at high density</td>
<td>K. Hashimoto</td>
</tr>
<tr>
<td>105</td>
<td>Holographic Entanglement and Causal Shadow in Time-Dependent Janus Black Hole</td>
<td>Y. Nakaguchi, N. Ogawa, T. Ugajin</td>
</tr>
<tr>
<td>106</td>
<td>Conditionally valid uncertainty relations</td>
<td>K. Fujikawa</td>
</tr>
<tr>
<td>107</td>
<td>Quantum Discord, CHSH Inequality and Hidden Variables -- Critical reassessment of hidden-variables</td>
<td>K. Fujikawa</td>
</tr>
<tr>
<td>108</td>
<td>Aharonov-Bohm effect and geometric phases -- Exact and approximate topology</td>
<td>K. Fujikawa</td>
</tr>
<tr>
<td>109</td>
<td>Eigenvalues of the Breit equation</td>
<td>Y. Yoshiho, H. Kasari</td>
</tr>
<tr>
<td>110</td>
<td>Linking loops in ABJM and refined theory</td>
<td>T. Kimura</td>
</tr>
<tr>
<td>111</td>
<td>Relativistic hydrodynamics from quantum field theory on the basis of the generalized Gibbs ensemble method</td>
<td>T. Hayata, Y. Hidaka, M. Hongo, T. Noumi</td>
</tr>
</tbody>
</table>

**RIKEN QHP**

<table>
<thead>
<tr>
<th>#</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>146</td>
<td>Di-jet asymmetric momentum transported by QGP fluid</td>
<td>Y. Tachibana, T. Hirano</td>
</tr>
<tr>
<td>147</td>
<td>Sine-Square Deformation and its Relevance to String Theory</td>
<td>T. Tada</td>
</tr>
<tr>
<td>148</td>
<td>Renormalized Q(N) model at next-to-leading order of the 1/N expansion: effects of the Landau pole</td>
<td>G. Fejos, A. Patkos, Zs. Szep</td>
</tr>
<tr>
<td>149</td>
<td>Entanglement Entropy of de Sitter Space o-Vacua</td>
<td>N. Iizuka, T. Noumi, N. Ogawa</td>
</tr>
<tr>
<td>150</td>
<td>Restricted phase-space approximation in real-time stochastic quantization</td>
<td>R. Anzaki, K. Fukushima, Y. Hidaka, and T. Oka</td>
</tr>
<tr>
<td>152</td>
<td>Adjoint QCD on $R^{3} \times S^{1}$ with twisted fermionic boundary conditions</td>
<td>T. Misumi, T. Kanazawa</td>
</tr>
<tr>
<td>153</td>
<td>Polarization of Direct Photons from Gluon Anisotropy in Ultrarelativistic Heavy Ion Collisions</td>
<td>G. Baym and T. Hatsuda,</td>
</tr>
<tr>
<td>154</td>
<td>Nonlinear electromagnetic response in quark-gluon plasma</td>
<td>D. Satow</td>
</tr>
<tr>
<td>Page</td>
<td>Title</td>
<td>Authors</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>155</td>
<td>Production of dileptons and photons in the semi-quark gluon plasma</td>
<td>Y. Hidaka, S. Lin, R.D. Pisarski, D. Satow</td>
</tr>
<tr>
<td>156</td>
<td>Real-time Feynman path integral with Picard--Lefschetz theory and its applications to quantum tunneling</td>
<td>Y. Tanizaki, T. Koike</td>
</tr>
<tr>
<td>157</td>
<td>Stressed Cooper pairing in dense QCD: effective Lagrangian and random matrix theory</td>
<td>T. Kanazawa, T. Wettig</td>
</tr>
<tr>
<td>158</td>
<td>QCD sum rules for magnetically induced mixing between $\eta_c$ and $J/\psi$</td>
<td>S. Cho, K. Hattori, S.H. Lee, K. Morita and S. Ozaki</td>
</tr>
<tr>
<td>159</td>
<td>Dispersion relations of Nambu-Goldstone modes at finite temperature and density</td>
<td>T. Hayata, Y. Hidaka</td>
</tr>
<tr>
<td>160</td>
<td>Inhomogeneous Polyakov loop induced by inhomogeneous chiral condensates</td>
<td>T. Hayata, A. Yamamoto</td>
</tr>
<tr>
<td>161</td>
<td>Fluctuation induced first order phase transition in $U(n):U(n)$ models using chiral invariant expansion of FRG</td>
<td>G. Fejos</td>
</tr>
<tr>
<td>162</td>
<td>Medium-Heavy Nuclei from Nucleon-Nucleon Interactions in Lattice QCD</td>
<td>T. Inoue, T. Hatsuda et al. (HAL QCD Collaboration)</td>
</tr>
<tr>
<td>163</td>
<td>Magnetic susceptibility of strongly interacting matter with $2+1$ quark flavors</td>
<td>K. Kamikado, T. Kanazawa</td>
</tr>
<tr>
<td>164</td>
<td>Many-body composite bosons from the viewpoint of functional renormalization</td>
<td>Y. Tanizaki</td>
</tr>
<tr>
<td>165</td>
<td>On the origin of the narrow peak and the isospin symmetry breaking of the $X(3872)$</td>
<td>S. Takeuchi, K. Shimizu, M. Takizawa</td>
</tr>
<tr>
<td>166</td>
<td>Lefschetz-thimble techniques for path integral of zero-dimensional $O(n)$ sigma models</td>
<td>Y. Tanizaki</td>
</tr>
<tr>
<td>167</td>
<td>Renormalization of the 2PI-Hartree approximation in a broken phase with nonzero superflow</td>
<td>G. Fejos</td>
</tr>
<tr>
<td>168</td>
<td>Quasi-instantons in QCD with chiral symmetry restoration</td>
<td>T. Kanazawa, N. Yamamoto</td>
</tr>
<tr>
<td>169</td>
<td>Asymptotically free lattice gauge theory in five dimensions</td>
<td>T. Kanazawa, A. Yamamoto</td>
</tr>
<tr>
<td>170</td>
<td>Complex Langvin simulation of quantum vortex nucleation in the Bose-Einstein condensate</td>
<td>T. Hayata, A. Yamamoto</td>
</tr>
<tr>
<td>171</td>
<td>Effective field theory for spacetime symmetry breaking</td>
<td>Y. Hidaka, T. Noumi, G. Shiu</td>
</tr>
<tr>
<td>174</td>
<td>Structure of Lefschetz thimbles in simple fermionic systems</td>
<td>T. Kanazawa, Y. Tanizaki</td>
</tr>
<tr>
<td>175</td>
<td>Holographic heavy quark symmetry</td>
<td>K. Hashimoto, N. Ogawa, Y. Yamaguchi</td>
</tr>
<tr>
<td>176</td>
<td>Holographic Entanglement and Causal Shadow in Time-Dependent Janus Black Hole</td>
<td>Y. Nakaguchi, N. Ogawa, T. Ugajin</td>
</tr>
<tr>
<td>179</td>
<td>Relativistic hydrodynamics from quantum field theory on the basis of the generalized Gibbs ensemble method</td>
<td>T. Hayata, Y. Hidaka, M. Hongo, T. Noumi</td>
</tr>
<tr>
<td>180</td>
<td>From quantum to classical dynamics: Dynamic crossover in the relativistic $SO(N)$ model at finite temperature</td>
<td>D. Mesterhazy, Y. Tanizaki</td>
</tr>
<tr>
<td>181</td>
<td>Jarzynski-type equalities in gambling: role of information in capital growth</td>
<td>Y. Hirono, Y. Hidaka</td>
</tr>
<tr>
<td>182</td>
<td>Evading the sign problem through Lefschetz-thimble path integral</td>
<td>Y. Tanizaki, H. Nishimura, K. Kashiwa</td>
</tr>
<tr>
<td>184</td>
<td>Phonons, Pions and Quasi-Long-Range Order in Spatially Modulated Chiral Condensates</td>
<td>Y. Hidaka, K. Kamikado, T. Kanazawa and T. Noumi</td>
</tr>
<tr>
<td>185</td>
<td>Infinite circumference limit of conformal field theory</td>
<td>N. Ishibashi, T. Tada</td>
</tr>
</tbody>
</table>
### LIST OF PREPRINTS

<table>
<thead>
<tr>
<th>CNS-REP</th>
<th>CNS Annual Report 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>T. Gunji, S. Ota, Y. Kishi</td>
</tr>
</tbody>
</table>

*Nishina Center Preprint server* (not including Partner Institution) can be found at [http://nishina-preprints.riken.jp/](http://nishina-preprints.riken.jp/)
IX. LIST OF SYMPOSIA
& WORKSHOPS
## List of Symposia & Workshops (April 2014 - March 2015)

<table>
<thead>
<tr>
<th>No.</th>
<th>Event Description</th>
<th>Location</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Approach to Equilibrium in Strongly Interacting Matter</td>
<td>BNL</td>
<td>Apr. 2-4</td>
</tr>
<tr>
<td>2</td>
<td>4rd Joint ISIS/RIKEN Muon Facility Development Workshop (ISIS/UK)</td>
<td>RAL</td>
<td>Apr. 4</td>
</tr>
<tr>
<td>3</td>
<td>The 3rd EURICA workshop</td>
<td>RIBF Conference Hall</td>
<td>Apr. 10</td>
</tr>
<tr>
<td>4</td>
<td>RIBF Discussion Plus! -Island of Inversion</td>
<td>RIBF Conference Hall</td>
<td>Apr. 25</td>
</tr>
<tr>
<td>5</td>
<td>The 3rd International Workshop on &quot;State of the Art in Nuclear Cluster Physics&quot;</td>
<td>KGU Kannai Media Center</td>
<td>May 26-30</td>
</tr>
<tr>
<td>6</td>
<td>ICNT workshop &quot;Physics of exotic nuclei: Theoretical advances and challenges&quot;</td>
<td>RIKEN Main Research Bldg.</td>
<td>Jun. 9</td>
</tr>
<tr>
<td>7</td>
<td>PALIS strategy meeting 2014</td>
<td>RIBF Conference Hall</td>
<td>Jun. 9</td>
</tr>
<tr>
<td>8</td>
<td>One-day intensive workshop on &quot;di-neutron and alpha-cluster correlations in exotic nuclei&quot;</td>
<td>RIBF Bldg. 203</td>
<td>Jul. 10</td>
</tr>
<tr>
<td>9</td>
<td>The 9th RIBF Discussion meeting on the spin-isospin excitations in neutron rich nuclei</td>
<td>Okouchi Hall</td>
<td>Jul. 31</td>
</tr>
<tr>
<td>10</td>
<td>RIKEN BNL Research Center Workshop: Thermal Protons &amp; Dilepton in Heavy-Ion Collisions</td>
<td>BNL</td>
<td>Aug. 20-22</td>
</tr>
<tr>
<td>11</td>
<td>HET-RBRC Symposium: Creutz Fest 2014 -A Celebration of the Career and Accomplishments of Michael Creutz</td>
<td>BNL</td>
<td>Sep. 4-5</td>
</tr>
<tr>
<td>12</td>
<td>SAMURAI International Collaboration Workshop 2014</td>
<td>Tohoku U.</td>
<td>Sep. 8-9</td>
</tr>
<tr>
<td>13</td>
<td>BigRIPS analysis workshop</td>
<td>RIBF Conference Hall</td>
<td>Sep. 11</td>
</tr>
<tr>
<td>14</td>
<td>The 3rd SUNFLOWER Workshop</td>
<td>U. Tokyo</td>
<td>Sep. 15-16</td>
</tr>
<tr>
<td>15</td>
<td>The 10th RIBF discussion meeting on Cluster states probed by reaction experiments</td>
<td>Kyoto U.</td>
<td>Sep. 25</td>
</tr>
<tr>
<td>16</td>
<td>Advances and perspectives in computational nuclear physics</td>
<td>Hilton Waikoloa Village</td>
<td>Oct. 6</td>
</tr>
<tr>
<td>17</td>
<td>The 3rd Japan-Korea PHENIX Collaboration Meeting</td>
<td>Okouchi Hall</td>
<td>Nov. 27-28</td>
</tr>
<tr>
<td>18</td>
<td>The 2nd RIBF Discussion Plus! -basic course of mean field theory</td>
<td>Nishina Hall</td>
<td>Dec. 24</td>
</tr>
<tr>
<td>19</td>
<td>Workshop for development of beam line detectors with high rate capabilities</td>
<td>RIBF Conference Hall</td>
<td>Jan. 19</td>
</tr>
<tr>
<td>20</td>
<td>Workshop on Multi-Hadron and Nonlocal Matrix Elements in Lattice QCD</td>
<td>BNL</td>
<td>Feb. 5-9</td>
</tr>
<tr>
<td>21</td>
<td>順研研究会「これからの弦理论 ～ 橋本研 closing 研究会 ～」</td>
<td>Okouchi Hall</td>
<td>Feb. 21-22</td>
</tr>
</tbody>
</table>
### CNS

<table>
<thead>
<tr>
<th>No.</th>
<th>Event Title</th>
<th>Organizer</th>
<th>Location/Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Advances in Radioactive Isotope Science (Jointly organized by the RIKEN Nishina Center and the CNS)</td>
<td>U. Tokyo</td>
<td>June 1-6</td>
</tr>
<tr>
<td>2</td>
<td>The first Sicily-East Asia Workshop for Low-energy Nuclear Physics</td>
<td>Sicily, Italy</td>
<td>July 28 - 31</td>
</tr>
<tr>
<td></td>
<td><a href="https://agenda.infn.it/conferenceDisplay.py?confId=8300">https://agenda.infn.it/conferenceDisplay.py?confId=8300</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Progress in nuclear shell-model calculations in CNS-RIKEN collaboration</td>
<td>Nishina Hall, RIBF Conference Hall</td>
<td>Nov. 26-28</td>
</tr>
<tr>
<td></td>
<td><a href="http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=180">http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=180</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>第一回放射線によるイメージングの展望</td>
<td>U. Tokyo</td>
<td>Nov. 29</td>
</tr>
<tr>
<td></td>
<td><a href="http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=195">http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=195</a></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>第二回放射線によるイメージングの展望</td>
<td>U. Tokyo</td>
<td>Jan. 24</td>
</tr>
<tr>
<td></td>
<td><a href="http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=204">http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=204</a></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### KEK

<table>
<thead>
<tr>
<th>No.</th>
<th>Event Title</th>
<th>Organizer</th>
<th>Location/Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>「宇宙核物理実験の現状と将来」研究会</td>
<td>RCNP</td>
<td>Aug. 7-8</td>
</tr>
</tbody>
</table>
X. LIST OF SEMINARS
# List of Seminars (April 2014 - March 2015)

## Nuclear Physics Monthly Colloquium

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker(s)</th>
<th>Title</th>
<th>Conference URL</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yasuhiro Okada (KEK), Sachio Komamiya (U. Tokyo) &amp; Kaoru Yokoya (KEK)</td>
<td>International Linear Collider: From Design to Reality</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1651">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1651</a></td>
<td>Nov. 10</td>
</tr>
<tr>
<td>2</td>
<td>Koji Hashimoto (RNC)</td>
<td>Quark and superstring</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1711">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1711</a></td>
<td>Dec. 26</td>
</tr>
</tbody>
</table>

## RIBF Nuclear Physics Seminar

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker(s)</th>
<th>Title</th>
<th>Conference URL</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Takehito Hayakawa (JAEA)</td>
<td>Nuclear physics for nuclear security and nonproliferation</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1488">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1488</a></td>
<td>Apr. 22</td>
</tr>
<tr>
<td>2</td>
<td>Newcomers to Nishina Center in 2014</td>
<td>New-Comers Seminar in 2014</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1504">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1504</a></td>
<td>May 14</td>
</tr>
<tr>
<td>3</td>
<td>Zhengyu Xu (RNC/U. Hong Kong)</td>
<td>β-Decay properties in the vicinity of 78Ni and their implications on nuclear shell structure far off the b-stability line</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1505">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1505</a></td>
<td>May 30</td>
</tr>
<tr>
<td>4</td>
<td>Yuma Kikuchi (RNC)</td>
<td>Two-neutron correlations in the ground and excited states of 6He</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1545">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1545</a></td>
<td>Jul. 8</td>
</tr>
<tr>
<td>5</td>
<td>Shinya Wanajo (RIKEN iTHES)</td>
<td>Origin of the r-process elements</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1546">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1546</a></td>
<td>Jul. 15</td>
</tr>
<tr>
<td>6</td>
<td>Giuseppe Lorusso (RNC)</td>
<td>Beta-decay half-lives of N~82 nuclei on the r-process path</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1618">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1618</a></td>
<td>Sep. 30</td>
</tr>
<tr>
<td>8</td>
<td>Karl-Ludwig Kratz (U. Mainz)</td>
<td>One-day Workshop Program &quot;Recent progress on r-process and nucleosynthesis”</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1650">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1650</a></td>
<td>Nov. 25</td>
</tr>
<tr>
<td>9</td>
<td>Wataru Horiuchi (Hokkaido U.)</td>
<td>Correlated basis approach to nuclear five- and six-body problems</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1688">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1688</a></td>
<td>Nov. 25</td>
</tr>
<tr>
<td>10</td>
<td>Jean-Michel Daugas (CEA) et al.</td>
<td>Workshop on &quot;Progress in nuclear shell-model calculations in CNS-RIKEN collaboration”</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1684">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1684</a></td>
<td>Nov. 26-28</td>
</tr>
<tr>
<td>11</td>
<td>Kathrin Wimmer (U. Tokyo/CNS/RIKEN)</td>
<td>CNS &amp; Nuclear Physics Seminar : In-beam gamma-ray spectroscopy with GRETINA at the NSCL</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1698">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1698</a></td>
<td>Dec. 1</td>
</tr>
<tr>
<td>13</td>
<td>Nobuaki Imai (CNS)</td>
<td>Low-energy nuclear physics program at CNS 201</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1735">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1735</a></td>
<td>Jan. 20</td>
</tr>
<tr>
<td>15</td>
<td>Yutaka Watanabe (KEK, JPS)</td>
<td>Present status of KEK isotope separation system (KISS)</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1747">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1747</a></td>
<td>Feb. 17</td>
</tr>
<tr>
<td>16</td>
<td>Makoto Ito (Kansai U.)</td>
<td>Studies of the reaction size with the method of the scattering radius</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1798">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1798</a></td>
<td>Feb. 24</td>
</tr>
<tr>
<td>17</td>
<td>Nodoka Yamanaka (RIKEN iTHES)</td>
<td>Nuclear electric dipole moment of 3-body systems in the Gaussian expansion method</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1770">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1770</a></td>
<td>Mar. 3</td>
</tr>
<tr>
<td>No.</td>
<td>Name</td>
<td>Topic</td>
<td>URL</td>
<td>Date</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>18</td>
<td>John L. Wood (Georgia Inst. of Tech.)</td>
<td>Coexistence in Nuclei</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1777">link</a></td>
<td>Mar. 10</td>
</tr>
<tr>
<td>19</td>
<td>Takeyasu Ito (LANL)</td>
<td>Development of neutron electric dipole moment experiments at Los Alamos</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1791">link</a></td>
<td>Mar. 13</td>
</tr>
<tr>
<td>20</td>
<td>Tatsushi Shima (RCNP)</td>
<td>GLOBAL - ultra-low background experiment on the Earth's surface</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1782">link</a></td>
<td>Mar. 17</td>
</tr>
<tr>
<td>21</td>
<td>Wenlong Zhang (CAS)</td>
<td>ADANES: accelerator driven advance nuclear energy system</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1813">link</a></td>
<td>Mar. 27</td>
</tr>
<tr>
<td>22</td>
<td>Lei Yang (IMP)</td>
<td>Development of high flux neutron source and ADANES</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1814">link</a></td>
<td>Mar. 27</td>
</tr>
</tbody>
</table>

### Lecture Series on Nuclear Physics

not held in FY2014

### Special Seminar

not held in FY2014

### Seminar by Each Laboratory

#### Theoretical Research Division

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Topic</th>
<th>URL</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Daisuke Sato (RIKEN Low Temperature Physics Lab.)</td>
<td>Strangeness Nuclear Physics Seminar: 2 次元ヘリウム 3 の基底状態</td>
<td>-</td>
<td>Apr. 18</td>
</tr>
<tr>
<td>2</td>
<td>Shunji Matsuura (McGil U.)</td>
<td>Math Phys Seminar: Charged quantum entanglement</td>
<td>-</td>
<td>Apr. 21</td>
</tr>
<tr>
<td>3</td>
<td>Vojtech Krejcirik (RNC)</td>
<td>QHP Seminar: Model-independent form factor relations at large $N_c$</td>
<td>-</td>
<td>Apr. 21</td>
</tr>
<tr>
<td>4</td>
<td>Akihisa Kohama (RNC)</td>
<td>TNP Internal Seminar: Deformed nuclei in the black-sphere approximation</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1496">link</a></td>
<td>Apr. 22</td>
</tr>
<tr>
<td>5</td>
<td>Noriaki Ogawa (RNC)</td>
<td>QHP Seminar: Applications of AdS/CFT Correspondence to Real Physics</td>
<td>-</td>
<td>Apr. 28</td>
</tr>
<tr>
<td>6</td>
<td>Xiang Liu (Lanzhou U.)</td>
<td>QHP Seminar: Interpretation of some exotic hadrons via the initial single chiral particle emission mechanism</td>
<td>-</td>
<td>May 12</td>
</tr>
<tr>
<td>7</td>
<td>Shinya Wanajo (RIKEN ITHES) &amp; Yuto Teraki (RIKEN ABB Lab.)</td>
<td>ABB &amp; TNP Joint Group Seminar: The r-process and nuclear physics</td>
<td><a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1503">link</a></td>
<td>May 19</td>
</tr>
<tr>
<td>8</td>
<td>Yuma Kikuchi (RNC)</td>
<td>ABB &amp; TNP Joint Group Seminar: The r-process and nuclear physics</td>
<td>-</td>
<td>May 20</td>
</tr>
<tr>
<td>9</td>
<td>Kazuki Maeda (RNC)</td>
<td>QHP Seminar: Orthogonal polynomials and solutions to the discrete Toda lattice</td>
<td>-</td>
<td>May 26</td>
</tr>
<tr>
<td>10</td>
<td>Sho Ozaki (KEK)</td>
<td>QHP Seminar: QCD vacuum and hadron properties in strong magnetic fields</td>
<td>-</td>
<td>Jun. 2</td>
</tr>
<tr>
<td>#</td>
<td>Name</td>
<td>Seminar Details</td>
<td>Date</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>-----------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Kazuya Mameda (U. Tokyo)</td>
<td>QHP Seminar: QCD theta-vacua from the chiral limit to the quenched limit</td>
<td>Jun. 9</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Takashi Nakatsukasa (RNC)</td>
<td>TNP Internal Seminar: Constraint or cranking?</td>
<td>Jun. 30</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Yukinao Akamatsu (KMI)</td>
<td>QHP Seminar: Heavy quark master equations in the Lindblad form</td>
<td>Jun. 30</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Takahiro Nishi (U. Tokyo)</td>
<td>QHP Seminar: Deeply bound-pionic atom and partial restoration of chiral symmetry in nuclear medium</td>
<td>Jul. 10</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Pablo Morales (U. Tokyo)</td>
<td>QHP Seminar: Spontaneous symmetry breaking and particle production in curved spaces</td>
<td>Jul. 14</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Koukei Washiyama (RNC)</td>
<td>TNP Internal Seminar: Microscopic analysis of fusion hindrance in heavy systems</td>
<td>Jul. 15</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Pablo Soler Gomis (Hong Kong U. of Sci. &amp; Tech.)</td>
<td>Math Phys Seminar: U(1) portals into hidden sectors</td>
<td>Jul. 18</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Toshiyuki Gogami (Kyoto U.)</td>
<td>Strangeness Nuclear Physics Seminar: Spectroscopic research of ¥Lambda hypernuclei with high quality electron beam at Jefferson Lab</td>
<td>Jul. 18</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Yuma Kikuchi (RNC)</td>
<td>ABB &amp; TNP Joint Group Seminar: Search for exotic n-n correlations in weakly-bound nuclei</td>
<td>Jul. 28</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Don Warren (North Carolina State U.)</td>
<td>ABB &amp; TNP Joint Group Seminar: Cosmic-Ray Acceleration and Photon Production during the Afterglow Phase of Gamma-ray Bursts</td>
<td>Jul. 28</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Alexander Karpov (FLNR)</td>
<td>Nuclear Theory Seminar: Superheavy nuclei: Which regions of nuclear map are accessible in nearest future?</td>
<td>Jul. 28</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Takahiro Sasaki (U. Tokyo)</td>
<td>QHP Seminar: Studying the QCD phase diagram with PNJL type effective model</td>
<td>Jul. 28</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Shin Nakamura (Chuo U.)</td>
<td>Strangeness Nuclear Physics Seminar: Ads/CFT 対応を用いた非平衡統計物理学への挑戦</td>
<td>Aug. 1</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Pengwei Zhao (Kyoto U.)</td>
<td>Nuclear Theory Seminar: Novel Nuclear Structure from Covariant Density Functional</td>
<td>Sep. 1</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Daisuke Satow (RIKEN)</td>
<td>QHP Seminar: Nonlinear Electromagnetic Response in Quark-Gluon Plasma</td>
<td>Sep. 17</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Sho Nagao (Tohoku U.)</td>
<td>Strangeness Nuclear Physics Seminar: Spectroscopy of electro-produced hypernuclei at Mainz Microtron</td>
<td>Sep. 29</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Yoshitomo Kamiya (RIKEN ITHES/CMT Lab.)</td>
<td>QHP Seminar: Magnetic Vortex Crystals in Frustrated Mott Insulator</td>
<td>Oct. 15</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Tomoya Takiwaki (RIKEN ABB Lab.)</td>
<td>ABB-TNP Joint Lunch Time Seminar: Impact of electron capture rate and equation of state on the supernovae explosions</td>
<td>Oct. 20</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Name and Affiliation</td>
<td>Seminar Details</td>
<td>Date</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Hajime Togashi (RNC)</td>
<td>ABB-TNP Joing Lunch Time Seminar: Supernova equation of state with the cluster variational method</td>
<td>Oct. 20</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Koichiro Asahi (Tokyo Tech.)</td>
<td>Pioneer project seminar: Search for a Permanent Electric Dipole Moment in Diamagnetic Atom 129Xe</td>
<td>Oct. 31</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Guido Cossu (KEK)</td>
<td>QHP Seminar: Magnetic Vortex Crystals in Frustrated Mott Insulator</td>
<td>Nov. 4</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Alexander G. Magner (Inst. for Nuclear Research)</td>
<td>Nuclear Theory Seminar: Semiclassical approaches to the macroscopic and microscopic nuclear dynamics</td>
<td>Nov. 14</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Hyun-Chul Kim (Inha U.)</td>
<td>Strangeness Nuclear Physics Seminar: The charge and spin structure of the nucleon and the pion</td>
<td>Nov. 14</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Seiji Terashima (YITP)</td>
<td>Math Phys Seminar: A Localization Computation in Confining Phase</td>
<td>Nov. 17</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Sahin Kaya Ozdemir (Washington U., St. Louis)</td>
<td>QHP Seminar: Controlling light at the exceptional points with whispering gallery microresonators</td>
<td>Nov. 17</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Nguyen Dinh Dang (RNC)</td>
<td>TNP Internal Seminar: Recent achievements in the study of highly excited nuclei: Thermal pairing and giant dipole resonance in not rotating nuclei</td>
<td>Nov. 18</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Masaki Murata (Academy of Sci. of the Czech Republic)</td>
<td>Math Phys Seminar: 境界のある共形場理論による透過率</td>
<td>Nov. 28</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>Kantaro Ohmori (U. Tokyo)</td>
<td>Math Phys Seminar: Anomaly polynomial of general 6d SCFTs</td>
<td>Dec. 15</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>Yuji Tachikawa (U. Tokyo)</td>
<td>QHP Seminar: Magnetic discrete gauge field in the confining vacua and the supersymmetric index</td>
<td>Dec. 22</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Hiromichi Nishimura (Bielefeld U.)</td>
<td>QHP Seminar: Complex saddle points in finite-density QCD</td>
<td>Dec. 22</td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>Yu Maezawa (Bielefeld U.)</td>
<td>QHP Seminar: Thermal modification of in-medium mesons from screening properties on lattice</td>
<td>Dec. 22</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>Koichi Sato (RNC)</td>
<td>TNP Internal Seminar: Proton-neutron mixing calculation with isospin breaking term</td>
<td>Dec. 24</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Kazunobu Maruyoshi (Imperial College London)</td>
<td>Math Phys Seminar: 4d N=1 SCFTs from M5-branes</td>
<td>Jan. 16</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Masafumi Fukuma (Kyoto U.)</td>
<td>QHP Seminar: Entropic formulation of (relativistic) continuum mechanics and a causal completion of relativistic fluid mechanics</td>
<td>Jan. 19</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Shu Lin (RBRC)</td>
<td>QHP Seminar: Axial charge dynamics in quark gluon plasma</td>
<td>Feb. 5</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Tohru Motobayashi (RNC)</td>
<td>ABB-TNP Joint Lunch Time Seminar: First access to the r-process path</td>
<td>Feb. 9</td>
<td></td>
</tr>
</tbody>
</table>

- 540 -
### X. LIST OF SEMINARS

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker</th>
<th>Seminar/Conference</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>Osamu Morimatsu (KEK)</td>
<td>QHP Seminar: Dynamic Critical Exponent from One and Two-Particle Irreducible 1/N Expansion of Effective and Microscopic Theories</td>
<td>Feb. 9</td>
</tr>
<tr>
<td>56</td>
<td>Sanjin Benić (U. Tokyo)</td>
<td>QHP Seminar: An effective model for the QCD phase transitions at finite baryon density</td>
<td>Mar. 2</td>
</tr>
<tr>
<td>57</td>
<td>Hironori Hoshino (Nagoya U.)</td>
<td>Math Phys Seminar: ホログラフィーによる非平衡密度物質の有限温度の解析</td>
<td>Mar. 9</td>
</tr>
<tr>
<td>59</td>
<td>Luca Delacrétaz (Stanford U.)</td>
<td>Math Phys Seminar: Wess-Zumino terms in theories with spontaneously broken space-time symmetries</td>
<td>Mar. 26</td>
</tr>
<tr>
<td>60</td>
<td>Hiroshi Isono (National Tsing Hua U.)</td>
<td>Math Phys Seminar: Note on the self-duality of gauge fields in topologically nontrivial spacetime</td>
<td>Mar. 30</td>
</tr>
</tbody>
</table>

**Sub Nuclear System Research Division**

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker</th>
<th>Seminar/Conference</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kaustubh Agashe (U. Maryland)</td>
<td>Joint HET/YITP/RIKEN Seminar: Using energy-peaks to measure particle (new and old) masses</td>
<td>Apr. 9</td>
</tr>
<tr>
<td>2</td>
<td>Adam Ritz (U. Victoria)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Light dark matter and neutrino beams</td>
<td>Apr. 16</td>
</tr>
<tr>
<td>3</td>
<td>Adam Bzdak (RBRC)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Apr. 17</td>
</tr>
<tr>
<td>4</td>
<td>Hong Liu (MIT)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Renormalized entanglement entropy and RG flows</td>
<td>Apr. 18</td>
</tr>
<tr>
<td>6</td>
<td>Roy Lacey (Stony Brook U.)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Apr. 24</td>
</tr>
<tr>
<td>7</td>
<td>Thomas Mehen (Duke U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Fragmentation Functions and Fragmenting Jet Functions in Quarkonium Production</td>
<td>Apr. 25</td>
</tr>
<tr>
<td>9</td>
<td>Toru Kojo (U. Illinois – Urbana-Champaign)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: The quark mass gap in strong magnetic fields</td>
<td>May 9</td>
</tr>
<tr>
<td>10</td>
<td>Shu Lin (RBRC)</td>
<td>RIKEN/BNL Lunch Time Talk: On the axial charge dynamics at strong coupling</td>
<td>May 15</td>
</tr>
<tr>
<td>11</td>
<td>J.D. Vergados (U. Ioannina)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Relic Neutrinos in Cosmology-The prospects of detecting relic antineutrinos by capturing them in nuclei</td>
<td>May 28</td>
</tr>
<tr>
<td>12</td>
<td>Martin Hentschinski (BNL)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>May 29</td>
</tr>
<tr>
<td>13</td>
<td>Takumi Doi (RNC) et al.</td>
<td>訪問講演 第2回 高エネルギーQCD・核子構造 講演会 <a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1515">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1515</a></td>
<td>May 30</td>
</tr>
<tr>
<td>14</td>
<td>Naoto Tanji (RIKEN/BNL)</td>
<td>RIKEN/BNL Lunch Time Talk: Real-time lattice simulations of fermion fields and Quark production in heavy-ion collisions</td>
<td>Jun. 5</td>
</tr>
<tr>
<td>15</td>
<td>Ron Longacre (BNL)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Flow or Flux Tubes or both</td>
<td>Jun. 6</td>
</tr>
<tr>
<td>No.</td>
<td>Speaker</td>
<td>Seminar Type</td>
<td>Topic</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------------------</td>
<td>----------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
</tr>
<tr>
<td>16</td>
<td>Masanori Hanada (YITP)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td>Why does black hole describe deconfinement phase?</td>
</tr>
<tr>
<td>17</td>
<td>Thomas Hambye (UCL, Brussel)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar</td>
<td>On the possibilities of probing a hidden sector dark matter particle</td>
</tr>
<tr>
<td>18</td>
<td>Sean Bartz (U. Minnesota)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td>A Dynamical Three-Field AdS/QCD Model</td>
</tr>
<tr>
<td>19</td>
<td>Masakiyo Kitazawa (Osaka U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Philipp Scior (TU Darmstadt)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Effective Theories with heavy quarks on the lattice</td>
</tr>
<tr>
<td>21</td>
<td>Ahmed Ismail (ANL &amp; UIC)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar</td>
<td>When is a top quark a parton?</td>
</tr>
<tr>
<td>22</td>
<td>Juchien Xu (Columbia U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Yuki Yokokura (Kyoto U.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Al Mueller (Columbia U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td>Fluctuations and geometric scaling in statistical and particle physics</td>
</tr>
<tr>
<td>25</td>
<td>Tigran Kalaydzhyan (Stony Brook U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td>Interaction of QCD strings and collective phenomena</td>
</tr>
<tr>
<td>26</td>
<td>Masashi Hayakawa (Nagoya U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td>Upgrade of QED contribution to lepton $\delta g-2$</td>
</tr>
<tr>
<td>27</td>
<td>Terukazu Ichihara (Kyoto U.)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>QCD phase diagram with both fluctuation and finite coupling effects in the strong coupling lattice QCD</td>
</tr>
<tr>
<td>28</td>
<td>Adrian Dumitru (Baruch College)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Tom Blum (Univ of Connecticut)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar</td>
<td>Nucleon Electric Dipole Moments</td>
</tr>
<tr>
<td>30</td>
<td>Koichi Hattori (RIKEN/RBRC)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Photon propagations and charmonium spectroscopy in strong magnetic fields</td>
</tr>
<tr>
<td>31</td>
<td>Gabriel Denicol (McGill U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Ralf Seidl, Yasuyuki Akiba (RNC) et al.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Shoichiro Tsutsui (Kyoto U.)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Parametric instabilities of color magnetic field</td>
</tr>
<tr>
<td>34</td>
<td>Qun Wang</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Chris Korthals Altes (NIKHEF &amp; Centre Physique Theorique au CNRS)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>What causes the instability of the Stefan-Boltzmann plasma?</td>
</tr>
<tr>
<td>36</td>
<td>Bjoern Schenke</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Name</td>
<td>Event details</td>
<td>Date</td>
</tr>
<tr>
<td>-----</td>
<td>---------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>39</td>
<td>Stefan Meinel (U. Arizona/RBRC)</td>
<td>RIKEN/BNL Lunch Time Talk: Heavy baryons in lattice QCD</td>
<td>Oct. 2</td>
</tr>
<tr>
<td>40</td>
<td>Ayres Freitas (U. Pittsburgh)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Opening the loops: The muon g-2 at the LHC</td>
<td>Oct. 8</td>
</tr>
<tr>
<td>41</td>
<td>Steffen Bass</td>
<td>RHIC &amp; Users’ Group Open Forum Meeting</td>
<td>Oct. 9</td>
</tr>
<tr>
<td>42</td>
<td>Isao Watanabe, Noraina Adam, Siadah Sakinah, Edi Suprayoga (RNC)</td>
<td>DFT 法によるミュオン位置計算セミナー</td>
<td>Oct. 16</td>
</tr>
<tr>
<td>43</td>
<td>Piotr Korczył (Columbia U.)</td>
<td>RIKEN/BNL Lunch Time Talk: A non-perturbative renormalization scheme in position space: A non-perturbative renormalization scheme in position space</td>
<td>Oct. 16</td>
</tr>
<tr>
<td>44</td>
<td>Ho-Ung Yee (U. Illinois – Chicago)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Aspects of Chiral Magnetic and Vortical Effects at Weak Coupling</td>
<td>Oct. 17</td>
</tr>
<tr>
<td>45</td>
<td>Majed Jawad (RNC)</td>
<td>Advanced Meson Science Lab. seminar</td>
<td>Oct. 23</td>
</tr>
<tr>
<td>47</td>
<td>Eugene Levin (Tel Aviv U. &amp; UTFSM)</td>
<td>RIKEN/BNL Lunch Time Talk: Large $b\bar{b}$ behaviour and CGC/saturation approach: the BFKL equation with massive gluon</td>
<td>Oct. 30</td>
</tr>
<tr>
<td>48</td>
<td>Yuji Hirono (Stony Brook U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Charge-dependent correlations from event-by-event anomalous hydrodynamics</td>
<td>Oct. 31</td>
</tr>
<tr>
<td>49</td>
<td>Itaru Nakagawa (RNC et al.)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: <a href="http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1653">http://indico2.riken.jp/indico/conferenceDisplay.py?confId=1653</a></td>
<td>Nov. 1</td>
</tr>
<tr>
<td>50</td>
<td>Simone Marzani (MIT)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: The Higgs Cross Section from Analyticity</td>
<td>Nov. 5</td>
</tr>
<tr>
<td>51</td>
<td>Alfonso Sastre (Bergische U. Wuppertal)</td>
<td>Joint Riken Lunch/Nuclear Theory/RIKEN Seminar: Some results on Lattice QCD at the physical point: SU(2) chiral perturbation theory and some words about hadron vacuum polarization</td>
<td>Nov. 6</td>
</tr>
<tr>
<td>52</td>
<td>Yuta Kikuchi (Kyoto U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Derivation of the Hydrodynamic Equation from the Quantum Transport Equation</td>
<td>Nov. 7</td>
</tr>
<tr>
<td>53</td>
<td>Zackaria Chacko (Maryland)</td>
<td>Joint HET/YITP/RIKEN Seminar: Colorless Top Partners, a 125 GeV Higgs and the Limits on Naturalness</td>
<td>Nov. 12</td>
</tr>
<tr>
<td>54</td>
<td>Kirill Boguslavski (U. Heidelberg)</td>
<td>RIKEN/BNL Lunch Time Talk</td>
<td>Nov. 13</td>
</tr>
<tr>
<td>55</td>
<td>Ismail Zahed (Stony Brook U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Holographic Strings in ep, pp and pA</td>
<td>Nov. 14</td>
</tr>
<tr>
<td>57</td>
<td>Jacquelyn Noronha-Hostler (Columbia U.)</td>
<td>RIKEN/BNL Lunch Time Talk: Bulk viscosity-driven suppression of shear viscosity effects on the flow harmonics at RHIC</td>
<td>Nov. 20</td>
</tr>
<tr>
<td>58</td>
<td>Anna Stasto (Penn State U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Scattering amplitudes and recursion relations in light-front perturbation theory</td>
<td>Nov. 21</td>
</tr>
<tr>
<td>59</td>
<td>Nils Strodthoff (Heidelberg U.)</td>
<td>RIKEN/BNL Lunch Time Talk: Exploring the phase structure and the dynamics of QCD</td>
<td>Dec. 4</td>
</tr>
<tr>
<td>60</td>
<td>Yachao Qian (Stonybrook U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Spin Asymmetries and P-odd effects through QCD instantons</td>
<td>Dec. 5</td>
</tr>
<tr>
<td>No.</td>
<td>Name</td>
<td>Seminar Type</td>
<td>Date</td>
</tr>
<tr>
<td>-----</td>
<td>---------------------------</td>
<td>--------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>62</td>
<td>Yuki Okura (BNL)</td>
<td>RIKEN/BNL Lunch Time Talk: LSST sensor effect in constraining the cosmological parameter</td>
<td>Dec. 11</td>
</tr>
<tr>
<td>64</td>
<td>Isao Watanabe, Norainah Adam, Siadah Sakinah, Edi Suprayoga, Sungwan Yoon</td>
<td>RIKEN Seminar: USM-Sophia-Riken International Workshop on Frontiers of Muon Physics Program</td>
<td>Dec. 15-16</td>
</tr>
<tr>
<td>65</td>
<td>Toh Pek Lan (U. Sains Malaysia)</td>
<td>Indonesia/Malaysia Seminar: Penyiasatan Teori Fungsi Ketumpatan untuk Struktur Elektronik dan Interaksi Hiperhalus bagi Muonium dalam Terbitan Imidazole</td>
<td>Dec. 17</td>
</tr>
<tr>
<td>66</td>
<td>Peter Lepage (Cornell)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: High-Precision QCD Parameters from Lattice QCD</td>
<td>Dec. 17</td>
</tr>
<tr>
<td>67</td>
<td>Satri Zulkarnaen Bisri (CEMS)</td>
<td>Indonesia/Malaysia Seminar: Electronic Transport in Nanomaterials</td>
<td>Dec. 18</td>
</tr>
<tr>
<td>68</td>
<td>Hans-Peter Schadler (U. Graz)</td>
<td>RIKEN/BNL Lunch Time Talk: Generalized quark number susceptibilities at finite chemical potential from fugacity expansion on the lattice</td>
<td>Dec. 18</td>
</tr>
<tr>
<td>69</td>
<td>Toru Kojo (U. Illinois - Urbana-Champaign)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Phenomenological QCD equation of state for massive neutron stars</td>
<td>Dec. 19</td>
</tr>
<tr>
<td>71</td>
<td>Vladimir Skokov (Western Michigan U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Anisotropy of the semi-classical gluon field of a large nucleus at high energy</td>
<td>Jan. 9</td>
</tr>
<tr>
<td>72</td>
<td>Yue Zhang (Caltech)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Exploring Dark Matter and Baryon Asymmetry: Higgs is the Key</td>
<td>Jan. 14</td>
</tr>
<tr>
<td>73</td>
<td>Sayantan Sharma (BNL)</td>
<td>RIKEN/BNL Lunch Time Talk: The origin of axial anomaly and the high temperature phase of QCD</td>
<td>Jan. 15</td>
</tr>
<tr>
<td>75</td>
<td>Julia Angel (Saitama U.)</td>
<td>Indonesia/Malaysia Seminar: Crystal Growth and Magnetism of Layered Antiferromagnet Deuterated κ-(BEDT-TTF)2Cu[N(CN)2]Br</td>
<td>Jan. 23</td>
</tr>
<tr>
<td>76</td>
<td>Wilke van der Schee (MIT)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Strong coupling QGP thermalization with longitudinal dynamics</td>
<td>Jan. 23</td>
</tr>
<tr>
<td>77</td>
<td>Grigory Ovanesyan (U. Massachusetts Amherst)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Regge behavior in effective field theory</td>
<td>Jan. 30</td>
</tr>
<tr>
<td>78</td>
<td>Antonin Portelli (U. Southampton)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Ab initio calculation of the neutron-proton mass difference</td>
<td>Feb. 4</td>
</tr>
<tr>
<td>79</td>
<td>Vincenzo Cirigliano (Los Alamos)</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: Electric Dipole Moments, New Physics, and (lattice) QCD</td>
<td>Feb. 11</td>
</tr>
<tr>
<td>80</td>
<td>Tigran Kalaydzyhan (Stony Brook U.)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Gravity waves generated by sounds from cosmological phase transitions</td>
<td>Feb. 13</td>
</tr>
<tr>
<td>82</td>
<td>Mariene Nahrgang</td>
<td>Theory and Modeling for the beam energy scan: From Exploration to Discovery</td>
<td>Feb. 26-27</td>
</tr>
<tr>
<td>83</td>
<td>Samuel MacDermott</td>
<td>High-Energy Physics &amp; RIKEN Theory Seminar: The Galactic Center Gamma-ray Excess: Have We Started to See Dark Matter?</td>
<td>Mar. 4</td>
</tr>
<tr>
<td>#</td>
<td>Name</td>
<td>Title</td>
<td>Date</td>
</tr>
<tr>
<td>----</td>
<td>---------------------------------------------------</td>
<td>--------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>84</td>
<td>Constantin Loizides</td>
<td>Collectivity in small colliding systems with high multiplicity</td>
<td>Mar. 4-6</td>
</tr>
<tr>
<td>86</td>
<td>Luca Vecchi (U. Maryland)</td>
<td>HET/RIKEN Seminar: Spontaneous CP violation and the strong CP problem</td>
<td>Mar. 18</td>
</tr>
<tr>
<td>87</td>
<td>Antonio Ortiz Velasquez (National Autonomous U. Mexico)</td>
<td>Nuclear Physics &amp; RIKEN Theory Seminar: Flow like behavior in small systems -- Multi-parton interactions and color reconnection effects at LHC energies</td>
<td>Mar. 20</td>
</tr>
<tr>
<td>88</td>
<td>Can Kilic (U. Texas – Austin)</td>
<td>HET/RIKEN Seminar: Flavored Dark Matter with Weak Scale Mediators</td>
<td>Mar. 25</td>
</tr>
</tbody>
</table>

### RIBF Research Division

<table>
<thead>
<tr>
<th>#</th>
<th>Name</th>
<th>Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hermann Wollnik (Giessen)</td>
<td>A mass spectrometer for the ROSETTA space-mission to a comet</td>
<td>Apr. 9</td>
</tr>
<tr>
<td>2</td>
<td>Toshiro Shigaki (Papua New Guinea National Agricultural Research Inst.)</td>
<td>パプアニューギニアおよびソロモン諸島におけるサツマイモ並びにアイビカ（トロロアオイ）の遺伝資源管理と品種改良</td>
<td>May 14</td>
</tr>
<tr>
<td>4</td>
<td>Claudio Ricci (Kyoto U.)</td>
<td>High Energy Astrophysics Lab. Seminar: X-ray reflection features as a probe of the structure and evolution of circumnuclear material in Active Galactic Nuclei</td>
<td>Jul. 4</td>
</tr>
<tr>
<td>5</td>
<td>Takayuki Yuasa (RNC)</td>
<td>High Energy Astrophysics Lab. Seminar: White dwarf mass estimation method based on X-ray spectral modeling</td>
<td>Jul. 17</td>
</tr>
<tr>
<td>6</td>
<td>Ken Takayama (KEK)</td>
<td>RIBF Accelerator Seminar: Induction microtron and its application</td>
<td>Jul. 31</td>
</tr>
<tr>
<td>7</td>
<td>Renata S. Cumbee (U. Georgia)</td>
<td>Charge Exchange in the Cygnus Loop?</td>
<td>Aug. 8</td>
</tr>
<tr>
<td>8</td>
<td>Hiroyoshi Sakurai &amp; Tomohiro Uesaka (RNC)</td>
<td>Lectures for theory researchers: Current status and future of RIBF experiments (I)</td>
<td>Aug. 18</td>
</tr>
<tr>
<td>9</td>
<td>Yoichi Nagashima (Copenhagen U.) &amp; Hiroshi Ezawa (Gakushuin U.)</td>
<td>Bohr's 8mm film in 1937</td>
<td>Oct. 24</td>
</tr>
<tr>
<td>10</td>
<td>Yukari Matsuo (Hosei U.)</td>
<td>Nuclear Spectroscopy Laboratory Seminar: 超流動ヘリウム中原子の精密レーザー分光 -OROCHI-</td>
<td>Oct. 31</td>
</tr>
<tr>
<td>11</td>
<td>Tomoko Abe (RNC)</td>
<td>戦略的オミクス育種技術体系の構築</td>
<td>Nov. 21</td>
</tr>
<tr>
<td>12</td>
<td>Benoit Gall (Strasbourg U.)</td>
<td>How did Earth generate and operate more than 15 Natural Nuclear Reactors?</td>
<td>Dec. 15</td>
</tr>
<tr>
<td>14</td>
<td>Yoshio Kobayashi (U. Electro-Communications)</td>
<td>Nuclear Spectroscopy Laboratory Seminar: 短寿命不安定核を用いたインビーム・メスバウアー分光法の物質科学への応用</td>
<td>Mar. 11</td>
</tr>
<tr>
<td>15</td>
<td>Shinsuke Fujoka (Osaka U.)</td>
<td>High Energy Astrophysics Laboratory Seminar: Application of laser-generated strong magnetic field to plasma physics research</td>
<td>Mar. 12</td>
</tr>
<tr>
<td>16</td>
<td>Hideki Ueno (RNC)</td>
<td>Lectures for theory researchers: Current status and future of RIBF experiments (II)</td>
<td>Mar. 20</td>
</tr>
</tbody>
</table>
### CNS

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker</th>
<th>Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Kathrin Wimmer (U. Tokyo/CNS)</td>
<td>In-beam gamma-ray spectroscopy with GRETINA at the NSCL</td>
<td>Dec. 1</td>
</tr>
<tr>
<td>2</td>
<td>Javier Menendez (U. Tokyo)</td>
<td>From nuclear structure to neutrinos and dark matter</td>
<td>Dec. 16</td>
</tr>
<tr>
<td>3</td>
<td>Tetsuya Sakurai (U. Tsukuba)</td>
<td>A Scalable Parallel Eigensolver for Large-scale Simulations on Petascale Computing Environment</td>
<td>Jan. 19</td>
</tr>
</tbody>
</table>

### Niigata Univ.

<table>
<thead>
<tr>
<th>No.</th>
<th>Speaker</th>
<th>Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yuma Kikuchi (RNC)</td>
<td>Two-neutron correlations in the ground and excited states of 6He</td>
<td>Sep. 18</td>
</tr>
<tr>
<td>2</td>
<td>A. G. Magner (Institute for Nuclear Research, Kyiv)</td>
<td>Semiclassical shell-structure moment of inertia within the phase-space approach</td>
<td>Nov. 11</td>
</tr>
<tr>
<td>3</td>
<td>Yoshihumi Shimizu (Kyushu U.)</td>
<td>角運動量射影法によるエキゾチックな歪形・回転状態の研究</td>
<td>Nov. 27</td>
</tr>
<tr>
<td>4</td>
<td>Takayuki Yamaguchi (Saitama U.)</td>
<td>重イオンビーム荷電変化反応による不安定核の陽子分布半径</td>
<td>Jan. 22</td>
</tr>
</tbody>
</table>
AUTHOR INDEX

A
ABDEL-JAWAD Majed 258, 273
ABE Hiroshi 313
ABE Tomoko 301, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316
ABE Yuzo 24, 76, 231, 232
ACHARI N.Lynda 42, 44, 45
ADACHI Shintaro 257
ADACHI Tadashi 257, 258
ADAM Noraina 268, 269
ABE Tomoko 301, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316
ABE Yasushi 24, 76, 231, 232
ABE Yugo 154
ACHOURI N.Lynda 42, 44, 45
ADACHI Shintaro 257
ADACHI Tadashi 257, 258
ADAM Noraina 268, 269
ADARE Andrew 112, 113, 114
ADAPRASAN Budi 269
ADRIANAL Biju Kumar 90
AHMAD Siti Nur Afifi 268
AHN Deuk Soon 6, 9, 11, 31, 32, 39, 54, 71, 72, 73, 74, 75, 235
AIHARA Toshimitsu 326
AIKAWA Masayuki 6, 97, 98, 99
AIKAWA Shu 125
AISO Hiroko 323
AKAISHI Yoshinori 140, 141, 142
AKASHIO Atsuko 238, 323
AKIBA Yasuyuki 111, 112, 113, 114, 122, 245
AKIMITSU Jun 265
AKIYOSHI Hideharu 168
ALAGU Manickavelu 314
ALHARBI Thamer 35
ANDREYEV Andrei 47, 48, 49, 202
AOI Nori 4, 33, 34, 36, 37, 38, 40, 61, 209, 210
AOKI Yasumichi 144
ASAI Masato 26, 70, 282, 283
ASAKURA Kiyotaka 275
ASAMI Fumi 179
ASANO Hidemitsu 111, 112, 113, 114, 245
ASSIÉ Mariène 7, 55
BABA Hidetada 3, 4, 5, 6, 7, 21, 25, 29, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 44, 45, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 62, 72, 202, 203, 204, 210, 215, 230, 246, 249
BABA Tatsuo 7, 55
BAHTIAR Ayi 272
BAN Tomohiro 314
BANERJEE Kaushik 77
BANERJEE Sudhee 38
BAQIYA Malik A. 257, 258
BARNEY Jon 204, 206
BEANE Silas 128
BEAUMEL Didier 7, 55, 56, 57, 62
BEDNARZYK Piotr 4
BELLO CARBOTE Frank L. 31, 32, 33, 34
BENNETT Douglas 77
BENNETT Douglas 77
BENTZ Wolfgang 132
BENZONI Giusanana 41
BERENCZY Réka Judit 315, 316
BERG Geor 59, 60, 235
BERNER Christian 69
BECKAKI Andre A. 62
BHATTACHARYA Sirjil 77
BLACK Kevin 175
BLANK Bertram 29
BLASI Niex 41
BLAZHEV Andrei 29
BOMMER Michael 47, 48, 49, 202
BOHANO Albenos 66
BOHANO Ciro 66
BOISSINOT Simon 4
BORETZKY Konstanze 39, 41
BOUYET Denis 5, 32
BRADY Angela 38, 39, 41
BRAFA Davide 247
BRAMBILLA Sergio 41
BRAND Holger 26, 282
BROWNE Frank 3, 5, 29, 31, 32, 33, 34, 35
BRUCE Alison 35
BRUSILOVSKYI Jason 111, 112, 113, 114
BRZYCZYKI Janusz 205
BUKKER Ian 247

C
CAESAR Christoph 38, 39, 52
CALYETT Denis 5, 32
CAMERA Francesca 38, 39, 41
CARROLL Robert 35
CAUSSEN Sarah 101, 103
CELIKOVIC Igor 29
CERUTI Simone 38, 41
CHAE Hyeonwoo 62
CHAE Kyeonguk 35
CHAKRABARTY Dipak R 90
CHANG Emmanuel 128
CHANG Woo-Chen 244
CHAO Wen-Chen 21, 51, 54, 203, 211
CHATEAU Frederic 5
CHEBRTOTTOV Sergey 62, 218, 224
CHEN Sidong 38, 41
CHIBA Masaki 97
CHICA Nobuko 50
CHITONISHIOI Lori 281
CHOI SungHo 62
CHU Miho Lee 244
CHUJO Tatsuro 120
CHUNG Le Xuans 5
CIEMALA Michal 4
CLOT Ian 132
COHEN Saol 128
COLE Ryan 175
COLEMAN-SMITH Patrick 247
CORI Ansa 4, 5, 52
CRESPI Fabio Cesio Luigi 41
CSATLÓS Marianna 54
CURCIEAȘU Carolina 12
CURRAN Mark 167

D
DAMDO Rue 31, 32, 33, 34
DANYSUKA Tomoyuki 328, 329, 331
DAS Sarah 167
DATAR Vivek M 90
DUMAGAN Jean-Michel 31, 32
DAVISON Thomas 247
DE Aleskrammer 77
DE FRANCE Gilles 29
DELAUNAY Francois 42, 44, 45
DELBART Alan 5, 52
DEMICHINI Kimikio 209
DERIVA Vincenzo 38, 39
DettMOLD William 128
DEY Babarun 77
DI NITTO Antonio 26, 282
DIDIERJEAN Francois 31
DENH DANG Nguyen 77, 80, 90, 91
DOBACZEWSKI Jakub 81
DOMBRADI Zsolt 5, 35, 40, 54
DOMBRADI Zolt 1, 3, 5, 6, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 44, 45, 50
DOORBIENBAUER Peter 77
DORRIESE William 12
DOZONO Masanori 7, 21, 47, 48, 49, 51, 52, 54, 55, 56, 57, 58, 59, 60, 202
DORRIO Andrea 203, 235
DÖLLMANN Christoph E. 26, 282

E
EBARA Yuki 8
EBATA Shuichi 97, 98, 99
EBBEL Holm 143
EDWARDS Rose 167
EGAMI Tatsushi 64, 65
EICHLER Robert 26, 282
<table>
<thead>
<tr>
<th>Name</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATANABE Yumi</td>
<td>217, 215, 216</td>
</tr>
<tr>
<td>WATANABE Yutaka</td>
<td>19, 197, 215, 326, 327, 331</td>
</tr>
<tr>
<td>WATANABE Yutaka X.</td>
<td>66, 234</td>
</tr>
<tr>
<td>WEECK Helmut</td>
<td>235</td>
</tr>
<tr>
<td>WERNER Volker</td>
<td>3, 5</td>
</tr>
<tr>
<td>WIDMANN Elberth</td>
<td>12</td>
</tr>
<tr>
<td>WIEHL Norbert</td>
<td>26, 282</td>
</tr>
<tr>
<td>WIELAND Oliver</td>
<td>38, 39, 41</td>
</tr>
<tr>
<td>WIMMER Kathar</td>
<td>38</td>
</tr>
<tr>
<td>WOLNINKI Hermann</td>
<td>22, 216, 226</td>
</tr>
<tr>
<td>WOODNI Philiph</td>
<td>247</td>
</tr>
<tr>
<td>WU Jia</td>
<td>3, 5, 29, 31, 32, 33, 34, 35, 40</td>
</tr>
<tr>
<td>WU Qiang</td>
<td>2</td>
</tr>
<tr>
<td>WYSOCKI Mark</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
</tr>
<tr>
<td>XI Fuming</td>
<td>2</td>
</tr>
<tr>
<td>XI Xing-Liang</td>
<td>262</td>
</tr>
<tr>
<td>XI Zhangu</td>
<td>1, 3, 5, 28, 29, 30, 31, 32, 33, 34, 35, 40</td>
</tr>
<tr>
<td>XI Zhiuan</td>
<td>261, 266</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>YADOMI Kanyoshibi</td>
<td>19, 327, 331</td>
</tr>
<tr>
<td>YAGI Arumi</td>
<td>3, 31, 32, 33, 34, 35, 71, 72</td>
</tr>
<tr>
<td>YAGI Eniko</td>
<td>252</td>
</tr>
<tr>
<td>YAKO Kentauro</td>
<td>7, 21, 51, 54, 55, 56, 57, 58, 59, 60, 203, 220, 319</td>
</tr>
<tr>
<td>YAKUSHIY Alexander</td>
<td>26, 262</td>
</tr>
<tr>
<td>YAMADA Aritos</td>
<td>291</td>
</tr>
<tr>
<td>YAMADA Kazumati</td>
<td>61, 187, 188, 191, 213, 217, 326, 327, 331</td>
</tr>
<tr>
<td>YAMADA Koji</td>
<td>23, 227</td>
</tr>
<tr>
<td>YAMADA Mieko</td>
<td>307</td>
</tr>
<tr>
<td>YAMADA Shinya</td>
<td>12, 17, 18, 179</td>
</tr>
<tr>
<td>YAMADA Takahiro</td>
<td>298, 299</td>
</tr>
<tr>
<td>YAMAGAMI Motonyuki</td>
<td>51, 85</td>
</tr>
<tr>
<td>YAMAGUCHI Hirotoshi</td>
<td>66, 67, 68, 240</td>
</tr>
<tr>
<td>YAMAGUCHI Masahide</td>
<td>158, 159</td>
</tr>
<tr>
<td>YAMAGUCHI Motonari</td>
<td>61</td>
</tr>
<tr>
<td>YAMAGUCHI Takeda</td>
<td>24, 215, 232</td>
</tr>
<tr>
<td>YAMAGUCHI Yasushiro</td>
<td>130</td>
</tr>
<tr>
<td>YAMAGUCHI Yoshiro</td>
<td>122</td>
</tr>
<tr>
<td>YAMAGUCHI Yoshitaka</td>
<td>24, 231, 232</td>
</tr>
<tr>
<td>YAMAGUCHI Yukio</td>
<td>38, 39, 60</td>
</tr>
<tr>
<td>YAMAHA Shizuki</td>
<td>327, 331</td>
</tr>
<tr>
<td>YAMAKAMI Hiroshi</td>
<td>235</td>
</tr>
<tr>
<td>YAMAKI Sayaka</td>
<td>26, 69, 70, 214, 215, 282, 293</td>
</tr>
<tr>
<td>YAMAMOTO Haruaki</td>
<td>255</td>
</tr>
<tr>
<td>YAMAMOTO Tetsuya</td>
<td>40</td>
</tr>
<tr>
<td>YAMASAWA Hisayuki</td>
<td>19, 331</td>
</tr>
<tr>
<td>YAMASHITA Yuichi</td>
<td>309</td>
</tr>
<tr>
<td>YAMAUCHI Hirokimo</td>
<td>186, 326</td>
</tr>
<tr>
<td>YAMAUCHI Tetsuya</td>
<td>254</td>
</tr>
<tr>
<td>YAMAUCHI Yoshiyuki</td>
<td>323</td>
</tr>
<tr>
<td>YAMAZAKI Hiroki</td>
<td>64, 65, 253, 319</td>
</tr>
<tr>
<td>YAMAZAKI Tomokazu</td>
<td>309</td>
</tr>
<tr>
<td>YAMAZAKI Yoshitomi</td>
<td>140, 141, 142</td>
</tr>
<tr>
<td>YAMAZAKI Yasunori</td>
<td>315</td>
</tr>
<tr>
<td>YAMAZAWA Hiroyuki</td>
<td>322</td>
</tr>
<tr>
<td>YANAGIIMA Yoshiyuki</td>
<td>7, 9, 11, 53, 56, 57, 58, 59, 60, 61, 71, 72, 73, 74, 75, 235, 234</td>
</tr>
<tr>
<td>YANG Zai</td>
<td>66</td>
</tr>
<tr>
<td>YANG Zaihong</td>
<td>52</td>
</tr>
<tr>
<td>YANO Satoshi</td>
<td>13</td>
</tr>
<tr>
<td>YANO Shinya</td>
<td>296, 299, 321</td>
</tr>
<tr>
<td>YASUDA Jumpei</td>
<td>21, 47, 48, 49, 51, 52, 54, 56, 57, 58, 202, 203</td>
</tr>
<tr>
<td>YASUDA Shingo</td>
<td>265</td>
</tr>
<tr>
<td>YASUDA Yoshi</td>
<td>280</td>
</tr>
<tr>
<td>YAZUMI Yuki</td>
<td>281</td>
</tr>
<tr>
<td>YEE He-Ung</td>
<td>133</td>
</tr>
<tr>
<td>YIENNELLO Sherry J.</td>
<td>206</td>
</tr>
<tr>
<td>YOKKEIKI Satoshi</td>
<td>242, 247</td>
</tr>
<tr>
<td>YOKOKITA Takeya</td>
<td>280, 287, 293</td>
</tr>
<tr>
<td>YOKOTAMA Akiko</td>
<td>281</td>
</tr>
<tr>
<td>YOKOYAMA Koji</td>
<td>275</td>
</tr>
<tr>
<td>YOKOYAMA Makoto</td>
<td>259</td>
</tr>
<tr>
<td>YOKOYAMA Rin</td>
<td>7, 31, 32, 33, 34, 35, 56, 57, 58, 59, 60, 72</td>
</tr>
<tr>
<td>YONEDA Akira</td>
<td>70</td>
</tr>
<tr>
<td>YONEDA Ken-ihiro</td>
<td>5, 8, 21, 36, 37, 38, 39, 40, 41, 42, 44, 45, 47, 48, 49, 50, 51, 52, 54, 61, 62, 202, 203, 319, 320</td>
</tr>
<tr>
<td>YONEYAMA Shunpei</td>
<td>23, 227, 228, 230</td>
</tr>
<tr>
<td>YOON Insook</td>
<td>103, 106</td>
</tr>
<tr>
<td>YOON Sungwon</td>
<td>258, 273</td>
</tr>
<tr>
<td>YOSHIDA Asaaki</td>
<td>239, 240, 254, 321</td>
</tr>
<tr>
<td>YOSHIDA Kenichi</td>
<td>84</td>
</tr>
<tr>
<td>YOSHIDA Koichi</td>
<td>9, 11, 25, 56, 57, 58, 59, 60, 71, 72, 73, 74, 75, 220, 225, 235, 254, 330</td>
</tr>
<tr>
<td>YOSHIDA Shinnosuke</td>
<td>35</td>
</tr>
</tbody>
</table>