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« Selection process of gravure and highlights »

Gravure and highlights will be selected by two-steps process. In the first step, referees will recommend manuscript for gravure or highlight. With the above recommendation, the editors will then give secondary recommendation.

After the following 1 and 2 are comprehensively considered, the editor-in-chief will draft a manuscript idea which will be thoroughly discussed by the editors for the final decision:

1. Approval based on the editor's judgment as an expert/non-expert in the field (thereby agreeing with the referee's recommendation)
2. Additional recommendation based on the editor's expertise.
The BigRIPS separator is a new-generation superconducting in-flight fragment separator at the Radioactive Isotope Beam Factory (RIBF). Since 2007, the BigRIPS has produced a wide range of radioactive isotope (RI) beams at unprecedented intensities. It is characterized by large ion-optical acceptances, a two-stage structure, and high resolving power for particle identification (PID).

The large acceptances (±40 and ±50 mrad in the horizontal and vertical directions, respectively, and ±3% in momentum) allow efficient production of RI beams using not only projectile fragmentation, but in-flight fission of a 238U beam with wide kinematical distribution as well.

The two-stage structure enables flexible operations, e.g. separator-spectrometer and separator-separator modes, and reduces demands for tagging detectors in the second stage. The latter point results in higher particle identification capability when combined with a high resolving power of the ion-optical system (see page v for details).
RI Beams & New Isotopes for Science

Since 2007, 317 RI beams have been supplied to nuclear physics experiments at the RIBF. The isotopes are produced from primary beams of $^{238}$U, $^{124}$Xe, $^{70}$Zn, $^{48}$Ca, and $^{18}$O, as shown with red circles in Fig. 1 (see page iv for details).

At the same time, yields and production cross sections have been measured for a total of 877 rare isotopes (light blue squares). Among them 47 (blue squares) and 4 (green squares, proton-rich side) new isotopes produced from the $^{238}$U and $^{124}$Xe beams are included. The total number of new isotopes produced at RIKEN, since Nishina’s discovery of $^{237}$U, is 87. This number is still increasing and preliminary results of 69 new isotopes will be reported soon.

New Isomers
~ Indications of new aspects of nuclear structure ~

We have discovered 18 and 25 new isomers in the new isotope search experiments performed in 2008 and 2011, respectively (see D. Kameda et al., Phys. Rev. C 86, 054319 (2012) for details). The existence and properties of new isomers provide us with information on the structure of the relevant nuclei that is otherwise unavailable.

The newly discovered isomers are of practical importance too. The characteristic $\gamma$-rays from the isomers enable unambiguous particle identification (PID) and can serve as an irreplaceable calibration standard for TOF-Bp-$\Delta$E PID. A good example is $^{117}$Ru shown in the figure on the right. The isomeric states discovered in 2008 have already been used for PID in RI beam production in the EURICA experiments.

Cross Section and Production Yields of Rare Isotopes
~Baseline of RI-beam science~

Cross section and production yields of rare isotopes are critical in designing RI-beam experiments. The measured production yields and cross sections are useful to improve our understanding of the reaction mechanism of RI production and refine the theoretical models. (see pages vi—viii for details)

In figure (a) on the right, the measured production rates from the $^{238}\text{U}+\text{Be}$ fission are compared with the LISE++ calculations (version 8.4.1) which employs the abrasion fission (AF) model for the nuclear fission.

The comparison clearly shows a large disagreement in the region of $Z > 50$.

The RI production cross sections by the fragmentation of the $^{124}\text{Xe}$, $^{70}\text{Zn}$, $^{48}\text{Ca}$, and $^{18}\text{O}$ primary beams are compared with predictions of the EPAX3.01 and EPAX2.15 models. EPAX2.15 is found to give better predictions for the $^{48}\text{Ca}$ beam, as shown in the figure (b) on the right, while EPAX3.01 produces successful predictions for the $^{124}\text{Xe}$ primary beam.

These yield and cross section data are available at http://www.nishina.riken.jp/RIBF/BigRIPS/intensity.html.

Future work

Primary-beam intensities at the RIBF are increasing every year. At the same time, the demand for RI beams with higher Z and/or with higher intensity is increasing.

Recently, several trials were successful in increasing the limits of the counting rate for the detectors and improving A/Q resolution for RI beams with high Z where many charge states are mixed; introduction of Ag electrodes to the parallel plate avalanche counters resulted in better rate duration, i.e. stable operation up to 70 kcps even for RI beams with $Z > 60$. A new mechanism to shift plastic-scintillator positions, with respect to the beam position, helps us to avoid deterioration of time resolution due to radiation damage by heavy-ion irradiation. New ion-optics is found to be useful in improving the A/Q resolution, where Bp resolution at the second stage is designed to be doubled compared with the previously used optics.

The BigRIPS team continues to make efforts to provide RI beams with higher intensities and higher qualities.

Hiroshi Suzuki for the BigRIPS team
RI beam production at BigRIPS since its commissioning in 2007

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Since the commissioning of the BigRIPS separator1) in March 2007, a variety of RI beams have been produced at the BigRIPS and used for experiments. Figure 1 shows the nuclear chart in which all isotopes produced at the BigRIPS from March 2007 to July 2013 are indicated in different colors. Red indicates isotopes used for experiments and light blue indicates isotopes whose production yields and cross sections were measured. New isotopes are shown in different colors according to the year in which they were discovered: blue in 2007 and 2008, green in 2011, and purple in 2012. Light isotopes with Z < 25 were produced using projectile fragmentations of 18O, 48Ca, and 70Zn beams. The projectile fragmentation of 124Xe is used for proton rich isotopes, and the in-flight fission of 238U for medium and heavy (Z = 20–68) isotopes. The production yields were measured for 569 isotopes. A total of 169 RI beams were used in the experiments, 89 new isotopes were discovered by the in-flight fission of 238U and 4 new isotopes were discovered by the projectile fragmentation of 124Xe.

The number of experiments performed using RI beams for various primary beams in each year is summarized in Table 1. Before 2010, RI beams were mainly produced using the 238U beam with low intensity and 48Ca. In December 2011, proton rich RI beams including 100Sn were produced from the accelerated 124Xe beam for the first time. In 2012, RI beams around 78Ni, 115Nb, 123Rh, 128Pd, and 130Sn including new isotopes discovered in 2008 were produced from the 238U beam with increased intensity (~10 pA) and delivered to EURICA. Another 18 new isotopes were discovered at this time.

In April 2013, 16C was delivered to ESPRI and 16O and 12C were delivered to SAMURAI. Heavy RI beams around 142Te, 150Ba and 136Nd and middle ones around 104,108Y, 108Zr, and 72Fe from 238U were delivered to EURICA in May and June 2013. Very proton rich RI beams of 100Sn and 73Sr from 124Xe were also delivered to EURICA in June 2013.

Production yields and cross sections of isotopes produced in 2013 are currently being analyzed.

Table 1. Number of experiments performed using RI beams in each fiscal year.

<table>
<thead>
<tr>
<th>Year</th>
<th>238U</th>
<th>124Xe</th>
<th>152Kr</th>
<th>78Zn</th>
<th>48Ca</th>
<th>18O</th>
<th>14N</th>
<th>3He</th>
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<td>21</td>
<td>12</td>
<td>5</td>
<td>1</td>
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References

RIKEN Nishina Center

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Identification and separation of radioactive isotope beams by the BigRIPS separator at the RIKEN RI Beam Factory†

N. Fukuda,*1 T. Kubo,*1 T. Ohnishi,*1 N. Inabe,*1 H. Takeda,*1 D. Kameda,*1 and H. Suzuki1

We have developed a method for achieving excellent resolving power for in-flight particle identification of radioactive isotope (RI) beams, which is routinely used with the BigRIPS fragment separator1) at the RIKEN RI Beam Factory (RIBF)2). In the BigRIPS separator, RI beams are identified by their atomic number Z and mass-to-charge ratio A/Q, which are in turn deduced from the measurements of time of flight (TOF), magnetic rigidity (BP), and energy loss (∆E). Such in-flight particle identification is essential for delivering tagged RI beams, making it possible to perform various types of experiments including secondary reaction experiments. Since the total kinetic energy is not measured in this scheme, and consequently A and Q cannot be determined independently, the resolution of A/Q must be adequately high to identify the charge state Q of RI beams. This is achieved in the Z versus A/Q particle identification plot as demonstrated in Fig. 1, where fully stripped and hydrogen-like peaks are very closely located.

We achieved a high A/Q resolution by precisely determining the BP and TOF values. Precise BP was determined by the trajectory reconstruction method for which ion-optical transfer matrix elements were experimentally determined up to the third-order. The significant improvement in A/Q resolution by our trajectory reconstruction technique is clearly seen in Fig. 2, where comparison of the A/Q resolution among three different transfer matrix elements in the trajectory reconstruction is shown. Precise TOF was determined by the slew correction method for TOF signals. We iteratively carried out the derivation of transfer matrix elements and slew correction such that the A/Q resolution was best optimized. Furthermore we completely removed background events to enhance the reliability of particle identification.

The excellent particle identification thus achieved allows us to supply tagged RI beams to a variety of experiments at RIBF. Furthermore it helps us to reliably identify new isotopes from a very small number of events. Such enhanced capability of the BigRIPS separator is significantly advancing the research on exotic nuclei at RIBF.

References

† Condensed from the article in Nucl. Instr. Meth. B 317, 323 (2013)
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Fig. 1. Z versus A/Q particle identification plot for fission fragments produced in the 238U + Pb reaction at 345 MeV/nucleon. The experimental conditions and BigRIPS setting are given in the G3 Setting section in Ref.3).

Fig. 2. Comparison of the A/Q resolution among three different transfer matrix elements used in trajectory reconstruction. The comparison is shown for Sn isotopes produced by in-flight fission of a 238U beam at 345 MeV/nucleon. The experimental conditions and BigRIPS settings are the same as those in Fig. 1.
Production cross section measurements of radioactive isotopes by BigRIPS separator at RIKEN RI Beam Factory†

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We have measured the production rates and production cross sections for a variety of radioactive isotopes which were produced from $^{124}$Xe, $^{48}$Ca, and $^{238}$U beams at an energy of 345 MeV/nucleon using the BigRIPS separator†.

Proton-rich isotopes with atomic numbers $Z = 40$–$52$ were produced by projectile fragmentation of the $^{124}$Xe beam on a Be target, during which we also measured their momentum distributions. We found that the exponential tails at the low-momentum region fall off faster than those of the LISE$^{++}$ calculation with the original parameterization. The EPAX3.01 cross-section formula3† agreed fairly well with the experimental cross sections. Furthermore, we have discovered four new isotopes on the proton-drip line, $^{85,86}$Ru and $^{81,82}$Mo. Figure 1 (a) shows a two-dimensional plot of $Z$ versus mass-to-charge ratio ($A/Q$) in the $^{85}$Ru setting. The four new isotopes were clearly identified on the left side of the solid lines, which indicate the limits of known isotopes. In the $^{105}$Te setting, $^{103}$Sb was not observed in our measurement, as shown in Fig. 1 (b). We obtained clear evidence that $^{103}$Sb is particle-unbound with a half-life upper limit of 49 ns.

Neutron-rich isotopes with $Z = 5$–16 were produced by the projectile fragmentation of the $^{48}$Ca beam on Be targets. The EPAX2.15 formula5 reproduces the experimental cross sections fairly well.

Neutron-rich isotopes with $Z = 20$–59 were produced by in-flight fission of a $^{238}$U beam on Be and Pb targets. The measured production rates were compared with the LISE$^{++}$ calculations, in which the abrasion fission (AF) model and the AF + Coulomb fission model were used for the $^{238}$U+Be and $^{238}$U+Pb cases, respectively. In the former case, the LISE$^{++}$ calculations reproduced the experimental production rates well for the $Z < 50$ region but underestimated them for $Z > 50$. In the latter case, the LISE$^{++}$ predictions reproduce them fairly well overall.

References

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Fig. 1. (a) Enlarged two-dimensional PID plot of $Z$ vs. $A/Q$ for $^{85}$Ru setting. $^{85,86}$Ru and $^{81,82}$Mo are the new isotopes. (b) PID plot for $^{105}$Te setting.
Comparison of production yields of neutron-rich nuclei between Be and W targets by in-flight fission of $^{238}$U beam

D. Murai,*1,2 T. Kubo,*1 N. Inabe,*1 D. Kameda,*1 N. Fukuda,*1 H. Takeda,*1 H. Suzuki,*1 K. Yoshida,*1 K. Kusaka,*1 K. Tanaka,*1 Y. Yanagisawa,*1 M. Ohtake,*1 T. Ohnishi,*1 H. Sato,*1 Y. Shimizu,*1 H. Baba,*1 M. Kurokawa,*1 K. Ieki,*1,4 D. Nishimura,*1,4,5 E. Ideguchi,*4 S. Go,*1,5 R. Yokoyama,*5 T. Fujii,*1,5 N. Iwasa,*1,6 T. Yamada,*6 A. Chiba,*1,6 S. Momota,*1,7 H. Nishibata,*1,8 O. B. Tarasov,*1,9 D. J. Morrissey,*1,9 B. M. Sherrill,*1,9 Y. Satou,*1,10 S. Kim,*1,10 J. W. Hwang,*1,10 and G. Simpson*11

We have measured production yields by the in-flight fission of a $^{238}$U beam at 345 MeV/nucleon with a Be target and a W target, and investigated the suitability of the targets for the production of neutron-rich nuclei with atomic numbers $Z$ ranging from 57 to 69. The isotopes were produced and identified using the BigRIPS separator. Particles were identified by the $B\beta$-TOF-$\Delta E$ method to determine $Z$ and the mass-to-charge ratio $A/Q$.

The target thicknesses were 5 and 0.7 mm for the Be and W targets, respectively; these thickness were energy-loss equivalent. The BigRIPS setting was the same as the $^{168}$Gd setting in the new-isotope-search experiment.1) The total rates were 79.9 counts/particle nA and 51.5 counts/particle nA for the Be and W targets, respectively. Figure 1 shows the $Z$ versus $A/Q$ plots for the Be and W targets. The resolutions of $A/Q$ and $Z$ are typically 0.045% and 0.45%, respectively. Figure 2 shows the production yield for each target. The squares and circles show the experimental data obtained with the Be and W targets, respectively. The result indicate that the production yield with the Be target is larger than that with the W target in the region where $Z > 62$.

Fig. 1. Particle identification plot of $Z$ versus $A/Q$ obtained with (a) the Be target and (b) the W target.

Fig. 2. Measured production yields with the Be (squares) and W (circles) targets. (a) Results for even-Z isotopes. (b) Results for odd-Z isotopes.

The transmission of the BigRIPS separator is not taken into consideration in these results. We are proceeding with the analysis to deduce the production cross sections.

References

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*11 LPSC-IN2P3
Production rates of new neutron-rich rare-earth nuclei via in-flight fission of a 345 MeV/nucleon $^{238}\text{U}$ beam


The reaction mechanism of in-flight fission is not clear yet due to the complexity of the abrasion fission process, in which many kinds of fissile nuclei can contribute to the production of fission fragments. The measurement of the production rates of various fission fragments is useful not only to plan various experiments but also to understand such a reaction mechanism. In 2011, using a 345 MeV/nucleon $^{238}\text{U}$ beam with a Be target, we searched for new isotopes and isomers whose atomic numbers roughly range from 56 to 68.1) Here, we report on the production rates of new isotopes, in addition to the improvements in particle identification (PID) compared to our previous report.2)

Fission fragments were separated and analyzed using the BigRIPS separator. We adopted two settings that targeted the regions of nuclei around $^{159}\text{Pr}$ and $^{160}\text{Gd}$. The mass-to-charge ratio ($A/Q$) was deduced from the time of flight (TOF) and magnetic rigidity measurements obtained using BigRIPS. The atomic number ($Z$) was deduced from the TOF and energy losses, which were measured using a stack of Si detectors in the focal plane. The PID plot in the region of $^{159}\text{Pr}$ is presented in Fig. 1. Since our previous report,2) we have modified the gate conditions to remove background events and improved the resolutions of the regions of nuclei around $^{159}\text{Pr}$ and $^{168}\text{Gd}$. The BigRIPS separator. We adopted two settings that targeted orders of magnitudes smaller than the measured rates. This

![Image](https://via.placeholder.com/150)

**Fig. 1.** $Z$ versus $A/Q$ PID plot in the region of $^{159}\text{Pr}$. The red lines indicate the known limits of neutron-rich isotopes.

![Image](https://via.placeholder.com/150)

**Fig. 2.** Measured production rates of (a) even-$Z$ and (b) odd-$Z$ isotopes in the region of $^{159}\text{Pr}$. The red arrows indicate the production rates of new isotopes. The LISE++ calculations are denoted by the dashed or solid curves without circles (see text).

References
Evidence for a new nuclear ‘magic number’ in $^{54}$Ca

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Over recent years, the evolution of nuclear shell structure in exotic, neutron-rich nuclei has attracted much attention on both the experimental and theoretical fronts. In the neutron-rich $fp$ shell, the onset of the $N = 32$ subshell closure is well established from the structural characteristics of $^{52}$Ca$^{1,2)}$, $^{54}$Ti$^{3,4)}$ and $^{56}$Ca$^{5,6)}$. This subshell gap is reproduced successfully by numerous theoretical predictions. In the framework of tensor-force-driven shell evolution$^7$, the onset of the $N = 32$ subshell closure results as a direct consequence of a sizable $\nu p_{3/2}/\nu p_{1/2}$ gap, which presents itself as the $\nu f_{5/2}$ orbital shifts up in energy owing to a weakening of the attractive $\pi f_{7/2}/\nu f_{5/2}$ interaction as protons are removed from the $\pi f_{7/2}$ orbital. Another important manifestation of some theories is the prediction of a large subshell gap at $N = 34$, which develops if the $\nu f_{5/2}$ orbital lies sufficiently high in energy above the $\nu p_{1/2}$ orbital. It has already been shown that no significant $N = 34$ subshell gap exists in $^{56}$Ti$^{4,8)}$ or $^{58}$Cr$^{6,9}$ and, therefore, the size of the energy gap in $^{54}$Ca is an important structural characteristic that requires experimental input. Moreover, the single-particle states of $^{54}$Ca should also reflect the nature of the $N = 34$ subshell closure in isotopes far from stability.

The structures of $^{54}$Ca and $^{55}$Ca were investigated using in-beam $\gamma$-ray spectroscopy at the RIBF to address this issue. A primary beam of $^{70}$Zn$^{50+}$ ions at 345 MeV/n was used to create a radioactive beam containing $^{55}$Sc and $^{56}$Ti, which was focused on a 10-mm-thick

![Fig. 1. (colour) Particle identification plots measured by (a) the BigRIPS separator and (b) the ZeroDegree spectrometer. The black circle indicates $^{54}$Ca events.

References

First physics data of the J-PARC E15 Experiment

Y. Sada,*1,∗2 M. Iwasaki,*1,∗3 Y. Ma,*1 H. Ohmishi,*1 F. Sakuma,*1 M. Sato,*1 M. Tokuda,*1,∗3 Q. Zhang,*1 for the J-PARC E15 Collaboration

1 Introduction

The KN interaction has been determined to be strongly attractive through extensive measurements of the kaonic hydrogen atom and low-energy KN scattering. As a consequence of strong KN interaction, there are many theoretical predictions of the deeply bound K-nuclear states. In particular, an extensive study on the simplest K-nuclear bound system, KNN, has been in progress on both the theoretical and experimental∗1 sides. Since available experimental information is limited, interpretations of the results are controversial. To completely understand the KN interaction, we require more experimental results on various interactions for formation of the KNN bound state. The E15 experiment at the K1.88BR beam-line aims to search for the KNN bound state2) with the in-flight 3He(K−, N) reaction at 1.0 GeV/c. Such measurement allows us to investigate the KNN bound state in terms of both its formation via missing-mass spectroscopy and its decay via invariant-mass spectroscopy.

2 Experimental setup

The experimental setup consists of three parts: a high-precision beam-line spectrometer, a cylindrical detector system (CDS) that surrounds a liquid 3He target system, and forward particle TOF detectors. The kaon beam at a momentum of 1.0 GeV/c is identified using an aerogel Cherenkov counter. The kaon beam momentum is analyzed by the beam-line spectrometer, which has a momentum resolution of 2.2 MeV/c at 1.0 GeV/c. The CDS is placed around the target in order to detect decay particles from the KNN bound state. The CDS consists of a solenoid magnet, a cylindrical drift chamber (CDC), and a cylindrical detector hodoscope (CDH). The decay particles from the target are detected by the CDS, which has a solid angle coverage of 59% of 4π. With the CDS, we can perform particle identification and track reconstruction (momentum resolution is 5% at 600 MeV/c ). A neutron TOF counter (NC), placed 15 m downstream from the center of the target at 0 degrees with respect to the beam direction, measures forward-going neutral particles. The TOF resolution is determined to be 150 ps (σ) using a gamma-ray data sample. The missing-mass resolution of the 3He(K−, n) reaction is estimated to be 9 MeV/c2 at the region of interest (Pn ~ 1.2 GeV/c).

The details of the spectrometer system can be found in another paper3).

3 First physics data

The first physics run of the E15 experiment was carried out in May 2013. By irradiating 5 × 109 kaons on the helium-3 target, 3 × 108 forward neutrons were successfully recorded. The accumulated data corresponds to 1% of the statistics requested in the original proposal. Fig 1 shows the missing mass of the 3He(K−, n) reactions measured by the NC. One or more charged tracks are required in the CDS to reconstruct the reaction vertex.

In the spectrum, a peak from the quasi-free reaction K−N → KN on 3He is clearly seen. The spectrum with K0 tagged in the CDS is superimposed on the figure, in which the excess below the KNN threshold (2.37 GeV/c2) is not observed. Therefore the excess below the KNN threshold in the semi-inclusive 3He(K−, n) spectrum is barely explained by the detector responses and the quasi-free reaction. Further analysis is in progress to understand the observed spectrum.

Fig. 1. Missing masses of the 3He(K−, n) reactions.

References
Measurement of the $^{248}\text{Cm} + ^{48}\text{Ca}$ fusion reaction products at RIKEN GARIS

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The reaction, $^{248}\text{Cm} + ^{48}\text{Ca} \rightarrow ^{296}\text{Lv}$ (Livermorium, Z = 116), has been studied at the RIKEN Linear Accelerator (RILAC) Facility using a gas-filled recoil ion separator (RILAC) Facility using a gas-filled recoil ion separator GARIS. Although this reaction was intensively studied at the Flerov Laboratory of Nuclear Reaction (FLNR), Russia1,2,3, and GSI, Helmholtzzentrum für Schwerionenforschung, Germany4,5, the number of observed events is still very small because of the small production cross sections. The first aim of the present study is to observe more events in the region of superheavy nuclei and possibly to obtain new spectroscopic information of those nuclei. The second aim is to examine the performance of the GARIS facility using the relevant reaction for a future project with the $^{50}\text{Ti}$ beam, instead of the $^{48}\text{Ca}$ beam, to search for new heaviest nuclei. Because of the limitation of target nuclear species, one needs to use beams heavier than $^{48}\text{Ca}$ for further investigation of superheavy nuclei.

A $^{48}\text{Ca}$ beam was accelerated by RILAC at 262 MeV, and it irradiated $^{248}\text{Cm}$ targets prepared by electro deposition of $^{248}\text{Cm}_2\text{O}_8$ on titanium foils. Eight targets were mounted on a wheel rotating at 1000 rpm. The diameter of the wheel is 10 cm. The average thickness of $^{248}\text{Cm}_2\text{O}_8$ was 0.290 mg/cm$^2$, which contained 0.265 mg/cm$^2$ $^{248}\text{Cm}$, and that of titanium foils was 0.903 mg/cm$^2$. The energy of the beam at half depth of the target was estimated to be 250 MeV by using a range-energy table. Reaction products were separated from beam particles and from unwanted particles by GARIS and then implanted in a position-sensitive detectors (MCPs) were set upstream of the PSD. The average beam intensity was 0.8 particle/µA. In a beamtime of 10 days, $4.3 \times 10^{18}$ $^{48}\text{Ca}$ ions irradiated the targets. The Bp value of the GARIS was set to 2.21 Tm.

We observed five correlated events during the experiment, all of which terminated by spontaneous fission (SF). Decay characteristics of those events agreed well with previous studies1,2,3. Although it is difficult to identify the nuclides of the products only from the present experimental study, we could state that two of the events were attributed to the decays of $^{290}\text{Lv}$ (3 n evaporation channel) and three of them to the decays of $^{292}\text{Lv}$ (4 n evaporation channel) by referring to the assignments in the previous studies. The two events attributed to the $^{290}\text{Lv}$ decay consisted of three consecutive alpha decays followed by SF. The two events attributed to the $^{292}\text{Lv}$ decay consisted of two alpha decays followed by SF. One of the events we tentatively assigned to the decay of $^{292}\text{Lv}$ consisted of three alpha decays followed by SF. The tentative assignment is based on the decay characteristics of the decay energies and decay times of $^{292}\text{Lv}$ and $^{294}\text{Fl}$ (Flerovium, Z = 114) and the decay time of $^{284}\text{Cn}$ (Copernicium, Z = 112). Because an alpha decay of $^{284}\text{Cn}$ has not been observed, this possibly involves a new decay mode of $^{284}\text{Cn}$ and new isotope $^{280}\text{Ds}$ decays by SF. The production cross sections of $^{293}\text{Lv}$ and $^{292}\text{Lv}$ were deduced to be 2.1±1.4 pb and 3.1±3.0 pb, respectively, by assuming the transmission of GARIS to be 0.35. Observed events are summarized in Table I.

Further analysis is now in progress.

Table I Observed decay events, energies, and time intervals of the events.

<table>
<thead>
<tr>
<th>Chain 1</th>
<th>Chain 2</th>
<th>Chain 3</th>
<th>Chain 4</th>
<th>Chain 5</th>
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<tr>
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<td>10.47 MeV</td>
<td>2.77 MeV</td>
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<td>0.032 s</td>
<td>0.253 s</td>
<td>0.020 s</td>
<td>0.0041 s</td>
<td>0.032 s</td>
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<tr>
<td>9.89 MeV</td>
<td>9.89 MeV</td>
<td>9.99 MeV</td>
<td>0.83 MeV+</td>
<td>9.72 MeV</td>
</tr>
<tr>
<td>0.548 s</td>
<td>3.97 s</td>
<td>0.243 s</td>
<td>0.0090 s</td>
<td>0.666 s</td>
</tr>
<tr>
<td>232 MeV</td>
<td>2.46 MeV</td>
<td>182 MeV</td>
<td>9.09 MeV</td>
<td>1.64 MeV</td>
</tr>
<tr>
<td>0.065 s</td>
<td>7.76 s</td>
<td>0.832 s</td>
<td>0.282 s</td>
<td>7.56 s</td>
</tr>
<tr>
<td>195 MeV</td>
<td>19.8 s</td>
<td>163 MeV</td>
<td>221 MeV</td>
<td>4.63 s</td>
</tr>
</tbody>
</table>

| $^{290}\text{Lv}$ | $^{294}\text{Lv}$ | $^{292}\text{Lv}$ | $^{292}\text{Lv}$+ | $^{294}\text{Lv}$ |

'escape energies (partly measured using PSD)'
" energies measured only using SSD
" tentative

References
In order to supply a high-intensity and stable \(^{48}\)Ca beam from the 18-GHz electron cyclotron resonance ion source (ECRIS), we have been conducting operational tests of a micro-oven for the \(^{48}\)Ca beam.

The structure of the micro-oven and the method to produce the \(^{48}\)Ca beam are described in Ref. 2.

In these test experiments conducted at the 18-GHz ECRIS, the material used was the element \(^{40}\)Ca. The beam intensity was measured using a Faraday cup installed at the exit of the analyzing magnet. Figure 1 shows the charge distribution of Ca ions when the beam intensity of 60 electric \(\mu\)A was obtained for Ca\(^{11+}\). In the test experiment from which this spectrum was obtained, a hot liner was installed into the plasma chamber, and a negative voltage bias was not applied to the micro-oven (both cases are mentioned below).

![Fig. 1. Charge distribution of calcium ions.](image)

For the supply of metallic beams, several facilities use a so-called “hot-liner” to reduce the material consumption rate. In this method, the inner surface of the plasma chamber is thermally decoupled from the cooling water jacket. The inner surface is heated by the plasma to enable the metallic atoms to re-evaporate from the inner surface. Fig. 2 shows the results of one of the long-term experiments in the cases in which the hot liner was not installed (without the hot liner) and installed (with the hot liner) in the plasma chamber. The beam intensities for Ca\(^{11+}\) are shown. In the case without the hot liner, the beam intensity was not maintained at a constant value. In the case with the hot liner, the beam intensity was maintained at 30 electric \(\mu\)A. The amounts of calcium placed in the crucible and subsequently consumed were 252 mg and 230 mg, respectively, for the case without the hot liner, and 246 mg and 105 mg, respectively, for the case with the hot liner. The consumption rates without and with the hot liner were estimated to be 0.88 mg/h and 0.44 mg/h, respectively.

![Fig. 2. Long-term experiment results when the hot liner was not installed and when it was installed in the plasma chamber.](image)

One method to enhance the beam intensity is the “biased disk” method. In this method, a negatively biased metal disk is installed in the plasma chamber. We investigated the effect of a negative bias applied to the micro-oven itself under the various oven positions. Beam intensity enhancement of up to 20% was observed. An effect similar to a biased disk was confirmed.

References

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Current status of RI beam production at electron-beam-driven RI separator for SCRIT (ERIS)

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The electron-beam-driven RI (Radioactive Isotope) separator for SCRIT (ERIS) at the SCRIT electron scattering facility1) consists of a RI generator and an ISOL-type RI separator employed to produce low-energy RI beams used for the electron scattering of unstable nuclei. In ERIS, the photofission of uranium driven by an electron beam is used for RI production. Details of ERIS were reported in Ref. 2. During the present year, uranium-carbide target was prepared, and the RI production has been started. In this paper, we report the first result of the RI production at ERIS.

For the RI production, we prepared uranium-carbide disks. Uranium carbide was obtained by the carbothermal reduction of uranium oxide in presence of carbon around 1800 °C. First, uranil nitrate was mixed with 20µm graphite grains, after which uranil nitrate was oxidized to UO3 under air flow by heating to 500 °C. Next, UO3 powders with graphite were manually ground, and they were formed into a disk without a binder at 180-MPa compression. The obtained disk was 20 mm in a diameter and around 2 mm in a thickness. It was heated to 1000 °C in a vacuum for outgassing, and the reduction reaction UO3 → UO2 proceeded. The finished disk consisted of about 0.7-g graphite and 1.9-g UO2 powders. Mass concentration of uranium in the disk was estimated as 1.9 g/cm3. In total, 20 disks were prepared. The sum of the thicknesses of 20 disks was almost 50 mm, and the total amount of uranium was about 30 g. Finally, all uranium-oxide disks were converted into uranium carbide at around 1800°C by using the heating system in ERIS.

The prepared uranium-carbide disks were irradiated with electron beams accelerated to 150 MeV by RTM 1). 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 target temperature was around 2000 °C. Produced RIs were accelerated to 20 kV and mass-separated by the analyzing magnet. They were transported to the particle identification system for ERIS (PIE) located at the exit of ERIS. PIE consists of a rotating Al disk and a Ge detector, and it measures γ rays corresponding to the decay of the RIs stopped inside the rotating disk.

Figure 1 shows the rate of Sn and Xe isotopes at PIE. These rate are estimated from the observed γ-ray yield using the efficiency of the Ge detector and the half-life of each isotope. By comparing with the expected production rate inside the target, the overall efficiency can be estimated. Here, the overall efficiency includes the efficiency of release from the target, ionization in the ion source, and efficiency of transport from ion source to PIE. For example, the measured rate for 137Xe is 1.1×10^5 atoms/s and the expected production rate is about 1.6×10^8 atoms/s. The overall efficiency for 137Xe is estimated to be 0.07%. In this experiment, the overall efficiency of stable xenon with a calibrated gas flow was measured to be 1%. Since the stable xenon was introduced into the ionization chamber through a gas inlet, the measured overall efficiency of stable xenon includes only ionization and transport efficiencies. The release efficiency of 137Xe is estimated as 7% from these results. In the case of 132Sn, the measured and expected production rates are 6.0×10^3 and 2.6×10^7 atoms/s, respectively. The release efficiency of 132Sn is evaluated as 2.3% using the same ionization and transport efficiencies as those of Xe. This assumption is supported by the results obtained at ALTO3). The release efficiency of Sn at ERIS is lower than that of Xe. One of the reasons is the inadequate conditions of the adsorption process at ERIS, such as temperature.

Further studies concerning the target fabrication and the optimization of the target and ion source conditions are in progress to increase the release efficiency.

Fig. 1. Rate of Sn and Xe isotopes at the particle identification system of ERIS. The electron beam power was almost 10 W during the measurement. These rates are estimated on the basis of the observed γ-ray yield.

References
In-beam validation of the MINOS device at HIMAC


MINOS1) is a new device aimed at the in-beam spectroscopy of very exotic nuclei by proton-knockout at the RIBF facility. It is composed of a thick liquid hydrogen target2) (10-20cm) to maximize the luminosity surrounded by a cylindrical Time Projection Chamber equipped with a bulk-Micromegas3) pad detection plane. The latter allows to track the recoiled protons and thence apply a Doppler correction to the gamma rays measured by a gamma array such as DALI24) at RIBF. As a final phase in the development of MINOS, a full in-beam test of the TPC and of its electronics system was performed at HIMAC in October 2013.

In this experiment, fragmentation reactions including (p,2p) were produced using a beam of 20Ne at 350 and 180 MeV/u impinging on 0.5 mm thick CH2 or C targets placed inside the beam pipe instead of the LH2 target. Beam detectors were placed upstream and downstream for both tracking and trigger purposes. As no particle identification was provided after the detector, two layers of plastic scintillators were placed on the left and right of the MINOS TPC to select events with charged particles passing through the device. A picture of the experimental setup is shown in Fig. 1.

The MINOS detector composed of about 4864 channels was for the first time read out with the electronics system constituted of front-end cards from the T2K experiment equipped with AFTER chips and of the newly-developed Feminos cards. The MINOS data acquisition was also successfully coupled to the RIBF data acquisition5) which handled the triggers and beam detectors information.

The use of two different gas mixtures (Ar+5%C4H10 and Ar+3%C4H10+15%CF4), several TPC voltages and two distinct detection pad geometries during this test also enabled a characterization of the TPC with track dispersion, gain as well as drift velocity changes on experiment-like data.

Eventually, this experiment tested the TPC vertex position resolution and its efficiency. The development of a tracking software for MINOS was carried out with the use of Hough filters, first to select the two-particle-like events in the two-dimensional detection plane and then to filter off the noisy signals in the tracks in three dimensions, before fitting the final tracks to obtain the vertex position. A full-width-half-maximum resolution around 5 mm in the beam direction was obtained with the 20Ne beam at 350 MeV/u and the CH2 targets, as shown on the right side of Fig. 2.

Full-scale GEANT4 simulations are also being carried out for comparison to experiment in terms of efficiency as the final step in the validation of MINOS6). This in-beam measurement at HIMAC opens the way to the upcoming physics experiments foreseen in Spring 2014 with the first physics results of the MINOS detector.

References
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Seniority isomer in $^{128}$Pd$^\dagger$

H. Watanabe$^{1,2}$ and EURLICA U-beam collaboration in 2012

The level structure of the very neutron-rich nucleus $^{128}$Pd has been studied for the first time. Neutron-rich nuclei below $^{132}$Sn were produced using in-flight fission of a $^{238}$U$^{86+}$ beam at 345 MeV/nucleon impinging on a 3-mm-thick beryllium target. The primary beam intensity ranged from 7 to 12 pA during the experiments. The nuclei of interest were separated by the BigRIPS separator and the following ZeroDegree spectrometer. The identified particles were implanted into a highly segmented active stopper named WASAABi$^1$, which consisted of eight double-sided silicon-strip detectors (DSSSD) stacked compactly. Each DSSSD had a thickness of 1 mm with an active area segmented into sixty and forty strips (1-mm pitch) on each side in the horizontal and vertical directions, respectively. The DSSSDs also served as detectors for electrons following β-decay and internal conversion processes. Gamma rays were detected by the EURICA spectrometer$^2$, which consisted of twelve Cluster-type detectors, each of which contained closely packed seven HPGe crystals.

Figure 1 shows a γ-ray energy spectrum measured in delayed coincidence with $^{128}$Pd ions. Four γ rays at energies of 75, 260, 504, and 1311 keV have been unambiguously observed. These γ rays are found to be in mutual coincidence and exhibit consistent time behavior. Therefore, we conclude that they proceed through a single cascade originating from one isomeric state. A least-squares fit of the summed gated time spectra of the isomeric-decay transitions yields $T_{1/2} = 5.8(8)$ μs half-life, as shown in Fig. 1. The relative intensities of these isomeric γ rays are in agreement within experimental errors, except for the 75-keV transition that is expected to be highly converted. The total internal conversion coefficient for the 75-keV transition derived from a comparison with the 1311-keV γ-ray intensity is 2.6(17), which is consistent with the theoretical value of 3.88 for an $E2$ multipolarity.

On the basis of the above arguments on the observed γ transitions, the level scheme of $^{128}$Pd is proposed as displayed in Fig. 1, where the spin and parity of the 5.8-μs isomeric state at 2151 keV is assigned as $J^\pi = 8^+$. The spin-parity assignment for the levels and the ordering of the transitions between the isomer and the ground state are based on a close resemblance to the yrast level energies below the analogous $8^+$ isomers in $^{130}$Cd$^3$ and $^{96}$Pd ($N = 50$)$^4$. A transition strength of $B(E2; 2^+ \rightarrow 6^+) = 0.22(3)$ W.u. can be obtained from the measured half-life of the 2151-keV isomeric state.

The excitation energies of the $J^\pi = 2^+ - 8^+$ states in $^{128}$Pd are comparable to those in $^{130}$Cd$^3$. The constancy of level energies is characteristic of the seniority scheme, where seniority $\nu$ counts the number of nucleons that are not in pairs coupled to spin zero. In the case of an $n$-particle (or $n$-hole) system in a single-$j$ shell, the level energies with identical $J^\pi$ and $\nu$ are independent of $n$. Such energy properties are also visible for the even $N = 50$ isotones from Mo ($Z = 42$) to Cd ($Z = 48$), in which the yrast $J^\pi = 2^+ - 8^+$ levels consist of the same multiplet that involves predominantly valence protons in the $\pi g_{9/2}$ orbital with $\nu = 2$. Since the single-proton levels in the $Z = 28 - 50$ shell are nearly identical in the $^{132}$Sn and $^{100}$Sn regions, it is expected that the level properties exhibited by the $N = 82$ isotones are similar within the valence proton space to those in the case of $N = 50$. Therefore, the excited states in $^{128}$Pd can be interpreted in terms of the $\nu = 2$ configuration of the $\pi g_{9/2}$ subshell.

References

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HIGHLIGHTS OF THE YEAR

Evolution of collectivity in neutron-rich Ru nuclei†


One of the central features in our understanding of the atomic nucleus is the appearance of magic numbers. Isotopes in their proximity can be described in terms of single-particle interactions with an inert core. Most nuclei, however, lie sufficiently far from magic numbers for collective behavior to dominate over the single particle structure. In the prolate-oblate transition regions comparable energy minima corresponding to different shapes can lead to shape coexistence and to stable intermediate shapes with different deformations on each axis, so called triaxial nuclei.

An experiment was carried out using at RIBF using a 238U beam with an energy of 345 MeV/u, and an average intensity of ~ 10 pA and a 555 mg/cm² beryllium target. After the target, BigRIPS and Zerodegree were used for separation and tagging of the nuclei of interest. The secondary beam was implanted into the WASSAIBi silicon detectors. The β-delayed γ-rays were detected with the EURICA13 detector array.

The β-delayed γ-ray spectra associated with 116Tc and 118Tc were analysed and interpreted in terms of observables of collectivity2). The energy ratio R(4/2) = E(41+)/E(21+) is one such observable, ranging approximately from the minimum at R(4/2) = 2 for spherical nuclei and the maximum R(4/2) = 3.33 for rigid rotors. The trends of this ratio as a function of N for Mo, Ru and Pd chains, shown in Fig. 1, indicate that these elements are well deformed in this region. The Pd chain exhibits a relatively stable value around the transitional limit, R(4/2) = 2.5, while the Mo chain is closer to the deformed limit and the Ru chain lies in between the former. For the most neutron-rich Ru isotopes the beginning of a shape transition towards sphericity can clearly be seen.

Calculations were also carried out for the even-even 108–118Ru isotopes with the interacting boson model and the algebraic collective model. The conclusions are that the very neutron-rich nuclei still show many features associated with triaxial γ-soft nuclei, represented by the O(6) symmetry, but are approaching a spherical structure, the U(5) symmetry, with increasing neutron number towards the N = 82 shell closure.

References

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Isomer spectroscopy of neutron-rich Nd isotopes

Prolate-deformed nuclei are found to appear in the neutron-rich part of the nuclear landscape around $Z = 60$ and beyond $N = 90$, after the systematic studies of excited states. In strongly deformed nuclei, quantum number $K$ is known to be a good quantum number. Since transitions with large changes in $K$ are suppressed, many nuclei in this region have isomeric states. In addition to the quadrupole deformation, appearances of higher-order deformations such as octupole and hexadecupole deformations have been predicted\(^1\); however, they are not yet understood well. Isomer spectroscopy is a useful method to gain information on such structures of these nuclei.

Neutron-rich 60Nd isotopes have been investigated by means of isomeric $\gamma$-ray spectroscopy. Such isotopes were produced by the in-flight fission of \(^{238}\)U at RI Beam Factory in RIKEN Nishina Center, and were selected and identified by using the BigRIPS separator. The identification of the nuclei was performed on the basis of the $\Delta E$-TOF-$B\rho$ method, which allows an event-by-event determination of their atomic number and the mass-to-charge ratio, where $\Delta E$, TOF, and $B\rho$ denote energy loss, time of flight, and magnetic rigidity, respectively. The identified particles were implanted into passive and active stoppers. A passive stopper made of Cu was used for the measurement at a high count rate, while the WAS3ABi\(^2\) active stopper consisting of five double-sided silicon strip detectors was used for the $\beta$-$\gamma$ spectroscopy. Delayed $\gamma$ rays were detected by the germanium cluster detector array EURICA\(^3\). Gamma rays previously known from the 5\(^-\) isomeric state of \(^{156}\)Nd\(^4\) were observed, and new \(K\) isomeric states of heavier isotopes were discovered.

Figure 1 shows the $\gamma$-ray energy spectra of \(^{158}\)Nd and \(^{160}\)Nd using both the passive and active stopper data. We have observed three strong peaks at 151.6, 233.4, and 1198.2 keV for \(^{158}\)Nd, and two strong peaks at 150.2 and 893.0 keV for \(^{160}\)Nd. In both \(^{158}\)Nd and \(^{160}\)Nd, the half-lives of $\gamma$ rays were preliminarily obtained as 0.339(20) $\mu$s and 1.63(21) $\mu$s, respectively. From the systematics of Nd isotopes, the energy of the first 2\(^+\) states will be around 70 keV. However, such low-energy $\gamma$ transition is highly converted, and accordingly, the 70-keV peaks could not be observed. Further analysis to make spin-parity assignments based on the decay pattern and coincidence relations is now in progress.

References

Proton scattering of $^{16}$C at 300 MeV/nucleon

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Neutron-rich carbon isotopes can provide opportunities to study the evolution of nuclear structure up to the neutron drip line. Even-even carbon isotopes have been extensively studied so far. $^{16}$C was identified as an exotic structure using lifetime measurement for the first time at RIKEN1). Then, the lifetime of the $2^+$ state in $^{16}$C was remeasured using different methods including more neutron-rich carbon isotopes, $^{18}$C and $^{20}$C $^{2–4}$. The existence of the anomalous behavior of $^{16}$C is still under discussion. Proton elastic and inelastic scattering can provide unambiguous optical potential and shape information of the ground state via the coupled channel effect with the deformation parameter $\beta_{2p}$. In addition, $^{16}$C is a first step to develop a neutron skin or neutron halo up to $^{22}$C. The angular distribution of elastic scattering is expected to provide us with density distribution information that includes not only the radius but also surface diffuseness.

In April 2013, an experiment the so-called Elastic Scattering of Proton with RI beam (ESPRI) setup was performed at the RIKEN Nishina Center. The $^{16}$C beam with an intensity more than $10^5$ Hz at approximately 300 MeV/nucleon was produced in BigRIPS using an $^{18}$O primary beam at 345 MeV/nucleon. The incident $^{16}$C with a purity of 95% was selected with a set of narrow slits setting ($\pm 2$ mm) at F1 and F2, and then, it was transported to the F12 area. The size of the beam spot was $\sigma = 3$ mm (5 mm) in the horizontal (vertical) direction on the secondary solid hydrogen target named SH TRICM (Solid-Hydrogen Target for Recoil detection In Coincidence with INVERSE Kineatics)$^5)$. The use of para-$H_2$ was critical in operating it safely during this experiment for one week.

Further, beam particle identification was performed using the energy deposit ($\Delta E$) of a plastic scintillator and beam trajectory using beam tracking detectors at F12. The thickness and effective diameter of the secondary target that was tilted at 45° at target center was 1 mm and 20 mm, respectively. The recoil protons were identified using time-of-flight(TOF)-$\Delta E-E$ technique by plastic scintillators and NaI(Tl)s; the scattering angle ($\theta_p$) and energy ($T_p$) of the recoil proton were reconstructed using the tracking detectors, position detectors, total energy calorimeters, and energy loss calculation in passive materials.

Figure 1 shows a kinematical correlation between $\theta_p$, and $T_p$, and the expected kinematical curves of elastic and inelastic scattering (6 MeV). The two strong loci are observed clearly. A line at most intense locus is the ground state, which includes the first excited state. Another line observed corresponds to a higher inelastic channel. Figure 2 shows an angler distribution of the elastic channel and theoretical calculation using relativistic impulse approximation(RIA) and relativistic Hartree density$^6$ as reference. Detailed data analysis for angular distribution of elastic and inelastic channels are currently in progress.

![Fig. 2. Preliminary result of angular distribution of elastic channel $p^{(16}C,p$ with the theoretical calculation using RIA and the relativistic Hartree density$^6$.](image)

References
Structure of $^{19}$C studied by one-neutron knockout at SAMURAI


The structure of light nuclei near the neutron drip line has been studied extensively over the past decades. With development in experimental technology, heavier nuclei have emerged as a major focus, and a large number of relevant experiments for neutron-rich carbon or more massive nuclei have been conducted. The present work aims to expose neutron-unbound states of $^{19}$C by one-neutron knockout. A study exploiting in-beam γ-ray spectroscopy for $^{19}$C concluded that $3/2^+$ and $5/2^+$ states are bound.1 A recent report on the inclusive measurement of one-neutron knockout cross section, however, argued that the experimental knockout cross section from $^{20}$C to $^{19}$C did not support the existence of the $5/2^+_1$ state below the threshold.2 In this research, the invariant mass measurement in inverse kinematics was carried out, which allows us to elucidate the issue of boundedness of the $5/2^+_1$ state.

The experiment was performed at RIBF. BigRIPS produced a $^{20}$C secondary beam with an energy of 280 MeV/nucleon. The beam intensity was 170 cps at the target position with a momentum acceptance of $\Delta P/P = \pm 3\%$. The beam impinged on a carbon target with a thickness of 1.8 g/cm$^2$, which produced $^{19}$C via the one-neutron knockout. The trajectory of the beam was determined with two drift chambers (BDCs). Charged fragments from the reaction were separated using SAMURAI, and their energy loss and time of flight were measured using a hodoscope, which is an array of plastic scintillators. Their momenta were reconstructed from their trajectories with two drift chambers (FDCs) placed before and after the magnet. Momenta of decay neutrons were measured with NEBULA using the TOF method. The experimental scheme is identical to that of Ref.5.

A preliminary spectrum for the relative energy of the $^{20}$C+$n$ reaction is shown in Fig. 1. Geometrical acceptance was estimated with a Monte-Carlo simulation. The observed resonance close to the threshold is consistent with the result of Thoennessen et al.6 A preliminary value for the cross section populating this state was derived, which seems to corroborate the argument that the $5/2^+_1$ state is unbound. A quantitative analysis will be carried out to obtain (1) the position of the resonance and (2) the angular momentum of the knocked-out neutron by examining the parallel momentum distribution of the knockout residue.

References
Exploration of cluster structure on neutron rich nuclei $^{16}$C with SAMURAI magnetic spectrometer

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The highly excited states in weakly bound unstable nuclei have been attracting considerable interest recently. In particular, an important question is whether alpha-cluster degree of freedom emerges near the threshold in unstable nuclei as in stable nuclei. For stable nuclei, the Ikeda diagram predicts such threshold-rule has not been examined for unstable nuclei.

The present study is aimed at searching cluster states in the neutron-rich nucleus $^{16}$C through $\alpha$ inelastic scattering at incident energy of 200 MeV/nucleon. Such a technique has been successfully applied on various stable isotopes2). Formed by using the SAMURAI spectrometer3). The large momentum acceptance property enables us to detect $A/Z=3$ particle and $A/Z=2$ particle including $\alpha$ simultaneously. The experimental setup is shown in Fig.1. The setup is similar to that used for the SAMURAI Day−one experiments5). The $A/Z=2$ particles were detected using $A/Z=2$ arm consisting of FDC3 and HODP. The $A/Z=3$ particles were detected using FDC2 and HODF ($A/Z=3$ arm). The correlation between $\Delta E$ and detector ID of HOD gated by the $\alpha$ particle in the $A/Z=2$ arm is shown in Fig.2, where $^{11,12}$Be arising from the breakup of $^{16}$C can be clearly identified.

From the measured four momenta of $\alpha$ particle and the corresponding Be isotopes, the invariant mass of $^{16}$C* will be reconstructed. For such a purpose, multiple track reconstruction techniques on drift chambers have been developed9). The analyses of the data are in progress.

Fig. 1. Experimental setup. Detectors on the SAMURAI focal plane are arranged for $\alpha +$ residual particle detection.

A secondary beam of $^{16}$C at 200 MeV/u and an intensity of $2 \times 10^5$ Hz is impinged on a 7 mm thick cryogenic liquid $^4$He target3). The experiment was performed by using the SAMURAI spectrometer3). The large momentum acceptance property enables us to detect $A/Z=3$ particle and $A/Z=2$ particle including $\alpha$ simultaneously. The experimental setup is shown in Fig.1. The setup is similar to that used for the SAMURAI Day−one experiments5). The $A/Z=2$ particles were detected using $A/Z=2$ arm consisting of FDC3 and HODP. The $A/Z=3$ particles were detected using FDC2 and HODF ($A/Z=3$ arm). The correlation between $\Delta E$ and detector ID of HOD gated by the $\alpha$ particle in the $A/Z=2$ arm is shown in Fig.2, where $^{11,12}$Be arising from the breakup of $^{16}$C can be clearly identified.

From the measured four momenta of $\alpha$ particle and the corresponding Be isotopes, the invariant mass of $^{16}$C* will be reconstructed. For such a purpose, multiple track reconstruction techniques on drift chambers have been developed9). The analyses of the data are in progress.

Fig. 2. Particle identification on SAMURAI focal plane. $Z = 4$ particles are identified on $A/Z=3$ arm in coincidence with $\alpha$ particles, which are gated on the $A/Z=2$ arm.

In summary, we first measured the $\alpha$ dissociation channel on excited $^{16}$C using the SAMURAI spectrometer. Our future scope will focus on $sd$ shell neutron rich nuclei such as $^{26−30}$Ne.

References
Structure study of $^{10}$He by $^{11}$Li(d,$^3$He) transfer reaction


All studies in which $^{10}$He has been populated by proton removal from $^{11}$Li and observed in invariant-mass spectroscopy agree that $E \sim 1.2-1.6$ MeV[1-4]. Recently, the analysis of the missing-mass spectrum from the transfer reaction $^8$He(t,p)$^{10}$He[5] lead to a sizeably higher value, $E \sim 2.1$ MeV.

Our experiment, performed in July 2010 at the RIKEN RIPS facility, used a secondary beam of $^{11}$Li at 50 AMeV on a CD$_2$ target. At forward angle, a wall of four MUST2 telescopes$^9$ were coupled with four 20 µm thick silicon detectors in order to perform an E-∆E identification of the light particles, and separation of $^4$He and $^3$He. At zero degree, a fifth MUST2 telescope and a two stages plastic detector were used for identification of heavy residues of reaction in coincidences. In addition a $^9$Li beam at 50 AMeV was used to perform a reference experiment populating the ground state of $^8$He.

The final excitation spectrum of the unbound $^{10}$He, reconstructed in coincidence with $^8$He decay products (Fig.1), exhibits two clean resonances located respectively at 1.3(3) MeV and 6.3(6) MeV above the two neutron threshold, with natural widths of 1.1(6) MeV and 2.7(7) MeV respectively. The associated differential cross sections have been extracted. They are about one order of magnitude smaller than those predicted in standard DWBA calculations. The implication of this reduction and possible explanations, such as the influences of different neutron binding energies, are explored and put into perspective with the measured cross section of the $^8$He ground state via the $^9$Li(d,$^3$He) reaction.

The spectrum obtained in coincidence with the $^6$He decay products (Fig.1) is showing a preferred decay to the $^6$He+4n channel when possible. This could be inferred to the important role played by the $^8$He(2+) excited state in the $^{10}$He structure, arguing for the development of models beyond the three-body approach.

References

New isotope candidates, $^{215}\text{U}$ and $^{216}\text{U}$

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Theory1) predicts that nuclei with $N = 126$ exist up to Fm($Z = 100$) because of the appearance of the fission barrier originating from the ground-state shell correction. The heaviest $N = 126$ nuclei reported so far is $^{218}\text{U}$($Z = 92$). In this paper, we attempt to produce heavier nuclei such as $^{220}\text{Pu}$. In our experiment, we observed a new isotope, $^{216}\text{U}$, which is the daughter nucleus of $^{220}\text{Pu}$.

We performed an experiment at the RIKEN Linear Accelerator (RILAC) facility. We used $^{82}\text{Kr}$ beams of 372 and 387 MeV to bombard a rotating BaCO$_3$ target foil having a thickness of approximately 400 $\mu$g/cm$^2$. To determine the efficient reaction for the production of $^{216}\text{U}$, we studied the reaction $^{82}\text{Kr} + 136,137,138\text{Ba}$ leading to the same nucleus $^{216}\text{U}$ with different neutron evaporation channels. Each $^{136,137,138}\text{BaCO}_3$ target was prepared by sputtering on 0.8–2.3-μm-thick aluminum foils, and they were also covered with 40 $\mu$g/cm$^2$ of aluminum by sputtering. Several 0.8-μm- and 1.1-μm-thick aluminum foils were prepared as the degraders. The beam energies at the center of the target were changed from 344 to 374 MeV by combining backings and degraders to obtain the excitation function. Evaporation residues (ERs) were separated from the beam particles and other reaction products using a gas-filled recoil ion separator (GARIS), and they were implanted into a position-sensitive strip detector (PSD; $58 \times 58$ mm$^2$) at the focal plane. Two timing detectors were set in front of the PSD to determine 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 for the α-γ coincidence measurement. In this experiment, $1.7 \times 10^{17}$ and $2.7 \times 10^{17}$ beam doses were accumulated at 372 MeV and 387 MeV, respectively.

Isotope identification was performed by using an α-decay chain with the help of known α-decay properties (energies and half-lives) of the descendants and the position correlations between the implanted ERs in the PSD and the subsequent α-decays. Figure 1 shows an α-α correlation spectrum obtained in this experiment. In Fig. 1, the candidates of the new isotopes, $^{215}\text{U}$ and $^{216}\text{U}$, were observed. These α-decay properties and the obtained cross sections are summarized in Table 1. The decay energies and half-lives of these descendants agree well with those of the references. In the future, an additional irradiation experiment will be performed to confirm the production of $^{215}\text{U}$ and $^{216}\text{U}$.

Table 1. α-α correlated 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. $E_{\text{beam}}$ represents the $^{82}\text{Kr}$ beam energy at the center of the target.

![Fig. 1. α-α correlation spectrum. The time difference between the implanted ERs and the parent α-decay, and between the parent and the daughter α-decays are within 150 ms and 2.2 s, respectively. The horizontal and vertical position windows in the PSD were within the same strip (~3.6 mm width) and ±1.5 mm, respectively.](image-url)
Production of $^{262}$Db in the $^{248}$Cm($^{19}$F,5$n$)$^{262}$Db reaction and decay properties of $^{262}$Db and $^{258}$Lr$^\dagger$

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We have been developing a gas-jet transport system coupled to GARIS as a novel technique for superheavy element chemistry.$^{1,3}$ So far, isotopes of element 104, $^{261}$Rf, and element 106, $^{262}$Sg, have been produced for chemical studies in the $^{248}$Cm($^{18}$O,5$n$) and $^{248}$Cm($^{22}$Ne,5$n$) reactions, respectively.$^{1,2}$ In this work, we produced element 105, $^{262}$Db in the $^{248}$Cm($^{19}$F,5$n$) reaction and investigated its decay properties in detail for future chemical studies of Db.

$^{248}$CmO$_2$ targets with thicknesses of 230, 290, and 330 $\mu$g cm$^{-2}$ were prepared by electrodeposition onto a 2-µm Ti foil. The $^{19}$F$^+$ or $^{19}$F$^{2+}$ ion beam was extracted from RILAC. The beam energies were 103.1 and 97.4 MeV at the middle of the target, and the typical beam intensity was 4 particle $\mu$A. The evaporation residues (ERs) separated by GARIS were guided into the gas-jet chamber through a 0.5-µm-thick Mylar window, which was supported by a grid with 84% transparency. Several magnetic rigidities were investigated in $B_p = 1.73–2.09$ Tm at a He pressure of 33 Pa; the optimal collection efficiency for $^{262}$Db was 8.1 ± 2.2% at $B_p = 1.89$ Tm. The ERs were then transported by a He/KCl gas jet to the rotating-wheel apparatus MANON for α/SF spectrometry. In MANON, aerosol particles were deposited on a Mylar foil of 0.5-µm thickness, 40 of which were set on the periphery of a rotating wheel. The wheel was stepped at 15.5 s intervals to position the samples between 15 pairs of Si PIN photodiodes.

We searched for time-correlated $\alpha_1$-$\alpha_2$ event pairs in the time window of 58.5 s and in the energy range of 8.0 MeV $\leq E_\alpha \leq$ 9.0 MeV. As a result, 71 and 4 $\alpha_1$-$\alpha_2$ pairs were found at 103.1 and 97.4 MeV, respectively. By referring to the $\alpha$-particle energies ($E_\alpha$) and half-lives ($T_{1/2}$) adopted for $^{262}$Db and its daughter $^{258}$Lr,$^3$ 74 $\alpha_1$-$\alpha_2$ were reasonably assigned to $^{262}$Db $\rightarrow$ $^{258}$Lr $\rightarrow$. One exceptional $\alpha_1$-$\alpha_2$ pair at 103.1 MeV was $^{262}$Db $\rightarrow$ $^{257}$Lr $\rightarrow$ via the $^{248}$Cm($^{19}$F,6$n$) reaction. No $\alpha_1$-$\alpha_2$ pair on $^{262}$Db produced in the $^{248}$Cm($^{19}$F,4$n$) reaction ($^{262}$Db $\rightarrow$ $^{259}$Lr $\rightarrow$) was observed. We also observed two SF events that correlated with the $\alpha$ decays with energies and decay times of $^{262}$Db. This suggests that small SF and/or EC branches exist in $^{258}$Lr; the EC decay daughter of $^{258}$Lr, $^{258}$No, is a short-lived SF decaying nuclide with $T_{1/2} \approx 1.2$ ms and $b_{SF} = 100\%$. On the basis of the semi-empirical systematics of nuclear mass and half-lives, the EC decay would be favored in $^{258}$Lr next to the $\alpha$ decay.$^4$

The observed decay patterns of $^{262}$Db and $^{258}$Lr are shown in Fig. 1. The $\alpha$-particle energies of $E_\alpha = 8.46 \pm 0.04$ (a intensity $I_\alpha = 70 \pm 5\%$) and 8.68 ± 0.03 MeV (30 ± 5%) were determined for $^{262}$Db, though three energies of $E_\alpha = 8.45$ (75%), 8.53 (16%), and 8.67 (9%) had been adopted.$^3$ The half-life of $^{262}$Db was measured to be $T_{1/2} = 33.8^{+4.4}_{-1.5}$ s, and this agrees well with $T_{1/2} = 34 \pm 4$ s in Ref.$^3$ In this work, the SF activity with $T_{1/2} = 30.2 \pm 0.3$ s was also assigned to $^{262}$Db with a SF branch of $b_{SF} = 52 \pm 4\%$. This is larger than the currently adopted $b_{SF} = \sim 33\%$. On the other hand, the $\alpha$-particle energies of $^{258}$Lr range from $E_\alpha = 8.43$ to 8.73 MeV and the average $\alpha$ energy of $E_\alpha = 8.61$ MeV agrees well with $E_\alpha = 8.605$ MeV deduced from the $\alpha$ energies and intensities of $^{258}$Lr in Ref.$^3$. The half-life of $^{258}$Lr, $T_{1/2} = 3.54^{+0.46}_{-0.36}$ s also agrees with that in Ref.$^3$ ($T_{1/2} = 3.9^{+0.4}_{-0.3}$ s). The EC branch in $^{258}$Lr was first determined to be $b_{EC} = 2.6 \pm 1.8\%$. The cross sections for the $^{248}$Cm($^{19}$F,5$n$)$^{262}$Db reaction were $2.1 \pm 0.7$ nb at 103.1 MeV and $0.23^{+0.18}_{-0.11}$ nb at 97.4 MeV, while those for the $^{248}$Cm($^{19}$F,4$n$)$^{262}$Db reaction were the upper limits of $\leq 0.064$ nb at 103.1 MeV and $\leq 0.13$ nb at 97.4 MeV.

Fig. 1. Observed decay patterns for the chain $^{262}$Db $\rightarrow$ $^{258}$Lr $\rightarrow$ $^{258}$No $\rightarrow$. The $\alpha$-particle energies and intensities ($I_\alpha$) of $^{258}$Lr and all decay data of $^{258}$No are taken from Ref.$^3$

References
4) H. Koura: private communication.
The study of unstable nuclei has been a major subject in nuclear physics for a couple of decades. The collective mode of excitation emerging in the response of the nucleus to an external field is a manifestation of the interaction among nucleons. Thus, the spin-isospin channel of the interaction and the spin-isospin part of the energy-density functional (EDF), which is crucial for understanding and predicting the properties of unstable nuclei and asymmetric nuclear matter, have been studied in much detail, especially through Gamow-Teller (GT) strength distributions.

The GT strength distribution has been extensively investigated experimentally and theoretically not only because of interest in the nuclear structure but also because \( \beta^- \)-decay half-lives set a time scale for the rapid-neutron-capture process (\( r \)-process), and hence determine the production of heavy elements in the universe. The \( r \)-process path is far away from the stability line, and involves neutron-rich nuclei. They are weakly bound and many of them are expected to be deformed according to the systematic Skyrme-EDF calculation\(^1\).

Recently, \( \beta^- \)-decay half-lives of neutron-rich Kr to Tc isotopes with \( A \simeq 110 \) located on the boundary of the \( r \)-process path were newly measured at RIBF\(^2\). The ground-state properties such as deformation and superfluidity in neutron-rich Zr isotopes up to the drip line have been studied by employing the Skyrme-Hartree-Fock-Bogoliubov (HFB) method, and it has been predicted that Zr isotopes around \( A = 110 \) are well deformed in the ground states\(^3\).

To investigate the GT mode of excitation and \( \beta^- \)-decay properties in the deformed neutron-rich Zr isotopes, we construct a new framework of the deformed HFB + proton-neutron QRPA employing the Skyrme EDF self-consistently in both the static and dynamic levels. Furthermore, the HFB equations are solved in real space for a proper description of the pairing correlations in weakly bound systems and coupling to the continuum states.

The \( T = 0 \) pairing interaction is effective for the GT excitation in systems where the ground states have the \( T = 1 \) pairing condensates. In the neutron-rich Zr isotopes under investigation, we find that the \( T = 0 \) pairing interaction enhances the low-lying GT strengths. The low-lying GT strength distribution strongly affects the \( \beta^- \)-decay rate. Thus, we can clearly see the effect of \( T = 0 \) pairing in the \( \beta^- \)-decay life time. We can calculate the \( \beta^- \)-decay half-life \( T_{1/2} \) with Fermi’s golden rule by using the GT strength distributions microscopically obtained in the self-consistent pnQRPA framework.

Figure 1 shows the \( \beta^- \)-decay half-lives of the Zr isotopes calculated with the SLy4 EDF combined with and without the \( T = 0 \) pairing interaction. We see that the attractive \( T = 0 \) pairing interaction substantially shortens the \( \beta^- \)-decay half-lives. \( \beta^- \)-decay rates depend primarily on the \( Q_\beta \) value, the residual interactions in both the p-h and p-p channels, and the shell structures. The framework developed here self-consistently treats these key ingredients on the same footing. Once the strength of the \( T = 0 \) pairing interaction is determined so as to reproduce the observed \( \beta^- \)-decay half-life of \(^{100}\)Zr, our calculation scheme well produces the isotopic dependence of the half-lives up to \(^{110}\)Zr as was recently observed at RIBF.

References
Heavy-quark measurement using distance of closest approach analysis

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Heavy quarks (charm and bottom) can be used as probes to study the interaction between partons and a quark-gluon plasma (QGP). Heavy quarks are created by initial hard scattering, and thus, the changes in their properties when passing through the QGP can be clearly extracted from their final states.

Separate measurements of modifications for charm and bottom quarks are informative because the dependence of the modification on the quark mass can be evaluated. The separation of charm and bottom quarks can be achieved by the analysis of the distances between the tracks and the beam collision vertex (DCA). The DCA distributions of bottomed hadrons are wider than those of charmed hadrons because the lifetimes of bottomed hadrons are considerably longer than those of charmed hadrons.

In this study, electrons and positrons from heavy-quark decay were measured, and the yields of charm and bottom quarks were evaluated by fitting the DCA distribution in the XY plane. We updated the following items from the previous results reported in ref. 1:

- Optimization of cut parameters for the isolation cut, which is explained in ref. 1.
- Evaluation of contributions of electrons from heavy quarkonia such as J/ψ.
- Evaluation of a systematic error from uncertainties of transverse momentum (pT) distributions of charm and bottom quarks.

Owing to the optimization, the purity of heavy-quark electrons in inclusive electrons is increased to more than 50% where pT is larger than 1 GeV/c. The left panel of Fig. 1 shows the S/N ratio, which is defined as the yield of heavy-quark electrons divided by that of the others. The solid and open circles represent the S/N ratios as a function of electron pT with and without the isolation cut, separately. The contribution from heavy quarkonia was evaluated using their cross sections. The right panel of Fig. 1 shows the yield fractions of electron components in inclusive electrons. The brown points represent the contributions of heavy-quarkonium decay. The contribution of heavy quarkonia is ~15% in inclusive electrons at pT > 3 GeV/c. The systematic error from the uncertainties of pT distributions of charm and bottom quarks was evaluated using the distributions obtained from a PYTHIA simulation and FONLL calculation and was found to be ~50% for all pT ranges.

![Figure 1](https://example.com/image1.png)

**Figure 1.** S/N ratio (left) and yield fractions of electron components in inclusive electrons (right). The black, red, green, and brown points in the right panel represent the fractions of heavy-quark electrons, electrons from π0 Dalitz decay, electrons from photon conversion, and electrons from decay of heavy quarkonia, respectively.

Figure 2 shows a comparison of the bottom fractions in heavy-quark electrons as a function of electron pT before and after the updates for p+p collisions with √s = 200 GeV. The open and solid circles indicate the fractions before and after the updates, respectively. The result after the updates is consistent with that before the updates. The increase in the systematic error is due to the error from the uncertainties of pT distributions of charm and bottom quarks.

![Figure 2](https://example.com/image2.png)

**Figure 2.** Bottom fractions in heavy-quark electrons. The open and solid circles indicate the fractions before and after the updates. The bars and squares represent statistical and systematic errors, respectively. The solid line indicates the result of FONLL calculation at rapidity y = 0, and the dashed lines indicate the boundaries of the error band for the calculation.

References
Search for a dark photon in $\pi^0$ Dalitz decays by PHENIX experiment at RHIC

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Several models of dark matter suggest the existence of a “dark photon,” an $U(1)$ gauge boson in the dark matter sector that mixes with an ordinary photon$^1$. In these models, a dark photon is responsible for annihilation of a pair of dark matter particles into an $e^+e^-$ pair. Such annihilation can explain the positron excess observed by PAMELA, FERMI, and AMS-2 satellite experiments. A dark photon can also explain the 3 $\sigma$ level deviation of the anomalous magnetic moment of the muon ($\muon g - 2$) from the Standard Model calculation.

In the simplest version of these models, a dark photon $U$ mixes with a QED photon $\gamma$ with a very small mixing term of the Lagrangian

$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} \epsilon^{\text{QED}} F_{\mu\nu} F_{\mu\nu}^{\text{dark}},$$

where $\epsilon$ is the mixing parameter.

The dark photon can have a small mass $M_U$. If $M_U$ is greater than twice the electron mass $m_e$, it can decay into an $e^+e^-$ pair. In the natural version of the model, this is the only decay mode. This means the following:

1. A dark photon can be produced in any process that can produce virtual photon with a small fraction $\epsilon^2$.
2. Once produced, it decays exclusively into an $e^+e^-$ pair.
3. The decay width of dark photon is very narrow and practically zero due to the small coupling $\epsilon^2$.

Therefore, if the mass of the dark photon is less than that of $\pi^0$, a clear signal of dark photon should show up as a narrow peak in $e^+e^-$ pair mass spectrum of $\pi^0$ Dalitz decays $\pi^0 \rightarrow e^+e^-\gamma$.

We searched for the signal of dark photon in $\pi^0$ Dalitz decay data measured by PHENIX experiment at RHIC. PHENIX is very well suited for this search since it has a very good electron identification capability, a high mass resolution of low mass $e^+e^-$ pairs, and a high statistics data sample of $\pi^0$ Dalitz decay. We used the data set of $p+p$ collision in 2006 run and $d+Au$ collisions in 2008 run, both at $\sqrt{s_{NN}} = 200$ GeV. We analyzed approximately 1.3 million $e^+e^-$ pairs for the search.

We did not find any significant peak in the Dalitz pair mass spectrum. Thus, we set the upper limit on the mixing parameter $\epsilon^2$ as a function of dark photon mass $M_U$ from our null search result. In setting the upper limit, we employed the CLs method, a statistical method now widely used by the LHC experiments for new particle searches.

The preliminary results of the search is shown in Fig.1. The magenta band shows the observed 90 % CL upper limit on $\epsilon^2$. The width of the band represents the systematic uncertainty of the limit. The fluctuation of the limit is due to statistical fluctuation of the background continuum, i.e., Dalitz pair mass spectrum. If the background $e^+e^-$ mass spectrum fluctuate up (down), the upper limit on the dark photon becomes higher (lower). The dashed curve represents the “expected level” of the upper limit if there is no such statistical fluctuation. The green and yellow bands are expected statistical fluctuation of the upper limit at 1$\sigma$ and 2$\sigma$ level, respectively. The fluctuation of the observed limit is within approximately 2$\sigma$ level.

The gray band in the figure shows the 90 % CL region that can explain the muon $g - 2$ deviation. The dashed curve shows the upper limit on $\epsilon^2$ from electron $g - 2$ at 2$\sigma$ level. Together with the limit from electron $g - 2$, our results have excluded almost all region of the muon $g - 2$ band.

We are now working to finalize the data. We will publish the final results soon.

References

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Primordial spectra from sudden turning trajectory†
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Inflation is strongly supported by recent observations of cosmic microwave background (CMB) anisotropies. In particular, single field slow-roll inflation predicts almost adiabatic, Gaussian, and scale invariant primordial curvature perturbations, and these predictions well fit the observational results. On the other hand, high energy theories such as supergravity and superstring theory generically predict additional scalar fields other than inflaton. To reconcile such a generic prediction of theories with recent observations, it may be suggested that only one light field plays a role of inflaton while the others are heavy. In fact, effects of such heavy fields are generically suppressed by their mass and the inflationary dynamics can be well approximated by single field inflation.

While such a scenario can explain the current observational results well, it would be quite interesting if we could detect some deviation from single field slow-roll inflation in the current and future observational experiments: such a deviation would be useful as a probe of high energy physics. In this report, we would like to investigate a possibility that heavy fields can affect inflationary dynamics and imprint some features on primordial spectra.

One typical situation heavy fields matter is the case when heavy fields are excited by the sudden turn of the potential and oscillates with high frequency. In general, oscillations of heavy fields generate the following two significant effects: the modification of the Hubble parameter and the conversion effect, that is, the mixing between adiabatic and isocurvature (heavy field) modes. We investigate these effects in detail and evaluate the power spectra and bispectra of the primordial curvature perturbations in two-field inflationary models with the canonical kinetic terms and a sudden turning potential.

Suppose that the background trajectory is first along the bottom of the potential (the slow-roll direction). The trajectory starts oscillating at the turning point and such a heavy field oscillation induces a deviation from single field slow-roll inflation. The primordial power spectrum of scalar curvature perturbations can then be calculated as

\[ P_{\zeta}(k) = \frac{H_{\text{sr}}^2}{8\pi^2 M_{\text{pl}}^2 \epsilon_{\text{sr}}} \left[ 1 + C_{\text{Hubble}}(k) + C_{\text{conv}}(k) \right], \tag{1} \]

where the first term represents the almost scale-invariant power spectrum in single field slow-roll inflation. The last two terms are the scale-dependent deviation originated from the heavy field oscillations.

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Fig. 1. Deviation in the primordial power spectrum. The orange/red/blue are \(-C_{\text{Hubble}}, C_{\text{conv}}, \) and \(C = C_{\text{Hubble}} + C_{\text{conv}}\), respectively. Free parameters of our model are the heavy field mass \(m\), the turning angular \(\alpha\), and the turning scale \(k_\ast\). Here we used \(m = 20 H_{\text{sr}}\) and assumed that \(\alpha\) is small enough, say \(\alpha \sim O(0.1)\).

The deviation \(C_{\text{Hubble}}\) is from the Hubble deformation effect and \(C_{\text{conv}}\) is from the conversion effect. As depicted in Fig. 1, the parametric resonance amplification occurs from both of the two effects and the peak at the turning scale arises from the conversion effect. It is, however, explicitly shown that resonance effects from the two effects accidentally cancel each other out for the case with the canonical kinetic terms. As a consequence, the peak at the turning scale becomes clear and this feature characterizes this class of models with heavy field oscillations.

We also evaluated primordial bispectra, whose main source comes again from the Hubble deformation effect and the conversion interaction. We find resonance and peak features in the bispectra as in the case of power spectra. Although the size of bispectra is not necessarily large, our results may be useful for probing these effects observationally.

In this work, we discussed two-field models with a sudden turning potential as a phenomenological toy model, and clarified features of heavy field oscillations. It would be interesting to investigate more realistic models with heavy field oscillations e.g. based on string theory. It must be important to discuss their detectability in the current and future observations.

References
Observations of prolonged γ rays emitted from thunderclouds are important for understanding how relativistic electrons are produced there. Recently, the Gamma Ray Observation of Winter Thunderclouds (GROWTH) experiment, successfully operated mainly by RIKEN and the University of Tokyo at the Kashiwazaki-Kariwa nuclear power plant since December 2006, has been conducting an increasing number of prolonged γ-ray observations. Here we report one particular event wherein γ-ray emission suddenly terminated immediately before a lightning flash.

At ~13:30 universal time (UT) on December 30, 2010 (22:30 local time), the GROWTH system of daq0 and daq1, consisting mainly of NaI counters, detected γ-ray increases lasting for ~3 min. Figure 1 shows the enhancements, together with those obtained by radiation monitoring posts (MPs) operated by the Tokyo Electric Power Company. The observed duration is consistent with previous GROWTH events\(^1\,\,^2\). Importantly, only three MPs located within ~1 km of the GROWTH system clearly detected the radiation bursts, while the remaining MPs (1–6) observed no increases with statistical significance >2σ. This means that the horizontal extent of γ-ray emission on the ground was within ~1 km at most.

A lightning event was recorded by our optical sensor and electric field mill at 13:35:55 UT (dashed line in Fig. 1). It is noted that a γ-ray termination seemingly coincided with the lightning occurrence. Interestingly, the Japan Lightning Detection Network system (Franklin Japan Co. Ltd.) registered no lightning within 5 km of our site between 13:05 and 14:05 UT. Thus, the termination is thought to be related to lightning that occurred >5 km away from the site.

As shown in Fig. 2, a notable feature of this event is that the γ-ray termination occurred not in an exact coincidence with the lightning, but 800 ms prior to it. In addition, it is obvious that only >3 MeV γ-ray radiation ceased before the lightning. This finding indicates that production of relativistic electrons to emit >3 MeV γ rays would stop 800 ms before the lightning.

Using an aircraft-onboard detector, McCarthy and Parks\(^3\) observed a similar termination event that follows an x-ray (5–110 keV) increase lasting for ~10 s, and estimated a source length of ~1 km by considering the duration, the aircraft velocity, and an attenuation length of 150 m for 100 keV x rays. It is certain from the present and these results that a local electric field in thunderclouds is enhanced, in a few seconds to minutes, to accelerate electrons and initiate lightning.

In summary, the present event shows that relativistic electrons were continuously produced in a limited acceleration region 800 ms before lightning.

References
μSR study of Al–Mg, Al–Si and Al–Mg–Si alloys†

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Al–Mg–Si alloys constitute most of the worldwide aluminium market as they have good mechanical strength and are easily formable into end products. An optimal heat treatment of alloys containing merely 1% solutes (Mg and Si) typically increases the hardness by a factor of 5 from pure aluminium. After the material is formed, an industrial hardening procedure consists of solution heat treatment (SHT), typically at 550 deg., some (unavoidable) storage at room temperature (RT) and artificial aging (AA), typically at 180 deg. Al–Mg–Si alloys quenched from SHT are unstable at RT, and atomic clusters (with Mg and Si at Al-fcc positions) form from the supersaturated solid solution.1,2) The clusters in general are too small and coherent with the Al matrix to be observed by transmission electron microscopy (TEM).

Muons undergo interstitial diffusion inside solids. In aluminium, they have been shown to be trapped by atoms in substitutional lattice positions and by vacancies,3-5) yielding a lower apparent muon diffusivity. In this work, we exploit this effect and identify the muon trapping behavior of Mg and Si atoms as well as vacancies in different stages of heat treatment of aluminium alloys. Due to its industrial and scientific interest, we study the ternary Al–Mg–Si system, and we also include the binary Al–Mg and Al–Si alloys mainly to isolate the ternary-specific features in the μSR data. Very dilute alloys have been probed with μSR before, and small additions of Si, Mg and Cu were found to greatly affect the muon kinetics.6) Our previous work on the Al–Mg–Si system revealed the presence of a muon trapping peak corresponding to clustering/precipitation.5) The main goal of the current work is to establish a connection between muon trapping rates and the microstructure of Al–Mg–Si alloys as found from TEM studies.

Observed muon spin relaxation spectra in zero-field were compared with those from a Monte Carlo simulation using four fitting parameters: the dipolar width (∆), the trapping rate (νt), detrapping rate (νd) and the fraction of initially trapped muons (pt), assuming that muon spins relaxed with the single ∆ value only when they were trapped. This data analysis is similar to those employed by Sato et al.7) and Hatano et al.8) The resulting temperature variation of the muon trapping rate is shown for eight selected samples in Fig. 1.

We note the following trapping rate characteristics for Al–Mg: 1) heat treatment does not change the muon behavior much in Al–Mg alloys at temperatures up 120K.

Fig. 1 Muon trapping rates (νt) for Al-Mg-Si, Al-Mg, Al-Si alloys and pure Al estimated using simulations.5) The symbol-label of 1.6-AQ denotes the trapping rate with the Al-1.6%Mg2Si sample quenched after SHT, those of 0.5Mg illustrate the results with the samples of Al-0.5%Mg quenched (0.5Mg-AQ), storage at RT for 13d (0.5Mg-13d), and annealed at 200 deg. for 1000 minutes (0.5Mg-200C), and the same manner used with the samples of Al-0.5%Mg. The open circle presents the trapping rate observed with a pure Al (purity is 99.99%).

2) 13d and AQ samples have higher trapping rates than pure Al at temperatures of 240–300 K. This is not the case for the 200C sample. Correspondingly, for Al–Si: 3) the muon behavior in 12d and 200C samples is very similar to that in pure Al, excluding only the lowest temperatures. 4) A significant difference was observed at high temperatures between AQ and 12d (or 200C) samples. 5) The higher trapping rates of 0.5Mg-13d than those of 0.5Si-12d around RT indicate that Mg atoms tend to keep vacancies more than Si atoms.

One of the authors (K. Nishimura) acknowledges JSPS KAKENHI No.25289260.

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Investigation of the magnetic states in new spin-tetrahedral \( \text{K}_4\text{Cu}_4\text{Cl}_{10}\text{O} \)

X.G. Zheng,*1 M. Fujihala,*1 and I. Watanabe*2

Geometrically frustrated magnets, in which localized magnetic moments on triangular, kagome or pyrochlore lattices interact through competing exchange interactions, have recently attracted a lot of interest owing to the diversity in the exotic ground states that they display. Various reports on unconventional magnetic properties provide a challenging and testing ground for theoretical models. Among the several systems reported, the \( S = 1/2 \) quantum systems have received particular attention.

While much of the kagome and pyrochlore antiferromagnets, which are much more complicated to theoretically model than the triangular lattice, are still not well understood, the isolated spin tetrahedral system with weak inter-tetrahedral couplings has recently attracted attention because it can directly demonstrate the interplay of inter-tetrahedral couplings with the built-in tetrahedral frustration. Of more wide interest, they also represent an interesting class of magnets consisting of weakly coupled magnetic clusters. Till date, the \( \text{Cu}_2\text{Te}_2\text{O}_5\text{X}_2 \) \((\text{X} = \text{Cl, Br})\) family and the related compound \( \text{Cu}_4\text{Te}_5\text{O}_{12}\text{Cl}_4 \) have been considered the only real systems of such tetrahedra, but they have remarkable structural anisotropies both inside and outside the tetrahedra, leading to much controversy about their anisotropic magnetic couplings and dimensionality [1-3]. There are several questions that prompt lot of discussion. The most important one is the magnetic dimensionality of the system due to the notable structural anisotropies inside and between the tetrahedra.

Recently, we have synthesized new \( S = 1/2 \) quantum systems of spin-tetrahedral \( \text{K}_4\text{Cu}_4\text{Cl}_{10}\text{O} \), where the magnetic moments (\( \text{Cu}^{2+} \) spins) occupy a three-dimensional tetrahedral lattice, as shown in Fig. 1.

The spin-tetrahedral \( \text{K}_4\text{Cu}_4\text{Cl}_{10}\text{O} \) showed a very broad susceptibility maximum centered around 10 K and a rapid increase below 5 K. \( \mu \)-SR measurements for the system were performed at RIKEN-RAL.

Fig. 2. Zero-field \( \mu \)-SR asymmetry spectra at typical temperatures for \( \text{K}_4\text{Cu}_4\text{Cl}_{10}\text{O} \) obtained from the RIKEN-RAL beam line. The solid lines on the back of the high-temperature data are fitted curves as described in Phys. Rev. B 87, 144425 (2013). The inset plot shows the estimated nuclear field distribution \( \Delta \).

Here, our work shows that similar incommensurate ordering also exists in a three-dimensional isolated spin tetrahedral system.

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I. PREFACE
Preface

The RIKEN RI Beam Factory has reached its harvest time. From its commissioning in 2006 to 2013, 71 experiments have been performed with $^{238}\text{U}$, $^{124}\text{Xe}$, $^{86}\text{Kr}$, $^{70}\text{Zn}$, $^{48}\text{Ca}$, $^{18}\text{O}$, $^{14}\text{N}$, and $^{4}\text{He}$ beams from the Superconducting Ring Cyclotron (SRC) and the isotope separator BigRIPS. The SRC recorded its highest $^{238}\text{U}$ current of 25 pnA in 2013, a performance far beyond that of any other accelerator facilities in the world. This edition of Accelerator Progress Report highlights the history of RI delivery at the RIBF in its gravure pages. While some are yet unpublished, we should be proud that more than 100 new isotopes have been discovered at the RIBF.

Our RI beams attract many users from all over the world. Following the great success of the EURICA (Euro-Riken Crystal Array) campaign, MINOS, a state-of–the-art setup with a hydrogen target and a vertex detector, arrived from Saclay, France. A large-scale Time Projection Chamber to be installed in the SAMURAI spectrometer has recently arrived from the USA. Furthermore, other detectors like NeuLand (highly segmented neutron time-of-flight counters from Germany) and BRIKEN (hundreds of neutron counters from the USA to surround the target) are to be shipped to the RIKEN RIBF.

To effectively explore new regions in the nuclear chart using such devices, we have introduced a new scheme of experimental proposal, Proposal for Scientific Project. With this new scheme, experimentalists are asked to propose a series of experiments based on common physics interests that uses the same experimental apparatus and targets not just one or two nuclei but a wide region of nuclei.

Under this new scheme, the SEASTAR project employing the MINOS and the DALI2 detectors was established to aim for a systematic search of new 2+ energies in the wide range of the neutron-rich nuclei accessible with the RIBF’s currently available $^{70}\text{Zn}$ and $^{238}\text{U}$ beam intensities. The proposal was approved and the first beam time was already allocated. Somewhat different from our traditional style of proposal, the new scheme requires the experimentalists to form a bigger and tighter collaboration. The Nishina Center appreciates an understanding by all users of the necessity of such an approach, and promises its fair operation to the user community.

As we have now reached the stage to reap the harvest of the RIBF research, many interesting results are being published. In 2013, we issued three press releases on the RIBF experiments, “Discovery of exotic isomers with a magic number”, “Evidence for a new nuclear magic number of 34 --- a key to access a dream region of island-of-stability”, and “Magic numbers’ disappear and expand area of nuclear deformation”. The Nishina Center thanks and congratulates all those involved in these experiments, and is convinced that this trend will continue to grow in the future. It should be noted and appraised that in 2013, prestigious prizes were given to the staffs in our accelerator group for their record-breaking accelerator operation, especially with the gas stripper developments.

Unfortunately, JFY2013 did not close peacefully. The STAP incident, a serious scientific misconduct that occurred at the RIKEN Center for Developmental Biology has affected RIKEN severely. I apologize for any inconveniences you have had to deal with to in complying with RIKEN’s countermeasures. If any similar incident ever occurred at the Nishina Center, the Center would cease to exist. We thus declare that such an incident will never happen in our field.

Hideto En'yo
Director,
RIKEN Nishina Center for Accelerator-Based Science
II. RESEARCH ACTIVITIES I
(Nuclear, Particle and Astro-Physics)
1. Nuclear Physics
Search for isomers in neutron-rich Cs isotopes


Neutron-rich nuclei in the northeast region of the doubly-magic $^{132}$Sn are attracting much attention for the investigation of shape evolution from spherical (single-particle like) shapes to deformed (collective-like) prolate shapes as a function of the neutron number. Additionally, a variety of collective modes, such as the octupole collective mode and so on, is expected to appear in this mass region. As isomers are efficient probes of nuclear structure, we performed an isomer search experiment for the neutron-rich Cs isotopes in the framework of the EURICA project.

The isomers were produced through in-flight fission of a 345 MeV/nucleon $^{238}$U beam. The fission fragment separator system of BigRIPS and Zero Degree Spectrometer was tuned for neutron-rich Sb, Te, I, Xe, and Cs isotopes with $A=140-150$. The isotopes with a rate of approximately 50 pps were implanted into a stack of 5 double-sided Si strip detectors (WAS3ABi). The $\beta$ rays and $\gamma$ rays emitted from the stopped isotopes were detected by WAS3ABi and EURICA, which consists of 12 cluster-type Ge detectors, respectively. Particle identification was performed on the basis of the information of time-of-flight (TOF), magnetic rigidity ($B\rho$) and energy loss of the fragments to deduce mass-to-charge ratio ($A/Q$) and atomic number. The particle identification for our $B\rho$ setting is shown in ref. 3. Figure 1 shows the $A/Q$ spectrum of the Cs isotopes deduced using the information of $B\rho$ at F5 and F7 as well as TOF between F3 and F7. The isomers were searched for on the basis of the timing information between the $\gamma$ ray detected by EURICA and ion passage in the plastic scintillator just upstream of WAS3ABi. The long flight time (approximately 650 ns) limited the half lives of longer than hundreds of nanoseconds.

In this time range, we found new isomers in the nuclei $^{145}$Cs, $^{146}$Cs, $^{147}$Cs, and $^{148}$Cs. As an example, a decay curve of the isomer in $^{146}$Cs is shown in Fig. 2. The half life and decay scheme obtained in this work for $^{144}$Cs were consistent with the results reported in ref. 4. The decay schemes of newly found isomers in $^{145-148}$Cs have been established. The isomers in odd-odd Cs isotopes are caused by the direct low-energy deexcitation from the isomer, which is effected by the proton and neutron interaction. In contrast, the decay pattern of the isomers in the odd-Cs isotopes suggests that these isomers are supposed to be $K$-isomer candidates.

Systematic studies of the isomers in the Cs isotopes are expected to provide new insights on shape evolution as well as proton-neutron interaction in various deformed systems. Detailed analysis is in progress.

Fig. 1. $A/Q$ spectrum of neutron-rich Cs isotopes.

Fig. 2. Decay curve of the newly found isomer in $^{146}$Cs.

References
3) R. Lozeva et al., in this report.
Decay spectroscopy in the neutron-rich A~140 region beyond the doubly-magic $^{132}$Sn


An isomer and $\beta$-decay experiment was performed in the framework of the EURICA project at RIBF1,2) aiming at detailed decay spectroscopy and systematic study of the nuclear shape in one of the most interesting, and yet unexplored regions of the nuclear chart, the one beyond the doubly-magic $^{132}$Sn. For these nuclei, we may expect gradual change from spherical shape with predominantly single-particle-like structures, to a more deformed, prolate shape with collective-type of excitations, while with the increase of the neutron-number also octupole collectivity may develop. Furthermore, the perturbed shell structure of these nuclei by e.g. sub-shell gaps or intruder high-j orbitals may also cause isomeric states, picturing in turn these exotic systems far off stability.

The experiment was performed using in-flight $^{238}$U fission at 345 MeV/$u$ on Be target with a thickness of 2.9 mm. The beam intensity was between 1-5 pnA. The nuclei of interest were transported and selected by Bi- gRIPS and implanted in the active stopper, WAS3ABi, consisting of five Si DSSD detectors3). Twelve Ge Cluster detectors and eighteen LaBr$_3$(Ce) detectors3), constituting the EURICA 4$\pi$ array surrounding the stopper, detected the isomeric- or $\beta$-delayed $\gamma$-rays. The experimentally obtained particle identification is shown in Fig. 1, where a line indicates the nuclei beyond which no half-lives are known according to5). Our preliminary data analysis of known half-lives for e.g. $^{138,139}$Sb nuclei show a very good agreement with the ISOLDE measurement 5), providing an important input to the nucleosynthesis data around the A = 130 solar-system r-process abundance peak.

Although the analysis is still in progress, our preliminary results show also several isomeric states before and after a $\beta$-decay in e.g. in Sb and I nuclei. Isomers are found also in the very neutron-rich Cs isotopes6). In addition, first excited states e.g. in the produced even-even nuclei with the neutron increase will provide new and vital information for the shell structure and the shape evolution in this region along with the detailed studies of the other exotic isotopes populated in the experiment.

References
6) A. Yagi et al: in this report.
Lifetime measurements of excited states in $^{102, 104}$Zr with a LaBr$_3$(Ce) array

F. Browne,$^{+1, +3}$ A. M. Bruce,$^{+1}$ T. Sumikama,$^{+2}$ S. Nishimura,$^{+3}$ P. Doornenbal,$^{+3}$ G. Lorusso,$^{+3}$ Z. Patel,$^{+3, +4}$ S. Rice,$^{+3, +4}$ L. Sinclair,$^{+3, +5}$ P.-A. Söderström,$^{+3}$ H. Watanabe,$^{+3, +6}$ J. Wu,$^{+3, +7}$ Z. Y. Xu,$^{+8}$ H. Baba,$^{+3}$ N. Chiga,$^{+2}$ R. Carroll,$^{+4}$ R. Daico,$^{+10}$ F. Didierjean,$^{+11}$ Y. Fang,$^{+10}$ N. Fukuda,$^{+3}$ G. Gey,$^{+12, +19, +3}$ E. Ideguchi,$^{+10}$ N. Inabe,$^{+3}$ T. Isobe,$^{+3}$ D. Kameda,$^{+3}$ I. Kojouharov,$^{+13}$ N. Kurz,$^{+13}$ T. Kubo,$^{+3}$ S. Lalkovski,$^{+14}$ Z. Li,$^{+7}$ R. Lozeva,$^{+11}$ I. Nishizuka,$^{+2}$ H. Nishibata,$^{+10}$ A. Odahara,$^{+10}$ Zs. Podolyák,$^{+4}$ P. H. Regan,$^{+4}$ O. J. Roberts,$^{+1}$ H. Sakurai,$^{+3}$ H. Schaffner,$^{+13}$ G. S. Simpson,$^{+12}$ H. Suzuki,$^{+3}$ H. Takeda,$^{+3}$ M. Tanaka$^{+10}$ J. Taprogge,$^{+15, +16, +1}$ V. Werner,$^{+17}$ O. Wieland,$^{+18}$ and A. Yagi$^{+10}$

Developments of novel scintillator materials have offered a step-change in performance characteristics of scintillation detectors for γ-ray measurements. In particular, cerium-doped lanthanum tri-bromide (LaBr$_3$(Ce)) has proven to be a promising candidate for measuring lifetimes of low-lying excited nuclear states in the ps-to-ns range. Such information is a powerful tool in extracting, for example, nuclear deformations.

An array of 18 LaBr$_3$(Ce) detectors was installed at the F11 focal plane of the BigRIPS spectrometer, augmenting the existing EURICA array$^{+1, +2}$. In order to examine the performance of the LaBr$_3$(Ce) array, the known lifetimes of the $2^+_1$ states in $^{102, 104}$Zr were measured by means of β-γ spectroscopy. The parent nuclei were produced by the in-flight fission of a 345 MeV/A $^{238}$U beam on a 555 mg/cm$^2$ thick $^8$Be target. The fission fragments were transported through BigRIPS and the ZeroDegree spectrometer before being implanted into the WAS3ABI active stopper (5 highly segmented DSSSDs), which lies between two plastic scintillators (β-plastics). To correlate a β-decay event with an implanted ion, a signal in the same DSSSD pixel to the implant was required. A time condition was placed on the ion implantation to β-decay time to reduce contamination from granddaughter decays.

The level lifetime was obtained by measuring the time difference between the β-plastic, and a signal in the LaBr$_3$(Ce) array. A systematic uncertainty of 10% was added to the measured $2^+_1$ lifetimes to account for the lifetimes of higher-lying levels. This was estimated from the time difference spectra for the $4^+_1 \rightarrow 2^+_1$ transitions. Figure 1 shows preliminary results of the background subtracted time difference spectra gated on the $2^+_1 \rightarrow 0^+_{gs}$ transitions, the energies of which are given in Table 1 along with the mean lifetime of the levels, which are in good agreement with literature values$^{+3}$.

The energy systematics indicate increased collectivity as N increases, however, the dependence of the transition probability on E$_r$ results in a longer lifetime for the $2^+_1$ state in $^{104}$Zr than for $^{102}$Zr. Future work will concentrate on a more complete characterisation of the low-energy background, the prompt-response function and the contribution of systematic uncertainties. The lifetimes of the $2^+_1$ states of more exotic Zr isotopes will also be measured.

Fig. 1.: Preliminary, background subtracted time difference spectra for, a) $^{102}$Zr and b) $^{104}$Zr. The extracted mean lifetimes of the $2^+_1$ states are listed below.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$E(2^+_1)$ [keV]</th>
<th>$\tau$ [ns]</th>
<th>ENSDF $\tau$ [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{102}$Zr</td>
<td>151.8(1)</td>
<td>2.7(3)</td>
<td>2.6(6)</td>
</tr>
<tr>
<td>$^{104}$Zr</td>
<td>139.3(3)</td>
<td>3.2(3)</td>
<td>2.9(4)</td>
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2) Z. Patel et al.: In this report.

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$^{+18}$ NPP, ILL, Grenoble

- 5 -
Progress of study of $\beta$-decay of neutron-rich nuclei with $Z \sim 60$

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Approximately half of the elements heavier than iron are formed by the rapid neutron-capture process ($r$-process). In the solar $r$-process abundance distribution, the region of rare-earth elements forms a peak around $A = 160$, which may have a different mechanism of formation compared with the other two distinct peaks at $A = 130$ and $A = 195$ relating to neutron-closed shells at $N = 82$ and $N = 126$, respectively$^{1}$. $\beta$-decay half-lives of the elements always play an important role at both the cold and hot $r$-process paths and will be expected to constrain the conditions in understanding the $r$-process nucleosynthesis.

To study the rare-earth peak, a $\beta$-decay experiment with $Z \sim 60$ was performed at the RIBF facility in June 2013. This experiment was carried out using the in-flight fission of a 345 MeV/nucleon $^{238}$U beam colliding with a Be target. The secondary beam, including a cocktail of highly neutron-rich isotopes, was implanted in the $\beta$-decay counting system WAS3ABi$^{2}$(Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection), which consists of a stack of five highly segmented DSSSDs (Double-Sided Silicon Strip Detectors). With the help of the high-purity germanium detectors (EURICA)$^{3}$, $\gamma$ rays with a high production rate emitted from implanted radioactive isotopes or the daughters nuclei fed through the $\beta$-decay can be measured. The $\beta$-decay half-lives could be determined by fitting the distribution of the time difference between the implantations in the WAS3ABi and the following $\beta$-decay events.

In this experiment, approximately 35 half-lives were measured, including approximately 25 new half-lives.

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Figure 1 displays some preliminary results of four decay curves obtained in this experiment. Daughter half-lives, granddaughter half-lives, as well as the constant background are taken into account by using the Likelihood fitting method. The $\beta$-decay half-lives can also be obtained by using $\beta$-delayed $\gamma$ rays detected by the EURICA detector, which can eliminate the uncertainties from the daughter and granddaughter half-lives. Figure 2 shows the $\beta$-decay curve of $^{149}$La gated the $\beta$-delayed $\gamma$ rays.

Fig. 1. Decay curves of four kinds of isotopes ($^{149}$Ba, $^{149}$La, $^{152}$Ce, $^{154}$Pr) are displayed. The red lines correspond to parent nuclei. The blue curves, black curves, and green lines correspond to the daughter nuclei, granddaughter nuclei, and a constant background.

Fig. 2. $^{149}$La decay curve obtained gating on the $\beta$-delayed $\gamma$-ray energy with 245.4keV.

In the latter phases of analysis, further new half-lives will be obtained. Simulation work of $r$-process will be performed by comparing the theoretical calculations with our experimental results.

References
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. The $\beta$-decay of a $0_\pi^+$-proton in $^{100}$Sn to a $g_7/2$-neutron in $^{100}$In shows the smallest $\log(t_f) = 2.62^{+0.13}_{-0.11}$ value in the nuclear chart. The Gamow-Teller strength $B_{GT} = 9.1^{+2.6}_{-3.0}$ as deduced from the last experiment at GSI$^1$. This value is consistent with the results of $B_{GT}$ calculations as derived from LSSM calculations. However, the uncertainties in the extracted $B_{GT}$ are still dominated by statistics. In particular, the contribution of the $\beta$-decay end-point energy $E_{\beta,\text{max}}$ amounts to 85% of the $B_{GT}$ uncertainty. In the present experiment, a 4 mm Be target was bombarded with a $^{124}$Xe beam of 345 MeV/u at intensities up to 36.4 pA to produce $^{100}$Sn by fragmentation. In total, 2525 $^{100}$Sn ions (Fig. 1) were identified during 8.5 days of beamtime. This exceeds the number obtained in the previous experiment at GSI$^1$ by nearly a factor of 10, and the uncertainties in $B_{GT}$ are expected to be improved by more than a factor of 2. Furthermore, a number of nuclides towards the proto dripline have been newly identified (see Čeliković et al.$^2$) and significantly higher statistics for $N=Z$ and $N=Z-1$ isotopes have been obtained.

In order to observe $\beta$- and $\gamma$-decays, $^{100}$Sn and most of the neighboring nuclei (see Fig. 1) were implanted into the WAS3ABi detector, which is a closed stack consisting of three highly segmented silicon detectors of 1 mm thickness each surrounded by 84 Ge- and 18 LaBr-detectors of the 4π-$\gamma$-spectrometer EUROICA. This WAS3ABi detector array is expanded by a stack of 10 silicon detectors of the same thickness in order to measure the total energy of the decay positrons accurately. Since $E_{\beta,\text{max}} = 3.29 \pm 0.20$ MeV is rather small$^1$, the decay positrons are stopped in the silicon stack, enabling a high-precision measurement in order to determine $E_{\beta,\text{max}}$. We find correlated $\beta$-decays by considering decay events occurring within a time window $t_c$ and active detector volume around the implantation. Thus, we can determine the half-lives of $\beta$-decays. From $\beta$-delayed $\gamma$-decays, using the largest data sample on $^{100}$Sn, we will be able to distinguish between two scenarios for the $\beta$-delayed $\gamma$-cascades to confirm a dominantly populated $1^+_1$ state in $^{100}$In after $\beta$-decay. Furthermore, we are looking for a 6$^+$ isomeric state in $^{100}$Sn, as predicted by Grawe et al.$^3$ based on LSSM calculations.

After a preliminary energy calibration of the WAS3ABi detectors, one of the most challenging tasks is to determine systematic uncertainties in the $\beta$-decay end-point energy $E_{\beta,\text{max}}$ and $\beta$-half-life $T_{1/2}$. A small (systematic) error in these quantities affects the $B_{GT}$, resulting in a large relative uncertainty. Since $^{100}$Sn has a long half-life, the background contribution on this measurement is also studied in detail to minimize these systematic uncertainties.

First results indicate a good agreement with known values$^1$ of both quantities $T_{1/2}(^{100}$Sn$)$ and $E_{\beta,\text{max}}(^{100}$Sn$)$.

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Decay spectroscopy around $^{78}\text{Ni}$ with the EURICA setup

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Exotic nuclei play an important role in nuclear shell structure studies since they allow to search for possible modifications of magic numbers with increasing N/Z ratio. The tensor force, one of the non-central components of the effective nucleon-nucleon interaction, is expected to modify the relative single particle energies owing to an increased attraction for orbitals with anti-parallel spin configuration and a repulsion for orbitals with parallel spin configuration. In such context, nuclei at Z=28, N=50 shell gaps are particularly interesting since they are good candidates to reveal changes into the shell structure. Astrophysical implications also involve the discussion on neutron-rich nuclei, since they are expected to dominate the nuclear composition throughout the collapse of massive stars.

In this view an experiment aiming at studying decay spectroscopy in the region close to $^{78}\text{Ni}$, i.e. in the isotopic chains of Cu, Ni, Co and Fe, was performed at RIKEN in May 2013 as part of the EURICA campaign at the Radioactive-Isotope Beam Factory (RIBF) facility.

The wanted species were produced by means of in-flight fission of a $^{238}\text{U}$ beam at a bombarding energy of 345 MeV/u. The resulting fragments were separated in the BigRIPS separator, by the use of degraders at the intermediate dispersive foci.¹³ The cocktail beam was transported in the ZeroDegree spectrometer down to the final focal plane F11. The beam was then slowed down in an Al degrader to ensure the implantation of the wanted species in the 5 silicon detectors of the WAS3ABi array.²³ This silicon array was surrounded by the EURICA spectrometer consisting of 12 EUROBALL cluster detectors.³ LaBr$_3$ scintillator detectors were also mounted in clusters to allow fast-timing measurements. The experiment collected data for an equivalent time of 3 days with an average primary beam intensity of 10pA. The total count rate at the final focal plane F11 was limited to 100pps to ensure ion-$\beta$ correlations. In Figure 1 a particle identification (PID) plot is shown. The plot does not include the full statistics of the experiment. The B$p$ setting of the separator was set in order to transport $^{74}\text{Fe}$ in its central trajectory.

The study of isomeric $\gamma$ transitions and $\beta$-delayed transitions in the populated nuclei is ongoing. The same reaction was also exploited to perform Coulomb excitation reaction to study the first excited states in $^{73-75}\text{Ni}$ isotopes.

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Fig. 1. PID plot of the cocktail beam implanted in the WAS3ABi array.
Structure of neutron-rich Zr and Mo isotopes


Neutron-rich isotopes in the vicinity of $^{110}$Zr have attracted much attention, because a shape transition from oblate or triaxial and a tetrahedral-shape isomer may be observed.1) The decay spectroscopy of the Zr and Mo isotopes was performed at RIBF at RIKEN Nishina Center to extend the previous experiment1) to more neutron-rich region. The neutron-rich nuclei were produced by the in-flight-fission reaction of $^{238}$U beam at 345 MeV/u in a 3-mm-thick Be target, and implanted into the double-sided silicon-strip detectors (WAS3ABi), which were placed at the center of the high-purity-germanium detector array (EURICA).2) A fast-timing LaBr$_3$(Ce) array was combined with EURICA for a half-life measurement of excited states.

Figure 1 shows the particle-identification (PID) plot of the radioactive-isotope (RI) beam separated by the BigRIPS separator. The $\beta$-$\gamma$ spectroscopy of $^{102,104}$Y, and $^{106}$Nb was performed individually by using a high-purity-beam setting. Figure 2 shows the PID spectrum of $^{102}$Y setting. The purity of $^{102}$Y was 46%. A preliminary result of the half-life measurement for $^{102,104}$Zr using the fast-timing array is given in another report.3) The beam setting shown in Fig. 3 is used to search for an isomeric state in $^{110}$Mo using a passive Cu stopper. Further analysis is in progress.

Fig. 1. PID plot of the atomic number $Z$ and the mass to charge ratio $A/Q$. A wider and more-neutron-rich region than Figs. 2 and 3 was selected by the BigRIPS separator.

Fig. 2. PID plot of a high-purity-beam setting for the spectroscopic study of $\beta$ decay from $^{102}$Y.

Fig. 3. PID plot of a high-purity-beam setting to search for an isomeric state in $^{110}$Mo.

References

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Search for K-isomers in neutron-rich $Z \approx 60$ isotopes


The neutron-rich $A \sim 150$ region contains a wide variety of shape phenomena, including shape coexistence and possible static octupole and hexadecapole deformations. Although quadrupole deformation has been extensively examined across most of the nuclear chart, both octupole and hexadecapole deformations remain much less well studied in comparison. These higher-order deformations can have a strong influence on gamma-decay rates and the quasi-particle energies of nuclei, and hence, their detailed studies are necessary to test the various differing predictions of several nuclear models. We have performed an experiment to search for $\mu$S isomers in the neutron-rich $A \sim 150 \sim 160$ Nd, Ce, Ba nuclei and to study their $\beta$-decay, in order to examine octupole and hexadecapole deformations in this region. These studies have become possible for the first time using the world’s highest intensity in-flight RI beams available at RIBF with the high-efficiency gamma spectrometer, EURICA.

To study the excited levels of these $A = 150 \sim 160$ isotopes, we have performed isomer and beta-gamma spectroscopy using EURICA in two different RI beam settings. One setting involves focusing on the Nd region and the other, on the Ba region.

During the experiment for the Nd setting (see Fig. 1), a previously reported isomer in $^{156}$Nd was confirmed and a new isomer in $^{158}$Nd was identified. We also succeeded to find some more isomers in neutron-rich Nd isotopes up to $^{160}$Nd. These findings will allow us to study the systematic analysis of isomers in neutron-rich Nd isotopes, and the development of quadrupole and hexadecapole deformations as a function of neutron numbers will be investigated. In addition, we have also found several new microsecond isomeric states in this region.

In the Ba setting run, RI beams of $^{149-151}$Ba, $^{151-153}$La, and $^{154,155}$Ce were mainly collected, as shown in Fig. 2. The isotopes were stopped at the active stopper, WAS3ABI, and beta-gamma spectroscopy of these isotopes was performed using the EURICA setup. All the isotopes indicated above are newly studied with the aim of systematic investigation of octupole correlations, a study that has not been possible so far. Detailed analyses are underway.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{Particle identification (A/Q vs Z) plot for the Nd setting run.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Particle identification plot for the Ba setting run.}
\end{figure}

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II-1. Nuclear Physics


It has been known that large prolate deformation develops in neutron-rich $Z \sim 60$ nuclei. This can be seen from the systematics of excitation energies of the first $2^+$ states of even-even $Z = 55$ to 66 nuclei as shown in FIG.1 of ref.9. In this deformed region, many K-isomers with micro second half-lives have been discovered. For example, $K^2 = 4^+$ isomers are systematically observed in $Z = 62$ to 68, $N = 100$ isotones2,3). It is interesting to investigate whether the same kind of isomers exist in lower $Z$ isotones, as this information will be helpful in understanding the deformed shell structure of such highly neutron-rich nuclei.

We performed isomer and $\beta$-$\gamma$ spectroscopy on neutron-rich $Z = 56$ to 61 isotopes at RIBF. The neutron-rich isotopes were produced using in-flight fission of a 345MeV/nucleon $^{238}$U beam. Fission fragments were identified by measuring the time-of-flight (TOF) and magnetic rigidity ($B\rho$) in the second stage of BigRIPS and by measuring the energy loss ($\Delta E$) by the ion chamber at the final focal plane, F11. The measurement was conducted in two different setups. In one setup, the beam was implanted into an active stopper, WAS3ABi4) which consists of five layers of Double-Sided-Silicon-Strip Detectors (DSSSDs) with $40 \times 60$ strips, in order to obtain $\beta$-$\gamma$ and isomer data at the same time. In this setup, the total implantation rate was limited up to $\sim 100$ cps. In the other setup, a copper stopper was introduced instead of the DSSSD to accept a wide range of nuclides with a high total rate, in order to optimize the isomer search. The $\gamma$ rays from the isomeric states were detected by EURICA5), which is an array of 12-cluster Ge detectors. Each cluster consists of seven crystals that enable adding back Compton-scattered events in the neighboring crystals.

After the analysis of the data, isomers were found in $^{158,159}$Pm isotopes with $A = 158$, 159, and 161. Fig. 1 shows the preliminary energy spectra of the delayed $\gamma$ rays for the $^{158}$Pm isotopes. Many new $\gamma$ rays were observed for them. Half-lives of $^{159}$Pm and $^{161}$Pm were obtained by fitting the timing spectra gated by the $\gamma$-ray energy. $^{158}$Pm was found to have a half-life much longer than the 16$\mu$s time window. Further analysis of the $\gamma$-$\gamma$ coincidence and relative intensities are in progress to construct the level schemes. $\beta$-$\gamma$ analysis will also be performed to obtain more information on the low-lying states of these nuclei.

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Beta-delayed proton emission of $^{73}\text{Sr}$ and effective lifetime of the rp-process waiting point $^{72}\text{Kr}$ in X-ray bursts environment

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The nuclide $^{72}\text{Kr}$ is a potential waiting point of the astrophysical rp-process. However, its lifetime under conditions of X-ray bursts may significantly be reduced by the two-proton capture reaction $^{72}\text{Kr}(p,\gamma)^{73}\text{Rb}(p,\gamma)^{74}\text{Sr}$. The rate of this reaction is highly sensitive to the characteristics of the low-energy states of the intermediate nucleus $^{73}\text{Rb}$ and, in particular, to the proton-separation energy, $S_p$, of $^{73}\text{Rb}$. No constraints from direct measurements exist, resulting in significant uncertainties in calculations of astrophysical interest.

Nuclear structure in the 70–80 mass-number region is particularly interesting. Rapid shape changes, shape coexistence, and np-pairing effects are all expected. This is a challenging region from a theoretical perspective and little experimental data exists for nuclei beyond the $N=Z$ line. This experiment affords an opportunity to access nuclei both at and beyond the $N=Z$ line in this mass-number region.

The nuclei of interest were produced by fragmentation of a 345 MeV/u $^{124}\text{Xe}$ primary beam colliding with a $^9\text{Be}$ target. The beam intensity ranged from 30–35 pA. The secondary beam purification and identification was performed using the BigRIPS fragment separator. The fragments of interest were unambiguously identified, and their subsequent decays were recorded using the WAS3ABi silicon stopper in conjunction with EURICA\textsuperscript{1}. Implantations were correlated with their subsequent $\beta$-decays on the basis of position and time, enabling measurement of half-lives and $\beta$-delayed $\gamma$ rays.

Two experimental settings were used to access proton-rich isotopes around $^{73}\text{Sr}$ (as shown in the particle-identification (PID) plot in Fig. 1 with $^{73}\text{Sr}$ highlighted). As a first setting, BigRIPS was set for maximum transmission of $^{73}\text{Sr}$, the number of implanted nuclei predicted by LISE$^{++}$ was 2500 and the requested beam time was 2.5 days. A second setting was optimized for the transmission of $^{74}\text{Sr}$, and the number of implanted nuclei predicted was 8000 for 0.5 days. The actual total beam time was 45 h for $^{73}\text{Sr}$ and 9 h for $^{74}\text{Sr}$. The number of implanted $^{73}\text{Sr}$ and $^{74}\text{Sr}$ were 186 and 590, respectively. The discrepancies observed between the expected counts and actual counts is due to the actual production cross-section being lower than that predicted by LISE$^{++}$ calculations.

Upon the experiment’s completion, an energy calibration of WAS3ABi was carried out using 482 and 972 keV conversion electrons emitted from a $^{207}\text{Bi}$ source.

The $\beta^+$-decay half-lives of nuclei $^{73}\text{Sr}$, $^{74}\text{Sr}$ and $^{76}\text{Y}$ have been measured. The accuracy of these measurements were verified by extracting the half-lives of previously studied nuclei and comparing with the literature values.

The isotopes $^{69}\text{Br}$, $^{72}\text{Rb}$ and $^{73}\text{Rb}$ were observed in BigRIPS, for which there is evidence of implantation and decay events in WAS3ABi. Future analyses will focus on these events, as well as the low-lying structure populated through $\beta^+$-decay of exotic nuclei produced around $^{78}\text{Sr}$. A search for new isomeric states, such as the one found in $^{70}\text{Sr}$, is also being carried out.

This large set of data will provide new half-lives, direct input for rp-process calculations, and new insights into the structure of nuclei in this region.

References

Commissioning of a LaBr$_3$(Ce) array with EURICA at RIBF

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An array of 18 LaBr$_3$(Ce) detectors were introduced to complement the HPGe EURICA (Euroball-RIKEN Cluster Array) detectors for the Spring 2013 campaign at RIBF. These detectors were supplied by The University of Surrey andnow University of Brighton to provide fast-timing information on the half-lives of excited states within radioactive nuclei$^1$.

LaBr$_3$(Ce) crystals are very fast scintillators with high effective Z and a fast decay time. This makes them superior to other detectors for γ-ray decay time measurements, as they are able to measure half-lives with a picosecond-nanosecond range while also possessing good energy resolution$^{2,3}$.

Radioactive isotopes were delivered by BigRIPS to the experimental area, where they were implanted into WAS3ABi (Wide Angle Silicon Strip Stopper Array for Beta and ion implantation). The resulting γ rays following the isotope’s decay were detected by the surrounding HPGe and LaBr$_3$(Ce) detectors (Fig. 1). Two plastic scintillators were added to WAS3ABi (one upstream and one downstream) to provide a stop signal for the short-range TDC of the LaBr$_3$(Ce) detectors, as the silicon detector’s time resolution is too poor at hundreds of nanoseconds.

The LaBr$_3$(Ce) crystals are $\varnothing$ 1.5” x 2”, each coupled to a H10570MOD Hamamatsu PMT. The crystals have removable 5 mm lead shields to prevent crosstalk between detectors. The configuration can be seen in figure 1. The plastic scintillators measured 45 mm x 150 mm x 2 mm and were placed approximately 3 - 5 mm from the first and last DSSDs.

The PMTs of the LaBr$_3$(Ce) detectors have an anode and a dynode output for timing and energy measurements respectively. The energy signal was taken from the last dynode of the 8-stage PMT and passed to a CAEN V785 shaping amplifier followed by a CAEN V775 short-range TDC and a CAEN V1190A long-range TDC. A stop signal from the plastic scintillator at F11 (∼ 1 m before WAS3ABi) or from WAS3ABi is used for the long-range TDC. The stop signal for the short-range TDC is taken from the plastic scintillators.

Fig. 1.: A schematic of one-half of EURICA with LaBr$_3$(Ce) detectors, viewed perpendicular to the beam line. The remaining unseen detectors are arranged at the bottom of the array.

Fig. 2.: Absolute efficiency of the LaBr$_3$(Ce) detectors measured using $^{152}$Eu and $^{60}$Co sources.

The absolute efficiency of the LaBr$_3$(Ce) array is shown in figure 2. This was measured using $^{152}$Eu and $^{60}$Co point sources placed inside the WAS3Abi chamber, with the LaBr$_3$(Ce) detectors positioned on average ∼ 10 cm from the silicon strip detectors.

Analysis of data taken by the LaBr$_3$(Ce) detectors is in progress: preliminary results from half-life measurements in Zr isotopes can be found in reference 4.

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Deuteron Analyzing Powers for $dp$ elastic scattering at 250–294 MeV/nucleon and three-nucleon force


The study of three-nucleon forces (3NFs) is essential for clarifying various nuclear phenomena. In addition to the first signals indicating 3NF effects in the binding energies of $^3$H and $^3$He, the significance of 3NFs has been recently pointed out for descriptions of discrete states in higher-mass nuclei. Three-nucleon scattering at intermediate energies ($E/A \sim 200$ MeV) is one attractive approach to investigate the dynamical aspects of 3NFs, such as momentum and/or spin dependences. With the aim of clarifying the roles of the 3NFs in nuclei, experimental programs with polarized deuteron beams at intermediate energies are in progress at RIBF. As the first step, we measured a complete set of deuteron analyzing powers ($iT_{11}$, $T_{20}$, $T_{21}$, $T_{22}$) in deuteron–proton ($dp$) elastic scattering at 250 and 294 MeV/nucleon (MeV/N).

A schematic diagram of the experimental setup can be found in Ref. (1). Vector- and tensor-polarized deuteron beams were accelerated by the injector cyclotrons AVF and RRC up to 90 (100) MeV/N; subsequently, they were accelerated up to 250 (294) MeV/N by the SRC. Typical values of the beam polarizations were 80% of the theoretical maximum values. The measurement for $dp$ elastic scattering was performed by using a detector system, BigDpol, installed at the extraction beamline of the SRC. Polyethylene (CH$_2$) of thickness 330 mg/cm$^2$ was used as the hydrogen target. In BigDpol, four pairs of plastic scintillators coupled with photo-multiplier tubes were placed symmetrically in the azimuthal directions to the left, right, up and down. Scattered deuterons and recoil protons were detected in the kinematical coincidence condition by each pair of detectors. The angles ($\theta_{c.m.}$) measured in the center-of-mass system are in the range 40°–162°.

In the experiment, the deuteron beams were stopped in a Faraday cup, which was installed at the focal plane F0 of the BigRIPS spectrometer.

Here, we report the results of energy dependence of the deuteron tensor analyzing power $T_{22}$. The angular distribution of $T_{22}$ is shown with open circles, together with the previously reported data at 70 and 135 MeV/N$^1$. The red (blue) bands in the figure are the Faddeev calculations with (without) Tucson–Melbourne’99 (TM99) 3NF$^2$ based on the modern NN potentials, namely CDBon$^3$, AV18$^4$, Nijmegen I, and Nijmegen II$^5$. The solid lines are the calculations including Urbana IX 3NF$^6$ based on the AV18 potential.

The tensor analyzing power $T_{22}$ reveals an energy dependence different from those obtained for the cross section and the other analyzing powers $iT_{11}$, $T_{20}$, and $T_{21}$$^1$. At 135 MeV/N and below, adding 3NFs degrades the description of data in a large angular region. It is contrary to what happens at energies above 250 MeV/N, for which large 3NF effects are supported by the $T_{22}$ data.

In order to obtain a consistent understanding of the spin dependence of 3NFs up to high momenta, we plan to perform deuteron analyzing power measurements at 190 MeV/N.

Fig. 1. Tensor analyzing power $T_{22}$ for $dp$ elastic scattering at 70–294 MeV/N.

References
Shallow and diffuse spin-orbit potential for proton elastic scattering from neutron-rich helium isotopes at 71 MeV/nucleon


Strong spin-orbit coupling in atomic nuclei plays an important role in nuclear structure and reactions. Its manifestation in neutron-rich nuclei has attracted extensive interest, since a number of experimental results suggest a change in the shell structure that could be explained by a reduction in the spin-orbit splitting. On the other hand, there has been no experimental study on how the spin-orbit coupling is modified in nuclear reactions. Spin asymmetry in proton–nucleus scattering is a prominent manifestation of the spin-orbit interaction. The spin-orbit term in the optical model potential is generally expressed by a derivative of the density distribution, and obtained parameters can be found in Refs. 5,6. The optical model potential is generally expressed by a derivative of the density distribution and the ampli-
magnitude of $rV_{ls}$ is remarkably larger than the systematics. More-
hover, it is interesting to find a close similarity between the behavior of $(r_{ls}^2)^{1/2}$ and the matter radius $r_m$, plotted as the open squares in Fig. 1(a). This indicates the particular sensitivity of the spin-orbit interaction to the nuclear surface structure.

Figure 1(b) displays the amplitude of $rV_{ls}(r)$ at the peak position. The peak amplitudes for $^6$He and $^8$He are considerably smaller than the standard values of 3.5–5.5 MeV fm. From these results, it is concluded that the spin-orbit potentials between a proton and neutron-rich $^6$He and $^8$He nuclei are considerably shallower and more diffuse than the global systematics of nuclei along the stability line. This is considered to be a consequence of the diffuse density distribution of these neutron-rich isotopes.

![Figure 1. See text for details. The symbols for $r_m$ are shifted vertically by –0.5 fm to prevent overlap.](image)

References

A systematic study of the nucleon density distributions of finite nuclei is important for understanding the isospin dependence of the nuclear many-body system. For example, the neutron skin thicknesses are known to be strongly correlated with the density-dependent term of the symmetry energy, and the isospin-dependent term of the nuclear equation of state.

In previous works, we have succeeded in extracting the neutron density distributions of stable nuclei such as Sn and Pb isotopes via proton elastic scattering. At the same time we have launched a new project aimed at measuring the Elastic Scattering of Protons with RI beams (ESPRI) with the purpose of the extraction of proton and neutron density distributions of unstable nuclei. We have newly developed and tested unique devices for the ESPRI measurements at NIRS-RIBF in April, 2013. Finally, we have successfully performed the ESPRI experiment at RIBF in April, 2013.

Unlike the case of stable nuclei, however, we have no information on the nuclear charge densities of unstable nuclei. Thus, we have proposed a new method to extract proton and neutron densities via two-energy proton elastic scattering. This method is based on the large difference between the energy dependencies of the p-p and p-n interactions. Recently, we performed an experiment to demonstrate this new method using real data of Zr isotopes. In this report, we show the preliminary results of $^{90}$Zr only. For other isotopes ($^{92,94}$Zr), the analysis is still ongoing.

The experiment was performed at RCNP, Osaka University. Polarized proton elastic scattering from $^{90,92,94}$Zr and $^{58}$Ni at 200 and 300 MeV was measured by using the Grand Raiden magnetic spectrometer. Figure 1 shows the angular distributions of cross sections ($d\sigma/d\Omega$) and the analyzing powers ($A_y$) of $^{90}$Zr($\vec{p}$,$\vec{p}$) at 200 and 300 MeV and of $^{58}$Ni($\vec{p}$,$\vec{p}$) at 200 MeV. The red lines denote the result of relativistic impulse approximation (RIA) with relativistic-Hartree (RH) densities. The $^{58}$Ni data was used to determine the effective interaction at 200 MeV (solid lines). Using the effective interaction, the proton and neutron densities of $^{90}$Zr were simultaneously searched and the results are denoted by the solid lines in Fig. 1 and 2.

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Spin-isospin response of the neutron-rich nucleus $^8$He via the $(p,n)$ reaction in inverse kinematics

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Charge-exchange $(p,n)$ reactions at intermediate energies ($E > 100$ MeV) serve as powerful tools to study spin-isospin responses of nuclei; Gamow-Teller (GT) transitions are a particular example of such reactions. In the present work, we focused on the neutron-rich nucleus $^8$He, which has the largest neutron-to-proton ratio among all known particle-stable nuclei ($N/Z = 3$). It can be described as an $\alpha$-particle surrounded by four valence neutrons, exhibiting a neutron halo or thick neutron skin. We measured the $^8$He$(p,n)^8$Li reaction at 1904 MeV in inverse kinematics in order to study the spin-isospin response of $^8$He. This is the first measurement of the charge-exchange reaction on $^8$He.

The experiment was performed at the RIKEN RI Beam Factory (RIBF). Recoil neutrons with low kinetic energies from the $(p,n)$ reactions were detected by the recently developed neutron detector WINDS. The residual nucleus $^8$Li and its decay product $^7$Li were detected using auxiliary beam line detectors, a plastic scintillator, and a multi-wire drift chamber (LP-MWDC)2, installed at FH10, which is downstream from the secondary target at FH9. A superconducting triplet quadrupole (STQ) was installed between FH9 and FH10. The triton decay channel of the excited state in $^7$Li was not tagged in this measurement.

Double differential cross sections for the $^8$He$(p,n)^8$Li reaction at excitation energies of 0–20 MeV and neutron energies of 2.0–4.4 MeV, which correspond to momentum transfers of 0.31–0.46 fm$^{-1}$, were obtained. Figure 1 shows the double differential cross sections for $T_n = 2.0$–2.6 MeV, corresponding to $q = 0.31$–0.35 fm$^{-1}$. In the spectrum, two peaks were observed at $\sim 1$ MeV and $\sim 8$ MeV. The lower peak corresponds to the first excited $1^+$ state of $^8$Li at 0.98 MeV.

The angular distributions of the cross sections for the peaks at $\sim 1$ MeV and $\sim 8$ MeV are shown in Fig. 2. In this figure, the differential cross sections were corrected for the transmission efficiencies between FH9 and FH10. They were compared to the results of distorted wave impulse approximation (DWIA) calculations. The angular distribution of the peak at $\sim 1$ MeV, which is a flat distribution, was reproduced well by the sum of the 0.98-MeV state ($J^\pi = 1^+$) and the ground state ($J^\pi = 2^+$). The cross sections at $q = 0$ for the 0.98-MeV and 8-MeV states were extracted. We then calculated the GT strength $B(GT)$ for the 8-MeV state by using the extracted cross sections at $q = 0$ and the known $B(GT)$ value of 0.24 for the 0.98-MeV state. The obtained GT strength was $B(GT) \sim 8$ for the neutron decay channel of the 8-MeV state.

It is known that the excited state at $\sim 9$ MeV with a large GT strength of $B(GT) \sim 5$ decays primarily by triton emission. In contrast, we observed, for the first time, a neutron decay channel of the resonance state with a large $B(GT)$ strength. This result suggests that most of the GT strength is concentrated in the resonance state at $\sim 8$ MeV. The observed state is most likely the Gamow-Teller resonance of $^8$He. Further analysis is in progress.

References

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Fig. 1. (Preliminary) Double differential cross sections for $T_n = 2.0$–2.6 MeV.

Fig. 2. (Preliminary) Angular distributions of the measured cross section for the 0.98-MeV (black) peak and the 8-MeV (red) peak.
New type of spectroscopy via heavy-ion double charge exchange $(^{12}\text{C},^{12}\text{Be}(0^+_2))$ reaction

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One of the most interesting features in atomic nuclei is the variety of spin and isospin responses. The Gamow–Teller (GT) transition is the simplest spin–isospin response within one-phonon excitations, and it has been well studied. In contrast, data on multi-phonon excitations have been scarce. The double GT giant resonance (DGTGR) is the most basic two-phonon excitation mode. However, DGTGRs have not been observed so far. The discovery of the DGTGR is an essential step in extending the research of the spin–isospin responses to multi-phonon space. Another interest for studying DGTGR relates to its relevance in neutrino physics; the GT transition is induced by the same transition operator as the $\beta\beta$-decay is, i.e., $\sigma\pi\pi$. However, the $\beta\beta$-decay has quite small DGT strength. A major part of the DGT strength is concentrated among highly excited states in DGTGR. A promising spectroscopic method to search for DGTGRs is through heavy-ion double charge exchange (HIDCX) reactions, which can induce two-phonon excitations with spin and isospin transfer by two units.

In 2011, we conducted a HIDCX $^{12}\text{C}(^{18}\text{O},^{18}\text{Ne})^{12}\text{Be}$ reaction experiment and found a large cross section of 1.5 $\mu$b/sr for the second 0+ (0⁺) state in $^{12}\text{Be}$ at 0.2 MeV. This is probably because all the initial $^{12}\text{C}(0^+_{g.s.})$, intermediate $^{12}\text{Be}(1^+_s)$, and final $^{12}\text{Be}(0^+_2)$ states are dominated by a $0^+\omega$ configuration. This led us to a new idea to use the $(^{12}\text{C},^{12}\text{Be}(0^+_2))$ reaction as a tool to investigate DGTGRs. In this probe, the excitation energy of target nuclei are measured using a missing-mass technique. Several final states in $^{12}\text{Be}$ can degrade the signal-to-noise ratio of an observed spectrum in the method. The key of this probe is to avoid the contamination by tagging the two 511–keV $\gamma$-rays emitted back-to-back from the $e^+e^-$ decay with the mean lifetime of 331 ns. In order to demonstrate the feasibility of the delayed $\gamma$-ray tagging method, we performed the HIDCX $^{18}\text{O}(^{12}\text{C},^{12}\text{Be}(0^+_2))^{18}\text{Ne}$ reaction measurement using the Grand Raiden (GR) spectrometer at RCNP, Osaka University. The primary $^{12}\text{C}$ beam at 100A MeV bombarded a 20-kg/cm² H2^{18}O 4 target. The momenta of outgoing particles were analyzed using GR. The two 511–keV $\gamma$-rays from $^{12}\text{Be}(0^+_2)$ were detected using a NaI(Tl) array surrounding a plastic-scintillator stopper at the GR focal plane. Figure 1 shows the GR horizontal position spectra. The position corresponds to the excitation energy of $^{18}\text{Ne}$. The peak of the spectrum without the $\gamma$-ray tagging, which originates from the $^{18}\text{Ne}$ ground state, is rather broad and has a tail. The broadening is probably due to contributions from different final states in $^{12}\text{Be}$, and the tail originates from accidental coincidence events of $^6\text{Li}$ and $^6\text{He}$. On the other hand, in a red spectrum with $\gamma$-ray tagging, the peak indicated by a red arrow is narrower, and the background has mostly vanished. The obtained energy resolution was ~3 MeV mainly because of an energy-loss difference in the target, and thus the difference between the peak positions of the two spectra is within the resolution. The result of the test experiment shows the feasibility of the gamma-ray tagging method. Our next step is to apply this method to nuclei exhibiting $\beta\beta$-decay, such as $^{48}\text{Ca}$.

References
Study of spin-isospin responses via exothermic charge exchange reaction ($^8$He, $^8$Li)


We performed the exothermic charge-exchange (CE) reaction of ($^8$He, $^8$Li) at the RIKEN RIBF facility by using the BigRIPS, the High-Resolution Beamline (HRBL), and the SHARAQ spectrometer.1,2) Missing mass spectra in the $^4$He, $^{12}$C($^8$He, $^8$Li) reactions were measured at the beam energy of 190 MeV/nucleon. The spin-isospin response of a spin-dipole transition with the radioactive isotope (RI) beam induced by the CE reaction was studied.

The intensity of the secondary $^8$He beam, which was produced via a projectile-fragmentation reaction of an $^{16}$O beam, was about 2 Mcps at the secondary target (SHARAQ-S0). The scattered $^8$Li was momentum-analyzed with the SHARAQ spectrometer. Low-pressure multiwire drift chambers3) were placed at the foci of the BigRIPS and the HRBL. Cathode readout drift chambers4) were installed at the final focal plane (SHARAQ-S2) of the SHARAQ spectrometer. The high-resolution achromatic (HRA) transport mode5) was set to obtain a momentum acceptance of 2%. The detail experimental setup is described in a previous report.5)

The secondary RI beam has momentum distribution. In order to perform high-resolution missing mass spectroscopy with the RI beam, measurement of the beam momentum ($\delta$) of incoming and outgoing particles at the target is required. At the momentum-dispersive focal planes, $\delta$ is correlated with the beam trajectory. In the HRA mode, it is important to measure the trajectory, namely the horizontal position ($x$), at the BigRIPS-F6 and the SHARAQ-S2. $\delta$ couples with the beam transfer matrix elements of $x$ and horizontal angle ($\alpha$). The matrix elements should be measured to obtain the missing mass energy in the CE reaction. The $^8$Li beam was transported to the S2 for checking the matrix elements of ($x|\alpha$) of the beamline and the SHARAQ spectrometer.

Figure 1(a) shows the correlations of $x_{S0}$ with $x_{S2}$ (a) before and (b) after correction. The five loci correspond to the particles with $\delta = -1\%$, $-0.5\%$, ..., $1\%$, which were tagged at the BigRIPS-F6.

Figure 1(b) shows the normal correlations of $x_{S0}$ with $x_{S2}$ for the momentum correction of the $^8$Li beam. The five loci correspond to the particles with $\delta = -1\%$, $-0.5\%$, ..., $1\%$, which were tagged at the F6. The inclinations of the loci indicate the matrix element of ($x|\alpha$). The difference in the inclinations for different $\delta$s is due to the effect of the second-order matrix element of ($x|\alpha$). This difference enables us to obtain the $\delta$ at high resolution by correcting the correlation, as shown in Fig. 1(b). The matrix elements of ($x|\alpha$) and ($x|\alpha\delta$) were determined to correct the tilt of the focal plane. These higher-order matrix elements of the beamline at F6 were determined by checking the correlation with tagging the beam momentum at S2. The missing mass resolution was evaluated to be 3.2 MeV in FWHM by using the matrix elements and 4.6 MeV in FWHM before the correction. Further analysis of the missing mass and angular distribution is now in progress.

References
Spectroscopy of single-particle states in oxygen isotopes via $^4\text{He}(\vec{p}, p\text{N})$ reaction with polarized protons

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The $(\vec{p}, p\text{N})$ reaction is an effective spectroscopic tool to examine single-particle states. One can determine the spin-parity of single-particle states in nuclei from the momentum dependence of the cross section and the vector analyzing power without model dependence.1) In this experiment, our goal was to determine the spin-orbit splitting of the $1p$ spin doublet in oxygen isotopes as a function of their neutron number.

We performed $^{14,22,24}\text{O}(\vec{p}, 2p)$ reaction measurements (SHARAQ04 experiment) with a polarized proton target at RIKEN RIBF to measure single-particle spectra and to determine spin-orbit splitting in $^{14,22,24}\text{O}$. For the experimental setup, see refs.2,3)

Figure 1 shows the time-of-flight (TOF)-$\Delta E$ correlations for (a) incident and (b) residual particles in $^{14}\text{O}$ runs. The particles are identified via the TOF-$\Delta E$ method on an event-by-event basis. For residuals, only their atomic numbers are identified. The proton separation energy ($S_p$) of the target nuclei can be obtained from the scattering angles and momenta of scattered protons:

$$S_p = (1 - \gamma) m_p - \gamma (T_1 + T_2) + \beta \gamma (p_{1\|} + p_{2\|}),$$

where $\gamma$ and $\beta$ are the Lorentz factor and the velocity of the beam, respectively; $m_p$ is the proton mass; $T_1$ and $T_2$ are the kinetic energies of the scattered protons; and $p_{1\|}$ and $p_{2\|}$ are the momenta of the scattered protons. In this formula, the momentum of the residual nucleus is ignored because its effect to $S_p$ is negligibly small compared with the resolution of $S_p$. Figure 2 shows the separation energy spectrum for the $^{14}\text{O}(p, 2p)^2\text{N}$ reaction. Some amount of strength can be seen above the separation energy of $^{14}\text{O}$ (4.627 MeV). However, it is difficult to distinguish excited states in the current result because of the small statistics. We intend to continue the analysis of these results by investigating different gating methods that may improve the efficiency, resolution, and S/N ratio.

The analysis for $^{22}\text{O}$ and $^{24}\text{O}$ beams is still ongoing.

References
Missing-mass spectroscopy of the 4n system via exothermic double-charge exchange reaction at high beam counting rates

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Since the report on candidates of bound tetra-neutron system, 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 have suggested that the tetra-neutron cannot exist as a bound system.

We performed missing-mass spectroscopy of the 4n system via an exothermic double-charge exchange reaction \(^4\)He\(^8\)He\(^{16}\)Be\(^4\)n. The purpose of this experiment was to obtain information on few-body forces, such as the T=\(3/2\) three body force, and the correlations between in multi-body scattering states that reflect final state interactions of sub-systems, such as di-neutron correlations. In order to produce the 4n system with a small momentum transfer of less than 20 MeV/c, we measured the momentum of two alpha particles, at BigRIPS-F6 with the High-Resolution Beamline and the T=3/2 three body force, and the correlations between in multi-body scattering states that reflect final state interactions of sub-systems, such as di-neutron correlations. 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, 190 A MeV, was used.

The experiment was performed at the RIKEN RI Beam Factory (RIBF) using the SHARAQ spectrometer and a liquid He target system. The Be target at BigRIPS-F0 was bombarded by a primary beam of \(^{16}\)O at 230 A MeV to produce the \(^8\)He secondary beam. We measured the momentum of the \(^8\)He beam at BigRIPS-F6 with the High-Resolution Beamline and also measured the momentum of two alpha particles, which were the decay products of the \(^8\)Be ejectile, with the SHARAQ spectrometer.

Because a small cross section was expected for this reaction, it was important to achieve a large yield and good S/N ratio. The highest \(^8\)He beam intensity in this experiment was \(2 \times 10^9\) counts/second, which was produced by the 13.7 MHz AVF cyclotron. The first bunch of triggered particles comprise 14.6 % of the multi-particle event, and the next bunch comprises 12.7 % (the bunch after that comprise 10.6 %). We developed new analytical framework that contains information of multi particles arranged in a bunch structure as a new dimension. Previous frameworks have assumed that one trigger event corresponds to only one particle.

By reading multi-hit TDCs and assigning bunches in plastic scintillators, we can increase the statistics by 12.1\%. With the multi wire drift chambers (MWDCs) as tracking detectors at the beamline, it is found that other particles in the later bunches of the triggered particle cause tracking errors. By treating the sum of drift times of the planes shifted to the half cell of MWDCs (Fig. 1), we can improve statistics by 10.3 % and eliminate multi-particles in each bunch.

References

Parity-transfer \((^{16}\text{O},^{16}\text{F})\) reaction for study of pionic \(0^{-}\) mode

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The spin-dipole (SD) \(0^{-}\) excitation is an important topic in the study of spin-isospin responses in nuclei. Because the \(0^{-}\) excitation carries the same quantum number as a pion, its strength distribution is expected to reflect pion-like correlations in nuclei such as tensor correlations\(^1\). Despite this importance, experimental information on \(0^{-}\) states is very limited because of a lack of experimental tools that are suitable for \(0^{-}\) studies.

In a previous report\(^2\), we proposed a new probe, a parity-transfer \((^{16}\text{O},^{16}\text{F}(0^{-}))\) reaction for \(0^{-}\) studies. The parity-transfer reaction uses \(0^{+} \rightarrow 0^{-}\) transition in the projectile to probe \(0^{-}\) states in a target nucleus. This reaction has unique sensitivity to unnatural parity states, which is an advantage over other reactions used so far.

For the first parity-transfer measurement, we plan to perform a \(^{12}\text{C}(^{16}\text{O},^{16}\text{F}(0^{-})){^{12}\text{B}}\) experiment at the RIKEN RIBF facility by using a SHARAQ spectrometer. Figure 1 shows the schematic of the experimental setup. A primary \(^{16}\text{O}\) beam of 250 MeV/A is transported onto a \(^{12}\text{C}\) target. The outgoing \(^{16}\text{F}\) are unbound to \(^{15}\text{O} + p\). Thus, we perform the coincidence measurements of the decayed \(^{15}\text{O} + p\) pairs. These particles are momentum analyzed using the SHARAQ spectrometer. The analyzed \(^{15}\text{O}\) are detected with the focal plane detectors of SHARAQ (two cathode readout drift chambers (CRDCs)), while the protons are detected at the low-momentum side of the first dipole magnet. The \(0^{-}\) state of \(^{16}\text{F}\) is identified by reconstructing the invariant mass of the \(^{15}\text{O} + p\) pairs.

For this measurement, we have been developing a proton tracking detector system, which consists of two multi-wire drift chambers (MWDCs) and one plastic scintillator (See Fig. 1). Table 1 shows the specifications of the MWDCs. Each MWDC has an effective area of \(480 \text{mm}^2 \times 240 \text{mm}^H\) to cover the acceptance for the protons emitted from \(^{16}\text{F}\). The readout electronics and data acquisition (DAQ) system are the same as those described in Ref.\(^3\).

The performance of the MWDC was tested in the SHARAQ04 experiment. A proton beam with an energy and intensity of 250 MeV and 1 kHz, respectively, was incident on the MWDC. The position resolution was estimated from the residual of \(x_{X} - x_{X'}\). Here, \(x_{X}\) (\(x_{X'}\)) is a hit position in the X (X’) layer. We also estimated the tracking efficiency, which was defined as the ratio of the number of events with the residual within \(3\sigma\) to the number of beams measured by using the scintillator at the upstream of the MWDC. The resulting position resolution and tracking efficiency were \(270 \mu\text{m (FWHM)}\) and \(96\%\), respectively, when we applied a voltage of -1.6 kV on the potential wires and cathode planes. This performance is sufficient for the \((^{16}\text{O},^{16}\text{F}(0^{-}))\) measurement.

The experiment is scheduled to be conducted in 2014.

References


**Missing mass spectroscopy on carbon isotopes beyond proton drip-line**


The $^8$C nucleus is one of the most proton rich nuclei existing outside of the proton drip-line. While the mass of the ground state and decay modes of $^8$C has been known, the energy and the spin-parity of the excited states have never been measured. Therefore, we investigated the excited states of $^8$C by using missing mass spectroscopy, which enabled us to search for the unbound nuclei $^8$C unbiasedly with respect to three-body, four-body, and five-body decay.\(^{(1)}\)

The experiment was performed at the RIPS facility\(^{(5)}\) in RIKEN. A 70 MeV/nucleon $^{12}$C primary beam with an intensity of 200 pA bombarded a $^9$Be production target with a thickness of 0.5 mm. A 50 MeV/nucleon $^{16}$C secondary beam was produced via projectile fragmentation and distributed to a reaction chamber located downstream of the second achromatic plane (F3) of RIPS. Particle identification of the secondary beam was carried out on event by event basis using the time of flight and energy loss, which were measured by two plastic scintillators placed at the first achromatic plane (F2) and F3 of RIPS. Two parallel plate avalanche counters (PPACs)\(^{(6)}\) placed at F3 and double PPACs in the reaction chamber were used to measure and adjust the beam position. We obtained the pure $^{16}$C beam with an intensity of about $2 \times 10^8$ Hz.

The secondary $^{10}$C beam was injected into a cryogenic H$_2$ gas target (CRYPTA)\(^{(7)}\). Temperature and pressure of the H$_2$ gas were kept around 30 K and 0.4 MPa, respectively. The H$_2$ gas was sandwiched by two 10-μm-thick Havar\(^{(8)}\) foils. The diameter and thickness of the target cell were 30 and 1 mm, respectively.

Recoil deuterons and tritons from the reactions were detected by silicon detectors called a RIKEN telescope\(^{(9)}\) and a Dubna telescope, respectively. The double-sided strip detector (DSSD) of the RIKEN telescope was installed at 120.5 mm downstream from the target. The Dubna telescope, which was installed downstream of the RIKEN telescope, consisted of 1-mm-thick DSSD and 16 trapezoid 25-mm-thick CsI(Tl) scintillators with photo-multiplier readouts. The DSSD has 16 sectors in front and 16 rings at the back. The DSSD is circular with a 28 mm φ hole, and the active radius ranges from 33 to 84 mm. The DSSD was placed at 300 mm from the target, followed by the CsI(Tl) scintillators at 5-mm intervals. The polar angular coverage of the Dubna telescope is about $3.0^\circ \leq \theta \leq 8.0^\circ$ in a laboratory frame.

Four plastic scintillators were installed at 0 degree, downstream of Dubna telescope. The first two scintillators were used to stop the $^{10}$C beam. They identified $Z = 4$ and $Z = 6$ particles from the reactions. The following two scintillators were used as the stopper and separator for lighter particles such as α particles and protons produced by the reactions. Therefore, we selected these scintillators with thicknesses of 2, 5, 2, and 15 mm from upstream.

Trigger sources of the data acquisition were the RIKEN telescope ⊙ beam, the Dubna telescope ⊙ beam, and the down-scaled beam. Data were taken for 31 hours under the condition with H$_2$ gas, and 11 hours without H$_2$ gas.

In the online analysis, the recoil deuterons and tritons detected by the Dubna telescope were well identified. From the energy information of these recoil particles, the excitation energy of $^8$C and $^9$C will be deduced by the missing mass method. A detailed analysis is now in progress.

References

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Design of experiment for search of $^{10}$N resonances with resonant scattering of $^{9}$C off polarized proton


The $^{9}$C+p elastic resonant scattering has been proposed for search of resonances in the unbound $^{10}$N nucleus whose structure is almost unknown at present. Theoretically, four low-lying $^{10}$N levels are expected as two very broad $1p_{1/2}$ proton single-particle resonances, each of which has a width much larger than 1 MeV. These resonances overlap each other and may not be clearly identifiable in the $^{9}$C+p excitation function. The level information obtained in the experiment is useful for discussing resonances in $^{10}$Li because $^{10}$N and $^{10}$Li are mirror partners that are expected to have similar structures. The $^{10}$Li structure provides us with valuable information for constructing the three-body model of the borromean $^{11}$Li nucleus.

We proposed to measure analyzing power to resolve these broad resonances. The combined information of the excitation function and analyzing power spectrum will enable us to impose more strict constraints on analysis of the resonances.

The range of center-of-mass energy was set to 1–5 MeV to cover the ground state of $^{10}$N, predicted at around 1.5 MeV, and several excited states (one experimentally observed at 2.6 MeV) (2)). For the measurement of analyzing power and excitation function, we considered to adopt the thick-target method in inverse kinematics (TTIK), where the excitation function can be scanned with a single beam energy utilizing the energy loss of the beam particle in the target.

We conducted Lise++ simulation to produce $^{3}$C beam on RIPS with a low energy of 5 MeV/A. In the simulation, using a $^{12}$C primary beam with 70 MeV/A and 200 pnA, 3.5 mm-thick Be target, and 583 mg/cm²-thick Al wedge degrader at F1, beam intensity obtained at F2 was $\sim 3.5 \times 10^{7}$ pps with a purity of >90%. RF deflector can be used to reduce the rate of contamination because the rate of contaminations such as $^{9}$B and $^{1}$Be is one order magnitude larger than the simulated value in the proton rich side. We also planned to replace Al wedges with (CH$_{2}$)$_{n}$ wedges to decrease the multiple scattering effect.

Polarized target is required for the measurement of analyzing power. A polarized proton solid target for low-energy beam experiments has been designed based on existing system for intermediate energies.

A single crystal of p-terphenyl doped with pentacene molecules with a concentration of 0.05 mol% was chosen as the target material, which allows us to operate the target in vacuum environment at room temperature. Thickness of the target was chosen to be 110 μm to cover the range of the secondary $^{9}$C beam. Strength of the magnetic field was chosen to be 0.2 T to maintain the polarization, and this does not severely affect the particle trajectory. The estimated polarization was 15% at this magnetic field.

Production and polarization of thin films (7 μm) have recently been realized at Osaka University (3), where the size of the grown single crystal was 3 x 4 mm$. However, production of large sized single crystals, with a desired diameter of 2 cm, remains a challenge. We designed a technique to grow a crystal between two thin films.

We consider use of silicon detector for detection of protons with energies of 3–18 MeV. Each telescope consists of one 65 μm-thick double sided silicon detector (DSSD) and two 1.5 mm-thick DSSDs with a detection area of 50 mm x 50 mm. Two telescopes are planned to be placed at both left and right sides of the beam line at a laboratory angle of ±22.5°, where the vector analyzing power is expected to have large absolute values. We plan to place another telescope at $\theta$. The distance between the target and the telescopes is 250 mm.

TTIK method allows us to archive an $E_{CM}$ resolution of approximately 76 keV with a proton energy resolution of 120 keV.

$$E_{CM} = \frac{1}{4 \cos^{2} \theta_{p}} \frac{A}{A} \frac{E_{p}}{E_{p}}$$

Equation 1 shows dependence of $E_{CM}$ on recoil proton energy, where $A = 9$ for $^{3}$C and $\theta_{p}$ is proton scattering angle in laboratory frame.

In conclusion, we proposed the first low energy RI experiment with polarized proton target. RIKEN polarized proton target has been redesigned for use with low energy RI beam. We plan to construct the target in the next fiscal year.

References

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Measurement of alpha elastic scattering on $^{15}$O

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The measurement of alpha elastic scattering on $^{15}$O for studying the resonance states of $^{19}$Ne was performed by using the CRIB (CNS Radioactive Ion Beam separator) at the Center for Nuclear Study, University of Tokyo. Alpha-cluster structures have been an interesting subject of study. Several investigations of alpha-cluster structures have been conducted on 4N nuclei such as $^8$Be, $^{12}$C, $^{16}$O, and $^{20}$Ne.$^{1–3}$ In the case of $^{19}$Ne, because the system of nuclei can be regarded as $^{20}$Ne plus one hole, weakly coupled states of the low-excitation energy region, but limited experimental data are available, till date. Therefore, experimental study of alpha elastic scattering on $^{15}$O is very crucial for understanding how alpha clustering is manifested in proton-rich nuclei. Unknown alpha-cluster states of $^{19}$Ne from 1$^–$ and 3$^–$ members ($K^\pi=0^+$ cluster band of $^{20}$Ne) as well as 4$^+$ and 6$^+$ members ($K^\pi=0^+$ cluster band of $^{20}$Ne) can be identified by performing alpha elastic scattering on $^{15}$O. Because the study of alpha cluster states of $^{19}$Ne has been carried out theoretically, this experimental result can be used to confirm the alpha-cluster structure of Z$>$N nuclei of Ne isotopes.$^{4,5}$

Moreover, astrophysically, the $^{18}$F($p,\alpha$)$^{15}$O reaction is very important because the amount of $^{18}$F produced in a nova depends sensitively on the reaction rates of $^{18}$F($p,\alpha$)$^{15}$O and $^{18}$F($p,\gamma$)$^{19}$Ne.$^{6}$ To date, experimental studies using $^{18}$F beams as well as theoretical works have been reported competitively. However, resonance parameters of relevant states above the proton threshold at $E_x=6.411$ MeV have not been confirmed and remain controversial.$^{7–9}$ Therefore, if the resonance properties of $^{19}$Ne using $^{18}$O($\alpha,p$)$^{16}$F are studied, which is a time reverse reaction of $^{18}$F($p,\alpha$)$^{15}$O, we can expect better results because the $^{16}$O + $\alpha$ threshold energy is only 3.53 MeV($E_x$ of $^{19}$Ne).

In this study, the $^{18}$O($\alpha,\alpha$)$^{15}$O reaction was measured in the energy range $E_{c.m.} = 1.5–7.1$ MeV, which corresponds to $E_x = 5.0–10.6$ MeV of $^{19}$Ne. The primary beam, $^{15}$N (7.0 MeV/u, 0.6 µA), was transported from the AVF cyclotron and impinged on a hydrogen gas target with a thickness of 1.09 mg/cm$^2$. The secondary beam, $^{15}$O, was obtained by the $p$(N,N)$^{15}$O reaction. Fig. 1 shows beam identification for $^{15}$O and other contaminations on the F2 focal plane. The main contamination of the secondary beam was $^{15}$N, the primary beam. $^{15}$O beams of $6\times10^5$ counts/s were collected at the F3 chamber which contains He gas and a Si telescope and the beams were 96% pure after passing through a Wien filter. The energy of the $^{15}$O beam was 34 MeV after the entrance window (Mylar 25 µm-thick) of the F3 chamber.

For inducing alpha elastic scattering, we filled He gas directly in the F3 chamber without a special gas cell. We installed the one-set telescope of consisting two Si layers (20 µm-thick and 480 µm-thick, respectively) at zero degrees; it was located at a distance of 200 mm from the entrance window of the chamber and the pressure of 4He gas was 760 Torr at room temperature, which is equivalent to that for an effective thickness of 3.33 mg/cm$^2$. The data are currently being analyzed.

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Study of unbound oxygen isotopes $^{25}$O and $^{26}$O using SAMURAI


Unbound states of the neutron-rich oxygen isotopes $^{25}$O and $^{26}$O have been studied by the invariant-mass method by using SAMURAI1) with the aim to elucidate the mechanism of the neutron drip line anomaly in oxygen and fluorine isotopes. Another interesting topic is the possible two-neutron radioactivity of the $^{26}$O ground state, predicted by a theoretical study.2) Experimentally, only the upper limit of the ground-state energy3,4) and lifetime with a large error5) are currently available. Details of the experimental setup are described in our previous report.6) Figure 1 shows a mass identification plot of outgoing $Z = 8$ charged particles observed in the breakup of $^{27}$F on a carbon target. Particle identification is performed by the $Bp$-$AE$-TOF technique. The magnetic rigidity $Bp$ is determined by the positions and angles at the entrance and exit of the SAMURAI magnet measured by means of the MWDCs (BDC1.2 and FDC1.2). Combining the $Bp$ value with energy loss $AE$ and TOF measured by a plastic scintillator hodoscope (HODF), outgoing particles can be clearly identified. The mass resolution $\Delta A = 0.18$ (FWHM), corresponding to $13\sigma$ separation, is achieved for $^{24}$O.

Figure 2 shows a preliminary decay energy spectrum of $^{24}$O+$\pi$ observed in the breakup of $^{27}$F. The sharp peak near the neutron decay threshold corresponds to the $^{26}$O ground state and the peak at approximately 0.8 MeV corresponds to the ground-state resonance of $^{26}$O. Since the obtained statistics is much larger than that obtained in the previous experiments,3,4) a better constraint on the $^{26}$O ground-state energy can be obtained. Analysis is currently in progress.

References
Two-neutron removal reaction from $^{22}$C†


We report the first measurement of the two-neutron removal reaction from a $^{22}$C secondary beam at around 240 MeV/nucleon. The experiment was performed at the RI beam factory in 2009, as detailed in Ref. 1). The extracted quantities are the inclusive cross section of $^{22}$C and the momentum distribution for the charged residues of $^{20}$C. $^{22}$C is known to be the most neutron-rich bound nucleus among C isotopes, whereas $^{21}$C is particle unbound. Hence, $^{22}$C is pictured as a three-body ($^{20}$C + n + n) Borromean system, which may be useful in deriving the two-neutron halo formation in $^{22}$C.

There is little knowledge about $^{22}$C. Until Gaudefroy et al. performed the mass measurement of $^{22}$C (i.e., $S_{2n}(^{22}C) = -0.14(46)$ MeV), 2) its experimental mass was never known. Hence, we followed the 2003 mass evaluation, 3) in which the two-neutron separation energy was 0.42(94) MeV. The ground state of $^{21}$C was assumed to be produced at a continuum energy of $\varepsilon^* = 0.30$ MeV after neutron removal with a ground-state separation energy $S_{1n}(^{22}C)$ of 0.70 MeV.

Based on the shell model with the WBP effective interaction 4) in a $psd$-model space truncated to allow $0\hbar \omega$ and $1\hbar \omega$ excitations, three final states of $^{21}$C are predicted below the $^{20}$C first neutron threshold of 2.90 MeV. These states are a 1/2+ ground state with $C^2S = 1.4$, a 5/2+ state at $E_x = 1.11$ MeV with $C^2S = 4.2$, and a 3/2+ state at $E_x = 2.19$ MeV with $C^2S = 0.34$. Using these $C^2S$s and an eikonal reaction model, 5,6) the theoretical inclusive cross section is calculated to be 283 mb, which is in agreement with the experimental cross section of 266(19) mb.

The measured and theoretical inclusive $^{20}$C parallel momentum distributions (convoluted with the experimental resolution of 27 MeV/c) are compared in Fig. 1. The theoretical distribution (solid curve) corresponds to the inclusive (unbound) $^{21}$C momentum distribution, which is calculated as the weighted sum of the momentum distributions to the individual final states. Prior to this sum being calculated, the neutron emission recoil broadening for the $^{20}$C residue is included for each final state according to its $\varepsilon^*$ value, i.e., $\varepsilon^* = E_x + 0.30$ MeV. The dashed (dot-dashed) curve shows the contribution of knockout via the 1/2+ (5/2+) state of $^{21}$C. Each of two states contributes almost half of the inclusive one-neutron removal cross section. The theoretical calculation is in good agreement with the experimental distribution, providing strong support for the weakly bound $\nu_{2S_{1/2}}$ character for the $^{22}$C ground state. This result is consistent with the result of the recent interaction-cross-section measurement and associated analysis presented in Ref. 7), which is suggestive of an extended $^{22}$C matter density.

References
One-neutron knockout reaction of $^{17}$C on a hydrogen target at 70 MeV/nucleon†


Much of our knowledge on the quantum nature of atomic nuclei comes from the studies of nuclear reactions. Among the various collision processes, the nucleon knockout reaction is recognized as one of the most sensitive tools for spectroscopy, especially of unstable nuclei. The knockout residue produced by removing a nucleon from a fast-moving beam particle is efficiently observed in inverse kinematics by a detector placed in the forward hemisphere. The removed nucleon(s) will be selected democratically from the valence space, allowing the states with unique, often rarely accessible, configurations to be populated in this process. The final state in the residue is identified by tagging de-excitation $\gamma$ rays and by observing decay neutrons and constructing the invariant mass. For one-nucleon knockout case, the momentum spread of the residue reflects the Fermi motion of the nucleon suddenly removed, and is sensitive to its orbital angular momentum (the $l$ value). The cross sections leading to the individual final states relate to the occupancy of single-particle orbits, providing a link to understand the details of the nuclear structure.

This study aims at exploring the unbound states in $^{16}$C through an application of the one-neutron knockout technique to a $^{17}$C beam. This is done by focusing on searching the lowest-lying cross-shell transitions, whose location reflects the shell gap between the $p$ and $sd$ orbits. The experiment was performed at the RIPS facility of RIKEN using the setup given in Refs.1,2. The $^{17}$C beam was produced from a 110-MeV/nucleon $^{28}$Ne beam, which impinged on a Be target. The secondary target was pure liquid hydrogen contained in a cylindrical cell. The average energy of $^{17}$C at the middle of the target was 70 MeV/nucleon. The target was surrounded by a NaI(Tl) scintillator array. The fragment was bent by a dipole magnet behind the target, and was detected by a plastic counter hodoscope. The neutrons were detected by plastic scintillator arrays placed $\sim 5$ m downstream from the target. The relative energy ($E_{rel}$) of the final system was calculated from the momentum vectors of the charged fragment and the neutron.

Fig. 1 shows the $E_{rel}$ spectra for the (a) $^{1}H(^{17}C,^{15}C+n)$ and (b) $^{1}H(^{17}C,^{15}C(5/2^{+};0.74 \text{ MeV})+n)$ reactions. Shown in the inset of Fig. 1 (b) is the energy spectrum for $\gamma$ rays emitted from $^{16}$C. Fig. 1 (a) was used in a fitting analysis to extract the resonance parameters.

Two new states at 5.45(1) and 6.28(2) MeV were populated together with a known state at 6.11 MeV. For the 5.45-MeV state, an attempt was made to deduce the $l$ value of the knocked-out neutron from the $p_{||}$ distribution associated with the unbound residue. This, together with a comparison in terms of the measured and calculated knockout cross sections, has led to a spin-parity assignment of $2^{-}$ for this state. Possible spins and parities have been suggested for the other states, bringing about an advanced understanding of the level scheme of $^{16}$C. The energy of the first $2^{-}$ state was adequately reproduced by the standard shell-model calculation using the WBT interaction without invoking modifications to the residual interaction.

References
Invariant mass spectroscopy of $^{17}$C at SAMURAI


Many properties of nuclei away from the $\beta$-stability line are important to better understand nuclear processes that control stellar nucleosynthesis and energy balance. These nuclei often exhibit exotic structures. For example, the appearance of anomalous parity intruder states at a low excitation energy region provides evidence for the shell-gap quenching and/or large nuclear deformation.

The present study focuses on low-lying negative parity states in $^{17}$C above the neutron decay threshold. Two $\beta$-delayed neutron emission measurements of $^{17}$B have reported such states: Raimann et al. indicated states at 2.25(2), 2.64(2), 3.82(5), and 1.18(1) MeV with no definite spin-parity ($J^\pi$) assignment. Achieving higher sensitivity for the $\beta$-n-$\gamma$ coincidence yield, Ueno et al. was successful to locate states at 2.71(2), 3.93(2), and 4.05(2) MeV with the suggested $J^\pi$ values of 1/2−, 3/2−, and (5/2−), respectively. This study aimed to populate these states and to examine their properties by the one-neutron knockout reaction of an energetic beam.

The measurement was performed using the SAMURAI spectrometer during the first physics run of the apparatus. A beam of $^{18}$C at approximately 250 MeV/nucleon provided by BigRIPS at RIBF impinged on a carbon target with a thickness of 1.8 g/cm². The unbound states in $^{17}$C produced by the one-neutron removal processes subsequently decayed into a $^{16}$C fragment and a neutron. These decay products were detected in coincidence. There should be some background events by the neutrons arising from the one-neutron removal processes; however, such background is expected to be relatively featureless and would not affect the resonance. The momentum vector of the $^{16}$C fragment was determined by (1) position information in the two drift chambers (FDCs) placed at the entrance and exit of the SAMURAI dipole magnet and (2) energy loss and timing information in the plastic scintillator hodoscope (HODF). The momentum vector of the neutron was determined using the position and timing information in the plastic scintillator neutron hodoscope (NEBULA). The energy spectrum of $^{17}$C was reconstructed using the invariant mass method involving the momentum vectors of the fragment and neutron.

A preliminary relative energy spectrum for the $^{16}$C + n system is shown in Fig. 1. A clear peak structure was observed at 2 MeV in relative energy, which corresponds to the excitation energy of $E_x = 2.7$ MeV. This energy is close to the energy of the first 1/2− state at $E_x = 2.71(2)$ MeV reported in Ueno et al. To examine the identity of these two states, an analysis is being carried out (1) to compare the populating cross section with the theoretical value based on the corresponding shell-model spectroscopic factor together with the Glauber model and (2) to extract the orbital angular momentum of the knocked-out neutron from the parallel momentum distribution. A search for the other reported states will also be performed.

References

Fig. 1. Preliminary relative energy spectrum of the $^{16}$C+n unbound system.
Structure of $^{18}$B

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The investigation of the light neutron-rich dripline nuclei, including in particular those exhibiting halos, is a central theme of nuclear structure physics. In the present work a series of measurements, aimed at elucidating the structure of the two heaviest candidate two-neutron halo systems, $^{19}$B and $^{22}$C,$^{1-3}$ and the associated unbound sub-systems $^{18}$B and $^{21}$C, the level schemes of which are critical to the defining the $^{17}$B+n and $^{20}$C+n interactions for three-body models, have been undertaken. In addition to being of direct importance to halo physics,$^{18,19}$B and $^{21,22}$C are of considerable interest in terms of the evolution of shell-structure far from stability as they span the N=14 and 16 sub-shell closures below doubly-magic $^{22,24}$O.

The measurements were accomplished using the SAMURAI spectrometer$^{4}$ coupled to the large area neutron array NEBULA$^{5}$ and were performed as part of the first phase of SAMURAI experiments. The analysis to date has concentrated on the fragment+neutron channels and, in particular, $^{17}$B+n which is known to exhibit a strongly interacting virtual s-wave threshold state$^{6}$. Beyond the intrinsic physics interest noted above, a well defined threshold state provides an ideal means to validate the calibration and analysis procedures.

In addition to populating $^{18}$B via proton removal from $^{19}$C (which should populate almost exclusively s-wave strength), the complementary probe of neutron removal from a $^{19}$B beam has been investigated. Figure 1 shows the reconstructed $^{17}$B+n invariant mass (or relative energy) spectra for the two reactions. As may be clearly seen the proton removal populates a very narrow threshold structure, the form of which is consistent with the s-wave virtual state deduced by Spyrou et al.$^{6}$. The neutron removal, however, in addition to the threshold peak shows clear evidence for the population of a state or states in the region of 0.5–1 MeV.

The further analysis of these preliminary results is currently underway as are the data sets for the analogue reactions populating $^{21}$C.

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References
Energy dependence of $\pi^-$ differential cross section in $^{28}\text{Si} + \text{In}$ with beam energies of 400, 600, and 800


Information on the nuclear equation of state (EoS) within a broad density range is important for understanding the physics of neutron stars. However, the isospin-dependent term in EoS, i.e., the density dependence of the symmetry energy $E_{\text{sym}}(\rho)$ has a large model dependence in the supra-normal density region ($\rho > \rho_0$, the saturation density $\rho_0 \approx 0.16 fm^{-3}$). As a result, the relationship between the radius and the mass of a neutron star cannot be reliably calculated. According to a transport model calculation (IBUU04),1 detailed studies of the pion yield ratio, $Y(\pi^-)/Y(\pi^+)$, in central nucleus-nucleus collisions at intermediate energies can be conducted to obtain significant constraints on $E_{\text{sym}}(\rho)$ in the supra-normal density region.

The IBUU04 predicts that the beam energy dependence of the pion yield ratio is strongly related to the behavior of $E_{\text{sym}}(\rho)$ in the supra-normal density region. We performed a series of experiments using 400, 600, and 800 MeV/nucleon $^{28}\text{Si}$ beams accelerated at the Heavy Ion Medical Accelerator in Chiba (HIMAC) and an In target with a compact centrality filter and a pion range counter (RC).2

The $\pi^+$ events can be clearly identified by the $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decay after they are stopped at the RC.3 The $\pi^-$ events were selected using $\Delta E_i - \Delta E_j$ (energy deposition at each layers of RC) correlations obtained experimentally for $\pi^+$ events, because in-flight energy depositions are same between the $\pi^+$ and $\pi^-$ events. However, a pionic atom, which is created by the stopped $\pi^-$ and surrounding nuclei, decays various particles and some of them hit the next counter. Next we estimated a $\pi^-$ leak rate to the next counter.

The leak rate $\alpha$ at which the decayed particles hit the next elements was estimated with CsI($^{129}\text{Xe},\pi^\pm$)X experimental data at 90° for which, the statistics is sufficient and the S/N ratio is large. We obtained a typical value of $\alpha$, 10.83±0.81(SYS) %. For obtaining the production cross section of the $\pi^-$, the reduction rate by the decay in flight, nuclear reaction, and multiple Coulomb scattering until the $\pi^-$ reaches the RC from the production point was estimated using Geant4.

The Lorentz-invariant cross sections of the $\pi^-$ as a function of the kinematic energy in the mid-rapidity frame ($E_{\text{mid}}$) for In($^{28}\text{Si},\pi^-$)$\text{X}$ reaction with 400(top part), 600(middle part) and 800(bottom part) MeV/nucleon beam with statistical errors.

Fig. 1. Lorentz-invariant cross sections of the $\pi^-$ as a function of kinematic energy in the mid-rapidity frame ($E_{\text{mid}}$) for In($^{28}\text{Si},\pi^-$)$\text{X}$ reaction with 400(top part), 600(middle part) and 800(bottom part) MeV/nucleon beam with statistical errors.

References
Study of symmetry energy using isospin diffusion process in heavy-ion collision at RIBF


The nuclear equation of state (EoS) is an important information that helps in understanding the astrophysical phenomena such as neutron stars and type-2 supernovae. The EoS shows highest uncertainty on a symmetry energy term, which is proportional to the square of the isospin asymmetry. We strive to improve the remaining uncertainties of constraints on the density dependence of the symmetry energy at subsaturation densities. \( \rho/\rho_0 \approx 0.4-1 \) in the so called isospin-diffusion process of heavy-ion collisions. The isospin diffusion process has been observed in the experiments performed at NSCL/MSU using stable nuclear beams\(^1\). We performed the experiment to measure the isotopic distribution of the projectile residues from the collision of cocktail beams, where the \(^{107}\)In and the \(^{112}\)Sn targets are on \(^{124}\)Sn and \(^{102}\)Sn respectively. The particle identification of projectile residues is performed by the \( B_\rho-\Delta E\)-TOF technique using the ZeroDegree spectrometer. The Washington University Microball\(^2\) was used to obtain the centrality information. We used \( B_\rho \) settings of 2.41 and 2.52 T.m in order to avoid beam particles with any charge states hitting the detectors at F11. The standard beam tracking and timing detectors at F10 and F11 were used for reconstructing the beam tracks through the spectrometer. Fig\#1 shows a preliminary PID plotted versus \( A = Q \) for the \(^{107}\)In on \(^{124}\)Sn reaction. Isotopes with \( Z=30-40 \) are clearly shown separated in the figure. Fig\#2 shows a preliminary plot of \( Z \) versus multiplicity of the charged particles obtained by the Microball. From the obvious correlation between the multiplicity and the size of the residue, we can determine the collision centrality with the help of a model calculation. In the offline analysis, we will select the data in the ZeroDegree Spectrometer only from the peripheral events using obtained information from the Microball. Then the measured yields of isotopes with \( Z = 30 \sim 40 \) will be compared with the theoretical predictions to extract a new constraint on the symmetry energy at sub saturation densities.

Fig. 1. PID of heavy-ion collision residue performed using ZeroDegree Spectrometer

Fig. 2. Correlation between multiplicity and \( Z \) of residue using Microball

References
Neutron and proton emission is one of many reaction observables that can be used to constrain the density-dependent nuclear symmetry energy\(^1\), which is important to describe isospin-asymmetric nuclear matter.

In the S\(\pi\)RIT project, we plan to measure the \(n/p\) ratio complementary to the \(t/\(^3\)He\) ratio measurement by making use of the TPC and the N\(\text{EBULA}\) array. In order to investigate the response of the N\(\text{EBULA}\) array before the actual experiment, we are performing a simulation with the N\(\text{EBULA}\) simulation package v2.0.5\(^2\) developed by Nakamura group at Tokyo Institute of Technology on the basis of GEANT4.9.2p02 and ROOT. We are using the Particle and Heavy Ion Transport code System(PHITS)\(^3\) v2.60 as an event generator to produce collision events with \(^{132}\)Sn projectiles and \(^{124}\)Sn targets. Detailed information on the physics processes used can be found in the link Ref. 4.

### Table 1. Information on generated events

<table>
<thead>
<tr>
<th>beam energy (AMeV)</th>
<th>neutron events</th>
<th>total events</th>
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</thead>
<tbody>
<tr>
<td>200</td>
<td>522,065</td>
<td>100,000,000</td>
</tr>
<tr>
<td>300</td>
<td>523,058</td>
<td></td>
</tr>
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In the simulation setup, the N\(\text{EBULA}\) array is placed 2 m away to the left side of the beam direction so that charged reaction particles having high \(p_z\) and beam remnants do not enter the array.

In the distribution of the number of neutrons for each beam energy shown in Fig. 1, lines with "Accepted" in the legend indicate that most of the neutrons generated by the collision are going outside of the acceptance range, and less than 40 neutrons enter the array in our setup.

Figure 2 shows the momentum distribution of neutrons detected by the N\(\text{EBULA}\) array. The distribution of neutrons with the assumption of 100% detection efficiency (blue) is slightly different from that obtained by taking the time of flight of each neutron’s first hit (pink). The difference originates from the exclusion algorithms that excludes some number of scintillator bars near the first detection. This result implies that if we can distinguish the first hit only from the secondary, tertiary, and so on, we can measure most neutrons’ momenta with precision. The red line shows the added background, which should be eliminated to obtain the proper neutron information.

We are building an algorithm to eliminate the background noise, which is about 10 times larger than primary neutron signals as shown in Fig. 2, in order to obtain precise information on as many neutrons as possible. Such information can reveal whether we can distinguish one theoretical model from the others in the actual experiment.

**Fig. 1. Number of neutrons in generated events and in accepted range of the N\(\text{EBULA}\) array**

**Fig. 2. Momentum distribution of neutrons with beam energy.** Blue line is the result with an assumption of 100% detection efficiency of the N\(\text{EBULA}\) array. Pink line is the result with the time of flight method for the primary reaction. Red line shows the signal plus noise expected in a real experiment without any cut parameter.

### References

2. N\(\text{EBULA}\) simulation package:
   http://be.nucl.ap.titech.ac.jp/~nebula/index.php
4. PHITS(Particle and Heavy Ion Transport code System):
   http://phits.jaea.go.jp/OvMapOfModels.html
In-beam γ-ray spectroscopy of $^{34,36,38}$Mg: Merging the $N = 20$ and $N = 28$ shell quenching†

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The neutron-rich $^{10}$Ne, $^{11}$Na, and $^{12}$Mg isotopes are located within a region known as the “Island of Inversion” and form one of the most notable regions of sudden shell structure change. Abnormally high masses were discovered for $^{31,32}$Na, leading to the presumption that the $\nu f_{5/2}$ orbitals intrude into the $sd$ shell orbitals, thereby quenching the $N = 20$ shell gap. Later theoretical works predicted, however, that not the entire orbitals are inverted but $\nu(s^2d^2)(fp)^2(2\hbar\omega)$ configurations are lowered so much in energy that they form the ground states for $10 \leq Z \leq 12, 20 \leq N \leq 22$ nuclei instead.

The $N = 28$ magic number is originally formed by the large $\nu f_{5/2} - \nu f_{5/2}$ spin-orbit splitting but is also known to vanish, as seen in the large deformation arising for $^{42}$Si$^{+2}$. Initially believed to be two isolated regions, we show in this letter that the $N = 20, 28$ shell quenching is interlinked via the neutron-rich magnesium isotopes, thereby forming a new connected large area of deformation in the Segré chart.

Key information on the shape of a nucleus can be obtained for even-even nuclei from the energy of the first excited $2^+$ state $E(2_1^+)$, the first $4^+$ state $E(4_1^+)$, and their $E(4_1^+)/E(2_1^+)$ ratio, $R_{4/2}$. Previous studies revealed a low excitation energy of 660(6) keV for the $2_1^+$ state in $^{36}$Mg and suggest that the “Island of Inversion” stretches at least to neutron number $N = 24$ for the magnesium isotopes and thus beyond its originally proposed boundaries$^3$. In the present study, the experimental knowledge of the $E(2_1^+)$ and $E(4_1^+)$ is extended to the $N = 26$ nucleus $^{38}$Mg via one- and two-proton removal reactions.

A primary beam of $^{48}$Ca with an average intensity of 70 particle nA and an energy of 345 MeV/nucleon was impinging on a 15 mm thick rotating Be target located at the BigRIPS fragment separator’s entrance. Secondary beams were selected and purified via the $Bp - \Delta E - Bp$ method, and identified with the $\Delta E - Bp - TOF$ method. The rate for $^{39}$Al and $^{40}$Si isotopes transported through BigRIPS was 75 and 3000 pps, respectively. The secondary beams were incident on a 2.5 g/cm$^2$ thick carbon secondary target, which was surrounded by the DALI2 spectrometer$^4$. Reaction residues from the secondary target were identified by the ZeroDegree Spectrometer, applying again the $\Delta E - Bp - TOF$ method.

Two $\gamma$-ray transitions were observed in $^{38}$Mg from the $1p$ and $2p$ knockout channels after correcting for the Doppler shift, as shown in Fig. 1, which were attributed to the $2_1^+ \rightarrow 0_2^+$ and the $4_1^+ \rightarrow 2_1^+$ decays. In $^{36}$Mg, following a different reaction channel, a second transition was observed and attributed to the $4_1^+ \rightarrow 2_1^+$ decays, while for $^{34}$Mg known values were determined with higher accuracy$^5$. Almost constant $R_{4/2}$ ratios of 3.14(5), 3.07(5), and 3.07(5) were obtained for $^{34,36,38}$Mg at $N = 22, 24, 26$, close to the ideal value of 3.33 for a rigid rotor. The values were in agreement with state-of-the-art shell model calculations and suggested that the $N = 20$ and $N = 28$ shell quenching merge for the neutron-rich magnesium isotopes.

References

In-beam $\gamma$-ray spectroscopy of $^{80}$Zn

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In-beam $\gamma$-ray spectroscopy of nuclei in the vicinity of the doubly-magic nucleus $^{78}$Ni was performed. In recent studies, a drastic change of the shell structure was elucidated for the neutron magic number $N = 8$, 20, and 28 in the regions far from stability. The energy trend of the low-lying states was investigated for even-even nuclei. In this study, the systematic energy trend of the low-lying states was investigated for the chain of Zn isotopes $^{74,76,78,80}$Zn which covers the magic number $N = 50$.

In order to produce RI beams around $^{80}$Zn, a $^{238}$U primary beam with an energy of 345 A MeV was made to impinge on a 925-mg/cm²-thick beryllium target. The fragments produced were separated and identified with the BigRIPS by the $Bp-E$-ToF method on an event-by-event basis. Then, the RI beams impinged on a 1889-mg/cm²-thick beryllium target to induce secondary reactions. The de-excitation $\gamma$-rays emitted from reaction residues were observed by the NaI(Tl) detector array DALI2, which surrounded the secondary target. The reaction residues were identified using the ZeroDegree spectrometer. Figure 1 shows the particle identification plots for the incoming particles obtained with the BigRIPS (left) and for the outgoing particles obtained with the ZeroDegree spectrometer (right).

Figure 2 shows the Doppler-shift corrected $\gamma$-ray energy spectrum obtained for the reaction channel $^9$Be($^{81}$Ga,$^{80}$Zn) with a restriction of a $\gamma$-ray multiplicity $M_\gamma$, being equal to 1. In the spectrum, five peaks were observed. The peak at 1:492(1) keV$^{31}$ is for the known $\gamma$-ray transition corresponding to the $2^+ \rightarrow 0^+$ decay, while the other four transitions are candidates for new levels and are still under analysis for confirmation. Further analysis is on-going to reconstruct the level scheme by $\gamma-\gamma$ coincidence, and to identify the spins and parities of the states by the analysis of momentum distribution of the outgoing reaction residues.

References

Intermediate energy Coulomb excitation of $^{73,74,75}$Ni


Doubly magic nuclei located in very exotic regions of the nuclear chart are key elements in nuclear structure studies. The appearance or disappearance of the shell gaps associated with magic numbers in very exotic nuclei is strongly related to the single-particle energies of nucleon orbitals and to the residual interactions among valence nucleons. The $^{100}$Sn and $^{78}$Ni regions are fundamental in this regard and are the focus of the efforts of many research laboratories worldwide. From the N=Z=50 Sn located at the proton drip line to the neutron rich N=50 $^{78}$Ni, it is currently possible to access the shell structure of these isotones. This very large excursion in isospin also allows to magnify and probe the isovector part of the nuclear mean field. In particular, the tensor part of the spin-isospin term of the residual interaction has been predicted to modify the single-particle structure, inducing a collective behavior in this region. For the Ni isotopic chain, the filling up of the $9/2^+_1$ neutron orbit is expected to induce a strong core polarization due to the spin-isospin interaction that enhances the B(E2;2+→0+), a measure of the quadrupole collectivity. We performed an intermediate energy Coulomb excitation study of the $^{73,74,75}$Ni isotopes, in order to fix the seniority-scheme pattern of the B(E2) strength. Neutron-rich Ni isotopes were produced by fission of a

238U beam on a 9Be target at a bombarding energy of 345 MeV/u, with an average intensity of 10 pmA. The resulting fragments were analyzed using the BigRIPS separator and transported to a secondary natural Pb target for Coullex reactions. After this target, the ions were again analyzed in the ZeroDegree spectrometer and delivered down to the final focal plane. The γ rays from Coullex have been detected by the DALI2 spectrometer in coincidence with the recoiling ions identified at the focal plane of the ZeroDegree spectrometer. A preliminary γ spectrum, after selection on $^{74}$Ni ions, is shown in Fig. 1. The γ peak corresponding to the $2^+→0^+$ de-excitation at 1024 keV of $^{74}\text{Ni}^{\text{4,5}}$ is clearly visible. Decay spectroscopy investigation with EURICA was performed at the final focal plane in conjunction with the in-beam part.

Fig. 1. The γ-ray spectrum detected in DALI2 after selection on $^{74}$Ni. The $2^+→0^+$ transition at 1024 keV is clearly visible.

References
Zeeman resonance spectroscopy of $^{84-87}$Rb in superfluid helium

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OROCHI is a newly developed laser spectroscopy method for optical determination of nuclear spins and moments of exotic radioisotopes (RIs)1). It aims to overcome several experimental limitations due to the low yield of RIs and large contaminations in the production of RIs by taking advantages of the characteristic properties of atoms in superfluid helium (He II). Firstly, it utilizes condensed He II as the trapping medium for the RI beam and the matrix of in situ laser spectroscopy of trapped atoms. Subsequently, by measuring the hyperfine and Zeeman splitting energies of atoms using optical pumping and laser microwave (MW)/radiofrequency (RF) double resonance method, nuclear moments and spins of RIs can be determined. Initial studies with the OROCHI method were concentrated in field of the technological research and development with a considerable number of off-line experiments, which confirmed the feasibility of the OROCHI method1). Recently, after extensive tests and calculations, the first on-line experiments with the $^{84-87}$Rb beam have been successfully performed. In this experiment, the primary $^{85,87}$Rb and secondary $^{84,86}$Rb beams produced from RIPS were precisely trapped in He II. Optical pumping and Zeeman resonance (ZR) for $^{84-87}$Rb and the isomer state $^{84m}$Rb have been successfully observed.

Figure 1 shows the measured spectra for $^{84m,84-87}$Rb isotopes, which are recorded by scanning the applied magnetic field ($B_L$) with a fixed-frequency RF field. The corresponding beam for each spectrum and isotopes for each observed ZR are marked in Fig. 1. Note that in the case of $^{86}$Rb, to reduce the deformation of the observed spectra owing to beam instability, the recording time for one cycle is changed to 1 s (10 s for $^{84,85,87}$Rb). The detailed measurement method is explained in an earlier report2). Conventionally, nuclear spin can be directly deduced from the resonance peaks with the relation (for the ground state of an alkali atom) $I = \frac{\nu B}{2\Delta} - \frac{1}{2}$, where $\nu$ is the RF frequency and $B$ is the magnetic field. In practice, the accuracy of the deduced nuclear spin is degraded by the residual magnetic field ($B_L$). The detailed information about how $B_L$ affects the results can be found in a recent article3). In this work, to eliminate the effects of $B_L$, we used a combination relation of the Bell-Bloom equation4), which describes optical pumping in longitudinal ($B_L$: $B_0 + B_{L\parallel}$ (parallel component of $B_L$)) and transverse magnetic fields ($B_L$: perpendicular component of $B_L$) (for details, see Yang et al.3) and $I_{LL} \propto N_{atom}(1 - P_z)$ to fit the peaks at $B_0 = 0$, while the ZR peaks are fitted with the Lorentz function (red curve in Fig. 1).

From the ZR, after eliminating the effect of $B_L$, nuclear spins were deduced as 1.9(1) for the $^{84}$Rb, 6.2(1) for $^{84m}$Rb, 2.5(1) for $^{85}$Rb, 1.9(2) for $^{86}$Rb, and 1.53(6) for $^{87}$Rb. The inaccuracy of the $B_0$ and the estimated $B_L$ is supposed to be the main experimental error. In addition, 3.3% of error arises from the field inhomogeneity within the observation region and uncertainty of the observation region (1 mm). Taking all the factors into account, the nuclear spins of $^{84m,84-87}$Rb were correctly deduced within the experimental error, which are consistent with the literature values.

Consequently, we have successfully observed the ZR spectra for $^{84-87}$Rb isotopes and their nuclear spin can be determined with a good accuracy, which directly confirms the feasibility of the OROCHI method. It is worth emphasizing here that the measured spectra were recorded in 30 minutes or less with a beam intensity of ~$10^4$ pps. All the results suggest that, after further being developed and improved, the OROCHI method can be established as a promising method to precisely measure nuclear spins and moments of various nuclear species near the drip line with a low yield.

Fig. 1: Zeeman resonance spectra for $^{84m,84-87}$Rb.

References
Study of high-spin states in $^{35}$S

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Superdeformed rotational bands in the mass 40 region have been discovered in $^{36}$Ar,$^{1,2}$ $^{40}$Ar$^{2)}$ and $^{40}$Ca$^{3)}$. The occurrence of the superdeformed structure in this region is related to the existence of large energy gaps that are formed between the down-sloping $f_{7/2}$ and the up-sloping $d_{5/2}$ and $d_{3/2}$ orbitals, as can be seen in the Woods-Saxon single particle diagram in Fig. 1. The diagram also indicates the superdeformed structure in sulfur isotopes since there is a large energy gap at $Z = 16$. The spin-parity of the superdeformed band heads in odd-mass isotopes could give information about the orbit that drives the superdeformed structure. Therefore, we performed the in-beam gamma-ray spectroscopy to search for superdeformed states in $^{35}$S at the Tandem-ALTO facility, Institut de physique Nuclérique d’Orsay.

High-spin states of $^{35}$S were produced by the fusion evaporation reaction, $^{26}$Mg($^{18}$O, 2$n$1$n$)$^{35}$S. $^{18}$O beam energies of 75 and 80 MeV were used. The thickness of the $^{26}$Mg target was 1 mg/cm$^2$. Gamma rays were measured using the ORGAM array consisting of EU- ROGAM germanium detectors. A total of 13 detectors were installed at 5 different angles. The energy loss of charged particles from compound nuclei was measured by Si-Ball, a $4\pi$ array of 11 silicon detectors of 170 $\mu$m in thickness.

In order to identify high-spin states of $^{35}$S, the gamma–gamma coincidence analysis was performed. For instance, the transitions reported in the previous study$^{7)}$ were observed by gating the de-excitation gamma ray from the first excited state at 1302 keV of $^{35}$S (see Fig. 2). All possible energy gates were examined to construct the level scheme. Thus, an 1576-keV E2 transition from the excited state at 8.8 MeV was found. The half-life was estimated to be less than a few hundred femto seconds due to the existence of the residual Doppler shift of the transition$^{8)}$. This means the transition has high-collectivity and indicates superdeformed band member in $^{35}$S. Further analysis is being carried out.

![Fig. 1. Woods-Saxon orbitals as a function of the quadrupole deformation parameter $\beta_2$. The calculation was performed by the WSBETA code.$^{4)}$](image1)

![Fig. 2. Gamma-ray energy spectrum of $^{35}$S in coincidence with the 1302 keV transition.](image2)

References
Measurement of $^{41}$S spin polarization

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Spectroscopic data have indicated the erosion of the $N = 28$ shell gap in several studies$^{1–4}$. In particular, the isomeric state of $^{43}$S at 320 keV is suggested to have a quasi-spherical shape with a spin-parity of $7/2^+$.$^5,6$ On the other hand, the spin-parity of the ground state of $^{43}$S has been neither confirmed nor predicted uniquely.$^5,7,8$ In order to investigate the mechanism of the $N = 28$ magicity loss through the determination of the spin parity of the ground state of $^{43}$S, we aim to measure systematically the ground state electromagnetic moments for $^{41,43}$S.

The electromagnetic moments of nuclei in their ground states are measured by combining the technique to produce spin-polarized RI beams$^9$ and the method of $\beta$-ray-detected nuclear magnetic resonance ($\beta$-NMR). In this scheme, the RIs are stopped in a crystal, which provides spin-lattice relaxation times $T_1$ that are longer than the $\beta$-decay half-life of the RI. In order to find out optimum conditions for the $\beta$-NMR measurement, the $T_1$ measurements were carried out for stopper crystal candidates, such as Si, ZnS, and CaS. In the measurements, an RI beam of $^{41}$S, for which a large yield was expected, was used, instead of $^{43}$S, to measure the relaxation time $T_1$.

The experiment was carried out at the RIPS$^{11}$ facility at RIBF. The RI beam of $^{41}$S was produced by the fragmentation of $^{48}$Ca projectiles at an energy of $E = 63$ MeV/nucleon on a 0.52 mm-thick $^9$Be target. The intensity of the $^{48}$Ca beam at the target was typically 200 pnA. The isotope separation of the $^{41}$S beam was conducted by the RIPS beam line, in which the emission angle $\theta_F$ and momentum $p_F$ of the fragment were selected so as to realize $^{41}$S spin-polarization. Under the condition of $p_F = p_0 \times (1.015 \pm 0.025)$ and $\theta_F > 1^\circ$, where $p_0$ represents the central momentum of the fragment $^{41}$S, the $^{41}$S beam was obtained from RIPS with a purity of 47% and an intensity of $1.6 \times 10^4$ particles/s.

The $^{41}$S beam was then transported to the final focal plane and implanted into a stopper crystal located at the center of the adiabatic field rotation (AFR) device$^{12}$. The AFR device enables us to extract the asymmetry of $\beta$-ray emission without relying on the NMR technique, by only rotating a pair of Nd permanent magnets adiabatically. The $\beta$ rays emitted from $^{41}$S were counted by plastic scintillators, two of which were set above the crystal and two others were set below it. The measurement was conducted according to the following sequence of cycles: beam irradiation for 2,900 ms, rotation of the AFR magnets for 150 ms, waiting time of 200 ms, and the $\beta$ ray counting for 2,900 ms. The irradiation and counting time periods were chosen to be comparable with the meanlife of $^{41}$S.

The waiting margin was inserted in order to avoid spurious effects that might arise from a tiny vibration of the magnets following the rotation. The value of $AP$ was deduced from $\beta$ rays counts obtained in the following four different configurations with the field directions up/down and the magnet rotation true/false (hence, the spin is flipped/not flipped). Here, $A$ and $P$ denote the asymmetry parameter for the $\beta$-ray emission and the degree of polarization of $^{41}$S, respectively. From the results of the AFR measurement, we obtained $AP = -0.14(4)\%$ with the CaS multi-crystal stopper of 0.5 mm thickness, and $T_1$ was found to be longer than 4,600 ms in $1\sigma$ confidence level.

Following the $T_1$ and $AP$ measurements, the $g$-factor search by means of the $\beta$-NMR method was carried out using the spin-polarized $^{41}$S with $AP = -0.14\%$ and the CaS crystal. 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$^{13}$ has been used. The results of the NMR measurement are under analysis.

References

Offline experiment of high-resolution resonance ionization spectroscopy on Titanium using injection-locked Ti:Sapphire laser system

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Resonant ionization is useful for precise optical spectroscopy of radioactive isotopes of many elements to investigate the structures of unstable nuclei. We have developed a high-resolution resonance ionization spectroscopy (HR-RIS) combined with a supersonic gas jet system1,2 in the Parasitic Laser Ion Source (PALIS) system at RIKEN and a narrow bandwidth tunable pulsed laser system, i.e., an injection-locked Ti:Sapphire laser system3,4. An offline experiment was performed using this injection-locked Ti:Sapphire laser system.

The experimental setup for HR-RIS on Ti are shown in Fig.1. Titanium atomic vapor was evaporated by resistive heating of a Ti filament in a vacuum chamber called a reference cell. For optical resonance excitation and ionization from the ground state or a thermally populated low-lying excited state using the Ti:Sapphire laser, an ionization scheme shown in Fig.2 (a) was used. The titanium atomic vapor was irradiated using the second harmonics of the injection-locked Ti: Sapphire laser tuned to the first step transition. The second harmonics of a standard Ti: Sapphire laser was additionally used for efficient ionization via autoionization states. Here, an external cavity diode laser (ECDL) was used as a master laser of the injection-locked Ti:Sapphire laser. We achieved a line width of 20 MHz and a 0.4 mJ/pulse at the maximum output of the injection-locked Ti:Sapphire laser operated at a repetition rate of 1 kHz. Titanium ions produced by resonance ionization were accelerated with an electric field and detected by a multi channel plate (MCP) after traversing the field free region. The number of pulses from MCP was obtained from a counter with a timing gate in the time-of-flight of Ti ions.

We investigated the Rydberg and autoionization states by scanning of the second step laser from 554800 cm\(^{-1}\) to 55600 cm\(^{-1}\) for a higher count rate. We identified a strong peak in the spectrum was estimated to be approximately 210 MHz, and five peaks corresponding to the 46,47,48,49,50Ti isotopes are clearly resolved in the spectrum. Further, their ratios were in good agreement with the natural abundances of Ti isotopes (46Ti-8.0% 47Ti-7.3% 48Ti-73.8% 49Ti-5.5% 50Ti-5.4%). The isotope shift of the optical transition of 46Ti and 50Ti to 47Ti were evaluated to be approximately 1.7 GHz and 1.6 GHz, respectively. Presently, the particularly narrow hyperfine splitting of 47Ti and 48Ti is not resolved because of the remaining Doppler broadening of the experimental geometry. In the near future, the resolution will be improved by applying the supersonic gas-jet system.

Fig.1 Experimental setup for HR-RIS on Ti

Fig.2 (a) Ionization scheme on Ti

(b) Optical spectrum of Ti isotopes.

References
First α-γ spectroscopic study using a Si-Ge detector array installed at the focal plane of GARIS

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A basic study on α-γ spectroscopy was performed using a Si-Ge detector array installed at a focal plane of a gas-filled recoil ion separator GARIS.

The GARIS has been applied for studying production and decay properties of superheavy element (SHE) nuclides produced via Pb/Bi-based fusion reactions (cold fusion); in particular, these studies focused on the search for 113th element on the basis of 209Bi(70Zn,n)278113 reaction from 2003 to 20121–3. In the most of these experiments, the number of identified atoms was limited because of the low production cross section of the SHE nuclides. The nuclide identification method was based on the genetic relation between mother and daughter. It involved measuring the α-decay and spontaneous fission SF. Therefore, a detailed decay scheme including γ-decay could not be obtained. In 2013, we newly installed a Si-Ge detector array, as shown in Fig. 1, at the focal plane of GARIS for studying the production and decay properties of reaction products for 248Cm+48Ca4). The Si-Ge array is useful as a probe for detecting prompt γ-ray coinciding with SF5). Before the experiment, we calibrated the Si-Ge array by using a 207Pb(48Ca,2n)253No reaction.

Projectiles of 48Ca with a charge state of 11+ were extracted from the 18-GHz ECR ion source and accelerated up to 218.5 MeV using the RILAC. The intensity of a typical beam incident on a target was 5.2×1012 s⁻¹ (0.86 ppA). The metallic 207Pb target was prepared by vacuum evaporation on a 60 µg/cm² carbon foil. Target thickness was 371 µg/cm² for 207Pb (enrichment of 99.59%). Sixteen frames of the sector targets were mounted on a φ3 cm rotating wheel, which was rotated at 3300 rpm. The reaction products were separated in-flight from projectiles and other by-products by GARIS, and they were guided into the focal plane detection system after they passed through the time-of-flight detector. The separator was filled with helium gas at a pressure of 73 Pa. The magnetic rigidity Bp was set to 2.064 T-m for 253No. Gamma rays emitted in prompt coincidence with α-particles registered by a conventional position-sensitive Si detector (PSD box)1–3 were measured using a planar-type Ge detector for counting low-energy photons (CANBERRA BE6550; active volume: φ91.5 mm×31.6 mm⁴). The distance between PSD and Ge detector was c.a. 6 mm (3 mm between PSD and 1 mm² Al window + 2 mm between Al window and Ge detector). The peak efficiency for 122-keV photons was 22.8% at the middle position of the PSD. Figure 2 (a) shows a two-dimensional energy plot of α- and γ-rays observed in prompt coincidence. The energy spectrum of γ-rays observed in prompt coincidence with α-decays is given in Fig. 2 (b). These data were obtained under low-background condition, despite the high beam intensity of 0.86 ppA. Observed α- and γ-transitions due to 253No agree well with previously reported values6).

The Si-Ge array will be applicable to study α-γ(X) spectroscopy of SHE nuclides.

References
4) K. Morita et al.: In this report.
5) M. Takeyama et al.: In this report.
We studied proton resonant states in $^{27}\text{P}$ via elastic scattering of $^{26}\text{Si}+\text{p}$ to scan the entire energy region of interest simultaneously. The excitation function was obtained from the scattered proton energy spectrum by a kinematics conversion process. A $^{24}\text{Mg}$ primary beam with an energy of 7.5 MeV/A and an intensity of 1.6 eµA extracted from the AVF cyclotron bombarded a $^{4}\text{He}$ gas target which was at 550 Torr and 90 K. The secondary beam was produced by the $^{3}\text{He}$(24$^{\text{Mg}}$,20$^{\text{Si}}$)n reaction. Protons elastically scattered to the forward angles in the laboratory frame were detected by a ∆E-E telescope using silicon detectors for a ∆E-E telescope. We applied the thick-target method to deduce resonance parameters such as excitation energy $E_{x}$, spin $J$, parity $\pi$, and proton partial width $\Gamma_{p}$ of resonance states. Figure 1 shows best-fit results for the excitation function.

Six new resonant states in $^{27}\text{P}$ have been suggested, and we mostly determined their resonance parameters such as resonance energy, width, and spin-parity with the R-matrix calculation. Two small bumps around 3.39 MeV and 3.59 MeV were introduced to improve the fitting because exclusion of these resonances resulted in a less satisfactory fit for near resonant states. Parameters of resonant states in $^{27}\text{P}$ are expected to contribute to the nuclear data for the nuclear reaction network calculation of the rp-process nucleosynthesis. The previous estimate of the total reaction rate of $^{26}\text{Si}(p,\gamma)^{27}\text{P}$, which was evaluated by Iliadis et al. [10], should be reanalyzed with the nuclear physics input newly obtained in present work.

References
Study of resonance states in $^{26}$Si by elastic scattering of $^{22}$Mg+$\alpha$


The data of $^{26}$Si are important not only in the astrophysics but also in the nuclear structure. The resonance states of $^{26}$Si are valuable for investigating the reaction rate of $^{22}$Mg$(\alpha,p)^{25}$Al and $^{22}Al(p,j)^{26}$Si reactions in the Supernovae II and X-ray bursts, which are important in understanding the astrophysical anomalies. In addition, the alpha-cluster structure, above the alpha decay threshold (E$_{thr}$ = 9.164 MeV), is expected to be obtained in the $^{26}$Si nucleus because of the alpha-cluster threshold rule. Furthermore, although the energy levels of the mirror nucleus, $^{26}$Mg, are well-known, there are many unknown spin-parities. These quantum parameters can be assigned using the $^{26}$Si data. There were some experimental efforts for the levels near and above the alpha decay threshold, but the data is still limited. Several resonance states in the energy region considered were obtained by the works in ref.1–3, but such states had a large uncertainty because of unknown spin-parities. Therefore, we performed the elastic scattering of the $^{22}$Mg$(\alpha,\alpha)^{22}$Mg reaction using a radioactive ion (RI) beam of $^{22}$Mg to obtain the experimental data corresponding to the mentioned aims for $^{26}$Si at the CRIB facility of RIKEN in October 2011. We performed the experiment of $^{22}$Mg+$\alpha$ by applying the thick-target method using the active-target detector GEM-MSTPC in inverse kinematics.3

The RI beam of $^{22}$Mg, which was produced via the $^4$He$(^6$Ne,$^2$Mg)n reaction, with the intensity of 1200 particles/s satisfied the energy condition of E$_{cm}$ = 0.5 – 3.0 MeV in the center-of-mass of the elastic scattering $^{22}$Mg$(\alpha,\alpha)^{22}$Mg.5 Therefore, the energy corresponds to the region of E$_{E}$ = 9.5 – 12.5 MeV in $^{26}$Si. The RI beam was incident on the gas target, which was a gas mixture of $^4$He+CO$_2$ (10%) at 140 Torr at room temperature. The gas was filled in a chamber in which the electrode structures of GEM-MSTPC and arrays of silicon detector telescopes were installed. The trajectory and timing information of the incoming $^{22}$Mg were obtained using the beam monitors PPACs for particle identification. The ejectiles coming from the elastic scattering $^{22}$Mg$(\alpha,\alpha)^{22}$Mg were distinguished from those due to the $^{22}$Mg$(p,p)^{22}$Al reaction based on the AE-E method by using the information from the silicon telescopes. The events due to the elastic scattering and the production of the beam contaminants were identified based on the Bragg curves of the outgoing $^{22}$Mg and the contaminants determined by GEM-MSTPC.

Table 1. The resonance states above the alpha threshold of $^{26}$Si obtained by the elastic scattering of $^{22}$Mg$(\alpha,\alpha)^{22}$Mg.

<table>
<thead>
<tr>
<th>Levels</th>
<th>E$_c$ (MeV)</th>
<th>I (MeV)</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.325 ± 0.071</td>
<td>0.218 ± 0.011</td>
<td>2, 1</td>
</tr>
<tr>
<td>2</td>
<td>10.678 ± 0.016</td>
<td>0.194 ± 0.006</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>10.831 ± 0.113</td>
<td>0.186 ± 0.013</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>11.245 ± 0.028</td>
<td>0.208± 0.027</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>11.493 ± 0.216</td>
<td>0.292 ± 0.010</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>11.807 ± 0.117</td>
<td>0.156 ± 0.032</td>
<td>0, 2</td>
</tr>
</tbody>
</table>

According to the study in ref.6), the first, third, and sixth level in the $^{26}$Si nucleus are very close to the three resonances located at 10.300 MeV (0), 10.844 MeV (1), and 11.828 MeV (2), respectively, in $^{12}$C. In addition, such states of $^{12}$C might have a structure of 3$\alpha$.7) Therefore, the $^{26}$Si may exist under alpha cluster as a structure of $(p^3\alpha\bar{\alpha}+3\alpha+p)$. The direct measurement of alpha elastic scattering was performed for the first time. The data of $^{26}$Si is very limited so far. The cluster structure of the isotopes with a number of nucleon nearby the value of 4N (N = 2, 3, 4, ...) is very uncertain. Hence, we need such type of data significantly more to investigate the structure of $^{26}$Si in future.

References
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Confirmation of the astrophysically important 6.15-MeV, $1^-$ state in $^{18}\text{Ne}$ via resonant proton scattering of $^{17}\text{F} + \text{p}$

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The $^{14}\text{O}(\alpha, \text{p})^{17}\text{F}$ reaction is important during the ignition phase of X-ray bursts. However, thus far, the rate of this reaction remains unknown. Therefore, studies on this reaction are of great importance in researching explosive stellar environments in a nuclear astrophysics context. The $^{14}\text{O}(\alpha, \text{p})^{17}\text{F}$ reaction is mainly resonant, and its reaction rate depends on the resonant properties of the excited states that are above the $\alpha$ threshold in the compound nucleus $^{18}\text{Ne}$. A state observed in $^{18}\text{Ne}$ at $E_x = 6.15$ MeV has been tentatively identified as the important state, which could be dominated at low temperatures.

The experiment was performed using the CNS radioactive ion beam separator (CRIB)$^1$. A primary beam of $^{16}\text{O}^{6+}$ was accelerated up to 6.6 MeV/nucleon with an average intensity of 560 eA. A D$_2$ gas target was bombarded with the primary beam, resulting in the production of a secondary beam of $^{17}\text{F}$ via the $^{16}\text{O}(d, n)^{17}\text{F}$ reaction in inverse kinematics. The $^{17}\text{F}$ beam, with a mean energy of 61.9 MeV and an average intensity of $2.5 \times 10^5$ pps, was then delivered to the F3 experimental chamber where it bombarded a thick H$_2$ gas target. The recoiled light particles were measured by using three sets of $\Delta E$-E Si telescopes at averaged angles of $\theta_{\text{lab}} \approx 3^\circ, 10^\circ$, and $18^\circ$, respectively.

The excitation function of $^{17}\text{F} + \text{p}$ elastic scattering cross sections at different scattering angle regions are shown in Fig. 1(a)–(b). Five resonances, i.e., at $E_x = 6.15, 6.28, 6.35, 6.85$, and 7.05 MeV, all of which with the exception of 6.85 MeV had been observed previously in other ways, were analyzed using the multichannel $R$-matrix calculations. The most probable fitting curves are shown in Fig. 1(a)–(b). As shown in the figure, the fitting results at different scattering angle regions are consistent with each other.

According to our $R$-matrix analysis, see Fig. 1(c), a dip structure around $E_{\text{cm}} = 2.21$ MeV corresponding to the 6.15-MeV level in $^{18}\text{Ne}$ can be fitted as $1^-$ ($s = 2^+, \ell = 1$), $\Gamma = 50$ keV very well. The shape of the dip structure is clear, in contrast to the bump shape reported previously.$^3$ The $1^-$ assignment with high statistics in this work firmly maintains the significant position of 6.15-MeV state at low temperatures.

Moreover, a shoulder-like structure around $E_{\text{cm}} = 2.93$ MeV was observed (Fig. 1(a) and (b)). This may imply that a new state was discovered at $E_x = 6.85$ MeV in $^{18}\text{Ne}$. Both $0^+$ or $0^-$ resonances can reproduce the observed shape, as shown in Fig. 1(d). Because of the small energy shift for the negative-parity states in this excitation energy region,$^5$ this new state is possibly the analog state of $^{16}\text{O}$ at $E_x = 6.88$ MeV ($0^-$). Another possibility also exists: This new state could be a candidate of the $0^+$ state, a band-head state of the six-particle four-hole (6p-4h) band.$^5$

A more comprehensive analysis and the inclusion of $\alpha$ particle information are in progress.

References

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Progress on the $^{16}$N beta delayed alpha decay studied using the Center for Nuclear Study Multi Sampling Time Projection Chamber

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The importance of measuring the cross section of the nuclear reaction $^{12}$C($\alpha$, $\gamma$)$^{16}$O at astrophysical energies is well known. Despite half a century long efforts to perform this measurement, knowledge regarding this cross section remains unsatisfactory. Direct and indirect approaches have been used in order to determine a reliable estimation of its value, which is buried in the realm of the tenth of femtobarn13. Direct measurements were performed down to a center of mass energy of approximately 1 MeV, however, the goal for the application to astrophysics requires to reach 300 keV. With regards to indirect methods, it has been shown that important pieces of information on the E1 component of the $^{12}$C($\alpha$, $\gamma$)$^{16}$O cross section can be derived from the study of the $^{16}$N beta delayed alpha decay2. Many attempts were conducted to measure the low energy tail of this latter alpha spectrum and the state of the art on these studies is reported in a paper by Tang and collaborators3.

In order to improve the available results on the measurements of the spectrum of the alpha particles emitted in the decay of $^{16}$N, we proposed a new experimental approach based on the use of the Multi Sampling Time Projection Chamber (MSTPC) of the Center for Nuclear Study (CNS) of the University of Tokyo. In this new approach the limitations arising from the use of implantation foils adopted in all previous experiments were eliminated, because the chamber itself becomes the implantation material, and the detection efficiency of the decay products is also increased.

The experiment required a long technical development phase. During this phase, two $^{16}$N beam production test runs were performed at the CNS Radiocative Ion Beam (CRIB) facility with very good results. The intensities of the $^{16}$N beam obtained during these tests reached $10^6$ ions per second. A key point in the experiment was the necessity of using MSTPC in pulsed mode: an implantation period, during which the beam is sent and stopped in the middle of the active region of the MSTPC, is followed by a time period in which the beam is stopped before entering CRIB and the $^{16}$N decay events are detected and registered by the MSTPC. In order to prevent the destruction of the active devices of the MSTPC, namely two gas electron multipliers, a gating grid was introduced to stop electron multiplication during the $^{16}$N beam implantation period. Various timings for the implantation (beam on) and counting (beam off) periods were tested. The final decision was to use an equal duration of 50 ms for these two periods.

Despite the fact that during the experiment the intensities of the beam reached a value that was lower than expected on the basis of the previous tests, the experiment was technically successful and data analysis is being initiated.

References

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Search for new isotopes near the proton drip-line close to $^{100}$Sn

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The $^{100}$Sn nucleus, the heaviest doubly magic and particle-stable nucleus with N = Z, has been the subject of numerous experimental and theoretical studies. It is one of the most important nuclei for testing nuclear structure models.

Prior to the main $^{100}$Sn experiment in 2013, we performed a test experiment in December 2011 with the aim of optimizing the configuration settings of the BigRIPS separator at RIKEN, for the production and selection of fragments of short-lived isomeric states in the region of the nuclear chart. In this contribution, we report the mapping of the proton drip-line in the region of $^{100}$Sn.

This experiment was subsequently used to set up our main $^{100}$Sn experiment, which was performed in June 2013 and was dedicated to the measurement of Gamow-Teller β-particles emitted after the decay of the implanted nuclei. The implantation detectors were surrounded by the EURICA array consisting of 12 seven-element Ge cluster detectors and 18 LaBr3 crystals for the detection of delayed γ-rays.

A confirmation of Z and A/Q identification was achieved by the observation of the characteristic γ-lines of known isomers in $^{96}$Cd and $^{96}$Pd. The relative r.m.s. Z and A/Q resolutions for the Sn and N = Z isotopes were 0.41% and 0.09%, respectively. Available signals from the PPACs, plastic scintillators, and ionisation chambers were used to apply additional off-line gates, which allows the removal of spurious events from the particle identification plot.

Fig. 1. Particle identification matrix Z vs A/Q around the $^{100}$Sn after applying cleaning conditions.

We have discovered 3 new isotopes with more than 3 counts: $^{94}$Cd, $^{92}$Ag, $^{90}$Pd. The consistency of all measured signals of interest for each nucleus has been checked, and the assignment of these new isotopes is unambiguous. We have also tentatively assigned events to $^{104}$Te, $^{98}$Sn, $^{96}$In observed with less than 3 counts. One event was assigned to $^{88}$Ru, the identification of which has been recently reported by H. Suzuki.

References
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Identification of 18 new neutron-rich isotopes produced in the EURICA uranium beam campaign

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The EUROBALL RIKEN Cluster Array (EURICA) collaboration aims to conduct isomer and $\beta$-delayed $\gamma$-ray spectroscopy of several hundred nuclei far from stability. In 2012, at the RIKEN Nishina Center RI Beam Factory (RIBF), the EURICA uranium beam campaign was conducted to investigate isomeric decays from very neutron-rich nuclei and their $\beta$ decays\(^1\rightarrow^9\).

In the EURICA uranium beam campaign, the nuclei of interest were produced by the in-flight fission of 345 MeV/nucleon $^{238}$U beam colliding with a 2.92-mm-thick Be target. The primary beam intensity was 8.24 particle nA on average. Table 1 summarizes the two settings used in the EURICA uranium beam campaign. Fission fragments were identified by using the superconducting in-flight separator Bi-gRIPS\(^4\) and the ZD spectrometer. The particle identification (PID) was performed using the $\Delta E$-TOF-$B_\rho$ method, which allows the event-by-event determination of the atomic number $Z$ and mass-to-charge ratio $A/Q$ of fragments\(^5\).

Table 1. Summary of the experimental conditions.

<table>
<thead>
<tr>
<th>Setting</th>
<th>$^{136}$Sn</th>
<th>$^{128}$Pd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target (mm)</td>
<td>Be 2.92</td>
<td>Be 2.92</td>
</tr>
<tr>
<td>$B_0$ (Tm)</td>
<td>8.004</td>
<td>7.391</td>
</tr>
<tr>
<td>Degrader at F1 (mm)</td>
<td>Al 2.82</td>
<td>Al 2.82</td>
</tr>
<tr>
<td>Degrader at F5 (mm)</td>
<td>Al 2.46</td>
<td>Al 2.46</td>
</tr>
<tr>
<td>F1 slit (mm)</td>
<td>$+43.0/−64.2$</td>
<td>$+22.0/−64.2$</td>
</tr>
<tr>
<td>F2 slit (mm)</td>
<td>$+12.0/−18.0$</td>
<td>$+8.0/−12.0$</td>
</tr>
<tr>
<td>Irradiation time (h)</td>
<td>99.6</td>
<td>102.9</td>
</tr>
</tbody>
</table>

$^\alpha$ Values from the magnetic fields of the first dipole magnet.

Figure 1 shows a two-dimensional PID plot of $Z$ versus $A/Q$ for the $^{136}$Sn setting. The solid red line indicates the limit of known isotopes. The relative root mean square (rms) $Z$ resolution and the relative rms $A/Q$ resolution achieved were typically 0.38 and 0.037%, respectively, for the $^{136}$Sn setting. Thanks to the excellent resolution in $A/Q$, we have produced and identified the following 18 new neutron-rich isotopes: $^{118}$Mo, $^{121}$Tc, $^{122}$Tc, $^{125}$Ru, $^{127}$Rh, $^{129}$In, $^{130}$Sn, $^{141}$Ag, $^{142}$Cd, $^{143}$In, $^{149}$Sn, $^{141}$In, $^{142}$Sb, $^{144}$Te, and $^{146}$I. A detailed analysis is currently in progress.

Fig. 1. Two-dimensional PID plot of $Z$ versus $A/Q$ for the $^{136}$Sn setting. Red line indicates the limit of known isotopes.

References

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Charge-state determination for new isotopes near the proton drip-line

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Particle identification (PID) based on the $\Delta E$-TOF-B$p$ method, in which atomic number $Z$ and mass-to-charge ratio $A/Q$ are calculated from measured energy loss ($\Delta E$), time of flight (TOF), and magnetic rigidity ($Bp$), does not work well for isotopes whose $A/Z$ value is close to an integer number, such as 2 or 3. This is because hydrogen-like and fully stripped events are very closely located in a $Z$ versus $A/Q$ PID plot. In these cases, measurement of total kinetic energy (TKE) is additionally located in a integer number, such as 2 or 3. This is because work well for isotopes whose $A/Z$ value is 0.48% on average. The resulting method.

The experiment was performed in December 2011 at RIBF using a $^{124}$Xe beam at 345 MeV/nucleon. The BigRIPS separator$^1$ was used to separate and identify produced isotopes, and was tuned for very proton-rich isotopes with $Z = 30-45$. The PID based on the $\Delta E$-TOF-B$p$ method was made at the second stage of the BigRIPS separator. The TKE measurement was made using a stack of eleven 1-mm-thick silicon detectors, placed downstream of the BigRIPS separator. The energy loss data from the silicon detectors were added to calculate the TKE. We calculated the $A$ value from the TKE and TOF, and the $Q$ value from the $A/Q$ value obtained by the $\Delta E$-TOF-B$p$ method.

The relative resolution achieved in the TKE measurement is 0.48% on average. The resulting $Q$ resolution was calculated to be $\sigma = 0.25$ on average, which allows $4.0\sigma$ separation for $A/Q = 1$ in charge-state identification plot. We observed the dependence of $Q$ resolution on the stopping range in the silicon stack detector. Figure 1 shows the $Q$ resolution as a function of the stopping range of the isotopes, where some deterioration of the $Q$ resolution is observed around a certain value of stopping range. This can be attributed to a thin dead layer on the surface of the silicon detectors. We expect that it is possible to improve the $Q$ resolution by selecting the stopping range according to the $Bp$ measurement or by using silicon detectors whose dead layer thickness is significantly small.

We can select events of fully stripped isotopes from a $Z$ versus $Z/Q$ plot, where $Z/Q$ gives the number of electrons. Figure 2 shows a $Z$ versus $A-2Q$ PID plot for the fully stripped events ($Z/Q = 0$). Here, the $Z$ value is obtained from the $\Delta E$-TOF-B$p$ method, while $A-2Q$ is calculated using the $A$ and $Q$ values obtained in the present work. Note that for isotopes with $A/Z \sim 2$, the resolution of $A-2Q$ is comparable to the $A/Q$ resolution achieved by the $\Delta E$-TOF-B$p$ method, because of the nature of error propagation.

As shown in Fig. 2, the present TKE measurement confirms the identification of four new isotopes, $^{81,82}$Mo and $^{85,86}$Ru, which we previously observed using the $\Delta E$-TOF-B$p$ method. This also confirms that the new isotopes are fully stripped.

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References
2. Nuclear Physics (Theory)
Giant monopole resonances in covariant finite-amplitude method†

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During the past decades, the covariant density functional theory has received widespread attention because it has successfully described many nuclear phenomena1). In this report, we mainly focus on the recent progress in the self-consistent relativistic random-phase approximation (RPA) established by using the finite-amplitude method (FAM).

The RPA is one of the leading theories applicable to both low-lying excited states and giant resonances. In the relativistic framework, quantitative RPA calculations were realized after recognizing the importance of the Dirac sea. Subsequently, great efforts on the relativistic RPA have been made. However, most investigations are essentially restricted within spherical symmetry. The conventional RPA calculations in the matrix form face a significant computational challenge when the number of particle-hole (ph) configurations \( N_{ph} \) becomes large.

The so-called finite-amplitude method was proposed as a promising solution for this computational challenge2,3). In this method, the effects of residual interactions are numerically evaluated by considering a finite density deviation around the ground state. Thus, the self-consistent RPA calculations become possible with a slight extension of the static Hartree-Fock code. Furthermore, by using the iterative methods, the computation time linearly depends on \( N_{ph} \), instead of \( N_{ph}^3 \), in the diagonalization scheme, which is crucial when \( N_{ph} \) becomes large.

Work is in progress for developing the self-consistent relativistic RPA by using both the iterative and matrix FAM schemes, i.e., i-FAM and m-FAM, the detailed formalism of which can be found in the original article†.

In Fig. 1, we show the isoscalar giant monopole resonances (ISGMR) in \(^{208}\text{Pb}\) calculated with the relativistic parametrization DD-PC1. The effects of the Dirac sea and the rearrangement terms can be examined by switching on or off the corresponding ph residual interactions.

First, the transition strengths calculated in the m-FAM scheme with and without the Dirac sea are compared in the upper panel. It is found that the Dirac sea shows profound effects on the centroid energy, and the experimental data4) is reproduced only when the Dirac sea is taken into account. Although the effects of the Dirac sea cannot be isolated in the coordinate-space representation, it can be clearly seen that the i-FAM results are exactly above the m-FAM results that include the Dirac sea. This confirms that these two FAM schemes are equivalent and the effects of Dirac sea can be taken into account automatically and implicitly.

It is tedious to calculate the rearrangement terms in the conventional RPA calculations; in contrast, in FAM, these terms can be simply taken into account by re-calculating the coupling strengths with new densities. In the lower panel, the transition strengths of ISGMR calculated using m-FAM with and without the rearrangement terms are shown, together with the i-FAM results calculated without the rearrangement terms. The equivalency of these two FAM schemes is demonstrated once more. It is also found that the rearrangement effects on the centroid energies is quantitatively substantial.

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Spin-orbit effects on pseudospin symmetry†

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Pseudospin symmetry (PSS)†2 was introduced in 1969 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 the pseudospin doublets with modified quantum numbers \((\tilde{n} = n - 1, \tilde{l} = l + 1, \tilde{j} = \tilde{l} \pm 1/2)\).

Although this concept was introduced for more than 40 years ago, the origins of PSS and its breaking mechanism in realistic nuclei have not been fully understood. Specifically, determining whether its nature is perturbative remains an unsolved problem.

Recently, we used the perturbation theory to investigate the symmetries of the Dirac Hamiltonian and their breaking mechanism in a quantitative manner by combining the perturbation calculations and the SUSY descriptions by using the group (SRG) technique fills the gap between the perturbative nature of PSS. On the other hand, supersymmetric (SUSY) quantum mechanics can provide a PSS-breaking potential without singularity, and naturally interpret the unique feature that all states with \(\tilde{l} > 0\) have their own pseudospin partners except for the intruder states4). Then, the similarity renormalization group (SRG) technique fills the gap between the perturbation calculations and the SUSY descriptions by transforming the Dirac Hamiltonian into a diagonal form and keeping every operator Hermitian5,6).

Therefore, understanding the PSS and its breaking mechanism in a quantitative manner by combining the SRG technique, SUSY quantum mechanics, and perturbation theory is considered promising.

Here, we highlight the PSS-breaking potentials \(\tilde{V}_{\text{PSO}}(r)\), which are derived from the Dirac equation with the SRG and SUSY transformations.

In the upper panel of Fig. 1, the \(\tilde{V}_{\text{PSO}}(r)\) obtained without and with the spin-orbit (SO) term are shown for the \(f\) orbitals. These potentials show several special features, which are crucial for understanding the PSS: (i) They are regular functions of \(r\). (ii) Their amplitudes directly determine the sizes of reduced pseudospin-orbit (PSO) splittings \(\Delta E_{\text{PSO}} \equiv (E_{\tilde{j}c} - E_{\tilde{j}a})/(2l + 1)\) according to the perturbation theory. (iii) Their shape, being negative at small radius but positive at large radius with a node at the surface region, can explain the general tendency of the PSO splittings becoming smaller with increasing single-particle energies.

To identify the SO effects, the \(\tilde{V}_{\text{PSO}}(r)\) obtained with the SO term is further decomposed into the contributions of the indirect and direct SO effects, because the former one represents the SO effects on \(\tilde{V}_{\text{PSO}}(r)\) via the superpotentials, while the latter is the SO potential itself. Comparison with the result obtained without the SO term shows that the indirect effect is small and eventually results in less influence due to the cancellation between the inner and outer regions. On the other hand, the SO potential is always positive with a peak at surface. It substantially raises the \(\tilde{V}_{\text{PSO}}(r)\), in particular for the surface region.

All of these properties are shown in the lower panel of Fig. 1, in which \(\Delta E_{\text{PSO}}\) are shown as a function of \(E_{av} = (E_{\tilde{j}c} + E_{\tilde{j}a})/2\). \(\Delta E_{\text{PSO}}\) match the amplitudes of \(\tilde{V}_{\text{PSO}}(r)\). The decreasing PSO splittings with increasing single-particle energies is due to the special shape of \(\tilde{V}_{\text{PSO}}(r)\). The SO term reduces \(\Delta E_{\text{PSO}}\) systematically, and this effect can be understood now in a quantitative manner.

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Shape evolution of giant resonances in Nd and Sm isotopes

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A giant resonance (GR) is a typical high-frequency collective mode of excitation in nuclei. Effects of nuclear deformation on GRs have been investigated both experimentally and theoretically. Among them, the deformation splitting of the isovector giant dipole resonance (GDR), due to different frequencies of oscillations along the major and minor axes, is well established. Emergence of a double-peak structure of the photoabsorption cross section of $^{150}\text{Nd}$ and $^{152}\text{Sm}$ clearly indicates the onset of the deformation in the ground state. For the GRs with higher multipolarity, although deformation splitting is less pronounced, peak broadening has been observed. The detailed and systematic investigations of GRs would give us unique information on the shape transition in nuclei.

In contrast to low-energy modes of excitation, GRs substantially reflect bulk nuclear properties. Thus, their studies may provide information on nuclear matter. Although various macroscopic models have been applied to GRs, a quantitative description of GRs requires a microscopic treatment of nuclear response. For heavy deformed open-shell nuclei, the leading theory currently for this purpose is the quasiparticle-random-phase approximation (QRPA) based on the nuclear energy-density-functional (EDF) method. The QRPA based on the deformed ground-state configuration with superfluidity can treat a variety of excitations in the linear regime.

We develop a new calculation code of the deformed HFB and QRPA for use in the massively parallel computers to examine the applicability of the Skyrme-EDF-based QRPA to the excitation modes in heavy deformed systems. Using this new parallelized code, the deformation effects on the GRs in Nd and Sm isotopes are investigated. We perform numerical analysis for GRs with a multipolarity $L = 0 - 3$ with both isoscalar (IS) and isovector (IV) characters, and examine the incompressibility and the effective mass both in spherical and deformed nuclei.

Figure 1 shows the strength distributions of IS monopole and quadrupole excitations in the Sm isotopes. We discuss first the giant quadrupole resonance (GQR). With an increase in the mass number, the peak energy of the ISGQR becomes smaller. This is consistent with the experiment on the systematic observation(1,2). The $K$ splitting, $E_{K=2} - E_{K=0}$, for the ISGQR is 2.8 MeV in $^{154}\text{Sm}$. This is consistent with the experimental observation. Since the energy splitting associated with deformation is comparable to the smearing parameter of 2 MeV, the deformation splitting, which is clearly visible in the photoabsorption cross sections does not appear in the ISGQR.

Next, let us discuss the giant monopole resonance (GMR). In the spherical nucleus, we can see a sharp peak at around 15 MeV which is identified as the ISGMR. The ISGMR in deformed nuclei has a double-peak structure. The higher-energy peak of the IS monopole strength is identified as a primal ISGMR and the lower-energy peak is associated with the coupling to the $K^\pi = 0^+$ component of the ISGQR. The lower peak of the ISGMR around 11 MeV is located at the peak position of the $K^\pi = 0^+$ component of the ISGQR.

For the ISGMR in $^{154}\text{Sm}$, the SkM* functional gives the excitation energy, which is very close to the observed value(1). However, in $^{144}\text{Sm}$, the SkM* underestimates the observation, and the SLy4 gives the reasonable energy. The present calculation suggests that the nuclear-matter incompressibility corresponds to about 230 MeV, as deduced from the comparison of the GMR excitation energy for $^{144}\text{Sm}$, and 210 MeV for $^{154}\text{Sm}$.

References
Tensor force and shape evolution of Si isotopes in Skyrme-Hartree-Fock model†

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In the present study, we focus on the tensor effect on the shape evolution of Si isotopes. We determined whether the tensor-force-driven deformation is present in neutron-rich Si isotopes, especially $^{30,32}$Si with a possible $N = 16$ subshell, because some models (e.g., the FRDM) predicted a spherical shape for these nuclei1 while their large $B(E2)$ values suggested a deformed nature2,3. For this purpose, we use the deformed Skyrme-Hartree-Fock model (DSHF)3 with BCS approximation for the nucleon pairing. We show in Fig. 1 the energy curves of $^{30}$Si (left panel) and $^{32}$Si (right panel) as a function of the quadrupole deformation parameter $\beta_2$ using the Skyrme interactions with tensor terms T22, T24, T44, T64, and T664,5. The energy minima are indicated with triangles. $^{30}$Si is suggested to be deformed, but T22 and T44 with relatively large pairing strengths ($\sim 1000$ MeV) fail to give deformed energy minima. In contrary, a deformed ground state can be achieved using the T24, T64 and T66 parametrization with a small pairing strength ($\sim 800$ MeV). Moreover, the predicted oblate shape of these nuclei is consistent with the recent RMF result5. A possibility of achieving a deformed ground state using weak nucleon pairing may stem from a well-known fact that the pairing interaction forms the $J = 0^+$ pairs of identical particles that have spherically symmetric wave functions. As a result, nuclei tend to be more spherical when a strong pairing coupling exists between neutrons and protons as in the cases of T22 and T44; otherwise nuclei are more likely to be deformed, as in the cases of T24, T64, and T66. This suggests that the resulting shape of a nucleus is sensitive to the nucleon pairing in this nucleus, and the experimentally determined deformed shape of $^{30}$Si suggests that a relatively weak paring correlation is present in the Skyrme effective forces T24, T64 and T66. We also notice that a large tensor force present in T64 and T66 tends to produce a deep energy surface; i.e., the tensor force exerts a dramatic effect that maintains a deformed ground state in $^{30}$Si. The effect of the tensor force is also observed in $^{32}$Si as shown in the right panel of Fig. 1. Its shape is predicted to be spherical using T22, T24, and T44 but oblate using T64 and T66 with large tensor forces. The spherical result in the first three cases is obviously not consistent with experiments, and the shape change from spherical to oblate when introducing a large tensor force is intriguing.

In summary, we used the DSHF model to investigate the shape evolution of the quadrupole deformation of Si isotopic nuclei. We found interesting manifestations of the tensor force and pairing effect in several isotopic nuclei, such as $^{30,32}$Si. The effect of tensor force is observed when we compare the predicted shape of $^{32}$Si using increasing tensor forces in the HF energy density. The tensor-force-driven deformation in these nuclei should be investigated in more details because it may result in a further improvement of many theoretical models or parameterizations toward a better description of theories on the shell structures of nuclei in general, such as the shell model and SHF model.

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Incompressibility in finite fermionic systems: application to stable and exotic nuclei†

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Recently, it has been inferred that the measurement of isoscalar giant monopole resonances (GMRs) may probe the incompressibility of the nucleus in a range below the saturation density, rather than exactly at the saturation density.1 Recent measurements of isotopic chains2,3, possibly extended to exotic nuclei4,5, are therefore relevant for constraining this more general density-dependent incompressibility. The use of isotopic chains also provided opportunities to study pairing and shell effects on incompressibility. It has been shown that one cannot rule out shell and pairing effects on nuclear incompressibility.6,7 We therefore focus on the nuclear incompressibility along isotopic chains and through magicity.

The calculations following fully microscopic approaches based on the energy density functionals (EDFs) to predict the GMR position are usually performed using the constrained Hartree-Fock-Bogoliubov (CHFB) or the quasiparticle random-phase approximation (QRPA) approaches.8 In the present study, we calculate the GMR energy for the Skyrme EDF with the CHFB approach. For completeness, results obtained using Skyrme and relativistic functionals are also given using the QRPA approach.

The results obtained using the various methods mentioned above are displayed in Fig. 1 for Sn and Pb isotopic chains. The nuclear incompressibility of a finite nucleus $K_A$ is evaluated using

$$K_A = \frac{2\langle r^2\rangle_{g.s.}}{m_1},$$

where $m_1$ is the inverse energy-weighted sum rule and $\langle r^2\rangle_{g.s.}$ is the mean-square radius of the ground state. First, it should be noted that the three microscopic methods provide $K_A$ values that do not differ by more than 10%. The nuclear incompressibility $K_A$ is almost constant at 140 MeV around stable nuclei but changes as a function of $A$ in the case of more exotic nuclei.

The incompressibility of fermionic systems has been studied using several approaches. Analytical relations using simple free Fermi gas and spherical Harmonic Oscillator (HO) models allowed us to show the direct link between the incompressibility and the zero-point kinetic energy $T_0$, implying that incompressibility is rooted in the localization properties of the constituents of the system. The HO model provides $K_A \approx 3T_0$, showing that 140 MeV is a sound estimation of the nuclear incompressibility in stable nuclei.

In order to study the evolution of nuclear incompressibility along isotopic chains, several microscopic EDF-based approaches have been used. In the case of exotic nuclei, a decrease in $K_A$ is predicted in all the models because of the emergence of a soft monopole strength. These results confirm the important role of the soft monopole resonance, and attempting to detect it would be useful. More generally, the behavior of the GMR in exotic nuclei and/or beyond magicity should be studied experimentally. Measurements of the GMR around $^{132}\text{Sn}$ and $^{210}\text{Pb}$ would be of interest.

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**Competition between $T=1$ and $T=0$ pairing in $pf$ shell nuclei with $N = Z$**

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The role of the neutron-proton isoscalar spin-triplet $(T=0, S=1)$ pairing interaction in finite nuclei has been a topic of discussion for long.1–3) The isoscalar spin-triplet pairing interaction is known to be stronger than the isovector singlet singlet $(T=1, S=0)$ one in nuclear matter.4) Nevertheless, nuclei favor the spin-singlet $T=1$ pairing between identical particles. A straightforward explanation for this contradiction is that most stable nuclei have different numbers of neutrons and protons; thus, protons and neutrons occupy different single-particle orbits near the Fermi surface, which leads to the inhibition of $T=0$ pairing. It was also suggested that the nuclear spin-orbit field largely suppresses the spin-triplet pairing, much more than the spin-singlet pairing.5,6)

To clarify the role of $T = 0$ pairing, we diagonalize the Hamiltonian with the spin-singlet and spin-triplet pairing terms in $pf$ shell model configurations for nuclei with the same number of protons and neutrons, $N = Z$. The pairing correlation energies of the $(J^* = 0^+, T=1)$ and $(J = 1^+, T=0)$ states are shown in Fig. 1 as a function of the scaling factor $f$ for the $T = 0$ pairing. The lowest energy state with $J^*=0^+$ for the $l = 3$ case acquires more binding energy than the $J^*=1^+$ state for the strength factor $f < 1.5$. In the case of strong $T=0$ pairing, that is, $f \geq 1.6$, the $J^*=1^+$ state acquires more binding energy than the lowest $J^*=0^+$ state. These results are largely attributed to the quenching of the $T=0$ pairing matrix element by the transformation coefficient corresponding to a change of the scheme from the $jj$ coupling to LS coupling. This quenching never happens for the $T=1$ pairing matrix element, since the mapping of the two-particle wave function between the two coupling schemes is simply implemented by a factor $\sqrt{j+1/2}$. For the $l = 1$ case, there is a competition between the $J^*=0^+$ and the $J^*=1^+$ states as seen in Fig. 1. Because of smaller spin-orbit splitting in this case, the couplings among the available configurations are rather strong, and the lowest $J^*=1^+$ state acquires more binding energy than the $J^*=0^+$ state when $f \geq 1.4$. These results are consistent with the spins observed for $N = Z$ odd-odd nuclei in the $pf$ shell, where all the ground states have the spin-parity $J^* = 0^+$, except for $^{28}\text{Cu}$. The ground state of $^{58}\text{Cu}$ has $J^* = 1^+$, because the odd proton and odd neutron occupy mainly the $2p$ orbits, wherein the spin-orbit splitting is expected to be much smaller than in $1f$ orbits.

In summary, by diagonalizing the pairing Hamiltonian, we have shown that the spin-triplet pairing correlation energy in the $1f$ shell configuration becomes larger than the spin-singlet pairing energy when the strength of the spin-triplet pairing is larger than that of the spin-singlet pairing by a factor of 1.6 or more. However, for the $2p$ configuration, the spin-triplet pairing correlation becomes dominant even when the factor $f$ is approximately 1.4.

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Fig. 1. (Color online) Pairing correlation energies for the lowest $(J^*=0^+, T=1)$ and $(J = 1^+, T=0)$ states with the $l = 3$ and $l = 1$ configurations as a function of the scaling factor $f$ of the $T = 0$ pairing. The strength of the spin-singlet $T=1$ pairing interaction is fixed at $G(T=1)=24/A$ MeV with mass $A=56$, while the strength for the spin-triplet $T=0$ pairing interaction, $G(T=0)$, is varied with the factor $f$ multiplied by $G(T=1)$.
Joint project for large-scale nuclear structure calculations

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A joint project for large-scale nuclear structure calculations has been under way since the year 2001, based on a collaboration agreement between RIKEN Nishina Center and Center for Nuclear Study, the University of Tokyo. We maintain PC servers, one of which has 1TB main memory and is suitable for large-scale nuclear shell-model calculations. In this project, we performed various shell-model calculations of the nuclides that had been measured at the RIKEN RI Beam Factory, such as 54Ca, 34Na, 35Na, 37Mg, 50Ar, and 55Sc, under collaborations with many experimentalists. Since these collaborations are presented in other reports, we here introduce two theoretical achievements of this project in 2013: The extended Kuo-Krenciglowa method and the shell-model analysis of Cr isotopes.

Until recently, most shell-model calculations were confined to a single oscillator shell like the sd shell or the pf shell. However, recent interest in nuclei away from the stability line requires larger shell-model spaces. Because the derivation of microscopic effective interactions has been limited to degenerate model spaces, there are both conceptual and practical limits to shell-model calculations that utilize those interactions. We develop a method to calculate effective interactions for a nondegenerate model space, based on the extended Kuo-Krenciglowa method, which is a natural extension of the conventional Kuo-Krenciglowa method.3,4) We calculated effective interactions within (i) a single oscillator shell (a so-called degenerate model space) like the sd shell or the pf shell and (ii) two major shells (nondegenerate model space) like the sd f7p3 shell (sd shell, 0f7/2 and 1p3/2) or the pf g9 shell (pf shell and 0g9/2). We also calculated the energy levels of several nuclei that have two valence nucleons on top of an inert core. Our results show that the present method works excellently in shell-model spaces that comprise several oscillator shells as well as in a single oscillator shell. This work is published in 2014.5)

The experimental observation in odd-mass neutron-rich Cr isotopes revealed that the excitation energy of 9/2− state decreases considerably with increasing neutron number.6) We performed shell-model calculations for these Cr isotopes with pf g9d5 model space, which consists of a full pf shell, 0g9/2, 1d5/2 orbits, with a certain truncation. We introduced a new Hamiltonian, which is composed of the GXPF1Br effective interaction1) for the pf shell and V_MU7) for the rest of the model space. The shell-model result agrees adequately with experimental data, as shown in Fig.1. We also dis-

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Fig. 1. The level scheme of 57Cr. The columns labeled ‘EXP’ and ‘This work’ represent the experimental data and the results of the shell-model calculation, respectively. The dashed lines denote the unassigned spin states.
Pairing correlation and quasi-particle resonances in neutron drip-line nuclei

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In neutron drip-line nuclei, which have an extremely shallow Fermi surface, the pairing correlation is expected to influence low-energy scattering and resonances of a neutron. An interesting phenomenon predicted in the theory of superfluid nuclei is quasi-particle resonance.1–3) A scattering neutron can couple to a hole state by creating a Cooper pair and thus resulting in a narrow resonance. The quasi-particle resonance has also been studied for neutron drip-line nuclei.4–6) As neutron drip-line nuclei are expected to provide better opportunities for observation of quasi-particle resonance, we study these drip-line nuclei to clarify the properties of quasi-particle resonance. In the present study, we focus on the influence of the pairing on the resonance width.

We use the coordinate space Hartree-Fock-Bogoliubov (cHFB) equation7) to describe the scattering wave function of a neutron under the pairing effect. We solve the cHFB equation such that the quasi-particle wave function satisfies the scattering boundary condition:

\[
\begin{pmatrix}
  u_{lj}(r) \\
  v_{lj}(r)
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  \cos \delta_{lj} \delta_{lj}(k_1 r) - \sin \delta_{lj} n_l(k_1 r) \\
  D h_{lj}^{(1)}(\kappa_2 r)
\end{pmatrix},
\]

where \( k_1 = \sqrt{2m(\lambda + E)}/\hbar \), \( \kappa_2 = \sqrt{-2m(\lambda - E)}/\hbar \). Here, \( m \), \( \lambda \) and \( E \) are the mass of neutron, Fermi energy and quasi-particle energy, respectively. Next, we calculate the phase shift \( \delta_{lj} \) and the elastic cross section.

We consider the \(^{46}\text{Si} + \text{n}\) system. According to several HFB calculations, \(^{46}\text{Si}\) is a neutron drip-line nucleus of Si isotopes. We assume that this nucleus has a spherical shape. Note that \(^{46}\text{Si}\) has a weakly bound \( 2p \) orbit. We use the Woods-Saxon potential as the nuclear potential, and the pair potential is also assumed to have the Woods-Saxon shape. The averaged pairing gap \( \Delta \) is a strength of the pair potential.

Fig.1 shows the calculated partial cross section. Narrow low-lying peaks seen in \( p_{1/2} \) and \( p_{3/2} \) are the quasi-particle resonances. These peaks disappear if we switch off the pairing as they are originally weakly bound \( 2p_{1/2} \) and \( 2p_{3/2} \) orbits in the Woods-Saxon potential. In order to analyze the effect of pairing on the resonance width, we calculate the width of the \( p_{1/2} \) resonance for various pairing strengths \( \Delta \). We extract the resonance width and resonance energy from the phase shift using a fitting method. The green line in Fig.2 shows the relation between the resonance width and the resonance energy for various values of \( \Delta \). As the pairing strength increases, both the resonance width and the resonance energy increase. For comparison, we plot the width vs. energy relation for the single-particle potential resonance of the \( 2p_{1/2} \) state (red line in Fig.2), which is obtained by varying the depth of the Woods-Saxon potential \( V_0 \). If we compare these two results at the same resonance energy, we find that the width of quasi-particle resonance is narrower than the width of single-particle potential resonance. We conclude that the pairing has an effect of reducing the resonance width.

Fig. 1. Partial cross section with \( \Delta = 1.0\text{MeV} \).

Fig. 2. Comparison of results of resonance width.

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Di-neutron correlation in pair-addition vibrational mode of the neutron-rich Sn isotopes†

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Recently, two-neutron transfer in unstable nuclei has attracted attention since the experiments using radioactive ion beams became possible.1,2) Anticipating future experiments, we have been theoretically investigating two-neutron transfer modes in heavy-mass neutron-rich nuclei. A good example is of neutron-rich Sn isotopes with $A \geq 132$, for which we predict enhanced pair-addition transfer populating the ground states (pair rotation) or the low-lying 0$^+$ states (pair vibration) in the neighboring $\Delta N = 2$ isotopes.3) In this work we analyze in detail the microscopic structure of the two-neutron transfer modes, and we show that di-neutron correlation appears in the pair vibrational mode of the neutron-rich Sn.

We describe the two-neutron transfer using the Hartree–Fock–Bogoliubov (HFB) mean-field theory and the continuum quasiparticle random phase approximation (QRPA)3,4). The Skyrme functional with the parameter SLy4 is adopted. For pairing interaction, we choose the density-dependent delta interaction.

We analyze the microscopic structure of the two-neutron transfer modes in the Sn isotopic chain, especially the pair-addition vibrational mode in $^{132-140}$Sn. Within the QRPA theory, one can characterize an excitation mode in terms of forward- and backward-propagating amplitudes $X^\nu_{ii'}$ and $Y^\nu_{ii'}$ for the two-quasiparticle configuration $ii' = (nlj) (n'l'j')$. The index $\nu$ is a label for QRPA normal modes, and excitation energy is denoted as $\hbar \omega^\nu$. Concerning the low-lying pair vibration state predicted to appear at $\hbar \omega^0 = 3.81$ MeV in $^{134}$Sn, for example, the main two-quasiparticle configurations ($|X^\nu_{ii'}| > 0.1$) are $[3p3/2]^2$, $[1h9/2]^2$, $[2f7/2]^2$, $[2f5/2]^2$, $[1i13/2]^2$, $[3p1/2]^2$, and $[3p3/2][4p3/2]$. These quasiparticle orbits are weakly bound or unbound resonant quasiparticle states. Similarly, the transition density $P^\nu_{R,L=0}(r)$ for the monopole ($L = 0$) pair-transfer operator can be decomposed as

$$P^\nu_{R,L=0}(r) = \sum_{ii'} P^\nu_{R,ii'}(r)$$

in terms of the two-quasiparticle configurations. For the main components, the amplitude of these decomposed transition densities are significantly smaller than that of the total transition density. Even if we sum the main decomposed transition densities, it reproduces approximately half of the total transition density. This suggests that the low-lying pair vibration in $^{134}$Sn has a some degree of collectivity.

Figure 1 shows the transition density $P^\nu_{R,L=0}(r)$ and the partial sums of the decomposed transition densities, $P^\nu_{R,ii'}(r) = \sum_{L=0} P^\nu_{R,ii'}(r)$, for various values of the angular momentum cut-off $l_{cut}$. Although the partial sums ($P^\nu_{R,ii'}(r)$) of each high-$l$ component are very small, the inclusion of these small transition densities is necessary to reproduce the total transition density. The highest orbital angular momentum of the occupied Hartree–Fock single particle orbit in $^{134}$Sn is $l_{occ} = 5(1h_{11/2})$. However it is clear that the large value of the orbital angular momentum contributes to the total transition density. The coherent accumulation up to high-$l$ contributions in the pair-addition vibrational mode suggests the di-neutron5) correlation discussed in the same manner in Ref.[4, 6].

We find that the di-neutron correlation in the low-lying pair vibration of $^{132-140}$Sn is formed by large numbers of weakly bound and unbound continuum quasiparticle states. Therefore, even if the positions of the quasiparticle states are varied for other Skyrme parameter sets, this di-neutron character may be observed in the low-lying pair vibration or pair rotation of the neutron-rich Sn isotopes with $N \geq 82$.

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References
Angular momentum dependence of moments of inertia due to Coriolis anti-pairing and blocking effects†

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In a series of papers1,2) we have developed the top-on-top model to systematically describe the level energies, and B(E2) and B(M1) values for in- and out-of-band transitions in the triaxial strongly deformed (TSD) bands in odd-A nuclei. Numerical analysis have been performed for the TSD bands in odd-mass Lu isotopes,1) 167Ta,5) and for the odd-odd nucleus 164Lu.3) Without the angular momentum dependence (I-dependence) of the moments of inertia, the level energies along the TSD bands cannot be reproduced.

In order to investigate how the I-dependence arises, we take into account both the Coriolis anti-pairing (CAP) effect6) and the blocking effect within the framework of the HFB theory. The cranking effect is described in terms of the second-order perturbation to the cranking term in the HFB equation based on the BCS solution.7) In dealing with the gap equation, we pay special attention to an integral wherein the finiteness of the system becomes tangible.

For the case of axially symmetric deformation, the moment of inertia $I_x$ is introduced through the constraint for the $x$-component of angular momentum $L_x$, i.e., $\langle L_x \rangle = I - I_0 = J_x \Omega_x$, where $(\cdot)$ stands for the quasimicroscopic expectation value. We have assumed that the system is independent of rotation (i.e., $\Omega_x = 0$) in the band-head state with $I = I_0$. Based on Refs.2,6), we assume that only large matrix elements of single-particle angular momentum $(j_x)_{\alpha \beta}$ have a common excitation energy of $\delta(=\varepsilon_{\beta} - \varepsilon_{\alpha})$ between two single-particle energy levels. After using the closure approximation, we get the relation $J_x$ and the rigid-body moments of inertia $J^{rig}_{x}$ for both even and odd nuclei.

In order to relate the gap value $\Delta$ to the angular momentum $I$, we need to solve the gap equation for both even and odd nuclei.7) We apply a technique similar to the one we used for deriving the relation between $J_x$ and $J^{rig}_{x}$ for both even and odd nuclei. Assuming that $\Delta$ is still not too small, relevant summations over the single-particle energies with a level density $\rho (=1/d)$ ($d$ is the average distance between single-particle energy levels) can be replaced by integrals. On the other hand, when $\Delta$ is much smaller than $d$, we carry out the summation without converting it into an integral, because an abnormal enhancement is found when $\Delta \ll d$. We adopt the picket fence approximation for the single-particle energies. The sum is expanded into an asymptotic series, and we derive the formula using a functional value of the Riemann Zeta function and Euler constant.

In Fig. 1, we compare $J^{(odd)}$ (solid line) and $J^{(even)}$ (dashed line) for the cases of $\Delta > d$ (low-spin part) and $\Delta \ll d$ (high-spin part). We adopt $\delta = 2$ MeV and $J^{rig}_{x} = 68$ MeV$^{-1}$; the starting pairing gap $\Delta$ is 0.8 MeV for an even nucleus and 0.6 MeV for an odd nucleus, and the last single-particle energy in an odd nucleus is 0.6 MeV based on measurements made from the fermi surface.

As shown in the figure, the increase in the moments of inertia becomes slow in high-spin parts, whereas the gap values continue to decrease, maintaining a finite value. The curve for $J^{(odd)}$ starts from a higher value than $J^{(even)}$ because of the blocking effect, and it increases gradually, showing concave upward, which agrees with the curve for the values adopted in Ref.3).

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Energy-density-functional calculations including proton–neutron mixing†

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We performed calculations based on the Skyrme energy density functionals that include an arbitrary mixing between protons and neutrons. This is the first step towards the density functional calculation including proton–neutron (p-n) pairing. The p-n pairing is a long-standing open problem in nuclear physics, and its possible relations to various nuclear phenomena have been widely discussed.2,3 However, in spite of several theoretical studies over the years since the late sixties, a consistent theoretical treatment of the p-n pairing is still missing. Our ultimate goal is to develop a consistent symmetry-unrestricted energy-density-functional (EDF) approach including the p-n mixing both in the pairing and particle–hole (p-h) channels. To treat the p-n pairing within the EDF framework, one needs to generalize the quasiparticle states as mixtures of protons and neutrons. In connection with this extension of quasiparticles, one also needs to extend density functionals to those with mixing between protons and neutrons. In this work, as a first step in achieving our goal, we consider an extension of EDFs including the p-n mixing in the p-h channel, with both the rotational and isospin symmetries conserved. 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 performed the so-called isocranking calculation by adding the isocranking term to the Hamiltonian: ̂h′ = ̂h − ̂λ · ̂t. Here, ̂t 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 ̂λ, we can control the size and direction of the isospin of the system. We first performed isocranking calculations for A = 14 and A = 48 systems with the Coulomb interaction switched off, and we confirmed that our code is correctly implemented. In this case, the total and single-particle energies are independent of the direction of the isospin of the system. Next, we performed calculations with the Coulomb interaction included. In this model, isobaric analog states (IASs) are calculated by adjusting the isocranking frequency. We developed an efficient method for determining the isocranking frequency, with which we successfully calculated the T ≃ 4 states in A = 40–56 isobars.

The isocranking calculation is a simple linear constraint method. We also implemented in our code an improved method for optimization with constraints, known as “the augmented Lagrange method,” and employed it for the calculation of the high-isospin states in 18Cr. Such calculations can be used to study the nuclear symmetry energy.

In Fig. 1, we plot the energies of the I = 0+, T = 1 triplet of states in the A = 14 isobars calculated using the SkM* EDF. The T2 = 0 IAS representing the excited I = 0+, T = 1 state in 14N is calculated by using the isocranking model and is described by a single time-even Slater determinant built of single-particle p-n mixed orbitals. Fig. 1 illustrates that the model is indeed capable of quantitatively describing the excitation energies of the 0+, T = 1 IASs. One can see that there is asymmetry between the energy differences |E(Tz = 0) − E(Tz = −1)| and |E(Tz = 0) − E(Tz = 1)|, which may be related to charge asymmetry and independence of the NN interaction. To investigate this point, we also started a systematic calculation of the T = 1 triplets in the A = 10–58 region.

Fig. 1. Energies of T = 1 states in A = 14 isobars in comparison with the experimental data.5 To correct the deficiency of the SkM* EDF, the calculated curve is shifted up by 3.2 MeV.

References

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Skyrme-RPA calculation for octupole vibrations of rotating superdeformed nuclei

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The superdeformed (SD) shell structure is significantly different from that of normal deformation. Each major shell at the SD shape consists of about equal numbers of positive- and negative-parity levels. This is a favorable situation for the appearance of negative-parity vibrations. In fact, low-frequency octupole vibrations have been predicted by random phase approximation (RPA) calculations with the Nilsson potential1) and discovered in several experiments for SD nuclei in Dy and Hg-Pb regions.

One of the central issues concerning the collective motions of SD nuclei is the octupole instability (appearance of the static shape) depending on angular momentum. Several authors have already demonstrated the importance of the Coriolis force at low-spin band head states of octupole vibrational bands.

Recently, SD bands were discovered in $^{36,40}$Ar, $^{40}$Ca, and $^{44}$Ti. In this mass-number region, we can expect rich experimental information on the collective modes of SD nuclei because the observation of rotational bands starting from the $0^+$ state and the linking transition between the SD bands and low-lying normal deformed bands are unique features characterizing the SD states in the region around mass number $A \sim 40$ (for example, see Ref.2).

In this study, we investigate the rotational effect on the octupole vibrations of SD states in the $A \sim 40$ region. We have already demonstrated the low-frequency octupole vibrations of the $0^+$ SD states through RPA calculations with the Skyrme force (Skyrme-RPA)3). For the excitations from the SD yrast bands, on the other hand, the Skyrme-RPA calculation has not yet been performed owing to computational limitations.

We develop a new framework of the Skyrme-RPA calculation. The single-particle Hamiltonian describing independent-particle motion in the triaxially deformed particle–hole potential that is uniformly rotating with rotational frequency $\omega_{\text{rot}}$ about the $x$-axis is adopted; $h' = h - \omega_{\text{rot}} \hat{x}$. The Skyrme SkM* interaction is employed for $h$. The particle–hole residual interaction is derived from the Skyrme force through the Landau–Migdal approximation:

$$V_{ph}(\mathbf{r}, \mathbf{r}') = N_0^{-1} \left[ F_0 + F_0' \hat{\sigma} \cdot \hat{\tau}' \right] + \left( G_0 + G_0' \hat{\sigma} \cdot \hat{\sigma}' \right) \delta(\mathbf{r} - \mathbf{r}') .$$

The single-particle wave functions $\psi_k$ and the two-particle wave functions $\Psi_{kk'} = \psi_k \psi_{k'}$ are represented by the Fourier-series expansion method in order to effectively treat the configurations involving unbound single-particle states.

We show the isoscalar octupole transition strengths for $K^\pi = 0^-$ and $1^-$ excitations of the triaxial SD state of $^{44}$Ti in Figs. 1 and 2. The results with $\omega_{\text{rot}} = 0.0$ and 0.6 MeV/h are compared.

In the $K^\pi = 1^-$ case, an octupole instability of the SD yrast states toward a reflection-asymmetric shape (banana-like shape) is suggested to take place at $\omega_{\text{rot}} > 0.6$ MeV/h (corresponding to the total angular momentum $I > 5\hbar$) because of the Coriolis effect.

![Fig. 1. Isoscalar octupole transition strength for $K^\pi = 0^-$ excitation of the SD state in $^{44}$Ti. The results with $\omega_{\text{rot}} = 0.0$ and 0.6 MeV/h are compared. The deformation is almost constant at $(\beta_2, \gamma) = (0.58, 9.4^\circ)$ in both cases. $B(IS3)$ is shown in Weisskopf units (W.u.).](image1)

![Fig. 2. The same as Fig. 1 but for $K^\pi = 1^-$ excitation.](image2)

References
Di-neutron correlation in asymptotic tail of weakly bound nuclei

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Neutrons penetrating far outside the nuclear surface often exhibit exotic features of neutron-rich nuclei close to the drip-line. An important question is whether and how neutrons are correlated in the external tail region. The di-neutron correlation in two-neutron halo nuclei, such as 11Li, has attracted attention in this context.1,2) However, theoretical analyses using the Hartree-Fock-Bogoliubov (HFB) models suggest that the di-neutron correlation also prevails in heavier mass nuclei, including nuclei close to the stability line.3,4) In the present work, we attempt to clarify the emergence mechanism of the di-neutron correlation by investigating the Cooper pair wave function in the Skyrme HFB model both numerically and analytically, with a focus on its asymptotic behavior at large distances.

We have performed a systematic Skyrme HFB calculation5,6,7) for even-even Ca, Ni, Zr, and Sn isotopes ranging from the stability line to the neutron drip-line. In order to guarantee convergence at large distances, we solve the HFB equation in the radial coordinate representation, using a very large radial cut-off at 100 fm and the orbital angular momentum cut-off at l = 72. We then evaluate the neutron pair condensate (equivalent to the pair density and the pairing tensor) \( \tilde{\rho}(R) \equiv \langle \Phi_0 \mid \psi(R, \uparrow) \psi(R, \downarrow) \mid \Phi_0 \rangle = \Psi_{\text{pair}}(R, R) \). Note that the pair condensate is a part of the neutron Cooper pair wave function, defined by \( \Psi_{\text{pair}}(r_1, r_2) = \langle \Phi_0 \mid \psi(r_1, \uparrow) \psi(r_2, \downarrow) \mid \Phi_0 \rangle \).

The asymptotics of the pair condensate is characterized by an exponential behavior \( \tilde{\rho}(R) \to C \exp(-\kappa R) \), and the exponential constant \( \kappa \) is extracted by a fitting to the microscopically calculated \( \tilde{\rho}(R) \). As shown in Fig. 1, the extracted exponential constants (solid symbols) follow a universal relation \( \kappa = \sqrt{8m|\lambda|/\hbar} \), where \( \lambda \) is the Fermi energy and \( m \) is the neutron mass. The result is different from the previous estimate \( \kappa_{\text{qp}} = \sqrt{2m(\lambda_1 + E_{\text{qp}})/\hbar} + \sqrt{2m(\lambda_2 - E_{\text{qp}})/\hbar} \) (open symbols), which relies on the asymptotic behavior of the quasiparticle wave function with the lowest quasiparticle energy \( E_{\text{qp}} \).

The universal relation can be interpreted as the penetration of a di-neutron with mass \( M = 2m \) and with the binding energy given by the two-neutron separation energy \( S_{2n} = 2\lambda \), i.e. \( \kappa = \sqrt{2M S_{2n}/\hbar} \). We can justify this interpretation via an analytic and general examination of the HFB theory. It should be noted that in the limit \( r_1, r_2 \to \infty \), the following two-particle Schroedinger equation holds for the Cooper pair wave function:

\[
(\hat{t}(1)+\hat{t}(2)+\hat{v}(1,2))\Psi_{\text{pair}}(r_1, r_2) = 2\lambda \Psi_{\text{pair}}(r_1, r_2) \]

where \( \hat{v}(1,2) \) is the \( nn \) interaction. As a consequence, the asymptotic form is given in terms of the di-neutron coordinate system \( r = |r_1 - r_2|, R = (|r_1 + r_2|/2 \) as

\[
\Psi_{\text{pair}}(r_1, r_2) \to C_0^\ast \phi_0^* \exp(-\kappa_d R)/R \quad (2)
\]

for small \( r \). Here, \( \phi_0^L=0(r) \) is the wave function of the \( S \)-wave virtual state of the \( nn \) system, representing the di-neutron, and the exponential constant \( \kappa_d = \sqrt{2M(2\lambda)/\hbar} \) arising from the center of mass motion of the di-neutron.

We also found that the di-neutron asymptotics, Eq.(2), dominates in weakly bound neutron-rich nuclei with a small neutron separation energy or small \( |\lambda| \). Conversely, single-particle (quasiparticle) components also contribute to the asymptotics of the Cooper pair in nuclei having a larger neutron separation energy, as the single-particle value (open symbol) and the full value (solid one) coincide in these nuclei. As a corollary, the condition for the dominance of the di-neutron correlation is given as \( |\lambda| \lesssim \Delta \) or \( S_{2n} \lesssim 2\Delta \).

Fig. 1. The asymptotic exponential constant \( \kappa \) of the neutron pair condensate \( \tilde{\rho}(R) \).

References

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Deformed nuclei in the black-sphere approximation

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The size of an atomic nucleus is one of the most fundamental quantities that characterize the bulk properties of the nucleus. 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.\(^1\) When studying the density derivative $L$ of the symmetry energy of nearly symmetric nuclear matter, the total reaction cross section, $\sigma_R$, of neutron-rich nuclei is one of the most important observables.

In this work, in order to obtain the value of $L$, we focus on the empirical data of the interaction cross section, $\sigma_I$, measured at $\sim 900$ MeV per nucleon,\(^2,3\) as a first step. Since the data of Ne and Mg isotopes at $\sim 240$ MeV per nucleon have already been obtained at the RI Beam Factory of RIKEN,\(^4\) systematic analyses are necessary. For the analyses, we adopt the black-sphere (BS) model of nuclei.

We have so far systematically analyzed the proton elastic scattering and $\sigma_R$ data for stable nuclei at a proton incident energy of $T_p \sim 800$–1000 MeV on the basis of a “black-sphere picture” of nuclei.\(^5\) We showed that for proton beams incident on stable nuclei, the cross section of a black sphere of radius $a$, which is determined by fitting the angle of the first elastic diffraction peak calculated for proton diffraction by a circular black disk of radius $a$ to the measured value, is consistent with the measured $\sigma_R$.\(^5\) This finding is also observed for $\sigma_R$ of nucleus-nucleus reactions down to approximately 100 MeV per nucleon.\(^6\)

In the model, the absorption cross section is written by $\sigma_{BS} = \pi \left( a_0(\text{proj.}) + a_0(C) \right)^2$, where $a_0(\text{proj.})$ is the BS radius of a projectile, $a_0(C)$ is the BS radius of the target nucleus obtained using the method mentioned above.\(^5,6\) For proton incident energies higher than $\sim 800$ MeV, $a_0(C) = 2.69 \pm 0.07$ fm.

According to the systematic analysis based on a macroscopic nuclear model, at large neutron excess, the calculated nuclear matter radius increases with $L$ via the $L$ dependence of the nuclear matter saturation density. It is indispensable to duly incorporate such dependence into the BS model for application to the reactions involving neutron-rich nuclei.

The relatively large neutron excess of the isotopes of Ne and Mg is advantageous for studying the value of $L$. However, nuclear deformation occurs in this region of nuclei. We change the black sphere into a spheroid of the same volume to take nuclear deformation into account before discussing the $L$ dependence. The values of the deformation parameter, $\beta$, are taken from microscopic nuclear structure models.\(^7\) Under the adiabatic approximation, the values of $\sigma_R$ for deformed nuclei should be evaluated by angle averaging of the cross section values over the deformation direction of nuclei.\(^8\)

The results are shown in Fig. 1. Although we adopt the values of $\beta$ given by a mean field calculation with the effective interaction SkM*, which tends to offer large deformation, the effect on $\sigma_R$ is rather small. This is consistent with the work of Christley and Tostevin,\(^8\) but inconsistent with the work of Horiuchi et al.\(^9\) Before drawing conclusions, we have to examine the interaction dependence by adopting SLy4, KTUY,\(^7,10\) etc. The study is now in progress.

**References**

Shell-model description of low-lying states in Rn isotopes

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Polonium and radon isotopes below the neutron closed shell at \( N = 126 \) provide an important region for testing shell-model structure. The isomeric \( 8^+_1 \) states in \(^{206-214}\text{Rn} \) were experimentally confirmed to be based on a proton \((0h_{9/2})^4\) configuration\(^1\). The low-lying near-yраст states were analyzed in terms of the interacting boson model plus two quasiparticles model\(^2\), where one of the bosons is replaced by a pair of nucleons at high spin. A good agreement with experiment was achieved for both the energy spectra and electromagnetic transitions.

In this work, the band structure of the Rn isotopes is studied in terms of the full-fledged shell model. As for single-particle levels, all the six orbitals, \( 0h_{9/2}, 1f_{7/2}, 0i_{13/2}, 1f_{5/2}, 2p_{3/2}, \) and \( 2p_{1/2} \), in the major shell between the magic numbers 82 and 126 are considered for both neutrons and protons. The effective interactions comprise single-particle energies and monopole and quadrupole pairing plus quadrupole-quadrupole interactions, whose strengths are adjusted to fit experimental data. The interaction strengths adopted in the present calculations are assumed to be the same for all the nuclei.

In Fig. 1, the measured spectra for even-even Rn isotopes are compared with the shell model results. The even-spin yrast sequences are well reproduced except for the \( 8^+_1 \) states, which are lower in energy than the experimental data. For better reproduction of the \( 8^+_1 \) states, multipole pairing interactions more than quadrupole might be necessary. Concerning other states, good agreements between theory and experiment are achieved.

In order to investigate the collective behavior at low energies and the effect of the single particle excitations at high spins, the energy spectra in the shell model are compared with those in a pair-truncated shell model (PTSM)\(^3,4\). The building blocks of this model are angular momenta zero (S) and two (D) collective pairs together with non-collective pairs. The Hamiltonian in this truncated space (PTSM space) is set identical to that used in the shell model. In Fig. 2, the energy levels obtained by the PTSM for \(^{208}\text{Rn} \) are compared with those of the shell model. There is a good correspondence between the energy levels of the shell model and those in the PTSM. This means that the model space spanned by the PTSM is sufficient for describing the shell model results.

In search for the microscopic structure of the yrast band, we analyze the expectation values of the numbers of pairs (not shown). It is found that the valence

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References
Shell-model study of nuclear structure around $^{100}$Sn

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The nuclear structure around the doubly-magic $N=Z$ nucleus $^{100}$Sn has been of great interest from various viewpoints such as the development of shell-structure and the proton-neutron correlations. For a reliable prediction of unknown targets by the shell model, one of our strategies is to minimaly modify so-called G-matrix interactions$^3$ by fitting the shell-model results to available experimental energy data. In the previous work$^2$, we have determined an effective interaction called JUN45 in the model space covering nuclei with $28 \leq N,Z \leq 50$. Also, we have tried the shell-model fits to describe Sn isotopes with $N=50 \sim 82$ and obtained an effective interaction SNBG1$^3$. Since the $^{100}$Sn fits is located at the end of the model space in both studies, it was impossible to discuss the excitation across the $N$ and/or $Z=50$ shell closure. In this report, we present another approach along this line, aiming at the description of nuclei including $^{100}$Sn.

We take four single-particle orbits $1p_{1/2}$, $0g_{9/2}$, $1d_{5/2}$ and $0\gamma_{7/2}$ for both protons and neutrons assuming a hypothetical “core” $^{50}$Sr$^{38}$. This choice is motivated by the excellent success of the ($1p_{1/2}$, $0g_{9/2}$) model space near the $N \sim 50$ lines due to the approximate degeneracy of these orbits around there, as suggested in Fig.1(a). Also, since the $7/2^+$ state comes down rapidly as the proton number is increased towards $Z=50$ (see Fig.1(b)), the last two orbits ($d_{5/2}$, $g_{7/2}$) are essential. Based on the information about the dominant configurations obtained with the JUN45 and the SNBG1 interactions, we have selected the experimental data in the range of $47 \leq N \leq 58$ for the fit. In order to reduce the amount of computation for the fitting, we take the $t=4$ truncated model space, where $t$ stands for the maximum number of nucleons that can excite from the ($1p_{1/2}$, $0g_{9/2}$) orbits to the ($d_{5/2}$, $g_{7/2}$) orbits relative to the naive lowest configuration. Starting from the G-matrix interaction derived from the N$^{3}$LO interaction$^4$, we have carried out a series of iterative fits. We assume the isospin symmetry, and adopt the $A^{-0.3}$ mass-dependence of the two-body matrix element (TBME). In the latest fit, 197 TBMEs and 4 single-particle energies have been determined with an rms error of 231keV for 528 data.

As examples of the fitted results, the energy levels of low-lying states are shown in Fig.1 for odd-mass isotones with $N = 50$ and $51$. It can be seen that the overall trends are reasonably described by the present shell-model calculations. As for $^{100}$Sn, using this interaction at the $t=6$ truncation level, the excitation energy of the $2^+$ state is predicted to be 4.8MeV, and the 0$p$-0$h$ component in the ground-state wavefunction is 71%. The calculated $B(E2; 0^+ \rightarrow 2^+ )=0.13e^2b^2$ with the effective charges $e_p=1.5$, $e_n=0.5$ is almost consistent with the shell-model result in a different model space$^7$.

![Fig. 1. Energy levels of low-lying states for (a) $N=50$ isotones with odd-number of protons and (b) $N=51$ isotones with even-number of protons. Calculated $1/2^−$, $9/2^+, 5/2^+$ and $7/2^+$ states are shown with dashed, long-dashed, solid and dotted lines, respectively, which are compared with the experimental data denoted by diamonds, triangles, circles and squares, respectively. Experimental data are taken from Ref.$^5$, where uncertain spin assignments are explicitly shown. The shell-model results are obtained by using the efficient code MSHELL64$^6$.](attachment:image.png)

References

5) Data extracted using the NNDC WorldWideWeb site from the ENSDF database.
Giant dipole resonance in $^{88}$Mo from phonon damping model’s strength functions averaged over temperature and angular momentum distributions†

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Many theoretical and experimental studies in nuclear structure during the last three decades were devoted to the giant dipole resonance (GDR) in highly excited nuclei. The GDR line shape and its full-width at half maximum (FWHM) $\Gamma_{\text{GDR}}$ are experimentally extracted from the statistical calculations by using the Lorentzian strength function to reproduce the $\gamma$-ray spectra detected from the decay of the highly-excited compound nucleus (CN) at the excitation energy $E^*$. They are often compared with the theoretical predictions, which are obtained at a given values of nuclear temperature $T$ and/or angular momentum $J$.

The extraction of $T$ and $J$ is crucial for a meaningful comparison between experiment and theory because the initial temperature $T_{\text{max}}$ and/or angular momentum $J_{\text{max}}$ at the first step in the decay of the CN are significantly higher than the mean values $\overline{T}$ and $\overline{J}$, obtained by averaging over all daughter nuclei in the decay process. Moreover, while the theoretical GDR strength function is calculated at a fixed value of $T$ and/or $J$, its experimental counterpart is extracted by fitting the spectrum, which is generated by a multistep cascade decay, where the nucleus undergoes a cooling down from $T_{\text{max}}$ (and/or $J_{\text{max}}$). Because of this mechanism, the authors of Ref. 1) have proposed to incorporate the theoretical strength functions into the full statistical decay calculations and compare the results obtained with the experimental data. This method was applied to test the validity of several theoretical models in Refs. 1, 2), including the phonon damping model (PDM), which describes the broadening of the GDR width at finite $T$ and $J$ via coupling of the GDR to non-collective particle-hole (ph), particle-particle (pp) and hole-hole (hh) configurations. However it is not clear if the GDR line shape obtained by averaging the GDR strength functions over the whole interval of $T$ and/or $J$ is equivalent to the GDR strength function obtained at the mean values $\overline{T}$ and $\overline{J}$ in these intervals.

In the present paper the PDM is employed to calculate the strength functions for the GDR in the statistical decays after the fusion-evaporation reaction$^{48}$Ti + $^{46}$Ca, which produces the CN $^{88}$Mo at various excitation energies $E^*$ 4). The calculations use the empirical probability distributions for $T$ and $J$ to produce the GDR average strength functions $S(\omega, E^*)$ as well as $\overline{T}$ and $\overline{J}$ at each energy $E^*$. The calculations show that, while the GDR width increases with $E^*$, it approaches a saturation at high $T = 4$ MeV when $J > 50h$. At a larger $J \geq 70h$, the width saturation shows up at any $T$. The GDR strength function $S(\omega, E^*)$ obtained by averaging the individual strength functions $S(\omega, T, J)$ over the empirical $T$- and $J$-probability distributions turns out to be almost identical to $S(\omega, \overline{T}, \overline{J})$ calculated at $\overline{T}$ and $\overline{J}$ (Fig. 1). Therefore, once $\overline{T}$ are $\overline{J}$ are known, one may compare the theoretical prediction for the individual strength function $S(\omega, T, J)$ and its width, obtained at $\overline{T}$ and $\overline{J}$, with the data, without the need of generating and averaging the strength functions over the whole $T$ and $J$ distributions.

Fig. 1. GDR average strength function $S(\omega, E^*)$ for $^{88}$Mo at different excitation energies $E^*$ obtained by using the $T$- and $J$-probability distributions. The dotted lines are the strength functions $S(\omega, T, J)$ obtained at the corresponding $T = \overline{T}$ and $J = \overline{J}$.

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On the importance of using exact pairing in the study of pygmy dipole resonance†

N. Dinh Dang*1 and N. Quang Hung*2

One of the major issues in the theoretical study of the pygmy dipole resonance (PDR) in medium and heavy nuclei is the discrepancy in the predictions of different approaches regarding the strength and collectivity of the PDR. While the relativistic random-phase approximation seems to predict a prominent peak identified as the collective PDR below 10 MeV in heavy nuclei1,2), the results of calculations including monopole pairing within the quasiparticle RPA (QRPA) do not expose any collective states in the low-energy region of the E1 strength distribution3). One of the possible sources of such discrepancy may well lie in superfluid pairing, which plays a crucial role in open shell nuclei in the vicinity of the neutron drip line. However all the theoretical calculations of the PDR so far either neglected pairing, such as the relativistic RPA, or adopted the mean-field pairing. The latter is taken into account within the Hartree-Fock-Bogolyubov, Hartree-Fock + BCS formalisms, or coupling of QRPA particle-hole (ph) states to more complicate configurations like the 2p2h ones. Given the progress in the exact solutions of the pairing problem in recent years, it is highly desirable to see how exact pairing affects the PDR as compared to the predictions given by the approaches employing the conventional mean-field pairing gap.

The present paper studied the effect of superfluid pairing on the PDR in light, medium and heavy neutron-rich oxygen, calcium and tin isotopes. Beside the conventional BCS gap, the exact pairing gap obtained by diagonalizing the pairing Hamiltonian with constant parameters $G_N$ and $G_Z$ for neutron and proton pairing interactions, respectively, is also employed to calculate the strength function of the giant dipole resonance (GDR) in these nuclei within the framework of the phonon-damping model (PDM)4). The analysis of the numerical calculations allows us to make the following conclusions: 1) Exact pairing decreases the two-neutron separation energy in light nuclei, but increases it in heavy nuclei as compared to that obtained within the BCS theory; 2) Exact pairing significantly enhances the PDR in medium (calcium) and heavy (tin) nuclei, whereas the BCS pairing causes a much weaker effect as compared to the case when pairing is neglected. This observation indicates that BCS pairing might not be sufficient to describe the PDR in medium and heavy neutron-rich nuclei; 3) The significant change in the line shape of the GDR with increasing the mass number A indicates that the values for the model’s parameters cannot be kept fixed when the calculations are extended to the nuclei in the vicinity of the neutron drip line. This includes the parameters of the nuclear mean field such as the parameters of the Woods-Saxon potential or the parameters of effective interactions such as various Skyrme types, which are used in microscopic calculations of the GDR and PDR.

The obtained results may serve as a hint to clarify while several microscopic approaches, mentioned in the Introduction, are in disagreement regarding the strength and fine structure of the PDR. The present paper also emphasizes the necessity of using exact pairing, whenever possible, instead of the BCS one or the HFB average pairing gap in the future study of the PDR.

References

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The interplay between nuclear structures and dynamical effects is crucial for appropriate descriptions of heavy-ion fusion reactions at energies around the Coulomb barrier. Coupled-channels calculations have been widely used to quantitatively describe the entrance channel of fusion reactions in light- and medium-mass systems whose charge product \((Z_1Z_2)\) is less than 1,600. On the other hand, in heavy systems \((Z_1Z_2 > 1,600)\), it is observed that the fusion probability is strongly hindered around the Coulomb barrier, compared with \(Z_1Z_2 < 1,600\) systems and with coupled-channels results.\(^1\) This is called fusion hindrance, and the extra energy needed to make such systems to fuse is called extra-push energy.\(^2\) Quasi-fission process, where a colliding system reseparates to projectile-like and target-like fragments before forming a compound nucleus, is considered to be mostly responsible for this hindrance. For a better description of the reaction mechanism in heavy systems, a dynamical diffusion model using a macroscopic Langevin equation has been developed.\(^3\) Moreover, extra-push energies and quasi-fission process have been analyzed using the time-dependent Hartree-Fock (TDHF) model.\(^4\)

Recently, we proposed a method to extract nucleus-nucleus potential and one-body energy dissipation from the relative motion of colliding nuclei to nuclear intrinsic excitations in fusion reactions from TDHF time evolutions.\(^5\) This method relies on the hypothesis that complex microscopic mean-field evolution of head-on collisions can be accurately reduced to a simple one-dimensional macroscopic evolution that obeys a Newton equation including potential and dissipation terms. In the present report, we apply this method to study the property of potential and energy dissipation in heavy systems and to understand the origins of fusion hindrance.

Figure 1 shows nucleus–nucleus potentials \(V\) as a function of relative distance \(R\) for the \(^{96}\text{Zr} + ^{124}\text{Sn}\) system \((Z_1Z_2 = 2,000)\) obtained with our method for three center-of-mass energies \(E_{cm}\). As a reference, we plot by the filled circles the frozen density potential calculated from the same energy density functionals as in TDHF with the density of colliding nuclei frozen to their ground-state one, meaning that no dynamical effects are included during collision. Note that for the case with \(E_{cm} = 228.4\) MeV, the relative velocity \(\dot{R}\) becomes almost 0 at \(R \sim 11.4\) fm, and we stop the extraction of potential at this stage (indicated by the blue filled diamond in Fig. 1). By comparing the obtained potentials in Fig. 1 with those in \(Z_1Z_2 < 1,600\) systems in Ref.\(^5\), we find two significant differences:

1) Energy dependence of potential, which appears around the Coulomb barrier in \(Z_1Z_2 < 1,600\) systems, is less pronounced in heavy systems. (2) While a barrier is observed in the frozen density potential at \(R \sim 12.8\) fm, there is no barrier in the obtained potentials, and the potentials monotonically increase as \(R\) decreases because of dynamical effects. Furthermore, we analyze the origin of the fusion hindrance from the TDHF trajectory with the fusion threshold energy, \(E_{cm} = 228.4\) MeV. Extra-push energy by TDHF can be defined as the difference between the fusion threshold energy and the barrier of the frozen density potential. In this system, this is calculated to be 14 MeV. According to our method of extracting potential, the origin of the extra-push energy can be identified from the sum of the total dissipated energy, increase in potential energy, and remaining kinetic energy. In this case at \(R \sim 11.4\) fm, the total dissipated energy and increase in potential energy are 4.0 MeV and 9.2 MeV, respectively. We conclude from this analysis that the main contribution to the extra-push energy is the increase in extracted potential at \(R \lesssim 12.8\) fm.

References
3. Nuclear Data
Compilation of nuclear reaction data from RIBF

A. Makinaga,*1 V. Devi,*2 M. Aikawa,*1 S. Ebata,*2 N. Furutachi,*1 D. Ichinkhorloo,*2 K. Katō,*1 M. Odsuren,*2 N. Otuka,*3,4 and K. Tsubakihara*5

Nuclear data, e.g. cross sections, half-lives, and decay radiation properties, can be obtained through scientific investigation of nuclear properties and reactions. The results of experimental measurements of different nuclear reaction data are distributed in various publications and hence are difficult for users to access. Therefore, there is a need to compile the data into a database. One of the database is the EXFOR library, which is maintained by the International Network of Nuclear Reaction Data Centres (NRDC) under the auspices of the International Atomic Energy Agency (IAEA). As one of the NRDC members, the Hokkaido University Nuclear Reaction Data Centre (JCPRG)*1 has contributed about 10 percent of the data on charged-particle nuclear reactions in the EXFOR library.

JCPRG compiles and accumulates charged-particle data obtained in Japanese facilities in their own database NRDF. The compiled nuclear reaction data is available through the online search system of the NRDF and the EXFOR library*2. In addition to the collaboration with the NRDC network, JCPRG established a collaborative research contract with the RIKEN Nishina Center in 2010, to increase the availability of the nuclear reaction data produced at the RIBF. The compiled files of the nuclear data produced at the RIBF are translated to the EXFOR format for the benefit of nuclear data users. We have addressed a smooth and high-quality compilation of the RIBF data as one of the important tasks in this collaboration. This write-up provides a brief overview of the JCPRG compilation activity in 2013 regarding experimental nuclear reaction data produced at the RIBF.

Among the papers compiled in 2013, thirteen contained RIBF data in the compilation scope of the EXFOR library, out of which eight papers*3–10 published in 2013 had already been registered on the EXFOR library. Five papers published in 2012*11–15 had also been registered on the EXFOR library in 2013. The data can be easily accessed from the EXFOR search system*2 by using the accession numbers given in Table 1. The list of RIBF data compiled into the EXFOR library is also available on the JCPRG website*1 along with additional information.

To ensure a high-quality database, we ask authors to provide the original data plotted in each figure so that the data compiled in the NRDF and the EXFOR library are accurate. If the original data could not be obtained from the corresponding author, we digitized numerical data from the plotted figures using the digitization software GSYS. If we receive the original numerical data in the future, we will replace the digitized data with the original data. We also correspond with the authors about inquiries for data, error, and experiments as necessary. The numerical data for almost all of the EXFOR entries compiled in 2013 were proofread by authors, and a detailed description of the entries has been revised according to the authors’ comments.

Table 1. Entry numbers with references compiled in 2013

<table>
<thead>
<tr>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
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<td>Entries</td>
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<tr>
<td></td>
<td>E288812</td>
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<td>E240319</td>
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<td>E240829</td>
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<tr>
<td></td>
<td>E240931</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
</tr>
</tbody>
</table>

As a result of the collaboration for four years, most of the compilation process was well established and is working well as reported above. We are continuously making efforts to improve the completeness and usability of the experimental nuclear reaction data produced at the RIBF. For such improvements, the first JCPRG-RNC joint workshop on nuclear data was held on August 8-9, 2013*16. The workshop was helpful for understanding the present and future status of the RIKEN-JCPRG research collaboration and related nuclear data activities.

References
1) http://www.jcprg.org/
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16) M. Aikawa et al.: in this report.

*1 Faculty of Science, Hokkaido University
*2 Meme Media Laboratory, Hokkaido University
*3 RIKEN Nishina Center
*4 NDS, IAEA
*5 Department of Engineering Science, Osaka Electro-Communication University

- 69 -
Nuclear reactions are useful in many fields related to nuclear physics, such as astrophysics, nuclear engineering, and radiation therapy. Many experimental studies have been performed worldwide to obtain nuclear reaction data, such as cross sections and product yields. The majority of such data is published in scientific journals, which may apply charges and are accessible only to researchers in the relevant academic fields. In addition, nuclear reaction experiments require enormous cost and huge researcher effort. Therefore, it is desirable to make such data freely available through the Internet.

One such database is the EXFOR database maintained by the International Network of Nuclear Reaction Data Centres (NRDC) under the auspices of the International Atomic Energy Agency (IAEA). Another is Nuclear Reaction Data File (NRDF) developed by the Hokkaido University Nuclear Reaction Data Centre (JCPRG). JCPRG and RIKEN Nishina Center established a collaborative research contract in 2010 to increase the availability of the nuclear reaction data produced at the RIBF. Under this collaboration, the nuclear reaction data obtained at the RIBF is compiled into the two databases above. However, including state-of-the-art experiments and physical quantities causes problems. For instance, the forthcoming electron scattering data from SCRIT is outside the compilation scope of NRDF and JCPRG on the EXFOR library at the moment. Therefore, we must extend the scope for the RIBF experiments.

In addition, the two databases have their own formats, which were defined more than forty years ago and designed for programming languages prevalent at that time, e.g., Fortran. Therefore, a new format suitable for the current situation and technology is desirable. The format must be applicable for the confirmation process of compiled data performed by experimentalists. It is also desirable for nuclear data users to read and manipulate data in the same format without detailed explanations. The format is now under development using XML technology, which is both human-readable and machine-readable. This feature is a requirement for the next-generation format to enable experimentalists to directly input data into the databases and to enable nuclear data users to retrieve them.

Here, we emphasize that this format does not affect other databases. The contents in the two databases above and evaluated libraries in the ENDF format, e.g., JENDL, can be converted one to one nearly equivalently into the new format. Figure 1 shows a schematic of the process of accessing the database with the format under development using XML technology.

Fig. 1. Schematic of the process of accessing the database with the format under development using XML technology.

References
1) http://www.jcprg.org/exfor/
2) http://www.jcprg.org/nrdf/
3) http://www.jcprg.org/
Development of nuclear data application software with “Webble World”

S. Ebata,* 1 A. Makinaga,* 2 and M. Aikawa* 2

Nuclear reaction data is applicable and considerably important for public societies and various academic communities, e.g., nuclear engineering, radiation therapy, and physics. Moreover, there exists a need for means to utilize this data efficiently and conveniently by individual users. To realize a system capable of utilizing such nuclear data, we are developing application software.

There are several open tools available for searching through data. However, these tools are versatile, and not optimized for individual users. It is difficult to satisfy both universality and optimization of the tools simultaneously. Under such situations, we are motivated to create a tool customizable by “users”. In Hokkaido University Meme Media Laboratory, the IntelligentPad (IP) system has been developed to circulate and manage the knowledge of information 1). On the IP system, data and functions are treated as objects, which are called “Pads”. Since Pads can be connected to each other, user can combine required Pads and constructs original tools for the suitable to their needs.

In the previous work, we developed a “Nuclear Reaction Data and Handling Tools for the NRDF” 2–5) and the “Charged particle nuclear reaction data retrieval system (CONTIP)” 4,5). Here in, we plan to introduce “Webble World” to develop the current systems on the Web. If the system can be extended through Webble World, it will be independent of operating systems; it is available through the Internet and can be shared between users. The users can customize and construct an original tool for their own purposes.

The fundamental idea of Webble World is same as that of the IP system. In the Webble World, an object with a function is called a “Webble” (Fig.1), instead of a “Pad”. Webbles connected by users are conserved in the Webble World, and they are used as components for a new Webble. Webble has some slots to connect with others. For instance, if we connect an appropriate slot in the “Text Webble” with the corresponding slot in the “Display Webble” correctly, we can send the text from the former Webble to the latter and view the text on the latter. A user, however, needs to know the basic structure detail of a Webble, which is part of the tasks in the development of a Webble tool.

The proposed new system can be utilized to search, retrieve, and plot nuclear data. As objectives, an appropriate connection between the system and a database and also the plot of the retrieved data are necessary. There have already been Webbles with functions for the purposes as shown in Fig.2. The proposed system is slightly difficulty in terms of intuitiveness. Therefore, we plan to develop simple usage manual to assist in developing the tools, while also considering the needs of nuclear data users.

Hokkaido University Nuclear Data Centre (JCPRG) is developing the system for using nuclear data with Webble World. Work on making set of Webbles for searching nuclear data, and manuals to use these compound Webbles, is progressing. In addition, we are constructing a new data format using XML in order to improve the usability7 of the system.

Fig. 1. Many Webbles on Webble World 6)

Fig. 2. Compound Webble to read and convert nuclear data, and to subsequently express them on a graph. Yellow lines show the relation between Webbles.

References
Systematic study of nuclear data for nuclear transmutation

A. Makinaga,*1 M. Aikawa,*1 K. Katō,*1 A. Kohama,*2 H. Otsu,*2 and H. Sakurai*2

Long-lived fission products (LLFPs) are problematic radioactive wastes in spent nuclear fuels. Because LLFPs have long half-lives, special techniques for safe management and disposal are required. A promising way to solve this problem is “nuclear transmutation technology”. The basic concept of this technology is to change LLFPs into “short-lived nuclei” or “stable nuclei” by using various kinds of particle beams from accelerators and neutron flux in nuclear reactors. Recently, the use of an accelerator-driven system (ADS) has been studied globally for this purpose. In Japan, J-PARC*1 plans to establish ADS techniques.

From the viewpoint of nuclear data, various kinds of cross section data for LLFPs are needed to design the nuclear transmutation system reliably. Cross section data of proton, neutron, and photon induced reactions on LLFPs are required to establish more effective procedures and to estimate costs. However, as listed in Table 1, most of the experimental data are still unavailable owing to the difficulty in preparing enriched procedures and to estimate costs. Howev

One possible way to access the cross sections is the inverse reaction method. For example, neutron capture cross sections can be estimated with photo nuclear reactions2–4. In addition, unstable LLFP beams at the RIBF facility are strong candidates to produce related nuclear data. In order to promote nuclear transmutation technology, the sharing of knowledge and information among researchers in related fields, e.g., nuclear engineering and nuclear physics, is imperative.

Simultaneously, management of the experimental nuclear reaction database to survey information, as shown in Table 1, and theoretical evaluations of the cross sections is also essential. Due to the lack of experimental cross sections, we performed theoretical estimation using the calculation code TALYS6. Figure 1 shows the total reaction cross sections induced by protons on LLFPs. We were able to determine the cross sections of the order of barn. The impact of this result must be assessed and the cost of the transmutation of LLFPs must be estimated.

Table 1. Half-lives of LLFPs and the current status of the experimental data of photon, neutron, and proton induced reactions in EXFOR5.

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Half-life (year)</th>
<th>Status of experimental data photon</th>
<th>neutron</th>
<th>proton</th>
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<tr>
<td>79Se</td>
<td>65,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>90Sr</td>
<td>29</td>
<td>-</td>
<td>5(5)</td>
<td>-</td>
</tr>
<tr>
<td>93Zr</td>
<td>150,000</td>
<td>-</td>
<td>3(8)</td>
<td>-</td>
</tr>
<tr>
<td>99Tc</td>
<td>210,000</td>
<td>-</td>
<td>16(428)</td>
<td>2(82)</td>
</tr>
<tr>
<td>107Pd</td>
<td>6,500,000</td>
<td>-</td>
<td>2(2)</td>
<td>-</td>
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<tr>
<td>126Sn</td>
<td>100,000</td>
<td>-</td>
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</tr>
<tr>
<td>129I</td>
<td>16,000,000</td>
<td>1(27)</td>
<td>5(5)</td>
<td>-</td>
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<td>133Cs</td>
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<td>137Cs</td>
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<td>-</td>
<td>3(3)</td>
<td>-</td>
</tr>
<tr>
<td>151Sm</td>
<td>89</td>
<td>-</td>
<td>4(17)</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 1. Calculation of total reaction cross sections induced by protons on LLFPs by using the code TALYS.

References
1) J-PARC (http://j-parc.jp/Transmutation/ja/ads-j.html)
5) IAEA-EXFOR (https://www-nds.iaea.org/exfor/exfor.htm)

*1 Faculty of Science, Hokkaido University
*2 RIKEN Nishina Center
JCPRG-RNC joint workshop on nuclear data

M. Aikawa,*1 A. Makinaga,*1 S. Ebata,*2 K. Katō,*1 A. Kohama,*3 H. Otsu,*3 and H. Sakurai*3

The Hokkaido University Nuclear Reaction Data Centre (JCPRG)3) and RIKEN Nishina Center established a collaborative research contract in 2010 to increase the availability of the nuclear reaction data produced at the RIBF. Under the collaboration, the data from the RIBF are compiled into two databases, Nuclear Reaction Data File (NRDF) and the EXFOR library. The former is the JCPRG original database and the latter is maintained by the International Network of Nuclear Reaction Data Centres (NRDC) under the auspices of the International Atomic Energy Agency (IAEA).

The major part of the compilation process has been well established during the collaboration period of four years2). Furthermore, we are continuously improving the coverage and usability of the data from the RIBF. For such improvements, the first JCPRG-RNC joint workshop on nuclear data was held on August 8-9, 2013 (Fig. 1). Its purpose was to discuss and share information on the following topics:

(1) Current status and problems of compilation
(2) Experiments at RIBF
(3) Usability of nuclear data
(4) Nuclear data evaluation

In this article, we briefly report on the workshop.

As reported in another article2), in 2013, we compiled 13 papers, which include experimental data from the RIBF. In the compilation, however, there still remain some problems such as the compilation scope, format, and author proofs. The compilation scope depends on the purpose of each database. For instance, the incident particles compiled in NRDF and transmitted from JCPRG to the EXFOR library are restricted to charged nuclei, mesons, and photons. Therefore, at the moment, the electron scattering data with SCRIT is outside the scope. Because of its importance, however, extension of the scope to include the SCRIT data was discussed. In addition, we also discussed the necessity to compile papers published in other than peer-reviewed journals such as proceedings and annual reports. Such papers are also important from the viewpoint of completeness, but in some cases, it is risky to include results of the works under progress in the reports.

As for the format, the two databases were initiated more than 40 years ago; hence, it is difficult to format these databases using the present-day state-of-the-art experiments and physical quantities. Therefore we discussed the extension of the format for the RIBF experiments. Furthermore, the format must be communicable to authors, as well as readable to nuclear data users. The format is now being constructed using the XML technology, which is both human-readable and machine-readable3). It is necessary to use a human- and machine-readable technology so as to enable the experimentalists in directly inputting the data into the databases and nuclear data users in retrieving the data. Another format for a simulation code PHITS is also requested from a participant.

In addition to the format extension, there is a request to create a new user interface to connect the databases not only with nuclear data users but also with nuclear physics experimentalists. The interface makes it possible for the nuclear data users and the experimentalists to interactively and directly access the databases. We developed an interface using the Weble World technology at the Hokkaido University Meme Media Laboratory4).

Nuclear reaction data are useful in many application fields; e.g., nuclear physics, nuclear engineering, and radiation therapy. In the workshop, we focused on two applications, nuclear transmutation and radiation therapy. Two invited talks were devoted to these fields in terms of the nuclear data point of view. We confirm the importance of the fields.

The workshop helped the participants in understanding the present and future status of the RIKEN-JCPRG research collaboration and related nuclear data activities. We continue to exchange valuable information and requests with nuclear data users and experimentalists to improve our activity more effectively.

References
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3) M. Aikawa et al.: in this report.
4) http://cow.meme.hokudai.ac.jp/WebleWorldPortal/
4. Hadron Physics
Neutral pion production with respect to centrality and reaction plane in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV†

Y. Aramaki*† for the PHENIX Collaboration

The suppression of high transverse momentum ($p_T$) hadrons in relativistic heavy ion collisions was observed at the Relativistic Heavy Ion Collider (RHIC). The phenomenon is interpreted as the energy loss of a hard-scattered parton in the hot, dense, strongly interacting quark–gluon plasma (QGP) formed in the collisions. The suppression patterns are quantified by the nuclear modification factor $R_{AA}$ of the neutral pion as

$$R_{AA}(p_T) = \frac{1/N_{coll}^A d^2 N/dp_T dy}{(T_{AA}) d^2 \sigma_{pp}^{inel}/dp_T dy}$$

where $\sigma_{pp}^{inel}$ is the production cross section of $\pi^0$ in $p + p$ collisions, $(T_{AA}) = (N_{coll})/\sigma_{pp}^{inel}$ is the nuclear overlap function averaged over the relevant range of impact parameters, and $(N_{coll})$ is the number of binary nucleon–nucleon collisions computed using $\sigma_{pp}^{inel}$. In this paper, the results of $\pi^0$ production and $R_{AA}$ and its azimuthal angular dependence are presented. The results are based on the data collected in the 2007 RHIC run. The data sample is four times larger than that of Ref. (1). Furthermore, the reaction plane detector installed in 2007 improved event-plane resolution.

Firstly, the measured $\pi^0$ invariant yields of Au+Au collisions for all centralities and for minimum bias data have been reported. These results are compared to the published $\eta$ yields (2). The measured $\eta/\pi^0$ ratios from minimum bias collisions for various data sets and colliding systems are compared. Although the uncertainties vary, the ratios of $\eta/\pi^0$ are consistent with previously published ones and are also consistent with the overlaid PYTHIA-6.131 $p + p$ calculation. The production rate of $\eta/\pi^0$, 0.46±0.01(stat)±0.01(syst), is constant with the centralities at $p_T > 2$ GeV/c for the same collision energy. These observations indicate that at high $p_T$, the fragmentation occurs outside the medium and the ratio is governed by vacuum fragmentation.

Secondly, the nuclear modification factor $R_{AA}$ of $\pi^0$ is compared to the previous result and the charged hadron $R_{AA}$ at the LHC energy. The yields of $\pi^0$ are suppressed by a factor of 5, as in earlier measurements; however, with the improved statistical and systematic uncertainties, the significant rise of $R_{AA}$ as a function of $p_T$ with a slope $dR_{AA}/dp_T$ of 0.0106±0.0034 (GeV/c)$^{-1}$ in central collisions has been observed for the first time at the RHIC energy. In comparison with the charged hadron $R_{AA}$ observed in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the Large Hadron Col-

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† Condensed from the article in Phys.Rev.C 87, 034911 (2013)

References
Study of medium properties with two particle correlations in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at PHENIX

C.-H. Chen *1

Two-particle correlation is a powerful method to study jet-medium interaction and the collective motion of particles. Interesting new results are revealed by LHC data when $p+p$ collisions with two-particle correlations are studied. Upon observing low-multiplicity $p+p$ collisions at 7 TeV, the $\Delta\eta-\Delta\phi$ correlation function is, as expected, found to have a single near-side peak at $\Delta\eta \approx 0$ and $\Delta\eta \approx 0$ and an away-side peak at $\Delta\phi \approx \pi$ along $\Delta\eta$. For high-multiplicity $p+p$ collisions at the same energy, an enhancement along $\Delta\eta$ at $\Delta\phi \approx 0$, or a “ridge” structure, is observed 1). Finally, $p+Pb$ collisions at 5.02 TeV with similar multiplicity selection, exhibit ridge structure as well 2).

This long-range correlation along the $\Delta\eta$ direction at $\Delta\phi \approx 0$ has been observed at RHIC previously. In two-particle $\Delta\eta-\Delta\phi$ correlations in central Au+Au collisions, an enhancement along $\Delta\eta$ at $\Delta\phi \approx 0$ has been observed 3). It has also been found that this long-range correlation extends to as far as $\Delta\eta \approx 4$ 4). Similar phenomena has been confirmed in Pb+Pb collisions at LHC 5).

This long-range correlation along $\Delta\eta$, or “ridge”, was originally believed to exist only in central Au+Au collisions, but now has also been observed in $p+p$ and $p+Pb$ collisions in LHC. The fact that the ridge appears in both system leads to the question of whether the ridge observed in $p+p$ and $p+Pb$ in LHC is the same as that seen in heavy-ion collisions at RHIC.

Triggered by the new results from LHC, it is important to investigate whether a similar effect exists in $d+Au$ collisions at RHIC. Studying $d+Au$ collisions will certainly provide new insights into the $p+Pb$ data at LHC. First, $d+Au$ is collided at 200 GeV, which is considerably smaller than $p+Pb$ at 5.02 TeV at LHC. Further, in $d+Au$ collisions, the two nucleons in the deuteron may make the initial colliding geometry more complicated than in $p+Pb$ collisions.

At PHENIX, it is possible to measure the two particle correlations with a large $\eta$ gap by correlating a charged hadron in the central arm spectrometer ($|\eta| < 0.35$) and the energy cluster in the Muon Piston Calorimeter (MPC, $3.1 < |\eta| < 3.9$). A large $\Delta\eta$ separation can strongly suppress the non-flow contribution, and thus the remaining correlation should reflect the properties of the produced medium.

Since $d+Au$ is an asymmetric system, in central $d+Au$ collision, the multiplicity distribution, or $dN/d\eta$, is asymmetric along the direction of $\eta$ 6), where the multiplicity is larger in the Au-going direction than in the d-going direction. Therefore a comparison of $d+Au$ and $p+p$ collisions.

Figure 1 depicts the correlation function of the charged hadron in mid-rapidity correlated with the energy clusters in MPC in the Au-going direction ($-3.9 < \eta < -3.1$) in $d+Au$ and $p+p$ collisions.

References
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Status of CuAu flow measurement

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The quark-gluon plasma (QGP) is a phase of matter in quantum chromodynamics (QCD). This phase is predicted to exist at high temperature and high density. Currently at RHIC and LHC, QGP is created by colliding nuclei. In the heavy-ion collisions, azimuthal anisotropy of produced particle emission exists. Collectively, this anisotropy is a quite important probe to understand the properties of QGP because this collectivity is sensitive to initial collision geometry and early time evolution. The strength of anisotropic flow is originated from initial spatial anisotropy. The anisotropic flow contribution. This non-flow is a correlation that does not originate from the event plane. Thus, it is better to choose the detector that is located at forward/backward rapidity as the event plane measurement detector.

In this analysis, the event plane is determined by beam beam counter (BBC) and a forward silicon vertex detector (FVTX). These detectors are located at forward/backward rapidity. In order to measure \( v_n \) precisely, there should be rapidity gap between the regions of measurement of \( v_n \) and \( \Psi_n \) because if are not separated these regions, \( v_n \) would include a non-flow contribution. This non-flow is a correlation that does not originate from the event plane. Thus, it is better to choose the detector that is located at forward/backward rapidity as the event plane measurement detector.

Figure 1 shows the event plane resolution of BBC and FVTX for \( \Psi_2 \). In the central region (0-20\%), the resolution of FVTX South resolution is larger than that of FVTX North. This behavior is also found in BBC. This behavior originate from the multiplicity that is used to measure the event plane and strength of \( v_2 \). Currently, I have calibrated \( \Psi_3 \) and am working on calculating \( \Psi_3 \) resolution.

\[ v_n = <\cos(n[\phi - \Psi_n]) > \]

where \( <\cos(n[\phi - \Psi_n]) > \) are the Fourier coefficient is important to determine the initial state anisotropy and \( \eta/s \) of QGP in the hydrodynamic. The anisotropic flow is originated from initial spatial anisotropy. The initial spatial anisotropy lead to anisotropic collectivity in momentum space. However, the hydrodynamic model does not completely agree with experimental data completely. There is still uncertainty in the theoretical model. Recently, the fluctuation of initial spatial anisotropy was focused upon. The fluctuation of eccentricity can lead to initial spatial triangularity. The initial spatial triangularity from the fluctuation is the origin of \( v_3 \) which is triangular flow strength. This Fourier coefficient is important to determine the initial state anisotropy and \( \eta/s \).

In 2012, Cu+Au collisions were investigated at RHIC. Such asymmetric collisions of heavy nuclei can provide different participant profiles through symmetric collisions of heavy nuclei such as Au+Au and Cu+Cu because of unique initial geometry. In symmetric collisions, initial geometry fluctuations lead to odd harmonics. However in Cu+Au collisions such an unique initial geometry could lead to non-zero odd harmonics. Cu+Au \( v_3 \) could come from such a initial geometrical triangularity, rather than fluctuation. Therefore, the measurement of Cu+Au non-zero harmonics is quite important to determine initial conditions.

In this paper, we report the current status of \( v_2, v_3 \) measurement at midrapidity in Cu+Au collisions. In order to measure \( v_2, v_3 \), an event-plane method is applied. To apply the event-plane method, the following relation between true \( v_3^{tr} \), \( \Psi_3^{tr} \) that could not be measured experimentally and observed \( v_n, \Psi_n \) is needed.

\[ v_3^{tr} = v_3^{ob} / <\cos(n[\Psi_n - \Psi_3^{tr}]) >, \]

where \( <\cos(n[\Psi_n - \Psi_3^{tr}]) > \) correspond to the event-plane resolution. The event plane is determined by

\[ Q_{xn} = \sum_{i=1}^{n} w_i \cos(n\phi_i), \quad Q_{yn} = \sum_{i=1}^{n} w_i \sin(n\phi_i), \]

\[ \Psi_n = \tan^{-1}(Q_{yn}/Q_{xn})/n, \]

where \( \Psi_n \) is the projection of \( \Psi_n \) to the x(y) axis. \( w_i \) is the weight and \( \phi_i \) is the angle of a particle.

In this analysis, the event plane is determined by beam beam counter (BBC) and FVTX. These detectors are located at central region. In order to measure \( v_n \) precisely, there should be rapidity gap between the regions of measurement of \( v_n \) and \( \Psi_n \) because if are not separated these regions, \( v_n \) would include a non-flow contribution. This non-flow is a correlation that does not originate from the event plane. Thus, it is better to choose the detector that is located at forward/backward rapidity as the event plane measurement detector.

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References
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2) arXiv:1111.5095v1 Lett. 2011
Study of direct photon azimuthal anisotropy in $\sqrt{s_{NN}}=200\text{GeV}$ Au+Au in RHIC-PHENIX experiment

S. Mizuno$^{\dag}$ for the PHENIX collaboration

High energy heavy ion collision experiments have been performed since 2000 at the Relativistic Heavy Ion Collider (RHIC), in order to study properties of quark-gluon plasma (QGP). Direct photon, which includes all sources from various processes except one from hadron decay, has been measured as a powerful tool. It is expected not to interact strongly with QGP, thus providing information on when it is created. Furthermore, because direct photons are created in various processes during the entire space-time history of collisions, they provide different probes from all stages, for example, initial hard scattering, thermal radiation from QGP, and bremsstrahlung from partonic energy loss. Photons originating from various sources are measured inclusively in the experiment, so there are difficulties in measuring photons while identifying their sources. To circumvent the difficulty, we measure the direct photon azimuthal anisotropy.

![Fig. 1. $v_2$ as a function of $p_T$ of $\pi^0$(Black) and inclusive photon(Red) in the left plots. Direct photon $v_2$ as a function of $p_T$ is in the right plots.](image)

Azimuthal anisotropy is defined as a relative amplitude of anisotropic azimuthal distribution with respect to the reaction plane. To quantify the anisotropy, Fourier series is used for the azimuthal distribution of the number of emitted particles.

$$\frac{dN}{d\phi} = N_0[1 + \sum 2v_n\cos{n(\phi - \Psi_n)}] \quad (1)$$

$$v_n = <\cos{n(\phi - \Psi_n)}> \quad (2)$$

where $\phi$ is the azimuthal angle of photons, and $v_n$ and $\Psi_n$ are the strength and direction of the $n$th-order harmonic azimuthal anisotropy, respectively. The second component ($v_2$) is referred to as elliptic flow and is measured for various dependences (e.g. $p_T$, particle species). It provides the collective properties of the high density matter, possibly QGP, that interacts and expands hydro-dynamically under given initial conditions. In addition, $v_2$ is found to be affected by the initial geometry.

It is found that direct photon $v_2$ is close to zero in the high $p_T$ region, although $\pi^0$ has finite $v_2$. This is consistent with the expectation that prompt photons from initial hard scattering are dominant at high $p_T$. It is also found that direct photon $v_2$ is almost the same as $\pi^0$ at low $p_T$, where thermal photons are thought to be dominant. The precise reason of this large $v_2$ is not well understood yet.

Higher order azimuthal anisotropy $v_n(n > 2)$ is considered to be more sensitive to initial geometry and QGP shear viscosity $\eta/s$ (the ratio of shear viscosity $\epsilon$ to entropy density $s$) under expansion. Hence, $v_n(n > 2)$ has been actively studied recently, and it is considered to be important for calculating the initial state model and the viscosity of QGP. The results of $\pi^\pm$, $K^\pm$, and $pp$ are shown in Fig. 2. It is found that $v_n(n > 2)$ also has collective motion.

The ongoing studies on direct photon $v_n(n > 2)$ could help in understanding the puzzle of direct photon $v_2$.

![Fig. 2. $\pi^\pm, K^\pm$, and $pp$ (a) $v_2$, (b) $v_3 \times 1.5$, (c) $v_4 \times 1.5$, and (d) $v_4(\Psi_2) \times 5.0$ as functions of $p_T$. The green band indicates $p_T$ correlated systematic uncertainties.](image)

References
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Result of the energy scan program at RHIC-PHENIX

Y. Ikeda

1 Introduction

According to quantum chromodynamics, quarks and gluons are confined with strong forces in hadrons. It is expected that they are de-confined at a high temperature or high density\(^1\)\(^-\)\(^2\). This is called Quark Gluon Plasma (QGP), which may have existed in the early universe according to the big bang theory or in the core of a neutron star\(^3\)\(^-\)\(^4\). Experimentally, it is formed by relativistic heavy ion collision with a collider. The system geometry is elliptical at the first stage of a non-central collision. The geometrical anisotropy generates the asymmetry in the yield of particles as a function of the azimuthal angle with respect to the event plane of an event. The azimuthal anisotropy indicates an interaction with a short mean free path of partons in a hot dense medium. It also gives information about the initial state and its expansion, possibly through the QGP phase. The magnitude of azimuthal anisotropy of particle emission is measured as the second term of a Fourier series (\(v_2\)),

\[
dN/\mathrm{d}\phi = N(1 + 2v_2 \cos 2(\phi - \Psi)),
\]

where \(N\) is number of the particle emissions, \(\phi\) is azimuthal angle of the particle emission [rad], and \(\Psi\) is the event plane angle [rad].

2 Quark number scaling of hadron \(v_2\)

The measured large \(v_2\) of hadrons is an indicator of the small mean free path in the hot dense medium and a hydrodynamic model with a low viscosity reproduces the collective behavior of the particles\(^5\)\(^-\)\(^6\). Meanwhile, the \(v_2\) value scales with the constituent quark number and is independent of the particle mass. It indicates that the flow of hadrons is built up by the flow of quarks in the QGP according to the quark coalescence model. The \(v_2\) of hadrons is the sum of the \(v_2\) of combined partons in the quark coalescence model as follows,

\[
v_2^{\text{hadron}}(p_T) = n v_2^{\text{parton}}(p_T/n),
\]

where \(n\) is the number of partons in hadrons\(^7\)\(^-\)\(^8\). The experimental result of quark number scaling of \(v_2\) suggests the quark level collectivity in the hot dense matter and the quark coalescence mechanism forms hadrons from quark matter via quark-gluon phase transition in the Au+Au \(\sqrt{s_{NN}} = 200\) GeV collision at RHIC-PHENIX\(^9\).

The study of \(v_2\) with the energy scan of heavy ion collision may provide information about the threshold behavior of collision energy, if the quark number dependency is an indicator of a QGP phase. A new reaction plane detector was installed to measure the \(v_2\) of hadrons with an enhanced event plane resolution at the RHIC-PHENIX experiment\(^10\). The higher resolution allows us to study \(v_2\) at low energy collisions, which have low statistics of particles.

3 Results of the energy scan program at RHIC-PHENIX

The \(v_2\) of \(\pi^+\pi^-\), \(K^+, K^-\), \(p\), \(\bar{p}\) and \(d\) were measured in the Au+Au \(\sqrt{s_{NN}} = 39\) and 62 GeV collisions\(^11\). The number of constituent quark scaling of the \(v_2\) of hadrons is mostly established in these energies (fig.1 shows the results of 39 GeV). Considering this as an indication of the QGP phase, the threshold energy of the QGP-hadron phase transition would be lower than \(\sqrt{s_{NN}} = 39\) GeV. In contrast, particle (especially \(p\)) \(v_2\) differs from anti-particle \(\bar{v}_2\) in these lower beam energy collisions. It could be given by interactions such as \(p\bar{p}\) annihilation in the high baryon density caused by the baryon stopping in the low energy collision.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{The scaled hadron \(v_2\) as a function of \(KE_T = m_T - m\) with the number of constituents quarks in the Au+Au \(\sqrt{s_{NN}} = 39\). The \(KE_T\) scale cancels the \(p_T\) shift by the collective behavior.}
\end{figure}

References
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Search for the strong magnetic field via di-electron measurement in heavy-ion collisions at RHIC-PHENIX

T. Hoshino*1, *2 for the PHENIX collaboration

A strong magnetic field is expected to be created in high-energy heavy-ion collisions. The intensity of the magnetic field created in the collisions at BNL-RHIC is estimated to reach about 10^{14} teslas. The field creation can be considered to be due to the effect of both of collision participants and collision spectators and the field direction is perpendicular to the reaction plane (Fig. 1).

The possibility of field creation was presented first about 35 years ago1. In recent years, this began to attract attention because achieving an increase in the field intensity with increasing energy of the collider is well beyond the critical field of an electron (eB_e = m_e^2). The time evolution of this field is also calculated based on theories. According to the theoretical calculation, the field intensity decreases rapidly, but maintains for a few fm/c above the critical magnetic field of an electron2. Chiral magnetic effects and other interesting effects, such as non-linear QED effects, are discussed based on the theories to be caused by the strong field. From experimental studies, charged particle asymmetry with respect to the reaction plane3 and direct-photon azimuthal anisotropy4 suggest the presence of the strong field. However, the field itself is yet to be directly detected experimentally.

Direct detection of the field in high-energy nuclear collisions is a very important issue. Detection of the strongest field in the universe has a major impact in itself. Further, the observation of the field leads to the confirmation of the chiral magnetic effect. Moreover, there is a possibility to verify non-linear quantum electrodynamics effects such as vacuum-birefringence and the decay of real photons.

Direct photons/virtual photons are good candidates for probing the field detection, because they are not affected by the strong interaction and they maintain the initial information. Pi0 decay photons/Dalitz-decay electron pairs are candidates for control probes because they are from the later time. Combinatorial pairs from mixed events could also be used as a control probe.

According to the calculation of photon vacuum polarization in a strong magnetic field, the production rate of di-electrons from virtual photon decay depends on the field direction5. Since PHENIX has a good electron-identification capability, we focus on virtual photon decays with a dependence on the magnetic field direction. By using electron pairs from virtual-photon decays as the probe, polarization measurement is possible without the using of a polarimeter.

We are using the √s_{NN} = 200 GeV Au+Au collisions data set collected in 2004 at the RHIC-PHENIX. Electrons and positrons are identified by RICH and EMCal, and momentum is decided by Drift Chamber and Pad Chamber. Global variables, z-vertex, centrality and reaction plane, are decided by Beam-Beam Counter.

We select two di-electron invariant-mass region, 0.12 < m_{ee} < 0.3 GeV/c^2 and 0 < m_{ee} < 0.1 GeV/c^2. The first region contains virtual photon components, and thus, this region is expected to contain the signal. The second is dominant Dalitz-decay di-electron, which has no-physics effect to polarization. The polarization is measured using the angular distributions of di-electron with a correlation to the reaction plane, as a function of centrality, because it depends on the strength of the created field. Now, we focus on polarizations of Dalitz-decay pairs and combinatorial pairs, which is important for background subtraction. We discuss what kind of background is included, how to subtract backgrounds, and how to extract the signal.

References

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High \( p_T \) hadron production in \( \text{Au+Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

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and the PHENIX VTX

One of the most significant discoveries at RHIC has been the suppression of high \( p_T \) hadrons in central \( \text{Au+Au} \) collisions\(^1\). In pQCD models, the data constrain the transport coefficient, \( \hat{q} \)\(^2\).

Currently the best measurement at RHIC is achieved by neutral pions\(^3\). For charged hadrons, the measurement is limited by a background from photon conversions and random tracks, both mimicking high-transverse momentum tracks.

With the recent addition of a Silicon Vertexing Tracker (VTX)\(^4\) to PHENIX, it is possible to significantly reject this background and to extend hadron measurement to a higher \( p_T \). Tracks need to be reconstructed with a small Distance of Closest Approach (DCA) of the track projection on the primary vertex. Real tracks are reconstructed with zero DCA convoluted with the detector resolution, whereas fake tracks can have any DCA.

Figure 1 shows the raw DCA distribution in the transverse plane. A peak is observed around zero DCA, which is dominated by real tracks, above a background of random tracks and weak decays.

Figure 2 shows the transverse momentum distribution of tracks with and without the small-DCA requirement. At high \( p_T \), the spectrum without the DCA requirement appears unphysically flat, whereas the spectrum with the requirement continues to fall. This observed behavior suggests that the DCA requirement successfully suppresses the background.

These plots indicate the potential of this method. Recently, significant progress has been made in rejecting misfunctioning parts of the detector and improving the tracking algorithm. The analysis is still in progress.

Fig. 1. Raw DCA distribution in the transverse plane. The peak around zero DCA is dominated by real tracks. The underlying background comes from random tracks and weak decays. The fall-off at ± 0.4 cm is an artifact of the tracking algorithm.

Fig. 2. Uncorrected hadron \( p_T \) spectra for different purity cuts. At high \( p_T \), the spectrum without the DCA requirement appears unphysically flat while the spectrum with the DCA requirement continues to fall.

References
Status of the charm and bottom measurement with PHENIX-VTX

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Heavy quarks (bottom and charm) are one of the clean probes for studying properties of hot dense medium created in the high energy heavy ion collisions. Due to their large mass, heavy quarks are mainly produced though the initial hard scattering. Once produced, the heavy quarks traverse and interact with the medium. Therefore, the modification of their production yield and emission angle reflects the medium properties.

The PHENIX experiment1) installed a silicon vertex tracker (VTX)2) and collected a large amount of $p+p$, Au+Au and Cu+Au collision events at $\sqrt{s_{NN}} = 200$ GeV successfully in the past three years. The VTX provides a clear separation of charm and bottom quarks via measurement of distance of the closest approach of electrons relative to the collision vertex (DCA).

The preliminary results of the fraction of $(b \to e)/(b \to e + c \to e)$ and the azimuthal anisotropy of charms were already reported3,4). In order to improve the DCA measurement, we recently updated the following items in the analysis:

1) Hot and dead channel status on the sensor:
   The bad channels that have extremely higher and lower hit rate were masked. In addition, the unstable channels that changed the hit rate by time were also newly masked. Figure 1 shows the map of the hot and dead channels for a readout chip. The colored channels indicate the bad channels caused by the faulty bump bonding between the sensor and the readout chip.

2) Parameter tuning of the track association between the VTX hits and the track measured in the central arm:
   The angular resolution of tracks measured in the central arm was an input for the $\chi^2$ calculation of the track fitting between VTX hits and the track. This resolution was updated to be realistic (1 m rad.). The blue histogram and black curve in Fig. 2 show the $\chi^2$ distribution for the reconstructed proton in simulation and the ideal $\chi^2$ function. The histogram suitably reproduces the ideal curve.

3) DCA decomposition method:
   The charm and bottom yields were obtained by fitting the measured DCA distribution with the DCA templates of charms and bottoms5). The DCA templates are correlated with the shape of their transverse momentum ($p_T$) distribution since the DCA is determined by convolution of two effects: the decay length of the parent particle and $p_T$ kick relative to the parent momentum. In order to include this effect, we fit both the DCA and $p_T$ distribution of electrons simultaneously. We are testing the several methods to decompose charm and bottom components.

References

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Measurement of $D^0$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV using the Silicon Vertex Tracker at RHIC-PHENIX


Measurements of the $D^0$ meson (and its charge conjugate) via the hadronic channel $D^0 \rightarrow K^- + \pi^+$ ($D^0 \rightarrow K^+ + \pi^-$) in $p + p$ collisions provide important information. First, the total cross section of charm production can be obtained and compared with perturbative Quantum Chromodynamics (pQCD) calculations. Second, it provides the baseline measurement of charm production in order to understand the properties of the hot and dense QCD medium, created by heavy ion collisions, by comparing $D^0$ production in $p + p$ and Au+Au collisions.

Direct reconstruction of the $D^0$ meson is challenging because of its short decay lengths, $\sigma_t = 122.9 \mu m$, and a very large combinatorial background. However, the Silicon Vertex Tracker (VTX) installed into the PHENIX experiment during the 2011 run, can separate the primary vertex and the $D^0 \rightarrow K^- + \pi^+$ decay vertex with high resolution. This can substantially eliminate the combinatorial background.

The strategy to extract $D^0$ production yield is based on an invariant mass analysis of all the possible pairs of two oppositely charged tracks. The invariant mass, $M_{K\pi}$, is defined as follows.

$$M_{K\pi} = \sqrt{(E_+ + E_-)^2 - (\vec{p}_+ + \vec{p}_-)^2}$$

$$E_\pm = \sqrt{m_\pm^2 + \vec{p}_\pm^2}$$

In the above equations, the subscript $+$ or $-$ indicates the charge of the track. We assigned the mass, $(m_+, m_-) = (m_K, m_\pi)$ or $(m_\pi, m_K)$.

In the absence of any ion pair selection, the signal to combinatorial background ratio would be too small to extract the $D^0$ signal in the invariant mass distribution. It is, therefore, mandatory to select tracks on the basis of kinematical and geometrical considerations.

One of the quantities that is useful for track selection is the distance of the closest approach (DCA) of the reconstructed track to the primary vertex in the plane transverse to the beam direction. DCA of the daughter track, $K^-$ or $\pi^+$, of the $D^0$ meson is larger than that of primary track, which comes from the primary vertex. Therefore, we can reject those primary tracks used in the invariant mass analysis by applying a DCA cut.

The intermediate result is shown in Fig. 1, which indicates the invariant mass distribution of $K^- \pi^+$ before and after applying a DCA cut. There is a hint of a small peak at the $D^0$ mass region in the mass spectrum with the DCA cut (the lower panel). However, there still remains a substantial combinatorial background. Therefore, it is necessary to further reduce the combinatorial background without sacrificing too many $D^0$ signals, and it is expected to be solved by selecting tracks in accordance with the $D^0$ decay kinematics using the VTX. We have been developing an analysis code that selects the decay kinematics of $D^0$ appropriately, leaving room for improving of the signal to background ratio.

References
Development of coordinate offset online calibration system at RHIC-PHENIX

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The PHENIX experiment in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been upgraded by installing a silicon vertex tracker (VTX)1). The VTX has been developed for heavy-flavor (charm and bottom) measurements and is dedicated to precise tracking for finding primary and secondary vertices. The first set of physics data including the VTX was recorded for the Au+Au collisions in RUN 11 (RHIC experiment performed in 2011).

The first and second layers of the VTX are comprised of pixel detectors, and the third and the fourth layers of VTX are comprised of stripixel detectors2), as shown in Fig. 1. Geometrical calibration is important because precise alignment is required in the VTX to identify primary and secondary vertices. To analyze the distance of closest approach (DCA) of tracks to the primary vertex, we require a drift chamber (DC) track is associated with the clusters on the VTX, as shown in Fig. 2.

Fig. 1. Cross section of the VTX. The VTX is separated into a west half barrel and an east half barrel.

In the PHENIX apparatus, the west and east half barrels of VTX and DC in the east and west arms are mechanically separated, and their relative positions may shift. After each time we open up the apparatus to access the detectors, we need to calibrate the relative positions of the detectors. We developed an online and automated system to calibrate the coordinate offset between each of the west and east half barrels of VTX and DC in the east and west arms. Once we access the detectors, we always take zero-magnetic-field data in which all tracks from the collision point are assumed to be straight. The online calibration system calculates the beam center position with respect to DC west/east and VTX west/east coordinate system. Once the zero-field data are taken, the online calibration system runs immediately, and its result is submitted to a database. This result is used in the tracking analysis. This module outputs QA plots so that we can confirm that the result is reasonable.

In summary, we developed a coordinate offset online calibration system for RHIC-PHENIX. The system outputs calibration parameters of the coordinate offset of VTX and DC for the tracking analysis with VTX and DC data.

Fig. 2. Cross section of the PHENIX detector. The relative position of VTX west/east and DC west/east can be moved during the experiment.

References
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Status of analysis of longitudinal double helicity asymmetry in $\pi^0$ production in $\sqrt{s} = 510$ GeV polarized proton–proton collision by PHENIX central arm

I. YOON$^{1,2}$ for the PHENIX Collaboration

The final goal of this research is to constrain polarized gluon distribution via measurement of the longitudinal double helicity asymmetry of $\pi^0$ production ($A_{LL}^{\pi^0}$) with $\sqrt{s} = 510$ GeV RHIC PHENIX data. Based on the results of EMC experiment and other following experiments, the quark-spin component of a proton is only $0.330 \pm 0.011(Theo.) \pm 0.025(Exp.) \pm 0.028(Evol.)$. The remaining spin might be carried by gluons or orbital momentum. However, the gluon-spin component is poorly measured because polarized gluon distribution has not been measured precisely.

Compared to the previous measurement with $\sqrt{s} = 200$ GeV RHIC data (Run09), the ongoing measurement with $\sqrt{s} = 510$ GeV RHIC data (Run13) will cover a lower momentum-fraction (Bjorken $x$) kinematic region, where the uncertainty large. The integrated luminosity of Run13 is much higher compared to that of Run09. The figure of merit ($\int L \times P_B^2 \times P_Y^2 dt$) considering beam polarization ($P_B$ and $P_Y$) is also higher. Table 1 presents a comparison between Run09 and Run13. Thus, this research can contribute toward constraining polarized gluon distribution. The progress of the analysis is presented herein.

Table 1. Measurement with RHIC Run09 and Run13 data

<table>
<thead>
<tr>
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<th>Run09</th>
<th>Run13</th>
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<tr>
<td>$\sqrt{s}$</td>
<td>200 GeV</td>
<td>510 GeV</td>
</tr>
<tr>
<td>Bjorken $x$ region</td>
<td>0.05~0.2</td>
<td>0.02~0.08</td>
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<tr>
<td>$\int L dt$</td>
<td>15 pb$^{-1}$</td>
<td>145 pb$^{-1}$</td>
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<tr>
<td>$\int L \times P_B^2 \times P_Y^2 dt$</td>
<td>1.4 pb$^{-1}$</td>
<td>14.7 pb$^{-1}$</td>
</tr>
</tbody>
</table>

In this experiment, $\pi^0$ is measured via $\pi^0 \rightarrow \gamma \gamma$ decays using a highly segmented electromagnetic calorimeter (EMCal) covering $|\eta| < 0.35$ and $\Delta \phi = \pi$.

Thus far, event selection and related low-level study, EMCal warmap generation, and EMCal TOF tower-by-tower correction have been done. An EMCal warmap is a map of abnormal EMCal towers. To reject events from the abnormal towers, a warmap has been generated wherein noisy, dead and uncalibrated towers are marked. EMCal tower-by-tower TOF correction has been performed. Before the correction, there was tower-by-tower TOF deviation, and the deviation depended on time. After the correction, the TOFs of all towers are well aligned.

For event selection, the shower-shape cut, charge-veto cut and TOF cut are applied to reject hadronic, charged and ghost events, respectively. Clusters in an EMCal can survive up to three bunch-crossings. Clusters from previous crossings are called ghost clusters. For the charge-veto cut and TOF cut, cut parameters are optimized by the signal-to-noise ratio. In addition to the three cuts mentioned above, the conventional minimum energy cut and vertex cut are also applied. After event selection, the statistics for remaining $\pi^0$ is $6.97 \times 10^7$. The results of the event selection are summarized in Fig. 1.

![Diphoton invariant mass distribution with various cuts](image_url)

**Fig. 1.** Diphoton invariant mass distribution with various cuts for all $P_T$ bins. After event selection, 70% of the noise is suppressed, whereas 30% of the signal is lost.

After the completion of event selection, $A_{LL}^{\pi^0}$ calculation has been started. $A_{LL}^{\pi^0}$ calculation is currently in preliminary stage. Estimation of statistical and systematic uncertainties is also being carried on. To validate the analysis, single-spin asymmetry is being calculated.

References

Status of $\pi^0$ pair $A_{LL}$ analysis in RHIC-PHENIX experiment

K.Hashimoto,*1,*2 R.Seidl,*1 and Y.Goto*1 for the PHENIX collaboration

1 Introduction

The proton has a spin of 1/2 that originates from internal quarks and gluons. Results from deep inelastic scattering (DIS) experiments show that the quark spin contribution to the proton spin is only about 25% . In the PHENIX experiment, the gluon-spin contribution to the proton spin has been studied for more than 10 years. In recent years, double helicity asymmetries, $A_{LL}$, have been measured in several types production ($\pi^0$, $\pi^\pm$, direct photon, etc). In the case of single inclusive $\pi^0$ production, $A_{LL}$ is defined as follows:

$$A_{LL}^{\pi^0} = \frac{\sum_{a,b,c} f_{a,b} f_{b,c} \sigma_{ab,c} x N_{LL}^{ab,c} D_{c}^{\pi^0}}{\sum_{a,b,c} f_{a,b} f_{b,c} \sigma_{ab,c} x N_{LL}^{ab,c} D_{c}^{\pi^0}}$$ (1)

where $f_{a,b}$ represent unpolarized parton distribution functions (PDFs) of partons a and b and $\Delta f_{a,b}$ represent polarized PDFs, $D_{c}^{\pi^0}$ is a fragmentation function (FF) of parton c to $\pi^0$, $\hat{\sigma}_{ab,c}$ and $\hat{\sigma}_{ab,c}$ denote the cross section and $A_{LL}$ of the partonic subprocess $ab \rightarrow cX$ respectively.

Experimentally, the $A_{LL}$ for $\pi^0$ production is determined as

$$A_{LL}^{\pi^0} = \frac{1}{<P_{b}P_{Y}>} N_{++,+} + R N_{+-} - R N_{++} + N_{+--}; R \equiv \frac{L_{++}}{L_{+--}}$$ (2)

where $N_{++,+}$ is the number of $\pi^0$s and R is the relative luminosity between bunches with the same and opposite helicities. $<P_{b}P_{Y}>$ are the averaged beam polarizations.

2 Simulation study on kinematics coverage

Bjornenko-x is a fraction of a proton’s longitudinal momentum. Let us imagine a reaction parton a interacting with parton b and producing jets(or partons) c and d: parton(a)+parton(b) $\rightarrow$ jet(c)+jet(d). In this case, Bjornenko-x can be determined by using pseudorapidity and the transverse momentum of scattered partons c and d

$$x_{1} = \frac{1}{\sqrt{s}} (p_{T,c}e^{\eta_{c}} + p_{T,d}e^{\eta_{d}})$$ (3)

$$x_{2} = \frac{1}{\sqrt{s}} (p_{T,c}e^{-\eta_{c}} + p_{T,d}e^{-\eta_{d}})$$ (4)

If both partons c and d are produced in the mid-rapidity region, $e^{\eta_{c}}$ and $e^{-\eta_{d}}$ are similar. Hence, $x_{1}$ and $x_{2}$ of the dijet production at the mid-rapidity region have a similar value. We can not measure total energy of scattered partons. We measured the $\pi^0$ pair instead of the dijet(or partons). If we select back-to-back hadron pair production at the mid-rapidity region, the Bjornenko-x of two incoming partons should be almost balanced. If values of two Bjornenko x are not balanced, the produced particles system is boosted, and these particles should move to the exterior of the PHENIX central arm acceptance, where the rapidity region is $|\Delta y| < 0.35$. Figure 1 is a result of PYTHIA6.4 simulation. The vertical the horizontal axes are the log of energy of scattered partons. We measured the $\pi^0$ production cross section, which is calculated on the basis of he fit.

3 Current status of this study

We calculated $A_{LL}$ as well as $A_{L}$ for $\pi^0$ pair production , $A_{LL}$ for the single inclusive $\pi^0$ production etc, for cross checking. We determined our analysis passed these tests. We are also checking for consistency in statistics between experimental data and simulated data with the PYTHIA 6.4 event generator.

This analysis is being preformed at RIKEN-CCJ31, and we are grateful for its smooth operation.

References
2) http://ccjsun.riken.jp/

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Measurement of longitudinal double-spin asymmetries of $J/\psi$ production in polarized $p+p$ collisions at $\sqrt{s}=500$ GeV for 2012 run

X. Wang,*1,*2 H. Yu,*2,3,*4 and M. Liu*4

Understanding the contribution of polarized gluons to the proton spin is a key step for resolving the proton-spin puzzle. A number of different channels have been used to study gluon polarization, including final state hadrons1 and jets2. Some rare processes involving direct photons or heavy-flavor production will allow us to measure the gluon contribution at the leading order, but their significantly lower production rates limit their impact on the $\Delta G$ constraints. At Relativistic Heavy Ion Collider (RHIC) energies, heavy-quark production is dominated by the gluon–gluon interaction; thus, measurements of the longitudinal double-spin asymmetry in heavy-flavor production in the polarized $p+p$ collisions will allow us to study the polarized gluon distributions. $J/\psi$ is a bound state of a $c$ and $\bar{c}$ pair. Here, we report the status of longitudinal double-spin asymmetries in $J/\psi$ production in polarized $p+p$ collisions in the PHENIX experiment at the RHIC for data collected during 2012.

In the case of the heavy-quark production at RHIC, the asymmetry is proportional to the gluon polarization at the leading order:

$$A_{LL} \sim \frac{\Delta g(x_1)}{g(x_1)} \times \frac{\Delta g(x_2)}{g(x_2)} \times a_{gq\rightarrow QQ}^{LL},$$

where $\Delta g(x)(g(x))$ is the (un)polarized gluon distribution, and $a_{gq\rightarrow QQ}^{LL}$ is the partonic asymmetry.

The $J/\psi$ production has been measured by the PHENIX muon spectrometers at forward and backward rapidities ($1.2 < |\eta| < 2.4$), where two muons go into the same arm.

The longitudinal double-spin asymmetry $A_{LL}$ can be measured according to the following equation:

$$A_{LL} = \frac{1}{P_b P_y} \frac{N^{++} - RN^{+-}}{N^{+-} + RN^{++}},$$

where $P_b$ and $P_y$ are the beam polarizations for blue and yellow beams, respectively; $N^{++}(N^{+-})$ is the $J/\psi$ yield from the same (opposite) helicity beam collisions; and $R = L^{++}/L^{+-}$ is the relative luminosity measured using beam beam counter (BBC) and zero degree calorimeter (ZDC) at very forward rapidity.

The invariant mass distribution of dimuons is shown in Fig. 1. Invariant mass distribution is fitted using a third-order polynomial and two Gaussian functions. The number of $J/\psi$ is calculated on the basis of he fitting with a 2$t\sigma$ cut. The measured inclusive asymmetry

$$A_{LL}^{incl}$$

is related to $A_{LL}^{incl}$ by

$$A_{LL}^{incl} = A_{LL}^{incl} - r \cdot A_{LL}^{BG},$$

$$\delta A_{LL}^{incl} = \frac{\sqrt{(\delta A_{LL}^{incl})^2 + r^2 \cdot (\delta A_{LL}^{BG})^2}}{1 - r},$$

where $r$ is the background fraction, and $A_{LL}^{BG}$ is the background asymmetry, which is measured using like-sign dimuons under the $J/\psi$ peak and the side-band unlike-sign dimuons.

Fig. 2 shows the sensitivity of $J/\psi$ $A_{LL}^{incl}$ vs. $p_T$ based on data obtained during the 500 GeV polarized $p+p$ run in 2012. The analysis is in progress and we are working towards preliminary results for $J/\psi$ cross section and its longitudinal double-spin asymmetry.

Fig. 2. Sensitivity of $A_{LL}$ vs. $p_T$ in $J/\psi$ production at $\sqrt{s} = 500$ GeV for data obtained during 2012.

References

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*4 P-25, Los Alamos National Laboratory
PHENIX local polarimetry analysis status

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One of the main goals of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) is to study the proton spin structure through spin asymmetry measurements of production cross sections using various probes from polarized $p + p$ collisions. In 2013, we ran longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV. Since the stable polarization direction of proton beams circulating in the ring is perpendicular to the ground, the polarization direction is kept perpendicular except in the experimental hall during longitudinally polarized beam collision runs.

Measuring proton beam polarization along the longitudinal direction at the collision is important in double longitudinal spin asymmetry $A_{LL}$ measurements. The polarization in RHIC is measured by RHIC polarimeters at the position where the spin vector is vertical; however, once the polarization direction is changed to be longitudinal, some transverse component of the beam polarization can remain. This should be accounted as a systematic error in the $A_{LL}$ calculation.

The PHENIX local polarimeter measures the transverse component of proton beam polarization at the collision point with single transverse spin asymmetry $A_N$ in forward neutron production. A large $A_N$ for the neutron production was measured in the PHENIX experiment.1) For forward neutron production, which has a small transverse momentum $p_T$, the large $A_N$ cannot be explained by perturbative QCD, but the One Pion Exchange (OPE) models explain it well. In the OPE model, finite $A_N$ is accompanied by the interference of the spin-flip amplitude of pion-exchange and the spin-nonflip amplitude of other Reggeon exchange. A detailed theoretical study is still ongoing.

The PHENIX local polarimeter consists of Zero Degree Calorimeters (ZDCs) and Shower Max Detectors (SMDs) and is located downstream of the beam dipole-bending-magnet outside of the interaction region. ZDC is a hadron calorimeter, and SMD is a hodoscope composed of plastic scintillator strips. The neutron’s position is calculated by centroid method using various probes from polarized $p + p$ collisions. In 2013, we ran longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV. Since the stable polarization direction of proton beams circulating in the ring is perpendicular to the ground, the polarization direction is kept perpendicular except in the experimental hall during longitudinally polarized beam collision runs.

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For obtaining the local polarimeter data, a transversely polarized commissioning fill, a longitudinally polarized commissioning fill, and physics fills are used. 81M events were taken for the transverse commissioning fill, and 280M events were taken for the longitudinal commissioning fill. During physics runs, the local polarimeter trigger was used with a prescale, and the scaled trigger rate was about 100-200 Hz.

Events with 70-300 GeV energy are considered in order to avoid background photons; beam scraping backgrounds from the beam pipe, which deposit low energy in ZDC; and events that directly hit the optical fibers for ZDC readout. Further, only the events with at least two hits in the SMD scintillator strips in both $x$, $y$ coordinates are considered in order to reject the photon background. A fiducial acceptance cut with radius $=0.5-4.0$ cm from the SMD center is applied in order to avoid shower leakage or the smearing effect at the center caused by the SMD with about 1 cm position resolution. After the event selection, 19M events are used for the transverse run analysis.

The measured analyzing power $A_N^{measured}$ is defined as

$$A_N^{measured} = \frac{1}{\sin(\theta - \phi_0)} \frac{e_N(\phi)}{p},$$

$e_N$ is the raw asymmetry calculated with the square root formula,1) and its values for the south detector (counter-clockwise direction from the collision point) in the transverse run are plotted in Fig.1. Only the statistical error is calculated for the error bars. $p$ is the proton beam polarization, and it is $0.369 \pm 0.061$ for the yellow beam (beam runs counter-clockwise direction) during the transverse run. The calculated $A_N^{measured}$ is $0.101 \pm 0.018$. For the transverse component calculation, we calculate $A_N^{measured}$ of longitudinal runs in the same manner, then divide that by $A_N^{measured}$ of the transverse run. The transverse component is about 1% or less during the commissioning run.

Currently, modification of the pedestal and gain parameters for ZDC and SMD is ongoing. After these are finalized, the codes with new parameters will be rerun. Further, the systematic errors will be estimated.

References
Sea quark polarization measurement by $W^\pm \to \mu^\pm$ in PHENIX 2012


The leptonically decayed $W^\pm$ bosons measurement at RHIC aims to achieve precise constraint of each flavor-decomposed sea quark's spin contribution to the whole proton spin $\frac{1}{2}$. The $W^\pm \to \mu^\pm$ analysis by using the dataset of year 2012 shares the basic strategy set in the 2011 analysis, but also has several advantages such as enhanced statistics and upgraded $W$ trigger for data acquisition. Table 1 shows a few key features of the recent longitudinally polarized pp collisions.

Table 1. Results of recent polarized pp collisions in PHENIX Muon Arms.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$</th>
<th>$L$ (pb$^{-1}$)</th>
<th>$P$ (%)</th>
<th>FoM ($LP^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>500</td>
<td>8.6</td>
<td>39.0</td>
<td>1.3</td>
</tr>
<tr>
<td>2011</td>
<td>500</td>
<td>16.7</td>
<td>48.0</td>
<td>3.8</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
<td>31.5</td>
<td>51.9</td>
<td>8.5</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>146.0</td>
<td>55</td>
<td>44.2</td>
</tr>
</tbody>
</table>

The main observable in this analysis is the single spin asymmetry ($A_L$) calculated by muons decayed from desired $W$ bosons. The major background source is muons from in-flight decayed low $p_T (p_T \leq 3$ GeV/$c$) hadrons, which mimic high $p_T$ muons as well as various irreducible muonic backgrounds. Owing to the dominance of these backgrounds in addition to smearing in momentum and charge determination, observing distinct Jacobian peak in $W^\pm \to \mu^\pm$ measurement in forward rapidity is not expected, unlike the $W^\pm \to e^\pm$ measurement in mid-rapidity. Therefore, accurate estimation of the S/BG ratio plays an essential role in a reliable signal extraction process.

Table 2. S/BG ratio in Run 12 (preliminary).

<table>
<thead>
<tr>
<th>Channel</th>
<th>$n_{sig}$</th>
<th>$n_{mu}$</th>
<th>$n_{had}$</th>
<th>S/BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>South $\mu^-$</td>
<td>$88.87^{+16.97}_{-16.28}$</td>
<td>44.42</td>
<td>$177.77^{+19.60}_{-18.60}$</td>
<td>$0.40^{+0.12}_{-0.10}$</td>
</tr>
<tr>
<td>South $\mu^+$</td>
<td>$92.48^{+20.57}_{-19.91}$</td>
<td>44.88</td>
<td>$258.74^{+23.38}_{-23.34}$</td>
<td>$0.30^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>North $\mu^-$</td>
<td>$38.95^{+11.90}_{-11.15}$</td>
<td>42.71</td>
<td>$139.78^{+15.45}_{-14.56}$</td>
<td>$0.21^{+0.09}_{-0.07}$</td>
</tr>
<tr>
<td>North $\mu^+$</td>
<td>$72.37^{+15.75}_{-15.04}$</td>
<td>38.67</td>
<td>$185.69^{+18.93}_{-17.98}$</td>
<td>$0.32^{+0.10}_{-0.09}$</td>
</tr>
</tbody>
</table>

To estimate the S/BG ratio properly, we use a partially indirect approach by using likelihood to the $W$. The procedure for the estimation is as follows. First, calculate the $W$ likelihood by using the data and NLO level Monte Carlo sample. Second, construct the overall probability density function (PDF) for signal and backgrounds by using three types of component PDFs based on $W$ likelihood. Each component PDF corresponds to a signal, muonic backgrounds, and hadronic backgrounds, respectively. Finally, estimate the S/BG ratio via the overall PDF and unbinned max. likelihood fit technique. The estimated S/BG ratio in the preliminary condition is summarized in Table 2. Also, $A_L$ calculated by applying the above S/BG ratio can be seen in figure 1.

Fig. 1. $A_L$ in Run 12 (preliminary). Empty squared box indicates systematic error by dilution factor.

After the preliminary, various refinements have been made or are underway, such as inclusion of kinematic variables from the Forward Silicon Vertex Detector (FVTX), applying overall trigger efficiency, update in detector efficiency, and further fine tune of hadronic PDF. Among them, inclusion of FVTX variables and fine tune of hadronic PDF are expected to play a significant role in improving statistics in the region of interest ($W$ likelihood $\geq 0.92$) as well as reduced errors, which will enable better estimation of the S/BG ratio and $A_L$.

References

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Study of the dimuon process for PHENIX $W^\pm \to \mu^\pm$ analysis using 2012 data

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Using the parity violation of weak interactions, we measured the single spin asymmetry of W production in longitudinally polarized p+p collisions. This enables us to access the flavor-separated sea quark polarization in protons1). PHENIX measured the single spin asymmetry $A^W_L$ via lepton decays of W bosons, $W^\pm \to e^\pm$ at midrapidity ($|\eta| < 0.35$) and $W^\pm \to \mu^\pm$ (1.2 < $|\eta|$ < 2.2) at the center of mass energy $\sqrt{s} = 510$ GeV at RHIC. After the first measurement in 2011 for the $W^\pm \to \mu^\pm$ channel, PHENIX collected data at an integrated luminosity of 50 pb$^{-1}$ in 2012 with fully upgraded detectors and a trigger system,2). The preliminary result of $A_L$ obtained using the 2012 data is shown in Fig. 1. The measured asymmetries are consistent with theory models within large uncertainty ranges.

![Fig. 1. Preliminary result of $A_L$ for $W^+$ (top) and $W^-$ (bottom) at forward/backward rapidity region with various theoretical predictions.](image)

After the preliminary result was obtained, there have been efforts toward the finalization of the 2012 data analysis. Understanding the background of the $W \to \mu$ analysis is one of the most important goals. The major background source is coming from decays of kaons and pions to muons in flight. In addition to this hadron background, there are muon backgrounds from the dimuon process that are open heavy flavor, quarkonia, and Drell-Yan process. Estimating the muon background is one of the essential steps to extract the signal-to-background ratio accurately. We simulate the dimuon processes using the PYTHIA event generator and GEANT4 detector simulation. The cross section of each process can be estimated by comparing the simulated dimuon yield to data. Fig. 2 shows the invariant mass spectrum of dimuon events in the 2012 data. We select unlike-sign muon pairs that travel to the same side of the PHENIX muon arm spectrometer. The discrepancy in the mass spectrum of the two muon arms reflects the difference in trigger efficiency. The simulated dimuon yields that take the trigger efficiency into account are used to extract analytical functions for each process. The scale factor of analytical functions for each process that contributes to the dimuon yields are then determined through simultaneous fit to the data. Currently, the simultaneous fit is being performed, and the result will be finalized shortly.

![Fig. 2. Invariant mass distributions of dimuon events from data for south (red) and north (black) muon arms.](image)

In addition to the dimuon study, dedicated analysis work is in progress on different fronts. Evaluation of the trigger efficiency and systematic uncertainty estimation are some of the tasks to be carried out. Furthermore, the signal-to-background ratio is expected to be improved through a review of the hadron background.

References
2) S. Park et al, RIKEN Accel. Prog. Rep. 46, 63 (2013)
PHENIX $W \rightarrow \mu$ measurements from the 2013 data-taking period

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The parity violation of the weak interaction accesses only left-handed particles and right-handed antiparticles. In longitudinally polarized proton-proton collisions one therefore can access fixed helicities of the quarks and antiquarks involved in the production of real $W$ bosons. Furthermore the charge of the produced $W$ predominantly selects the quark and antiquark flavors involved. $W^+$ are mostly generated by a $u$ and anti-$d$ quark while $W^-$ are mostly generated by a $d$ and an anti-$u$ quark. The PHENIX experiment has the capabilities to detect $W$s inclusively through their electron and muon decays at central and forward rapidities respectively. In the 2013 data taking period RHIC was entirely run with polarized protons at center of mass energies of $\sqrt{s} = 510$ GeV to finish the RHIC $W$ program1). In PHENIX all major muon trigger upgrades installed and commissioned over the last several years as well as the forward vertex tracker FVTX were fully operational for this run. Furthermore PHENIX implemented various improvements in the operation of the detector to increase the data taking efficiency without sacrificing quality. In a limited vertex region of the detector to increase the data taking efficiency a d and an anti-u quark while $W^-$ are mostly generated by a $d$ and an anti-$u$ quark. The PHENIX experiment has the capabilities to detect $W$s inclusively through their electron and muon decays at central and forward rapidities respectively. In the 2013 data taking period RHIC was entirely run with polarized protons at center of mass energies of $\sqrt{s} = 510$ GeV to finish the RHIC $W$ program1). In PHENIX all major muon trigger upgrades installed and commissioned over the last several years as well as the forward vertex tracker FVTX were fully operational for this run. Furthermore PHENIX implemented various improvements in the operation of the detector to increase the data taking efficiency without sacrificing quality. In a limited vertex region ( more can be used for the forward $W$ analysis ) a total luminosity of about 146 pb$^{-1}$ were accumulated with average longitudinal beam polarizations of 54%, which is close to five times the data accumulated in the previous year with comparable polarizations. The accumulated figure of merit for single spin $W$ asymmetries are displayed in Fig. 1 for the three most recent 500 or 510 GeV data taking periods.

Having developed the $W \rightarrow \mu$ analysis already in the previous two years, most of the offline quality assurance is finished and the analysis to the single spin asymmetries relevant to access the sea quark polarizations in the nucleon is close to be available to the public. One aspect relevant in this analysis and in particular the extraction of $W$ production cross sections is the evaluation of the overall trigger efficiency for candidate events found to be likely $W$ signal events in a MC and data based $W$ likelihood calculation. As various muon triggers cover only certain rapidity ranges these trigger efficiencies need to be obtained independently for various rapidity bins, detector arms and muon charges. Fig. 2 shows the total trigger efficiencies after weighting each according to their relative contribution to the final $W$ candidate event sample.

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1) E. C. Aschenauer et al., arXiv:1304.0079 [nucl-ex].
Improvement of global alignment of PHENIX muon tracker

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The alignment of tracking chambers is one of the long-standing challenges for nuclear physics experiments. The PHENIX muon system measures the charged-particle momentum using three tracking stations with cathode readout chambers, namely muon tracker (MuTr), implemented in a magnetic field volume.1 The precision of the relative alignment between the three tracking chambers directly affects the resolution of momentum measurement. Over the past few years, the PHENIX spin program has been focusing on polarized sea-quark measurements in protons through asymmetry measurements of the W-boson production.2 Because of the large mass of W-boson, the muon decayed (which we detect) from the W-boson has a high transverse momentum of ~ 40 GeV/c. Such a high-momentum trajectory is barely bent in the magnetic field, and its sagitta is about a few to several mm in the MuTr volume. The possible misalignment of MuTr chambers will result in further momentum smearing over its intrinsic resolution. The higher the momentum, the more serious the side effect on the charge determination of the traversing particles. The possible charge misconstruction is a fatal error for the asymmetry measurement, since the opposite charge (either W+ or W−) production is predicted to appear in opposite asymmetry. The goal of this study is to achieve the intrinsic resolution of 150 µm as currently, an intrinsic resolution of only ~ 300µm achieved.

We developed a global alignment program that calculates the smallest χ2 solution of actual hit locations when the straight tracks pass through the three MuTr stations assigning the relative location of chambers as free parameters. In this manner, the program will find the relative alignment of chambers to minimize the residuals. The residual is the distance between the linear interpolation of front- and back-plane hit positions and the actual hit position in the middle plane. The alignment parameters are limited to transverse shifts and rotations. The result of the new alignment demonstrated narrower residual distributions than that previously achieved; however, it was found that unresolved non-linear radial dependences of the residual distributions remain even with the present algorithm.

As a rough quantitative estimate of the misalignment effect, the width of the residual distribution between radial dependent and non-dependent regions were compared. The resulting estimate showed difference of 100 to 500 µm depending on the octants. Note that this indicates a possible room for the improvement of the alignment by fixing the alignment to the radial direction. In order to investigate further problems in the present alignment scheme, of the azimuthal-direction dependence (orthogonal to radial direction) was also checked. Odd dependences were also found in the azimuthal direction. As an overall trend, bad alignment octants are problematic in both radial and azimuthal directions, and thus, a somewhat complicated correlation needs to be addressed. Since there are 16 chamber planes involved simultaneously in the alignment, finding the cause of these dependences is nontrivial. To obtain some hints to disentangle the complication, the local alignment was evaluated. The plane-based local residual was defined using two or three gaps (stations 1 and 2 have three gaps, and station 3 has only two gaps) and two planes (one is a stereo plane; the other is a non-stereo plane). The local residual distributions are again evaluated for radial and azimuthal dependence. Since local residual distributions are independent of other stations, one can expect some localized misalignment in a particular station if the cause of the global misalignment comes from the single plane or station; however, we did not observe that any octant shows such a trend, as shown in Fig. 1. It is interesting to investigate how closely we can reproduce the global residual distribution in comparison with the observed local ones. A toy Monte-Carlo simulation (MC), which includes the multiple scattering effect, is under development. Since the MC assumes perfect alignment, any fraction of the residual width that cannot be explained by the MC can be interpreted as room for the improvement of the alignment.

Fig. 1. Standard deviation of local residuals plotted for all non-stereo planes (Run9 after alignment).

References
Forward spectrometer upgrade of the PHENIX experiment

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The PHENIX experiment proposes substantial detector upgrade for long-term enhancement of major physics programs using full luminosity of the recently upgraded RHIC accelerator.\textsuperscript{1)} The proposed midrapidity upgrade replaces the present magnet with a solenoid, and removes the large iron yoke at forward rapidity that provides the hadron absorber for the muon detectors. The open geometry of the forward direction of the proposed upgrade will allow for addition of a forward spectrometer covering forward rapidity region, $1 < \eta < 4$, with capability of measuring hadrons, photons, electrons, muons and jets. We have been investigating requirements for detector design and performance of the forward upgrade consisting of charged-particle tracking, particle identification, electromagnetic and hadronic calorimeters as shown in Fig. 1.

A physics topic regarding the forward upgrade is Cold Nuclear Matter (CNM) effects in proton- and deuteron-nucleus collisions. We aim to measure nuclear gluon distribution, $G_A(x)$, to know initial state of heavy-ion collisions and to understand the strongly coupled Quark-Gluon Plasma. It is important to investigate gluon suppression, or suppression of $G_A(x)$, at small-$x$ and verify the Color Glass Condensation framework, which is an effective field theory for describing saturated gluon.\textsuperscript{2)} We also aim to know the perturbative-QCD (pQCD) mechanism of the energy loss of partons in the CNM, its relation to transverse momentum broadening, and detailed hadronization and time scales.

Another physics topic is measurements of single transverse-spin asymmetry. The asymmetries have been measured in the Fermilab fixed-target experiment with transversely polarized proton beams\textsuperscript{3)} and in the RHIC transversely polarized proton collider experiments at much higher energies.\textsuperscript{4)} pQCD models have been developed to explain the asymmetries. At small transverse momenta, the asymmetries have been explained using transverse-momentum dependent (TMD) factorization framework.\textsuperscript{5)} They have been explained with correlations between the transverse spin of the target proton and intrinsic transverse momentum of quarks in the initial state, which is called the Collins effect\textsuperscript{6)} and described by the Sivers function. They have also been explained with correlations between quark spin and the transverse momentum of hadrons in the final state, which is called the Collins effect\textsuperscript{7)} and described by the Collins fragmentation function. At larger transverse momenta, higher-twist effect explains the asymmetries with spin-dependent transverse momentum components generated through quark-gluon and multi-gluon correlations using the collinear factorization framework.\textsuperscript{8)}

The Sivers function contributes with opposite sign to the transverse-spin asymmetries in the semi-inclusive DIS process and the Drell-Yan process due to non-universality of the TMD factorization framework.\textsuperscript{9)} This is a fundamental QCD prediction based on gauge invariance and its verification is an important milestone in the field of hadron physics. The verification allows testing of non-perturbative aspects of QCD and the concept of factorization. The forward upgrade will enable us to measure the Sivers function in the Drell-Yan process.

The Collins effect will be investigated through an azimuthal anisotropy in the distribution of hadrons in final-state jets with the forward upgrade detectors. The asymmetry of single identified hadrons described by the Collins fragmentation function will give a measurement of quark transversity distribution at large $x$ which will determine the tensor charge of the nucleon.

There is a new possibility in collisions of polarized protons and nuclei. Transverse single-spin asymmetries in $p \uparrow + A$ collisions may have a sensitivity to the saturation scale in the nucleus. This link between the physics of the CNM and spin structure of the nucleon is one of the most interesting recent developments.

References

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Design for an eRHIC detector based on the sPHENIX detector†

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The PHENIX experiment has recently submitted a plan1) for a detector design at eRHIC, a version of the Electron Ion Collider (EIC) planned at Brookhaven National Laboratory (BNL) which makes use of one of the current RHIC hadron rings. The EIC will collide polarized electrons with heavy nuclei and polarized protons, with its primary purpose to explore the gluon (the strong force carrier). eRHIC is expected to turn on in 2025.

A detailed description of the EIC physics case has been laid out in the recent White Paper2), eRHIC is expected to probe through polarized electron-proton collisions the properties of (sea)quarks and gluons in the nucleon, such as spin, orbital motion and spacial distributions. The kinematic coverage of ePHENIX in parton momentum fraction x and 4-momentum transfer Q^2 is compared to that of other measurements in Fig. 1. Measurements of the gluon helicity over a wide kinematic range will allow unprecedented constraints of the gluon polarization, ∆g. In Semi-Inclusive scattering, correlations between transverse momentum of gluons and quarks and the proton spin will be fully explored. Through Deeply Virtual Compton Scattering, eRHIC will measure the orbital angular momentum contributions to the proton spin.

As it will also be able to scatter electrons off nuclei, eRHIC will be able to explore the nature of gluons at high density, where the effects of gluon saturation (when gluon splitting and recombination balance) are expected. By varying kinematics as well as the nuclei species, we will be able to vary the path length of a struck quark through the nuclei, and probe the nature of hadronization in and out of nuclear matter.

The ePHENIX detector design is shown in Fig. 2, and makes use of the BABAR solenoid3) and the sPHENIX detector upgrade4) being planned for later this decade. We plan to add a high resolution electromagnetic calorimeter in the electron-going direction for precision measurement of the scattered electron. GEM based trackers will allow for charged sign identification and hadron rejection based on energy to momentum cuts.

In addition to the sPHENIX electromagnetic and hadronic calorimetry, we plan to add a Time Projection Chamber (TPC) for tracking and a Detector of Internally Reflected Cerenkov radiation (DIRC) for hadron particle identification (PID), based on the BABAR DIRC detector. PID in the central barrel allows for measurements of sea quark spin and transverse momentum distributions at low momentum fraction, x.

In the hadron-going direction, new electromagnetic and hadronic calorimeters are planned, as well as additional trackers and PID detectors. The combination of an Aerogel-based Ring Imaging Čerenkov (RICH) detector for low momentum tracks and a gas-based RICH detector for tracks up to ~ 60 GeV/c will allow for measurements at highest and moderate x over the full available Q^2 range.

ePHENIX will be capable of doing the physics possible with eRHIC. Efforts on fully simulating the detector is currently underway.

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The Application of Gaussian Process Regression to Background Spectrum Modeling at PHENIX

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Often in nuclear and particle physics, we need to estimate the area under a peak which sits over an oddly shaped background (see figure 1). Occasionally we are able to perform an analytical first principles calculation to calculate a shape for the background, but more often we are faced with little or no information about what the shape of the background should be. Faced with this, we typically choose a polynomial and fit this functional form to the background. The choice of this polynomial and its fitting leaves an unquantified uncertainty.

Fig. 1. A sample background (sampled from a known third order polynomial) and Gaussian peak spectrum.

Gaussian processes1,2) are a mathematical concept that allow for a method of data regression and predictive functional modeling using a minimal set of prior assumptions. A nice feature of this method is that simultaneously with the predictions, uncertainties are provided.

Gaussian processes are a specific type of stochastic process where the variance of each of the random variables comprising the process is Gaussian. An important feature of stochastic processes is that, mathematically, they sample over the space of functions similar to how a random variable samples over a set space of possible outcomes. In defining the variances to be Gaussian, we’ve narrowed down the space of possible functions and simplified the math needed to specify the process. Specifically, with this requirement of Gaussian uncertainties, the expectation of the process can be defined entirely in terms of a mean function and a covariance function similar to how the Gaussian distribution is defined purely by a mean and a variance.

The specific background spectrum that we are interested in applying this technique to is the background sitting beneath the Jacobian peak, in W± production in p+p collisions4). This is a steeply falling spectrum that isn’t modeled well by using power laws or exponentials. This particular problem requires the extension of the Gaussian process technique to multi-scale problems, which required transforming the data3) and applying the Gaussian process regression in this warped space. Our current application of Gaussian processes to modeling this spectrum can be seen in figure 2.

Fig. 2. The W Jacobian peak and background spectra. The black line and blue band represent the Gaussian process best fit and uncertainty band.

The uncertainty band currently encompasses a large space of functions, many of which we don’t expect to be physical (e.g. an undulating, falling spectrum). We are currently working to add shape constraints to the Gaussian process modeling by sampling individual, though coarsely grained, functions from the constrained space and then accepting or rejecting those functions based on their individual shapes.

References

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Fragmentation function measurements with the Belle detector


The transition of quasi-free, high-energetic partons into confined hadrons cannot be described from first principle QCD as the related parton and hadron masses are typically too low to apply perturbative QCD. The fragmentation functions (FF), describing this transition, therefore need to be measured experimentally, similarly to the parton distribution functions (PDFs) in the nucleon. Their definition is also rather similar as for example the fragmentation function \( D_{1,q}(z,Q) \) describes the number density of producing a hadron \( h \) from a parton \( q \) with fractional energy \( z = E_h/E_q \) and an energy scale \( Q \). Until recently most data was obtained close to the \( Z \) resonance in \( e^+e^- \) annihilation, while little data at smaller scales was available and therefore the gluon fragmentation was not well constrained. The Belle experiment at KEK has collected more than a 1 ab\(^{-1}\) of luminosity close to the \( Y(4S) \) resonance at \( \sqrt{s} = 10.58 \) GeV and about 63 pb\(^{-1}\) were used to extract unpolarized fragmentation functions in the process \( e^+e^- \rightarrow hX \) which was published recently\(^1\). The results can be seen in Fig. 1 as a function of the fractional energy \( z = 2E_h/\sqrt{s} \). Before this measurement very little low-energy scale data and almost no high-z data was available. It is expected that this data will soon be used in a global QCD analysis to parametrize the flavor dependence of pion and kaon fragmentation functions. In addition the analysis of unpolarized fragmentation functions continues in Belle with the aim to extract direct flavor information via the use of di-hadrons in opposite hemispheres. In this case the different combinations of favored (eg. \( u \rightarrow \pi^+ \)) and disfavored (eg. \( u \rightarrow \pi^- \)) fragmentation functions can be disentangled by the various charge combinations of the two detected hadrons. It is expected that preliminary results will be available soon. Also the extraction of the explicit transverse momentum dependence of fragmentation functions is ongoing which so far is only assumed to be of a certain form in various global fits, but explicit measurements are not available so far.

Furthermore, the published results on the spin dependent fragmentation function measurements\(^2\) are in the process to be augmented to also access the flavor dependence by not only concentrating on charged pions, but also on charged kaons and neutral mesons as well as their transverse momentum dependence. Also here the inclusion of various hadron types allows the flavor decomposition of the corresponding spin dependent fragmentation functions. By making use of them, the flavor decomposition of the quark transversity distribution of the nucleon in semi-inclusive deep-inelastic scattering and proton-proton experiments. Also here a QCD global transversity analysis for either the Collins function related measurements\(^3\) or the interference related measurements\(^4\) is available with the present data.

References

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Probing flavor asymmetry of antiquarks of the proton in the E906/SeaQuest experiment

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E906/SeaQuest is an extension of the earlier Drell–Yan experiments at Fermi National Accelerator Laboratory (Fermilab), such as E772 and E866/NuSea1), and it studies the internal structure of the proton at the parton level using the Drell–Yan process. In the leading order, the Drell–Yan process is described by the quark–antiquark annihilation process: \( q + \bar{q} \rightarrow \gamma \rightarrow \mu^+ + \mu^- \). SeaQuest uses a 120-GeV proton beam extracted from the Fermilab Main Injector.

The ratio \( d/\bar{u} \) was measured in the Bjorken \( x \) range 0.015 < \( x < 0.35 \) in the E866 experiment. The statistically precise part of the data in the range 0.015 < \( x < 0.2 \) tends to agree with several models, such as the meson cloud model. However, the data appear to deviate from these models in the larger \( x \) region. SeaQuest will determine the ratio up to \( x = 0.45 \) more precisely than the E866. The SeaQuest spectrometer consists of four tracking stations. Each station has drift chambers or drift tubes for tracking and hodoscopes for triggering. The Japanese group is in charge of the drift chambers of the third station. Two drift chambers are aligned at the station to cover the large acceptance. SeaQuest completed a two-month commissioning run in spring 2012. After an upgrade, a two-year physics run began in late 2013.

In the commissioning run, we successfully reconstructed the di-muon mass distribution, and a \( J/\psi \) peak was clearly observed (Fig. 1). The mass resolution was \( \sim 0.3 \text{ GeV} \), which meets the requirement. This proves that the detectors and tracking software work adequately. After the commissioning run, three main hardware upgrades were performed. The first one was an upgrade of the beam quality. During the commissioning run, we observed high-multiplicity events because the beam had high instantaneous intensity. This made the track reconstruction difficult. An improvement of the duty factor was confirmed in the current run. The beam tuning is now ongoing, and we will have a full-intensity beam (10^{12} protons per second) once it is completed. The second main upgrade is the installation of a Cherenkov detector in the beam line to measure the beam intensity at 53 MHz RF frequency. This allows us to determine the absolute cross section of the Drell–Yan process and to generate a veto trigger in order to avoid the high-intensity part of the beam. The last main upgrade is the improvement of the hodoscopes and drift chambers. For hodoscopes, we upgraded the existing PMT bases with a new circuit board to achieve higher rate capabilities. For drift chambers, one new chamber was constructed to ensure a larger acceptance at the third station. The chamber has 5,300 wires, and we manually constructed it in 2012. The chamber was installed at the bottom part of the third station. The construction of another new drift chamber is ongoing. It will be also installed at the first station.

After the current physics run began, we were working on the optimization of every component for stable data accumulation. Our current focus is to optimize the trigger system. The system examines the hit pattern of the hodoscopes to identify the pattern characteristics of the high-mass muon pairs produced from the Drell–Yan process or \( J/\psi \) decay. We are now trying to suppress the background as much as possible through the hit-pattern study. The preliminary result of the mass distribution shows a suppression of the background compared to the distribution obtained in the commissioning run. Once the optimization is completed, we will start taking the Drell–Yan data. The data accumulated in the next two years will have a significant impact on our understanding of the internal structure of the proton.

Fig. 1. Di-muon mass distribution reconstructed using the data taken in the commissioning run. The \( J/\psi \) peak is clearly observed. The inset shows the mass distribution in which the normalized background is subtracted.

References
Elliptic flow of neutral pion in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by ALICE experiment

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It has been observed in central Pb+Pb collisions at ($\sqrt{s_{NN}}$) = 2.76 TeV at the Large Hadron Collider (LHC) facility at CERN that the yield of charged particles at a high transverse momentum ($p_T$) is strongly suppressed compared with the expected yield from $p+p$ collisions, assuming scaling with the number of binary collisions. This suppression is attributed to the energy loss of hard-scattered partons at a high transverse momentum ($p_T$) is strongly suppressed compared with the expected yield from $p+p$ collisions, assuming scaling with the number of binary collisions. This suppression is attributed to the energy loss of hard-scattered partons as they traverse the dense medium. To compare these models, improved experimental control of multiple models employing different approaches that reproduce these models, improved experimental control of a high-

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{\langle 1/N_{AA}(\Delta \phi) \rangle}{d^2\sigma_{pp}/dp_T dy}.$$ 

Experimental data can be well reproduced by using multiple models employing different approaches that are used to calculate the energy loss of hard-scattered partons as they traverse the dense medium. To compare these models, improved experimental control of the path length $L$ is required because the energy loss of a high-$p_T$ parton increases rapidly with increase of the distance traveled through the medium.1) Thus, the measurement of the energy loss with respect to the path length is expected to provide detailed information about the mechanism of the energy loss of the parton. If $R_{AA}$ is measured as a function of centrality ($c_{cent}$) and the azimuthal angle ($\Delta \phi$) with respect to the event plane, $R_{AA}(L)$ can be determined. Therefore, the differential observable $R_{AA}(\Delta \phi)$ directly probes the path length dependence of the energy loss.

The $R_{AA}(p_T, c_{cent}, \Delta \phi)$ with respect to the azimuthal angle is factorized as

$$R_{AA}(p_T, c_{cent}, \Delta \phi) = F(\Delta \phi, p_T) \cdot R_{AA}(p_T, c_{cent}),$$

where $F(\Delta \phi, p_T)$ is the ratio of the relative yield, given as

$$F(\Delta \phi, p_T) = \frac{N(\Delta \phi, p_T)}{\int d\phi N(\Delta \phi, p_T)}$$

and $N(\Delta \phi, p_T)$ can be expressed in terms of a Fourier expansion with $\Delta \phi$.

$$N(\Delta \phi, p_T) \propto 1 + 2 \sum_{n=1}^{\infty} (v_n \cos(n \Delta \phi)),$$

where $v_n$ is the magnitude of the n-th order harmonic.

The second harmonic, $v_2$, represents the strength of elliptic azimuthal anisotropy. The anisotropy $v_2$ at a low $p_T$ is caused by the collective flow, which gives rise to the background in the measurement of $R_{AA}(p_T, \Delta \phi)$ for investigating energy loss.

The values of $v_2$ were calculated. $\pi^0 v_2$ was extracted by using the $dN/d\phi$ method. In this method, $v_2$ is obtained by fitting the azimuthal angular distribution of $\pi^0$ with

$$N(\Delta \phi, p_T) = N(1 + 2v_2 \cos(2\Delta \phi)).$$

$\pi^0$ values are reconstructed by the invariant mass method with reconstructed energy obtained using a photon spectrometer (PHOS) in the ALICE experiment.2) Fig.1 shows $\pi^0 v_2$ values as a function of $p_T$. In this figure, all data for semi-central triggered events in 2011 are analyzed. Centrality is defined by V0 detectors, which are scintillation detectors, and covers the range from -3.7 to -1.7 and from 2.8 to 5.1 in pseudo rapidity. In this plot, $\pi^0 v_2$ values denote the same tendency of the $v_2$ values of the charged particles qualitatively.3) Calculations of $\pi^0 v_2$ are presently ongoing.

References
Measurement of high-\(p_T\) neutral mesons with a high-energy photon trigger at ALICE

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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 of 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 has a high-resolution and high-granularity electromagnetic calorimeter called PHOS\textsuperscript{1).} One of the main achievable physics goals by PHOS is the study of the 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 and 7 GeV in \(p\text{-}Pb\) collisions at \(\sqrt{s_{NN}} = 5.02\) 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.

In this analysis, 0.3\(nb^{-1}\) MB-trigger data and 70\(nb^{-1}\) PHOS-triggered data in \(pp\) collisions at \(\sqrt{s} = 8\) TeV are used. The PHOS-trigger efficiency as a function of measured photon energy is evaluated with real MB-trigger data. By using this efficiency, the efficiency for a parent particle is estimated through a simulation. For instance, neutral-pion trigger efficiency in \(pp\) collisions at \(\sqrt{s} = 8\) TeV is shown in Fig. 1.

The rejection factor of the PHOS trigger for the MB-trigger data, \(R\), was determined with real data in this analysis. \(R\) corresponds to the number of MB-trigger events inspected while one PHOS trigger is issued. It is 150 for 2-GeV threshold in \(pp\) at 8 TeV, 4800 for 4-GeV threshold in \(pp\) at 8 TeV, and 6500 for 7-GeV threshold in \(p\text{-}Pb\) at 5.02 TeV.

Fig. 2 shows the invariant raw yield of neutral pions measured with the MB trigger (open circles) and that with the PHOS trigger (closed circles) in \(pp\) collisions at \(\sqrt{s} = 8\) TeV. Only the statistical errors are shown in Fig. 2. Up to 40 GeV/\(c\), neutral pions can be measured with PHOS trigger. No other experiments have successfully measured neutral pions up to 40 GeV/\(c\). At the low-\(p_T\) region, MB- and PHOS-trigger results are consistent with each other within statistical errors.

In summary, we began investigating PHOS-triggered data and attempting to extract the invariant yield of neutral mesons for the PHOS-triggered data. The final result of the invariant yield up to 40 GeV/\(c\) in \(pp\) collisions is expected to be obtained shortly. Furthermore, 1.6\(nb^{-1}\) PHOS-triggered data are recorded in \(p\text{-}Pb\) collisions at \(\sqrt{s_{NN}} = 5.02\) TeV. Neutral pions above 40 GeV/\(c\) can be measured with this data set. The analysis of PHOS-trigger data will extend our understanding of high-\(p_T\) particle production beyond the previously published result\textsuperscript{2) of MB-trigger data. In Pb-Pb collisions, neutral pions near 40 GeV/\(c\) can be measured with data taken in 2011. By analyzing this data set, the extraction of \(R_{AA}\) for single particles up to 40 GeV/\(c\) will be possible, which is one of the future plans of our data analysis.

References

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Azimuthal distributions of jets with respect to high-$p_T$ neutral pion triggers in pp collisions from ALICE

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Jet measurements play a critical role in probing the hot and dense QCD medium created in heavy-ion collisions. Detailed transport properties of the medium can be extracted through measurements of parton energy loss and medium response with respect to the lost energy.

In general, the energy loss of recoil jets and leading jets depends on the path length in the medium (i.e., creation point and moving direction in the medium). For example, jet pairs with a large energy asymmetry in the final states can be from the surface of the medium, as shown in Fig. 1. While leading jets escape the medium from the surface recoil jets traverse in the medium with loss to its energy. We use this surface bias to acquire deeper insight into the medium properties: The stronger the surface bias, the greater is the bias to acquire deeper insight into the medium properties.

Fig. 1 shows the single-electron spectrum. Electrons are identified using dE/dx. TOF is essential to remove hadrons, and Inner-Tracking System (ITS).

This analysis used the shower shape and cluster splitting method$^{4}$ to identify high $p_T$ $\pi^0$. With this method, high $p_T$ $\pi^0$ around 40 GeV/c can be identified with the signal-to-noise ratio of 90%.

Fig. 2 shows the azimuthal angular correlation between $\pi^0$ and jet in pp collisions, where $\pi^0$ $p_T$ is from 8 to 12 GeV/c and the associated jet $p_T$ is higher than 10 GeV/c. From this distribution, two main observables will be discussed as the functions of trigger and associated $p_T$. One is the away-side yield per trigger yield, and the other is the width of the near-side and away-side correlation. These quantities will be discussed in the future, and similar analysis will be done for p-Pb and Pb-Pb collisions in order to understand the ordinal nuclear matter effects and the properties of the hot and dense medium.

Fig. 1. Simple geometry of hadron-jet correlation with the leading particle in a recoil jet momentum threshold $p_T > 0.5$ (GeV/c)$^2$

In this paper, we report the jet azimuthal distribution with neutral pion triggers in pp collisions at $\sqrt{s} = 7$ TeV from LHC-ALICE, which is very important as a baseline study for heavy-ion collisions. The ALICE detector was built as a general-purpose detector for measurements of ultra relativistic heavy ion collision at the LHC.$^3$ For neutral pion identification, an electromagnetic calorimeter (EMCAL) is used. Jets are measured by a Time-Projection Chamber (TPC).

Fig. 2. $\pi^0$-jet azimuthal correlation with trigger $p_T$ region of 8-12 GeV/c and associated jet threshold $p_{T,jet} > 10$ GeV/c

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Measurement of dielectron production in $\sqrt{s_{NN}} = 5.02$ TeV $p$-Pb collisions at LHC-ALICE

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In high-energy heavy-ion collisions, heavy quarks are primary produced during the initial hard scattering and experience the entire evolution of system. Therefore, they are sensitive to the transport properties of the hot and dense matter created in the collisions. In particular, the correlation of heavy quark pairs provides key insight into the mechanisms of the energy loss and thermalization1). This can be studied through the measurement of dielectron production because correlated electron-positron pairs from semi-leptonic decays of heavy quarks are the dominant source of dielectrons above 1 GeV/c. The dielectron measurement around the intermediate-mass region in $p$-Pb collisions reveals cold-nuclear-matter effects such as gluon shadowing and gluon saturation on the heavy-quark production.

In the ALICE experiment, the Transition Radiation Detector (TRD) has a capability of the online electron identification and provides an electron trigger to enrich the data samples for the study of heavy-flavor electron production. In 2013, ALICE successfully collected data in $p$-Pb collisions with the TRD trigger ($L_{\text{int}} = 1.4$ nb$^{-1}$) and the minimum bias trigger ($L_{\text{int}} = 0.067$ nb$^{-1}$).

In the central barrel of the ALICE detector, charged tracks are reconstructed with the Inner Tracking System (ITS) and the Time Projection Chamber (TPC)2). Electrons are identified using $dE/dx$ obtained in the TPC and time-of-flight measurement with the TOF detector (120ps resolution). TOF is essential to remove contaminants such as of kaons, protons and deuterons up to 2 GeV/c. The hadron contaminations can be reduced less than 1% up to 6 GeV/c by the TOF information. Figure 1 shows the single-electron spectrum.

![Fig. 1. Single-electron $p_T$ distributions for the minimum-bias trigger and the TRD single-electron trigger.](image)

A clear enhancement of electron samples by more than 20 times can be observed above 3 GeV/c for the TRD triggered data.

![Fig. 2. Upper panel: The dielectron spectrum after background subtraction. Lower panel: the signal to background ratio.](image)

For the estimation of the dielectron background, like-sign pairs in the same-events technique are used. Since the acceptance depends on the sign of charge, acceptance difference between unlike-sign and like-sign pairs is evaluated using mixed unlike-sign and mixed like-sign pairs. Equation 1 is calculated, and the R-factor is corrected to like-sign pairs to estimate the background.

$$R = \frac{N_{++} - |\text{mix}|}{N_{++}|\text{mix}} + \frac{N_{--} - |\text{mix}|}{N_{--}|\text{mix}}$$ (1)

where $N_{++}|\text{mix}$, $N_{--}|\text{mix}$ and $N_{+-}|\text{mix}$, $N_{-+}|\text{mix}$ are like-sign and unlike-sign pairs in mixed events, respectively. The estimated background is defined as $N_{CB} = 2R\sqrt{N_{++}N_{--}}$, where $N_{++}$, $N_{--}$ are like-sign pairs in the same event.

Figure 2 shows the inclusive dielectron spectrum after background subtraction, and the signal-to-background ratio. The vector mesons and $J/\psi$ peaks can be seen clearly. The signal-to-background ratio agrees with the result of the $pp$ collisions3), in different $p_T$ bins.

References

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5. Hadron Physics (Theory)
Quark contribution for center domain in heavy ion collisions†

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The quark-gluon plasma (QGP) is characterized by large color opacity and near-perfect fluidity in high-energy heavy ion experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). While hydrodynamic analyses have been quite successful in quantitative description of the hot medium, there are continuing debates on the origin of fluidity. It is recently proposed that center domain structure can be the key to the problem. QCD has SU(3) symmetry, and the Polyakov-loop potential has three minima in the QGP phase. Since the color glass condensate, a description of pre-collision state, implies the typical correlation length on the transverse plane is characterized by the inverse of saturation scale that the medium can suddenly lose fluidity in heavy ion collisions, a domain structure can appear in the hot medium. This indicates a short mean free path as the domains are separated by energy barrier.

In the present work, we introduce quark contribution to the center domain picture. We consider the gluon and quark perturbative one-loop effective potentials:

\[ F_g = \frac{2\pi^2 T^4}{3} \sum_{a,b} \left( 1 - \frac{\delta_{ab}}{3} \right) B_4(|q_a - q_b|_{\text{mod } 1}), \]

\[ F_f = -\frac{4\pi^2 N_f T^4}{3} \sum_a B_4\left( |q_a + \frac{1}{2}|_{\text{mod } 1} \right), \]

where \( T \) is temperature, \( a \) and \( b \) are color indices, \( B_4 \) is the forth Bernoulli polynomial, \( N_f \) is the number of flavors. \( q_a \) is defined by the classical part of the time-like component of the vector potential \( (A_4^a)^{ab} = (2\pi T/g)|q_a\delta^{ab}, \) where \( g \) is the gauge coupling.

The overall effective potential is shown in Fig. 1. One can see that the three minima have the same free energy in the pure gauge case while imbalance is induced as the number of flavors increases. We label the three states as \( v = 0, 1 \) and \( 2 \) corresponding to the fact that Polyakov loop at the minima can be written as \( \Phi = \exp(2\pi i\nu/3) \) in the high temperature limit.

The emergence of the stable \( (v = 0) \) and the metastable \( (v = 1, 2) \) states is important because pressure imbalance among the domains can lead to longer mean free path. Schematic pictures of parton scattering with different number of flavors/temperatures are summarized in Fig. 2: (a) In the pure gauge system, the typical mean free path is characterized by the domain size. (b) When the system has small number of flavors, the stable domains expand while the metastable ones shrink, leading to the longer mean free path on average. (c) Domain percolation can occur as the temperature further increases. (d) Finally, the metastable states vanish completely and the system can become weakly coupled above the topological critical temperature defined as \( T_{\text{cri}} = T(P_1 = P_2 = 0) \) where \( P_L \) is the pressure. The increase in shear viscosity from RHIC to LHC temperatures is roughly estimated as \( \sim 1.5-1.6 \) in our model, which is in agreement with the hydrodynamic implication from experimental data \( \sim 1.7^{5}\).

We developed a model that can provide a bridge from hydrodynamic to perturbative QCD pictures. A new critical temperature is proposed, which implies that the medium can suddenly lose fluidity in heavy ion collisions of very high energies. Future prospects include investigation on the system size dependence.

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† Condensed from the article in Phys. Rev. D 89, 011501(R) (2014).
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Signatures of chiral magnetic wave in heavy ion collisions

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Chiral magnetic wave1 is a collective hydrodynamic mode of chiral charge densities in the presence of background magnetic field, as a consequence of underlying triangle anomaly of QCD. It has a longitudinal dispersion relation along the direction of the magnetic field

$$\omega = \pm v_\chi k - iD_L k^2 + \cdots ,$$

(1)

where the chiral magnetic velocity $v_\chi$ is completely fixed by the thermodynamic charge susceptibility $\chi$ as

$$v_\chi = \frac{eN_c B}{4\pi^2 \chi},$$

(2)

whereas the sign in front of the first term in the dispersion relation depends on the chirality, that is, left-handed charge fluctuations propagate in the opposite direction to that of the right-handed charge fluctuations. Since off-central heavy ion collisions can create magnetic fields as large as $eB \sim m_\pi^2$ at RHIC and about ten times larger at LHC, they provide an interesting environment where one can potentially test possible experimental signatures of chiral magnetic wave.

One observable that might be affected by the chiral magnetic wave is the elliptic flows of early photons and dileptons, for which the recent experimental data from RHIC indicate a value larger than the current theory estimate without taking into account the presence of magnetic fields. Earlier studies have suggested possible enhancement of the elliptic flows of photons due to the magnetic field, but a proper account of possible effects coming from chiral magnetic wave was first examined in Ref.2 in the framework of AdS/CFT correspondence. We observed that the chiral magnetic wave can significantly modify the elliptic flows for the momentum $p < 1$ GeV. Also, the quadrupole to the elliptic flow square ratio, $v_4/v_2^2$, is largely different from a constant, violating a typical scaling $v_4 \sim v_2^2$ for charged hadrons. We also predicted a distinctive signature in the polarization of photons originating from chiral magnetic wave. Future experiments probing the momentum range $p < 1$ GeV will be interesting to potentially see such behaviors due to chiral magnetic wave.

Another observable of interest is the charge dependent elliptic flows of pions, $\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+)$, which was recently measured at RHIC. The QCD plasma formed by heavy ion collisions naturally has a small average positive vector charge density as a remnant of the colliding two positively charged nuclei, but one can also select events with any sign of the net charge that exist via statistical fluctuations. Recalling that $Q_V = Q_L + Q_R$ and $Q_A = -Q_L + Q_R$ where $Q_{V,A}$ are vector (axial) charge densities and $Q_{L,R}$ are left (right)-handed chiral charge densities, the initial vector charge density with average zero axial charge corresponds to having equal amounts of chiral charges $Q_L$ and $Q_R$. Chiral magnetic wave acting on these chiral charges will move them apart in opposite directions along the magnetic field, which leads to a net vector charge quadrupole moment that is proportional to the initial vector charge density. Based on this, we predicted in Ref.3 that this quadrupole moment, in conjunction with the radial flow developed by hydrodynamic evolution, will eventually result in $\Delta v_2$ proportional to the initial vector charge density,

$$\Delta v_2 = rA_\pm, \quad A_\pm = \left(\frac{N_+-N_-}{N_++N_-}\right),$$

(3)

with a positive slope parameter $r$, which has been confirmed by the experimental analysis of RHIC. The simulation in Ref.3 for $r$ to compare with experimental value was crude, neglecting many realistic elements in heavy ion collisions, and in Ref.4 we significantly improved the simulation by implementing a realistic 2+1 dimensional hydrodynamic code with isothermal Cooper-Frye freeze out condition, as well as chiral phase transition effect on the chiral magnetic wave. Our result for $r$ and its dependence on the impact parameter compare well with experiments, although our analysis does not exclude other contributions unrelated to triangle anomaly.

In Ref.5 we systematically classified possible P and CP odd observables in photon and dilepton emission rates. Since axial charge is P and CP odd, which is a unique characterization of it, these observables must be proportional to event-by-event fluctuations of axial charges in the QCD plasma formed in heavy ion collisions. Our observables are related to spin (helicity) alignments of the photons and dileptons, and we have shown that they probe the imaginary part of the chiral magnetic conductivity of the plasma at finite momenta, which ultimately arises from the underlying triangle anomaly of QCD.

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Dihadron Fragmentation Functions in the NJL-Jet Model

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[QUARK FRAGMENTATION FUNCTIONS]

In order to describe the scattering of high energy electrons on nuclear targets in terms of quark degrees of freedom, the Nambu-Jona-Lasinio (NJL) model is often used as an effective theory of QCD. For example, this model was successfully applied in Ref.1) to describe quark distribution and fragmentation functions observed in semi-inclusive deep inelastic scattering (SIDIS) processes. Here we extend the model to the description of dihadron fragmentation functions (DiFFs), which are expected to play an important role for extracting the transversity parton distribution functions from SIDIS processes with two final detected hadrons2).

The unpolarized DiFFs \( D_{h1h2}^{+}(z, M_{h}^{2}) \) for the process \( q \to h_{1}h_{2} \) depend on the sum of the light-cone momentum fractions \( z = z_{1} + z_{2} \) and the invariant mass squared \( M_{h}^{2} = (P_{1} + P_{2})^{2} \) of the produced hadron pair. In order to calculate these functions, we use the quark jet picture, with the elementary fragmentation functions for \( q \to h \) calculated in the NJL-jet model3).

The multihadron emissions from a high energy virtual quark (flavor \( q = u, d, s \)) are described by using Monte-Carlo techniques, averaging over a sufficiently large number of events \( (10^{10}) \) in the results shown below) and restricting the total number of primary emitted hadrons for each fragmentation chain to a predefined number (equal to eight in the results below). In this study we include the pseudoscalar \( \pi, K \) and vector \( (r, \omega, K^{*} \) and \( \phi \)) mesons. The strong 2-body and 3-body decays of the primary vector mesons to secondary \( \pi \) and \( K \) are also included in the simulations, and are very important to describe the invariant mass spectra of the final \( \pi \) and \( K \) pairs.

Fig.1 shows the DiFF for \( u \to \pi^{+}\pi^{-} \), integrated over \( z \) in the region 0.2 to 0.8, for the cases of primary mesons only (dashed line) and the full final states including the decay products of the primary vector mesons (solid line). The \( \rho^{0} \) peak around \( M_{h}^{2} \approx (0.78 \text{ GeV})^{2} \), and the enhancement in the region below 0.4 GeV\(^{2} \) coming from \( \omega \to \pi^{+}\pi^{-}\pi^{0} \) with shifted invariant mass due to the unobserved \( \pi^{0} \), are clearly seen in the figure. Fig.2 shows the results obtained by performing the \( Q^{2} \) evolution in leading order (LO), where we assign a typical NJL-jet scale of 0.2 GeV\(^{2} \) to the model results shown by the solid lines in Figs. 1 and 2. The vector meson decays have an important influence on the shape of the DiFFs even at very high values of \( Q^{2} \).

The future development of our model will allow us to extract also the so called interference DiFFs by considering the fragmentation of a transversely polarized quark, which also play an important role to extract the transversity distribution functions from measured SIDIS two-hadron asymmetries.

Fig. 1. Fragmentation function for \( u \to \pi^{+}\pi^{-} \) calculated in the NJL-jet model, including only primary (dashed line) and full (solid line) final states.

Fig. 2. The solid line is the same as in Fig.1, and the other lines show the results obtained by the \( Q^{2} \) evolution in leading order (LO) to higher energy scales.

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Twist-3 fragmentation and transverse single-spin asymmetries†

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Transverse single-spin asymmetries (TSSAs) in inclusive hadron production (denoted by $A_N$) have been the subject of intense study since the late 1970s. These are defined as

$$A_N = \frac{d\sigma(\vec{S}_\perp)}{d\sigma_{\text{unp}}} - \frac{d\sigma(-\vec{S}_\perp)}{2d\sigma_{\text{unp}}},$$ (1)

where $d\sigma(\vec{S}_\perp)$ ($d\sigma(-\vec{S}_\perp)$) is the cross section with transverse spin $\vec{S}_\perp$ oriented “up” (“down”) and $d\sigma_{\text{unp}}$ is the unpolarized cross section. Experiments have measured large effects for these observables (with the most recent results from proton-proton collisions at RHIC\(^1\-3\)), which contradict the prediction of the naive collinear parton model\(^4\). However, a framework using twist-3 multi-parton correlators can potentially describe these large TSSAs\(^5\-7\).

The assumption for many years was that the so-called soft-gluon pole (SGP) piece dominates over the other contributions\(^8\). This part involves the non-perturbative twist-3 Quill-Sterman (QS) function $T_F(x,z)$\(^6\), which was extracted several years ago\(^9\). However, a later analysis revealed that this extraction of $T_F(x,z)$ does not satisfy the model-independent relation with the Sivers function extracted from semi-inclusive deep-inelastic scattering (SIDIS) off a transversely polarized proton: the two different extractions disagree in sign\(^9\). This “sign mismatch” crisis has led to a reexamination of whether the QS function is the most significant part of TSSAs in inclusive hadron production — see, e.g., the recent discussion\(^10\). The focus has now shifted to whether a contribution involving twist-3 fragmentation functions can resolve the “sign mismatch” and provide the dominant effect.

The complete analytic result for the twist-3 fragmentation term in the single-spin dependent cross section for $p^+p \rightarrow hX$ was given for the first time by the present author and A. Metz\(^11\):

$$\frac{d^2\sigma(\vec{S}_\perp)}{d^2P_h} = -\frac{2\alpha_s^3 M_h}{S} \int_{z_{\text{min}}}^{1} \frac{dz}{z^3} \int_{x_{\text{min}}}^{1} \frac{dx}{x^7} \frac{1}{x'x'S + T/z}$$

$$\times \left[ H_i^0(z') \frac{d\bar{H}^c(z)}{dz} \right] S^i_H + \frac{1}{z} H^0(z) S^i_H$$

(2)

See the paper\(^11\) for more details. In particular, Appendix A of the aforementioned reference contains the hard scattering coefficients $S_i$ in (2).

The piece in (2) also involves two independent non-perturbative functions: $\hat{H}(z)$ and $\hat{H}_F^c(z)$. (The function $\hat{H}(z)$ can be written in terms of the other two.) In principle one has information on $\hat{H}(z)$ through its relation to the Collins function in SIDIS. One must then parameterize the unknown function $\hat{H}_F^c(z)$ and see if a fit to the data\(^1\-3\) is possible. We propose the following form for this (3-parton) fragmentation correlator that is consistent with its support properties:

$$\hat{H}_F^c(z, z_1) = Nz^\alpha(z/z_1)^\beta(1-z)^\gamma(1-z/z_1)^\eta$$

$$\times D_1(z) D_F(z/z_1),$$

(3)

where $D_1$ is the unpolarized fragmentation function. We are in the process of carrying out a numerical study of $A_N$ in $p^+p \rightarrow \pi X$ using (3). This will be an important step towards solving an almost 40 year problem of what causes large TSSAs in inclusive hadron production from proton-proton collisions.

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Polarized fragmentation functions and electron-positron annihilation†

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Electron-positron annihilation into (possibly polarized) hadrons, where one or more hadrons are identified, gives one access to fragmentation functions (FFs), which embody the process of a parton forming a hadron, and they contain important information about the strong interaction in the non-perturbative regime. These are analogous to parton distribution functions (PDFs) that look at partons inside of hadrons.) Such experiments have been run by both the Belle Collaboration at KEK in Japan and the BABAR Collaboration at SLAC in the US. In order to have a complete framework to analyze FFs in electron-positron annihilation, one must write the cross section in a general form involving structure functions, which can then be calculated (for small transverse momentum of the exchanged boson) in terms of twist-2 transverse momentum dependent (TMD) FFs. For the future International Linear Collider (ILC), it is also beneficial to have complete results for polarized leptons including electroweak effects. Given its similarity to Drell-Yan, one should also be able to transcribe such results to that reaction, which would be useful for double-polarized Drell-Yan experiments at RHIC.

Here we extend earlier works1–5 in order to address these issues. The cross section for the reaction $e^+e^- \rightarrow h_a h_b X$ is given by

$$
\frac{d^3P_a d^3P_b}{d^3P_a d^3P_b} \frac{d\sigma}{d^3P_a d^3P_b} = \frac{2\alpha^2}{q^2} (L_{\mu\nu} W_{\mu\nu})_{\gamma\gamma} + \frac{M_Z^2 G_F^2}{64\pi^2 q^2} (L_{\mu\nu} W_{\mu\nu})_{ZZ} + \frac{\alpha_{em} \sqrt{2} M_Z^2 G_F}{8\pi^2 q^2} ((L_{\mu\nu} W_{\mu\nu})_{\gamma Z} + h.c.),
$$

where one has leptonic tensors $L_{\mu\nu}$ and hadronic tensors $W_{\mu\nu}$ for $\gamma$-exchange, $Z$-exchange, and their interference. As the present author, M. Schlegel, and A. Metz discuss in detail6, one can write down the first term in (1) in terms of 72 structure functions using electromagnetic gauge invariance, hermiticity, and parity (see Eq. (3.21) of 6). The second and third terms are more involved due to the fact that one no longer has the parity constraint. Nevertheless, one can calculate these terms (as well as the first) within the parton model at twist-2. The result leads to 128 structure functions (see Eqs. (4.34), (4.35) and Appendix A of 6). Where relevant, we have checked our results with those in1–4. Thus, we have for the first time a complete framework for the study of TMD FFs within $e^+e^- \rightarrow h_a h_b X$ including electroweak terms and the polarization of all particles.

We also note that if we make the replacements (4P_a 4P_b d\sigma/d^3P_a d^3P_b)e^+e^- \rightarrow (4P_a 4P_b d\sigma/d^3P_a d^3P_b)_D Y, z_a (z_b) \rightarrow x_a (x_b), and N_c \rightarrow 1/N_c, the structure functions associated with unpolarized leptons for the pure electromagnetic case are the same as those given in Drell-Yan5 with the TMD PDFs replaced by their TMD FF analogues. The only additional change one must remember is that $h_a (h_b)$ in the $e^+e^-$ case has a large minus- (plus-) component of momentum, whereas for Drell-Yan one normally uses the reverse convention. Along the same lines, one can easily transcribe the results in Appendix A of 6) to obtain the relevant expressions for Drell-Yan when one allows the $q\bar{q}$ pair to annihilate into a $Z$-boson. Thus, we have for the first time full results for double-polarized Drell-Yan that include electroweak effects, which would be needed if such experiments were conducted at RHIC.

We would finally like to highlight a structure function that appears in 6) for first time:

$$
C_{UU}^{\gamma e,\gamma e} = \sum_{q} F_{\gamma}^{-}(s) C_{\gamma W}^{q} [w_3 H_{1}^{\perp} H_{1}^{\perp}],
$$

where $F_{\gamma}^{-}(s)$ is a prefactor that is nonzero if $Z$-exchange is included, $C_{\gamma W}^{q} \cdots$ is the convolution of a weight $w_3$ and the Collins function $H_{1}^{\perp}$. One could access (2) at a future ILC and extract the Collins function. This result could then be checked against the Collins function that has been obtained recently from Belle and BABAR data7. Given that the ILC would have around two orders of magnitude higher center-of-mass energy than Belle and BABAR, such an analysis would also be an important test of the TMD evolution formalism and its application to phenomenology, which has been of recent interest.

References
Spatial Wilson loops in high-energy heavy-ion collisions

A. Dumitru*1,∗2

Collisions of heavy ions at high energies provide opportunity to study non-linear dynamics of strong QCD color fields. The field of a very dense system of color charges at rapidities far from the source is determined by the classical Yang-Mills equations with a recoilless current along the light cone. It consists of gluons characterized by a transverse momentum \( p_T \) on the order of the density of valence charges per unit transverse area \( Q_s^2 \); this saturation momentum scale separates the regime of non-linear color field interactions at \( p_T \lesssim Q_s \) or distances \( r \gtrsim 1/Q_s \) from the perturbative regime at \( p_T \gg Q_s \).

Right after the impact strong longitudinal chromomagnetic fields \( B_z \sim 1/g \) develop due to the fact that the individual projectile and target fields do not commute. They fluctuate according to the random local color charge densities of the valence sources. Here we show that magnetic loops

\[
W_M(R) = \frac{1}{N_c} \langle \text{tr} \mathcal{P} \exp \left( ig \oint dx^i A^i \right) \rangle
\]

effectively exhibit area law scaling, \( W_M(R) \sim e^{-\theta \alpha g \sqrt{R^2}} \), and we compute the magnetic string tension \( \sigma \). Furthermore, we argue that at length scales \( \sim 1/Q_s \) the field configurations might be viewed as uncorrelated Z(N) vortices. We also compare to the expectation value of the \( Z(N_c) \) part of the loop; thus, for two colors we compute

\[
W_M^{Z(2)}(R) = \langle \text{sgn} \mathcal{P} \exp \left( ig \oint dx^i A^i \right) \rangle
\]

where \( \text{sgn}() \) denotes the sign function.

The field in the forward light cone immediately after a collision, at proper time \( \tau \equiv \sqrt{t^2 - z^2} \to +0 \), is given by \( A^i = \alpha^i_1 + \alpha^i_2 \). In turn, before the collision the individual fields of projectile and target are 2d pure gauges,

\[
\alpha^i_m = \frac{i}{g} U_m \partial^i U^i_m, \quad \partial^i \alpha^i_m = \rho_m,
\]

where \( m = 1, 2 \) labels projectile and target, respectively, and \( U_m \) are SU(N) matrices. Note that for a non-Abelian gauge group, the sum \( A^i \) of two pure gauges is not a pure gauge, so \( W_M \neq 1 \).

The large-x valence charge density \( \rho \) is a random variable. For a large nucleus, the effective action describing color charge fluctuations is quadratic, \( S_{\text{eff}} = \rho^2(x) \rho^2(x')/2 \mu^2 \). The variance of color charge fluctuations determines the saturation scale \( Q_s^2 \sim g^2 \mu^2 \).

\[\text{References}\]

Bose-Einstein Condensation in “the very hot”

J. Liao\textsuperscript{*1,*2}

In relativistic heavy ion collisions, a highly occupied gluonic matter is created shortly after initial impact, which is in a non-thermal state and often referred to as the glasma. How the glasma evolves quickly toward an emergent hydrodynamic behavior remains a significant challenge for theory as well as phenomenology. Recently there has been important progress in understanding the pre-equilibrium evolution using the kinetic theory description, in a highly overpopulated regime\textsuperscript{1–3)} where the system is weakly coupled yet strongly interacting with the possibility of a transient BEC during the course of thermalization.

Inspired by the Color Glass Condensate description of the initial conditions, the gluon distribution in the glasma is schematically given by $f(p \leq Q_s) = f_0 \cdot f(p > Q_s) = 0$ with $Q_s$ the saturation scale. One may introduce the overpopulation parameter $n_\epsilon^{-3/4}$ which is directly related to the ratio between inter-particle distance $d$ and typical de Broglie wavelength $\lambda$, i.e. $n_\epsilon^{-3/4} \sim (\lambda/d)^{\alpha}$ thus measuring the degrees of quantum coherence: when $n_\epsilon^{-3/4} \to \delta(1)$ then $\lambda \to d$ and one expects BEC to occur. In the glasma distribution $n_\epsilon \equiv n_\epsilon^{-3/4} \approx \frac{f_0}{\frac{3\pi}{4}} 2^{3/4}$ and, compared with thermal case $n_\epsilon^{-3/4} \sim \frac{f_0}{30^{3/4}} \zeta(3) \approx 0.28$, the system becomes overpopulated when $f_0 > f_0^* \approx 0.154$. One thus see in the glasma with $f_0 = 1/\alpha_s$, even with rather modest weak coupling $\alpha_s \approx 0.3$ the system is highly overpopulated and will develop Bose condensate.

So how does the thermalization proceed in such a overpopulated glasma? Numerical solutions reported in \textsuperscript{2)} suggest two generic features. First, two cascades in momentum space will quickly develop: a particle cascade toward the IR momentum region that quickly populates the soft momentum modes to high occupation number at IR is quickly achieved, a energy cascade toward the UV momentum region that quickly spreads the energy out. As a consequence $\lambda \to d$ always filling up the infrared regime extremely quickly. Such general link from initial overpopulation to the onset of BEC in a finite time with a scaling behavior appears to be very robust against different choices of initial distribution shapes and possible initial anisotropy, including longitudinal expansion, as well as adding finite medium-generated mass.

There is one particularly important issue related to the role of inelastic processes. One may even wonder if such onset (manifested as the development of an infrared singularity in the kinetic evolution) would happen anymore. To answer this, one needs to study the kinetic evolution including both processes: a first attempt has been done, recently in \textsuperscript{3)}).

Fig. 1. Local thermal form (upper) of $f(p \to 0)$ and the vanishing of local chemical potential $\mu^* \to 0$ (lower).

\begin{itemize}
  \item $f_0 > f_0^*$. Such general link from initial overpopulation to the onset of BEC in a finite time with a scaling behavior appears to be very robust against different choices of initial distribution shapes and possible initial anisotropy, including longitudinal expansion, as well as adding finite medium-generated mass.

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Out-of-equilibrium chiral magnetic effect at strong coupling†

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The chiral magnetic effect in relativistic heavy-ion collisions has been proposed as a signature of local parity violation in QCD above deconfinement phase transition. The manifestation of the chiral magnetic effect requires both a strong magnetic field and chiral imbalance in fundamental quarks. Despite continuous theoretical efforts in understanding the effect, many quantitative questions remain unanswered. One of them is the value of the chiral magnetic conductivity, which is complicated by the fact that the magnetic field produced by the spectators exists only at the early stage of the collisions, when quark-gluon plasma (QGP) is not yet thermalized. An accurate calculation of the chiral magnetic conductivity should be carried out for QGP in an out-of-equilibrium setting. In this work, we report on our attempt in this direction.

We considered chirally imbalanced QGP undergoing thermalization. It can be modeled by a gravitationally collapsing shell in 5D Anti-de Sitter (AdS) space. The shell carries an axial charge density, described by an axial chemical potential \( \mu_A \). The end point of the gravitational collapse is the formation of the AdS-Reissner-Nordstrom (AdS-RN) black hole, which is dual to QGP with an axial charge density. The central quantity is the chiral magnetic conductivity in the thermalization process. It is defined for at finite frequencies as the response of the vector current to the external magnetic field

\[
\mathbf{J}_{EM} = \sigma_A(\omega) \mathbf{B}(\omega).
\]

This is to be evaluated at different times in the thermalization history. Note that (1) assumes the current response is much faster than the evolution of QGP toward equilibrium, which is not true in the near-equilibrium regime. We restricted our study to the far-from-equilibrium regime. We obtained the chiral magnetic conductivity for different frequencies in Fig. 1. The end point QGP has a temperature \( T = 300 \text{ MeV} \) and an axial chemical potential \( \mu_A = 50 \text{ MeV} \). We found that in general the chiral magnetic conductivity increases as QGP thermalizes, which is consistent with the expectation that more and more thermalized constituents are available in conducting the current. We also found that the magnitude of conductivity changes only slightly as the frequency of the magnetic field is varied, while increasing the frequency does results in longer delay in the response. We stress that the conventional conductivity has the opposite behavior.

We also studied the chiral magnetic wave in the same thermalization model for QGP with vanishing axial charge density. The chiral magnetic wave rises from a coupled fluctuation of the axial and vector charges in the presence of a background magnetic field. In equilibrium, it has the dispersion \( \omega = \pm v(k) \), with the wave velocity proportional to the magnetic field and the velocity changes sign when the chirality of the charge is reversed. We found that the dispersion relation is modified to

\[
\omega = v_{\text{out}} k \mp \Delta \omega(k, B).
\]

We see that the frequency splits into two terms: The first term is entirely of off-equilibrium origin: the wave velocity \( v_{\text{out}} \) vanishes as QGP thermalizes; It is also independent of the chirality of the charge. The second term depends on the chirality, and it is linear in both \( k \) and \( B \). It is reminiscent of chiral magnetic wave velocity in equilibrium. This shows that the physical effect of the chiral magnetic wave may be enhanced owing to the out-of-equilibrium effect.

References
General conditions ensuring relativistic causality in an effective field theory based on the derivative expansion†

Y. Minami† and Y. Hidaka†

We discuss the general conditions ensuring relativistic causality in an effective field theory based on the derivative expansion. Relativistic causality implies that the Green function vanishes in a space-like region. It is known that a naive derivative expansion violates causality in some cases such as the first-order relativistic dissipative hydrodynamics. We note that the Lorentz covariance and time and space derivatives of equal order do not ensure causality. We derive the general conditions for causality that should be satisfied by any effective theory consistent with special relativity.

Derivative expansion is a useful tool at a low-energy scale and widely used in effective theories. Chiral perturbation theory is a good example of a successful low-energy effective theory in hadron physics. From a modern perspective, hydrodynamics is also a low-energy effective theory; the leading-order hydrodynamic equations are called Euler equations, and the first-order hydrodynamic equations are called Navier–Stokes equations.

Causality is an important concept in physics. In relativistic systems, the propagation of any information cannot exceed the speed of light (relativistic causality). However, it seems that a low-energy effective theory in medium is incompatible with relativistic causality. For example, in first-order relativistic hydrodynamics, shear and heat flows violate causality because the first-order equation has the form of a diffusion equation.

We note that the first-order hydrodynamic equation is Lorentz covariant, i.e., the covariance does not ensure the causality. It is argued that the acausality of the first-order hydrodynamics originates from the difference between the order of time- and space-like derivatives in the equation of motion. In the diffusion equation, the time-like derivative is of the first order, while the space-like one is of the second order. However, we note that equality in the order of time- and space-like derivatives does not ensure the causality. For example, let us consider the following equation:

\[
\tau (u^\mu \partial_\mu)^2 + u^\mu \partial_\mu + \Gamma (\eta^{\mu\nu} - u^\mu u^\nu) \partial_\mu \partial_\nu \\text{n}(x^\mu) = 0, \tag{1}
\]

where \(n(x)\) is a scalar density, \(u^\mu\) is a constant time-like vector, \(\eta = \text{diag}(-1,1,1,1)\), \(\tau\) is the relaxation time, and \(\Gamma\) is the diffusion constant. In this equation, the time-like derivative is of the same order as the space-like one. This equation has the form of the telegraphic equation such that the propagation is restricted in the region defined by \(v x_t > x_s\), where \(v = \sqrt{\frac{\Gamma}{\tau}}\), \(x_t = u \cdot x\), and \(x_s = \sqrt{-(\eta^{\mu\nu} - u^\mu u^\nu)x_\mu x_\nu}\).

If \(\Gamma < \tau\), causality is satisfied because the velocity is smaller than the speed of light, i.e., \(v < c^2\). However, if \(\Gamma > \tau\), the propagation speed exceeds the speed of light. Furthermore, if \(\Gamma = 0\), causality is not violated even though the order of the time and space derivatives are different. Therefore, the equal order of space and time derivatives in the equation of motion does not ensure in itself that the Green function is causal.

What ensures the causality in general?

The purpose of this paper is to derive the conditions ensuring relativistic causality in an effective theory based on the derivative expansion. We will consider the retarded Green function in a scalar theory at tree level, i.e., thermal and quantum fluctuations will not be taken into account. In this case, the retarded Green function in the derivative expansion is generally written as a rational function in the momentum space:

\[
G_R (\omega, k) = \frac{Q(\omega, k)}{P(\omega, k)}, \tag{2}
\]

where \(P(\omega, k)\) and \(Q(\omega, k)\) are polynomials in \(\omega\) and \(k\):

\[
P(\omega, k) = p_n (k) \omega^n + p_{n-1} (k) \omega^{n-1} + \ldots + p_0 (k), \tag{3}
\]

\[
Q(\omega, k) = q_m (k) \omega^m + q_{m-1} (k) \omega^{m-1} + \ldots + q_0 (k). \tag{4}
\]

Here, \(n > m\), and \(p_j (k)\) and \(q_j (k)\) are the polynomials in \(k\). Because we assumed isotropy, the Green function turns becomes a function of \(k \equiv |k|\). The relativistic causality implies that the retarded Green function must vanish in the space-like region. Therefore, we derive the general condition ensuring Eq. (2) vanishes in the space-region, which is given by

\[
\lim_{k \to \infty} \left| \frac{\omega(k)}{k} \right| < 1 \quad \text{and} \quad \lim_{k \to \infty} \frac{\omega(k)}{k} < \infty, \tag{5}
\]

and the condition that \(p_n (k)\) must not depend on \(k\). Here, \(\omega(k)\) is a pole of Eq. (2). These conditions ensure causality in effective theories based on the derivative expansion, and they are the main results of our paper.

References

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Boundary Restoration of Chiral Symmetry†

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One of the hallmark features of the theory of strong interactions is spontaneous breaking of chiral symmetry. While quark masses explicitly break the chiral symmetry of the QCD action, the lightest quarks (up and down) have masses that can be treated as a perturbation about the symmetric $SU(2)_L \otimes SU(2)_R$ chiral limit. The formation of a chiral condensate by the QCD vacuum in the chiral limit, namely $\langle \bar{\psi} \psi \rangle \neq 0$, spontaneously breaks the chiral symmetry down to the vector subgroup, $SU(2)_V$. This symmetry breaking pattern along with the explicit breaking due to the quark masses gives an explanation of the lightness of the iso-triplet of pseudo-scalar pions because they must be the emergent Goldstone bosons.

Lattice gauge theory provides a first principles method for solving QCD numerically on finite Euclidean space-time lattices. Strictly speaking, spontaneous symmetry breaking cannot occur in a finite volume. In practice, the formation of a chiral condensate on periodic lattices is determined by the size of the pion Compton wavelength compared to the lattice size. 1–4). In this work, we explore a different restoration of chiral symmetry. We consider the fate of chiral symmetry on a Euclidean manifold with three infinite directions, and one compact direction that, unlike the periodic case, has a boundary. Specifically the compact direction is subject to homogeneous Dirichlet boundary conditions (DBCs), as have been utilized recently in various lattice gauge theory computations.

The effect of a boundary on the chiral condensate cannot be ascertained within chiral perturbation theory, because the chiral condensate is determined by the expression

$$\langle \bar{\psi} \psi \rangle := -\frac{1}{4} \sum_{\mathbf{x}} \langle U(\mathbf{x}) + U^\dagger(\mathbf{x}) \rangle + \cdots. \quad (1)$$

Due to the unitarity of the coset manifold, the right-hand side of this relation does not vanish at the boundary in contradiction with the quark boundary conditions satisfied on the left-hand side. A consistent treatment of the chiral condensate in the presence of DBCs necessitates including the dynamics of isoscalar scalar mesons. For this reason, we employ the sigma model which shares the same symmetry breaking pattern as QCD with two light quark flavors, and provides the simplest model of spontaneous chiral symmetry breaking. The parameter $\Sigma$ in Eq. (1) becomes a field $\Sigma(\mathbf{x})$ satisfying DBCs. The chiral condensate $\langle \bar{\psi} \psi(\mathbf{x}) \rangle$ is determined by minimizing the action to find the vacuum configuration.

† Condensed from Reference 1)

**References**

Cutoff effects on lattice nuclear forces†

T. Doi†

Nuclear forces, the interactions among nucleons, serve as the cornerstone in nuclear physics. While they have been traditionally determined through the scattering experiments, their theoretical understanding by using the fundamental theory, quantum chromodynamics (QCD), has not been established yet. Recently, a novel approach was proposed to determine nuclear forces on a lattice[1,2]. In this approach, now called the HAL QCD method, nuclear forces are directly obtained from Nambu-Bethe-Salpeter wave functions calculated on the lattice. The method has been successfully extended to general hadron interactions such as three-nucleon forces[3]. See Ref.[4] for a recent review.

For the quantitative determination of nuclear forces, systematic uncertainties in lattice simulations should be carefully examined, such as the effect of discretization artifacts. There have been, however, no work that performs the continuum extrapolation on nuclear interactions. The aim of this work is to perform the first systematic study for the lattice cutoff dependence of nuclear interactions.

We employ $N_f = 2$ configurations with clover fermion generated by CP-PACS collaboration[5]. The measurements are performed at three lattice spacings, $a = 0.2150, 0.1555, 0.1076$ fm. The physical lattice size is $L^3 \times T \simeq (2.5 \text{fm})^3 \times 5 \text{fm}$, and the hadron masses are $(m_N, m_N) \simeq (1.1, 2.2) \text{ GeV}$. The computational cost in the Wick and color/spinor contractions is reduced by the unified contraction algorithm[6]. For details about the simulation parameters, see Doi (2013)[7].

In Fig. 1, we plot the nuclear central potential in $^1S_0$ channel for each lattice cutoff. We observe that cutoff dependence is nonnegligible at short distances, while it is suppressed at long distances. This is a natural consequence of the discretization being an intrinsically short-range effect. It is also interesting that repulsive core is enhanced on a finer lattice, which is consistent with the study on the operator product expansion[8].

Although the lattice cutoff dependence on potentials looks sizable at short distances, such effect is expected to be suppressed in physical observables such as phase shifts and scattering length, because of the phase space factor of $\propto r^2$, as is shown in the inset of Fig. 1.

In order to quantitatively study the cutoff effect on physical observables, we fit the potential and solve the Schrödinger equation in infinite volume. In Fig. 2, we show the preliminary results for the scattering length against the lattice spacing $a$, with only a statistical error. Because the scattering length represents the low-energy phenomena, the cutoff dependence is found to be negligible compared to the statistical errors. Detailed studies for the systematic uncertainties on phase shifts and scattering length are in progress.

References


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Nucleon axial charge in lattice QCD with nearly physical pion mass

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We report the status of lattice quantum chromodynamics (QCD) calculations of nucleon isovector axial and vector charges using the four recent domain-wall fermions (DWF) ensembles with 2+1 dynamical flavors jointly generated by the RIKEN-BNL-Columbia (RBC) and UKQCD collaborations1): the strange-quark mass is set at physical value and degenerate up- and down-quark mass is varied with the pion mass of about 420, 330, 250 and nearly physical 170 MeV.

Spontaneously broken chiral symmetry drives the axial charge, \( g_A \), of nucleon away from its chiral partner, the vector charge, \( g_V \), to a larger value. The current experimental estimate of the ratio of these charges is \( g_A/g_V = 1.270(25)^2 \). This ratio is an important quantity that not only determines neutron life time but also the interaction of pion and nucleon through the Goldberger-Treiman relation3), and hence nuclear stability, syntheses and abundance. Numerical lattice-QCD calculations underestimate the ratio by about 10 %4,5,6,7). The cause of this deficit is not known: insufficient lattice volumes4,5,6,7) and excited-state contaminations8) have been discussed as possible cause.

We have improved the statistical accuracy7) of our calculations so the statistical errors now stand at around 4 %. The AMA method9) was important in achieving this for the pion mass of about 330 and 170 MeV. With these improved statistics we have now excluded excited-state contamination as the cause of the deficit7). On the other hand, in the two cases with the pion mass of 170 MeV and 330 MeV the ratio has been found to suffer from very long-range autocorrelation7). At 170 MeV the calculated charge ratio, \( g_A/g_V \), starts with a value that is statistically consistent with the experiment at the beginning quarter of the calculation, but then monotonically decreases quarter by quarter to a value drastically low (see Fig. 1.) A similar but less drastic autocorrelation has been observed at 330 MeV as well. This results in the observed deficit, but we are yet to understand what causes this very long-range autocorrelation. We do not find such long-range autocorrelation at 250 and 420 MeV: the autocorrelation for these two cases are much shorter-ranged.

The absence of a long-range autocorrelation at lighter pion mass of 250 MeV in contrast to the presence at heavier 330 MeV suggests this peculiar autocorrelation is related to insufficient lattice spatial volume. The finite-size effect can be parametrized by a dimensionless product, \( m_q L \), of the calculated pion mass, \( m_\pi \), and linear spatial extent of the lattice, \( L \): Indeed the autocorrelation is milder at 330 MeV with \( m_q L \) of about 4.5 than at 170 MeV with \( m_q L \) of about 4.0, and absent for 250- and 420-MeV with \( m_q L \) of about 5.87). Thus the observed autocorrelations seem consistent with finite-size scaling in terms of \( m_q L \): the nucleon as seen by its isovector axialvector current or interaction with pion may be much larger than its electric charge distribution indicates.

Though our statistics is still too low to conclude more definitely, we captured an important clue toward understanding the deficit, likely in its relation with the finite-size effect that may scale with \( m_q L \).

References
Lattice QCD calculation of $n - \bar{n}$ transition amplitudes

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In searches for physics beyond the Standard Model, violation of baryon number conservation is an essential direction. The absence of experimental data on baryon number violation has made it possible to understand the observed baryon asymmetry of the Universe. Two important hypothetical processes may signal the baryon number violation, one is the proton decay changing the baryon number by $\Delta B = 1$ and the other is neutron-antineutron oscillation, $\Delta B = 2$. A number of new experiments with stored neutrons and cold neutron beams have been proposed to look for $n - \bar{n}$ transitions. These experiments have potential to improve current bounds on such by a few orders of magnitude and, as a result, significantly improve bounds on beyond the Standard Model physics.

Bounds on new physics, however, will strongly depend on uncertainties arising from hadron physics. Symmetries of the Standard Model constrain the form of six-quark effective interaction that may turn the pion into the antineutron $\pi \rightarrow \eta \rightarrow \bar{n}$ or $\chi \rightarrow \eta \rightarrow \bar{n}$. We are excited to report that, as our preliminary results demonstrate, lattice QCD will likely remove hadron physics uncertainties from interpreting future $n - \bar{n}$ oscillation searches.

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Columbia plot and ’t Hooft loop at imaginary chemical potential†

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The investigation of the phase structure in Quantum Chromodynamics (QCD) at finite temperature (T) and real chemical potential (μR) is an important subject in the particle and nuclear physics. If we obtain the QCD phase diagram from first-principles calculations, the phase structure would be clear, in principle. First-principles calculations such as the lattice QCD (LQCD) simulation, however, has a sign problem at finite μR, and it is therefore not feasible there. Even if we use several methods and approximations, we cannot reach the μR/T ≥ 1 region. Therefore, several effective models such as the Nambu–Jona-Lasinio model are widely used to investigate QCD phase diagrams. The effective model approach, however, has large ambiguities. Therefore, at the present, we cannot obtain a reliable phase diagram at finite μR by using the lattice QCD simulation and effective model approach.

To overcome this problem, we consider the imaginary chemical potential (μI). At finite μI, there is no sign problem, and thus we can successfully perform the LQCD simulation. In fact, phase structures have already been investigated by lattice QCD simulations; for example, see References2,3). In addition, it is possible to prove that the μI region has almost all the information of the μR region5). QCD has some characteristic properties at finite μI. One of the characteristic properties is the Roberge-Weiss (RW) periodicity, which is the special 2π/3 periodicity along the μI/T axis. This periodicity is a remnant of the Z3 symmetry in the pure gauge limit. Also, the RW transition and its endpoint which is called the RW endpoint are expected at finite T in the μI region. This means that we can obtain some important constraints for model design from these special properties of QCD.

In this study, we consider the heavy-quark mass region, which corresponds to the upper part of the Columbia plot. The Columbia plot is the figure drawn as a function of the light-quark and strange-quark masses and shows the phase boundary. In the paper, we reported the following three results:

(1) ’t Hooft loop can be well defined at the RW endpoint.
(2) Model ambiguities can appear largely at the RW endpoint.
(3) Thermodynamics with imaginary chemical potential shows unexpected behavior comparing to standard thermodynamics.

The ’t Hooft-loop is related with the deconfinement transition at finite T in the pure-gauge limit. It is known that this quantity cannot be well defined in the system with dynamical quarks4,5). In the calculation of the ’t Hooft loop, we should set different Z3 images (charges) at the boundary of the box and consider its surface. If the potential energies in both sides of the surface are different, there is a force that modifies the surface, and thus the ’t Hooft loop cannot be well defined. However, we showed that the effective Z3 charges are identical at two of the Z3 images, and thus the ’t Hooft loop can be well defined at the RW endpoint for degenerate Z3 images because there is no force to modify the surface.

The Columbia plot at the heavy-quark mass region was calculated by using the matrix model for deconfinement and the logarithmic-type Polyakov-loop effective potential for describing the deconfinement transition by the Polyakov loop. Those models are low-energy effective models of QCD. In the case of the matrix model, there is a phase boundary that separates the first-order and second-order transition regions. Conversely, the logarithmic-type Polyakov-loop effective potential does not have any phase boundary down to 1 GeV. Therefore, there exists a large model dependence in the upper part of the Columbia plot at the RW endpoint.

Several thermodynamic quantities, such as the pressure, energy density, quark number density, entropy density, and interaction measure, are calculated by using the matrix model for deconfinement. We observed that the energy density and interaction measure show unexpected behavior near the RW transition line, which is induced by the contribution of the quark number density. This behavior can be exploited to remove the model ambiguities when accurate lattice QCD data will be available in the future.

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Progress towards an \textit{ab initio}, Standard Model calculation of direct CP-violation in K-decays

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Direct CP-violation in $K \to \pi\pi$ decays manifests as a difference in phase between the decay amplitudes in the $I = 2$ and $I = 0$ channels and is parameterized experimentally as $\epsilon'$. This quantity is extremely sensitive to Beyond the Standard Model sources of CP-violation; therefore, an accurate Standard Model calculation is greatly desired. As low-energy strong interactions play an important role, use of lattice QCD is required to study these processes. Although $\epsilon'$ has been known experimentally since the late 1990’s, it is only recently that the techniques and raw computing power for performing a realistic first-principles calculation have become available. The main technical difficulty is finding a strategy for obtaining an energy conserving decay because only the ground state is easily accessible in lattice calculations. The lowest-energy two-pion state comprises stationary pions, and its energy (assuming physical quark masses) is only 270 MeV, far below the 500 MeV mass of the kaon.

The RBC and UKQCD collaborations have successfully performed calculations of the $I = 2$ channel amplitude\cite{1,2}, solving the issue of obtaining physical kinematics by modifying the lattice boundary conditions (BC) of the down quarks from periodic to antiperiodic such that the charged-pion ground state is moving. Unfortunately this manifestly breaks the isospin symmetry. For the $I = 2$ decay, it is possible to relate the amplitude to an unphysical one in which the final state cannot mix with other isospin states, but this cannot be performed for the $I = 0$ decay. Instead, we intend to use G-parity boundary conditions (GPBC).

G-parity is a combination of charge conjugation and an isospin rotation by $\pi$ radians about the y-axis. Both charged and neutral pions are eigenstates of this operation with eigenvalue $-1$; hence, its application at a spatial boundary causes the pion states to become antiperiodic in that direction, removing the stationary ground state. However, in this setup, operators involving both strange and light quarks cannot be combined to form G-parity eigenstates e.g., the $K^0$ state $\bar{s}d$ transforms to the unphysical $\bar{s}u$ state at the boundary. We solve this issue by placing the $s$-quark in an isospin doublet with a fictional degenerate partner, referred to as $s'$, and impose GPBC on this pair. We can then form a state, $\bar{K} = \frac{1}{\sqrt{2}}(\bar{s}d + \bar{u}s')$, which is an eigenstate of G-parity with eigenvalue $+1$, and thus has a stationary ground state. For the $K \to \pi\pi$ measurement the effects of the fictional state $\bar{u}s'$ are expected to be small as it must propagate across the boundary to interact with the decay operator.

To demonstrate that the GPBC have the desired effect, we generated several fully dynamical ensembles with a relatively small volume and a large (420 MeV) pion mass, with GPBC in zero, one, and two directions, each with periodic BC in the remaining directions. In Fig. 1, we plot the measured pion and kaon energies as the number of directions with GPBC; we observe that this is indeed the case.

We have since began generating a fully dynamical ensemble with a large volume and physical quark masses using the USQCD collaboration’s IBM Bluegene/Q machine at BNL, and we expect to soon begin measurements. Once completed, the results can be combined with those for the $I = 2$ channel to finally obtain a first-principles value for $\epsilon'$.

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6. Particle Physics
Improved estimate of neutral $B$ meson mixing in static limit of $b$ quark with AMA technique

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The Cabibbo–Kobayashi–Maskawa (CKM) matrix plays a key role in elementary particle physics, and constraints on the elements $V_{ts}$ and $V_{td}$ can be obtained from $B^0 - \overline{B}^0$ mixing. Treatments of $b$ quark on the lattice QCD are, however, challenging because of a multi-scale problem where a large hierarchy in mass exists between light quarks ($u$ and $d$) and $b$ quark. A solution to this problem is using Heavy Quark Effective Theory (HQET), in which the theory is expanded by $1/m_b$, where $m_b$ is $b$ quark mass. The leading order of the HQET is a static approximation of the $b$ quark and is the formulation used in this work. While the static approximation is known to have $O(\Lambda_{\text{QCD}}/m_b) \sim 10\%$ uncertainty, it is useful for an interpolation strategy, where the physical $b$ quark mass point ($\sim 4.2$ GeV) is reached by the interpolation between the static limit and simulations in the lower quark mass region ($c$ quark mass region). For this purpose, high precision calculations in the static limit are required.

RBC/UKQCD Collaboration has worked on such calculations for several years 1)2)3)4). While we have successfully improved the estimate, the statistical error remains a major part of the total uncertainty. Recently, an efficient method called All-Mode-Averaging (AMA)4) has been proposed for significantly reducing the statistical error. The AMA technique is an operator improvement using symmetries on the action and approximations. The most useful symmetry is translational invariance of space-time. The idea involves locating many source points in the measurement, but using an approximation in obtaining quark propagators to reduce computational cost. As an approximation, we use a sloppy CG, where its stopping condition is relaxed. A crucial point here is the existence of correlation between the original and the approximated operators; thus, we choose the stopping condition so that the good correlation is kept, but the computational cost is reduced significantly. We also note that a low-mode deflation technique helps the cost reduction in addition to enhancement of the correlation in the AMA procedure.

In Fig. 1, we show chiral and continuum extrapolation of the $B$ meson decay constant $f_B$ and the neutral $B$ meson mixing matrix element $M_B$ without and with AMA. We use gluon ensembles with two lattice spacings, which are depicted as “24c” (coarse) and “32c” (fine). “HYP1” and “HYP2” represent link smearings in the static $b$ action, whose results should coincide each other in the continuum limit. To obtain the AMA results approximately 30% – 40% cost increase is required from the original one (“before AMA” in the figures). A remarkable improvement in statistics is obtained compared with the small increase in the cost. At the physical point of light quark mass and in the continuum limit, the central values only slightly move by using the AMA; the statistical errors are, however, significantly reduced. In addition, the improvement makes a qualitative fact clear: the results with HYP2 smearing have very small scaling violation. We conclude that the AMA technique has potential to enable us to reach statistically decisive results.

References
Lorentz invariant CPT violation†
M. Chaichian,*1 K. Fujikawa,*2 and A. Tureanu†∗

A Lorentz invariant CPT violation, which may be termed as the long distance CPT violation in contrast to the familiar short distance CPT violation, has been recently proposed1). This scheme is based on the non-local interaction vertex and characterized by the infrared divergent form factor. We show that Lorentz covariant T*-product is consistently defined and the energy-momentum conservation is preserved in perturbation theory if the path integral is suitably defined for this non-local theory, although unitarity is generally lost. It is illustrated that T-violation is realized in the decay and formation processes. It is also argued that the equality of masses and decay widths of the particle and anti-particle is preserved if the non-local CPT violation is incorporated either directly or as perturbation by starting with the conventional CPT-even local Lagrangian. However, we also explicitly show that the present non-local scheme can induce the splitting of particle and anti-particle mass eigenvalues if one considers a more general class of Lagrangians.

We study the specific realization of CPT violation

\[ \mathcal{L} = \bar{\psi}(x)[i\gamma^{\mu}\partial_{\mu} - M]\psi(x) + \frac{1}{2}\partial_{\mu}\phi(x)\partial^{\mu}\phi(x) - \frac{1}{2}m^2\phi(x)^2 + g\bar{\psi}(x)\psi(x)\phi(x) - V(\phi) + g_1\bar{\psi}(x)\psi(x) \int d^4y\theta(x^0 - y^0)\delta((x - y)^2 - l^2)\phi(y) \]

as a main theoretical model. This Lagrangian is formally hermitian and the term with a small real \(g_1\) and the step function \(\theta(x^0 - y^0)\) stands for the CPT and T violating interaction; \(l\) is a real constant parameter. It is interesting that the CPT and T violating term is real in the present case. We define the interaction part

\[ \mathcal{L}_I = g\bar{\psi}(x)\psi(x)\phi(x) + g_1\bar{\psi}(x)\psi(x) \int d^4y\theta(x^0 - y^0)\delta((x - y)^2 - l^2)\phi(y). \]

We treat this highly non-local Lagrangian in path integral as described in2). Namely

\[ \langle 0, +\infty | 0, -\infty \rangle_J = \int D\bar{\psi}D\psi D\phi \exp\{i \int d^4x[\mathcal{L}_0 + \mathcal{L}_I + \mathcal{L}_J] \} \]

with the source term \(\mathcal{L}_J = \bar{\psi}(x)\eta(x) + \bar{\eta}(x)\psi(x) + \phi(x)f(x)\), and one may generate Green’s functions in a power series expansion of perturbation as

\[ (i)^n(T^*\phi(x_1)...\phi(x_N)) = \int d^4y_1\mathcal{L}_I(y_1)...\int d^4y_n\mathcal{L}_I(y_n). \]

We use the \(T^*\)-product which is essential to make the path integral on the basis of Schwinger’s action principle consistent2).

The present way to introduce CPT violation is based on an extra form factor in momentum space as

\[ \int d^4x\bar{\psi}(x)\psi(x)\int d^4y\theta(x^0 - y^0)\delta((x - y)^2 - l^2)\phi(y) = \int dp_1dp_2dq(2\pi)^4\delta^4(p_1 + p_2 + q)\bar{\psi}(p_1)\psi(p_2)f(q)\phi(q) \]

with

\[ f(q) \equiv \int d^4z\theta(z^0)\delta(z^2 - l^2)e^{iqz} \]

namely, CPT violation is realized by a form factor \(f(q)\) which becomes complex for time-like momentum. The ordinary local field theory is characterized by \(f(q) = 1\). The above form factor is infrared divergent, and it is quadratically divergent in the present example. This infrared divergence arises from the fact that we cannot divide Minkowski space into (time-like) domains with finite 4-dimensional volumes in a Lorentz invariant manner. The Minkowski space is hyperbolic rather than elliptic. CPT symmetry is related to the fundamental structure of Minkowski space, and thus it is gratifying that its possible breaking is also related to the basic property of Minkowski space.

Based on this setting, we confirmed the followings:

1. The present model produces T-violation in the decay \(\phi \to \psi + \psi\) and its reversed formation process \(\psi + \psi \to \phi\).

2. The equality of masses and decay widths of the particle and anti-particle is preserved if the non-local CPT violation is incorporated either directly or as perturbation by starting with the conventional CPT-even local Lagrangian.

Some of the more realistic applications of the present CPT violation scheme to the particle-antiparticle mass splitting, in particular, the neutrino-antineutrino mass splitting in the standard model have been already discussed elsewhere3,4).

References

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Conditionally valid uncertainty relations†

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It is shown that the well-defined unbiased measurement or disturbance of a dynamical variable is not maintained for the precise measurement of the conjugate variable, independently of uncertainty relations. The conditionally valid uncertainty relations on the basis of those additional assumptions, which include most of the familiar Heisenberg-type relations, thus become singular for the precise measurement. We clarify some contradicting conclusions in the literature concerning those conditionally valid uncertainty relations: The failure of a naive Heisenberg-type error-disturbance relation and the modified Arthurs-Kelly relation in the recent spin measurement is attributed to this singular behavior. The naive Heisenberg-type error-disturbance relation is formally preserved in quantum estimation theory, which is shown to be based on the assumptions of unbiased joint measurements or unbiased measurement and disturbance, thus fails if one formulates the relation in terms of well-defined bounded operators such as spin variables. In contrast, the Heisenberg-type error-error uncertainty relation and the Arthurs-Kelly relation, as conditionally valid uncertainty relations, are expected to be consistently maintained.

A recent experiment11), which invalidated a naive Heisenberg-type error-disturbance relation2), revived our interest in the subject of uncertainty relations. In contrast to the naive Heisenberg-type error-disturbance relation, the relations which are based on only the positive definite Hilbert space and natural commutator algebra are expected to be valid as long as quantum mechanics is valid, namely, "universally valid"2)3). It was recently shown4) that all the known universally valid uncertainty relations are derived from Robertson’s relation written for suitable combinations of operators. It is important to distinguish the uncertainty relations which are universally valid from those relations based on additional assumptions and thus only conditionally valid.

In this paper, we analyze the implications of the assumptions of unbiased joint measurements or unbiased measurement and disturbance which are widely used in the formulation of uncertainty relations5). We clarify the origin of quite different conclusions concerning the conditionally valid Heisenberg-type relations in the measurement operator formalism2) and in the quantum estimation theory6) which is a new approach to uncertainty relations.

We first note that the well-defined unbiased measurement or disturbance of a quantum mechanical operator is not maintained for the precise measurement of the conjugate operator in the framework of the ordinary measurement theory. For example, those assumptions lead to

$$\langle [M^{\text{out}}, N^{\text{out}}] \rangle = \langle [A, B] \rangle,$$

$$\langle [M^{\text{out}}, B^{\text{out}}] \rangle = \langle [A, B] \rangle.$$  \hfill (1)

We work in the Heisenberg picture and the variables without any suffix stand for the initial variables; $A$, $B$ stand for dynamical variables and $M$, $N$ stand for the corresponding measurement operators, respectively. The variables $M^{\text{out}} = U^\dagger (1 \otimes M) U$ and $N^{\text{out}} = U^\dagger (1 \otimes N) U$ stand for the variables after the measurement, and $B^{\text{out}} = U^\dagger (B \otimes 1) U$ stands for the variable $B$ after the measurement of $A$. By assumption, $\langle [M^{\text{out}}, N^{\text{out}}] \rangle = \langle [M^{\text{out}}, B^{\text{out}}] \rangle = 0$, and thus relations in (1) are contradictions.

The conditionally valid uncertainty relation such as naive Heisenberg-type error-disturbance relation12),

$$\sigma(M^{\text{out}} - A)\sigma(B^{\text{out}} - B) \geq \frac{1}{2}\langle [A, B] \rangle,$$  \hfill (2)

which is based on the assumptions of unbiased measurement and disturbance, thus fails if one formulates the relation in terms of well-defined bounded operators. The naive Heisenberg-type error-disturbance relation is formally preserved in quantum estimation theory, but the disturbance of the bounded operator is forced to be singular and divergent for the precise measurement of the conjugate variable5).

In contrast, the Heisenberg-type error-error uncertainty relation

$$\sigma(M^{\text{out}} - A)\sigma(N^{\text{out}} - B) \geq \frac{1}{2}\langle [A, B] \rangle,$$  \hfill (3)

and the Arthurs-Kelly relation,

$$\sigma(M^{\text{out}})\sigma(N^{\text{out}}) \geq \langle [A, B] \rangle,$$  \hfill (4)

as conditionally valid uncertainty relations, are expected to be consistently maintained.

References

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Heisenberg uncertainty relation revisited†

K. Fujikawa†

Kennard and Robertson formulated the uncertainty relation which appears in any textbook on quantum mechanics

$$\sigma(A)\sigma(B) \geq \frac{1}{2} |\langle [A, B] \rangle|.$$  (1)

Another important development in the history of uncertainty relations is the analysis of Arthur and Kelly. They introduce the measuring apparatus \( M \) for \( A \) and \( N \) for \( B \), respectively, with \( [M, N] = 0 \). The notion of unbiased measurement is important in their analysis, which is defined by

$$\langle M^{\text{out}} \rangle = \langle A \rangle$$  (2)

for any state of the system \( \psi \) in the total Hilbert space of the system and apparatus \( |\psi\rangle \otimes |\xi\rangle \) in the Heisenberg picture. Here variables \( M \) and \( N \) (and also \( A \) and \( B \)) stand for the variables before the measurement, and the variable \( M^{\text{out}} = U^\dagger MU \) stands for the apparatus \( M \) after measurement.

Traditionally, it has been common to take the relation\(^2\)

$$\sigma(M^{\text{out}} - A)\sigma(B^{\text{out}} - B) \geq \frac{1}{2} |\langle [A, B] \rangle|$$  (3)

as the naive Heisenberg error-disturbance relation; we use the adjective "naive" since no reliable derivation of this relation is known. An elegant experiment of spin measurement by J. Erhart et al.,\(^3\) invalidated the naive Heisenberg-type error-disturbance relation, which initiated the recent activities on uncertainty relations.

It is shown that all the uncertainty relations are derived from suitably defined Robertson’s relation\(^4\). We start with Robertson’s relation

$$\sigma(M^{\text{out}} - A)\sigma(B^{\text{out}} - B) \geq \frac{1}{2} |\langle [M^{\text{out}} - A, B^{\text{out}} - B] \rangle|$$  (4)

and use the triangle inequality

$$\sigma(M^{\text{out}} - A)\sigma(B^{\text{out}} - B) \geq \frac{1}{2} |\langle [A, B] \rangle| - |\langle [A, B^{\text{out}} - B] \rangle|$$  (5)

$$- |\langle [M^{\text{out}} - A, B] \rangle|,$$

where we used \([M^{\text{out}}, B^{\text{out}}] = [M, B] = 0\). Using the variations of Robertson’s relation, we obtain\(^2\)

$$\sigma(M^{\text{out}} - A)\sigma(B^{\text{out}} - B) + \sigma(M^{\text{out}} - A)\sigma(B)$$

\(+\sigma(A)\sigma(B^{\text{out}} - B) \geq \frac{1}{2} |\langle [A, B] \rangle|,$$  (6)

and\(^5\)

$$\{\sigma(M^{\text{out}} - A) + \sigma(A)\} \{\sigma(B^{\text{out}} - B) + \sigma(B)\}$$

$$\geq |\langle [A, B] \rangle|.$$  (7)

We thus conclude that all the known universally valid relations are the secondary consequences of Robertson’s relation. Also, the saturation of Robertson’s relation is a necessary condition of the saturation of universally valid uncertainty relations. If one assumes the unbiased measurement and disturbance, one obtains (3).

By assuming unbiased joint measurements, we conclude\(^6\)

$$\langle [A, B] \rangle = \langle [M^{\text{out}}, N^{\text{out}}] \rangle = 0$$  (8)

which is a contradiction since \( \langle [A, B] \rangle \neq 0 \) in general. Similarly, one concludes\(^6\)

$$\langle [A, B] \rangle = \langle [M^{\text{out}}, B^{\text{out}}] \rangle = 0$$  (9)

if one assumes the precise measurement of \( A \) and the unbiased disturbance of \( B \) which implies \( \langle B^{\text{out}} - B \rangle = 0 \) for all \( \psi \). Here \( B^{\text{out}} = U^\dagger (B \otimes 1)U \) stands for the variable \( B \) after the measurement of \( A \). Note that \([M^{\text{out}}, B^{\text{out}}] = [M, B] = 0\).

We interpret the algebraic inconsistency (9) as an indication of the failure of the assumption of unbiased disturbance of \( B \) for the precise projective measurement of \( A \), if all the operators involved are well-defined. Thus the naive relation (3) fails. On the other hand, the Heisenberg error-error relation

$$\epsilon(M^{\text{out}} - A)\epsilon(N^{\text{out}} - B) \geq \frac{1}{2} |\langle [A, B] \rangle|$$  (10)

and the Arthus-Kelly relation

$$\sigma(M^{\text{out}})\sigma(N^{\text{out}}) \geq |\langle [A, B] \rangle|$$  (11)

are expected to be valid as conditionally valid uncertainty relations. In this case the apparatus variable \( N^{\text{out}} \) becomes singular for the precise measurement of \( A \), namely, \( M^{\text{out}} - A \to 0 \) if the unbiasedness condition \( N^{\text{out}} - B \to 0 \) is imposed.

References

Note on intersecting branes in topological strings

T. Kimura*

The intersection of branes is an important object in string theory, in order to study non-perturbative aspects of branes, and also its applications to quantum field theory. In this report we investigate some aspects of the intersecting branes in topological string theory, especially through its matrix model description.

We consider the topological B-model on the Calabi-Yau threefold \( w - H(p, x) = 0 \) with \( H(p, x) = p^2 - W'(x)^2 - f(x) \). This geometry realizes at the large \( N \) limit of the matrix model with the potential function \( W(x) \). There are seemingly two kinds of non-compact branes in the topological B-model, which correspond to the characteristic polynomial and the external source in the matrix model.\(^1\) They play a role of the creation operator of branes for \( x \) and \( p \) coordinates, respectively. By considering both kinds of the branes simultaneously, we can discuss intersection of branes in the B-model. The corresponding matrix model partition function \( \Psi_{N, M}(\{a\}_k; \{\lambda\}_\alpha) \) is given by

\[
\int_{N\times N} dX e^{-\frac{1}{\hbar} \text{Tr} W(X) + \text{Tr} AX} \prod_{\alpha=1}^M \det(\lambda_{\alpha} - X). \tag{1}
\]

This is the \( M \)-point function of characteristic polynomials in \( N \times N \) Hermitian matrix model with external source \( A \). In order to evaluate the partition function (1), we first rewrite it only in terms of eigenvalues by integrating out the angular part of the matrix \( X \). Then, after some calculations, we obtain the determinant expression of the partition function

\[
\frac{1}{\Delta(a)\Delta(\lambda)} \det \left( \begin{array}{cc} Q_{j-1}(a_{k}) & Q_{N+\alpha-1}(a_{k}) \\ P_{j-1}(\lambda_{\beta}) & P_{N+\alpha-1}(\lambda_{\beta}) \end{array} \right), \tag{2}
\]

where \( \Delta(x) = \prod_{i<j}(x_i - x_j) \) is the Vandermonde determinant, and \( P_k(x) = x^k + \cdots \) is arbitrary \( k \)-th monic polynomial. The function \( Q_k(a) \) is the Fourier (Laplace) transform of \( P_k(x) e^{-\frac{1}{\hbar} W(x)} \). Therefore, from the expression (2), we can see an explicit duality between \( \tilde{a} \) and \( \tilde{\lambda} \) through the Fourier transformation. In terms of the topological strings, this duality reflects the symplectic invariance of the canonical pair \( (p, x) \) in the B-model, which is also seen as the open/closed string duality. We also note that this kind of symplectic invariance appears quite generally in the topological expansion of the spectral curve.

If we apply the Gaussian potential, two functions \( P_k(x) \) and \( Q_k(x) \) are essentially equivalent, since it is self-dual against the Fourier transformation. In this case we can rewrite the partition function in terms of \( U(N) \times U(M) \) bifundamental chiral fermions, which are seen as effective degrees of freedom on the intersecting branes. The corresponding effective action is given by

\[
S_{\text{eff}} = \frac{g_2}{2} \bar{\psi}_i^\alpha \psi_j^\beta \bar{\psi}_j^\beta \psi_i^\alpha + \text{Tr} A \bar{\psi}_i^\alpha \psi_j^\beta - \text{Tr} \Lambda \bar{\psi}_i^\alpha \psi_j^\beta, \tag{3}
\]

In this expression the duality between \( A \) and \( \Lambda \) is manifest. In this action the full symmetry of \( U(N) \times U(M) \) is partially broken due to the source terms.

Let us then comment on the integrability of the brane intersection partition function (2). This kind of determinantal formula generally plays a role as the \( \tau \)-function,\(^2\) and satisfies the Toda lattice equation by taking the equal parameter limit. To show that, we now consider the equal position limit of (2) as \( a_j \rightarrow a \) and \( \lambda_{\alpha} \rightarrow \lambda \). Then we have

\[
\prod_{j=0}^{N-1} \frac{1}{j!} \prod_{\alpha=0}^{M-1} \frac{1}{\alpha!} \det \left( \begin{array}{cc} Q^{(k-1)}_{j-1}(a) & Q^{(k-1)}_{N+\alpha-1}(a) \\ P^{(k-1)}_{j-1}(\lambda) & P^{(k-1)}_{N+\alpha-1}(\lambda) \end{array} \right). \tag{4}
\]

This is just a hybridized version of Wronskian. If we apply the simplest choice \( P_k(x) = x^k \), \( Q_k(a) \) is just given as \( k \)-th derivative of the generalized Airy function

\[
Q_k(a) = \left( \frac{d}{da} \right)^k \int dx e^{-\frac{1}{\hbar} W(x) + ax}. \tag{5}
\]

Applying the Jacobi identity for determinants to the expression (4), we obtain the following 3-term recurrence relations

\[
\Psi_{N+1, M} \cdot \Psi_{N, M+1} = \frac{N}{M} \frac{\partial^2}{\partial a^2} \log \Psi_{N, M}, \tag{6}
\]

\[
\Psi_{N+1, M+1} \cdot \Psi_{N, M} = \frac{\partial^2}{\partial a \partial \lambda} \log \Psi_{N, M}. \tag{7}
\]

where we have rescaled the partition function as \( \Psi_{N, M}(a, \lambda) = e^{-\lambda} \Psi_{N, M}(a, \lambda) \). The equations (6) and (7) are the Toda lattice equations in one and two dimensions. This means that the brane intersection partition function is the \( \tau \)-function for the Toda lattice hierarchy in both senses. We can also introduce infinitely many “time” variables for this \( \tau \)-function in the Miwa coordinate

\[
t_n = \frac{1}{n} \text{Tr} A^{-n}, \quad \tilde{t}_n = \frac{1}{n} \text{Tr} \Lambda^{-n}. \tag{8}
\]

If we take the large \( N \) limit of the matrix model, which corresponds to the continuum limit of the Toda lattice equation, we obtain the KdV/KP integrable equations.

References

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Non-Lagrangian theories from brane junctions

L. Bao, V. Mitev, E. Pomoni, M. Taki and F. Yagi

In a seminal article, Gaiotto argued that a large class, called class \( \mathcal{S} \), of \( \mathcal{N} = 2 \) superconformal field theories (SCFT) in four dimensions (4D) can be obtained by a twisted compactification of a 6D \((2,0)\) SCFT on a Riemann surface of genus \( g \) with \( n \) punctures. The building blocks of the class \( \mathcal{S} \) theories are tubes and pairs of pants that correspond to gauge groups and matter multiplets, respectively. Subsequently, a relation between the partition functions of the \( \mathcal{N} = 2 \) \( SU(N) \) gauge theories and the correlation functions of the 2D \( A_{N-1} \) Toda CFTs was proposed. Computation of 2-point and 3-point functions in a CFT would in principle yield a complete understanding of the \( n \)-point functions.

It is important to note that there is a fundamental difference between the \( SU(2) \) and the \( SU(N) \), \( N > 2 \), cases. For the \( SU(2) \) quiver gauge theories that are related to the 2D Liouville CFT, there is only one type of puncture on the Riemann surface and hence the Liouville CFT has only one class of 2D 3-point functions to be calculated. On the other hand, the \( SU(N) \) case with \( N > 2 \) has more than one kind of puncture. So far, the case with three special \( SU(N) \) punctures \( T_N \) has remained elusive, since neither the \( T_N \) Nekrasov partition functions nor the Toda three-point correlators are known. The situation is further aggravated by the fact that the corresponding 4D theories do not have a Lagrangian description. Even though there is no known Lagrangian description of the 4D \( T_N \) theories, we are able to obtain the partition functions for their 5D uplift using topological strings on the dual geometry of the 5-brane junctions.

In this paper, we compute the Nekrasov partition functions of the \( T_N \) junctions as refined topological string partition functions. At this point, we make use of the quite recent conjecture of Iqbal and Vafa that says that the 5D superconformal index, which is the partition function on \( S^4 \times S^1 \), can be obtained from the 5D Nekrasov partition function and thus from the topological string partition function

\[
I^{5D} = \int da \left| Z_{\text{Nek}}^{5D}(a) \right|^2 \propto \int da \left| Z_{\text{Top}}(a) \right|^2.
\]

The \( E_6 \) superconformal index is obtained from the \( T_3 \) Nekrasov partition function by using the idea presented in Iqbal and Vafa, and we find that the results coincide with those of Kim et al. computed via localization. When parallel external 5-brane legs appear in the toric web diagram, the corresponding partition functions contain extra degrees of freedom. In contrast to the massive spectrum in 5D, which forms a representation of the Wigner little group \( SU(2) \times SU(2) \), referred to as the full spin content representation, these extra states do not transform as a correct representation under the Poincaré symmetry. Therefore, we call them non-full spin content contributions. We interpret this part as the contribution to the extra degrees of freedom appearing from the parallel 5-branes explained above. It should therefore be removed.

To obtain the superconformal index from the topological string partition function, we have to eliminate all the non-full spin content from the partition function. Schematically, the partition function can be expressed as a sum of Young diagrams assigned to the product of strip geometries as

\[
Z_{TN} = \frac{1}{Z_{\text{non-full spin}}} \sum_{Y} \prod_{i=1}^{N} Z^{\text{strip}}(Y).
\]

The factor \( Z_{\text{non-full spin}} \) is the BPS spectrum, which does not form a representation of the Poincaré symmetry, and \( Z^{\text{strip}} \) is the partition function of the strip geometry.

Finally, the 5D version of the AGTW relation, which suggests that the 5D Nekrasov partition functions are equal to the conformal block of \( q \)-deformed \( W_N \) Toda, implies the following relation between the superconformal index and the correlation functions of the corresponding \( q \)-deformed Toda field theory:

\[
T^{5D}(x, y) = \int [da] \left| Z_{\text{Nek}}^{5D}(a, m, \beta, \epsilon_{12}) \right|^2 \propto (V_{a_1}(z_1) \cdots V_{a_n}(z_n))_{q\text{-Toda}}.
\]

This is an important entry in the dictionary of the 5D/2D AGTW correspondence. The partition functions of the \( N \) brane junctions predict, up to an overall coefficient, the corresponding DOZZ formula for the three-point functions.

References
Holomorphic blocks for 3D non-Abelian partition functions\textsuperscript{†}

M. Taki\textsuperscript{†}

The pioneering work by Pestun\textsuperscript{1} on the partition function of four-dimensional (4D) $\mathcal{N} = 2$ theories has served as a trigger for great progress on localization computations of supersymmetric gauge theories in diverse dimensions and on various manifolds. The localization of three-dimensional (3D) theories is a recent focus of research. Kapustin, Willett, and Yaakov\textsuperscript{2} extended Pestun’s idea to gauge theories on $S^3$, and they obtained matrix model representations for the supersymmetric partition functions of these theories. We can solve these matrix-models in the large-$N$ limit; for instance, the ABJM partition function was computed by Drukker, Marino, and Putrov\textsuperscript{3}). They found that the free energy of the ABJM theory actually shows the $N^3/2$ scaling behavior, which had been suggested in the AdS/CFT argument. This result is a typical example of the power of the localization approach.

The efficiency of localization reaches beyond the large-$N$ approximation. The matrix models for partition functions of $\mathcal{N} = 2$ gauge theories on $S^3$ was derived in Ref.\textsuperscript{4,5).} The integrant of this matrix model consists of a complicated combination of double-sine functions, and it appears difficult on first glance to evaluate it exactly. In Ref.\textsuperscript{6),} however, the authors successfully solved these matrix models exactly. In particular, the partition functions of 3D $\mathcal{N} = 2$ $U(1)$ theories computed in Ref.\textsuperscript{6)} show the following factorization property:

$$Z_{U(1)}^{SU(N)}[S^3] = \sum_{i=1}^{N_f} Z_{\text{vort}}^{(i)} Z_{\text{anti-vort}}^{(i)}.$$  \hspace{1cm} (1)

Here, $Z_{\text{vort}}$ and $Z_{\text{anti-vort}}$ are the partition functions of the vortex and antivortex configurations on $S^3 \times \mathbb{R}^2$ respectively. The summation is taken over the supersymmetric ground states that specify the vortex sector. This factorization into vortices is the 3D analogue of Pestun’s expression,

$$Z_{U(1)}^{SU(N)}[S^3] = \int da Z_{\text{inst}}(a) Z_{\text{anti-inst}}(a).$$  \hspace{1cm} (2)

In this 4D case, ground states are labeled by the continuous moduli parameter $a$; therefore, we take the integral over it after combining the contributions from instantons and anti-instantons. The three-dimensional factorization is therefore expected to originate from the localization after changing the way of carrying out the localization computation.

In this paper, we extend this observation (1) to gauge theories with a more generic gauge group $SU(N)$. To compute the localization partition functions of these non-Abelian gauge theories, we need to evaluate the following complicated matrix integral:

$$Z = \frac{1}{N!} \int d^4x \ e^{-\pi k \sum x_\alpha^2 + 2\pi i \xi \sum x_\alpha} \prod_{1 \leq \alpha < \beta \leq N} \times 4 \sinh \pi b(x_\alpha - x_\beta) \sinh \pi b^{-1}(x_\alpha - x_\beta) \times \prod_{a=1}^{N_f} \prod_{i=1}^{N_f} s_b(x_\alpha + m_i + \mu_i/2 + iQ/2) \times \prod_{\alpha < \beta \leq N} \prod_{i=1}^{N_f} s_b(x_\alpha + m_i - \mu_i/2 - iQ/2).$$  \hspace{1cm} (3)

Here, $s_b(x)$ is the double-sine function\textsuperscript{7).} Employing the Cauchy formula

$$\prod_{1 \leq \alpha < \beta \leq N} 2 \sinh(x_\alpha - x_\beta) \sinh(\chi_\alpha - \chi_\beta) = \sum_{\sigma \in S^N} (-1)^\sigma \prod_{\alpha < \beta < \sigma(\alpha)} 2 \cosh(x_\alpha - \chi_\beta),$$  \hspace{1cm} (4)

we succeeded to compute the matrix integral, and we found the following factorization:

$$Z^{SU(N)}[S^3] = \sum_{i_1}^{N_f} \cdots \sum_{i_N}^{N_f} Z_{\text{vort}}^{(i)} Z_{\text{anti-vort}}^{(i)}.$$  \hspace{1cm} (5)

where $N_f$ is the number of flavors. This result suggests that the factorization is universal for the gauge theories in three dimensions, and we can expect a similar relation for gauge theories with other gauge groups on more generic three-dimensional manifolds. It would be also possible to re-derive our result physically without computing the partition functions explicitly.

References


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Notes on the enhancement of flavor symmetry and 5d superconformal index†

M. Taki†

Perturbative renormalizability has been a criterion for the predictable quantum field theory. Needless to say, this is because renormalization removes ultraviolet (UV) divergences from Feynman diagram, giving a meaningful finite value to a physical quantity. While an effective theory is permitted to include non-renormalizable interactions, this criterion must be satisfied by a fundamental theory without any cut-off scale, and it excludes many models of the quantum field theory. The renormalizable theories, however, do not exhaust all possibilities.

A quantum theory endowed with a UV fixed point is well defined and valid at the whole energy scale. This possibility is known as the Weinberg asymptotic safety scenario1), which perhaps preserves the non-renormalizability of the perturbative quantum gravity. This scenario is also very attractive because a renormalizable but asymptotically non-free theory such as pure QED involves the Landau pole, and the convergence radius of the perturbation becomes zero according to popular opinion. By assuming the existence of the UV fixed point, we can avoid such a theoretical inconsistency included in perturbative quantum field theory.

UV fixed point is a very important notion in the quantum field theory, but it is very difficult in general to determine whether a theory has a UV fixed point. 5d minimal supersymmetric gauge theories are typical and attractive exceptions to circumvent this difficulty. Perturbative five-dimensional gauge theories are non-renormalizable, but Seiberg2) showed that perturbative description breaks down at high energy but some of these theories flow up to a strongly coupling, non-Gaussian, UV fixed point. $SU(2)$ gauge theory with $N_f = 0, 1, \ldots, 7$ fundamental flavors provides a concrete example3,4). The flavor symmetry of this gauge theory is $SO(2N_f) \times U(1)_f$, where $U(1)_f$ is associated with the instanton current $J = *\mathrm{Tr} F \wedge F$. The UV fixed point is described by a strongly coupled conformal field theory. At this fixed point, the flavor symmetry is expected to enhance to the larger group $E_{N_f+1}$: $E_1 = SU(2)$, $E_2 = SU(2) \times U(1)$, $E_3 = SU(3) \times SU(2)$, $E_4 = SU(5)$, $E_5 = SO(10)$, and $E_{6,7,8}$ are the usual exceptional Lie groups.

This enhancement of the flavor symmetries was conjectured by employing superstring theory2), and so far it has not been easy to show this enhancement based only on field theory arguments. This is because the UV fixed point theories in question are strongly coupled, and it has prevented us from verifying this conjecture directly. Fortunately, with recent progress in the theories of localization and the superconformal index, we can discuss the strongly coupled fixed point theories quantitatively by evaluating the protected indexes of these theories5). The 5d superconformal index is the following extended version of the Witten index:

$$I_{5d}(u, z_f, \ldots) = \mathrm{Tr}_{\mathcal{H}_4} (\lambda^{H_f} \ldots) u^k \prod_f z_f^{H_f} \ldots.$$  

Here $k$ is the $U(1)$ charge with respect to the instanton current, and $H_f$ is a Cartan generator of the flavor symmetry. $u$ and $z_f$ are the fugacities for these symmetries. In this paper, we study the detailed structure of the superconformal index, and we provide a justification of the enhancement of the flavor symmetry for $N_f = 0, 1, 2$. We find that the superconformal index satisfies

$$I_{5d}(u, z_f, t, q) = I_{5d}(u^{-1}, z_f, t, q).$$

This result indicates that the index is actually invariant under the action of the Weyl group of the expected $SU(2)$ flavor symmetry. We then conclude that the $U(1)$ global symmetry of 5d gauge theory is enhanced to $SU(2)$ at the UV fixed point. This $SU(2)$ flavor symmetry is the core of the full $E_{N_f+1}$ symmetry, and therefore we can expect that extending our result should yield a proof of the full enhancement.

References


From the Berkovits formulation to the Witten formulation in open superstring field theory†

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Gauge invariance plays a fundamental role in the current formulation of covariant string field theory. In open bosonic string field theory,1 behind the gauge invariance is the algebraic structure called the \( A_\infty \) structure,2,3) which is closely related to the covering of the moduli space of Riemann surfaces. In open superstring field theory, we therefore expect that the structure underlying its gauge invariance be a supersymmetric extension of the \( A_\infty \) structure, which would be closely related to the covering of the supermoduli space of super-Riemann surfaces. However, there is very little understanding of gauge invariance, and some of the problems we are confronted with in open superstring field theory seem to be related to the lack of our understanding in this perspective.

For example, in the Witten formulation of open superstring field theory,4) the gauge symmetry has proven to be singular because of the collision of picture-changing operators.5) There are related divergences in tree-level amplitudes, which are also caused by the collision of picture-changing operators. It is possible that the source of these divergences is related to the singular covering of the supermoduli space of super-Riemann surfaces. At the moment, however, such understanding is negligible.

On the other hand, gauge transformation does not suffer from any singularity in the Berkovits formulation of open superstring field theory6) in the Neveu-Schwarz sector. We do not, however, understand why it works well in the context of the covering of the supermoduli space of super-Riemann surfaces. In the Berkovits formulation, the action contains interaction vertices higher than cubic. We know that the bosonic moduli space of Riemann surfaces is covered by Feynman diagrams with cubic vertices alone, and the higher-order vertices do not contribute to the covering of the bosonic moduli space. Since gauge invariance requires the higher-order vertices, it is expected that these vertices play a role in the covering of the supermoduli space. At the moment, however, such understanding is missing.

In view of recent developments in the understanding of the supermoduli space,7–10) the exploration of the relation between gauge invariance in open superstring field theory and the covering of the supermoduli space of super-Riemann surfaces can be crucially important for the profound question of whether open superstring field theory can be a consistent quantum theory by itself. In this report, as a first step towards this direction, we address the question of how the divergences in the Witten formulation can be resolved in the Berkovits formulation.

The Hilbert space of the string field in the Berkovits formulation is larger than that in the Witten formulation and, correspondingly, the gauge symmetry in the Berkovits formulation is larger than that in the Witten formulation. We perform partial gauge fixing in the Berkovits formulation to associate it with the Witten formulation. We introduce a one-parameter family of judicious gauge choices labeled by \( \lambda \), and the cubic interaction in the Berkovits formulation reduces to that in the Witten formulation in the singular limit \( \lambda \to 0 \). We can think of the Berkovits formulation which is partially gauge fixed with finite \( \lambda \) as a regularization of the Witten formulation. We find that the divergence in the four-point amplitude as \( \lambda \to 0 \) is canceled by the quartic interaction. We also find that the divergence in the gauge variation of the action to the second order in the coupling constant as \( \lambda \to 0 \) is resolved by incorporating the quartic interaction. Our approach based on the one-parameter family of gauge choices enables us to discuss the nature of these divergences in a concrete and well-defined setting. Our next step will be to translate the mechanism of canceling the divergences into the language of the covering of the supermoduli space of super-Riemann surfaces, and our ultimate goal is to reveal a supersymmetric extension of the \( A_\infty \) structure underlying open superstring field theory.

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A landscape in boundary string field theory: new class of solutions with massive state condensation†

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We solve the equation of motion of boundary string field theory allowing generic boundary operators quadratic in X, and explore string theory non-perturbative vacua with massive state condensation. Using numerical analysis, a large number of new solutions are found. Their energies turn out to distribute densely in the range between the D-brane tension and the energy of the tachyon vacuum. We discuss an interpretation of these solutions as perturbative closed string states. From the cosmological point of view, the distribution of the energies can be regarded as the so-called landscape of string theory, as we have a vast number of non-perturbative string theory solutions including one with small vacuum energy.

As a non-perturbative formulation of open bosonic string, boundary string field theory (BSFT)† was proposed as well as cubic string field theory (CSFT). In general, solutions of string field theories are quite important as they would provide non-perturbative vacua of string theory, to look at the true capability of string theory.

Recently, the multiple D-brane solutions, which have greater energies than the trivial vacuum, were proposed in CSFT. It would have a significance equivalent to the proof of the original Sen’s conjecture, since the D-brane creation is thought of as a necessary ingredient for a complete non-perturbative formulation of string theory. To climb up the SFT potential hill instead of rolling down the hill to get to the tachyon vacuum, it is indispensable to treat the string massive modes.

After the construction of the analytic solution for tachyon condensation, various analytic solutions in CSFT have been found. In recent times, analytic forms of lump solutions and multiple D-brane solutions were proposed. In BSFT, as well, an analytic solution for tachyon condensation and lump solutions have been found.

To solve the equation of motion of CSFT, we encounter the infinite-dimensional equation, which is hard to solve. In fact, there are some subtleties of proposed solutions. On the other hand, there is a consistent truncation scheme which reduces BSFT to a standard field theory with a finite number of fields. The BSFT action was constructed also for boundary interactions quadratic in the worldsheet field X, corresponding to a subset of massive modes of open string.

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Fig. 1. The plots of the energies for Lorentz invariant solutions of the BSFT. Values are in units of $T_{25}/V_{26}$ which is the total energy (tension) of a D25-brane. $k_c$ is a cut-off integer for truncating the excited level considered in the BSFT.

The purpose of this paper is to solve the equation of motion of the BSFT action for the quadratic boundary operators. In contrast to CSFT, only the tachyon field plays a significant role in the BSFT exact solution for tachyon condensation and the lump solutions such that the analysis is rather simple. For this reason, it is natural to expect that one may obtain a new class of solutions by involving some more boundary operators, aiming at new string vacua and a construction of a multiple-D-brane solution.

We adopt the BSFT action for quadratic boundary interactions with arbitrary number of derivatives on the worldsheet, and solve the equation of motion numerically to find homogeneous static solutions. The condensation of the massive fields is taken care of to their all orders. So the solutions are non-perturbative ones at the classical level of SFT, in the same sense as for the non-perturbative tachyon vacuum solutions of the BSFT. We discover a large number of new solutions of BSFT. Interestingly, those energies turn out to be smaller than the D-brane energy, see Fig. 1. Our analysis strongly suggests the existence of an infinite number of solutions. We also find that an approximately uniform distribution of the energies of the solutions, which suggests a relation to closed string excitations at the tachyon vacuum. Furthermore, from a cosmological point of view, the distribution of infinitely many solutions is reminiscent of the so-called string landscape.

References
Vacuum instability in electric fields via AdS/CFT: Euler-Heisenberg Lagrangian and Planckian thermalization†

K. Hashimoto*1,2 and T. Oka*3

Extreme environments, such as a strong electric field, is one of the frontiers to test physical systems and to reveal new physical phenomena. Particle physics is not an exception. The physics of quantum fields in strong external electric fields, i.e., “strong-field quantum field theory” has a very long history which even dates back to the development era of QED. Nevertheless, the dynamics of quantum fields and their vacuum in strong electromagnetic fields has not been understood well yet, both theoretically and experimentally. One of the present frontiers of strong field QFT is to understand the instability of strongly interacting systems such as the confining vacuum in QCD.

A particular interest is a relation between the confinement in QCD and the strong electric field. Because quarks have electric charges, a strong electric field can induce a vacuum decay at which pairs of a quark and an antiquark are produced from the vacuum to cancel the background electric field. However to estimate the threshold critical electric field, as well as to describe the physical decay process, is a difficult problem, because of several reasons; first, QCD is strongly coupled so the standard perturbative calculation does not work at low energy, and second, strong electromagnetic fields induces effective multi-photon vertices resulting in a complicated nonlinear electromagnetic effective action.

The renowned method for analyzing strongly coupled system, such as QCD, is the AdS/CFT correspondence1). This is a well-developed tool in string theory which enables us to analyze strongly coupled CQD analytically. In this paper, we apply the gauge/gravity duality to a certain strongly coupled QCD-like gauge theory, and analyze the instability caused by a strong electric field.

We analyze vacuum instability of strongly coupled gauge theories in a constant electric field using AdS/CFT correspondence. The model is the $\mathcal{N} = 2$ 1-flavor supersymmetric large $N_c$ QCD in the strong ’t Hooft coupling limit.2) We calculate the Euler-Heisenberg effective Lagrangian $\mathcal{L}(E)$, which encodes the nonlinear response and the quantum decay rate of the vacuum in a background electric field $E$, from the complex D-brane action in AdS/CFT. We find that the decay rate given by $\text{Im} \mathcal{L}(E)$ becomes nonzero above a critical electric field set by the confining force between quarks. A large $E$ expansion of $\text{Im} \mathcal{L}(E)$ is found to coincide with that of the Schwinger effects in QED, replacing its electron mass by the confining force.

Then, the time-dependent response of the system in a strong electric field is solved non-perturbatively, and we observe a universal thermalization at a shortest timescale “Planckian thermalization time” $\tau_{th} \sim \frac{\hbar}{k_B T_{\text{eff}}} \sim \frac{\hbar}{k_B} E^{-1/2}$. Here, $T_{\text{eff}}^\infty$ is an effective temperature which quarks feel in the nonequilibrium state with nonzero electric current, calculated in AdS/CFT as a Hawking temperature. Stronger electric fields accelerate the thermalization, and for a realistic value of the electric field in RHIC experiment, we obtain $\tau_{th} \sim 1 \text{ [fm/c]}$, which is consistent with the believed value.

The main result of the present paper is an analytic computation of the full electromagnetic effective Lagrangian for a strongly coupled QCD-like gauge theory. In particular, the imaginary part of the effective Lagrangian shows the decay rate of the vacuum of the gauge theory. The computed imaginary part is shown in Fig. 1.

References

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Unitarity bounds from generalised Kähler identities

J. Schmude

A textbook result in Kähler geometry relates the de Rham with the Dolbeault Laplacian, \( \Delta = 2\Delta_\partial \). The topic of this note is a similar identity in the case of Sasaki-Einstein manifolds and its application in to the unitarity bounds in superconformal gauge theories (SCFTs):

\[
\Delta = 2\Delta_\partial - \partial^2 + 2(n - d^0)\cL_\eta + 2L\Lambda + 2(n - d^0)\cL_\eta\Lambda_\partial + 2\iota(L_\eta\partial*_\Lambda - \partial*_{\Lambda_\partial}). \tag{1}
\]

The right hand side features the tangential Cauchy-Riemann operator, the Lefschetz operator, and the action of the Reeb vector. The equation \( \Delta = 2\Delta_\partial \) can be derived from the Kähler identities, commutators between the Dolbeault and Lefschetz operators and their adjoints. The proof of equation 1 follows a similar route by obtaining Kähler-like identities that hold on Sasaki-Einstein manifolds. Those identities as well the details of the proof were worked out in\(^1\).

Equation 1 finds application in the AdS/CFT correspondence. Freund-Rubin compactification on Sasaki-Einstein manifolds yields supergravity duals of superconformal field theories. The AdS/CFT dictionary links the conformal energy of SCFT operators to the spectrum of \( \Delta \), their R-charge to that of the Lie-derivative along the Reeb vector, \( \cL_\eta \). The conformal energy, R-charge, and spin of any SCFT operator have to satisfy the unitarity bounds\(^{3,5}\), which should be reflected on the supergravity side in the spectrum of \( \Delta \). Indeed, it is possible to re-derive the unitarity bounds from supergravity when using equation 1 in conjunction with the calculations in\(^{2,3}\).

This leads us to the spectral problem for \( \Delta \). Decompose the cotangent bundle as \( T^*S = D^* \oplus \eta = \Omega^{1,0}_S \oplus \Omega^{0,1}_S \oplus \eta \) and consider a k-form \( \omega \) with \( L_\eta\omega = q\eta, \ q \geq 0 \), and \( d^0 \leq n \). Clearly all terms on the right hand side of 1 are positive definite except for the mixed term \( M = \iota(L_\eta\partial* - \partial*_{\Lambda_\partial}) = N + N^* \). \( M \) is self-adjoint and its spectrum is real. Moreover, \( N^2 = 0 \) and \( N(\Lambda^* D^*) \subset \Lambda^* D^* \wedge \eta \) and \( N(\Lambda^* D^* \wedge \eta) = 0 \). That is, \( N \) maps horizontal to vertical forms and annihilates the latter. \( N^* \) behaves accordingly and it follows that \( \om^2 \) vanishes if \( \omega \) is horizontal or vertical. This is also the case if \( \omega \) is neither horizontal nor vertical yet holomorphic in the \( \partial* \)-sense. As long as we restrict to one of these cases, 1 takes the form of a bound on the spectrum of \( \Delta \).

This was conjectured and partially shown in the context of the calculations of the superconformal index in\(^{2,3}\). Here, the spectrum was constructed from primitive elements of \( \Omega^{p,q} \). For such forms, 1 clearly implies

\[
\Delta \geq q^2 + 2q(n - d^0) \tag{2}
\]

with equality if and only if \( \partial*\omega = \partial*_{\Lambda_\partial}\omega = 0 \). In the Kähler case, the latter of these is implied by transversality \(- d^\omega = 0 \). Here however, \( d^\omega = 0 \) leads only to the vanishing of the horizontal component of \( \partial*_{\Lambda_\partial}\omega \). Indeed,

\[
\partial*_{\Lambda_\partial}\omega = iL_\eta\Lambda\omega, \quad \partial*_{\Lambda_\partial}\omega = -iL_\eta\Lambda\omega, \tag{3}
\]

which vanishes since \( \omega \) was assumed to be primitive. Assuming that every element of \( H^p_{\partial\bar{\partial}}(S) \) has a representative closed under \( \partial*_{\Lambda_\partial} \), the bound 2 is saturated on the elements of \( H^p_{\partial\bar{\partial}}(S) \). These are the forms that correspond to the short multiplets in the SCFT, and 2 together with the expressions for the derived eigenmodes of \( \Delta \) given in\(^3,5\) allows to recover the unitarity bounds from supergravity.

Since we found Sasaki-Einstein equivalents of both \( \Delta = 2\Delta_\partial \) and the Kähler identities, it is tempting to ask how much more of Kähler geometry can be generalized. For example, since \( \Delta_\partial \) is self-adjoint and elliptic, one can show that \( \Omega^k_S = \mathcal{H}^k \oplus \Delta_\partial(\Omega^k_S) \) which implies Hodge’s theorem. Similarly, the relation between the de Rham and Hodge Laplacians allows for an isomorphism between the respective spaces of harmonic forms. However, \( \Delta_\partial \) is not elliptic. Recall that \( \Delta_\partial \) is elliptic if the symbol \( \sigma_\Delta_\partial : \text{Hom}(\Omega^k_S, \Omega^k_S) \otimes S^2(T^*S) \) maps any non-zero \( \omega \in T^*S \) to an automorphism on \( \Omega^k_S \). When calculating the symbol one essentially keeps only those terms of \( \Delta_\partial \) that are of highest order in derivatives. In the context of the tangential Cauchy-Riemann operator, this means that \( \partial*_{\Lambda_\partial} \) can be taken to be anticommuting and that the overall result is essentially the same as for the symbol of the Dolbeault Laplacian on a Kähler manifold. It turns out, that \( \sigma_\Delta_\partial(\eta) = 0 \) and \( \Delta_\partial \) is not elliptic, yet transversally elliptic.

An obvious problem of interest is the extension of the results presented here beyond the Sasaki-Einstein case. As long as there is a dual SCFT, there is a unitarity bound meaning that there should be some equivalent of 1.

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The superconformal index\cite{Kinney:2005ej, Eager:2013sxa} of a three-dimensional superconformal field theory can be expressed as the trace over all operators in the theory weighted by their fermion number

\[ I(t, z_i) = tr[(-1)^F t^{j_3} z_i^{h_i}]. \tag{1} \]

Here \( \epsilon \) is the operator dimension, \( j_3 \) is the spin of the operator, \( F \) is its fermion number, and \( h_i \) label the charges of the operator under global symmetries.

In this note we summarise\cite{Eager:2012ay} the derivation of the gravity superconformal index for any theory of the form \( AdS_4 \times SE_7 \). Previously the supergravity index was computed for the homogenous Sasaki-Einstein seven-manifolds using known Kaluza-Klein spectra\cite{Imamura:2014mja}. However, to match the field theory index and the supergravity index, several of the Kaluza-Klein modes had to be dropped. Since the spectrum has not been well tested, the authors suggested that the Kaluza-Klein spectrum should be revisited. We find that a careful analysis of the Kaluza-Klein modes agrees with known results about field theory index. Our general form of the supergravity index succinctly reproduces previous computations of the gravity index\cite{Kinney:2005ej, Eager:2012ay, Eager:2013sxa, Imamura:2014mja}. We find complete agreement with previous large-\( N \) computations of the index\cite{Kinney:2005ej, Eager:2012ay, Eager:2013sxa, Imamura:2014mja}.

We construct the Kaluza-Klein multiplets on \( AdS_4 \) from various tensors defined on the Sasaki-Einstein manifold following the methodology of\cite{Kinney:2005ej}. Our analysis focuses on generic Sasaki-Einstein manifolds. Much of our analysis builds upon previous work on Kaluza-Klein spectroscopy for coeast manifolds.

Multiplet shortening and the short multiplets contributing to the index can be described using the tangential Cauchy-Riemann operator \( \partial_b \) and the associated Kohn-Rossi cohomology groups \( H^p_{\partial_b} \). In general, the cotangent bundle over a Sasaki-Einstein manifold \( Y \) can be decomposed as

\[ \Omega_Y = \mathcal{C}_Y \oplus \Omega^{0,0}_Y \oplus \Omega^{0,1}_Y. \tag{2} \]

The operator \( \partial_b \) is the projection of the exterior derivative on \( \Omega_Y^{0,1} \), the cohomology of this complex is \( H^p_{\partial_b} \). The Kohn-Rossi cohomology groups are isomorphic to \( H^q(X, \wedge^p \Omega_X) \) defined on the cone, where \( \Omega_X \) is the part of the holomorphic cotangent bundle \( \Omega_X \) perpendicular to the dilatation vector field. Our main result is a formula for the gravity superconformal index as a trace over linear combinations of the groups \( H^q(X, \wedge^p \Omega_X) \).

Table 1 lists the multiplicity of each short multiplet appearing in supergravity solutions of the form \( AdS_4 \times SE_7 \) and their contribution to the superconformal index. When calculating the index, only states with

\[ \{Q, S\} = \epsilon - j_3 - y = 0 \tag{3} \]

contribute, where \( y \) is the R-charge. An element \( f \) of cohomology has R-charge \( \mathcal{L}_D f = 2iDf \). Here \( \mathcal{L}_D \) denotes the Lie derivative along the dilation vector field and \( 2D \) is its corresponding eigenvalue. We normalize each multiplet so that its primary has R-charge \( y \). The R-charge \( y \) differs from the R-charge \( 2D \) of the corresponding cohomology element by a constant shift.

Summing the contributions of the short multiplets, we find that the single particle supergravity index is

\[ 1 + I_{s,t}(t) = \sum \text{tr} [t^{2D} \mid H^0(X, \mathcal{O}_X) \oplus H^0(X, \wedge^2 \mathcal{O}_X) \oplus H^1(X, \mathcal{O}_X) \oplus \wedge^2 H^0(X, \mathcal{O}_X) \oplus \wedge^2 H^1(X, \mathcal{O}_X) \oplus \wedge^2 H^2(X, \mathcal{O}_X)] \tag{4} \]

The superconformal index has proven to be a powerful tool in checking proposed dualities. All proposed field theory duals to Sasaki-Einstein seven manifolds can be tested by computing the field theory index and comparing it with the above gravity index. Currently, there is no general procedure for constructing the field theory dual to a general Sasaki-Einstein seven manifold. One hopes that the superconformal index will help explore new holographic dualities.

### Table 1. Short multiplets and their contribution

<table>
<thead>
<tr>
<th>Multiplet</th>
<th>((\epsilon, j_3, y))</th>
<th>Multiplicity</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>s. graviton</td>
<td>((y + 2, 1, y))</td>
<td>(H^0(X, \wedge^2 \mathcal{O}_X))</td>
<td>(-t^{y+3})</td>
</tr>
<tr>
<td>s. graviton</td>
<td>((y + 1, 2, y))</td>
<td>(H^0(X, \mathcal{O}_X))</td>
<td>(-t^{y+3})</td>
</tr>
<tr>
<td>s. vector</td>
<td>((y + 2, 1, y))</td>
<td>(H^1(X, \mathcal{O}_X))</td>
<td>(-t^{y+2})</td>
</tr>
<tr>
<td>s. vector</td>
<td>((y + 2, 1, y))</td>
<td>(H^2(X, \mathcal{O}_X))</td>
<td>(t^{y})</td>
</tr>
<tr>
<td>hyper</td>
<td>((y, 0, y))</td>
<td>(H^0(X, \mathcal{O}_X))</td>
<td>(-t^{y+3})</td>
</tr>
<tr>
<td>hyper</td>
<td>((y, 0, y))</td>
<td>(H^2(X, \mathcal{O}_X))</td>
<td>(-t^{y+2})</td>
</tr>
</tbody>
</table>

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### References

Sine square deformation and its implications to string theory†

T. Tada*1

It was recently found that certain 1d quantum systems with an open boundary condition can share the same vacuum state with a similar system having a closed boundary condition, if the coupling constants of the system with an open boundary are modulated in a certain way called sine square deformation1−3). Sine square deformation works similarly in two-dimensional conformal field theories, which describe string theory 4). We have investigated sine square deformation in the context of string theory, focusing in particular on open/closed duality.

Sine square deformation is the modulation of the coupling of open boundary systems so that

\[ J_{i,i+1} = J \sin^2 \left( \frac{n_i}{N} \pi \right) \] (1)

keeping the boundary coupling \( J_{0,1} = J_{N,N+1} = 0 \) at the both ends (Fig. 1) for the following 1d quantum system:

\[ \mathcal{H} = - \sum_n J_{n,n+1} (\sigma_n \cdot \sigma_{n+1}). \] (2)

In the case of conformal field theory, the Hamiltonian \( \mathcal{H}_{\text{SSD}} \) that is sine square deformed is

\[ \frac{\pi}{l} \left( L_0 + \bar{L}_0 - \frac{L_1 + L_{-1} + L_{1} + L_{-1}}{2} \right) - \frac{\pi c}{12l^4} \] (3)

while the original Hamiltonian is

\[ \mathcal{H}_0 = \frac{2\pi}{l} (L_0 + \bar{L}_0) - \frac{\pi c}{6l}. \] (4)

Then, the vacuum \(|0\rangle\) for \( \mathcal{H}_0 \) is also the vacuum of \( \mathcal{H}_{\text{SSD}} \) with half the energy.

To interpret the sine square deformation in terms of the dynamics of the world sheet, we need to find the corresponding Lagrangian. We found that the Lagrangian corresponding to \( \mathcal{H}_{\text{SSD}} \) is obtained by taking \( \alpha \) to 1 in the following expression:

\[ \mathcal{L}_\alpha = \frac{1}{2} \int dx \left\{ \left( \partial_t \phi \right) f_t (\partial_t \phi) - \left( \partial_x \phi \right) f_x (\partial_x \phi) \right\}, \] (5)

where

\[ f_t(x) = 1 - \alpha \cos \frac{x}{l}, f_x(x) = \sum_{k \in \mathbb{Z}} e^{2\pi ikx/l}, \] (6)

and

\[ r = 1 - \sqrt{1 - \alpha^2}, \quad N = \frac{1}{\sqrt{1 - \alpha^2}}. \] (7)

One can readily see that the \( g_{00} \) component of the world sheet metric in the Lagrangian, \( f_t \), diverges severely as we apply sine square deformation. This in some sense expected because at the SSD point there occurs an event as singular as the change of the boundary condition.

One can apply \( \text{sl}(2, \mathbb{C}) \) transformation \( e^{\frac{1}{2} \frac{L_{-1}}{2} \frac{L_{1}}{2} \frac{L_{-1}}{2}} \) to (the holonomic part of) \( \mathcal{H}_0 \) to obtain

\[ \cos \alpha L_0 - \sinh \alpha \frac{L_1 + L_{-1}}{2}. \] (8)

The right-hand side of the above would have corresponded to \( \mathcal{H}_{\text{SSD}} \) if \( \cos \alpha = \sinh \alpha \), which is a direct contradiction with the identity \( \cosh^2 \alpha - \sinh^2 \alpha = 1 \). One, therefore, needs to take \( \alpha \to \infty \) and suitably rescale. Hence, \( \mathcal{H}_{\text{SSD}} \) is not connected with \( \mathcal{H}_0 \) through the ordinary \( \text{sl}(2, \mathbb{C}) \) transformation, but through a certain limiting procedure.

We also found that \( \mathcal{H}_{\text{SSD}} \) has the following different vacua other than \(|0\rangle\)

\[ e^{\frac{1}{2} L_{-1} |h \rangle}, \] (9)

where \(|h \rangle\) is the state corresponding to the primary fields of CFT. However, the norm of (9) is divergent. One also needs a certain limiting process to properly define (9).

In summary, we have investigated sine square deformation of string theory to shed light on the relation between open and closed strings. Recent studies of string dualities suggest that one needs to go beyond the realm where open and closed are inseparable to understand the true dynamics of string theory. We hope that we can further uncover the nature of this realm through insights offered by sine square deformation.

References

Phase structure of two-dimensional topological insulators by lattice strong-coupling expansion

Y. Araki*1 and T. Kimura*2

Topological insulators have recently attracted a great interest in the field of materials physics, which are characterized by the topologically protected gapless modes localized on the boundary of the system. The effect of electron correlation in such an electronic system has always been an important problem. Even in non-topological Dirac fermion systems, such as graphene, it has been proposed that a sufficiently strong electron-electron interaction can lead to a spontaneous breaking of some symmetries of the system and a dynamical generation of band gap.

Fig. 1. The phase diagram of the Kane-Mele model in the \((t',\sigma_1)\)-space. One of the Dirac cones loses its band gap at the phase boundary.

In this report, we study the effect of a sufficiently strong electron-electron interaction on the topological phase structure of 2D quantum spin Hall insulators. By the techniques of strong-coupling expansion of lattice gauge theory, we observe the behavior of the spontaneous antiferromagnetic (AF) order in the strong-coupling limit of the interaction. As a result, we find that the topological phase structure is modified from that of the noninteracting system by the emergence of a new “tilted AF” phase in-between the normal insulator and the topological insulator phases as shown in Fig. 1. Here we use the “modified” mass \(\sigma_1\), instead of the bare mass (staggered magnetic field) \(m\), and \(t'\) is the spin-orbit coupling constant. As a consequence of the interplay between the electron-electron interaction and the spin-orbit interaction, there appears a new “tilted antiferromagnetic (AF)” phase, where the imaginary part of the order parameter becomes non-zero \((\sigma_2 \neq 0)\), between the normal AF phase and the topological phase.

The AF order is not parallel to the direction pointed by the spin-orbit interaction and the staggered magnetic field in the spin SU(2) space in the tilted AF phase. \(\sigma_1\) and \(\sigma_2\) are antiferromagnetic (AF) orders corresponding to two directions in the remnant U(1) spin space, which we denote \(M_x\) and \(M_z\{fig:2} here. If we extend this argument to the full SU(2) spin space, another direction \(M_y\) is restored, so that the tilted AF acquires U(1) degree of freedom in choosing its direction, which may result in a massless Nambu-Goldstone mode (Fig. 2).

We also show the analogy between the phase structure of topological insulators and that of the strongly coupled lattice QCD with the Wilson fermion formalism in Fig. 3. In this analogy, \(\sigma_1\) and \(\sigma_2\) correspond to \(\langle \bar{\psi}\psi \rangle\) and \(\langle i\bar{\psi}\gamma_5\psi \rangle\). The tilted AF phase is similar to the so-called “Aoki phase” in lattice QCD in that both of them are characterized by an order parameter orthogonal to the external source term in the continuous symmetry space.1) Such an analogy may help us understand the behavior of topological insulators with an electron-electron interaction from the strong-coupling to the weak-coupling regime.

References

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Fig. 2. Schematic picture of the order parameters derived in this study. It is expected that a gapless NG mode appear when the full SU(2) is restored.

Fig. 3. The schematic phase structure of a graphene-like system with the spin-orbit interaction, conjectured in analogy to that of lattice QCD with the Wilson fermion formalism, for (left) \(t' < t'_{C}\) and (right) \(t' > t'_{C}\).
Effective gravitational interactions of dark matter axions†

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Recent developments of observational studies have constrained the properties of dark matter significantly, yet its origin is unknown. The axion is one of leading candidates of dark matter, which emerges out of the solution to the strong CP problem in QCD. One important property of dark matter axions is that it is produced non-thermally in the early universe and described as a coherently oscillating scalar field. Since this coherent oscillation is interpreted as highly condensed Bose gas, dark matter axions may form Bose-Einstein condensate (BEC) in the universe.

The formation of axion BEC dark matter, if it occurred, leads to some interesting phenomenological implications. It was argued that the angular momentum distribution of infalling dark matter particles affects the structure of inner caustics (the over dense region produced by the fall of dark matter surrounding the galaxy).† If the particles have a net overall rotation, which is predicted by axion BEC dark matter,† the inner caustics become ring-like structure. Since such a structure is not predicted in another leading candidates such as the weakly interacting massive particle (WIMP) dark matter scenario, there is a possibility to distinguish dark matter candidates observationally.

The crucial point for the above scenario is that the thermalization occurs due to gravitational interactions. Gravitational thermalization of dark matter axions was first discussed in detail in Ref. The authors claimed that the formation of axion BEC occurs in the condensed regime, where the interaction rate is large compared to the typical energy exchanged in the interaction. The thermalization process in the condensed regime was further studied by two of the present authors.† By representing coherently oscillating axions as coherent states, they evaluated the gravitational self interaction rate Γ of axions within the flat space Newtonian approximation. They showed that the interaction rate Γ exceeds the expansion rate H of the universe when the temperature of the universe is $T \approx 0.1 \text{keV}$. This result might imply that the gravitational self interactions affect the evolution of dark matter axions and their occupation number changes rapidly at that time.

In the BEC formation process, however, low energy modes, i.e. superhorizon modes, will play an central role and such a subhorizon mode is sensitive to the cosmic expansion. Therefore, it is not clear whether we can apply the previous result based on the flat space Newtonian approximation. In this report, to clarify this issue, we reanalyze the interaction rate Γ of the axion gravitational self interactions taking into account effects of the cosmic expansion based on general relativity. In the general relativistic framework, the gravitational interaction is mediated by metric perturbations $\delta g_{\mu \nu}$. The kinetic and mass terms of the axion $\phi$ generically contain cubic interactions schematically in the form $\delta g_{\mu \nu} \phi^3$ and these cubic interactions induce the following effective quartic interactions (Fig. 1).

$$H_{\text{eff}} \simeq - \sum_{k, i \sum k_i = 0} \frac{2\pi G m^2}{a^3} \left( \frac{f(x)}{(p) \sum i} \right)^3 \left( \delta p \right)^{i} a_{k_1} a_{k_2} a_{k_3},$$

with the function $f(x)$ being

$$f(x) = 1 - \cos x - x \sin x \begin{cases} 1 & (x \gg 1), \\ \frac{1}{2} x^2 & (x \ll 1). \end{cases}$$

Here $\delta p = |k_1 - k_3|/a$ is the physical exchange momentum and $x = c_s \delta p / H$ represents how it is inside the (sound) horizon. We can see that the gravitational interaction is well approximated by Newton gravity when the exchange momentum is inside the horizon $x \gtrsim 1$, while it is suppressed for $x \lesssim 1$. An important point is that even if some of external momenta are superhorizon, the interaction is not suppressed unless the exchange momentum is superhorizon.

Applying the obtained effective gravitational interaction, we showed that the interaction rate Γ exceeds the expansion rate H of the universe when the temperature of the universe is $T \approx 0.1 \text{keV}$, as in the previous studies. However, it should be noted that the thermalization process of axion BEC has been not fully understood yet in the previous studies and it is still nontrivial whether the thermalization occurs at that time (see e.g. for recent arguments). Further studies in this direction will be required.

References
Composite dark matter and lattice simulations†

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The existence of a dark matter sector, which interacts gravitationally with ordinary, baryonic matter, solves several known observational puzzles in astrophysics and cosmology. However, the observed relic abundance of dark matter (DM) in the Universe today differs from the abundance of baryonic matter by a relatively small factor, \( \rho_{DM}/\rho_b \approx 5 \). This apparent coincidence motivates the existence of some sort of coupling of the dark sector to the Standard Model (SM), to give rise to the DM relic density by way of a primordial asymmetry or by coupling to the early-universe thermal bath of SM particles. Such interactions between DM and SM are strongly constrained by present-day experiments which seek to directly detect the impact of galactic dark matter particles with SM targets.

If the dark sector contains a new, strongly-coupled gauge force, then it may give rise to a composite dark matter candidate as an electroweak-neutral bound state of charged, fundamental constituent particles. This structure generically leads to very strong momentum dependence in interactions of the bound state with the SM, which can resolve the tension since the momentum scales probed in modern direct-detection experiments are much lower than those relevant for early-universe cosmology.

As part of the LSD collaboration, my research focuses on the use of lattice simulation as a tool to study the physics of strongly-coupled gauge theories, of which QCD is only a single example in a broad class. Gauge theories with different choices of the number of colors \( N_c \), number of light fermions \( N_f \), or fermion gauge representation \( R \) can exhibit strikingly different properties1).

In connection with the study of composite dark matter, we have undertaken a calculation from first principles of electromagnetic “nucleon” form factors in SU(3) gauge theories with \( N_f = 2 \) and \( N_f = 6 \), in particular the magnetic moment \( \kappa \) and electromagnetic charge radius \( r_E^2 \)2). In a candidate composite dark matter theory, these form factors would govern the interaction of the baryon-like dark matter with ordinary nuclei through single photon exchange. Our calculation results for the magnetic moment (shown in Fig. 1 below) and charge radius indicate no significant trend as the number of fermions \( N_f \) is increased. This suggests that regardless of other dynamical considerations, bounds on composite dark matter states may apply quite generally. As studied in the reference2), these bounds can be quite wrong, with the magnetic moment interaction excluding composite dark matter states in this model below 10 TeV.

Additional studies have focused on the properties of SU(2) gauge theories. The fundamental representation of SU(2) is real, leading to an enhancement of the chiral symmetry group. For a gauge sector in which this chiral symmetry spontaneously breaks, this can lead to the existence of “baryonic” pseudo-Goldstone modes, which can play the role of a dark matter candidate with interesting and unique properties3). Recent LSD collaboration results on SU(2)4) have clarified the range of \( N_f \) values for which the spontaneous breaking of chiral symmetry will take place, paving the way for future dynamical studies relevant to SU(2) composite dark matter models.

Finally, extension of our results for composite dark matter form factors to SU(4) gauge theory is planned, with a model construction and a detailed lattice study to be published soon. With an even choice of \( N_c \), the “baryon” states will be bosonic, and can exhibit internal symmetries which cause the leading electromagnetic form factors (magnetic moment and charge radius) to vanish. Our initial studies will therefore focus on the next leading operator, the electromagnetic polarizability, as well as on scalar form factors for Higgs boson exchange.

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7. Astrophysics and Astro-Glaciology
Dynamics of X-ray–emitting ejecta in the oxygen-rich supernova remnant Puppis A revealed by the XMM-Newton RGS†

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The Galactic supernova remnant (SNR), Puppis A, is one of the brightest X-ray SNRs with energies below 1 keV. A number of oxygen-rich, fast-moving, optically emitting ejecta knots (OFMKs) are detected in this SNR. Interestingly, all these OFMKs are located in the eastern, mostly northeastern (NE) portion, whereas a neutron star is running in the opposite direction of the OFMKs. Given that this ejecta-neutron star recoil phenomenon is consistent with the recent promising supernova (SN) explosion model for explaining core-collapse SN explosions, Puppis A is an extremely important target for the study of SN explosion mechanisms.

Since significant fractions of SN ejecta are often seen only in X-rays, it is important to reveal ejecta structures in the X-ray domain. In fact, mapping observations with X-ray observatories in orbit, i.e., XMM-Newton, Chandra, and Suzaku have recently recognized signatures of ejecta. These ejecta are found to be localized in three locations. All of them are located in the NE quadrant, further supporting the one-sided ejection of SN debris. Interestingly, one of them showed a hint of blueshifted K-shell line emission. However, the moderate spectral resolution of these X-ray charge coupled devices (CCDs) used in the previous observations did not allow for conclusive arguments.

To reveal the precise Doppler velocities of two of the X-ray ejecta features (hereafter, the ejecta knot and the ejecta filament), we performed an XMM-Newton observation of Puppis A on October 20, 2012. We primarily used the Reflection Grating Spectrometer (RGS). The RGS is usually considered to be unsuitable for extended sources such as Galactic SNRs, because it is a slitless spectrometer, and hence, the extended sources suffer from energy resolution degradation. However, if the angular size of the target is sufficiently small (less than a few arc minutes) and is brighter than its surroundings, it is possible to obtain high-resolution spectra for such a target. Fortunately, our targets allow for an order-of-magnitude higher resolution spectra ($E/\Delta E \sim 150$) than nondispersive CCDs ($E/\Delta E \sim 20$).

As shown in Fig. 1, we successfully obtained a high-resolution RGS spectrum, which enabled us to reveal unambiguous Doppler velocities of $1500 \pm 200$ km s$^{-1}$ (blueward) for the knot and $650 \pm 130$ km s$^{-1}$ (redward) for the filament. In addition, line broadening at 654 eV (corresponding to O Ly$\alpha$) is obtained to be $<0.9$ eV, indicating an oxygen temperature of $<30$ keV. This temperature is significantly lower than that expected ($>100$ keV) for a (collisionless) forward shock with a speed of $\sim 2000$ km s$^{-1}$ (= 4/3 times 1500 km s$^{-1}$). We showed that the low oxygen temperature can be reconciled if the ejecta knot was heated by a shock with a velocity of $\sim 600$–1200 km s$^{-1}$ and was subsequently equilibrated due to Coulomb interactions. Therefore, the ejecta knot was likely heated by a (slower) reverse shock rather than a (faster) forward shock. This result provides significant support for the idea that a reverse shock reheat the SN ejecta, which has been expected for a long time; however observational evidence is still sparse.

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**NuSTAR** observation of the fast rotating magnetized white dwarf AE Aquarii†

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AE Aquarii (AE Aqr) is a cataclysmic variable classified as a member of the DQ Herculis or intermediate polar (IP) class, consisting of a white dwarf (WD) and a K4–5 V star. In the IP class, the WD is generally thought to possess a magnetic field \( B \sim 10^{6–7} \) G sufficiently strong to channel the accretion flow from the secondary star to the WD poles. Accordingly, hard X-rays are produced by the shock-heated gas, which reaches temperatures of a few tens of keV near the WD surface. The X-ray emission exhibits spin modulation caused by the varying aspect of the accreting poles with respect to the rotation of the WD\(^2\).

The 33.08 s period makes AE Aqr the fastest-spinning magnetic WD with intriguing emission features. In comparison to many IPs, AE Aqr shows a thermal soft X-ray spectrum with a very low luminosity, and therefore the mechanism and location of the X-ray emission are uncertain. In addition, a **Suzaku** observation\(^2\) showed that AE Aqr may emit non-thermal hard X-rays with a narrow pulse profile at the spin period, suggesting that the source may accelerate charged particles in a manner similar to rotation-powered pulsars\(^3\). However, a more recent **Suzaku** observation\(^2\) did not reproduce the earlier result, leaving the detection of non-thermal X-rays uncertain.

The Nuclear Spectroscopic Telescope Array (**NuSTAR**) satellite\(^4\), launched in 2012 June, carries the first focusing hard X-ray (3–79 keV) telescope in orbit. Owing to focusing optics, **NuSTAR** achieves the highest sensitivity ever observed in this band, and it has the capability to detect hard X-ray point sources with a flux down to sub \( \mu \)Crab. Therefore, **NuSTAR** can help measure the maximum temperature of the thermal plasma in AE Aqr and test the presence of any beamed non-thermal component. We performed a long observations of this source with **NuSTAR** for an exposure of 125 ks in 2012 September.

Spectral analysis shows that hard X-rays are well fitted by an optically thin plasma model with three temperatures of \( 0.8_{-0.5}^{+0.2}, 2.3_{-0.8}^{+1.0} \) and \( 9.3_{-2.2}^{+6.1} \) keV, the highest of which is higher than that previously observed for this source (3.0 keV)\(^2\). In addition, the spectrum is also characterized by an optically thin thermal plasma model with two temperatures of \( 1.0_{-0.2}^{+0.3} \) and \( 4.6_{-0.8}^{+1.6} \) keV in combination with a power-law component with index of 2.5±0.2, although the derived index is inconsistent with the **Suzaku** value (1.1±0.6)\(^2\) and is steeper than those found for rotation-powered pulsars (0.6–2.1)\(^3\). Compared with the three-temperature model, the fit with the two-temperature model with the power-law emission is slightly but not significantly preferred. We cannot distinguish whether the hard X-ray component detected with **NuSTAR** is thermal or non-thermal emission.

A timing analysis with \( Z_1^2 \)-statistic or Rayleigh test\(^5\) shows that the spin period in the 3–10 keV band is 33.0769 ± 0.0004 s, which is consistent with previously measured values\(^2\). The 3–20 keV pulse profile obtained by folding data at the best determined period is broad and approximately sinusoidal with a pulsed fraction of 16.6 ± 2.3%. We do not find any evidence for a sharp feature in the pulse profile.

Two energy sources could, in principle, power the observed X-ray luminosity: liberation of gravitational energy of accreting matter and the rotational energy of the WD. The observed X-ray emission is difficult to explain as a result of rotation-powered emission because synchrotron radiation, which is observed for rotation-powered pulsars, is expected to be strongly beamed along the field lines, which is inconsistent with the observed broad pulse profile. Instead, accretion-powered emission is more probable, although the observed spectrum with the highest temperature of \( 9.3_{-2.2}^{+6.1} \) keV is softer than a postshock temperature of \( \sim 30 \) keV predicted by the standard accretion column model\(^6\) under the assumption that the WD mass is \( 0.7 M_\odot \) as determined in the optical measurement\(^7\).

The standard model assumes a high-accretion column heated by the shock close to the WD surface and cooled by thermal bremsstrahlung. However, the accretion rate in AE Aqr is considerably small, which is a consequence of the low X-ray luminosity. We suggest two modifications of the standard model to explain the AE Aqr spectrum: the shock temperature could be low because of a tall accretion column comparable with the WD radius, and cyclotron emission with \( B > 10^6 \) G could additionally cool down the accretion plasma. Detailed calculations of such models will hopefully reproduce the spectrum and pulse profile of AE Aqr with the optically determined WD mass.

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Measurement of nitrogen and oxygen isotope ratios in considerably low nitrate concentration ice core samples

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Nitrate (NO_3\textsuperscript{-}) concentration in polar regions is caused by relevant stratospheric sources\textsuperscript{1)}, related extraterrestrial fluxes of energetic particles, and solar irradiation. In the Talos Dome ice core (Antarctica), NO_3\textsuperscript{-} data exhibit highly significant agreement with cosmic ray flux reconstructions\textsuperscript{2).}

Nitrogen and oxygen isotope ratios (δ\textsuperscript{15}N and δ\textsuperscript{18}O) of NO_3\textsuperscript{-} in the polar ice core are expected to reflect the difference of isotope fractionations through photochemical reactions in the stratosphere caused by cosmic ray and solar irradiation. Our final object is to clarify the history of solar activity and cosmic events, on the basis of precise analyses of the stratosphere caused by cosmic ray and solar irradiation.

In this study, we examined the method of measuring δ\textsuperscript{15}N and δ\textsuperscript{18}O with high sensitivity for 11 ice core samples from Dome Fuji drilled in 2010, corresponding to relatively high NO_3\textsuperscript{-} concentration (average 22.3 µg l\textsuperscript{-1}) using the denitrifier method\textsuperscript{4) and we successfully obtained accurate data. In this method, 10 ml of each sample was used and NO_3\textsuperscript{-} in sample water was quantitatively converted to N_2O, utilizing denitrifying bacteria (Pseudomonas aureofaciens) that lack N_2O-reductase. The isotopic composition of N_2O is then measured using the mass spectrometer (IsoPrime100) in RIKEN. The results of the measurements of δ\textsuperscript{15}N and δ\textsuperscript{18}O are summarized in Fig.1. Each sample is referenced to the internationally recognized standard USGS32, USGS34 and USGS35. In Fig. 2, the blue frame indicates the maximum and minimum values in the measured 11 ice core samples. These standards were diluted with ice core water in which NO_3\textsuperscript{-} and NO_2\textsuperscript{-} were removed using the ion exchange resin for minimizing the effect of the exchange of oxygen atoms between the nitrogen oxide intermediates and water\textsuperscript{5).} We corrected the background NO_3\textsuperscript{-} data associated with the medium for bacteria, atmosphere and ice core water used for dilution of standard. The error of the δ\textsuperscript{15}N and δ\textsuperscript{18}O in 11 samples were calculated by the propagation of errors including uncertainties in the background and in sample measurement. The maximum errors of the δ\textsuperscript{15}N and δ\textsuperscript{18}O were ±0.75‰ and ±0.34‰, respectively.

The δ\textsuperscript{15}N and δ\textsuperscript{18}O range from 201.7‰ to 258.5‰ and from 45.9‰ to 64.1‰, respectively (Fig.2). The variations of δ\textsuperscript{15}N and δ\textsuperscript{18}O show 24% and 34% for 20% NO_3\textsuperscript{-} change, respectively. δ\textsuperscript{15}N values are inside a certain range except for one sample (201.7‰). High positive δ\textsuperscript{15}N values may be attributed to the nitrate post-depositional effect because of low accumulation rate in Dome Fuji\textsuperscript{5).} NO_3\textsuperscript{-} and δ\textsuperscript{18}O show significant correlation (r = -0.69, p < 0.05), while there is no correlation between NO_3\textsuperscript{-} concentration and δ\textsuperscript{15}N.

We have successfully established the method to measure δ\textsuperscript{15}N and δ\textsuperscript{18}O of NO_3\textsuperscript{-}. Further detailed measurements are expected to contribute to elucidate the origin of NO_3\textsuperscript{-} produced by photochemical reactions in the stratosphere.

![Fig. 1. The δ\textsuperscript{15}N and δ\textsuperscript{18}O of ice core samples and international standards USGS32, USGS34 and USGS35.](image)

**Fig. 2. NO_3\textsuperscript{-} concentration, δ\textsuperscript{15}N and δ\textsuperscript{18}O of NO_3\textsuperscript{-} in Dome Fuji ice core. Red arrow indicates the range of δ\textsuperscript{15}N in Dome C ice core, inland Antarctica\textsuperscript{5).} The unit of NO_3\textsuperscript{-} concentration in Dome C converts assuming ice density 850 kg m\textsuperscript{-3).**

References
8. Accelerator
Conceptual design of SC linac for RIBF-upgrade plan

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An upgrade plan for the RIKEN RI-Beam Factory is under discussion, with the objective of significantly increasing the uranium beam intensity. Difficulty in the present acceleration scheme mainly stems from the two-stage charge stripping located at 11 and 50 MeV/u, respectively, which yields a maximum total stripping efficiency of 5%. In the upgrade plan, the fixed-frequency Ring Cyclotron will be replaced by a new cyclotron1) that will be designed to accept U^{35+} ions without charge stripping at 11 MeV/u, and the RIKEN ring cyclotron will be replaced by a new linac, mainly consisting of superconducting (SC) cavities, to improve the transmission of the high current beam. To evaluate the feasibility of the new linac, we started a design study of the SC linac in fiscal year 20132).

A layout plan of the new linac is shown in Fig. 1. The present injector, RILAC2, will be used at the low-energy end. We will add a short room-temperature (RT) section to RILAC2, which will boost the beam energy from 0.68 to 1.4 MeV/u. The main part is the succeeding SC section working in the energy range from 1.4 to 11 MeV/u.

The beam energy at the border of the RT and SC sections was chosen so that the SC section could be covered by a single structure of a quarter-wavelength resonator (QWR) with two acceleration gaps. Because a broad range of velocity had to be covered, the gap length and cavity diameter of the SC section were optimized to minimize the number of QWRs in the section. The energy gain of each gap was calculated based on hard-edge approximation. The gap voltage was assumed to be 800 kV, and the synchronous phase was determined a length $d = 160$ mm, which is the length between the gap centers, and a total cavity number of 56. The gap length was decided to be 60 mm.

The modular configuration of the SC section was optimized based on first-order approximation for the transverse and longitudinal motions. Some configurations were checked to determine whether a semi-periodic envelope could be obtained with moderate-strength focusing elements, while keeping the longitudinal acceptance large enough to capture the output beam from the RT section. Finally, we chose a configuration that consists of 14 cryomodules, each of which contains four QWRs operating at 73 MHz, and a RT quadrupole doublet placed in each space between the cryomodules. Quadrupoles with an aperture diameter of 50 mm and a field gradient of less than 20 T/m would be easier for us to make and operate compared to the SC solenoid.

The SC QWRs were designed using CST Microwave Studio 2013. The RF surface resistance is assumed to be 25 nΩ on the safe side, where the BCS resistance is negligibly small. The currently used parameters of the SC section are listed in Table 1. The definition of the effective length for the determination of $E_{acc}$ is selected to be $\beta_{geom} \lambda$.

Further study is under way on the SC QWR, including the mechanical considerations, tuner design, and coupler design. We are also going to start thermal and mechanical studies of cryostats based on the initial design shown above.

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Fig. 1. Layout plan of new linac injector.

| Frequency [MHz] | 73 |
| Duty [%] | 100 |
| Mass-to-charge ratio (m/q) | $\sim$7 |
| Input energy [MeV/u] | 1.4 |
| Output energy [MeV/u] | 11.0 |
| Number of cavities | 56 |
| Number of cryomodules | 14 |
| Number of quadrupole magnets | 28 |
| Total length [m] | 43 |
| Cavity inner diameter [mm] | $\phi$300 |
| Cavity height [mm] | 1103 |
| Gap length g [mm] | 60 |
| Gap voltage $V_{gap}$ [kV] | 800 |
| $\beta_{geom}$ of cavity | 0.078 |
| Beam aperture a [mm] | $\phi$40 |
| Synchronous phase $\phi_s$ for $\beta_{geom}$ [°] | -25 |
| Operating temperature T [K] | 4.5 |
| $G = Q_0 \times R_s$ [Ω] | 22.6 |
| $R_s/Q_0$ [Ω] | 718 |
| $R_s = R_{BCS} + R_{res}$ [nΩ] | 25 |
| $Q_0$ | $9.0 \times 10^8$ |
| Shunt impedance $R_s$ [Ω] | $6.5 \times 10^7$ |
| RF power loss $P$ [W] | 4.0 |
| $E_{acc}$ [MV/m] | 4.5 |
| $E_{peak}/E_{acc}$ | 6.0 |
| $B_{peak}/E_{acc}$ [mT/(MV/m)] | 9.5 |
Recent development of RIKEN 28-GHz superconducting electron cyclotron resonance ion source†

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Over the past several years, we have endeavored to improve the performance of the RIKEN superconducting electron cyclotron resonance ion source using several methods.1,2) For the production of U vapor, we employed the sputtering method, although the beam intensity in this method is assumed to be weaker than that in the oven technique. We also used an aluminum (Al) chamber instead of a stainless steel (SS) one. It is possible to observe the so-called “wall-coating effect.”3) Using these methods, we successfully produced ~180 eμA of U35+ and ~230 eμA of U33+ at the injected radio frequency (RF) power of ~4 kW (28 GHz). Very recently, with the aim of further increasing the beam intensity of U35+, we have developed high-temperature oven and successfully produced a highly charged U ion beam.

In this paper, we present a detailed report on the effect of the Al chamber on the beam intensity of highly charged U ion beams. We also report the effects of the two-frequency injection method on the U ion beam intensity.

For this experiment, the maximum mirror magnetic field strength at the RF injection side (Bmin), minimum strength of the mirror magnetic field (Bmin)5), maximum mirror magnetic field strength at the beam extraction side (Bmax), and minimum magnetic field strength at the surface of the plasma chamber (B0) were fixed at 3.2, 0.65, 1.8, and 1.85 T, respectively. The microwave frequency generated by the gyrotron was 28 GHz. The diameters and lengths of both plasma chambers (Al and SS) were 150 and 575 mm, respectively. The typical sputtering voltage was approximately ~5.5 kV. We used oxygen as the ionized gas. The gas pressure was (4−5) × 10−5 Pa. The extraction voltage was fixed at 22 kV in these experiments. Figure 1 shows the charge state distributions of the highly charged U ion beams. The open and closed circles denote the results in the cases where SS and Al chambers, respectively were used. The injected RF power was 2 kW for both cases. The beam intensity at a Bmin of 0.57 T (18 + 28 GHz) was slightly higher than that at a Bmin of 0.66 T (28 GHz). On comparing results with those at Bmin of 0.66 T with a 2 kW injection (28 GHz), we did not find any beam enhancement in this experiment. However, as shown in Fig. 2, the X-ray heat load with a Bmin of 0.57 T is lower than that with a Bmin of 0.66 T; this is mainly due to the magnetic field gradient effect. As we obtained nearly the same beam intensity with a lower X-ray heat load, this result indicates that the two-frequency injection method could be advantageous for our SC-ECRIS.

Fig. 1. Charge state distribution of the U ions with the Al chamber (closed circles) and SS chamber (open circles).

Fig. 2. Beam intensity of U35+ with two frequencies (18 + 28 GHz) for several Bmin values and with a single frequency (28 GHz) for Bmin = 0.66 T (upper panel). X-ray heat load in the cryostat with two frequencies (18 + 28 GHz) (closed circles) and a single frequency (28 GHz) (closed squares) for several Bmin values (lower panel).

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Development of high-temperature oven for 28-GHz ECR ion source

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U^{35+} ions extracted from the 28-GHz superconducting ECR ion source1) are used to supply uranium beams to the RIBF. Although we have thus far used the sputtering method, in which uranium is supplied in the ion source plasma by directly inserting a metal uranium rod, we began developing a high-temperature oven2) with the aim of increasing and stabilizing the beams. Because the oven method uses UO₂, a crucible must be heated to a temperature higher than 1900°C to supply an appropriate amount of UO₂ vapor to the inside of the ion source.

Figures 1 and 2 show the dimensions of the crucible and illustrate the oven in its entirety. The crucible is joule-heated with a large DC electric current. The crucible, made by machining a tungsten rod, is supported with upper and lower water-cooled copper blocks. The electric current and cooling water are supplied through brass double pipes. The crucible was designed by performing the electric, thermal, and structural analyses simultaneously using ANSYS.3) Figure 3 shows the temperature distribution of the oven, calculated by ANSYS. The boundary conditions are as follows: The temperature of the cooling water is 27°C, the heat transfer coefficient from the water to the copper block is 5000 W/m²/K, and the voltage between the upper and lower copper blocks is 1.25 V. The radiation coefficient of tungsten was assumed to be 0.25. The electric current was calculated to be 439 A. The maximum temperature of the body is 2041°C, and the temperatures of the bottom and the cap are 1960−2000°C.

The oven is placed in a solenoid magnetic field of approximately 3.3 T, which is orthogonal to the axis of the crucible. Therefore, if an electric current of 450 A flows through the crucible, the crucible is subjected to an electromagnetic force of approximately 40 N. According to the ANSYS calculation, a maximum stress of 160 MPa is generated around the tapered parts on the crucible body sides of the upper and lower rods. Since the temperature of these tapered parts increases to higher than 1800°C, it was expected that this stress level could result in the deformation and destruction of the crucible with the decrease in the tungsten’s strength. In fact, bends in the upper and lower rods were observed after operation.

We installed the oven loaded with UO₂ in the 28 ECR ion source and tested the generation of uranium beams in April 2013 after a temperature rise test and temperature measurement in a test chamber. In the first test, the oven was operated for 42h and a U^{35+} beam current of 140 µA was successfully obtained at an RF power of approximately 3 kW. After the first test, operation tests of the oven were executed intermittently from July to December. The operation time was a total of 29 days. Although we could maintain a U^{35+} beam current of 50–80 µA at an RF power of 1.5 kW for a maximum of one week, the beam currents often decreased to less than half in 7–8h. This decrease resulted from UO₂ blocking the crucible ejection hole. Since the cause of the ejection hole’s blockage was assumed to be that the temperatures of the cap of the crucible and the upper part of the hole are lower than the temperature of the bottom, we reduced the thicknesses of the cap and brim by 0.2 mm. Figure 1 shows the schematic after this reduction. Presently, we have just started to test the crucible of the new design. We are also investigating the use of rhenium instead of tungsten, which has better creep characteristic strength at high temperature for solving the bends and fracture of the rods of the crucible.

References
3) http://www.ansys.com/

*1 RIKEN Nishina Center
Improved beryllium disk stripper for uranium acceleration at RIKEN RIBF

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In 2012, we first attempted to use a rotating beryllium (Be) disk with 0.1 mm thick as the second charge stripper for uranium (U) acceleration1). The Be stripper was successfully provided stable high-intensity U beam (several electric μA on average) during a beam time of 37 days using a single disk with no exchange. The lifetime of the stripper was extended drastically compared to before. The total number of U particles irradiated on one foil/disk increased from $7.12 \times 10^{15}$ (carbon foil in 2011) to $1.18 \times 10^{18}$ (Be disk in 2012). A remaining problem was improvement of the thickness uniformity for improving the transmission efficiencies of the subsequent cyclotron IRC and SRC. In addition, the Be disk with a slightly thinner thickness of 0.085 mm was found to be better to match the injection energy of the IRC.

A thinner Be disk, with a thickness of 0.085 mm, was fabricated by Pascal Co., Ltd.2), who proposed a special machining method. They reduced the Be disk thickness of 0.15 mm to the desired thickness of 0.085 mm by only diamond-polishing both sides of the disk; diamond polishing was used because in the previous study, we had found that the standard buff finish process made thickness uniformity worse.

The polished new Be disk was used for a beam time from April to May 2013. The outer diameter of the disk was 120 mm, and the thickness was 0.085 mm, with a tolerance of ± 0.005 mm. The arithmetic average roughness (Ra) was less than 0.01 μm. A U$^{64+}$ beam at 50 MeV/nucleon was irradiated on the Be disk, which rotated at 1000 rpm. Figure 1 shows the polished new Be disk before installation. Figure 2 shows a photograph of the disk after the beam time. As in the previous beam time, the outer circumference of the beam-irradiated part (black band in Fig. 2) was deformed when the irradiated U beam intensity was increased to several electric μA. However, unlike the last beam time, no cracks were observed.

The improvement in the thickness uniformity is shown in figure 33). The figure shows the beam intensity trends as monitored by Phase Probe (PP-G01) (G01: downstream of SRC). The vertical and horizontal axes indicate the beam intensity and scan time, respectively. Signals stay at “beam-on level” in the figure if beams are provided from the SRC, whereas signals drop to the bottom “beam-off level” if no beam is available. The upper and lower parts are the trends measured in November 2012 and May 2013, respectively. The red square parts denote a single rotation period of the Be disk (60 ms). Availability of the U beams was improved from 90.7% to 98.8%. A total of $9.29 \times 10^{17}$ U particles were irradiated on the Be disk over 30 days. It has been shown that the polished new Be disk is now ready for practical use.

![Fig. 1. Polished new Be disk.](image1)

![Fig. 2. Slightly deformed Be disk after irradiation.](image2)

References
2) PASCAL CO., LTD.
URL: http://www.pascal-co-ltd.co.jp/home.html
Test of differential pumping system with plasma window using gas cell

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A differential pumping system with a plasma window (PW) has been developed for application to charge strippers using high-density hydrogen or helium (He) gases, which have a small atomic number. We tested the system with a PW operation using a gas cell where argon (Ar) or He gases were confined up to 100 kPa (1 atm). Figure 1 shows a schematic of the system. The system consists of a gas cell, a PW, and two chambers. The PW has a central bore of 2 mm diameter, which isolates the gas cell from the first chamber. Gas was injected to the gas cell and flowed into the first chamber through the PW. As stated in the previous report, the two chambers were differentially pumped. The first chamber was mainly evacuated by two mechanical booster pumps with a total pumping rate of approximately 730 m³·h⁻¹. The second chamber was evacuated by a turbomolecular pump (TMP) with a pumping rate of 792 m³·h⁻¹. The first and second chambers were connected via a flow constrictor with an inner diameter of 6 mm and length of 15 cm.

At first, the plasma was ignited by Ar gas injection. Next, gas flow rates were increased so that a pressure of 100 kPa was attained at the gas cell (P₀). The typical flow rate for Ar was maintained at 2.3 SLM to keep P₀ at 100 kPa at an arc current of 15 A per cathode. Subsequently, we replaced the injected Ar gas with He gas. We successfully operated the PW with He gas maintaining P₀ at 100 kPa. The flow rate of He for keeping P₀ = 100 kPa was 4.5 SLM at an arc current of 26 A. The differential pumping efficiency was evaluated by the pressures at the first (P₁) and second chambers (P₂). The pressures P₁ and P₂ in the cases of Ar and He are plotted as functions of arc currents in Figs. 2 (a) and (b), respectively. The solid circles and triangles denote Ar and He data, respectively. The plotted data were adequately corrected depending on the gas species. The maximum pressures of P₀ in the absence of the PW operation were 15 and 9 kPa, maintaining P₁ at 20 and 40 Pa in the cases of Ar and He, respectively. The maximum P₀ values were increased by 6.7 times for Ar and 11.5 times for He when the PW operation occurred. We found that the lowest arc currents per cathode for keeping P₀ at 100 kPa were 11 and 26 A for Ar and He, respectively.

The gas flow rates for keeping P₀ at 100 kPa are also dependent on the arc currents, as shown in Fig. 2 (c). It is noteworthy that the flow rate of He can be reduced by more than one order of magnitude as compared to the conventional differential pumping system without a PW, as estimated in advance. Also, P₀ reached 130 kPa, which is the maximum value of the gauge. The P₁ and P₂ values were 30 and 4.5×10⁻² Pa for Ar and 36 and 1.4×10⁻¹ Pa for He, respectively. Further tests using a PW with an enlarged orifice of 4 mm diameter are planned in the near future.

Fig. 1. Differential pumping system with PW.

Fig. 2. Pressures (a) P₁ and (b) P₂, and (c) flow rates in cases of Ar and He are plotted as functions of arc current. Please see the text for details.

References

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Charge state distribution measurement of $^{86}$Kr in $H_2$ and He gases at 2.7 MeV/nucleon

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We can obtain heavy ions with higher charge states in gases with small atomic numbers (low-Z gas) such as hydrogen ($H_2$) or helium (He) as compared to other standard gases (nitrogen (N$_2$) or argon). Recently, a windowless He gas stripper utilizing a strong differential pumping system has been constructed for uranium (U) beams at the RIKEN RI Beam Factory (RIBF). It has successfully functioned and has provided high intensity U beams stably.

The possibility of application of low-Z gas charge strippers to krypton (Kr) beam acceleration at the RIBF has been studied. The first stripper for $^{86}$Kr acceleration is located downstream of the RILAC, where the exit energy becomes 2.7 MeV/nucleon. Carbon foils with thicknesses of 40–80 $\mu g/cm^2$ have been used as the first stripper to obtain $^{86}$Kr$^{26+}$ for acceleration by the subsequent cyclotron RRC. A low-Z gas stripper can be one of the candidates for a long-lived stripper if a sufficient fraction of 26+ is obtained.

We have developed a prototype of a gas stripper and measured the charge state distributions of $^{86}$Kr in $H_2$ and He with different thicknesses. The $^{86}$Kr$^{20+}$ beams at 2.7 MeV/nucleon were transported to the gas stripper. A schematic of the gas stripper with its differential pumping system is shown in Fig. 1. Gases were injected in the target region (stage 1) located at the center. The length of the target region was 100 cm.

The other stages, U2, D2, U3, and D3, are also shown along with the pumping speeds of their respective attached pumps. A 10-cm-long tube with 4-mm inner diameter was installed between each stage. The charge state distributions of $^{86}$Kr in $H_2$ and He are shown in Fig. 2. The fractions calculated for $H_2$, He, and $N_2$ are plotted in the figure. In Fig. 2 (a), the data for the $H_2$ gas with thicknesses of 10, 23, 46, 68, and 107 $\mu g/cm^2$ are denoted by asterisks, x-marks, open triangles, open squares, and open diamonds, respectively. In Fig. 2 (b), the data for the He gas with thicknesses of 16, 29, 59, 124, and 247 $\mu g/cm^2$ are denoted by asterisks, open triangles, open circles, open squares, and open diamonds, respectively. Finally, in Fig. 2 (c), the data for $N_2$ gas with thicknesses of 13, 36, 817, and 1221 $\mu g/cm^2$ are denoted by asterisks, open triangles, open circles, open squares, and open diamonds, respectively. The mean charge states of $^{86}$Kr in $H_2$ and He gases attained equilibrium at 25.1 and 23.2, respectively. The fraction of $^{86}$Kr$^{26+}$ in $H_2$ is 32% at equilibrium. The mean charge state in $N_2$ at equilibrium was estimated to be lower than 20+. Since the maximum magnetic rigidity of the dipole magnet for selecting charge states was 0.97 Tm, the data are insufficient to reproduce charge distributions in $N_2$ gas.

It is found that the $H_2$ gas stripper can be used for $^{86}$Kr acceleration. In addition, the charge states in He are sufficiently high for $^{78}$Kr acceleration, since the lowest charge state of $^{78}$Kr acceptable for RRC is 23+. Further development of a differential pumping system using orifices with a bore diameter larger than 10 mm is necessary for practical use.

Fig. 1. Schematic of the gas charge stripper. Please see the text for details.

Fig. 2. Charge distributions of $^{86}$Kr in (a) $H_2$, (b) He, and (c) $N_2$ gases. Please see the text for details.

References

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Air stripper for high-intensity xenon beam

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Intensity upgrade of very heavy ions such as U and Xe beams is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF). A new injector, RILAC2, which includes a 28-GHz superconducting electron cyclotron resonance ion source1) has been successfully developed and became fully operational in the fiscal year 2011. In the acceleration with RILAC2, the possible output intensities have been principally limited by the lifetime problem of the carbon foil strippers. The recently developed recirculating helium gas stripper successfully solved the lifetime problem of the first-stage carbon foil stripper in the use with U beams at 11 MeV/u2). However, the lifetime problem was an issue for the second-stage stripper as well. In the previous runs with Xe beams in 2012, it was necessary to replace the second-stage carbon-foil stripper every 8 h because of the decreasing thickness.

In the present study, we developed a very-thick air stripper as a second-stage stripper applicable for Xe beams at 51 MeV/u. We also tried Xe-beam acceleration only with gas strippers (the first-stage is N2 gas and the second stage is air) for the first time in the RIBF user runs.

The thickness required to obtain the equilibrium charge state of the beams increases significantly at higher beam injection energies. In the present case, the second-stage stripper also functions as an energy degrader that changes the output energy of a fixed-frequency cyclotron (fRC) which is approximately 51 MeV/u, to the injection energy of the subsequent cyclotron IRC which is approximately 46 MeV/u. The required thickness of the second air stripper is about 30 times higher than the thickness for the first-stage helium stripper. Also, the required pressure at the target region is four times higher than that for the helium stripper.

The new charge stripping system was constructed in the E1 room after the fRC. The same technology of differential pumping for windowless gas confinement as the prototype He gas stripper2) was applied to the new system. The stripper consists of two tube-separated five-stage differential pumping systems with 17 pumps (Fig. 1). It is designed to achieve vacuum reduction from the target pressure of 25 kPa to 10−5 Pa within a length of 1 m while ensuring a 8.5-mm beam path.

We confined a very thick gas target, up to 20 mg/cm2 of air, in a 51-cm target chamber. Air in the E1 room was continuously compressed and the inlet pressure of a pressure regulator was kept at 0.7 MPa with a relief valve. The regulator’s secondary pressure was set to 0.4 MPa to deliver a steady flow to the target via a mass-flow controller. High-flow air up to 400 STL/min was introduced to the target chamber. Because we used air in the room, which could be inexhaustible, we did not need any recirculation system in the air stripper.

The stripper construction was completed in March 2013 and stably operated as the second-stage stripper in user runs performed in June 2013. We also used nitrogen gas (0.2 mg/cm2), which is confined in the same system of the recirculating helium gas stripper as the first-stage stripper in the user runs. The availability (actual beam service time/scheduled beam service time) of Xe beams at 345 MeV/u in the user runs reached 91%3). The maximum beam intensity reached 38 pnA, and the average intensity provided to users becomes approximately four times higher than it was in 2012. The new down time-free gas stripper contributed substantially to these improvements.

We note that this is the first observation of successful of the acceleration only with gas strippers at the RIBF, which is an important cornerstone for next-generation high-intensity heavy ion accelerators.

Fig. 1. A schematic view of the air stripper (upper). Pictures of the air stripper and glowing 100-pnA xenon beams (lower).

References
2) H. Imao et al., Cyclotrons 2013, Vancouver (2013).
3) N. Fukunishi et al., Cyclotrons 2013, Vancouver (2013).
Design and construction of drift tube linac cavities for RIKEN RI Beam Factory†

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A recent intensity upgrade for uranium and xenon beams at the RIKEN RI Beam Factory required the construction of a new injector linac, RILAC2. The acceleration system consists of three drift tube linac cavities (DTL1, DTL2, and DTL3) that operate at \( f_0 = 36.5 \text{ MHz} \) in CW mode. The cavity structure is based on a quarter-wavelength resonator, since its size is the smallest in this frequency range among the available cavity structures. The DTL3 was built by modifying the decelerating cavity of the Charge State Multiplier (CSM)1−3. Because specifications for the DTL3 were similar to those for the CSM, the design was performed carefully, comparing our simulation with the actual cavity to check the validity of the design procedure. Finally, the DTL3 was built by removing a movable shorting plate and relocating the drift tubes. The other two cavities were newly constructed.

The most significant characteristic of the design is the adoption of the direct coupling method for amplifiers connected to the cavity. The amplifier using a tetrode 4CW50.000E (Eimac) is directly connected to the cavity with a capacitive coupler. Load resistance for the tetrode, or an input impedance, was assumed to be \( Z_0 = 700 \Omega \) in the design. Direct coupling reduces the number of parts, such as the stub and output capacitor, thereby reducing size and construction cost. However, as the resonant frequency of the cavity changes significantly because of the capacitance of the tetrode, the cavity design cannot be independent of the amplifier design.

The design procedure we used comprises the following two steps. We first design the cavity itself without the coupler. We then design the combined cavity and amplifier system, determining the coupling capacitance and size of the cavity. It is helpful to evaluate load impedance of the tetrode using the lumped circuit model, but modeling the coupler as a lumped element neglects some effects; namely, the coupler occupies a certain volume inside the cavity, so capacitance between the outer conductor and the coupler is non-negligible, making it difficult to estimate the resonant frequency shift due to the coupler. Because of this frequency shift, geometric parameters such as cavity height must be carefully determined. We design the cavity without a coupler was designed first using CST Microwave Studio 2009 (MWS)4). We optimized the shape of parts constituting the resonator, such as gaps between the drift tubes, stem geometry, and the inner diameters of the coaxial section, using the eigenmode solver of the MWS to obtain a high parallel shunt impedance considering height and radius limitations. We also calculated RF power loss distributions to determine the flow rate of cooling water for each part. When determining the frequency of the resonator, it is crucial to consider the effect of the coupler; attaching the coupler to the cavity can result in a frequency shift as large as \(-300 \text{ kHz}\). The target frequency \( f_0 \) of the cavity determined by considering the coupler effect can be realized by adjusting the cavity height. The measured frequency shift against the cavity height of DTL3 was approximately 18 kHz/mm. We must determine the cavity height within an accuracy of \(\pm 4 \text{ mm} \) to realize a frequency within \(\pm 73 \text{ kHz} \) around \( f_0 \).

RF simulations of the cavity including the coupler were performed next. The calculated frequency shift due to the coupler was \(-290 \text{ kHz} \). Further frequency shifts due to the tetrode were estimated with the aid of the frequency domain solver. The load impedance of the tetrode \(Z'(f)\) was roughly estimated by adding a lumped capacitance of tetrode \(C_p\) in parallel as \(1/Z'(f) = 1/Z(f) + j(2\pi f C_p)\). \(Z'(f)\) takes a real value of 750 \(\Omega\), which was close to \(Z_0\). The frequency shift due to the tetrode was estimated to be \(-19 \text{ kHz} \).

The cavity height of the DTL3 was finally determined by taking these frequency shifts into account. The calculated shift with the tetrode and coupler was \(-309 \text{ kHz} \), and the measured frequency shift was \(-288 \text{ kHz} \). The estimation agreed well with the measurement. We also estimated the coupling strength using the frequency domain solver. Input impedance was calculated with various diameters of the coupling disk. Combining the result with the frequency dependence of the impedance \(Z'(f)\), we concluded that a plate disk with a diameter of approximately 130 mm would be suited to obtain the desirable load resistance of 700 \(\Omega\) at \( f_0 \). Based on these estimations, the diameter of the coupling disk was adjusted by making iterative measurements with the real structure of the cavity, so that the desirable load resistance was successfully obtained.

References

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Renewal of automatic tuning systems for RILAC cavities

K. Yamada,*1 K. Oyamada,*2 and N. Sakamoto*1

The RIKEN Linear Accelerator (RILAC) plays an important role with an injector to the RIBF for heavy-ions up to krypton as well as solo acceleration for super-heavy element synthesis. The resonance frequency of RILAC cavities is conserved by moving a large compensator using a feedback system, which mainly varies according to the capacitive reactance of cavity, because the frequency is fluctuated by disturbances such as heat or pressure. The basic principle of a frequency tuning system is that a relative phase difference between rf signals from a cavity pickup and an amplifier input is detected and the compensator is moved so as to keep the phase difference constant. The previous frequency tuning system caused much interruption of the machine time, because the inert response of feedback led to tripping of amplifier, and the drift of phase reference during a long-term operation had to be adjusted locally by stopping the beam acceleration. Therefore, a new frequency tuning system has been developed to realize long-term operation without interruption.

We replaced the tuning system for RILAC cavities 5 and 6 at first, because their rated voltage was higher and they experienced frequent trips. Figure 1 shows a block diagram of the new frequency tuning system. Although the basic principle is the same as the old one, much improvement was achieved, as follows.

A tuning controller (phase detector) was newly developed based on the concept of digital signal processing. Since the required response speed of the feedback is not very high (it includes a mechanical system), the two input rf signals are reduced to an intermediate frequency (455 kHz) by a double-balanced mixer with a local-oscillator signal, and converted to a 14-bit digital signal. Each digital signal is translated to in-phase (I) and quadrature-phase (Q) signals and the phase difference is determined by digital processing in a field-programmable gate array. The phase difference data is corrected by an applied reference phase to produce the phase deviation from the reference phase and output to a digital interface. The reference phase can be set to an arbitrary value or the present value of the phase output by a local and remote one-push button.

The old tuning system used a geared print motor, which was a DC motor whose rotation speed could not be controllable accurately. By fabricating a mounting plate and driveshaft coupling, the motor was replaced by a new stepping motor. The stepping motor is controlled by a programmable logic controller (PLC) with the principle of proportional speed control feedback based on the phase difference data. The maximum moving speed, feedback gain, and neutral zone can be accurately set locally and remotely.

Figure 2 shows the control unit of the new tuning system built in the existing RF control system for RILAC cavity 5. Owing to the renewal, the stability of feedback was significantly improved and work on its availability during long-term operation is currently in progress.

At the time of the renewal of amplifiers for RILAC cavities 1 and 2 in the winter of fiscal year 2013, the new tuning controller was introduced for these cavities. The residual tuning system for cavities 3 and 4 will be replaced in parallel with the renewal of amplifiers in the future.

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Replacement of main coils of RRC-W sector magnet

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The RIKEN Ring Cyclotron (RRC) has been in stable operation for over 27 years, and it is expected to work as a first-stage energy booster in any acceleration mode of the Radioactive Isotope Beam Factory (RIBF) in the future. Recently, some problems caused by age-related deterioration have often been occurring in the RRC. In 2011, a layer shorting was found at the upper main coil of the RRC-E sector magnet, and we replaced it with a new one in the summer of 2012.1) Furthermore, the lower main coil of RRC-W sector magnet also showed signs of layer shorting in June 2012. This layer shorting of the RRC-W sector magnet was a recurrence of the instance of shorting experienced and repaired in 1999. We again attempted to repair it, as in 1999, but the fluctuations of the coil voltage and magnetic fields were not fully improved. So, we decided to replace the damaged lower main coil and the deteriorated upper main coil of the RRC-W sector magnet with new main coils in FY2013. Fabrication of the new main coils required four months, and the replacement task had been scheduled over a period of eight weeks within the summer maintenance period. This was done because we had no experience in replacing the lower main coil of the RRC in our twenty-six year operation. Table 1 lists the replacement schedule of the main coil of the RRC-W sector magnet in 2013.

In the replacement task, three difficulties were anticipated, as shown in Fig. 1. The first one is how to deposit and store yokes, poles, the main vacuum chamber, and the beam injection line that was removed temporarily in the RRC room. Because of their heavy weight and large size, these removed parts were carried to and stored on the S, N, and E sector magnet, in addition to the south side of resonator No. 2, and in front of the shield door between the RRC room and the D room. The removed main coils were carried out from the RRC room and stored in the IRC room. The second difficulty is that we have to loosen and tighten 13 bolts for fixing the vacuum chambers onto the magnetic pole surfaces. Since these bolts were in the deep and narrow vacuum chamber, we ran a test successfully by using an air drive tool having a long grip in advance in the winter of 2013. The last difficulty is the silver alloy brazing of copper pipes used for cooling water and electrification of trim coils. 116 pipes were cut to remove main vacuum chamber and poles, and parts of the cut pipes were newly fabricated and cleaned for a new silver alloy brazing. Because of the high number of copper pipes, it took a week to braze these pipes with a silver alloy. Furthermore, because several pipe fixing plastic plates were used for the fixation of pipes and maintaining vacuum, we had to frequently investigate the vacuum leak from the sub-vacuum chamber.

The present performance of the RRC-W sector magnet is greatly improved, as shown in Fig. 2. Though the magnetic field of the RRC-W sector magnet before the replacement had been fluctuating over a wide range of ±5ppm, at present, the RRC-W sector magnet has a stable magnetic field without a fluctuation.

### Table 1 Replacement schedule of main coils in 2013.

| Mar. | Initiation of production of new main coils |
| 11-31 Jul. | Removal of resonators, beam injection line, valley chamber, yokes, main coils, main chamber/poles, certain cables, pipes, decks, etc. |
| 1-10 Aug. | Fabrication/cleaning of copper pipes for trim coils |
| 5-16 Aug. | Carrying in and out of main coils, restoration of main chamber/poles and vacuum test |
| 19 Aug. - 6 Sep. | Restoration of yokes, beam injection line, resonators, valley chamber, certain cables, pipes, decks, etc. |
| 26-31 Aug. | Silver alloy brazing of copper pipes and leak test |
| 6-13 Sep. | Starting up of RRC |

1) Y. Watanabe et al.: RIKEN APR 2012, p.130.
Replacement of the RIKEN ring cyclotron (RRC) power supplies

K. Kumagai,*1 M. Nagase,*1 and N. Fukunishi*1

The RIKEN ring cyclotron (RRC) has been in operation since 1986. The magnet power supplies that have been operating for 28 years were generally aging. For example, their capacitors have exceeded their service life and cooling water has been leaking from pinholes that open on the blocks for thyristor cooling.

This year, we decided to replace the main coil power supply and several trim coil power supplies. The specifications of these power supplies are shown in Table 1.

The replaced six power supplies for the trim coil are being used for the coils 4E, 4S, 5E, 5S, 26E, and 27E. The maximum current of the power supplies has been increased from 500 to 600 A in order to obtain a margin of adjustment for cyclotron’s magnetic field. The 4th trim coils were used at the same polarity for various beam operations, the polarity switching systems were not equipped.

The main coil of each sector magnet was composed of two coils. One coil was connected to power supply M1, and the other was connected to power supply M2. M2 also had four bypass circuits (100A-34V), which compensated for the variation in the magnetization of four sector magnets. The new main-coil power supply is connected to two coils that are rewired in series as shown in Fig. 1.

Table 1. Specifications of the new main coil power supply and trim coil power supplies.

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<th>Number</th>
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<th>Trim coil power supplies</th>
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</table>

*2 The ratio of the maximum current.

It is necessary to slightly adjust the current of the main coil power supply in order to cancel the variation of the magnetic field due to temperature rise of the yoke. The power supply of M1 and M2 had a resolution of 16 bits. However, the change in the current per bit corresponds to 11.1 ppm for M1 and 4.2 ppm for M2, which is insufficient for the fine adjustment of the current. As the new main coil power supply has a digital-to-analog convertor (DAC) with a resolution of 20 bits, the change in the current per bit is 0.95 ppm, which is equivalent to 0.001A/bit. As the NIO-S board used for the remote control of the power supply is capable of setting a current of 16 bits, we used two NIO-S boards for controlling 20 bits. One board is used for coarse current adjustment, and the other is used for fine adjustment of ±33.75A of the preset value.

The main coil power supply is exposed to radiation under the beam operation because it is placed in the same room as the RRC magnets. As a result, there is a risk of malfunction due to the radiation for the precise electronic devices installed in the power supply, such as the programmable logic controller (PLC), NIO-S boards, and the field-programmable gate array (FPGA). These devices are stored in a small chassis and are connected to the main power supply unit by optical cables and serial cables. They can be placed at a maximum distance of 15 m to avoid exposure to radiation.

The current stability over 8 hours was less than ±1 ppm excluding the initial drifts when the environmental temperature change was less than 3 °C, as shown in Fig. 2.

Fig. 1. Wiring of the RRC main coil.

The trim coil power supplies were installed in January 2014 and they began to operate smoothly at the beam service time by the end of January. The installation of the main coil power supply was completed in February 2014. Its usage began in the middle of March.
Vacuum leaks in accelerators

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The vacuum system for accelerators in RIBF has been running without serious problems. However, vacuum leaks have been observed in the following equipments: (1) resonator of CSM-A1, (2) cooling pipe in resonator #2 of RRC, (3) W-resonator of fRC, and (4) a chamber in the dipole magnet DM-G5.

The vacuum chamber that houses the resonator of CSM-A1 has a leakage of vacuum in its bottom plate, which is made of steel with a thickness of 40 mm and copper-plated inside and painted outside. The precise location of the leak in has been searched but has not been specified yet. Because the response of the helium leak detector was very slow. The route of the leak in the bottom plate would be complicated. Then it took time to respond to helium gas. We will continue searching for the leak point. The vacuum pressure of the A1 resonator was around 2x10^{-5} Pa, which is worse than those of other resonators, by a factor of 2 or 3.

A buildup of pressure was generated in RRC resonator #2 in the spring of 2013. The leak was found in exist somewhere in the cooling pipe of the lower inner conductor of the resonator. The cavity was opened in July, and the inside of the inner conductor was investigated carefully. As a result, water leakage was found in the chamber. However, there is no space around the pipe connection. To solve this problem, a new bypass line was made. The pipe line was cut at two shallow spots, and the spots were connected with a new pipe. The pipe connections were treated with silver braze. This equipment is running without any problems now.

At fRC, a small leak in the W-resonator has been observed for several years. However, with rf power on, the leak was so small that operations had been possible. To investigate the cause of the leak, the upper part of the resonator was removed in June 2013. On doing so, a bad rf-electrical contact was found in a part of the metal C-ring, and the elastomer O-ring seal near to it was damaged. The C-ring was replaced with a new one. To improve the clamping capacity, a long bolt was introduced through an upper flange and the resonator, and the upper flange and the resonator were tightly fastened by a nut. Moreover, the clamping capacity was reinforced by new jigs like a C-clamp.

A vacuum chamber inside a dipole magnet named DM-G5 in the injection beam line into SRC has a leakage of vacuum. The chamber was shaped like a 60-degree arc and had a rectangular cross-sections (58 mm x 86 mm). The main part of the chamber was composed of four aluminum plates with a thickness of 2 mm. The four edges of the chamber were welded. A rough location of the leak could be determined by keeping the chamber inside the magnet pole gap. For precise investigation, we took out the chamber from the magnet yoke. The first anticipated point was confirmed to be the leak point. However, the leak soon became small enough and was not detected. The cause of this phenomenon was considered. The chamber would be pressed by the magnet. Then the leak would be generated by the deformation of the chamber. To confirm this, we pressed onto the chamber using a C-clamp at a place near the leak point; doing so, a leak was detected at the same time, the vacuum pressure changed by a factor of 10. The leak point of the chamber was determined to be on the welding bead. Additional welding on it will result in another deformation on the chamber. Therefore, the leak point was treated with epoxy resin (Torr Seal). The leak was fixed.

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Reinforcement of magnetic shield for HTc SQUID beam current monitor at the RIBF†

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To measure the DC current of high-energy heavy-ion beams nondestructively at a high resolution, a high-critical-temperature (HTc) superconducting quantum interference device (SQUID) beam current monitor henceforth referred as HTc SQUID monitor has been developed for use in the radioactive isotope beam factory (RIBF) at RIKEN.1) Beginning this year, the magnetic shielding system has been greatly reinforced. Since the measurement resolution is determined by the signal to noise ratio, this resolution is improved by attenuating the external magnetic noise and RF back ground noise. These noises are mainly produced by the distribution and transmission lines from the high-current power supplies and high-power RF cavities of the cyclotrons.

To reinforce the existing magnetic shield, we developed a hybrid magnetic shielding method based on the properties of perfect diamagnetic materials and ferromagnetic materials; we were able to realize a high shielding effect despite the compact system. This system consists of two shielding parts: one for the HTc current sensor and the other for ferromagnetic shielding materials. The HTc current sensor used to produce a shielding current produced by the beam1) also works as the superconducting shield via the Meissner effect (perfect diamagnetism). The ferromagnetic shielding materials are composed of high permeability alloys (Permalloy, Mu-metal, etc.). The HTc SQUID is installed inside the frame and onto the HTc current sensor, and the frame is covered by the cap. Consequently, the HTc SQUID is almost completely surrounded by the hybrid magnetic shielding system. A photograph of the completed hybrid magnetic system is shown in Fig. 1.

In the acceleration facility, since there exist AC magnetic noises of 50 Hz and higher order and which are much stronger than terrestrial magnetism, an active magnetic field canceller system (JEOL Ltd.) was designed and introduced to the HTc SQUID monitor. This system is comprised of a magnetic field control unit, combined AC/DC magnetic field sensors, and compensation coils. The compensation coils consist of three pairs of coils that are arranged perpendicular to each other. Each of these pairs forms a so-called "Helmholtz-Coil-Pair," able to produce a homogenous magnetic field in between the pairs; each pair controls one direction (along x-, y-, or z-axis). A photograph of the active magnetic canceller system is shown in Fig. 2.

To evaluate the performance of the hybrid magnetic shielding system and the active magnetic canceller system, the output signals of the HTc SQUID were analyzed in the time and frequency domains. The signal was measured in the room next to where the power supplies for RIBF were located, where the leakage magnetic field of the 50 Hz component was measured by a Gauss meter as 4.5×10⁻⁴ T. On the other hand, the output signal of the 50 Hz component of the HTc SQUID monitor was 6×10⁻¹⁴ T. Based on these findings, we consider that the combination of the hybrid magnetic shielding system and the active magnetic canceller system can attenuate the external magnetic noise to 10⁻¹⁰.

References

Online monitoring of beam intensity using current transformer at CRIB

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The industrial cooperation team in RNC is developing a method for wear diagnostics of industrial materials using RI beams as tracers in collaboration with SHIEI Ltd. and CNS.1) RI nuclei are implanted in the near surface of the machine parts within a depth of 10–100 μm, and its wear-loss is evaluated by the decrease in the measured radioactivity. Continuous γ-ray detection from the exterior of the machine enables real-time diagnostics of the wear in running machines.

In this technique, an intense low-energy RI beam with an intensity of 107–108 cps are produced at CRIB 2) and implanted in a sample continuously for a few days in order to obtain the intended activation of a few hundred kBq. The stability of a RI beam irradiation needs to be monitored but it is too intense to monitor using a destructive detector and its energy loss in a detector disturbs the effective activation of a sample. Therefore, we examined the monitoring of the primary beam intensity detected nondestructively by a current transformer (CT) using a monitoring system that incorporates lock-in amplifiers (LIAs). The CT, called the E7 core monitor (E7CM), was developed for precise evaluation of the nuclear-reaction cross section at CRIB.3) The monitoring system using LIAs has been developed for stable operation of RIBF.4)

The schematic layout of CRIB and the examination setup are shown in Fig. 1. 5.0 MeV/nucleon 11B beam accelerated by the AVF cyclotron was used. The beam-bunch signal detected by E7CM was fed to three LIAs via the three directional couplers in order to measure the three frequency components (1–3f, 1f: acceleration rf of 13.8 MHz) simultaneously, as shown in Fig. 2(a). The isochronism measured for 10 frequency bands (OSC zero-cross, OSC FFT, and LIA) with a discrepancy less than 0.2 ns (≅ 0.001 ns) was also in good agreement with the remaining phase difference between LIA and oscilloscopes (OSC zero-cross, OSC FFT, and LIA) with a discrepancy of less than 0.4 ns (≅ 0.004 ns).

The phase difference was improved to a discrepancy of less than 0.4 ns (≅ 0.004 ns). From these results, we can conclude that the E7CM and LIA system can fulfill a role for the beam-intensity monitoring.

Fig. 2. Lineararity between beam current detected by Faraday-cup 7A1 (FC-7A1) and E7CM amplitudes.

Fig. 3. Correlation between count-rate of secondary beam and E7CM amplitudes. The primary beam current was 1870–2100 enA.

Fig. 1b. A linearity of E7CM amplitudes to the beam current detected by Faraday-cup 7A1 is confirmed, as shown in Fig. 2. In addition, the correlation between E7CM amplitudes and the count-rate of the secondary beam detected by PPAC at F3 was observed, as shown in Fig. 3. For more precise comparison, however, we have to standardize the measurement condition such as time-constant and sampling-rate for the LIA and PPAC systems. At a beam current of 2850 enA, comparable to that of actual experiment, the S/N ratio of 1–3f was 770, 3990 and 1680, respectively. They are all acceptable values but it is favorable to monitor no less than the 2f component, because the origin of background is acceleration-rf and its reference signal, and thus, its 1f component has relatively large amplitude with some fluctuation. From these results, we can conclude that the E7CM and LIA system can fulfill a role for the beam-intensity monitoring.

References
Online monitoring of beam phase and intensity using lock-in amplifiers

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We developed a monitoring system dedicated for RIBF that incorporates lock-in amplifiers (LIAs) that can measure the beam phase and intensity of signals from the phase probe (PP) with an amplitude of a few hundred nanovolts. The configuration of the LIA system is schematically shown in Fig. 1. The rf is also monitored using the LIA system. We compared the performance of the LIA system with that of a conventional system that incorporates oscilloscopes (OSCs). It was confirmed that LIA has much higher precision and smaller deviation than the OSC; LIA has a resolution of 0.02° for a 1.0 V standard signal and can measure a signal as small as 200 nV, which corresponds to 10 electric nA of beam current.

Since the PPs are placed at relevant positions along the beam lines of the RIBF, we can easily find the instability or decrease of beam intensity caused by the variation of rf or magnetic field by using the LIA system. The correlations between rf, beam phase, beam intensity, and environmental factors such as the ambient temperature and cooling water temperature have also been revealed.1,2) In addition, we can clearly observe the deterioration of a solid-state charge stripper and the pressure variation of a gas charge stripper.3)

The isochronism measurement results for the SRC, which has a low velocity gain of 1.5, showed excellent agreement between the three measurement methods (OSC zero-crosses, OSC FFT, and LIA) with a discrepancy less than 0.2 ns (±2 rf degree), as shown in Fig. 2(a). The isochronism measured for 10 frequency components (1f–10f) was also in good agreement with an accuracy discrepancy less than 0.5 ns (±5 rf degree). However, in the RRC, which has a high velocity gain of 4.0, a phase difference of up to 0.7 ns (±7 rf degree) was observed between the three measurement methods. The phase difference was improved to a discrepancy of less than 0.4 ns (±4 rf degree) when we corrected for the radial variation of the observed bunch width, as shown in Fig. 2(b).

The remaining phase difference between LIA and OSC is considered to be the effect of the cable dispersion. In fact, it was observed that the cable dispersion via 80 m increases asymmetric distortion of the bunch shape, and it produces a timing advance of 0.14 ns relative to the actual timing, as shown in Fig. 3. Because we measure the single-frequency component of the beam-bunch signal in the LIA system, such cable dispersion does not disturb the beam-phase measurement, and it is concluded that the LIA system gives a more accurate beam phase if the measurement is performed at the control room.

Fig. 1. Configuration of the LIA system.

Fig. 2. Comparison of isochronism in a) the SRC and b) the RRC on the basis of three measurement methods.

The references are as follows:


References
Modification of beam diagnosis chambers in RILAC2 high-energy beam transport

K. Yamada,*1 R. Koyama,*2 T. Nakamura,*2 M. Hamanaka,*2 M. Fujimaki,*1 and N. Fukunishi*1

The vacuum chambers in the high-energy beam transport line between the RILAC2 and the RRC have been modified in order to extend the beam diagnosis devices such as a beam profile monitor and movable slits. Figure 1 indicates the schematic view of the beam line. The vacuum level in the section including a rebuncher located at S31 (S3-REB) has also been enhanced by mounting additional vacuum pumps in an arrangement previously presented in report 1. The modifications are listed as follows.

- location C22 (just upstream of the wall between the AVF and RRC vault):
  The existing vacuum chamber has been replaced by a larger one to increase the number of the port for movable slits that define the beam emittance of RRC injection by combining with the slits at location C21a. A plastic scintillator for time-of-flight measurement, a beam attenuation mesh, a 220 L/s turbo molecular pump, and a beam stopper for radiational safety are also mounted on the C22 chamber. A wire-scanning beam profile monitor will be attached on the chamber to check the beam size on the plastic scintillator.

- location S31a (upstream of the S3-REB):
  The existing chamber has been replaced by a middle-sized chamber used for a standard in RIBF. A 350 L/s turbo molecular pump has newly been attached to the S31a chamber to improve the vacuum level. A beam attenuation mesh, a wire-scanning beam profile monitor, and a Faraday cup are mounted on the chamber as well.

- location S31b (just downstream of the S3-REB):
  A new small chamber has been installed only for mounting a wire-scanning beam profile monitor. This beam profile monitor is used to adjust the beam trajectory in the S3-REB section by combining with the beam profile monitor at S31a.

- S6-REB (rebuncher located at the S61):
  Two gate valves have been installed at each end of the S6-REB. This installation enables maintaining the devices without breaking the vacuum in the long section between S41 and S71.

- location S64:
  A new large vacuum chamber has been installed, as shown in Fig. 2. A plastic scintillator, a beam attenuation mesh, a wire-scanning beam profile monitor, a build up secondary-electron suppressor, a Faraday cup, and a 220 L/min turbo molecular pump have been attached to the chamber. Two other diagnosis devices are expected to be appended onto the chamber. A fast current transformer (C.T.) has newly been installed just upstream of the chamber.

Fig. 1. Schematic view of high-energy beam transport between RILAC2 and RRC.

Fig. 2. Photograph of the new chamber installed at S64.

References

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Upgrading the server system using virtualization technology in the RIBF control system

A. Uchiyama,*1 M. Komiyama,*1 and N. Fukunishi*1

In an RIBF control system, the Experimental Physics and Industrial Control System (EPICS) has been introduced on Linux and vxWorks since 20011). Owing to a centralized management system, all computers for EPICS programs share common network storage that implements a file transfer protocol (FTP) and a network file system (NFS) as key services. In order to achieve service reliability enhancement of the key services, we constructed failover clusters in 20082). Considering the short life cycle of server hardware, aging servers should be replaced periodically. In term of the reliability, the replaced system should enhance the efficient operation of server hardware resources, for example improvement of CPU utilization. Currently, virtualization technologies, such as KVM, Xen, and VMware are widely used in many scenarios. For the RIBF control system, virtualization software, which realizes a hardware sharing system, was selected for the following reasons:

1) To reduce operational costs, it is efficient to make virtualized image files from current physical servers without modifications to the system.
2) Other required services should be constructed by a High-availability (HA) system.
3) Complex clustering should be avoided in order to minimize maintenance cost.
4) Virtualization software with reliable support services are commercially available.
5) Even if physical servers encountered an issue, there should be no downtime for the guest operating system.

Therefore, we adopted VMware vSphere 5 as a virtualization software for the RIBF server system, and Network Attached Storage (NAS) manufactured by NetApp as a shared storage with an HA system has been implemented (See Fig. 1). In this system, the services for the shared EPICS programs and the virtualized image files in VMware environment are provided by the NAS. To improve service reliability, live-migration, which moves the guest hosts to other physical servers without downtime, is provided by VMware vMotion.

For ensuring the scalability and availability of the network, the network between NAS and a network switch uses the Link Aggregation Control Protocol (LACP). LACP bundles several physical Ethernet ports in a single logical channel. In fact, EPICS Input/Output Controllers (IOCs), Domain Name System (DNS), Lightweight Directory Access Protocol (LDAP), PostgreSQL, MySQL, Process Variable gateway3), backup systems, and EPICS application servers were constructed on the virtualization environment (See Table 1).

The VMware cluster consists of three physical servers (dual-socket Intel Xeon E5-2630), and 20 virtualized servers have been running on this cluster since Jan 2014. Replacing an aging system with a virtualization system with HA, it can facilitate efficient use of server resources and operational costs.

Table 1. Comparison of the old redundant system and the new server system in the main services.

<table>
<thead>
<tr>
<th>Service</th>
<th>Old methods</th>
<th>Replaced system</th>
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<tbody>
<tr>
<td>NFS</td>
<td>Failover cluster</td>
<td>Dual NAS controllers</td>
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<td>PostgreSQL</td>
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<td>vMotion</td>
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<tr>
<td>LDAP</td>
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<tr>
<td>EPICS applications</td>
<td>DNS round robin</td>
<td>DNS round robin, vMotion</td>
</tr>
</tbody>
</table>

Fig. 1. System chart of the upgraded virtualization server system, NAS, and LACP-based network.

References
Development of a system for measurement beam service time in RIBF operations

A. Uchiyama,*1 M. Komiyama,*1 and N. Fukunishi*1

To assess the performance of the accelerator facility, it is essential to measure the beam service time provided for the request from experiment users. Previously, beam service time was measured by using the handwritten log notebook records maintained by accelerator operators. In order to measure beam service time more efficiently and accurately, we developed a beam service time measurement system called Beam Status History.

The outline of Beam Status History is shown in Fig. 1. The RIBF control system consists of a distributed control system constructed using Experimental Physics and Industrial Control System (EPICS)1). On the other hand, Beam Status History consists of EPICS-based client applications, MySQL-based database, and Web applications. Faraday cup statuses set or out, are input as digital signals into EPICS databases, and an event that identifies information about beam service availability status is triggered by the system when all faraday cups reach the out state in the experiment course.

By contrast, when even one of the faraday cups state changes from out to set, the system considers it as the beam-off status. The information of the beam on/off status is stored in the MySQL-based database by the EPICS-based client application that is written in C, and then, beam service time is calculated based on a timestamp of the beam-on/off status by the PHP-based Web applications.

For Beam Status History, servers were constructed by Linux (CentOS 5.9) on a virtualization environment for the RIBF control system2). This system consists of the Web server (Apache), MySQL server, and the server for caMonitor, which is an event-driven program that uses the Channel Access protocol, in three virtual hosts. On the other hand, user interfaces are utilized by Web applications using Asynchronous JavaScript and XML (Ajax) technology. From the viewpoint of providing many users with accelerator information, this Web technology is a convenient system. Ajax is a Web development technique used on the client-side to create asynchronous Web applications for implementing a real-time display on the Web browser. In the beam service time measurement system, Ajax is used to display the beam on/off status and the chart of the beam service time (See Fig. 2).

As a system function, all the beam-on and beam-off times, experiment user name, type of beam (ion, charge, energy, and mass) used in the experiment are recorded in the MySQL-based database automatically. Additionally, it is possible to determine the total beam-on time, beam-off time, and current status (beam-on-target or not) in the experiment at first sight.

In the future, we will attempt to improve system usability to entirely satisfy accelerator operators and users requirements.

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NISHINA RIBF water-cooling system 2013

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1. Operation condition
In the fiscal year 2013, the Nishina and RIBF water-cooling installation was operated for five and three months, respectively. These operation periods correspond to the scheduled beam service time of RIBF, that is three months. In addition, Nishina’s cooling installation was used not only for the full RIBF operation but also for the AVF standalone and AVF + RRC operations. During FY2013, there were no severe problems that caused beam service interruption for the Nishina and RIBF cooling water systems. In addition to the existing system, the new water-cooling system was built only for the rare-R1 ring, and its test operations also started in FY2013.

2. Periodic maintenance
Routine maintenance works as listed below are performed during the scheduled summer and winter maintenance periods of the RIBF accelerators.

1) Cleaning the cooling towers
2) Checking and overhauling the cooling-water pumps
3) Checking the control system of the RIBF water-cooling system
4) Replacing some dated UPSs used for the control system of the RIBF water-cooling system
5) Cleaning the plate heat exchangers
6) Checking and overhauling the air compressor
7) Replacing some superannuated hoses, joints, and valves used in the system
8) Cleaning of the strainers and filters used in the deionized water production system
9) Extending the sensing-wires of the water leakage alarm to floors of new areas

3. Extension and improvement of the water-cooling system
A new beam transport line connecting the Intermediate-stage Ring Cyclotron (IRC) to the E5 experimental vault is now under construction, aiming at more efficient production of seaweed mutations induced by heavy-ion beams. Branches of cooling-water supply system were added to the existing system in order to supply cooling water to the magnets and other devices used in this IRC-E5 beam line. The construction of a new experimental apparatus, called SLOWRI, is also ongoing, and a new water-cooling system for SLOWRI has also been constructed. In addition, in order to raise the cooling capability of the RF amplifiers used in IRC and the Superconducting Ring Cyclotron (SRC), we plan to divide the existing supply system commonly used for IRC and SRC into two independent supply systems dedicated to each cyclotron. The present improvement will be effective for achieving high-power operation of the RF amplifiers.

4. Others
Because 30 years have passed since the construction of the Nishina water-cooling system, its deterioration is now remarkable. Performance degradation of the water-cooling system, especially in its temperature stability, is a possible source of the unstable behavior in the RIBF accelerator complex. Hence, the author recommended that the superannuated parts of the Nishina’s water-cooling system should be updated as soon as possible.

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A new set of vanes for the radio frequency quadrupole (RFQ) accelerator was commissioned using the highly charged iron beam in Brookhaven National Laboratory (BNL). To supply high intensity heavy ion beams from a laser ion source (LIS) to the RFQ, the direct plasma injection scheme (DPIS) [1,2] with a confinement solenoid was adopted. By introducing the solenoid field, the plasma expanding angle can be controlled and the capability of LIS drastically enhanced [3]. In an LIS, the peak value of beam current is inversely proportional to the cube of the plasma drift distance. In order to stretch the ion beam pulse length, a longer plasma drift length is required, which simultaneously reduces the current amplitude. The solenoid can compensate this reduction effortlessly. However, the solenoid field causes another difficulty. The fringe field of the solenoid overlaps the ion extraction area where exist a static extraction electric field and focusing RF field. Generally, when we apply a magnetic field on a high-gradient electric field, discharges may be induced. To accelerate Fe^{14+} in the DPIS set up, the nozzle emits ions that have a static voltage gap of 33.3 kV overlaid by the fringe of the RFQ field of ±20.5 kV at 100 MHz. A magnetic field of few hundreds Gauss is present in the same space simultaneously. To investigate the fields, OPERA2D and 3D [4] were used.

Figure 1 shows an example of the electric static field simulation by OPERA2D. The nozzle is filled by the laser plasma, and ions are extracted by the field gradient between the vanes and nozzle. The plasma and the extracted ion beams move along the z axis from bottom to top in the figure. The plasma sheath is formed at the top of the nozzle. Another high electric field is induced towards the end wall of the RF cavity. When we apply a solenoid field, magnetic flux of the same direction as the electric field is induced. When discharges occur, electrons emitted from the vane surface are accelerated by the electric field towards the nozzle and guided by the magnetic field. This easily triggers further discharges. To prevent this, the copper-made end wall flange, which is a part of the cavity, was replaced by a plated iron flange. Another iron-made disk called barrier flange was also installed. The magnetic field was reduced to a few gauss, as shown in the simulation in Fig. 2. This modification enabled us to apply sufficient extraction voltage on the nozzle.

Using the modified magnetic structure, we observed the accelerated iron beams at the downstream of the RFQ. The pulse width was about 1.5 µs on using a 1.0 m length solenoid field at 105 G. The RF power was adjusted to maximize the current, which was about 3 mA. The result was obtained without beam analysis behind the RFQ, and the currents include all accelerated particles. The test was not intended to obtain maximum beam current; however, we could confirm that all the devices are working as intended.

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Creation of cocktail beam from alloy target with laser†

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Lasers can create many types of heavy ions from a solid target. Therefore, with the use of a laser and an alloy target, an ion beam composed of several elements can be easily created. The cocktail beam can be used to simulate cosmic rays in a laboratory. A recent paper reported the enhancement of a plasma flux by mixing a few different types of species with an original target. However, the charge state distribution of each ion was not studied. To create a controllable cocktail beam, we investigated the charge state distributions of laser plasma from an alloy composed of Al and Fe.

Fig. 1. Schematic of experimental setup.

Figure 1 shows a schematic of the experimental setup. We used a Nd:YAG laser (1064 nm, 6 ns, 615 mJ, and 7.9×10⁻⁷ cm² spot size) for ablation. As the targets, we used pure Al, Fe sheets, and an alloy of Al and Fe (AL-FE-01-F.ALLY) with Al:Fe = 10:19 (number). The chamber was evacuated to 5×10⁻⁴ Pa. The charge state distribution was measured through a time-of-flight (TOF) method using a cylindrical electrostatic ion energy analyzer. The device was composed of two coaxial electrodes, with a slit in front of the electrodes, and a secondary-electron-multiplier detector (SEM) placed at 3.3 m from the targets. Only the particles with a specific velocity and ratio of charge to mass could pass through the electrode. In addition, we could determine the velocity of particle reaching the SEM from the time of flight. Consequently, we could obtain the ratio of charge to mass and identify the ion.

Figure 2 shows the experimentally obtained results ratios of peak ion flux from the alloy target to the peak ion flux from the pure targets. As shown in the figure, they were Al 1+: 0.5, Al 2+: 0.68, Al 3+: 0.58, Al 4+: 0.27, Al 5+: 0.27, Al 6+: 0.65, Al 7+: 0.84, Al 8+: 0.89, Al 9+: 0.34, Fe 1+: 0.72, Fe 2+: 0.60, Fe 3+: 0.51, Fe 4+: 0.65, Fe5+: 3.5, Fe 6+: 15. Total peaks up to a 4⁺ charge state of the Al and Fe ions from the alloy targets were around half those from the pure targets. Hence, the ratios of the peak value were close to the stoichiometric ratio in the target material (Al:Fe =10:19). On the other hand, the ratios of highly charged states were larger than the composition ratio; in particular, Fe 5⁺ and Fe 6⁺ were much larger than those of the other ions.

The results showed that we can control the ratio of the flux of the Al to Fe ions, except for Fe 5⁺ and Fe 6⁺, as a function of composition ratio of alloy. A large increase in Fe 5⁺ and Fe 6⁺ indicates that we can substantially increase the charge state of a specific ion using an alloy.

Fig. 2. Ratios of peaks value of Al and Fe ion flux from alloy target to those from pure targets

References
Interaction of plasmas in laser ion source with double laser system†

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A laser ion source can provide intense and low-emittance pulsed ion beams. For these advantages, various applications have been studied, such as DPIS (Direct Plasma Injection Scheme) to RFQ (Radio Frequency Quadrupole) Linac 1) and a seed-ion beam provider for the EBIS (Electron Beam Ion Source) at BNL (Brookhaven National Laboratory) 2-3). The laser ion source functions on a simple principle. Figure 1 shows the schematic layout of a laser ion source. Laser irradiation with an energy density above the target’s ablation threshold generates plasma. This plasma drifts to an extracting electrode and an ion beam is formed. A change in the laser power density on the target can adjust the produced ions’ charge states and the expanding velocity of plasma.

In conventional laser ion sources, a nano-second laser has been used. With single nano-second laser irradiation, thermal mechanisms are the dominant processes in plasma production and it results in a Maxwellian ion energy distribution. Since the plasma expands in three dimensions in the drift region from the target to the extracting electrode, an ion beam pulse width is proportional to the drift length $L$, and the peak ion beam current is inversely proportional to $L^{-3}$. Therefore, if we need a longer beam pulse width, the total peak current is steeply decreased.

A multi-pulse laser system may be used to elongate the ion beam pulse length or to intensify the beam current. To test the feasibility of these ideas, a double-pulse laser system was used in BNL.

Previous research showed that a multiple laser shot scheme is useful in extending the ion beam pulse length for a low-charge state mode. However, if the interval between the two laser is less than 10 $\mu$s, the observed current profile is not just sum of two laser plasmas 4). In this research, we carried out a more detailed study for the case in which the interval between laser pulses was less than 10 $\mu$s, in order to understand this phenomenon.

In our experiment, each laser energy on the target was 560 mJ at maximum and the laser spot was an ellipse of height 3 mm and width 4 mm. The estimated laser power density of each laser shot was between $10^8$ and $10^9$ W/cm$^2$.

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Fig. 1. Schematic layout of a laser ion source

and the induced charge states of ions were mostly single.

Ion current was measured using a Faraday cup. Two lasers were operated with various intervals of trigger timing range from 0.1 $\mu$s to 10 $\mu$s. In the measured current profile, a prominent peak that does not correspond to any single laser’s current profile was observed. Figure 2 shows a typical result. This peak had a maximum peak current for the laser interval from 1 $\mu$s to 1.5 $\mu$s and the peak height was multiplied five times. This peak appears to have formed owing to the interaction between the second laser and the neutral vapor or particles produced by the first laser.

Fig. 2. Comparison of the measured ion current profile between single-laser plasma (blue and green plots) and double-laser (red plots).

References

Control of plasma shape with pulsed solenoid on laser ion source

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A laser ion source (LIS) can supply high-current ion beams with solid target. However, the LIS typically forms a sifed-Maxwell-Boltzmann distribution in their current output. This distribution has a peaked output that does not provide constant current over the pulse length. The ability to shape the current output of LIS would increase its versatility as an ion source. In our experiments, we used pulsed magnetic fields to alter the shape of the current output and change the sifed-Maxwell-Boltzmann distribution that is typically produced.

In our experiments, we assembled the test setup shown on the right in Fig. 1. We used a 1064 nm wavelength Nd:YAG laser of Q-switch delay 250 µs and pulse energy 600mJ. Laser pulses were fired into the target chamber at an iron target. The target then ablated into a plasma consisting of ±1 iron ions and electrons. The plasma moved past 20 cm of empty space into a 12 cm long solenoid, the pulsed solenoid. The plasma then passed through drift tubes and into a Faraday cup 3.3 m away and of aperture 10 mm. We could control the time for which the pulse was fired relative to the laser’s firing time $t_p$, and the peak of the magnetic field $B_{max}$. The solenoid had turns 50, its length was 12 cm, and its radius was 44 mm.

Fig. 1: Experimental setup

The pulsed solenoid was exposed to various magnetic fields ranging from 26 gauss to 510 gauss, as shown in Fig. 2. We altered the time for which the pulsed solenoid was fired from 1µs after the laser was fired to 20 µs after the laser was fired.

Fig. 2: Supplied magnetic shape by pulsed solenoid

The obtained current shape for different delays is shown in Fig. 3. Magnetic pulses with delays ranging 15 µs and 20 µs range yielded results that appeared nearly identical to the results obtained without a pulsed solenoid. In all cases, the plasma followed the curvature of the pulsed solenoid’s magnetic field lines into the pulsed solenoid. Fig. 4 shows the maximum current for different delays and magnetic fields in our experiments. Magnetic pulses with magnitudes lower than 188 gauss also had almost no effect on the shape of the plasma that we recorded. These results show that our technique can be effective in shaping the current of LIS. We found that the solenoid field could change the beam shape. To control beam flexibility, we may need to control the pulsed field using multiple power supplies or multiple coils. Although the further studies are required, the pulsed solenoid is useful to control the beam current shape, which is a unique.

Fig. 3 current shapes for different delays

Fig. 4 Maximum current for different delays and magnetic fields

References


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Analyses of the plasma generated by laser irradiation on sputtered target for determination of the target thickness used for plasma generation†

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A Laser Ion Source (LIS) has been developed at Brookhaven National Laboratory (BNL) 1). A focused high-power laser is used to generate plasmas containing highly charged ions from solid targets. For every laser shot, we provide a new surface because the irradiation creates a crater, and the second irradiation on the same spot causes beam instability. However, the depth of the target required to generate the plasma is not yet clear. We assumed that only the surface layers of the material were converted to the plasma, and knowledge of the surface layers to be converted to the plasma is necessary to understand the initial processes of laser-ablation plasma creation. We prepared a carbon-coated aluminum plate as a target. By analyzing the contents of the ablation plasma, the effective depth required to generate the laser plasma was investigated.

The target surface was divided into four segments, and each segment has different carbon coating thickness; the thicknesses were about 25 nm, 125 nm, 250 nm, and 500 nm. To generate ablation plasma, the segmented target with multi-thickness coating was irradiated by a Nd:YAG 1064 nm focused laser (Brilliant Quantel, Energy: 728 ± 5 mJ (rms); Pulse Width: 6 ns). We analyzed the generated plasma using an electrostatic ion analyzer (EIA) and a secondary electron multiplier (SEM) to measure the current distribution of ions of each charge state 2).

Figures 1 and 2 show the charge-state distribution of measured ions of the un-coated aluminum target and 500 nm carbon-sputtered target, respectively. These current distributions were reconstructed from the signals obtained using the SEM with the scanning EIA voltage. The C⁶⁺ could be clearly separated, but C⁵⁺ and C⁴⁺ were contained by the Al¹¹⁺ and Al⁹⁺ signals.

Figure 2 indicates that the plasma was generated from the layers deeper than 500 nm because the Al ions still occupy the biggest fraction of the plasma contents. It is also noted that the C⁶⁺ ions appeared in the earliest part of the observed plasma, and the combination of Al +9 and C⁴⁺ produced the highest yield of ions at the peak position.

Fig. 3 shows the total yield of C⁶⁺ ions for each carbon-thickness case. The amount of C⁶⁺ ions was not linearly increased by the sputtered carbon thickness. The result implies that the surface layer has less contribution to form the ablation plasma. The layers from 250 nm to 500 nm were used more efficiently than the surface layer up to 250 nm depth to generate the plasma.

Using the carbon-coated aluminum target, the charge-state distribution was measured. We confirmed that the required thickness of the target for the plasma generation is more than 500 nm. We also found that the surface layer up to a few hundred nanometers in depth has less contribution than the deeper carbon layers. To investigate further, we need to prepare thicker carbon-sputtered targets thicker than 500 nm.

References
9. Instrumentation
Ion-optical measurements using uranium primary beam with different charge states

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Transfer matrix elements are essential for various ion-optical diagnoses, especially for trajectory reconstruction1) to improve the particle identification power of the BigRIPS. Thus, it is very important to measure the transfer matrix elements precisely to realize the best possible performance of the BigRIPS.

Primary beams of heavy ions such as uranium could be unique tools for measuring the transfer matrix elements because they are distributed into several charge states after passing through materials such as targets, degraders, and detectors. Such beams with different charge states have the following characteristics:

1. Small widths at position x and angle a.
2. Discrete peaks in magnetic rigidity (δ) spectrum. (Each peak is narrow and the peak position is definitely known.)
3. Same velocity for all the charge states.

Some ion-optical parameters can be measured precisely by utilizing these characteristics. Indeed, we performed such measurements in 2007 during the first BigRIPS commissioning by using uranium beams.

Positions of a 238U beam were measured with parallel plate avalanche counters (PPACs) installed in the BigRIPS foci F3, F5, and F7. The ion-optical system from F3 to F7 is a four-bend achromatic spectrometer with an intermediate dispersive focus F5. Figure 1 shows a spectrum of horizontal position x at F7 versus x at F5 of the 238U beam after it passes through the PPACs at F3. Different charge states generated by the F3 PPACs had different positions at F5 due to the F3-F5 dispersion (x|δ)35, as indicated by red (dashed) lines. The measured result was 31.5 mm/%, which is consistent with the designed value of 31.7 mm/% calculated by COSY INFINITY. Charge state transition because of the PPACs occurred at F5 also. Events connected by each blue (solid) line in Fig. 1 have the same charge state between F5 and F7. They have very different positions at F5 but have the same magnetic rigidity. This situation allows measurement of the F5-F7 magnification (x|δ)57, which corresponds to the slope of the blue lines. The measured and COSY results were 1.069 and 1.080, respectively. Each green (dash-dot) line in Fig. 1 indicates events of the same charge state transition (∆Q) at F5. The vertical distances of the green lines indicate the F5-F7 dispersion (x|δ)57. The measured and COSY results were -32.9 mm/% and -34.2 mm/%, respectively. Because the slope of the green lines is (x|δ)35/(x|δ)57, the green lines become horizontal due to the achromaticity of the F3-F7 optical system. Indeed, the F3-F7 dispersion of -1.1 mm/% deduced from the slope of the green lines was small.

Charge states are also useful to measure the (ℓ|δ) parameter, where ℓ is a flight-path-length difference with respect to the central orbit. Because all the charge states have the same velocity, ℓ can easily be deduced by the time-of-flight (TOF) measurements. Figure 2 shows the TOFs from F3 to F7 as a function of δ measured by plastic scintillators at F3 and F7 with 238U primary beam. Different charge states were generated by the F3 scintillator. BigRIPS was tuned so that the 90+ charge state came at the center of F3, F5, and F7. 89+, 90+, and 91+ charge states were selected individually with slits at the dispersive focus F5. The (TOF|δ) value was obtained as -0.0498 ms/% by a quadratic fitting, indicated by a solid curve in Fig. 2. Then, (ℓ|δ) was estimated as -10.2 mm/%, while the COSY result was -6.53 mm/%.

References

Fig. 1. Spectrum of F7-x vs. F5-x measured with a 238U primary beam after it passes through PPACs at F3. Red and blue lines have information on the F3-F5 dispersion and the F5-F7 magnification, respectively. The F3-F7 dispersion and the F5-F7 dispersion can be deduced from green lines.

Fig. 2. Measurement of (ℓ|δ) with primary beams. TOF from F3 to F7 was measured for each charge state by selecting the charge state with the F5 slits. The solid curve represents a quadratic fitting, and the slope corresponds to (ℓ|δ).
Database of radioactive isotopes produced at the BigRIPS separator

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We have been developing a database of radioactive isotopes (RI) produced at the BigRIPS separator1). The RI database entries include the following information:

- Production cross section
- Production yield
- Calculated value by LISE++ code2)
- Experimental conditions
  - Primary beam
  - Target
  - Device settings
  - Magnetic rigidities
  - Measurement date
- Publication list
  - Title
  - Journal
  - First author
  - Journal digital object identifier (DOI)
  - Produced RI beam(s)
- Isomeric nucleus
  - Gamma ray energy
  - Half life

All entries are stored in a relational database that is based on Microsoft Access 2010.

The RI database is synchronized with a web site. The web site is coded using PHP. The top panel of Fig. 1 shows the web interface of the RI database. The RI database consists of nuclides, which includes RIs produced at the BigRIPS separator. RIs differentiated using red color text. The bottom panel of Fig. 1 shows an example, 128Pd isotope. The production cross section and yield together with calculated value by LISE++ code are listed. Two journals about 128Pd are also shown there. The detailed BigRIPS setting for 128Pd can be accessed through the hyperlinked ID value, 80.

This web site also has a retrieval interface. This search allows a Boolean search over several categories (mass number A, atomic number Z, neutron number N, and so on). The results of search are listed on the user’s browser. Furthermore, the cross section file for LISE++ and figures of production cross sections and production yields can be obtained from the result searches.

The RI database and its web site assist on RIBF user to design RI beam experiments using the BigRIPS separator. Work on the system is currently ongoing and it is planned for practical implementation in the near future.

References
Extraction of 3D field maps of magnetic multipoles from 2D surface measurements†

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In large-aperture, short-length magnets with strong magnetic fields, such as superconducting triplet quadrupole (STQ)† magnets in the BigRIPS2) magnets in the BigRIPS, the fringing field region is generally very large, and the shape and effective length of the magnetic field distribution change with the excitation current due to saturation of the iron core. Further, higher-order pseudo terms become relatively large in these magnets compared to those in small-aperture, long-length magnets because they originate from the changes of the magnetic field in the direction along the beam axis. It is indispensable to correctly extract pseudo quadrupole components as well as first-order quadrupole components from measured 3D field maps even for first-order ion-optical simulations.

Pseudo terms have the same azimuthal angle dependence as that for the leading term, such as \( \cos 2\theta \) for a quadrupole, but have a higher-order radial dependence, such as \( r^3 \) rather than \( r \) for a quadrupole. At first glance, it appears that field map data measured at different radii are required to solve the \( r \) dependence. However, we present a practical numerical method that eliminates the need for this data. In this method, the measurement data for one radius of one component in the cylindrical coordinates, i.e., 2D field measurements on the surface of a cylinder, are sufficient to determine the full 3D magnetic multipole field in the cylinder. Using this novel method, we can extract the distributions along the beam axis for the coefficient of the first-order 2n-pole component \( b_{n,0}(z) \), which is the leading term of the 2n-pole components in the multipole expansion of magnetic fields. Higher-order pseudo components \( b_{n,m}(z) \) can be deduced from the leading term via recursion relations. The full 3D field map of 2n-pole is completely described by these components. See the original paper† for details about the formalism and procedure of the method. Steps of the process of extraction of full 3D field maps of magnetic multipoles from 2D surface measurements are summarized in Fig. 1.

The proposed method was applied to large-aperture STQ magnets in the BigRIPS fragment separator at the RIKEN Nishina Center RI Beam Factory. Figure 2 shows the leading term \( b_{2,0}(z) \) together with the pseudo terms \( b_{2,1–4}(z) \), which were obtained from the measurement result of \( B_{2,2} \) at 100 A. Here \( b_{2,1} \) is relatively large, showing that the pseudo terms cannot be ignored.

The obtained \( b_{2,0}(z) \) distributions were parametrized using the Enge functions to fit the fringe field shapes at all excitation current values, so that unmeasured values are interpolated. We implemented these parameters in the ion-optical calculation code COSY INFINITY3) and realized a first-order calculation that incorporates the effect of large and varying fringe fields more accurately.

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Radiation damage of plastic scintillation counter

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We studied radiation damage of a plastic scintillation counter in an isospin diffusion experiment (NP0709-RIBF42-01) using the BigRIPS separator1) of RIKEN RIBF. Heavy-ion cocktail beams (108Sn, 107In, 106Cd) with high intensity (0.7~1 MHz) were produced by projectile fragmentation of a 124Xe beam at an energy of 345MeV/nucleon.

Figure 1 shows the experimental setup of the scintillation counter at F3 of the BigRIPS separator1). To change the position of the scintillation counter after radiation damage, the movable ladder stage was designed to be remotely operated during the experiment. The EJ-212 scintillation counter2) was used in an isospin diffusion experiment with a high-intensity beam, and the position of the scintillation counter was changed after 50% damage, which was identified by checking the relative peak position of the light output.

![Fig. 1. Experimental setup of the scintillation counter](image)

The radiation damage was reported with respect to the absorbed dose. The radiation absorbed dose was calculated using Eq. 1. A dose of one Gray is equivalent to a unit of energy [J] deposited in a kilogram of a substance.

\[
Dose[\text{Gy}] = \frac{N_{\text{beam}} \cdot \Delta E \cdot R_{\text{beam}}}{\text{volume} \cdot \text{density}}, \tag{1}
\]

where \(N_{\text{beam}}\) denotes beam intensity, \(\Delta E\) is the energy loss of isotopes at the scintillation counter, and \(R_{\text{beam}}\) is the ratio of the number of events taking place in an exposed volume to the total number of events taking place at the scintillation counter. The volume is defined as 10×6×0.2 mm³ after checking the beam spot size by the beam profile, and the density of the EJ-212 scintillator2) is 1.023 g/cc.

To define the exposed area, the concentrated irradiation region of the scintillation counter was determined using the beam profile shown in Fig. 2. Fig. 2(a) shows a scatter plot of beam profile and (b) and (c) show the \(x\) and \(y\) distributions of the beam, respectively.

![Fig. 2. Beam profile: (a) scatter plot of beam profile and (b), (c) shows \(x\) and \(y\) distribution of beam, respectively.](image)

black square box in Fig. 2(a) indicates the defined exposed area, which is the concentrated irradiation region with 96.3% isotopes. The energy loss of isotopes at the scintillation counter was calculated with the ratio of the cocktail beams as 108Sn:107In:106Cd = 2.51%: 74.0%: 22.86%. It is noteworthy that the ratio of isotopes rarely influences the energy loss calculation because the difference of energy loss between isotopes is only in the range of 2-3%.

Figure 3 shows the results of a relative light output as a function of the accumulated dose. The relative light output is defined as the relative peak position of the light output before and after irradiation. It is clearly seen that the light output decreases with the increase in the accumulated radiation dose at all the different positions, and a similar decreasing tendency is found at all the positions. The results indicate that about 50% radiation damage of the EJ-212 scintillation counter occurs at an accumulated dose of 12×10³ Gy.

![Fig. 3. Relative light output as a function of the accumulated dose. The different colors indicate different positions on the scintillation counter.](image)

References
2) http://www.eljentechnology.com/
Development of the fast interlock system at the BigRIPS separator


A beam interlock system is particularly important for protecting beam line devices from the failure of magnets and other devices. The failure of beam line magnets can lead to the miss-steering of the beam and the beam might hit the beam pipe or other devices mounted along the beam line. If the beam power is high, such unexpected beam irradiation can cause serious damage to devices. The $^{238}$U beam with an energy of 345 MeV/nucleon and the intensity of 1 particle $\mu$A can melt stainless steel even in 1 ms if it is focused at a diameter of 2 mm. In order to prevent damage, the beam should be stopped as soon as possible. The Beam Interlock System (BIS)1,2) is installed at RIBF for this purpose. The BIS monitors the normal operation of devices and sends a beam-stop signal to the beam chopper installed at the exit of the ion source when a device fails. The beam chopper stops the beam within a few microseconds upon receiving a stop signal. The total response time of the existing BIS is only several milliseconds since the system uses Programmable Logic Unit (PLC) as signal processing. To cope with high-power beams extracted from the Superconducting Ring Cyclotron (SRC) at RIBF, the response time of the existing interlock system is currently inadequate and hence, a new interlock system with a fast response is developed.

A prototype of the fast interlock system with 4 analog inputs and 8 logic inputs has been developed to evaluate the speed of the response. In order to achieve a fast response time, a compact RIO system (cRIO), cRIO-9075 of National Instrument Co. Ltd. is utilized as the processing unit. The cRIO consists of a CPU and a field-programmable gate array (FPGA) that are closely related to each other. The FPGA allows a fast response between the input and output and the CPU provides versatile control of the unit. A fast sampling ADC module, NI-9222 with 500 k sample/sec, is used for analog inputs, and fast digital I/O modules, NI-9401 with 100 ns propagation delay, are used for logical inputs and outputs. Fig. 1 shows the block diagram of the interlock logic. As seen in the figure, an analog input is digitized in the ADC and compared with pre-defined upper and lower limits; the fault output is produced if the digitized value exceeds those limits. The fault output is then masked with an enable/disable flag and latched in a Set-Reset flip-flop in order to hold a fault situation. A logic input is exclusive-or'd with a polarity flag and latched in the same way. The values in the flip-flops are or'ed together to produce a failure output. These control logics are stored in the FPGA of the cRIO and executed at a fast speed. The CPU of the cRIO is used as the interface to the comprehensive control system of the BigRIPS3) that utilizes EPICS4) as the base. Statuses of faults and digitized values of the analog inputs are monitored by the control system of the BigRIPS. The upper and lower limit values of the analog input and input masks are dynamically set from the control system. The programming of cRIO is performed in a LabVIEW developer environment.

The response speed of the prototype of the fast interlock system was measured with a test signal. A step signal was inputted to the logical and analog input and the time delay between the input and output signals was measured. The response times are 0.2 $\mu$s for logical inputs and 5 $\mu$s for analog inputs. These are sufficiently fast for the fast interlock system. The prototype was also examined with the actual current monitor signal of the power supply of the first dipole magnet at BigRIPS. The current monitor signal was connected to one of the analog inputs and the digitized value was monitored. The digitized value was fluctuated within 0.25% due to the noise that appeared in the monitor signal. This is similar to the value compared with the hardware comparator built in the power supply to detect the output current drift.

Based on the successful test results on the prototype, the fast interlock system of the BigRIPS has been designed to monitor the analog and logical signals from power supplies of the 34 magnets placed at the primary beam line and the BigRIPS where a high-power primary beam is transported. The system consists of 4 cRIOs and sends the beam stop signal to the beam chopper as well as BIS. The fabrication of the system will be completed by the end of March 2014 and the system is expected to be operational by the end of July 2014.

References

Fig. 1 Logic diagram of the prototype of the fast interlock system.

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Energy resolution of a gas ionization chamber for high-energy heavy ions†

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Gas ionization chambers are used for the BigRIPS spectrometer to identify the atomic number of the flight particles by using the energy deposition.1,2) Since the key parameter of the detector in this application is its energy resolution for heavy ions, an understanding of the energy resolution behavior of high-energy heavy ions is essential in discussing the particle identification performance. We report the energy resolution of the gas ionization chamber for heavy ions from the atomic number Z=31 up to Z=52 at low counting rates below 1 kcps, and which have an energy of nearly 340 MeV/nucleon.

The ionization chamber is installed at the F7 focal plane of the BigRIPS1) spectrometer, which is operated using a counting gas mixture of Ar(90%)+CH₄(10%) at approximately 760 Torr. The effective gas thickness of 48 cm is divided into six segments, and energy spectra can be obtained for every 8 cm of gas thickness.2) The dependence of energy resolution on the gas thickness is plotted in Fig. 1. As an example, we show the analysis results for ions Z=38 and Z=51. With the horizontal axis scaled as the inverse-square-root of the gas thickness, L⁻¹/₂, a linear relationship is observed, as shown by the solid linear-fitting result lines; this observation is in good agreement with the experimental data. We conclude that the energy resolution is linearly dependent on L⁻¹/₂. These results indicate that the energy resolution, Ω/ΔE, is expressed by statistical fluctuations in the energy loss, i.e., the energy straggling of heavy ions, Ω, and the mean energy deposition within the gas, ΔE, which are explained by the Bohr expression (Ω ∝ ZL⁻¹)2) and the Bethe-Bloch formula (ΔE ∝ Z²L), respectively.3,4)

In Fig. 2, we plot the energy resolution as a function of the heavy ion atomic number for the cases of L=24 cm ≡ L₁ (open circles) and L=48 cm ≡ L₂ (solid circles). According to the Bohr expression Ω is also proportional to the incident ion atomic number, Z. Therefore, the energy resolution, Ω/ΔE, should be proportional to Z⁻¹ because ΔE ∝ Z². The solid and dotted lines show the fitting results of CZ⁻¹, where C is the fitting parameter. The best-fit parameters were found to be C₁ = 61.2±1.2 and C₂ = 43.5±1.0 for L₁ and L₂, respectively. The ratio of these values is C₁/C₂ = 1.41±0.04, which shows excellent agreement with the value of (L₁/L₂)⁻¹/₂ ≈ 1.41. This result is consistent with the above discussion, Ω/ΔE ∝ L⁻¹/₂.

In future works, the experimental energy resolution data for heavier ions up to uranium (Z=92) are required to discuss the performance of the ionization chamber for the identification of these heavy ions. In addition, the performance at high counting rates up to 1 Mcps is still unclear and requires further investigation.

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Development of intense $^{22}$Na beam for application to wear diagnostics


The industrial cooperation team in RIKEN and SHIEI Ltd. are developing a method for application to the wear diagnostics of industrial materials using RI beams as tracers. RI nuclei are implanted in the near surface of machine parts within a depth of 100 μm, and the wear-loss of the near surface is evaluated by the decrease in the measured radioactivity. Continuous γ-ray detection from outside the machine enables real-time diagnostics of wear in running machines. For this purpose, we studied intense RI beams of $^{22}$Na ($T_{1/2} = 2.6\text{y}$) at the RIPS separator with an energy of 26.6 MeV/u, and $^{18}$Be ($T_{1/2} = 53\text{d}$) at the CRIB separator with an energy of 4.1 MeV/u. From the point of view of beam cost and beam-time flexibility, the low-energy RI beam production at CRIB using the AVF cyclotron independently is favorable. Then, we studied a low energy $^{22}$Na beam production using CRIB.

The $^{22}$Na beam was produced via the $p( ^{22}\text{Ne},^3\text{He})^*\text{Na}$ reaction. A primary beam of $^{22}\text{Ne}7^+$ with an energy of 6.1 MeV/u and intensity of 0.3 μA was introduced to the cryogenic gas target. The H$_2$ gas at a pressure of 400 Torr was cooled to 90 K and was circulated to the gas cell at a rate of 17 slm. The primary beam was focused on a Havar foil placed at the entrance of the gas cell with a spot size of diameter 1 mm. The target was stable during this experiment. The produced $^{22}$Na beam was introduced to the F2 focal plane without a degrader foil at F1. Contaminant nuclei of $^{19}\text{F}9^+$ (stable) and $^{22}\text{Ne}10^+$ (primary beam) were then observed (Fig. 1). The $^{22}$Na beam had two components with different charge states: $q=10^+$ and $11^+$. Because the $^{22}$Na$^{10^+}$ component had large $^{22}$Ne$^{10^+}$ contamination, we have investigated the optimum magnetic rigidity for the $^{22}$Na$^{11^+}$ beam.

The magnetic rigidity of the CRIB separator was scanned in the range of 0.53 – 0.59 Tm (Fig. 2). At the optimum condition of 0.5535 Tm, the energy and radius of the $^{22}$Na$^{11^+}$ beam were 81.2 MeV (3.7 MeV/u) and $\sigma = 1.6 \text{ mm}$, respectively, with a momentum slit of ± 3.1% (± 50 mm) at F1. The $^{22}$Na beam was 78 % in purity. The intensity was $3.1 \times 10^7 \text{ pps}$ and was obtained by the following γ-ray measurement. To investigate the implantation-depth profile of $^{22}$Na, a stack of 2-μm-thick aluminum foils with 16 mm diameter were irradiated. After irradiation, the stack was disassembled and the intensity of the γ ray ($E_\gamma = 1274 \text{ keV}$) was measured using a Ge detector. From the obtained profile, $^{22}$Na was implanted in aluminum at 38 ± 6 μm with a total approximate activity rate of 0.9 kBq/1h irradiation.

Fig. 2 $^{22}$Na$^{11^+}$ beam intensity dependence on the magnetic rigidity.

The total activation rate of $^{22}$Na$^{11^+}$ beam using RIPS was 5 kBq/1h irradiation, which is five times greater than the intensity of CRIB. However, this difference is nearly compensated with the difference in beam production cost between RIPS+RRC and CRIB+AVF.

References
Development of ion-optics mode for the SAMURAI beam line

H. Suzuki,*1 T. Kubo,*1 H. Takeda,*1 H. Sato,*1 N. Inabe,*1 N. Fukuda,*1 D. Kameda,*1 and Y. Shimizu*1

We have developed an ion-optical mode for the SAMURAI beam line, which connects the SAMURAI spectrometer1) to the BigRIPS separator2). The schematic view is shown in Fig. 4 of Kobayashi et al. (2013)1). There are four standard focal planes: F7, which is the last focal plane of the BigRIPS separator; F8; F12; and F13, which is the reaction target position of the SAMURAI spectrometer. There are two STQ magnets3) between F7 and F8, and two between F8 and F12, while only one STQ is located between F12 and F13. The beam shutter between F7 and F8 and the D7 dipole magnet for the ZeroDegree spectrometer restrict the space in the vertical direction in this beam line. To diagnose the beam emittance, we use the PPAC detectors at F7, F8, and F12, and beam drift chambers at F13.

In order to fabricate the beam optics of the SAMURAI beam line, two problems need to be resolved. First, there is only one STQ between F12 and F13; therefore, stronger magnetic fields are required for focusing the beam at both F12 and F13. Second, the beam envelope inside the D7 magnet in the vertical direction needs to be made thin, because the gap in D7 is ±61 mm. To solve these problems, we focus the beam inside the D7 magnet instead of on F8 and F12. At F8 and F12, the beam is set to parallel. This makes it easier to diagnose the beam optics using the PPAC detectors and adjust the magnetic field of each quadrupole magnet. The magnification from F7 to the focal point inside the D7 magnet in the vertical direction is set to be around 2 to reduce the angular magnification and make the beam envelope thinner. The beam trajectories for the SAMURAI beam line are shown in Fig. 1. The position and angular spreads at F7 are set to be ±6 mm and ±10 mrad, respectively, in both the horizontal and vertical directions, which are the typical root-mean-square (r.m.s.) values for the fragments produced from light projectiles such as 18O and 48Ca. Table 1 summarizes the transfer matrices from F7 to F8, F12, and F13. The matrices in the horizontal direction \[
\begin{pmatrix}
(x|x) & (x|a) \\
(a|x) & (a|a)
\end{pmatrix}
\] and those in the vertical direction \[
\begin{pmatrix}
(y|y) & (y|b) \\
(b|y) & (b|b)
\end{pmatrix}
\] are shown in the left and right columns, respectively.

From May 2012, we have used this ion-optics mode for transporting the secondary beams to the SAMURAI spectrometer. The typical r.m.s. spot size at F13 was around 10-15 mm, when the r.m.s. spot size of F7 was 6 mm. In such a case, the transmission efficiency from F7 to F13 is around 90%.

Table 1. Transfer matrices from F7 to F8, F12, and F13.

<table>
<thead>
<tr>
<th>beam line</th>
<th>horizontal</th>
<th>vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7-F8</td>
<td>-0.99 4.28</td>
<td>-2.80 2.20</td>
</tr>
<tr>
<td>F7-F12</td>
<td>0.76 -2.99</td>
<td>0.85 -2.20</td>
</tr>
<tr>
<td>F7-F13</td>
<td>0.33 0.00</td>
<td>0.45 0.00</td>
</tr>
<tr>
<td>F7-F13</td>
<td>1.86 0.00</td>
<td>2.16 0.00</td>
</tr>
<tr>
<td>F7-F13</td>
<td>-0.43 0.54</td>
<td>-0.66 0.46</td>
</tr>
</tbody>
</table>

Fig. 1. Beam trajectories from F7 to F13. F13 is the reaction target position of SAMURAI. Top and bottom panels show the trajectories in the horizontal and vertical directions, respectively. The position and angular spreads at F7 are ±6 mm and ±10 mrad, respectively, in both the directions. The box triplet shows each STQ magnet.

References

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Operational status of the superconducting SAMURAI magnet

H. Sato,*1 K. Kusaka,*1 M. Ohtake,*1 Y. Shimizu,*1 K. Yoneda,*1 and T. Kubo*1

Operation of the superconducting SAMURAI magnet was started in June 2011, and experiments using the SAMURAI spectrometer was started in March 2012.1,1 So far, a commissioning and five experiments have been performed.2–6 During this period, we had maintained the operation of the cryogenic system of the magnet and overhauled the cryocoolers in October 2012.7 However, the operation policy for the magnet was changed from “continuous cooling” to “irregular cooling” in order to save the operation time of the cryocoolers, where “irregular cooling” means that the magnet will be cooled down for every SAMURAI campaign experiments and warmed up after the experiments. Thus, the operation of the magnet was stopped temporarily in September 2013. In this report, the alteration in the temperature of the magnet when it was stopped is shown.

The upper and lower superconducting coils are installed in two separate cryostats and cooled by the liquid helium bath cooling method.7,8 Each cryostat is equipped with one 4-K GM/JT cryocooler, which condenses the evaporating liquid helium. The 20-K as well as 80-K thermal shields are cooled by two GM cryocoolers. Each cryostat is equipped with another GM cryocooler that cools the power leads made by a high-Tc superconductor.

The warming-up procedure was started by stopping these cryocoolers. In order to keep the recovery volume of the liquid helium within the load limit of the recovery compressor at RNC Liquid Helium Plant, the warming-up timing of the lower cryostat was delayed. As a result, the liquid helium was fully recovered, 215 L in 37 h and 227 L in 34 h from the upper and lower cryostats, respectively.

The temperature rise at the major points in the cryostats is shown in Fig. 1. In the figure, the structure is seen when the temperature of the coil vessels exceeded 77 K (Fig. 1(a)). This is because of the heat exchange between the coil vessels and other parts, which happened when the condensed residual atoms such as nitrogen at the outer wall of the coil vessels evaporated into the vacuum layer of the cryostat.

Figure 1(a) shows the temperature of the coil vessel, which corresponds to the cold mass of the cryostat. The cold-mass weight of each cryostat is about 3.5 ton, and it took about 48 and 41 days to reach room temperature for the upper and lower cryostats, respectively. The speed of the temperature rise for the lower cryostat was faster than that for the upper cryostat at all points, as shown in Fig. 1. This is assumed to be due to the difference of the heat load, which results from the difference of the length of the chimney pipe between the liquid helium reservoir vessel and the coil part of the cryostat (see Fig. 1 in Sato et al.7).

Fig. 1. Temperature rise at each point: (a) coil vessels, (b) 20-K cryocoolers, (c) 80-K cryocoolers, and (d) cryocoolers for power leads. The cryocoolers of the upper and lower cryostats were stopped on 9/18 and 9/25.

References
6) H. Otsu et al.: In this report.

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Vacuum system for the SAMURAI spectrometer†

Y. Shimizu,*1 H. Otsu,*1 T. Kobayashi,*1,†2 T. Kubo,*1 T. Motobayashi,*1 H. Sato,*1 and K. Yoneda*1

The first commissioning experiment of the SAMURAI spectrometer1 and its beam line was performed in March, 2012. The vacuum system for the SAMURAI spectrometer includes its beam line and the SAMURAI vacuum chamber with the windows for detecting neutrons and charged particles.

The window for neutrons is made of 3 mm-thick stainless steel designed in the shape of a partial cylinder to support itself against atmospheric pressure. The deflection of the window caused by the pressure difference and the induced stress are calculated using the general purpose finite element analysis program code ANSYS2. Figure 1 shows the ANSYS calculation result. The calculated displacement by the atmospheric pressure at the central region and the maximum induced stress are 0.17 mm and 44 MPa, respectively. It should be noted that the latter is smaller than 1/10 of the tensile strength. This window is achieved a safety factor of 12.

![Fig. 1. ANSYS calculation result for the shape of a partial cylinder with a thickness of 3 mm.](image)

The window for charged particles was composed of a combination of Kevlar and Mylar with thicknesses of 280 and 75 µm, respectively. The Kevlar and Mylar were glued with an Araldite® to the top of the window frame, which is made of SUS304. The open geometry of the exit window of the vacuum chamber is 2800 × 800 mm², while a 2800 × 400 mm² window was used in the commissioning experiment. This was a result of tradeoff between the experimental requirement and the safety and risk management for the breaking of the window. The deflection and stress for the Kevlar textile are calculated by ANSYS. Since the elastic properties of the Kevlar textile are not known, they are determined to reproduce the vacuum test. In order to reduce the displacement and elongation of the Kevlar textile, we performed a calculation considering a flexure of 193 mm in the initial condition. The result is shown in Fig. 2. The displacement and elongation of the Kevlar textile are 73 mm and 6.3%, respectively.

![Fig. 2. ANSYS calculation result for Kevlar textile with a flexure of 193 mm in the initial condition.](image)

In order to have a flexure of 40 mm around the center region in the initial condition, both sides of the Kevlar and Mylar were slacked by about 5 mm. The flexure of 40 mm was determined to be the maximum flexure without inducing wrinkles in the Mylar at the corners. The maximum deflection around the center region was estimated to be approximately 60 mm. This indicates that the Mylar elongated about 3.2% due to air pressure, which was 1/3 smaller than that of the tensile elongation at the break. Since this window is achieved a safety factor of only 2.8, the window materials have to be replaced every year for reasons of safety.

The deflections of these windows by visual observation were consistent with the ANSYS calculation results. The pressure in the SAMURAI vacuum chamber was successfully maintained at a few Pa during the commissioning experiment without any problems caused by the windows.

References
2) URL: http://www.ansys.com/

† Condensed from the article in Nucl. Instrum. Meth. B 317, 739 (2013)
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Full-size partition window for the SAMURAI spectrometer

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For future SAMURAI experiments measuring coincident heavy fragments and light charged particles, light charged particles are fully spread on the exit window of the SAMURAI spectrometer. In order to detect light charged particles efficiently, the vacuum partition window should have a maximum vertical size of 800 mm. In this report, the design and development of a full-size partition window for the SAMURAI spectrometer are described.

The window material deflects penetrating particles by multiple scattering and causes their energy fluctuation by energy loss struggling. At the same time, it is necessary to ensure that the material is strong enough to hold the vacuum. The vacuum partition is of the combination of a Kevlar textile for tensile strength support and a Mylar foil for vacuum partitioning. The thicknesses were 280 and 75 μm, respectively. The deflection of the Kevlar textile caused by the pressure difference and the induced stress is calculated by the general purpose finite element analysis program code ANSYS†. Since the elastic properties of the Kevlar textile are not known, they are determined to reproduce the vacuum test‡. Figure 1 shows the results of ANSYS calculation of the displacements for the several flexures in the initial condition. At a larger flexure than 150 mm in the initial condition, the displacement becomes small enough. We determined a flexure of 155 mm in the initial condition.

Because of wrinkles of the Mylar at corners, a flat window cannot have larger flexure than 100 mm‡. In order to have large flexure in every position, a window was designed having the shape of a partial cylinder with a radius of curvature of 715 mm. Figure 2 shows a drawing of the full-size partition window for the SAMURAI spectrometer. A flexure of 155 mm in the initial condition was achieved. The Kevlar and the Mylar were glued with an Araldite to the side pipe of the window frame. Owing to the pipe structure, every adhesion side was perpendicular to the direction in which the Kevlar and Mylar were pulled by the pressure difference.

This window was mounted on the test vacuum chamber. The achieved vacuum level was a few kPa. Figure 3 shows a photograph of the full-size partition window on the test vacuum chamber. The deflection was about 10 mm by visual observation. Therefore, since the Mylar foil is hardly extended, there is no fear of it collapsing. However, because this value differs from the ANSYS calculation, it may be necessary to improve the boundary condition in the ANSYS calculation.

References
1) URL: http://www.ansys.com/

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*2 Department of Physics, Tohoku University
Development Of Multiple-Particle Tracking Algorithm For Forward Drift Chamber In SAMURAI

M. Kurata-Nishimura,*1 H. Otsu,*1 and T. Isobe*1

The Superconducting Analyzer for MUlti-Particles from Radionisotope Beam (SAMURAI)1 has been playing an important role in studying unstable nuclei in RIBF since 2012. In April 2013, 16C(α,α') experiment2 was carried out to investigate a degree of freedom for an exotic cluster which appears above an α emission threshold in high excited states. In the SAMURAI spectrometer, four momenta of α and a residue were measured simultaneously to reconstruct the invariant mass of the excited states. Thus far, no result has been obtained for multiple charged particle tracking, the primary issue being that track reconstruction takes a long CPU processing time to find a true hits combination from numerous hits combinations. With this algorithm, a new framework and is described here.

In the SAMURAI spectrometer, two Forward Drift Chambers (FDC1 and FDC2) are installed to reconstruct the tracks of scattered reaction residues in the forward direction. FDC1 and FDC2 are located upstream and downstream of the SAMURAI dipole magnet, respectively. Each FDC consists of three kinds of wire orientation planes referred to as X, U, and V planes, and two planes of the same type are placed next to each other. This pair of two planes is hereafter called a super pair plane. In the X plane, the wires are parallel to the Y axis and, in the U and V planes, the wires are tilted +30° and −30°, respectively to resolve the three-dimensional flight path. The planes are assembled in the order of X, X’, U, U’, V, V’, X, X’, U, U’, V, V’, X, and X’ in FDC2 and in the opposite order in FDC1.

In the beginning, reliable hits on each plane are selected. When a charged particle passing through ionizing gases around a wire, a δ-ray or X-ray would generate signals on adjacent wires. Since a real hit signal reaches the wire faster than fake ones, it can be chosen as the fastest timing signal delivered from a multiple hit TDC on a common stop mode.

Using these candidates, two hits on the super pair plane are coupled if the difference between the hit wire positions is within the pitch size of the wires. Multiple use of a hit is allowed. Even if a hit is not associated in the super pair plane, it can be used with the same method for coupled hits in the following analysis.

With considerat all combinations of coupled hits among X planes, a track in X-Z plane is evaluated by a linear fitting. If the number of hits included in a track is more than 4 and if χ^2 divided by the number of degree of freedom (NDF) is within 10%, the track information is stored as a candidate. Then, a precise hit position on the plane is calculated from the drift time for the candidate tracks. Two possibilities, i.e., whether the particle passed through in the left side or right side of the wire, are resolved by calculating the minimum χ^2 configuration.

The track reconstructed in the X-Z plane is projected onto the U and V planes, and the wire positions in the Y axis are evaluated. By combining the Y position on these planes, a linear fitting is applied for them with spatial resolution of the wire pitch size. If the χ^2/NDF is less than 1, the ambiguity of the left or right side path is resolved in the same manner as in X-Z plane.

As a result, three-dimensional multiple tracks in FDC1 were reconstructed as shown in Fig.1. In this event, two tracks were found in both FDC1 and FDC2 independently. Tracks reconstructed without bias caused by other detectors enable us to estimate the intrinsic tracking efficiency. This code is applicable for any experiments performed in the SAMURAI spectrometer.

Fig. 1. Two reconstructed tracks in FDC1. Top and bottom figures show the track in the X-Z plane and Y-Z plane, respectively. The color of the linear fitting function indicates correspondences.

References
2) H. Otsu, et. al.: In this report

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Effect of stray field of the SAMURAI spectrometer on the neutron detector array WINDS

Y. Kubota*1,*2 and M. Sasano*2

The $(p, n)$ reaction has been used as a powerful probe to study nuclear isovector responses such as Gamow–Teller transitions, as extensively done in the region of stable nuclei1). The extension of such studies to unstable nuclei can be realized by combining the neutron detector array WINDS2) with the SAMURAI spectrometer3) for measuring high-intensity radioactive ion beams at the RIKEN RIBF.

From an experimental point of view, however, there is concern that the stray field of the SAMURAI magnet may deteriorate the gain of photomultiplier tubes (PMTs) of the WINDS bars. It is well known that the effect of the stray field is maximized when the direction of the magnetic field is parallel to that of the PMT. In this experiment, we examined this effect with several magnetic settings and also tested the restoration of gain with additional magnetic shielding on PMTs.

One of the WINDS bars was vertically placed near the entrance of the SAMURAI spectrometer. Thus, the PMTs (Hamamatsu H7195) attached at both ends of the bar are also aligned vertically. The direction of the stray field can also be considered more or less vertical, and the strength is large around the PMTs. Therefore, this setup provides the most severe gain-deterioration conditions. In the present work, three settings — (i) without any additional shielding, (ii) with one-fold shielding, and (iii) with two-fold shielding — were tested, as shown in Fig. 1. The magnetic field settings were 1.6, 2.2, 2.9, and 3.0 T. For these settings, the stray field at the location of the PMT was measured to be 0.5, 0.7, 4.5, and 6.0 mT, respectively.

The left panel of Fig. 2 shows the light output spectra of $^{137}$Cs for 2.2 T. The relative gain was calibrated with the Compton edge of the 661.7-keV $\gamma$-ray emitted from $^{137}$Cs. For each spectrum, we assumed the position corresponding to 70% of the maximum height as the Compton edge. The relative gain of the PMT decreased to 28% at 2.2 T when no additional shielding was used. With the addition of one-fold shielding, the relative gain was restored up to 97%. It was also confirmed that a relative gain of 92% or more can be achieved up to 2.9 T by using two-fold shielding, if necessary. However, at 3.0 T, a relative gain of 59% was obtained even with two-fold shielding. This is because of the drastic increase of the stray field due to the saturation effect of the iron yoke of the SAMURAI magnet around 3 T4).

The right panel of Fig. 2 shows the light output spectra of $^{241}$Am. Gamma rays of 60 keV from $^{241}$Am produce almost the same light output as 100-keV neutrons. The spectrum was strongly distorted when the magnetic field was changed from 2.9 to 3.0 T because of the same reason as stated above. Below 2.2 T, the effect of the distortion can be made negligibly small with at least one-fold shielding.

In summary, the additional one-fold or, at most, two-fold magnetic shielding is sufficient to restore the gain for the SAMURAI magnet settings up to 2.9 T, but at 3.0 T, shielding of more than three-fold or thicker will be necessary. Thus, the setting of 2.9 T is practically much better than that of 3.0 T for the similar setup with PMTs, if there is no significant difference between 2.9 and 3.0 T in the performance of the SAMURAI spectrometer.

We acknowledge H. Sato for his support with the operation of the SAMURAI magnet.

Fig. 1. Schematic view of the additional shielding consisting of 2-mm-thick iron (SUY-1). We use only inner (a) as a one-fold, and both (a) and (b) as a two-fold shielding.

Fig. 2. Left panel shows light output spectra of $^{137}$Cs without additional shielding (purple) and with one-fold shielding (green) at 2.2 T. Black line shows that at 0.0 T. Each vertical line shows the position of each Compton edge. Right panel shows light output spectra of $^{241}$Am with two-fold shielding at 0.0 T (blue), 2.9 T (green), and 3.0 T (red).

References
Development of a silicon detector array with large dynamic range

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We have developed an array of strip silicon detectors for the Coulomb beakup experiments with proton-rich heavy nuclei at intermediate energies. The breakup reaction, where the final state consists of one or two protons and the residual heavy charged particle, is an inverse reaction of the radiative proton capture and has been considered one of the most promising methods to extract the reaction rate of the capture process. The extracted rate gives us insight into the nucleosynthesis through the rp process, consisting of sequential proton captures on nuclei for producing heavier ones. The array measures the four momentum of each particle in the final state for specifying the excitation energy of the state along with the SAMURAI spectrometer. We plan to build an experimental setup capable of measuring the rates involving nuclei with masses up to 100.

The heaviest case is the breakup of a $^{101}$Sb nucleus. The energy deposit of the breakup fragment $^{100}$Sn is $50^2$ times that of a proton. The dynamic range of the array must be larger than the difference in the energy deposit. The design value for the upper and lower detection limits were set to 1 GeV and 200 keV, respectively, after taking into consideration the possibility of the pile-up of events.

The total number of signal channels becomes more than one thousand for sufficient momentum resolution. In order to effectively treat such a large number of signal channels and to suppress the cost per channel, we need to employ the Application Specific Integrated Circuits (ASIC) technology for the array.

In view of the above requirements, we constructed an array consisting of newly developed preamplifier ASIC providing a large dynamic range by implementing high- and low-gain channels, another ASIC system called HINP for subsequent pulse shaping, and the silicon detector developed for the GLAST mission. The items in the following list were examined for the characterization of the array by irradiating the detector directly at the HIMAC facility.

1. Linearity in the range from 390 keV to 300 MeV
2. Cross talk between neighboring strips
3. Yields of $\gamma$ rays for the irradiation of heavy

Fig. 1. Energy peak at around 390 keV obtained from the irradiation of a 150-MeV proton beam.

Fig. 2. Measured energy as a function of calculated energy. The slope of the line is 1.

charged particles

The smallest energy deposit 390 keV was made by a 150-MeV proton beam (Fig. 1). For larger deposits, $^{56}$Fe and $^{84}$Kr ions were accelerated as primary beams and we selected secondary beams having a mass-to-charge ratio of two. The linear response of the low-gain channel shown in Fig. 2 indicates that the dual gain system of the preamplifier ASIC succeeded in extending the upper limit to higher than 100 MeV, which is the limit of the high-gain channel. The results obtained for the last two items will be used for the estimation of the background rates for the proton detection. The determination of the upper and lower limits is the subject for the next irradiation.

References
Development of a γ-ray calorimeter for the measurement of highly excited states

Y. Togano,*1,∗2 M. Shikata,*1 Y. Kondo,*1,∗2 and T. Nakamura*1,∗2

The γ-ray calorimeter CATANA (CAlorimeter for γ-ray Transitions in Atomic Nuclei at high isospin Asymmetry) has been developed to measure highly excited states such as the pygmy dipole resonance and/or the giant dipole resonance. CATANA will be used with the SAMURAI facility at RIBF.1) The excitation energy spectrum will be reconstructed by combining the invariant mass of the reaction products measured by SAMURAI and γ-ray energies from CATANA. CATANA is focused on achieving a high detection efficiency because the probability of multiple γ-ray emissions is high in the decay of the highly excited states. Our goal is to achieve 55% photo peak efficiency for a 1 MeV γ ray from a beam with velocity \( \beta = 0.6 \).

The cross-sectional view of the CATANA array is shown in Fig.1. The array consists of 200 CsI crystals, whose thickness ranges from 9 cm to 15 cm. The colors indicate the different crystal shapes. The array is composed of six crystal shapes to minimize the empty space between the crystals. The crystals at the forward angle are thicker to cope with the Doppler shift of the γ energy. The array covers angles from 10° to 120° along the beam axis. The angular coverage per one crystal along the beam axis is about 9 degrees, and perpendicular to the beam axis, it is 18 degrees. The space inside the array is of ellipsoidal shape, whose major radius is 25 cm and minor radius is 20 cm. R11265 (Hamamatsu) PMTs will be used for two types of forward detectors, shown as yellow and saffron yellow in Fig. 1, and R580 (Hamamatsu) PMTs will be used for other detector shapes. Signal from a PMT will be processed in the spectroscopic amplifier 4494 from Clear Pulse Corporation. The pulse height information from the amplifier is digitized by a Mesytec MADC32 ADC. The timing information is processed in the 4494 amplifier using a build-in constant fraction discriminator, and digitized by a CAEN V1190A TDC. The logic trigger signal is generated as an “or” signal from the timing information.

The detection efficiency and the energy resolution of the CATANA array was estimated by using a Monte-Carlo simulation based on the code GEANT4. The efficiency was calculated as 56% and 36% for 1 MeV and 10 MeV γ rays, respectively, from a beam at velocity \( \beta = 0.6 \).

The prototype CsI crystal was tested at the Tokyo Institute of Technology. Fig. 2 shows the prototype CsI(Tl) crystal. The thickness of the crystal is 9 cm, and the shape of the prototype crystal corresponds to the blue one in Fig.1. The R11265 PMT is attached at the top side of the crystal. The crystal is wrapped by the ESR film (3M) of 65 µm and Teflon tape as reflectors. An energy resolution of 8.5% was achieved for the 662 keV γ ray with the prototype crystal. Based on the measured resolution, the energy resolution (FWHM) of 13% and 9% for 1 MeV and 10 MeV γ rays, respectively, from a beam at \( \beta = 0.6 \) is expected with the entire CATANA array.

The fabrication of 200 crystals will commence in spring 2014, and the entire system will be completed by spring 2015.

References

Fig. 1. Cross-sectional view of the CATANA array. Colors of crystals correspond to their shapes.

Fig. 2. Photograph of the prototype CsI(Tl) crystal.

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The azimuthal angle correlation of neutrons (n) and charged particles (p, d, t, ...) with respect to the reaction planes in heavy-ion collisions is a powerful approach for studying equation of state (EOS) in high density nuclear matter.

A next-generation neutron detector, NiGIRI (Neutron, ion, and Gamma-ray Identification for Radioactive Isotope beam), is designed to achieve (a) particle identification capability with pulse-shape discrimination (PSD), (b) high detection efficiency, and (c) high energy resolution. Feather, it is designed to be applicable for multiple particle detections.

NiGIRI is comprised of arrays of detectors, consisting of plastic scintillators (ELJEN EJ299-33, 35×35×60 mm³), ultra-high quantum efficiency photomultiplier tubes (Hamamatsu H11265-200), and MPPCs (Multi-Pixel Photon Counter, Hamamatsu S10985-100C). The arrays are capable of particle discrimination and position sensitivity. A newly developed plastic scintillator EJ299-33 with PSD capability is employed for identifying neutrons from gamma-rays. A novel concept followed by NiGIRI is that it reconstructs the particle interaction points in the scintillator by measuring the pulse height and the timing of the PMT and each MPPC attached on the side of the scintillator (Fig.1).

The performance of the PSD was investigated using a neutron source ($^{252}$Cf), where two charge-integrated QDCs with different gate widths were measured. One gate covers the whole signal and the other covers only the tail part of the signal. The duration of the two gates (total and tail) were 850 ns and 800 ns. Figure 2 shows the correlation plots between the tail and the total QDC values. The neutrons and gamma rays are separated.

Fig. 2. Pulse shape discrimination between neutrons and gamma rays in EJ299-33.

Position reconstruction of the particles on the surface of the entrance window (35×35 mm²) was estimated using β rays from $^{88}$Sr source, where a 10 mm Al plate with a 1.5 mm diameter hole was used as a collimator. The time difference of signals between PMT and MPPCs was measured. The deviation of the interaction point with regard to depth was ignored in the position calibration owing to its relatively shorter range of β-ray relative to the length of the scintillator. We reconstructed the incident position from the time difference of the averaged two MPPCs between diagonal corners. The position resolution is estimated to be $\sigma_x = 5.8 \pm 0.2$ mm and $\sigma_y = 6.9 \pm 0.4$ mm after the position calibration. Improvement of the position resolution is anticipated by further correction.

Reconstruction of the interaction point in beam direction is under investigation. After the optimization of the prototype NiGIRI detector, mass production of the NiGIRI array will be initialed.

References
Development of gating grid driver for SPiRIT TPC

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The symmetry energy part of the nuclear equation of state (EOS) influences various phenomena in nuclear astrophysics, nuclear structure, and nuclear reactions. The behavior of nuclear symmetry energy can be probed through a measurement of the $\pi^-/\pi^+$ ratio in heavy ion collisions. For this purpose, experiments using the Time Projection Chamber (TPC) installed in SAMURAI magnet1 have been proposed.2 The TPC is necessary to measure charged particles such as pions, protons, and light ions in high multiplicity environment produced by heavy ion collisions. When we perform the experiments at SAMURAI, heavy ions pass through TPC as well as charged particles, resulting in gain reduction due to the production of a large amount of ions from the avalanche process around anode wires. To avoid such a gain reduction, gating grid wires are located prior to the avalanche region. Techniques to protect the avalanche region have been well established.3 In the open gate mode, all the gating grid wires are held at the same potential $V_G$, admitting electrons from the drift volume to enter the avalanche region. In the closed gate mode, the gating grid is biased with a bipolar field (positive side:$V_G + \Delta V$, negative side:$V_G - \Delta V$), which prevents electrons from the drift volume to reach the avalanche region. The closed gate prevents ions created in the avalanche processes of previous events from drifting back into the drift volume. A gating grid driver (GGD) was developed to realize such protection of the TPC. Figure 1 shows a prototype of the GGD. The design is based on the E907 TPC GGD.4

![Fig. 1. Prototype of gating grid driver.](image)

The GGD performance was studied by using a Xe beam at HIMAC. Since we could not use the TPC for SAMURAI, we used the BRAHMS TPC5 to check the GGD performance. A CsI target was located in front of the TPC so that light charged particles can be measured as well as the Xe beam. T2K-TPC electronics were used to read out 256 (4 × 64) pads. Without switching the gating grid wire using the GGD, we observe a gain attenuation at the beam rate of 10 kpps. On the other hand, such a gain attenuation can be suppressed by switching the gating grid wire. The switching potential $(V_G)$ is the same as that for the BRAHMS experiment.5 Though we can suppress the gain attenuation, the base line is fluctuated every time by the gate operation, which generates a large noise on the pad readouts with respect to the signal from the MIP particles. One of the main reasons of the noises from the GGD is the different rise times in the positive and negative sides although the sum of the positive and negative side voltages $(2V_G)$ should be controlled to be constant. Since the noise shape caused by the GGD is similar among different events, we calibrate the baseline shape with a pedestal run and reconstruct the hit position after the subtraction of the baseline. Figure 2 shows the position resolution along the wire axis of the TPC after the calibrated baseline is subtracted. The position resolution under the bad noise condition created by the GGD is similar to the resolution with GGD. This implies that the noise created by the GGD can be made insignificant by subtracting the baseline as far as the position resolution is the same.

![Fig. 2. Position resolution along wire axis as a function of flash ADC sampling frequency for each case, with and without GGD.](image)

References
SPYBOX: Clock Monitoring at the GET Electronics

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The SPYBOX is a device that measures the time differences between the clock signals of the various AsAd boards (ASIC Support and Analog-Digital conversion) at the GET electronics (General Electronics for TPC) in order to monitor the clock synchronisation. It will be used at SPIRIT - the TPC at the SAMURAI experiment.

At the GET electronics a total number of 120 AsAd boards are available, enabling GET to read out more than 30000 channels of a TPC. At each AsAd board, there are two inspection lines available which can be used to monitor various internal signals such as clock signals. These clock signals are fed into the SPYBOX.

For the SPYBOX two stages of multiplexer are implemented in FPGAs (see figure 1): At the first stage, 64 signals are multiplexed to two. Up to four of these FPGAs exist. The second stage reduces the remaining eight signals to two which are used as start and stop signal for an external TDC. Thus, a total number of 256 clock signals can be monitored, slightly exceeding the 240 inspection lines available in GET.

The time difference between the two signals is read from the TDC by a microcontroller which also serves as communication interface to the user’s computer.

So far, two prototypes have been developed. The first prototype houses all components on one board. Tests with clock signals show that the principle is feasible and yield a maximum skew of about 0.5 ns (see figure 2).

Nevertheless, this prototype has some drawbacks. For instance, the connectors as implemented on the board are not compatible with the AsAd board, and only about half the total number of clock signals can be processed. Moreover, the large size of this board turns out to be unhandy. By this, the need for a second prototype arose.

The second prototype is compatible with the AsAd board. It has a compact and modular design consisting of an own board for each stage of multiplexer. Thus, it allows the use of a reduced setup – for example at SPIRIT where only about 50 AsAd boards are used. Additionally, the second prototype leaves space for further developments. One of the inspection lines at AsAd is for example bidirectional. It either outputs internal signals or receives external trigger signals for the AsAd pulse generator. The design of the second board accounts for the bidirectional line.

One additional feature of the second prototype concerns the timing resolution. As this prototype has a significant number of integrated circuit chips, the individual channels are prone to experience different travel times. To improve the timing resolution individual delay can be added to each channel compensating for the different travel times. This is done inside the FPGAs by a chain of LUTs (look-up-tables) which leads to freely selectable wire delay (see figure 3). First tests of the delay adjustment implemented in the FPGA yield additional delays of (0.7 to 0.8) ns per LUT. The time difference between two channels can be measured with a standard deviation of slightly less than 0.05 ns.

Currently, the second prototype is about to be finalized and will be evaluated afterwards.

References
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Development of TPC readout system for SπRIT project

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For the measurement of multiple charged particle tracks in a heavy-ion collision experiment at RIBF, a time projection chamber (TPC) will be installed in the SAMURAI superconducting dipole magnet. The main aim of the experiment is to study the density dependence of symmetry energy defined in the nuclear equation of state. This project is carried out by an international collaboration, the “Sπ(P)RIT collaboration”; SπRIT means Samurai PIon Reconstruction and Ion Tracker. As the readout electronics for more than 12k channels of TPC, a novel readout system, GET,1) is employed. GET stands for General Electronics for TPC and has been developed mainly by a collaboration between French institutes and American institute. The details of the GET system for the SπRIT project have been reported by Isobe et al.2).

For the first experiment at RIBF, we obtained the pre-production AsAd board, which is one of the important boards of the GET system and which was tested with SπRIT TPC at MSU. The pre-production AsAd board is controlled using the Xilinx evaluation board of ML507. ML507 can control only one board. For the massive readout of TPC, a dedicated concentration board, the CoBo board, which can control up to 4 boards, will be produced. Figure 1 shows the cosmic ray signal height of each channel as a function of the time bucket. There are 512 time buckets for one channel, and a sampling rate of up to 100 MHz is available. In the case of SπRIT TPC, a sampling rate of 50 MHz with 256 time buckets is planned to be used to cover the 10 μs drift time, which corresponds to a drift length of 50 cm with a 5 cm/μs drift velocity in P10 gas. Based on the information taken by the GET electronics, we succeeded to reconstruct the track as shown in Fig. 2. Now the analysis of the cosmic ray data is ongoing. It is planned that electron track data will eventually be taken with radioactive source.

As the data acquisition system, we plan to employ NARVAL,3) which is used in the French nuclear physics laboratory, such as GANIL. The size of data produced by the SπRIT plus GET system is estimated to be more than 100 MByte per second. NARVAL is selected as it can handle data of such large size.

Finally, 48 electronic boards will be mounted on the TPC and will be tested with cosmic rays in 2014. AF-

Fig. 1. Cosmic signal detected by SπRIT-TPC with GET electronics. Each line corresponds to one channel. One AsAd board contains four ASIC chips (AGET). One ASIC corresponds to 32 channels. The GET system employs SCA type flash ADC. Up to 512 time buckets can be used for analog data buffering. The pedestal is not suppressed in this figure.

Fig. 2. Cosmic track reconstructed by SπRIT-TPC. The black line denotes the 3D track. The red and blue lines denote the projected track on each plane. A 100-MHz sampling rate is used.

References

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Simulation study of a trigger scintillator array for the SPiRIT experiment

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The SPiRIT (SAMURAI Pion Reconstruction Ion Tracker) experiment was performed at RIBF using unstable heavy-ion beams with various N/Z ratios. The aim of the experiment was to determine the nuclear equation of state (EOS) by investigating the production ratio of $\pi^-$ to $\pi^+$ in heavy-ion collisions. We designed a scintillator array to trigger central collision events by using a detailed detector simulation, which was performed using the GEANT4 toolkit with the Monte-Carlo transport code PHITS; the PHITS is used as an event generator of heavy-ion collisions.

First, we evaluated charged-particle multiplicity distribution in heavy-ion collisions to confirm the validity of the simulation by comparing the simulated distribution to the measured distribution in the H292 experiment. The H292 experiment was performed with 400 AMeV $^{132}$Xe beam on CsI target at HIMAC in March 2013. In H292, a multiplicity counter, which consisted of 60 plastic scintillators, was used to trigger central collision events. By constructing the same setup of H292 in the simulation, we evaluated the charged-particle multiplicity distribution as shown in Fig. 1. The obtained distribution reproduces the experimental result well; in particular, the multiplicities of more than 6 show good agreement.

Then, we examined geometrical configuration of the trigger scintillator array for the SPiRIT experiment to maximize geometrical acceptance for the central collision events. In the experiment we used two sets of trigger arrays located just downstream of the SPiRIT TPC. Here, we assumed scintillator arrays with size 1200 mm (horizontal) $\times$ 400 mm (vertical) $\times$ 10 mm (thickness) segmented into eight units vertically. Figure 2 shows the obtained acceptance as a function of the centrality in 300 AMeV $^{124}$Sn + $^{124}$Sn collisions when the trigger scintillator arrays were installed to cover the polar angles ranges of $-40 < \theta < -20$ and $20 < \theta < 40$ degrees. In this configuration, the trigger array can accumulate the central events with more than 30% acceptance in the region of the 0 – 60% centrality, which satisfies the experimental requirement. We also evaluated the charged-particle multiplicity of the trigger array and found that we can precisely investigate the production ratio of $\pi^-$ to $\pi^+$ with track information reconstructed by the SPiRIT TPC.

Fig. 1. Comparison of charged-particle multiplicity distribution between the simulation and the H292 experiment, with multiplicities of more than 2. The simulated distribution is normalized to the experimental yield.

Fig. 2. Acceptance of the trigger scintillator array as a function of the centrality in 300 AMeV $^{124}$Sn + $^{124}$Sn collisions when the trigger scintillator arrays were installed to cover the polar angles ranges of $-40 < \theta < -20$ and $20 < \theta < 40$ degrees.

References
SHARAQ spectrometer for high-resolution studies for RI-induced reactions†


The SHARAQ project1, which began in 2004, aims at high-resolution spectroscopy for reactions induced by radioactive ions (RI’s) at 100A–350A MeV using the missing-mass method and at exploring new experimental techniques in the field of nuclear physics. In 2009, the construction of the High-Resolution Beamline (HRB)2 and SHARAQ spectrometer1,† was completed at the RI Beam Factory (RIBF). The design specifications of the SHARAQ spectrometer are provided in Ref.3. To date, the SHARAQ and HRB have been used for six experiments involving charge exchange reactions with radioactive isotope beams.

For experiments at SHARAQ, detector developments and ion optics studies are underway to improve the performance for high-resolution nuclear spectroscopy. A CVD diamond detector was developed in collaboration with NSCL/MSU to measure beam timings at achromatic foci with extremely good time resolution. The detector consists of a CVD diamond crystal of active area 28 mm² and thickness 0.2 mm, with four strips on one side and one pad on the other side. We performed a test of the diamond detector using a 32-MeV α beam. The time resolution was deduced to be 27 ps (σ). Details of the test and the performance of the CNS diamond detector were reported in Ref.3.

Multi-wire drift chambers operating at low gas pressure (LP-MWDC’s) were successfully installed at the beamline foci. A tracking detector with high-rate capability and good position resolution enables us to obtain high-statistics data and to correct them through event-by-event momentum tagging. In our previous experiments, because the beam and reaction products were light nuclei with Z = 1–7, operation with low gas pressure was essential for reducing energy straggling and multiple scattering in the tracking detectors. The LP-MWDC achieved a position resolution of better than 300 μm (FWHM) for light ions and successfully operated with RI beams of intensities greater than 1 Mcps during a 1-week experiment. The high-rate performance is described in detail in Ref.4.

As in the ion-optics studies for SHARAQ, we also report here the results of the high-resolution achromatic (HA) and dispersion-matching (DM) transport modes. The HA mode is achromatic transport to the secondary target. One advantage of the HA mode is a wider momentum acceptance (Δp/p = 2%) compared to the DM mode (Δp/p = 0.6%), and thus, higher intensity RI beams can be delivered to the SHARAQ spectrometer. Momentum tagging by LP-MWDC at the intermediate dispersive focus (F6) enables us to improve the spectroscopic resolution of the reaction kinematics with respect to the momentum spread of the radioactive beam. We demonstrate the validity of the correction in Fig. 1.

![Fig. 1. (a) Correlation plot between F6 and the final dispersive focus of the SHARAQ spectrometer (S2). (b) Energy spectra with and without the event-by-event momentum correction.](image)

The DM mode of SHARAQ spectrometer and HRB was designed to achieve extremely high resolution of reaction kinematics by the lateral and angular dispersion matching conditions in the entire system. Thus far, in the DM mode, we have achieved a momentum resolution of 1/8100 (FWHM) by taking into account the positions and angles of the beam constituents at the third focal plane (F3) of BigRIPS.

References

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Development of dual effective gas gain multiplication in CNS Active Target for a high-intensity beam injection

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We are developing a GEM-TPC-based gaseous active target with a pure deuterium gas, called CNS Active Target (CAT),1 for performing deuteron inelastic scattering experiments. The CAT is operated with a low-pressure (0.2-0.5 atm) deuterium gas for measuring the scattering to the forward angle closer to 0°. A 400-μm Thick GEM (THGEM) is chosen for the CAT to achieve a gas gain of 10^4 for a low-pressure deuterium gas; its performance was investigated for the first time in our previous work.2,3 However, when the gain of THGEM is set to such a high level as 10^4, the amplified charges from the energy loss of the heavy ion beam, which is impinged with a high-intensity of 10^5–6Hz, become too large for the GEM-TPC to operate stably. The effective gas gain along the beam trajectory (BT) area should be reduced by an order of 10-100, keeping the effective gas gain in the region where the recoiled particles (RP) are measured.

A new type of THGEM, called DGGEM (Dual-Gain THGEM), was manufactured via mechanical drilling and it has a thickness of 400 μm, a hole diameter of 450 μm (900-μm-pitch) on the BT region, and a hole diameter of 300 μm (700 μm-pitch) on the RP region; the DGGEM was used to study the dependence of the gain on the hole diameter. Since the electric field is stronger in a hole with a smaller diameter, a gas gain in the RP region is expected to be larger, by a factor of four, than that in the BT region. Figure 1 shows the obtained gain curves in single, double, and triple DGGEM layer setups as functions of the induction field strength E_{induction} in kV/cm/atm. The measured difference of gas gain between the BT and RP regions was much smaller than expected. Another solution was suggested, in which a grid mesh covered only the area along the beam path with a triple (normal) THGEM configuration. By changing the electric field in the drift field using the grid along the beam path, a partial gain reduction and a more stable operation of CAT is expected. A test experiment was performed with a high-intensity 132Xe (100 MeV/μ) beam at the HIMAC facility. A mesh grid with a 2cm width was set along the beam path (4-mm above the THGEMs). The most suitable voltage setup for the grid was identified using a defocused 132Xe beam. Figure 2 shows the relation between the sampled charges after multiplication and the readout pad ID. The widely hatched area, pad ID 60-340, corresponds to the entire beam trajectory region; and the narrowly hatched area, pad ID 130-270, includes the grid. A significant reduction of gain was achieved only on the grid area. The CAT was stably operated via the optimized grid operation under a high-intensity injection of 132Xe beam up to 10^5 particles per pulse, in combination with tuning of the protection circuit for the high-voltage supply. Further analysis is in progress.

Fig. 1. Results for each layer structure of DGGEM.

For each measurement, the drift field strength was 1 kV/cm/atm and the transfer field strength was 2 kV/cm/atm.

Fig. 2. An example of correlation between sampled charges after the multiplication and readout pad IDs with a defocused beam injection. Reduced multiplication of charges is achieved under the grid area. The color bar indicates the number of events.

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Development of enlarged spin-polarized proton target for RI beam experiments

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Spin-dependent interactions play an important role in nuclear structure and reactions. Spin-orbit coupling is one of manifestations of spin-dependent interactions. One of the most straightforward approaches to investigate spin-orbit coupling is the determination of the spin-orbit potential through the nuclear optical model analysis of the vector analyzing power in the $p - A$ scattering (proton elastic scattering from nuclei).

At RIBF in experiments involving short-lived unstable nuclei, a spin-polarized proton target is required, since unstable nuclei are supplied as RI beams. Center for Nuclear Study, Univ. of Tokyo and RIKEN groups have developed a spin-polarized proton target system. The target material is a crystal of naphthalene doped with a small amount of pentacene (0.005%), which serves as a polarization agent. The method of production of spin polarization employed in our target system, is based on the cross-polarization technique, where polarization of electrons system is transferred to protons by means of dipolar interaction in the presence of microwave irradiation.

Several RI beam experiments have been done with this polarized proton target. For further application the size of the target (14 mm in diameter) is a limiting factor because the typical position spread of RI beams is as large as 20-30 mm. This leads to loss of statistics and also increase in background events from the surrounding materials such as a target holder. Due to the above reasons the crystal size needs to be enlarged.

We performed upgrade of the polarizing system to accommodate an enlarged sample and successfully obtained spin polarization signal from a sample of 24 mm and 3 mm in diameter and thickness, respectively. This is the largest sample that has been polarized with this method. Measurement of a spin polarization was performed by means of the pulsed-NMR method.

To facilitate polarization transfer based on the cross-polarization technique, the energy gaps of electron and proton systems should be made equal, so that these two systems are coupled. This condition: $\hbar \omega_{\text{eff}} = \hbar \omega_1$, is known as the “Hartmann-Hahn condition”. Here, $\omega_{\text{eff}}$ is the electron effective Larmor frequency in a coordinate system rotating with frequency $\omega$ - the frequency of oscillating microwave magnetic field, and $\omega_1$ is proton Larmor frequency. $\omega_{\text{eff}}$ is written as

$$\omega_{\text{eff}} = \sqrt{(\omega_1 - \omega)^2 + \omega_R^2},$$

where $\omega_R$ is the Larmor frequency of the electron, $\omega = \gamma_s H_1$ is the Rabi frequency which depends on the amplitude of the oscillating magnetic field $H_1$ and electron gyromagnetic ratio $\gamma_s$. In actual measurements after a resonance condition $\omega_s = \omega$ was met by adjusting a static magnetic field $H_s$ as $\omega_s = \gamma_s H_s$, then $\omega_{\text{eff}}$ was tuned to satisfy “Hartmann-Hahn condition”. Tuning of $\omega_{\text{eff}}$ is done by changing the $H_1$ field amplitude, which is proportional to the square root of input power $\sqrt{P_{\text{MW}}}$. The $\omega_R$ is connected to $P_{\text{MW}}$ as $\sqrt{P_{\text{MW}}}$.

We note here that a maximum proton spin polarization is produced, provided the “Hartmann-Hahn condition” is met. In the proton spin polarization measured as a function of $\sqrt{P_{\text{MW}}}$ shown in Fig. 1, however, no such maximum was identified as a peak. The peak was not obtained even with the highest power that the currently used source can supply. To achieve “Hartmann-Hahn condition”, we are redesigning the microwave resonator in order to reduce power loss due to radiation to the outer region.

At the present, we successfully obtained spin polarization signal with very large sample of $24 \times 3$ mm. Although, magnitude of the polarization can be enhanced by improving the microwave system.

References
**β-NMR measurement of unstable nuclei with cross-polarization technique**

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A polarized solid proton target for RI beam experiments has been developed at RIKEN and the Center for Nuclear Study, University of Tokyo. By means of electron polarization in photo-excited triplet states of pentacene, proton polarization of approximately 20% has been achieved in a low magnetic field of 0.1 T and at a high temperature of 100 K. The target has been applied to RI beam experiments for several times. One of the next directions in the research is the polarization of unstable nuclei. If the polarization of protons can be transferred to unstable nuclei stopped in the target, measurements of magnetic moments would become possible with the β-NMR method. The polarization condition of high temperature and low magnetic field, which is the distinct advantage of the target, is indispensable in such low-energy beam experiments. In this article, we report on our attempt of transferring proton polarization to 13C nuclei contained in the sample.

As a sample, we used a single crystal of p-terphenyl doped with pentacene molecules. Most of 1H nuclei in p-terphenyl molecules were replaced by deuterium to obtain a higher 1H polarization. The abundance of the 1H was 2%. The weight of the sample was 28 mg. The crystal was irradiated by the pulsed laser light with a wavelength, an average power, pulse width, and repetition rate of 514 nm, 0.3 W, 13 µs, and 7.5 kHz, respectively. The sample temperature was controlled at 293 K by flowing cold nitrogen gas. The optimum power of the microwave was 3 W. Under these conditions, a proton polarization of 6.2±1.2% was obtained.

In the next step, the obtained 1H polarization was transferred to the 13C system by the cross-polarization method. The 13C (or 1H) spin rotates along the static magnetic field at a certain Larmor frequency. In the cross-polarization method, we apply a transverse magnetic field rotating with the Larmor frequency. This rotating field, produced by radio-frequency (RF) waves, effectively changes the level gap between spin up/down states. When the effective level gaps of 1H and 13C are equal, these systems couple to each other and polarization transfer takes place. The level gap is given as \( h\omega_R = \gamma hH_{RF} \), where \( \omega_R \) and \( \gamma \) are the Rabi frequency and gyromagnetic ratio, respectively. The \( H_{RF} \) is the strength of the rotating field, which is proportional to the square root of the RF power.

In the present case, the Larmor frequencies of 13C and 1H are 3.167 and 12.59554 MHz, respectively, in a static field of 0.3 T. By irradiating these two RF waves at the same time and by tuning their powers to satisfy the Hartmann-Hahn condition, \( \gamma^*hH_{RF}^* = \gamma hH_{RF}^C \), one can realize the polarization transfer between two systems. Here, the superscripts “H” and “C” represent 1H and 13C, respectively. By changing \( H_{RF}^* \) with fixed \( H_{RF}^C \), we searched the point where the Hartmann-Hahn condition is satisfied. The result is shown in Fig. 1.

![Fig. 1. The RF power dependence of 13C polarization](image-url)

As seen in the figure, the 13C polarization was successfully obtained for the RF power of ~160 W. The magnitude of 13C polarization was 0.12 ± 0.05%. The polarization-transfer efficiency, which is the 13C polarization divided by 1H polarization (6.2%), is found to be 1.9%. While this value is not high, it is reasonable because the sample is deuterated and the abundance of 1H is 2%. If the sample is not deuterated, the number of 1H nuclei to which 13C couples becomes 50 times larger. In that case, a polarization transfer efficiency of close to 100% would be obtained.

In conclusion, we obtained a high proton polarization of 6.2% via temperature control and the use of a deuterated p-terphenyl crystal. By transferring the proton polarization, the 13C polarization was successfully obtained with the cross-polarization method. The next step would be the polarization transfer to unstable nuclei stopped in the target. As the gyromagnetic ratio of the unstable nuclei is not precisely known, the parameter search for the Hartmann-Hahn condition will become more difficult. Finding an efficient method of the search is a challenge for the future.

References
The spin polarization of proton target in SHARAQ04 experiment


A (p,2p) knockout reaction was used in the SHARAQ04 experiment to extract the spectroscopic factor of orbital protons, and a spin-polarized proton target was used to extract the analyzing power for distinguishing the spin-up \((I_u)\) and spin-down \((I_d)\) orbits of the knockout proton. The analyzing power can be determined using the cross section acceptance (Figure 1).

By assuming that the reaction point is along the z-axis of the lab frame, we calculated the weighted reaction position (Z-vertex) from the MWDCs’ tracking result. The Z-vertex was gated by an opening angle with a central gate \((84^\circ-89^\circ)\) and a side gate \((81.5^\circ-84^\circ\) or \(89^\circ-91.5^\circ\)). The central gate contained the elastic scattering peak and background, while the side gate contained only background because the opening angle is not allowed by kinematics and detector acceptance (Figure 1).

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Proton polarization in photo-excited aromatic molecule at room temperature enhanced by intense optical source and temperature control†

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For the study of unstable nuclei with polarization observables, we have constructed a solid polarized proton target1) based on the electron polarization in photo-excited aromatic molecules. Proton polarization of about 20 percent has been obtained at a temperature of 100 K, which is much higher than that under conventional conditions. The target has been successfully applied to several RI-beam experiments2) carried out at intermediate energies of several tens to a few hundred MeV/nucleon. One of the future directions of this research is conducting experiments at low energies of several to a few tens of MeV/nucleon. This will open up new possibilities such as resonant scattering and polarization transfer to embedded RIIs. For such applications, the target should be placed in a vacuum environment and be polarized at room temperature. In our previous measurement at room temperature, a polarization of 4.8±1.2% was achieved by using p-terphenyl as the material. The aim of the present work is to investigate the possibility of achieving a high proton polarization of 30 percent for application to scattering experiments.

The magnitude of the polarization is expressed as

\[ P_p = \frac{A}{(A + \Gamma)} \]

Here, \( P_e \) is the electron polarization, \( A \) is the build-up rate, and \( \Gamma \) is the relaxation rate. In order to achieve a high polarization, we need to increase \( A \) and \( P_e \) or decrease \( \Gamma \). To enhance the build-up rate \( A \), we should increase the laser power for photo-excitation. However, in Inuma et al.3) reported that a high laser power does not necessarily lead to a high polarization. This is considered to be because of the temperature rise of the sample. At temperatures higher than 300 K, the intrinsic relaxation rate \( \Gamma_{int} \) rapidly increases4) because of the molecular motion. Thus, it is expected that the polarization can be enhanced by using an intense optical source with the sample temperature controlled at \( T \approx 300 \) K.

The sample used in the present work is a single crystal of p-terphenyl doped with pentacene molecules with a concentration of 0.005 mol%. The target temperature was monitored with a platinum resistance thermometer. The temperature of the crystal was controlled by flowing cold N₂ gas. For the light source, we used an Ar ion laser with a wavelength of 514 nm.

The polarization was measured under two different conditions. The first condition (averaged laser power of 80 mW, w/o temperature control) is the same as that used in our previous measurement, where a polarization of 4.8% was achieved. The other condition (1.5 W, w/ temp. control), referred to as “present,” was also considered. The time evolution of the polarization is shown in Fig. 1. In the present condition, the polarization is enhanced by a factor of three as compared with the polarization under the first condition. Although the absolute measurement is to be done in the future, the magnitude of achieved polarization corresponds to about 15% if we assume the polarization of 4.8% in the previous condition.

![Time evolution of proton polarization](image)

Fig. 1. Time evolution of proton polarization.

Finally, it should be mentioned that optimization of the time structure of the laser pulse would enhance the polarization rate \( A_{\pi} \) by a factor of ~5 without increasing the relaxation rate \( \Gamma \) (see Ref.5). Thus, such optimization would almost directly improve the magnitude of polarization. Room-temperature polarization of 30 percent would be realized by combining a high power laser with a wavelength of ~590 nm, through optimization of laser pulse structure, and employing a sophisticated temperature control system.

References
Dynamic nuclear polarization with photoexcited triplet electrons in a glassy matrix†

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In this decade, dynamic nuclear polarization (DNP) using equilibrated electron spin has attracted considerable attention in the fields of NMR spectroscopy and MRI as a method to enhance sensitivity.1) The intensity of a signal from nuclear spins is proportional to the spin polarization. DNP is a means of transferring spin polarization from electrons to nuclei, and the equilibrated polarization of electron spins is 660 times larger than that of 1H spins. Developing special peripheral equipment, we are able to combine hyperpolarization at cryogenic temperatures around liquid helium temperature with high-resolution NMR spectroscopy or MRI. For such applications, the sample preparation method which materials of interest are codoped into a glassy matrix together with free radicals is one of the most important factors in terms of versatility.

On the other hand, by using single crystal of organic molecules, we have developed a polarized solid-state target with DNP using photoexcited triplet electron spin (triplet-DNP) of pentacene.2) The polarization of such non-equilibrated electron spins is more than 70% independent of temperature and magnetic field. Using this method, we can overcome the upper limit (660) of the polarization enhancement factor achieved by conventional DNP. Herein, we report the first demonstration of triplet-DNP in a glassy matrix for application in NMR spectroscopy and MRI.

We applied two types of host molecules that have higher glass transition temperature than conventionally used glasses. One is a non-polar molecule, o-terphenyl (OTP).3) The other is a polar molecule, benzophenone (BZP).4) Using partially deuterated OTP and BZP as host materials, we obtained 1.5% and 0.7% 1H spin polarization under 0.4 T at 120 K, respectively (Fig. 1). The enhancement factor for OTP and BZP was 4,250 and 1,900, respectively. We have also succeeded in polarizing third molecules, 2, 3, 4-trifluorobenzoic acid and 5-fluorouracil, codoped into a glassy matrix with polarizing agent (Fig. 2). 19F spin in the third molecules were polarized using the field cycling method.5) The use of photoexcited triplet electrons is a promising method to extend the limitation of DNP to higher temperatures. If hyperpolarization can be achieved above liquid nitrogen temperature, the peripheral equipment and the experiments for spectroscopy will be simplified, and the application field will be broadened. There are many samples of interest for which a higher temperature is preferable. DNP using photoexcited triplet electrons has the potential to significantly enhance the NMR/MRI sensitivity while the sample is kept at room temperature.

References
Hyperpolarization of thin films with dynamic nuclear polarization using photoexcited triplet electrons†

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With dynamic nuclear polarization using the photoexcited triplet electron spin (triplet-DNP) of pentacene,† nuclear spins can be hyperpolarized more than 10% even in a low magnetic field at room temperature. DNP is a means of transferring spin polarization from electrons to nuclei. In the field of experimental nuclear physics, a nuclear spin polarized target in a low magnetic field (<0.5 T) opens new research possibilities. The polarized target used presently in RI beam experiments is 1-mm thick.2) The relatively large target thickness prevents us from applying the target to low-energy experiments. In the experiments, beam and scattered particles have energies as low as several MeV/nucleon and cannot penetrate the 1-mm thick material. In order to perform low-energy scattering experiments, a polarized film with a thickness of less than 100 µm is desirable. However, it is difficult to cut the fragile organic crystals to such a thickness from a large crystal prepared by the conventional method.1,2) In this work, we succeeded in polarizing 1H spins in a thin film of p-terphenyl and trans-stilbene doped with pentacene fabricated with a new method.

In order to achieve the ideal sample thickness and pentacene concentration, we applied the cell method to the sample preparation.3,4) The method is as follows: A powder mixture of p-terphenyl doped with pentacene was melted and absorbed into a gap between two quartz plates adjusted with copper foils. When this arrangement was cooling at room temperature, a single crystal, shown in Fig. 1(a), was grown in one minute. After removing one of the plates, we measured the thickness of the sample using a surface profiler. The result is shown in Fig. 1(b). From experiments, we determined that the film plane is the cleavage plane. Optimizing the sample thickness and the pentacene concentration, we obtained 1H spin polarization of 12.9% in a 7-µm thick film of p-terphenyl doped with 0.05 mol% pentacene in 0.4 T and at room temperature. The slightly lower value of the achieved polarization compared to that for the bulk crystal grown by the conventional method may be due to the degradation of the crystal quality.

The advantage of the cell method is not only in the adjustability of the thickness over a wide range but also in a short crystal growth time. trans-Stilbene cannot be grown up to a single crystal doped with pentacene by the conventional method because melted trans-stilbene decomposes pentacene immediately. By adopting the cell method, we succeeded in avoiding considerable decomposition, preparing a single crystal of trans-stilbene doped with pentacene, and polarizing it with triplet-DNP for the first time. The achieved polarization was improved to 3.9% at 150 K in a 60-µm thick film of trans-stilbene doped with 0.05 mol% pentacene.

The polarized thin films also enable new applications of triplet-DNP in general NMR spectroscopy with the realization of Tycko’s proposal,5) which claims that the use of multi layered structures of hyperpolarizing layers and any material of interest allows polarization transfer through the interfaces. This will open new opportunities in various fields such as chemistry, life science, and medical science.

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Room-temperature hyperpolarization of nuclear spins in bulk†

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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. However, as long as electron spins in thermal equilibrium are used as polarizing agents, the upper limit of the polarization enhancement will be 660 for $^1$H spin and cryogenic temperatures of around 4.2 K will be required for hyperpolarization in the order of 10% even under the strong magnetic fields used for NMR.1) One approach for overcoming the upper limit of the enhancement factor is to use non-thermalized electron spins. DNP with electron spins in the photo-excited triplet state (triplet-DNP) can achieve hyperpolarization independent of the magnetic field strength and temperature.2) We report 34% $^1$H spin polarization in 0.40 T at room temperature.

We employed pentacene as a polarizing agent in which the excited electron spins polarize 75%, and p-terphenyl as a host material because of its stability at room temperature and large pentacene capacity. The curve obtained using ThPh in Fig. 1 is the buildup curve of $^1$H spin polarization by triplet-DNP in a single crystal of p-terphenyl-$h_{14}$ doped with pentacene-$h_{14}$ 0.05 mol%. We attained a $^1$H spin polarization of 14%.

The key breakthrough in the present work for attaining higher polarization at room temperature is the suppression of the spin-lattice relaxation by stable-isotope labeling of the constituent molecules. 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.3) To suppress the spin-lattice relaxation, we synthesized p-terphenyl-$2’,3’,5’,6’-d_{4}$, with which the $^1$H spin-lattice relaxation time was increased from 11 min to 37 min. The attainable polarization was increased to 16% in the region-selectively-deuterated host doped with pentacene-$h_{14}$ (TdpPh in Fig. 1).

There is another source of $^1$H spin-lattice relaxation that affects DNP. The triplet electrons play the role of a polarizing agent as well as contribute to $^1$H spin-lattice relaxation through a perturbation of the local field of the $^1$H spins in the vicinities. To suppress the spin-lattice relaxation, we used pentacene-$d_{14}$ as the polarizing agent. The attainable polarization was increased to 18% in the p-terphenyl-$h_{14}$ doped with pentacene-$d_{14}$ (Tdpd in Fig. 1).

Suppressing either of the two relaxation sources was not sufficient. By using p-terphenyl-$2’,3’,5’,6’-d_{4}$ doped with pentacene-$d_{14}$ (Tdpd in Fig. 1), we achieved a bulk $^1$H spin polarization of 34% at room temperature in 0.40 T, which results in an enhancement factor of 250,000.

Room-temperature hyperpolarization techniques using photoexcited triplet electrons 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 for the polarized target for RI beams4) and the polarized filter for neutron beams.5)

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Development of $^3$He comagnetometer for $^{129}$Xe EDM measurement


A permanent electric dipole moment (EDM) that directly violates time reversal symmetry attracts much attention, because an unknown CP-violating phase which is necessary for understanding the present matter-dominated Universe, is expected to be probed by EDM. The present study aimed to measure the EDM in a $^{129}$Xe atom to the order of $10^{-28}$ cm, which is beyond the present upper limit. We employed an active nuclear spin maser to sustain the spin precession of $^{129}$Xe over a long duration. The active spin maser operates in the following manner. The $^{129}$Xe spin is longitudinally polarized through spin exchange relaxation time for $^{129}$Xe and over 50 hours of the longitudinal spin relaxation time for $^3$He at 100 °C.

The experimental setup used to test the $^3$He comagnetometer is shown in Fig. 1. The gas cell is placed in a solenoid coil which generates a static magnetic field $B_0$ ($\sim$ 30 mG), and is enclosed in a 4-layer magnetic shield. A circularly polarized pumping laser is incident on the cell parallel to $B_0$. A probe laser passes through the cell in a direction orthogonal to $B_0$ and is detected by a photodiode. The signal from the photodiode is divided into two, each being lock-in-amplified with $^{129}$Xe or $^3$He precession frequency, and the resulting two beat signals are obtained and processed individually at the same time to generate their feedback magnetic fields through two separate coils.

We succeeded in operating the masers of $^{129}$Xe and $^3$He concurrently. The individual determination precisions of the average frequencies achieved in $10^6$ seconds for both $^{129}$Xe and $^3$He are $\sim$100 mHz. However, the frequency shift due to contact interaction with polarized Rb atoms prevents the $^3$He comagnetometer from realizing its full potential because the strengths of the Rb-$^{129}$Xe and Rb-$^3$He contacts are different. Therefore, we decided to employ a double-cell geometry in which the gas volume is divided into a section for optical pumping and another for optical spin detection in order to suppress Rb polarization in the optical detection section and thus reduce the frequency shift. Development of the $^3$He comagnetometer with the double-cell geometry is in progress.

References
The SCRIT electron spectrometer is being constructed at the SCRIT electron scattering facility\(^{1,2}\). In this report, the current status of the construction is described. The spectrometer, shown in Fig. 1, will be used to measure the cross section for elastic electron scattering off short-lived nuclei to determine their charge-density distributions\(^{3}\). It consists of a dipole magnet, two drift chambers, and a pair of plastic scintillators. The drift chambers sandwich the magnet for trajectory measurements, and the plastic scintillators trigger data acquisition. Knowing the detailed magnetic-field distribution, the momenta, scattering angles, and scattering positions of the electrons are determined. The spectrometer should have large acceptance and a good momentum resolution of the order of \(10^{-3}\) to identify the elastic scattering events.

## 1 Magnet

The window-frame magnet, the gap region of which is 170 cm (width) × 140 cm (length) × 29 cm (height), is employed. The field cramps were carefully designed to reduce the fringing field down to a few gauss at the electron beam position. Magnetic-field measurements have been performed, and the detailed field distribution was obtained\(^{4}\) . The magnet is placed on a movable platform, as shown in Fig. 2, such that the magnet can be moved away from the beam line by 1.5 m. The re-positioning accuracy was confirmed to be better than 50 \(\mu\)m. The magnet system will be ready for operation immediately after the power line and cooling water are set up; this is expected to be completed in the first half of 2014.

## 2 Detectors

A large drift chamber, which is placed in the rear side of the magnet, was constructed in 2013. The small drift chamber used in the previous SCRIT studies will be used as the front drift chamber. A new readout system, RINEI RP 1212N, which digitizes the drift times on board is currently being tested\(^{5}\). A pair of large plastic scintillators of dimensions 220 cm (length) × 30 cm (width) × 2 cm (thickness) are used for detecting the scattered electrons, and their coincidence triggers data acquisition. To reduce non-negligible false triggers due to cosmic rays, veto detectors will be arranged. The drift chambers and the plastic scintillators will be ready for use in the first half of 2014.

## 3 Spectrometer commissioning

The SCRIT electron spectrometer will be commissioned using the W-wire target installed inside the SCRIT chamber in the second half of 2014. Using the scattered electrons from the W wire target, one can determine the track-reconstruction efficiency, momentum resolution, etc. After commissioning, we will immediately conduct experiments on electron scattering off a short-lived nucleus, which will be \(^{132}\)Sn . The world’s first observation of electrons scattered off an exotic nucleus is expected to take place in the fiscal year 2014.

Fig. 2. The magnet with the movable platform.

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Field measurement of SCRIT electron spectrometer

T. Tamae, *1,2* T. Miyamoto, *1,2* and T. Suda*1,2*

A large-acceptance magnetic spectrometer for electron scattering on unstable nuclei was constructed, and its magnetic field was measured. The analysis of the field distribution and the development of a program of track reconstruction are in progress.

The design*1) and construction*2, 3) of the spectrometer have been reported elsewhere. The spectrometer is designed to have a reasonably good resolution of $\Delta p / p : 10^{-5}$, a large solid angle of about 100 msr, and a large scattering coverage of 30-60° .

The spectrometer consists of a single window-frame dipole magnet with an aperture of 29 cm in height ($y$), 1.4 m in length ($z$) and 1.71 m in width ($x$). As the spectrometer has no focal plane, the momentum and vertex position of scattered electrons are fixed through the track reconstruction using the information of drift chambers, as shown in Fig. 1. This implies that the knowledge of the precise distribution of the magnetic field is essential for analysis.

The magnetic field distribution was measured using a Hall probe at 37,118 points in 1/8 of the entire volume of the aperture and connecting regions. The absolute magnetic-field values were calibrated using an NMR set at a fixed position in the mid-plane. The field map was obtained at three strengths ((a) 4,096, (b) 7,628, and (c) 8,017 G at the NMR). The measured values were corrected for the drift of a Hall probe and for inaccuracy of the probe orientation. They were normalized to the NMR values.

The field strength for case (c) is contoured in Fig. 2; numbers attached to lines show the ratio of the field strength to the central field strength. The order of lines in the figure is same as the order of lines in the legend. Light-grey region: aperture region of the magnet; dark-grey region: coil; black region: return yoke.

The field strengths were also compared to calculations using the program OPERA-3D. The difference between the measured and calculated field strengths is much less than $10^{-3}$ in the aperture region, but it becomes larger at the fringe field region, especially at positions close to magnetic poles and field clamps. The estimation of errors for the electron momentum and vertex positions due to inaccuracy of the field distribution is in progress.

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Design of Recoil-Arm for the SCRIT Experiment

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The self-confining RI Ion target (SCRIT) electron scattering facility¹ is now under construction. Electrons scattered from target ions trapped in the SCRIT device are detected, and their angular distribution is obtained. A recoil ion detector referred to as the “recoil-arm” is being designed. It will be used for the determination of the luminosity distribution in the ion trapping region along the beam axis. We also plan to use the recoil-arm for estimating the contribution of residual gas ions, which are trapped simultaneously with target ions in scattering events².

Figure 1 shows a schematic of the recoil-arm. It consists of returning meshes, multi-stage slits, two quadrupole benders³, and a channeltron array consisting of 15 channeltrons. Ions that are recoiled from the trapping region in the SCRIT are accelerated by the electrostatic potential applied to the SCRIT electrodes. Returning meshes are used to reduce the background ions that leak in the trapping region in the SCRIT. Multi-stage slits confine the angular acceptance of recoil ions. Fig.2 shows the first quadrupole bender designed by us. Two quadrupole benders are used to deflect the transported recoiled ions and reduce the background produced by the synchrotron radiation. The channeltrons are arranged in a line so as to minimize dead space. The aperture of every channeltron is rectangular (15mm×30 mm).

Perpendicularly recoiled ions as a result of forward electron scattering are extracted and transported in parallel to the channeltron array. The counting rates of the 15 channeltrons indicate the trapped ion distribution, i.e., luminosity, along the beam axis. We can identify the mass number of the recoil ions in scattering events by measuring the time delay from the instant when forward scattered electrons are detected by the plastic scintillator; accordingly, we can estimate the attributable fraction of residual gas ions in scattering events.

The off-line test bench of the recoil-arm is now under construction. We will be studying the performance of the recoil-arm before its installation in the SCRIT device.

References

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Test of new readout card for the SCRIT drift chamber

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The SCRIT electron spectrometer consists of a set of dipole magnets, the front and rear drift chambers (DC), and plastic scintillators for event triggering. The rear DC has a volume of 274 cm x 36 cm x 78 cm, and it has a total of 5 layers of UVX consisting of 1130 channels, which have an intrinsic 150-μm position determination capability with 1-ns timing resolution. It covers a solid angle of 100 mSr for scattered electrons to achieve a good momentum resolution (~10⁻³) with a wide scattering coverage (30°-60°). We employed a new TDC card (RIKEN RP1212) based on SiTCP technology for DC data readout. In this article, we report the results of readout tests of RP1212 using the actual experimental setup.

RP1212 has dimensions of 150 mm x 190 mm, and it is capable of processing ADC and TDC data for 64 channels. TDC is implemented in FPGA (Xilinx Kintex7) with 1-ns timing resolution. It is directly attached to the DC, and signals are immediately digitalized by FPGA on the board. The data is transmitted to a PC via Gigabit Ethernet. An advantage of using RP1212 is that the path length of the analog signal can be minimized such that the data is less influenced by analog noise as compared to the earlier readout system using the ASD card and TDC module. Nevertheless, since the DC and RP1212 will be located very close to the RF power source for the electron storage ring, the background effect that originates from the RF noise was investigated.

Figure 1 (A) shows a typical β ray signal (⁹⁰Sr) using prototype DC and RP1212 under the RF environment. The top panel indicates that the pulse height of the β signal is ~800mV, and the bottom panel in a different time scale clearly illustrates 5-msec-period oscillation, which is apparently caused by the 191-MHz RF noise. The noise amplitude is less than ~150 mV, which is much smaller than that of the β signal, at the full RF power condition. Fig 1 (B) shows the comparison of noise counts between RF off and on cases as a function of the threshold voltage for the ASD discriminator (Vth). The noise count is zero at Vth ~200 mV, while the noise rate is not negligible below a Vth of 150 mV when RF is on. In fact, the count at Vth = 100 mV is rather dominated by noise from powerline of RP1212. Since a typical height of a β signal is ~100 mV to 500 mV, which is sufficient to trigger a β signal and eliminate RF noise simultaneously.

We measured the timing distribution of β signals using RP1212 and the actual SCRIT-DC for He+CH₄ (50:50) gas mixture. We examined the plateau region of detection efficiencies and then found that the operational voltage range for good efficiency is 2550 V to 2800 V. Therefore, the normal operation voltage is set at 2750 V.

Figure 2 shows the timing distribution of β signals. For better statistics, the histogram adds up TDC data from 64 channels. Since RP1212 has a common stop trigger, which is provided by a trigger scintillator, the right edge of distribution originates from β signals that were received near the anode wire. Since the rising edge is clear, we can use it as a calibration point. We are working on the timing calibration to achieve ~150 μm position resolution.

In 2014, we will proceed to developments of calibrations and tracking framework aiming at the first result of the ¹²⁴Sn electron scattering experiment.

Fig. 1. (A) The top panel shows an analog signal for a beta ray measured with RP1212, and the bottom panel shows the RF noise in expanded scale for both time and pulse height. (B) Noise count rate as a function of threshold value for ASD chip on RP1212.

Fig. 2. The timing distribution of the beta signal.

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Construction status of the Rare-RI Ring (R3)

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The Rare-RI Ring (R3) was constructed smoothly1), and the installation of the magnets and power supplies were completed by the end of March 2013. Subsequently, we tested a cooling water conduction of the magnets and prepared the interlock system for the magnets in order to perform the excitation tests of the magnets. The excitation test was successfully completed at the beginning of July 2013. Subsequently, we performed the precise magnet alignment by using a laser tracker. All the magnets were aligned to the design value by less than 0.1 mm. Figure 1 shows the picture of R3 at the beginning of July 2013.

Fig. 1. Picture of R3 at the beginning of July 2013.

Next, we installed vacuum pumps and vacuum gauges. Figure 2 shows a vacuum pump combination for the arc section. The turbo molecular pump (TMP) is movable, and is used as a rough pumping system with a scroll pump. The nominal pumping speed of the TMP is 250 L/s for N₂. Ion and non evaporable getter (NEG) pumps are used for the ultra-high vacuum condition. The nominal pumping speed of the ion pump is 500 L/s for N₂ and that of the NEG pump is 2000 L/s for H₂. The combination of the ion and NEG pumps for R3 is 26 units.

In order to bake the R3 chamber, we installed heater wires on all the chamber surfaces and glued a heat insulator, which is an alumina-silica sheet, onto the heater wires, as shown in Fig. 3. The chamber surface is typically warmed up to about 250 °C. K-type thermocouple is used for thermal control.

Fig. 2. Vacuum pump combination using TMP, ion pump, and NEG pump.

Recently, we succeeded in establishing a control system for power supplies by using EPICS2). In addition, we confirmed that a vacuum-integrated control system worked normally. We are now testing beam-monitoring systems3,4) and a kicker system. We will carry out an off-line performance test for R3 using the α source.

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Developments of time-of-flight detectors for Rare-RI Ring

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Construction of the Rare-RI Ring, which will be used to measure masses of short-lived rare-RI with a relative precision of 10−6, is underway at RIBF.1,2) We are developing three types of time-of-flight (TOF) detectors for installation in the Rare-RI Ring: two of the three are placed at the entrance (start detector) of the ring and the third is placed inside the ring as the circulative ion detector (CD). The start detector provides the start signal of the TOF system for the mass measurement. The CD provides a signal corresponding to each circulation. The CD is indispensable for monitoring the motion of the particle inside the ring at the beginning of the storage.

The required specifications for the start detector are i) a good timing resolution less than 100 ps because the total TOF is about 0.7 ms, ii) a large effective area (100 mm × 50 mm) to cover the large beam size, iii) small energy loss and energy straggling so as not to affect the mass resolution of mass measurement in the ring, and iv) no change in the charge state of the nuclei, achieved by passing them through a detector to avoid reduction of the transmission efficiency in the ring. On the other hand, the required specifications for the CD are i) small energy loss to maintain the momentum of the nuclei within the momentum acceptance during 100 circulations, ii) a high detection efficiency, iii) a large effective area (100 mm × 50 mm) to match the large beam size, and iv) a good timing resolution to separate each circulation (the typical time for one revolution is about 350 ns.) Furthermore, the CD should be maintained in ultra high vacuum.

To mount the detector in a limited narrow space, we developed a "T-shaped" TOF detector, as shown in Fig. 1(a). The left part of the detector consists of two 1" photomultipliers (R4998) coupled to the top and bottom parts of a 100 μm-thickness scintillator, while the right part contains one 2" photomultiplier (H2431-50) coupled directly to the right side of the scintillator. It is noted that, in the "T-shaped" TOF detector, we can obtain the horizontal position information, which may be used to improve the timing resolution. In the case of heavy nuclei and changes in the charge state, the 100-μm-thickness of the scintillator is not sufficiently thin. We thus consider introducing a micro channel plate (MCP) detector, as has been used at ESR3) and CSRF4), which has a sufficiently thin carbon foil. To cover the larger beam size at the entrance of Rare-RI Ring, we are developing the detector with a larger sensitive area.5)

As the CD, we developed a similar MCP-type detector, used at the Gas filled Recoil Ion Separator (GARIS).6) When the beam passes through the thin carbon foil (60 μg/cm²), secondary electrons are generated in the foil. The generated electrons are transported to the MCP by only the electric field. A schematic view of the detector is shown in Fig. 1(b). A mirror electric field and an acceleration electric field are how they are created using wires. Wires (W+Au) with a 40-μm diameter are set at distance of 8.0 mm from carbon foil with a 1.0-mm pitch, and wires (W+Au) for the triangular part are set with a 3.0-mm pitch.

References
Performance of a resonant Schottky pick-up for the Rare-RI Ring project

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Construction of a new storage ring called “Rare-RI Ring” was started in 20121,2) at RIBF. This project aims at precise isochronous mass measurements for extremely neutron-rich exotic nuclei in the r-process nucleosynthesis. To precisely tune the ion-optical condition to be isochronous, the resonant Schottky noise pick-up technique will be employed. We performed an off-line test of the resonant Schottky pick-up.

Figure 1 shows the resonant Schottky pick-up that will be installed in the Rare-RI Ring. It consists of a pillbox-type resonant cavity electrically isolated from the beam pipe by a ceramic tube. A schematic view of the pick-up is shown in Fig. 2(a): a chamber shown in blue is the beam pipe and the shaded cylinder surrounding the beam pipe is the cavity equipped with two ports (yellow). The ports are movable plunger pistons that can adjust the resonance frequency \( f_{\text{res}} \) of the eigenmode. Fig. 2(b) shows the cross-sectional view of the cavity, and the detailed structure of the gap can be seen at the center. The cavity itself is filled with air and has the shape of a pillbox with an outer diameter of 750 mm and length of 200 mm. The inner diameter is 320 mm. The lower flanges (see Fig. 1) are prepared for feedthroughs to take out signals from a loop coil that magnetically couples to the cavity field induced by the beam.

Using a network analyzer, we measured the basic quantities characterizing the resonant cavity: the resonance frequency, the shunt impedance \( R_{\text{sh}} \), and the unloaded \( Q \) factor \( Q_0 \). To measure \( R_{\text{sh}} \), the perturbation method was adopted. From the measurements, \( f_{\text{res}} = 171.54(\pm0.44) \text{ MHz} \), \( R_{\text{sh}} = 169 \text{ k\Omega} \), and \( Q_0 = 1884 \) were obtained.

For tuning the isochronous field settings, the proposed pick-up is required to have an excellent single-ion sensitivity. By using the results of the off-line test, the output signal power corresponding to a single ion with charge \( q \) at resonance3) is estimated to be \( P = q^2 \times 2.8 \times 10^{-21} \text{ W} \), and the power of thermal noise \( P_{\text{noise}} \) is \( 7.1 \times 10^{-19} \text{ W} \). For \( q \geq 16 \), the signal power exceeds the noise floor, and the signal from the beam can be detected by the present Schottky pick-up. Therefore, the performance is sufficient for precise tuning of isochronous field settings of the Rare-RI Ring.

The resonant Schottky pick-up will be soon installed into the Rare-RI Ring. Detailed results of the off-line test and online beam performance test will be reported in forthcoming publications.

References
Control system for the magnet power supplies of the Rare-RI Ring

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We report on the status of the control system of the magnet power supplies of the rare-RI ring. The development of the control system was started at the beginning of 2013, and it has become possible to remotely control the main and trim coils of dipole, septum, and quadrupole magnets since November 2013.

Components to be controlled in the rare-RI ring are classified into two groups: components for operating the rare-RI ring as a storage ring and other components used solely for precise mass measurements. The components belonging to the former group, such as magnets and vacuum systems, are similar to those used in the existing RIBF accelerators. As a first step in implementing the control system for the rare-RI ring, we have started developing the control system for the magnet power supplies that will be first used for magnetic-field measurements of the rare-RI ring. Control systems for vacuum components will be integrated into the control system for the magnet power supplies.

The control system of the rare-RI ring is developed on the basis of Experimental Physics and Industrial Control System (EPICS)1). To save construction cost and time, the integrated into the control system for the magnet power supplies of the rare-RI ring. We report on the status of the control system of the magnet power supplies for the rare-RI ring. F3SP66 is a conventional ladder PLC-CPU for the FA-M3 system, and it is controlled by using netDev, an EPICS device, and driver support for general network devices developed by KEK and RIBF control groups2). Old power supplies are reused for the trim coils; these are controlled via serial communication, RS422. We have connected a serial-Ethernet converter to the magnet power supply and controlled it via Ethernet by using StreamDevice, an EPICS device support for devices controlled by sending and receiving strings3).

For an operator interface (OPI) application, we have selected Control System Studio (CSS).4) CSS is a user interface framework for control systems based on Eclipse, which has functions of not only a graphical user interface (GUI) but also an alarm system and a data archiving system. It is at the forefront of recent OPIs.

Regarding a network, we have recently installed a local area network (LAN) dedicated to the rare-RI ring (hereafter, rare-RI ring LAN), which will be used in combination with the LAN of the RIKEN Wako campus (hereafter, Wako LAN). Servers and controllers for each component in the rare-RI ring are connected to the rare-RI ring LAN, and client PCs are connected to the Wako LAN. The two networks are connected to each other across a firewall. We can obtain information on the rare-RI ring from every PC on the Wako LAN; however, controlling the components is permitted for only a few dedicated client PCs.

Three types of servers are installed in the rare-RI ring LAN. The first functions as a network file system (NFS) and EPICS-Input/Output Controller (IOC) server and as a firewall and router in the connection of the rare-RI ring LAN and the Wako LAN. As an IOC server, it serves as a soft IOC to control ladder CPUs. The second server is a backup server. The files on the NFS and EPICS-IOC servers' local hard disks are copied to this backup server to avoid loss of files and data. The third server manages a relational database (RDB), in which PostgreSQL is installed to operate the data archiving system and the alarm system of CSS on client PCs. This server also simultaneously executes a data acquisition program to save operation data and a program for operating the GUI of the CSS alarm system.

Table 1: Controllers used in the rare-RI ring

<table>
<thead>
<tr>
<th>Type of Magnet (Number)</th>
<th>Number of magnet power supplies</th>
<th>Type of controller (Number)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main coil of dipole magnets (24)</td>
<td>1</td>
<td>F3SP66 (1)</td>
</tr>
<tr>
<td>Trim coil of dipole magnets (10)</td>
<td>10</td>
<td>Serial-Ethernet Converter (1)</td>
</tr>
<tr>
<td>Septum magnet (4)</td>
<td>2</td>
<td>F3SP66 (2)</td>
</tr>
<tr>
<td>Kicker magnet (5)</td>
<td>10</td>
<td>Under discussion</td>
</tr>
<tr>
<td>Correction coil magnet (24)</td>
<td>6</td>
<td>Under discussion</td>
</tr>
<tr>
<td>Quadrupole magnet (10)</td>
<td>10</td>
<td>F3SP66 (5)</td>
</tr>
</tbody>
</table>

Magnet power supplies, except for those exciting the trim coils, were newly developed for the rare-RI ring. F3SP66 is a conventional ladder PLC-CPU for the FA-M3 system, and it is controlled by using netDev, an EPICS device, and driver support for general network devices developed by KEK and RIBF control groups2). Old power supplies are reused for the trim coils; these are controlled via serial communication, RS422. We have connected a serial-Ethernet converter to the magnet power supply and controlled it via Ethernet by using StreamDevice, an EPICS device support for devices controlled by sending and receiving strings3).

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References
1) http://www.aps.anl.gov/epics/
3) http://epics.web.psi.ch/software/streamdevice/
4) http://cs-studio.sourceforge.net/

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The installation of SLOWRI\cite{1}, a principal facility at RIBF that will provide low-energy, high-purity RI-beams of all elements, started in FY2013. SLOWRI consists of two gas catchers (GasCell-A and -B), mass separators, a 50-m beam transport line, a beam cooler-buncher, and lasers.

The necessary infrastructure was prepared in the summer of 2013. Two 400-mm-diameter holes in the shielding block were drilled for the beam transport line. A 3.5-m long hole was drilled between the laser room and BigRIPS room for creating a laser path. A staircase was closed by a steel roof to extend the SLOWRI experimental room. The cable rack of BigRIPS was modified, and the electronic racks and compressors for the cryogenic cooling system were relocated to install GasCell-A. Large concrete blocks were also relocated to install the mass separator for GasCell-B. A laser hut was built to install pulsed lasers, and utilities for the high-power lasers were prepared.

GasCell-A (RF carpet gas cell)\cite{2} 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\cite{3,4}. It will convert the main beams of BigRIPS to low-energy, low-emittance beams without any restrictions on the chemical properties of the elements. GasCell-B (PALIS)\cite{5} will be installed in the vicinity of the second focal plane slit of BigRIPS. It will provide parasitic RI beams from 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 ready for off-line testing by March 2014.

The 50-m beam transport line under installation (Fig. 1) consists of four dipole magnets (SD1 to SD4), two focal plane chambers, 62 electrostatic quadrupole singlets, 11 electrostatic quadrupole quartets (EQQ1 to EQQ11), and 7 beam profile monitors (BPMs). SD1 and SD2, located immediately 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 structures with phase space matching using EQQs. The EQQs have multipole elements made of 16 rods on which various potentials can be applied to produce 6-pole and 8-pole fields, simultaneously, to compensate for ion optical aberrations. This multipole element can also produce dipole fields for steering and scanning the beam. The BPMs have a classical cross-wire beam monitor as well as a channel electron multiplier with a pinhole collimator. Combining the scanning capability of the EQQs and the pinhole detector, we can observe a beam profile even for very low-intensity RI-beams.

In the SLOWRI experiment room, a beam cooler-buncher\cite{6} and a multi-reflection time-of-flight mass spectrograph\cite{7} will be installed for conducting various precision experiments.

Off- and on-line commissioning will take place in FY2014, and the low-energy RI-beams will be provided for users in FY2015.

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4) F. Arai et al., Int. J. Mass Spectrom., in press.
5) T. Sonoda et al.: In this report.
6) Y. Ito et al.: In this report.
7) P. Schury et al.: In this report.
Performance of an ion surfing rf-carpet in high gas pressure for application in a high energy RI beam gas catcher

F. Arai,*1,2 Y. Ito,*1 I. Katayama,*1 P. Schury,*1 M. Wada,*1 and H. Wollink*1,*3

High-energy radioactive isotopes produced in-flight by fragmentation or fission are used in ion trap-based precision experiments after being stopped in a large gas cell. The stopped ions can be extracted from the large gas cell as a low-energy ion beam. In order to transport and extract 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. However, such a method is restricted by the transport time to longer half-life isotopes owing to the upper limit on the dc gradient that can be supported before electric discharges occur in the large gas cell. For studying 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 as illustrated in Fig. 1(a), called "ion surfing". This technique has recently been experimentally verified with a linear RFC.

As in the standard method, rf signals are applied to the electrodes such that adjacent electrodes are 180° out of phase, creating an effective repelling force for the ions. In the "ion surfing" method, in order to keep the ion just above the RFC surface, the repelling force needs to be balanced by a push force, which is created by a push electric field \( E_{\text{push}} \). The confined ions can be transported along the RFC surface by superimposing a weak audio-frequency (AF) signal such that adjacent electrodes are 90° out of phase, forming a traveling potential wave. Under optimal conditions, the ion speed approaches the wave’s speed, which is proportional to the AF frequency \( f_{\text{AF}} \).

Recently, we have demonstrated the transport and extraction of \( K^+ \) ions using a circular RFC in 2 kPa of He gas pressure. However, in the practical gas cell, the gas pressure is higher than this value.

In this study, the transport and extraction of \( K^+ \) ions were tested in high He gas pressure using a 160 mm cylinder electrode, which created a push electric field \( E_{\text{push}} \) and circular RFC with 0.32 mm diameter orifice. The RFC consists of 245 ring electrodes, each 0.08 mm with 0.16 mm pitch. Fig. 1(b) shows the efficiency measurement method. The study required the measurement of two ion currents: the current reaching the RFC electrodes (with rf off) \( I_{\text{RF}} \) and the ion current reaching the FC \( I_{\text{FC}} \). The FC was biased at −10 V to pull ions out from the extraction orifice. We define the combined transport and extraction efficiency as \( \varepsilon_{\text{ext}} = I_{\text{RF}}/I_{\text{FC}} \).

Fig. 2 shows the \( \varepsilon_{\text{ext}} \) as functions of the gas pressure \( P_{\text{He}} \). At \( E_{\text{push}} = 5 \) V/cm, more than 90% \( \varepsilon_{\text{ext}} \) was obtained. However, at \( E_{\text{push}} = 10 \) V/cm, \( \varepsilon_{\text{ext}} \) dropped in high pressure. For higher pressure, the effective repelling force becomes small. As a result, \( E_{\text{push}} \) exceeds the effective repeller field of the RFC and causes ions to hit the RFC electrodes. To allow operation at higher pressures and \( E_{\text{push}} \), a larger effective repelling force is needed.

We intend to apply the ion surfing transport method to the SLOWRI gas cell with improved geometry.

Fig. 3. Comparison of ion motions in 2 mbar He using RF and DSB. RF: 5 MHz (see Fig. 3). Taking

References

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A gas-cell ion cooler and buncher for SLOWRI

Y. Ito,*1 M. Wada,*1 P. Schurry,*1 F. Arai,*1 T. Sonoda,*1 I. Katayama,*1 and H. Wollnik*1,∗2

For future experiments at SLOWRI, ion cooling and bunching will be indispensable for various experiments such as collinear laser spectroscopy, and for all ion trap experiments. The ion beams from SLOWRI gas catchers will be continuous with a beam energy of 30 keV. They must be decelerated and cooled in an ion trap for bunched ions. In general, linear RF quadrupole (RFQ) traps have been used for such a purpose after electrostatic deceleration. Such systems typically use Hg gas at a pressure of the order of 10⁻² mbar to cool ions in a ~1 m length RFQ. Due to the limited acceptance of the RFQ, the typical efficiency of such cooler and buncher is a few ten percent.¹ ²

We propose here a new gas-cell cooler and buncher (GCCB) scheme (Fig. 1). It consists of a gas cell (GC) with an RF carpet (RFC) and a flat trap (see Fig. 1). The GCCB will be filled with He gas at up to 2 mbar — much less than the ~100 mbar used in conventional GC — and cryogenically cooled to <77 K. According to calculations with TRIM, a stopping efficiency of ≈100% can be obtained for any 30 keV beams with Z > 3 if the GCCB is at least 420 mm long.

Fig. 1. Schematic diagram of the GCCB. Continuous ion beams will be cooled in the grounded GCCB, transferred to the flat trap, and extracted as a pulsed beam.³

The RF carpet is a proven technique for efficient and fast ion transport. Recently, the so-called ion surfing method, in which a traveling potential wave is superimposed on the RF, has been developed for faster transport.⁴ The transport speed was as high as 75 m/s with a linear RFC and an extraction efficiency of ≈100% was obtained using a circular RF-carpet.⁵ However, it has yet to be used at pressures as low as 2 mbar.

To verify the performance of the RFC at low pressures, the extraction efficiency of the RFC was investigated with a fine-RFC that has an electrode pitch of 0.16 mm and 0.08 mm exit hole. The experimental parameters were optimized to achieve high efficiency using an RF frequency of frf = 5 MHz. However, when operated at 2 mbar, few ions could be extracted from the GC; at 5 mbar, the efficiency was 22%.

Simulations with SIMION indicated that the low efficiency was the result of unstable ion motion arising from the ions moving between adjacent electrodes in fewer RF periods than required for the validity of the pseudo-potential approximation (see Fig. 2). By increasing the RF frequency to 12 MHz, the simulation indicated that the ion motion would become stable and a high extraction efficiency could be achieved.

Fig. 2. Comparison of ion motions for fRF = 5 MHz and 12 MHz.

Since the resonance RF frequency is, however, limited by the impedance of the system, such higher frequency is difficult to obtain; however, increasing the electrode pitch should yield a similar effect. In simulation, doubling the electrode pitch and the exit hole diameter yielded near unity extraction efficiency with 2 mbar He for fRF = 5 MHz (see Fig. 3). Taking into account the transport and trapping efficiencies of a multipole ion guide and a flat trap³ after the GC, the overall efficiency of the GCCB is expected to be >50%. Such a larger-pitch RF-carpet is being manufactured and will be tested soon. An offline test using 30 keV ion beam coupled to a multi-pole ion guide and the flat trap³ will be performed in early FY2014.

Fig. 3. Comparison of ion motions in 2 mbar He using 0.16 mm and 0.32 mm pitch.

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³ Department of Chemistry and Biochemistry, New Mexico State University
Conceptual design of a post accelerator for SLOWRI

S. Arai*† and M. Wada*†

As an extension plan of the slow radioactive nuclear ion beam facility (SLOWRI)‡, construction of a post accelerator has been proposed. The radioactive ions from SLOWRI are mass-analyzed, charge-bred, and injected into the post accelerator. The post accelerator is a normal conductive linear accelerator complex composed of a radio-frequency quadrupole (RFQ), a medium energy beam transport (MEBT), and a drift-tube linac (DT linac). The RFQ accelerates ions with mass to charge ratio \((A/q)\) of less than 9 from 5 to 500 keV/u. The beam from RFQ is transported to the DT linac through the MEBT. The output beam energy of the DT linac varies between 500 keV/u and 1.5 MeV/u. The layout and main parameters of the post accelerator are shown in Fig. 1 and Table 1, respectively.

![Fig. 1. Layout of the post accelerator.](image)

Table 1. Main parameters of the post accelerator

<table>
<thead>
<tr>
<th>Structure</th>
<th>RFQ</th>
<th>Drift-tube linac</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank No.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>79</td>
<td>158</td>
</tr>
<tr>
<td>A/q</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Input energy (keV/u)</td>
<td>5</td>
<td>500 1000 1230</td>
</tr>
<tr>
<td>Output energy (keV/u)</td>
<td>500</td>
<td>640 1000 1230</td>
</tr>
<tr>
<td>Normalized emittance (π cm mrad)</td>
<td>0.047</td>
<td>0.047</td>
</tr>
<tr>
<td>Number of cells</td>
<td>290</td>
<td>14 15 16 16 16</td>
</tr>
<tr>
<td>Bore radius (cm)</td>
<td>0.54</td>
<td>1.2 1.1 1.6 1.6 1.6</td>
</tr>
<tr>
<td>Electrode voltage (kV)</td>
<td>65.1</td>
<td>160 200 220 250</td>
</tr>
<tr>
<td>Synch. phase (deg)</td>
<td>-30</td>
<td>-25</td>
</tr>
<tr>
<td>Cavity diameter (cm)</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>Total cell length (cm)</td>
<td>719</td>
<td>46.4 56 66.7 74.2 82</td>
</tr>
<tr>
<td>Power loss (kW)</td>
<td>186</td>
<td>31 44 62 72 91</td>
</tr>
</tbody>
</table>

RFQ parameters were determined with reference to the RFQ “TALL”‡. The RFQ has a split coaxial-type structure, which is almost the same as that of the INS-type SCRFQ‡, while the mechanism for supporting the vanes is modified as shown in Fig. 2 in order to reduce the electrode capacitance. The cavity comprises 18 module cavities each of which is 30 cm in inner diameter and 40 cm in length. The cavity dimensions and RF parameters such as resonant frequency, unloaded Q, and power loss were estimated by means of numerical analysis based on an equivalent circuit.

As the DT linac, an interdigital-H (IH) type comprising five tanks and five quadrupole doublets is adopted to obtain high shunt impedance and variable output energy. Quadrupole doublets are placed in a short space of 37 cm between the tanks to avoid the reduction of longitudinal acceptance of the linac. The IH cavities were designed in the same manner as those of the RFQ were. The longitudinal sectional view of a cavity and the gap-voltage distribution along the beam axis for tank1 are shown in Fig. 3. The goal frequency and uniform distribution are obtained by optimizing the ridge-cut shapes of both the ends. Ridges are made from the flat plate with 4 cm thickness. Stems supporting the drift tubes are in the form of a truncated cone with the top and bottom diameters of 1 cm and 4 cm, respectively.

The beam simulation results are as follows: For the beam with a normalized emittance of 0.047 π cm mrad, the RFQ transmission is more than 90%. The output beam emittance profile of the RFQ is well matched with the acceptance profile of the IH linac by means of two quadrupole doublets and a 4-gap rebuncher of the quarter-wave resonator in the MEBT. Transmission of the IH linac is 100%.

![Fig. 2. Cross-sectional views of INS-type SCRFQ (left) and modified RFQ (right).](image)

![Fig. 3. Longitudinal sectional view (left) and gap-voltage distribution (right) for the 158.1-MHz IH tank1.](image)

References
Wide-band mass measurements with a multi-reflection time-of-flight mass spectrograph†

P. Schury,*1 F. Arai,*1 Y. Ito,*1 T. Sonoda,*1 M. Wada,*1 and H. Wollnik*1

The multi-reflection time-of-flight mass spectrograph (MRTOF-MS), first proposed more than 20 years ago1, uses a pair of electrostatic mirrors to compress a flight path of several hundred meters (or even many kilometers in some cases) within a reflection chamber of ≈1 m length. The MRTOF-MS can achieve mass resolving powers of \( R_m > 10^5 \) while operating at rates of 100 Hz or more2,3,4).

Recently, these devices have begun to prove useful for online measurement of nuclear masses5,6). The technique has been demonstrated to accurately provide mass precision of \( \delta m/m \sim 5 \times 10^{-7} \) or better.

However, the multi reflection nature of the measurement has made analysis of rich, wide-band mass spectra difficult or impossible. Much like runners of widely varying skill racing on a circular track, after some time ions with sufficiently differing mass-to-charge ratios make different numbers of laps and create a difficult to interpret spectrum. By developing an analytic method to interpret such spectra, we believe the device could eventually provide wide-band measurements of nuclear masses much in the way of storage rings7). The device could also be useful in analytic chemistry, providing wide-band analysis much like FT-ICR Penning traps, but with greater sensitivity.

Fig. 1. Example spectra with \( n_m = 78 \) and 79 laps. Abscissa reflects the time-of-flight of the NaNH\(^+\) reference.

As reported8), using a time-of-flight peak corresponding to a reference ion with known mass-to-charge ratio that makes a known number of laps in the reflection chamber it is possible to determine the mass-to-charge ratio corresponding to any other peak as

\[
m_2 = m_1^{(n)} \left( \frac{\zeta + n_{m_1}}{\zeta + n_{m_1} + \Delta n} \right)^2,
\]

where reference ions with mass-to-charge ratio \( m_1^{(n)} \) make \( n_{m_1} \) laps and unknown ions with mass-to-charge ratio \( m_2 \) make \( n_{m_1} + \Delta n \) laps, while \( \zeta \) is a system-dependent constant; for our system \( \zeta = 0.686893(20) \).

Determining \( \Delta n \) requires a pair of spectra with different values of \( n_{m_1} \). Using this method, it is possible to determine the mass-to-charge ratio of ions over a wide range with a relative mass accuracy of \( \sim 10^{-6} \), which is typically sufficient to uniquely identify the ions. Such a pair of spectra with ion identity determined is shown in Fig. 1 using NaNH\(^+\) as a reference.

Once \( \Delta n \) is known, a more precise determination of the ion’s mass-to-charge ratio can be determined using the time-of-flight of the reference and unknown with each undergoing the same number of laps, as previously demonstrated online for \( ^6\text{Li}^+ \)6). If there exist isobars, one isobar can be used as a reference while the others are treated as unknown masses and simultaneous accumulation of reference and unknown can be performed, removing possible drift-related errors.

We foresee the possibility of performing such wide-band mass measurements of r-process nuclei at SLOWRI. As demonstrated in the calculated spectra shown in Fig. 2, it should be possible to measure masses of 20 or more nuclei simultaneously. This would allow the entire region from \(^{78}\text{Ni}\) to \(^{132}\text{Sn}\) to be investigated with less than 10 tunes of BigRIPS.

Fig. 2. Calculated spectra at SLOWRI from nuclei produced by in-flight fission of Uranium. In the hashed region, ions will experience time-dependent electric fields from extraction switch and cannot be analyzed.

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Design work for PALIS system

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In FY2013, the construction budget for a low-energy RI-beam facility SLOWRI was finally founded. The design drawing for the PArasitic slow RI-beam production by Laser Ion Source (PALIS)1 was finalized.

We will restore unused RI-beams for producing slow RI-beam by installing a gas catcher in the vicinity of the second focal plane (F2) of the fragment separator BigRIPS. This will enable the use of parasitic slow RI-beams for various precision experiments whenever BigRIPS experiments are in operation.

In order to realize the reasonable performance under various constrained conditions, there are a lot of novel methods taken into the PALIS design. In particular, the following three worthwhile items were resolved as to avoid any interference to the BigRIPS main beam experiments. The first item is the position of the gas cell, which should be able to move horizontally on the x-axis perpendicular to the BigRIPS beam direction. At F2, RI-beams with slightly different isotopes are focused on along side the x-axis. By applying an overhead beam extraction, the PALIS gas cell collects such the isotope beams neighboring a BigRIPS main beam at both the neutron-rich and neutron-deficient sides, respectively. The extracted RI-beams from the gas cell are transported along the y-axis to the height of 70 cm from the BigRIPS beam, where it bends by 90 degrees in another beam line comprising several bellow combinations. Using a stepping motor, the PALIS gas cell can be moved -60 mm away from the central axis of the BigRIPS beam, and is also pulled by +160 mm toward the evacuation site.

The second item is the differential pumping system for realizing the gas cell pressure for Ar/He up to 10^5 Pa under the totally separated vacuum condition between the PALIS beam line and the BigRIPS F2 chamber. So far, we developed a novel implementation of differential pumping, in combination with a sextuple ion beam guide (SPIG), which allows a pressure difference from 10^3 to 10^-3 Pa within a drastically miniaturized geometry compared to conventional systems2). This system can utilize a large exit hole platform for ion acceleration, which is necessary for the electrical isolation between the PALIS gas cell, following the beam extraction system including the evacuation lines of differential pumping, and the grounded beam lines. The low-energy RI-beam from PALIS should be transported to the SLOWRI experimental room via 50 m long low-energy beam line. Therefore, ion acceleration is indispensable, while any problem induced from high voltage breakdown should be avoided for the protection of BigRIPS beam profile detectors placed in the F2 chamber. For the first phase, we will adopt the pulsed cavity method3 located at the outside of the F2 chamber. The extracted low-energy RI-beam transported via SPIG and QMS first enters a linear ion cooler-buncher, and then, the produced pulsed beam is accelerated toward a cavity at the potential of about 1 kV. When the ion pulse reached the field-free region inside the cavity, the fast switch applies a high voltage potential about 30 kV, the latter is switched again to ground potential for ion acceleration. This pulsed cavity consists of MRTOF4 in expectation of future isobar purification. By this way, the electrical isolation is no longer necessary.

The PALIS design work has been almost finalized, as shown in Fig. 1. The off-line and on-line commissioning test for PALIS will be started from June 2014.

Fig. 1. BigRIPS F2 chamber implemented with PALIS.

References

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*2 Japan Atomic Energy Agency
Transportation of laser beams for PALIS

H. Iimura,*1,*2 T. Sonoda,*1 and M. Wada*1

PARasitic RI-beam production by Laser Ion-Source (PALIS)1 is under construction as a part of the slow RI-beam facility, SLOWRI, at RIBF. The PALIS is based on resonant photoionization of reaction products cached in a gas cell. According to the present plan, the gas cell will be installed in the vicinity of the slit at the F2 focal plane in BigRIPS. However, the laser system for PALIS is set up in a room on a different floor located at approximately 50 m in the horizontal and 10 m in the vertical direction from the F2 chamber of BigRIPS. Thus, to transport the laser beams across this long distance we designed an optics system.

The laser system newly installed for the PALIS consists of two dye lasers (Spectra-Physics Credo) pumped by a Nd:YAG laser (EdgeWave IS) at a repetition rate of 10 kHz. We will use a two-step two-color scheme or a three-step two- or three-color scheme for the resonant ionization of atoms. For example, in case of the three-color scheme, the Nd:YAG laser will be used in the third step from an intermediate state to the ionization continuum.

The planned optics system is shown in Fig. 1. Three sets of this system will be installed to transport three different-color laser beams independently. We prepared a few spares of each lens and mirror to exchange them according to the wavelength of laser. Three laser beams overlap each other at the PALIS gas cell. Because mirror M3 is close (~1 m) to the gas cell, it reflects all three laser beams; this is different from other optical components that are used for only one laser beam.

Because the beam size of the laser is small (0.8 mm horizontally and 2 mm vertically) at the exit of the dye laser, it diverges after long distance transportation (with divergence of 1 mrad). Therefore, we expand the laser beam to approximately 7 mm x 17 mm using an expander consisting of a concave lens (L1) and an achromatic lens (L2). The estimated divergence of this beam is 0.1 mrad, and the beam size does not change significantly after a transportation distance of 45 m. Then the laser beam is focused with a long focal length using a combination of convex (L3) and concave (L4) lenses. Finally, the laser beam is injected into the PALIS gas cell in the F2 chamber of BigRIPS. The resonant photoionization occurs inside the SextuPole Ion Guide (SPIG) to which atoms move from the gas cell. We designed the optics system such that the beam size of laser changes to 3 mm x 3 mm along the 25-cm length of SPIG and the laser beam matches the 3-mm inside diameter of SPIG.

Regarding the intensity of the laser beam, outputs of the dye lasers are less than 15 W, or in case of using a second harmonic generator, they are less than 2 W. In many of the ionization schemes, the intensity of ions is not saturated with these laser powers. Therefore, higher transport efficiency of the laser beams is necessary to achieve higher intensity of ions. The designed optics system uses a minimum number of optical components, and the transport efficiency estimated from the transmission and reflectance of the optical components is approximately 50 % at a wavelength of 350 nm. If we use an optical fiber instead, the efficiency lowers to approximately 10 %.

The experimental room where BigRIPS is located cannot be entered when the RI beams are injected, although the laser room can be entered at any time. To handle the laser beams without entering the experimental room, we placed actuators to change the angles of 2-inch mirrors M1 and M2. These actuators can be controlled via Ethernet by a computer. Additionally, several CCD cameras will be installed to monitor the laser beam spots from a distance. We also plan to place a photo detector inside the gas cell to finally confirm that the laser beams pass through apertures of the PALIS.

Transportation of dye laser beam is currently being examined for attenuation of the intensity, spatial fluctuation of the beam spot, and so on. Besides the dye lasers, a narrow band-width injection-locked Ti:Sapphire laser2 is being developed for the in-source laser spectroscopy. Transportation of this laser beam is also planned.

References

Fig. 1. Planned optics system for transportation of laser beams to PALIS.

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New laser system installation for PALIS

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A new laser system for PArasitic slow RI-beam production by Laser Ion Source (PALIS)1) has been installed. This system has higher laser power and repetition rate compared to those previously we used. A gas-jet laser spectroscopy can be applied owing to high repetition rate. A room partition was recently constructed for the laser equipments having laser shield noise barriers. The room is complete with an air conditioning system.

So far, we have developed a resonant ionization laser system and a new laser ion source configuration for future PALIS project. Old laser components consist of two pulsed dye lasers (Lambda Physik) pumped by two excimer XeCl lasers (Lambda Physik). The maximum power and repetition rate for the excimer laser is 150 mJ/pulse, 200 Hz, which corresponds to 30 W. Additionally, Ti:Sapphire laser pumped by YLF laser (10 W, 1 kHz) is available through collaboration with Nagoya university. By using these lasers, off-line resonant laser ionization for stable Co, Cu, Fe, Ni, Ti, Nb, Sn, In, and Pd inside the gas cell, ion extraction and transport to high-vacuum region via SPIG and QMS have been confirmed2). The feasibility study for the gas jet laser spectroscopy was investigated in combination with dye and TiSa lasers3,4).

In terms of the efficiency of the gas cell based resonant laser ionization system, the laser power and its duty cycle are important. The ionization efficiency depends on the atomic transition strength determined by the type of the element. High power lasers are widely adopted for a number of elements. Moreover when the moving speed for photo-ionized atoms increases as in the case of ionization inside a gas jet, the duty cycle of the laser pulse should be set suitably high5). Thus, a high power and high duty cycle laser is necessary to realize a higher performance PALIS system.

In FY2013, the construction budget for a low-energy RI-beam facility SLOWRI was finally founded. New high power, high duty cycle lasers were prepared for PALIS experiments. In order to install the new laser assembly, the room size for laser setting and off-line experiment was also extended. New laser components consist of two pulsed dye lasers pumped by one YAG laser. The maximum repetition rate and power for a YAG laser (Edge wave) is 10 kHz and 90 W for 532 nm with a single mode and 36 W for 355 nm and 40 W for 532 nm with a multimode. Two pulsed dye lasers (Sirah) provide a wide range wavelength from 215 to 900 nm with about 10 W for fundamental frequency and 1 W for a frequency-doubled by a secondary harmonic generator. These dye lasers accept both wavelengths (355/532) from pump laser beam and have an additional option for selecting a line width of 1.5 GHz and 6 GHz, alternately. Additionally, a new YAG laser (Lee) was installed for pumping Ti:Sapphire lasers. The maximum power and repetition rate is 50 W and 10 kHz, respectively. An injection locked Ti:Sapphire laser operated at up to 10 kHz with a line width of 20 MHz will be prepared for high precision laser ionization spectroscopy.

Fig. 1. The photograph of new PALIS lasers: shining two dye lasers pumped by YAG laser.

We confirmed that the new laser system works with a reasonable performance. Fig. 1 shows a photograph taken during tests of the new lasers in October 2013. The off-line and on-line commissioning test for PALIS will begin from April 2014.

References
A laser interlock system has been developed to facilitate safe operation and machine protection in the new laser system for PARasitic slow RI-beam production by Laser Ion Source (PALIS)\(^1\).

Fig. 1 shows the overview of the interlock system for the current PALIS laser setups. There are many items pertaining to laser operation, for example dye circulator, chiller, air compressor, laser beam shutter, power meter, wave meter, and so on. These often depend on each other. If some interruption in dye flow occurs during the irradiation of strong pump laser beam, the dye cell and dye itself are damaged almost immediately. Further, if cooling water stops or leaks, those devices that require refrigeration stop functioning. These accidents are dangerous and can potentially start a fire or cause fatal damage to laser devices. The irradiation of laser beams direct on to the human body, especially on to the eyes must be avoided. Therefore, some safety devices like a beam shutter or door interlock, are necessary. Additionally, a monitoring system is essential to establish a robust system and to reduce the frequency of operator interventions for reading laser beam power, laser beam position, and wavemeter.

In this circumstance, one needs to build an automated system using a programmable logic controller for operating all devices remotely. We adopted a National Instruments (NI) Compact RIO system that are referred from ISOLDE RILIS\(^2\). NI CompactRIO incorporates a real-time processor and reconfigurable FPGA. The hot-swappable industrial I/O modules can directly connect to sensors and actuators. CompactRIO embedded systems are developed using high-productivity LabVIEW graphical programming tools for rapid development.

The sensor devices for dye circulation are necessary to monitor the dye flow at all times. However, the dye solution is often composed of volatile liquid, and the interconnection of sensor surface on the liquid flow is not adequate. Here, we use two types of sensors on an experimental basis. One is a vibration sensor that can detect a small oscillation of the flow tube synchronized with a circulator’s pumping action. The other is an ultrasonic sensor that evaluates the echo of high frequency sound waves received back by the sensor. If any sensor detects an interruption in dye flow, the beam shutter immediately acts to stop the pump laser beam. In addition to these sensors, alcohol sensors monitor a dye leak. Several sensors are used for cooling water to detect a leak and to monitor the dye temperature stability. The laser power meters and beam shutters are coupled with air cylinders. Therefore, the air pressure is also monitored by a pressure sensor. The door interlock system for laser beams was prepared in the BigRIPS room. The laser beams cannot be sent to the BigRIPS room unless any door in the BigRIPS room is closed.

The overview of the interlock system with interactive equipments for current PALIS laser experiment.

The laser interlock system for PALIS experiment is being developed. This system is motivated not only for human and machine protection but also for facilitating an efficient and robust experimental environment. By effective utilization of these system, the off-line and on-line commissioning test for PALIS will be started from April 2014.

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We have developed a new laser spectroscopic technique called Optical Radioisotope atom Observation in Condensed Helium as Ion-catcher (OROCHI) for investigating the structure of exotic nuclei. In this method, we observe atomic Zeeman splitting (ZMS) and hyperfine splitting (HFS) by using optical pumping and laser-microwave (MW) double resonance spectroscopy in superfluid helium (He II) to derive nuclear spins and electromagnetic moments. The characteristic optical properties of atoms in He II, for example, blue-shifted and considerably broadened absorption spectra, enables us to apply the optical pumping technique to several elements. Recently, we performed a series of on-line experiments by using energetic (up to 66 MeV/u) 84-87Rb beams from Riken Projectile-fragment Separator (RIPS), and confirmed the feasibility of the OROCHI method. Furthermore, we succeeded in producing a large atomic spin polarization (>80 %) of 197Au by means of optical pumping in He II by the laser light of the fourth harmonics of a LD-pumped pulsed Nd:YLF laser (263.5 nm, 3 kHz). Subsequently, we plan to measure the spins and moments of neutron-deficient Au isotopes possessing interesting structures.

As the first step, we measured the HFS of a stable 197Au atom in an off-line experiment. Fig. 1 shows the experimental apparatus. An open-topped cubic quartz cell in a cryostat is fully filled with He II. The produced Au atoms are introduced into He II by using laser sputtering of the sample material with two pulsed lasers. We observed the intensity of Laser Induced Fluorescence (LIF) by means of a photomultiplier tube (PMT) through a monochromator for wavelength selection, and performed the laser-MW double resonance spectroscopic measurements (MW power: typically 1 W).

Fig. 2 shows an HFS resonance spectrum of 197Au in He II. In fact, the observed HFS resonance frequencies were shifted because of the Zeeman interaction with the applied magnetic field. Then, we derived the HFS with the zero-magnetic field effect from two HFS resonance frequencies measured by employing opposite polarization directions of the pumping laser, $\sigma^+$ and $\sigma^-$, respectively, for cancelling the shift due to the Zeeman effect. The deduced HFS in this study was consistent with the literature value of 197Au in vacuum (with an accuracy of 0.5 %).

The obtained value was slightly different from the literature value as well as the values for 133Cs and 85,87Rb. The shift is due to the pressure from surrounding helium atoms. However, the slight shift can be neglected in the discussion regarding the structure of nuclei.

The successful HFS measurement indicates the feasibility of future measurements for neutron-deficient nuclei of Au by using the OROCHI method. In the near future, we plan to propose experiments with exotic Au isotopes.

References
We developed a new gas-filled recoil ion separator (GARIS-II) to study asymmetric actinide-target based fusion reactions\(^1\). As the first step, we measured the solid angle of the separator offline using a standard \(\alpha\)-source of \(^{241}\)Am, and it was determined to be 18.2 msr\(^1\). As the second step, we performed online testing to evaluate the separation capability of GARIS-II from background particles, and its transmission using \(^{40}\)Ar-induced fusion reactions. These reaction products were collected onto a focal plane detection (FPD) system with high efficiency under extremely low background conditions\(^2\).

As the third step of commissioning \#3, we performed online operating tests on GARIS-II using \(^{22}\)Ne-induced fusion reactions of \(^{197}\)Au, \(^{205}\)Tl, \(^{208}\)Pb, \(^{209}\)Bi, \(^{232}\)Th, and \(^{238}\)U. The reaction products were separated in-flight from projectiles and other by-products using GARIS-II, and then they were guided into the FPD system after passing through the time-of-flight detector\(^3\). The separator was filled with He gas at the pressure of 10, 33, 80, and 173 Pa. For further background rejection using GARIS-II, we tested He-H\(_2\) mixture as the filled gas at the same gas pressure. Figure 1(A) shows the intensity distribution of \(^{215}\)Ac, which is produced via the \(^{197}\)Au\((^{22}\)Ne,4n\) reaction, at FPD in the case of filling at \(33\) Pa He gas and \(33\) Pa He-H\(_2\) mixture (He:H\(_2\)=2:1). The optimum \(B\rho\) was shifted up to 11% and the transmission was increased from 11.4% to 14.6%. The \(B\rho\) shift implies that the average equilibrium charge state of recoil ions moving in a filled gas becomes small. The improvement of transmission is due to a decrease in the multiple scattering between the recoil ion and filled gas atom. Figure 1(B,C) shows a comparison of background (BG) level at each peak of the recoil ion and filled gas atom. Figure 1(B,C) shows two-dimensional views of energy measured by Si detector vs. recoil velocity measured using the timing counter.

As the fourth step of commissioning \#4, we performed online testing on GARIS-II using \(^{48}\)Ca-induced fusion reactions of \(^{208}\)Pb. We measured an excitation function of \(^{208}\)Pb\((^{48}\)Ca,2n\)\(^{254}\)No and the transmission of GARIS-II for \(^{254}\)No. The maximum transmission was 73% assuming \(\sigma = 2.05\ \mu\)b\(^3\) when the separator was filled with He gas at a pressure of 73 Pa, and the magnetic rigidity \(B\rho\) was set to 2.064 Tm. The maximum transmission of GARIS-II is two times higher than that of GARIS, which is 36%. Further, it is better than design value of 61% for GARIS-II. Transmission data are summarized in Fig. 2.

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**References**

Study on detector response to spontaneous fission events of heavy nuclides using the $^{206}$Pb+$^{48}$Ca reaction

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Detector response to spontaneous fission (SF) of products by the $^{206}$Pb+$^{48}$Ca reaction was studied using a new focal plane detector that has a Si-Ge array installed at a focal plane of the gas-filled recoil separator GARIS.

By using GARIS and GARIS-II, we plan to study the production and decay properties of the superheavy element (SHE) produced via actinide-based fusion reaction (hot fusion). It is reported that SHE nuclides produced by the hot fusion are radioactive and decay by $\alpha$-particles emission or $SF$, and all decay chains are terminated in $SF$ (1), which emit $\gamma$-rays. Therefore, it is important to measure the $\gamma$-rays of the SF of heavy nuclides. In 2013, we newly installed the Si-Ge detector array (2) for studying the production and decay properties of reaction products by including $^{248}$Cm+$^{48}$Ca (3). Thus far, we have searched for SF using Si detectors, however, the Si-Ge array can carry out a more accurate identification than the Si detector because the Si-Ge array is expected as a probe for the detection of prompt $\gamma$-ray coincided with $SF$. Before the experiment, the Si-Ge array was calibrated using a well-known $^{206}$Pb($^{48}$Ca,2$n$)$^{252}$No reaction. The $^{252}$No decays by $73.1\%$ $\alpha$-particle emission and $26.9\%$ $SF$ (5). We assigned this reaction based on its branching and half-life.

A $^{48}$Ca$^{1+}$ beam was extracted from the 18-GHz ECR ion source and accelerated up to 218.5 MeV by the RILAC. The typical beam intensity was $1.0 \times 10^{12}$ particle/s (0.17 pA). The metallic $^{206}$Pb (enrichment of 99.3%) target was prepared by vacuum evaporation on a backing of 60 $\mu$g/cm$^2$ carbon foil. The target thicknesses had a mean value of 353 $\mu$g/cm$^2$. Sixteen frames of the sector targets were mounted on a 30 cm rotating wheel, which was rotated at 3300 rpm. The reaction products were separated in flight from projectiles and other by-products by GARIS, which was filled with helium gas at a pressure of 73 Pa, and then the products were transported into the focal plane detection system after passing through the time-of-flight (TOF) detectors. The detector system comprised two TOF detectors, a PSD box (4-5), which is composed of a position-sensitive detector (PSD) and four solid state detectors (SSDs), and a planer typed Ge-detector for counting low-energy photon (CANBERRA, BE6530). The Ge-detector was separated from the other detector vacuum by a 1-mm thick aluminum window. Magnetic rigidity was set to 2.064 T·m for $^{252}$No. Gamma rays emitted in coincidence with SF events registered by the PSD box were measured by the Ge-detector.

Figure 1 (A) shows a two-dimensional plot of energy measure between PSD and SSD. $SF$ fragment energy is measured by SSD based on the implantation depth in PSD. When the recoil energy of evaporation residues is low, recoil ions are stopped at the surface of the detector. Then, $SF$ fragments are detected in both PSD and SSD (region a). Conversely, both $SF$ fragments are either stopped in the detector or one of fragment escapes in the backward direction if the recoil energy is high, the implantation depth is deep (region b).

Figure 1 (B) shows a two-dimensional energy plot of $SF$- and $\gamma$-rays observed in prompt coincidence. The probability of coincidence is 52.6% because an $SF$ event emits some $\gamma$-rays. From this probability, the Si-Ge array is considered to be useful for the identification of $SF$ fragments.

References
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Fig. 1. (A) Two-dimensional plot of energy measure between PSD and SSD. (B) Two-dimensional plot of $SF$-$\gamma$ coincidence.
Identification of every target mounted on a rotating wheel and its application

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Several pieces of sector-shaped targets mounted on a rotating wheel have been employed for superheavy element (SHE) production experiments with high-intensity beams. Thus far, it had not been possible to determine the thickness difference between each target without which, we adopted the average thickness of all the pieces. To distinguish it, we have developed a new wheel frame with an extra ID-tag placed between the spoke-position-indicator tags on the circumference of the wheel (Fig. 1).

![Fig. 1. (A) New wheel frame with an ID-tag. (B,C,D) Observed pin-holes on irradiated targets #11, 12, and 14, respectively.](image1)

A circuit block diagram for identifying each target frame is shown in Fig. 2. To avoid unnecessary beam irradiation of the spokes, timing signals of each tag detected by a photo-diode sensor are used. In the case of a rotational speed of 2000 rpm, the timing signals from the spoke tags are periodically generated for every 1.875 ms, whereas an additional signal from the ID-tag is generated for every 30 ms in one rotation. A signal timing chart [A], shown in Fig. 2, indicates that an original signal is generated from the photo sensor. The chart [B] is modified from the signal [A] by changing its delay and width. The chart [C] is obtained by a logical 'AND' operation of the signal [A] with [B], resulting in a useful timing for one rotation of the wheel. This pulse is delivered to a reset scalar and the scaler measure the timing in every rotation. This angle-timing information is recorded together with the reaction-event data measured at the focal-plane detector for each separate event. The chart [E] indicates the timing of the spokes with elimination of the timing of the ID-tag. The [E] is obtained by a logical 'AND' operation of the signal [A] with [D], which is an inverted signal of [B]. This pulse is delivered to the accelerator in order to chop the beam.

As a typical example, a two-dimensional plot (Fig. 3) of the event rate is monitored over a long irradiation period (abscissa) for a rapid rotation timing (ordinate). Event rates for targets #11, 12, and 14 become relatively higher than those for other targets caused by pin-holes on the target foils as shown in Fig 1(B,C,D). Thus, this plot is useful in identifying the condition of every target foil. Moreover, it enables additional beam chopping for masking the broken target, as shown in Fig. 3. The masking signal can be easily obtained with a logical 'OR' operation of the inverted signal [E] with a certain delayed signal of [C].

![Fig. 2. Block diagram for ID of every target-frames.](image2)

![Fig. 3. A target-condition monitoring chart using event timing. Sudden changes in event density at A, B, C, and D indicate the broken parts of the target sector #12, 14, 11, and 14, respectively.](image3)

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Radioisotopes (RIs) have long been used as tracers for wear diagnosis of mechanical parts. We proposed a surface activation method that utilizes RI beam implantation\(^1\) instead of the conventional ion-beam irradiation.

The degree of wear is determined by the decrease of the radioactivity of the object part or the increase of the radioactivity of the lubricant, through external gamma-ray measurements. Therefore, a lubricant circulation system is required for removal of activated surface debris from the machine. If the spatial distribution of the radioactivity in a running machine can be obtained, wear diagnosis can be performed for a closed system without a circulation system.

In many cases, the mechanical parts being subject to wear diagnosis work in continuous and periodical motions such as rotation. We are developing a new method to determine the spatial distribution of positron-emitting RIs on periodically-moving objects in a closed system, which is based on the same principle as medical PET systems but is simpler and less expensive.

Reconstructed from the sinogram. Therefore, with only two detectors, the RI distribution on a rotating object contained in a vessel can be inspected without stopping the rotation, if \( y \) and \( \phi \) at the time of coincidence detection are determined.

![Prototype setup.](image)

In order to prove the feasibility of the method, we have constructed a prototype (Fig. 2). A pair of NaI scintillator detectors are placed on the opposite sides of a rotating turntable (diameter of 14 cm) that holds RI sources and moves back and forth. Gamma rays from the sources are collimated by a pair of Pb blocks placed in front of each detector. A pin fixed to the turntable generates a pulse signal from a photoelectric sensor at each turn. The orientation of the turntable is determined by a clock-pulse counter that is started by the photoelectric sensor. At each coincidence detection the orientation and the position of the turntable and the pulse heights from the detectors are recorded.

Figure 1 shows the geometrical concept. A positron-emitting point source is located at \((r, \theta)\) in the polar coordinate fixed to the object. The orientation of the object is denoted by \(\phi\). A pair of gamma-ray detectors are located at both sides of the object to detect the 511-keV photons from positron annihilations. Since the photons are emitted in the opposite directions, the coincident detection is allowed only when the source is on the straight line between the detectors (line of response: LOR). This condition is followed by an equation \( y = r \cos(\theta + \phi) \), where \( y \) is the distance between LOR and the rotation center. If the pair of detectors is moved in parallel so that LOR scans the object and the coincidence rate is measured as a function of \(\phi\) and \( y \), the coincidence events from a point source fall on a sinusoidal curve in the \(\phi-y\) plane. If the source is spatially distributed on the object, the coincidence rate on the \(\phi-y\) plane yields a diagram called sinogram, which is a superposition of the sinusoidal curves. Conversely, the spatial distribution of the source can be reconstructed from the sinogram.

![Geometrical Concept.](image)

In Figure 3 shows a sinogram and a reconstructed radioactivity distribution for two \(^{22}\)Na sources, (A) 65 kBq and (B) 1.55 kBq, fixed on the turntable that rotates at 150 rpm and moves back and forth by 2-mm step/minute over a 140-mm range. The aperture width of the collimator is 6 mm. The sinusoidal curves marked A and B in the sinogram correspond to each source. The positions of the sources are reconstructed within 3.5 mm. Details of the reproduction algorithm are described elsewhere.

References
Image reconstruction algorithm for gamma-ray inspection of rotating objects

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We develop a new method to determine the spatial distribution of positron-emitting radioisotopes (RIs) on rotating objects and construct a prototype system. The details of the principle and the prototype system based on this method are described elsewhere. This method is based on the same principle as the medical positron emission tomography (PET) systems in which projection data from all angles are collected. In the PET system, gamma-ray detectors are placed in a circular manner around a stationary object, or the gamma-ray detectors rotate around the object in order to collect projection data. In this method, a pair of gamma-ray detectors are placed in a stationary position and the object being imaged is rotated.

Here, we present the image reconstruction algorithm of the prototype system. The most conventional image reconstruction algorithm in PET is filtered back-projection (FBP). Projections from all angles are back-projected onto and overlaid in the image plane using the inverse Radon transform to reconstruct the image. Then, an appropriate image filter is applied to deblur the image.

An alternative to the FBP is the maximum likelihood—expectation maximization (ML–EM) algorithm. We assume a two-dimensional distribution \( \lambda(x, y) \) of RI (image), and the projection data \( p(r, \phi) \) at an angle \( \phi \) from the y-axis and at a distance \( r \) from the center. ML–EM is an iterative method. The iteration starts with an arbitrary image that is updated gradually as

\[
\lambda^n_j = \frac{\lambda^{n-1}_j}{\sum_i c_{ij}} \left( \sum_i (c_{ij} p_i / \sum_k c_{ik} \lambda^{n-1}_k) \right),
\]

where \( \lambda^n_j \) is the \( j \)-th pixel value in the image \( \lambda \) of the \( n \)-th iteration, \( p_i \) is the value at the \( i \)-th position in the projection \( p \), and \( c_{ij} \) is the probability that a gamma-ray emitted from the \( j \)-th pixel position is counted at the \( i \)-th position in the projection (see Fig. 1).

At each iteration, the projection of the current estimate image is calculated and compared with the actual projection. Then, the difference between the estimated and actual projections is back-projected and used to update the current estimate image.

Thus, Equation 1 reads as follows. First, the projection of the current estimate image is calculated \( (\sum_k c_{ik} \lambda^{n-1}_k) \). Second, the ratio of the actual projection to the estimated projection is calculated \( (p_i / \sum_k c_{ik} \lambda^{n-1}_k) \). Finally, the ratio is back-projected to the image coordinate \( (1 / \sum_i c_{ij} (\sum_k c_{ik} p_i / \sum_k c_{ik} \lambda^{n-1}_k)) \). This ratio is multiplied by the current estimate image \( (\lambda^{n-1}_j / \sum_i c_{ij} (\sum_k c_{ik} p_i / \sum_k c_{ik} \lambda^{n-1}_k)) \). In the prototype system, the iteration requires 99 steps from the initial uniform image to obtain the current estimate image.

ML–EM is advantageous over FBP for wear diagnosis of mechanical parts in that the image values are all non-negative, the signal to noise ratio is higher, and there are less linear artifacts (see arrows in Fig. 2) around strong RI sources in the image. These advantages are important for the easy detection of weak sources near strong sources. Further, ML–EM is more suitable for quantitative evaluation because the sum of the image values is preserved during the iteration and the gamma-ray attenuation in the machine and collimators can be implemented in \( \lambda^p \).

Figure 2 shows a comparison of the FBP and ML–EM images. The FBP image was obtained using MATLAB iradon. The ML–EM image is based on an in-house program.

![Image](image-url)

Fig. 2. Comparison of the FBP (left) and ML–EM (right) images (top) and their projections (bottom). The color maps are scaled and optimized for individual images.

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MINOS (acronym for Magic Numbers Off Stability) is a device dedicated to perform the spectroscopy of highly exotic nuclei produced at fragmentation facilities such as the RIBF accelerator of RIKEN. The device\(^1,2\) consists of a thick liquid H\(_2\) target (50–200 mm) surrounded by a time projection chamber (TPC) used to track the vertex position inside the target. The advantage of using such a thick H\(_2\) target is twofold: it increases the luminosity and minimizes the energy loss and straggling of the beam. Furthermore, the use of a structureless probe allows an accurate theoretical description of the reaction mechanism. The vertex information obtained from the TPC helps in preserving the experimental resolution.

The target was developed at the Accelerator, Cryogenics and Magnetism Division - CEA Saclay. The liquid H\(_2\) is contained in a Mylar envelope less than 150 \(\mu\)m thick, composed of two parts glued on an Inox support connected to the H\(_2\) circuit. The target is connected to the cryostat (Fig. 1) equipped with a cryocooler, allowing to reach the liquefaction temperature of 20.3 K. Within the cryostat, the condenser connected to the cold head cools down the H\(_2\) that is transferred by gravity to the target (Fig. 2). This system works in a close loop allowing to minimize the amount of H\(_2\) to be used. A specificity of this system is the possibility to empty the target in less than 30 s. This can be attained by closing a valve on the return circuit, hence producing an overpressure that pushes the liquid to the condenser situated 1 m above. The target can be kept empty for up to 10 h and filled again in 20 s by opening the valve. This functionality allows to easily perform a measurement of the background due to reactions of the beam on the Mylar envelope. Installation and dismounting of the system take 3 and 1 d, respectively.

The system was tested successfully at the RIBF facility in July 2013. A full operation cycle was performed in 72 h: H\(_2\) liquefaction and filling of the target, a demonstration of the "empty target" functionality, H\(_2\) evaporation, and emptying of the target. The liquid H\(_2\) target is expected to be used, coupled with the MINOS detection system, to perform physics experiments at RIBF from Spring 2014.

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Development of KEK isotope separation system

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We have been constructing 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 research\(^1\)-\(^3\). In the KISS, a gas cell filled with argon gas at a pressure of 50 kPa, which stops and collects unstable nuclei in it, is an essential equipment for selectively extracting the isotope of interest by using a resonant ionization technique. The absolute extraction efficiency of the gas cell and beam purity of the KISS gas cell can be evaluated only from the measurements of the intensities of beams implanted in and extracted from the gas cell in an on-line test.

We performed on-line tests using the \(^{56}\)Fe beam with the energy of 90 MeV/nucleon and the maximum intensity of 4 pA. The energy of \(^{56}\)Fe beam was degraded to 1.5 MeV/nucleon in front of the gas cell by using an aluminum energy degrader in order to implant at the center of the argon gas cell. The thermalized and neutralized \(^{56}\)Fe atoms were re-ionized in the gas cell, and the ions were extracted and detected by using a Channeltron detector for ion counting after mass separation.

We successfully extracted laser-ionized \(^{56}\)Fe atoms by cleaning the gas cell system and by using a “bent type” gas cell, which was designed to reduce the plasma effect. Figure 1 shows the measured efficiency and beam purity as a function of the primary beam intensity. The extraction efficiency was defined as \(S/I\). Here, \(S\) and \(I\) present the numbers of laser-ionized \(^{56}\)Fe atoms and implanted \(^{56}\)Fe atoms in the gas cell, respectively. The measured efficiency was about 0.25% after the correction of the detector efficiency (16%)

![Image](http://example.com/image.png)

Fig. 1. (a) Extraction efficiency of \(^{56}\)Fe ions and (b) beam purity measured as a function of \(^{56}\)Fe beam intensity.

and the laser repetition rate (20%). The efficiency was independent of the primary beam intensity, as shown in Fig. 1-(a), owing to the bend structure of the gas cell. Beam purity was defined as \(S/(S + N)\). Here, \(N\) is the number of the extracted ions with \(A = 56\), which was measured without irradiation with ionization lasers. Figure 1-(b) shows the obtained beam purity of > 98%, and it depended on the primary beam intensity. The beam purity decreased with increasing primary beam intensity. However, the impurities probably consist of molecular ions of argon, which are stable against radioactive decay and do not affect the β-decay lifetime measurements.

In the case of the primary beam intensity of \(2.5 \times 10^7\) pps, we measured mass distributions without and with ionization lasers, as shown in Figs. 2, in order to investigate how many laser-ionized \(^{56}\)Fe atoms formed impurity molecules with \(\text{H}_2\text{O}, \text{Ar}_2\), and hydrocarbons. Figure 2-(a) shows background ions extracted from the gas cell, which are ionized by the primary beam injection. Dimers of argon isotopes and their compounds with hydrogen were dominant. In the case of ionization laser irradiation, we clearly observed laser-ionized \(^{56}\)Fe peak and molecular ion peaks of \(^{56}\text{Fe}(\text{H}_2\text{O})\) and \(^{56}\text{FeAr}_2\). By reducing the amount of water molecules in the gas cell, the number of laser-ionized \(^{56}\)Fe atoms would increase, and as a result, the extraction efficiency of \(^{56}\)Fe would be doubled.

![Image](http://example.com/image.png)

Fig. 2. Measured mass distributions (a) without using ionization lasers and (b) using ionization lasers.

References
Detection efficiency of segmented neutron detector at 200 MeV

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Nucleon-knockout \((p,pN)\) reactions at intermediate energies \((200-300\text{ MeV})\) provide a powerful probe of the nature of single particle states (SPSs) in nuclei\(^1\). The goal of our study is to determine the neutron separation energy with a high resolution of about \(500\text{ keV}\) at full-width at half-maximum (FWHM) via the \((p, pN)\) reaction. This is technically challenging because a high position resolution is necessary for neutron detection which cannot be achieved with a conventional design.

At RIKEN RIBF, we are developing a segmented neutron detector consisting of 64 scintillating fibers. Each fiber has dimensions of \(3.75\text{ mm (W)} \times 3.75\text{ mm (D)} \times 1\text{ m (H)}\) and has two multi-anode photomultiplier tubes (Hamamatsu H7546B) at both ends. Using this setup, we confirmed that the position resolution of \(3.75\text{ mm}\) in the total width, corresponding to the fiber size, was actually realized by performing a neutron irradiation experiment at the Cyclotron Radioisotope Center (CYRIC), Tohoku University in November 2012. Furthermore, we determined the neutron detection efficiencies of neutrons at 181 and 199 MeV were determined to be \(2.0 \pm 0.5\%\) and \(2.0 \pm 0.5\%\), respectively\(^2\).

For higher neutron energies, we performed another experiment using neutron beams at 200 MeV at the Research Center for Nuclear Physics (RCNP), Osaka University in November 2013. Monoenergetic neutron beams at 199 and 181 MeV were produced from \(^7\text{Li}(p, n)\) and \(^{12}\text{C}(p, n)\) reactions using a proton beam at 200 MeV. The Li and C targets, each with natural isotopic abundance, had thicknesses of 0.94 and 2.1 mm, respectively. Neutrons flew in the neutron time-of-flight (NTOF) tunnel and, were then detected by the segmented neutron detector placed at a distance of 50 m from the target position. The intensity of the proton beam was about 100 nA and the rate of neutrons bombarding on the detector was typically \(10^4\) particles per second.

A preliminary analysis shows that the detection efficiencies for 181- and 199-MeV neutrons were \(2.6 \pm 0.4\%\) and \(2.5 \pm 0.4\%\), respectively. The threshold for neutron detection, \(4.2\text{ MeV electron equivalent (MeV}_{\text{ee}}\) was applied to the light output information obtained from the charge amplitude of the dynode signal.

Figure 1 shows the distribution of the detection position, which is defined as the most upstream fiber hit. When there are several hit fibers at the same depth, the fiber with largest light output is selected. Here, the threshold of each channel was set to \(0.5\text{ MeV}_{\text{ee}}\). The distribution was found not to be uniform near the surface. Along the beam direction, most events were concentrated on the first plane, and the fibers on the left and right sides had a larger number of events than the inner fibers. This enhancement in the number of events near the surface, which was not observed clearly in the previous experiment because of the lack of the uniformity on the threshold of each channel, is still not understood and is being investigated for details. The inner array of \(6 \times 6\) fibers had a uniform distribution within \(10\%\), possibly reflecting the uniformity of the neutron flux.

The most downstream fibers had a smaller number of events compared to upstream fibers. For these fibers, the light output deposit by recoil protons can be small because the protons go out of the detector volume within a short distance.

In summary, we are developing the segmented neutron detector with a high position resolution for the study of SPSs via the \((p, pN)\) reaction. The detection efficiencies of neutrons at 181 and 199 MeV were determined to be \(2.6 \pm 0.4\%\) and \(2.5 \pm 0.4\%\), respectively. The distribution of the detection position shows a large enhancement in the number of events at the surface which is being analyzed.

We acknowledge the staff at the RCNP for their efforts and support.

References

Fig. 1. Distribution of detecting positions indicated by the heights of the \(8 \times 8\) blocks. The neutron beam travelled from top left to right bottom.

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Preparation status of the J-PARC E16 experiment: measurement of vector meson mass in nuclei

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We have proposed the experiment E16$^1$ 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. The proposal of the experiment was granted scientific (“stage 1”) approval by the PAC in March 2007. For the full approval, we need to establish the experimental feasibility as well as to show the prospects of acquiring sufficient funds and of beam-line construction. Toward the full approval, the technical design report is under preparation for submission to PAC to be held in May 2014.

The mass modification of vector mesons in hot and/or dense matter is predicted on the basis of the QCD because of the restoration of the chiral symmetry in such matter. Mass modifications in matter, however, due to hadronic many-body effects are also predicted. The predictions from these two viewpoints should agree in principle, however, still no clear connections are established between the two thus far.

Many experimental studies, including dilepton invariant mass measurements, have been conducted to approach the problem, and mass modifications in hot and/or dense matter have been observed. However, the origin of the modification has not yet been confirmed; in other words, there is no consensus on the interpretations of the phenomena. Among the experiments, the experiment KEK-PS E325$^2$, which was conducted by a collaboration including some of the authors, measured the $e^+e^-$ invariant mass spectra in 12-GeV $p+A$ reactions and reported enhancements on the low mass sides of $\omega$ and $\phi$ mesons. These enhancements are consistent with the decrease in the mass of vector mesons predicted using the QCD sum rule. The mass-shape modification of a narrow resonance, $\phi$, can be observed only in E325.

The aim of the J-PARC E16 experiment is to perform a systematic study of the mass modification of vector mesons, particularly the $\phi$ meson, in nuclei, with statistics that are two orders larger in magnitude than those of the preceding E325 experiment. 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 deduce the dependence of the modification on the matter size and meson momentum, which have never been measured. Furthermore, the $e^+e^-$ decays of the $\rho$, $\omega$, and $J/\psi$ mesons can be measured at the same time.

For this 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 development of the detectors is underway as reported elsewhere$^3$–8, funded by a MEXT Grant-in-Aid$^9$. To summarize, basic studies and beam tests of the two key detectors, the GEM Tracker$^{1,4}$ and HBD$^5$, have been performed. For the former, the required performance has almost been achieved. The specification of GEM is fixed and production of GEM has been underway since 2013. For the latter, stability in a high background environment has been confirmed$^6$. The GEM specification is also fixed and we will move to production in 2014. The development of read-out and trigger modules are on going$^7$. In particular, for the GEM readout, a CERN-made system has been tested and adopted$^8$.

Construction of the high-momentum beam line has been on-going since 2013 by KEK. The first beam will be delivered by the end of JFY 2015. In spite of the radiation accident at J-PARC in May 2013, the planned schedule of the spectrometer magnet construction has not changed. Therefore, it is expected to be completed in Jan. 2015. After completion of the magnet construction, we can start the installation of the detectors in the magnet. The target day of the construction is the planned first beam, Mar. 2016. Due to the budgetary limitation, our first goal of the staged construction plan is to construct one-third of the spectrometer.

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8) Y. Morino et al.: in this report.

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Background estimation and operation test of the GEM detectors for the J-PARC E16 experiment

D. Kawama*1 for the J-PARC E16 collaboration

In the proposed J-PARC E161) experiment, we will use a 30 GeV primary proton beam at the J-PARC high-momentum beam line. Because the beam intensity will be \( \approx 1 \times 10^{10} \) per spill and expected particle counting rate is 5 kHz/mm\(^2\) at most, we will use two types of GEM detector: the GEM tracker2) and the Hadron Blind Detector (HBD)3). These detectors need to be operated in high-rate background environment during the experiment. In a test experiment using the 1.0 GeV/c pion beam at the J-PARC K1.1BR beamline, several breakdowns were observed with HBD (30 cm \( \times \) 30 cm \( \times \) 100 \( \mu \)m\(^2\) LCP GEM in CF\(_4\) gas, 3 \( \times \) 10\(^3\) gain). The breakdowns are considered to be caused by hadronic background such as neutrons or slow hadrons, because we did not observe such breakdowns with electron beams. In addition, no breakdowns were observed with the GEM trackers (10 cm \( \times \) 10 cm \( \times \) 50 \( \mu \)m\(^2\) PI GEM in Ar/CO\(_2\) gas, 1 \( \times \) 10\(^4\) gain). Therefore we estimated the background particles and their energies for the E16 experiment and performed an operation test of the GEM detector in the high-rate neutron background.

The background particle counting rate was estimated using the Geant4 simulation. The simulation employed the physics list of “QGSP_BERT_HP”4) which includes high-precision treatment of low-energy neutrons \((E_{kin} \leq 20 \text{ MeV})\). The validity of this simulation for estimation of background particle counting rate was checked by comparing the background calculation with PHITS5) calculation6) at the K1.1BR area; both agreed within a factor of 2. For example, the neutron rate was 0.01 Hz/mm\(^2\) at the broken GEM of K1.1BR case.

![Schematic model of the E16 experiment](image_url)

**Fig. 1.** Schematic model of the E16 experiment used in the simulation. The area is surrounded by concrete blocks, and is filled by air.

The model used in the E16 background simulation is shown in Fig. 1. Using this model, we estimated the particle rate at the detector position, which is located at approximately 120 cm from the target surrounded by the lead-glass calorimeters. Fig. 2 shows the energy spectra from the beam dump and the target, and reveals that the main contribution is by neutrons of several hundred keV. By integrating these spectra, we estimated the neutron counting rate of the E16 detector to be in the order of 0.1 kHz/mm\(^2\) for the beam-dump origin and 0.01 kHz/mm\(^2\) for the target origin.

![Energy distribution of the background particles](energy_distribution_url)

**Fig. 2.** Energy distribution of the background particles from the beam dump (left panel) and the target (right panel).

We performed an operation test of the GEM detector at AVF cyclotron room in the RIKEN RI beam factory. The detector includes triple-stack 30 cm \( \times \) 30 cm \( \times \) 50 \( \mu \)m\(^2\) PI GEMs in the CF\(_4\) gas. This is the same configuration as that employed in the E16 experiment. During the operation, a 12 MeV deuteron beam with an intensity of 10 pA was used in the room. The dominant energies of the neutrons were 0.1-10 MeV according to the Geant4 simulation, and the GEM detector was operated in the room background. The neutron radiation level monitored during the operation was 87 mSv/h on average, which is in the order of 1 kHz/mm\(^2\). The counting rate of the GEM itself was approximately 10 Hz/mm\(^2\). The GEM could be stably operated for 15 h without breakdowns with \( V_{gem} = 510 \text{ V} \), which corresponds to a gain of \( 2 \times 10^5 \). The total amount of neutrons corresponds to the 2-month operation in the E16 experimental area. From the test operation, we can confirm that PI GEMs can work stably in high neutron background. Further study is necessary to clarify the reason for stable operation.

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3) K. Kanno et al., in this report
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Development of the tracking detector with large GEM foils for the J-PARC E16 experiment

Y. Komatsu*1,*2 for the J-PARC E16 Collaboration

The J-PARC E161) experiment is proposed to measure the mass spectrum of the $\phi$ meson in nuclear matter. In the spectrometer, the momentum of charged particles is measured using the tracking detectors (called “GEM trackers”) in a magnetic field. The details of the GEM detector are described elsewhere2)3). The development of the tracker with an effective area of 300 mm $\times$ 300 mm is reported in this article. A schematic view of the 300 mm $\times$ 300 mm readout board is shown in Fig. 1. Cartesian strips called “X” and “Y” are made of copper and patterned on the top and the bottom of a polyimide sheet of thickness 25 $\mu$m. For charge sharing between X and Y, the base polyimide is etched using the chemical method, except just under the X strips. The glass epoxy of thickness 100 $\mu$m is laid under the Y strips as a support.

The positions of the strips were measured using a coordinate measuring machine (Nikon VMR-10080). The coordinates of the cross-points of the left edge of the X strips and the upper edge of the Y strips ($x_{i,j}$, $y_{j}$)($i,j=0,\ldots,71$) were measured for every 12 strips. The subscripts $i$ and $j$ denote the row and column numbers. The deviations of the coordinates of the cross-points from the mean values were calculated for each strip and plotted in Fig. 2. The deviations of the X and Y strips are defined as $x_{i,j} = \sum_{i=0}^{71} x_{i,j}/72$ and $y_{j} = \sum_{i=0}^{71} y_{j}/72$. The maximum deviation of the X and Y strips were 43 $\mu$m and 42 $\mu$m, respectively. The deviations were small compared to the spatial resolution of the X and Y strips, which are 100 $\mu$m and 400 $\mu$m, respectively. The precision of the readout strips was confirmed. GEM foils with an effective area of 300 mm $\times$ 300 mm were also fabricated. The average diameters of the holes were 65 $\mu$m for copper and 33 $\mu$m for polyimide in the top and the middle GEM of the stack, and 56 $\mu$m and 27 $\mu$m in the bottom for copper and polyimide, respectively. The spatial resolution of the GEM tracker was evaluated using positron beams at the Research Center for Electron Photon Science, Tohoku University. The setup is shown in the left panel of Fig. 3. The GEM tracker was located between two Silicon Strip Detectors (SSDs). The position resolution was evaluated on the basis of the residual of the hit positions calculated from the hits on SSDs and the GEM tracker. The obtained residual distribution for the 0° beam is shown in the right panel of Fig. 3. The residual distribution was fitted with a Gaussian, and the standard deviation was 73 $\mu$m. The requirement of the position resolution is 100 $\mu$m, and the 300 mm $\times$ 300 mm GEM tracker has sufficient resolution for the experiment.

References
1) S. Yokkaichi et al.: In this report.
Development of a prototype module for the lead-glass calorimeter readout and an ASIC for GEM foil trigger for J-PARC E16 experiment

T.N. Takahashi*1 for the J-PARC E16 Collaboration

Development of detectors for the new spectrometer1), GEM tracker (GTR), Hadron Blind Detector (HBD) and lead-glass electromagnetic calorimeter (LG), and electronics is currently in progress.

The number of readout channels of LG is about 1100. Therefore, a dedicated and cost effective readout module has been developed in collaboration with Open-It2). The specification of the prototype module is listed in Table 1 and the picture is shown in Fig. 1, which has been delivered and is currently undergoing tests. The prototype module is fabricated as the KEK-VME 6U standard. The analog input signals are split into two lines, one is fed into the comparator to generate binary outputs used for trigger primitives, and the other is followed by an analog memory. The analog memory is realized by DRS43) ASIC, which contains 1024 sampling cells per channel and can store the waveform in a gigahertz range. To extend the analog buffer, two channels are cascaded for one analog input on the prototype module. Therefore, 2 µsec analog buffer is available if the sampling speed is set at 1 GHz, which implies that a long delay cable is unnecessary for delaying analog pulses. The waveform stored in the DRS4 is digitized by AD9637 at 33 MHz. Since the DRS4 supports a readout only in the region of interest, the dead time for an analog pulse with the width of ∼100 nsec is expected to be less than ∼5 µsec. The slow control for setting a discriminator threshold and the data readout are performed by the Xilinx FPGA Spartan6-LX150 via the Ethernet.

The $e^+e^-$ event trigger consists of three-fold coincidence of GTR, HBD, and LG. We will use a cathode plane of a GEM foil of the most outer GTR chamber. The GEM foil is divided into 24 segments. Each segment has detector capacitance of 2 nF and its hit rate is expected to be 1-2 MHz in the forward region of the spectrometer. In order to cope with such a high rate with large input capacitance in the small form factor, we have developed a new Amplifier-Shaper-Discriminator (ASD) IC with low noise and fast shaping time in collaboration with Open-It. The specification is summarized in Table 2 and the photos are shown in Fig. 2. The analog part works nearly as expected. The digital part is currently undergoing tests.

Table 1. Specification of the prototype module for the LG.

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<th>value</th>
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<tbody>
<tr>
<td>number of analog inputs</td>
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<tr>
<td>analog input range</td>
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<tr>
<td>resolution</td>
<td>12 bit</td>
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<td>analog memory</td>
<td>2048 samples / channel</td>
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<tr>
<td>readout time</td>
<td>30 nsec / sample</td>
</tr>
<tr>
<td>discriminator out</td>
<td>LVDS</td>
</tr>
<tr>
<td>readout / slow control</td>
<td>TCP (100 Mbps) / UDP</td>
</tr>
<tr>
<td>power supply</td>
<td>± 3.3 V (KEK-VME J0 bus)</td>
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</tbody>
</table>

Table 2. Specification of the GEM trigger ASD.

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<td>shaper time constant</td>
<td>25 ns</td>
</tr>
<tr>
<td>pulse width</td>
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<tr>
<td>conversion gain</td>
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<tr>
<td>ENC</td>
<td>20000 ($C_d$ = 2 nF)</td>
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<tr>
<td>number of channel</td>
<td>6</td>
</tr>
<tr>
<td>power supply</td>
<td>± 2.5 V</td>
</tr>
</tbody>
</table>

Fig. 1. A picture of the prototype module for the LG.

Fig. 2. Pictures of the GEM foil trigger ASIC and its evaluation board.

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Testing a GEM tracker in a magnetic field for the J-PARC E16 experiment

W. Nakai*1,*2 for the J-PARC E16 Collaboration

The J-PARC E16 experiment was conducted to measure the mass modification of φ 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 report1).

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. To use this detector, a position resolution of 100 µm up to an incident angle of 30° in a high counting rate environment up to 5 kHz/mm2 is required. Our GEM tracker consists of a drift cathode, a triple GEM, and a readout strip board. We chose a strip pitch of 350 µm to achieve the required position resolution.

Since the directions of the electric and magnetic field in the drift gap are perpendicular, the drift velocity of ionization electrons is inclined to the E field by Lorentz angle α. Therefore we tested the operation of the detector in a large dipole magnet located at the J-PARC Hadron Hall in Apr. 2013. The setup is shown in Fig. 1. A laser with a wavelength of 266 nm was used to make the primary electrons, and the incident angle was fixed at 30°. The E fields of the drift gap, transfer gap, and induction gap were 600 V/cm, 3600 V/cm, and 3600 V/cm, respectively, and the B field was from 0.0 T to about 0.7 T.

As shown in Fig. 2, the expected Lorentz angles were calculated using a Garfield++ toolkit3). Because the Lorentz angle in the drift gap is accidentally almost equal to that of the transfer and induction gap, electrons should drift straight from where they are generated to the readout strip board. The Lorentz angle α can be represented as

\[ \tan \alpha = \frac{\Delta x}{d} \] (1)

where \( d \) is the distance between the mesh and the readout, and \( \Delta x \) is a shift in the edge position of charge cluster measured in the non-magnetic field to that at readout. The result is plotted in Fig. 3. We found that the result is almost consistent with the calculation but there exists 14% of systematic difference. The reasons behind this systematic error need to be discussed.

References
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Fig. 1. A schematic view of the setup. Red arrows indicate the drift directions of electrons.

Fig. 2. The results of simulations using Garfield++ codes with various drift electric fields.

Fig. 3. The measurement of the Lorentz angle as a function of the magnetic field (black points), and the calculation using Garfield++ (red line).

Fig. 4. The setup showing a laser, a drift cathode, and a readout strip board.
Measurement of photoelectron yield in a hadron blind detector for the J-PARC E16 experiment

K. Kanno\textsuperscript{1,\textsuperscript{2}} for the J-PARC E16 collaboration

A hadron blind detector (HBD) has been developed for the J-PARC E16 experiment.\textsuperscript{1)} The E16 experiment aims to detect the in-medium modification of a $\phi$ meson in a nucleus via the $\phi \rightarrow e^+e^-$ decay. The HBD identifies the positrons and electrons by converting the emitted Čerenkov photons in CF\textsubscript{4} into photoelectrons with a CsI photocathode. The converted photoelectrons are amplified by a triple gas electron multiplier (GEM)\textsuperscript{2}) stack to obtain a signal on readout pads. The CsI photocathode is evaporated on the surface of the top GEM of the stack. We perform the measurement in the momentum region (up to 4 GeV/c) where only positrons and electrons can emit Čerenkov photons in the HBD. Although almost all of the ionization electrons emitted from charged particles are removed by applying reversed drift-field before the triple-GEM section, a huge amount of such charged particles would contaminate the HBD signal. Therefore, the detection yield of the photoelectrons is the most significant value required to discriminate the Čerenkov photons at the trigger level.

The detection yield of the photoelectrons depends on the quantum efficiency of the CsI photocathode and photoelectron collection efficiency. The collection efficiency is defined as the ratio of the number of photoelectrons that are collected and subsequently amplified by the GEMs to the number of photoelectrons produced at the CsI photocathode. The collection efficiency is, therefore, supposed to depend on the electric field at the surface of the CsI photocathode, whose strength is determined by the size and pitch of the GEM holes.

To evaluate the pitch dependence of the detection yield of the photoelectrons, we produced a prototype HBD with two types of GEMs: type-A has the hole and pitch sizes of 55  m and 140 m, respectively, while type-B has the pitch size of 110 m with the same hole size. The length of the Čerenkov radiator is 50 cm, and the size of the photocathode is 60 cm \times 60 cm, which is divided into four parts with size 30 cm \times 30 cm, as shown in Fig. 1. For the prototype, one 30 cm \times 30 cm type-A photocathode and one 30 cm \times 30 cm type-B photocathode were prepared. Using the prototype HBD, we performed a beam test with a 1.0 GeV/c positron beam at the Research Center for Electron Photon Science, Tohoku University. Figure 2 shows the obtained charge distribution, where we observed \textasciitilde 7.6 mean photoelectrons with type-A and \textasciitilde 10.7 with type-B.

Because we confirmed that these photocathodes have almost the same quantum efficiency, the difference in the detection yield of the photoelectrons is attributed to the difference in the photoelectron collection efficiency. Based on this result, which fulfills the experimental requirement with type-B GEMs, we have decided to adopt type-B GEMs as the E16 HBD. This is the first result of the HBD made in Japan with large (30 cm \times 30 cm) GEMs.

Fig. 1. Photograph (left) and schematic view (right) of the HBD prototype.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{
Charge distribution of two different photocathodes.
}\end{figure}

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\textsuperscript{2} Department of Physics, Graduate School of Science, The University of Tokyo
Performance of scalable readout system

Y. Morino *1 for the E16 Collaboration

The aim of the E16 experiment to be conducted at J-PARC is to study the nature of vector mesons in nuclei in order to investigate chiral symmetry restoration in dense nuclear matter1). A readout system is required for measuring the high rate and the large datasets. Our expected trigger rate is approximately 1 kHz, and the expected occupancy reached to be 30% at maximum.

We plan to construct a readout system for the Hadron Blind Detector (HBD) and Gas Electron Multiplier (GEM) trackers using APV Hybrid chips and Scalable Readout System (SRS) module2). An APV chip is an analogue pipeline ASIC3). The chip consists of 128 channels of preamplifiers and shapers driving a 192-column analogue memory. The SRS module is used for the slow control of APV chips, the digitization of analog data from the APV chips, and transfer of digital data to a computer using UDP/IP4). The SRS module has an 8-port HDMI interface to connect APV chips. Therefore, one SRS module can support 8 Master/Slave APV (16 APV chips) hybrid chips. It corresponds to 128 × 16 = 2048 detector outputs.

The data size of the SRS output for unit sampling time per event per channel is 2 bytes. If we take data with 27 sampling time units which is sufficient length for the E16 experiment, the entire data size per event per module is 2 × 2048 × 27 ~ 110 kBytes. Since our planned trigger rate is approximately 1 kHz and the expected occupancy is 30% at maximum, the SRS module must read out and transfer data at a rate of 110 k × 1000 × 0.3 = 33 MBytes/s. A transfer rate of 33 MBytes/s is the requirement of the E16 experiment for evaluating the performance of the SRS module.

We discovered that the SRS module satisfied the requirement of the E16 experiment. Initially, one SRS module was connected to a computer. Four ADC channels (corresponding to 512 channels) were read out. A trigger was generated by a function generator. We measured the data transfer rate on the computer as function of trigger rate. Figure 1(a) shows the measurement results. In Fig. 1(a), the red line represents the theoretical value at the given trigger rate. Measured values are consistent with the theoretical values until the data transfer rate reaches 110 MBytes/s. The measured value dropped with the rate, 4 kHz, because a part of the trigger was injected within the dead time of the SRS module. This result satisfies the requirement of the E16 experiment. Next, two SRS modules were connected to a computer via a network switch. Then we measured the data transfer rate for this case. Figure 1(b) shows the measurement results. The Y-axis in Fig. 1(b) denotes the sum of the transfer rate. Black squires denote the results when four ADC channels were read out in both SRS modules. Red circles show the results when two ADC channels were read out in one module and six ADC channels in the other. These measured values were consistent with the theoretical values until the transfer rate sum reached 120 MBytes/s. This result supports that the network switch do not affect the data transfer rate. A single computer can handle several SRS modules. In addition, we confirmed the same manner that the readout performance does not degrade using the zero-suppression process. Since the data transfer was carried out by using UDP, data loss may occur. Since the rate of data loss is less than once per 10 hours of operation, the efficiency of the data taking will not be affected by the rejection of the errors at the event build. Consequently, hardware performance of the SRS module satisfies the requirement of the E16 experiment.

Fig. 1. Data transfer rate. (a) one SRS module. Four ADC channels were read out (b) two SRS module. Black squires show the results when 4/4 ADC channels were read out. Red circles show the results when 2/6 ADC channels were read out.

Approximately 95,000 channels must be read out via the APV chips and the SRS modules. A minimum of 780 APV chips and 49 SRS modules will be necessary. The number of SRS modules handled by one computer will be determined based on the writing speed of the disk. Since the expected occupancy will be about 10% on an average, one computer may handle 8 ~ 10 SRS modules. Therefore, 5 ~ 6 computers will be used for DAQ. Further, the performance study with random trigger is also in progress.

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Status of silicon pixel detector for PHENIX experiment toward RHIC Run-14

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The silicon vertex tracker (VTX) was installed in the PHENIX experiment in 2010, and it successfully collected approximately 5 billion events of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the 2011 RHIC run (Run-11) at Brookhaven National Laboratory (BNL). The main function of the VTX is the separation of heavy flavor (HF) hadrons, charm and bottom, with the measurement of the distance of closest approach of single electrons from their decays. The nuclear modification factor and azimuthal anisotropy for HF were measured, and analysis results have already been reported1).

The VTX is composed of two inner silicon pixel detectors and two outer silicon strip detectors. The silicon pixel ladder is the basic component of a silicon pixel detector. The ladder consists of four silicon sensor modules, two readout buses, and a cooling support. The I/O pads of the silicon sensor module are electrically connected to that of the readout bus via aluminum bonding wires that are encapsulated in epoxy resin. The silicon sensor module is an assembly of a silicon pixel sensor and four readout chips bump-bonded with 25-µm-diameter bumps to the silicon sensor. During Run-11, a small fraction of bump bonds were defected due to thermal stress. In addition, some bonding wires were broken due to a thermal stress caused by the difference in the thermal coefficient between the encapsulation and the readout bus. The active area of a VTX was decreased to 60% because of defected bump bonds and broken bonding wires. The solutions for these issues are to change the operation temperature from 0 degree to the room temperature to avoid thermal stress, and to use a different type of encapsulation. The operation temperature was changed from that used in the physics run in 2012.

After the shutdown of the physics run in 2013, the VTX was dis-assembled at BNL to replace the encapsulation with a different type of encapsulation. All pixel ladders that had broken wires were sent to HAYASHI WATCH-WORKS CO., LTD. where pixel ladders had been mass produced. In total, 15 pixel ladders had been repaired with the yield of almost 100% during 6 months. A small fraction of dead area (< 1%) was remained because of the damage to I/O pads during repair process.

The repaired ladders were electrically tested at RIKEN before being shipped to BNL, and the final electrical test was performed at BNL before the reassembly of the VTX. The following are the test items.

1) Current consumption of a pixel ladder.
2) Optimization of a reference voltage for DACs on the readout chip of a pixel module.
3) Bias voltage dependence of the leakage current for a silicon pixel sensor.
4) Response of the pixel ladder to a $\beta$ source ($^{90}$Sr).

No issue was found in all tests. Figure 1 shows the typical response of a pixel ladder to the $\beta$ source.

![Fig. 1. Response of pixel ladder to a $\beta$ source. The horizontal and vertical axes represent $z$ and $\phi$ direction in the PHENIX coordinate, respectively. Low gray-levels represent low number of hits.](image)

Since some pixel ladders had faulty bump bonds, there is a small fraction of unfixable dead area(< 1%) in the pixel ladder, and the configuration of pixel ladders in the VTX affects physics data. The optimization of the performance of the pixel detectors had been done by arranging the configuration based on the test results at BNL.

The reassembly of the VTX had been successfully performed at the end of 2013. As a results of the repair work, the active area of the VTX was significantly improved to about 90%. Final optimization of operation parameters for pixel ladders is ongoing. We will collect 200 GeV Au+Au collision data with around 10 times more statistics than that collected in Run-11.

References

Construction of PHENIX Silicon Pixel Tracker

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The PHENIX experiment is upgraded with a central silicon vertex tracker to enhance its physics capabilities in nearly full azimuthal coverage over |η| < 1.2. The main goal of the upgrade is to track the production vertex of charged particles with the resolution of 50µm. The central vertex tracker consists of four layers, two layers of silicon pixel type and two layers of silicon strip type. The tracker has been constructed in 2009 and has been producing fruitful physics results. During the operation before 2012, the heat cycle during its operation resulted in about 30% of inactive area on the constructed silicon pixel type. In this paper, we will report the status of repairing such the damaged pixel-type tracker and new construction.

The silicon pixel tracker consists of 10 ladders for inner layer and 20 ladders for outer layer. Each ladder is made of mainly three components; a supporting thermo-plate, four hybrid sensor, and a readout bus. The hybrid sensor is made of a silicon sensor plate and four readout chips, with 32 × 256 readout pixels whose each size is 50 × 425µm. All the three components are glued each other by epoxy resin with the thickness of 100µm ± 30µm while the relative distance between two hybrid sensor is kept within 15µm accuracy, which is smaller than the estimated electron-drift diffusion of 20µm. They are electrically connected by 25µm aluminum bonding-wire. The wires are encapsulated by soft silicon resin in order to prevent any damage from an accidental contact during construction and from vibration caused by the electrical alternative current of 10MHz through the wire and the PHENIX magnetic field. For the damaged ladder, the electrical connection together with the silicon encapsulation are redone after old bonding-wires and old silicon resin are cleaned.

While entire construction procedure, the readout test by the PHENIX readout system using electrical pulse and 0.546MeV beta-ray from Sr90 are performed three times; before the encapsulation, before the transportation from Wako to RHIC, and before the installation. The main goal of the test is to ensure the electrical connection between the sensor hybrids and the readout bus and to measure the ratio of the active pixels to all pixels. The threshold during the test is set at about 3,000 e− while the nominal noise of the hybrid sensor is expected to be 200e−. When a minimum ionization particle penetrates the silicon sensor with the thickness of 200µm, 14,000 electrons are estimated to be created and collected by pixel pads. The distribution on the pixel pad surface depends on where the electron and hole pairs are created. If we assume the average distance from pixel pads to such the electrons is 100µm that is in the middle of pixel sensor thickness, the 14,000 electrons distributes on pixel pads like gaussian distribution with 100µm sigma from a naive estimate. Because one pixel pad has 50 × 425µm, two pixel pads is expected to be more than the threshold on average.

Figure 1 depicts the number of fired pixels per event in 500k beta-ray events by Sr – 90 radio active source.

Figure 1 1

Fig. 1. Number of fired pixels per event in 500k beta-ray events by Sr – 90 radio active source.

The average of the number of pixels is 2.1, which is consistent with the above estimate. This fact enables us to measure the accurate rate of the active pixel to all pixel by this beta-ray test. Because some beta-ray enters the silicon sensor with angles due to scattering in materials between the radioactive source and the silicon sensor, some gamma-ray produce wider distribution, that is also observed in the figure.

After repairing procedure of 15 ladders, the selected ones were installed with <10% inactive pixels, which is caused by due to faulty bump-bonding between the silicon sensor plates and readout chips. For further improvement, new construction procedure with improved bump-bonding already started. All hybrids sensor and readout buses are under gluing. At least seven new ladders will be ready for installation before next run of RHIC starting in the beginning of 2015.

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Quality assurance test of hybrid sensors for new silicon pixel detector

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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. We are currently fabricating new spare pixel detector ladders. A pixel ladder is composed of a mechanical stave, four hybrid sensors, and two readout buses. A hybrid sensor is an assembly consisting of a silicon pixel sensor and four readout chips (ALICE LHcb13) bump-bonded to the sensor. One readout chip has 8,192 pixels, with a pixel size of 425 μm × 50 μm, organized in 32 columns and 256 rows. For production of new pixel ladders, a quality assurance (QA) test is required for the hybrid sensors. The test was conducted by HAYASHI WATCHWORKS CO., LTD.

Figure 1 shows a schematic of the QA system. The test system consists of a probe station (SUSS MicroTec), a probe card, a DAQ adapter board, VME equipment for a DAQ system, and a Windows PC3). The following tests are performed for each sensor.

1) Current consumption:
The current consumptions of analog and digital circuits of the chip are measured.
2) JTAG functionality:
It is confirmed whether the configuration settings in the chip can be controlled by using Joint Test Action Group (JTAG)3) protocol.
3) Minimum threshold:
The minimum threshold in all pixels is determined.
4) Test with β-ray source (90Sr):
Faulty bump bonds are evaluated by the source test.

The sensor is biased at 50 V during the measurements in items (3) and (4).

The criteria for the hybrid sensor to be used for a ladder are as follows.

• Current consumptions of analog and digital circuits must be lower than 350 mA and 270 mA, respectively.
• The configuration settings in the chip must be controllable using JTAG protocol.
• The number of defect pixels must be less than 163 (≈ 2%) in the source test.

A total of 50 hybrid sensors have been tested, and 33 hybrid sensors met the criteria. The average number of defect pixels is about 21 (≈ 0.3%). A typical result of a readout chip in the source test is shown in Fig. 2. The main reason for failure to meet the criteria was faulty bump bonds. About one or two readout chips out of four readout chips on the sensor may have caused higher current consumption than the upper limit of the criteria.

In summary, we obtained 33 hybrid sensors to be used for new pixel ladders. Currently, the production of new pixel ladders using these sensors is underway.

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Development of SOI pixel sensor for environmental radiation monitor†

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We have developed a prototype SOI pixel sensor, called RADPIX, for a radiation monitor. This is based on the silicon-on-insulator (SOI) pixel CMOS technology and developed by Y. Arai et al.1) The RADPIX is a monolithic pixel detector that consists of a thin CMOS readout array (40 nm, 10 Ω), a buried oxide layer (200 nm), and a thick high-registivity Si-sensor (260 µm, 700 Ω) vertically on a single chip. Figure 1 shows the schematic view of the Nested-Well structure SOI detector (p-in-n type sensor). The buried N-well suppresses the back gate effect from the electric field in the sensor and reduces the cross-talk by isolating the sensor from the circuit.

Fig. 1. Schematic diagram of the nested-well SOI structure

RADPIX aims to count the rate of the radiation and to visualize the hit pattern in real time for environmental radiation. From the hit pattern, one can estimate the radiative source such as beta-ray, γ-ray, or α-ray. The sensor is a DC-coupled device and the sensor’s capacitance is in a few tens of femtofarads. The typical leakage current for a 40 µm × 40µm pixel is of the order of picoamperes at room temperature, which saturates the baseline within about 10 ms. Therefore, this device needs to reduce the leakage current or compensate the current to be able to measure the environmental radiation, which is of the order of 10⁻² Hz/cm² in 1 µSv/h from ¹³⁷Cs. The Krummenacher feedback scheme2) is used for long exposure, which has an individual leakage current compensation circuit. Figure 2 shows the schematic of RADPIX. We implemented charge-sensitive preamplifiers with different gains (1fF and 5fF as feedback capacitors). Two inverter chopper comparators are implemented to generate a trigger signal, and the latched output can be read from each pixel. The analog signal is sampled by the 230 fF store capacitance and is readout from each pixel. This analog information can be used for the pattern recognition and identification of the radiative source.

Fig. 2. Schematics of RADPIX

Figure 3 shows the pixel-by-pixel gain variation for two different charge-sensitive preamplifiers. This was studied by using test pulses. The average of the gain is 23 µV/electron (RMS~1.4) and 94 µV/electron (RMS~5.1) for the low gain type and high gain type, respectively. Position dependence is not found. We also evaluated the performance of the comparator. Figure 4 shows the counts of comparator output as a function of comparator threshold. We observe a 5%-10% fake hit rate even at high threshold. This is due to the large noise, which shows up when the digital signal is readout. The reason of the large noise and the strategies for further improvement are under investigation.

Fig. 3. The pixel-by-pixel gain variation: low gain (left) and high gain (right)

Fig. 4. Counts of comparator output as a function of comparator threshold for four typical pixels: low gain (left) and high gain (right)

References
High rate capability of gas ionization chamber with flash ADC

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At world-leading RI beam facilities such as RIBF, the region of the nuclear chart containing nuclei to be studied simultaneously, or the yield of every nuclear species is often restricted by the high rate capabilities of beam detectors. Herein, we examined the high rate capability of gas ionization chambers (ICs)1–4). We recorded the waveforms of preamplifier output signals using a flash analog–to–digital converter (FADC) and corrected for the so-called pile-up effect in the offline analysis, as previously done in a pioneering work4). We also shortened the time needed to release amplified charge for recovering the ground level from 10 µs, a commonly used duration, to 1 µs, thereby reducing the probability of pile-up events.

A test has been performed at the Heavy Ion Medical Accelerator in Chiba (HIMAC) during other experimental programs as a parasite setup. Primary beams of Ne and Xe at 180 and 200 AMeV, respectively, were incident on our setup, after passing through other experimental setups. As a result, the beam energy was degraded and well spread at the location of our setup. An IC with an effective length of 440 mm composed of 12 cathode and 11 anode planes, each with an area of 60 mm by 60 mm and placed at 2-cm intervals, was filled with P10 gas at a pressure of 720 Torr and used in our setup. A positive bias of 400 V was applied to the anode planes to yield a typical drift time of 360–400 ns for 2-cm drift length. Five signals, each from two neighboring planes, plus one signal from the last plane were preamplified with Mesytec MPR-16L, which has a time constant of 1µs. After the amplified signals were split into two, one part was sent to a CAEN V1740 digitizer with a 62.5-MHz sampling period, and the waveform was recorded. In parallel, using the other part of the split signals, the preamplified charge was digitized with peak-sensing ADCs (Mesytec MADC32) through a shaping amplifier (Mesytec MSCF-16) with a shaping time of 0.5 µs (σ).

The left window of Fig. 1 shows the correlation between the amplitudes of energy loss in the IC obtained using the above two readout methods for the data of Xe beam at 50 kilo particles per spill (kppp) with a duration time of ~1 s for each spill. In addition to well-correlated events, there are events in which the amplitude calculated using the conventional method deviates from the systematics. In such events, the pulse of interest lies on top of the tail of the preceding pulse, producing an unwanted rise of the amplitude of the MADC value, as exemplified in the right figure. Such effects can be removed by decomposing neighboring pulses through the fitting of the waveforms, as shown with the red curve in the figure.

In that example, there are about 10 beam particles in a time window of 188 µs. After time averaging, this can be considered as a beam rate of about 50 kHz in cyclotron facilities such as RIBF but without a RF-periodic time structure. In the Xe beam, the rate defined thus varies from a few tens of kilohertz to about 200 kHz within each spill. The probability of pile up as a function of the beam rate is under analysis. The analysis of the energy resolution requires the correction of the beam energy dependence of the energy loss, which is ongoing.

In summary, we performed an experiment to test a signal-readout method based on FADCs coupled with a preamplifier having a short time constant and showed that the method is feasible for beam rates up to a few hundreds of kilohertz at least, while the method based on the shaping amplifier exhibits a pile-up effect from about several tens of kilohertz. Further analysis is ongoing.

We acknowledge the staff at HIMAC for their efforts and support.

Fig. 1. Two dimensional correlation (left) between the amplitudes of the energy loss obtained from the FADC (vertical axis) and MADC32 (horizontal axis), and a typical waveform for the events enclosed with the dashed curve in the left window (right). See the text for details.

References
Development of MWDC readout nuclei for the spectroscopy experiment of $\eta'$ mesic nuclei at GSI and FAIR

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The $\eta'(958)$ meson has an exceptionally large mass, compared with other pseudoscalar meson such as pions. Theoretically, it has been pointed out that a large mass reduction ($\sim 100$ MeV) is expected at the normal nuclear density, which leads to existence of an $\eta'$ mesic nucleus, a bound state of an $\eta'$ meson and a nucleus. From an experimental observation of $\eta'$ mesic nuclei, we may take the first step to understand the $\eta'$ mass generation mechanism. For this purpose, we perform spectroscopy of $\eta'$ meson bound states in $^{12}\text{C}$ nuclei by missing-mass measurement of the $^{13}\text{C}(p,d)$ reaction near the $\eta'$ production threshold at the GSI-SIS facility.

In this experiment, a 2.5 GeV proton beam extracted from SIS synchrotron will be injected into a $^{12}\text{C}$ target, and the ejectile deuterons with the momenta of $\sim 2.8$ GeV/c are momentum-analyzed by the fragment separator (FRS) at a dispersive focal plane with detection of the tracks by two sets of multi-wire drift chamber MWDCs. The first experiment is scheduled in July 2014.

We are working on upgrading the current DAQ system, particularly the readout of MWDCs. We will adopt a 64ch all-in-one readout board equipped with ASD, Flash ADC, and TDC. Almost all the digital processes are designed in the FPGA. This board was originally designed for Belle-II Central Drift Chamber (CDC). According to Ref. 3), they achieved a dead time of about 0.5% at a trigger rate of 10 kHz in a test experiment. This is approximately a factor 10 improvement compared to the current (our) system.

The digitalized data are transferred through a network with the SITCP sub-system, which is an implementation of TCP/IP on FPGA. We have been customizing the FPGA program and investigating the potential of the board. In case that the readout board is equipped with performance of reading data at a several kHz trigger, the quality and the quantity of the experimental data will exhibit significant improvement compared to that of the VME based DAQ without the readout board.

The readout board is being updated, so as to operate under a trigger distribution system, which is already adopted in J-PARC hadron experiments. Along with readout boards, we are developing a new “sub trigger module” (STM), for distributing trigger information including the event tag to each readout board. The distribution system with STM is useful to ensure the event matching and to avoid overlooking event slips among different DAQ subsystems.

We will make a performance test of the readout board with respect to the radiation tolerance and the DAQ rate, exploiting the opportunity of beamtime at GSI in July, 2014. By loosening the trigger condition, the performance under a high trigger rate will also be evaluated.

In summary, we will introduce a network-based DAQ with the readout board for MWDCs in the $\eta'$ experiment at GSI beyond 2014 and FAIR, which is currently under construction. As it will enable us to handle a higher trigger rate, a high-statistics measurement will be possible by using a more intense beam and/or a thicker target.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{readout_board.png}
\caption{View of 64ch Readout Board.}
\end{figure}

References

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The motivation of the PHENIX experiment is to search the origin of proton spin. The proton spin is 1/2, however, it cannot be explained by valence quarks only. The other fraction of the proton spin can be carried by gluons, sea quarks, and their orbital angular momentum. The existing gluon polarization measurements indicate a small contribution. However, the present measurement region is limited in the relatively high-x region, where gluons are less populated. A newly installed detector, Forward Silicon Vertex Detector (FVTX), has the potential to extend the measurements to low-x region where gluons exist with higher probability. Moreover, heavy meson production is advantageous for the measurement of gluon spin as it produces a high gluon purity in its subprocesses. Thus, the detection of heavy mesons at forward rapidity region is an ideal probe to measure gluon polarization. FVTX distinguishes muons decayed from heavy quarks by measuring the distance of the closest approach using its precise position measurement near the vertex.

However, the existing high-momentum muon trigger does not provide sufficient rejection power to detect muons from heavy flavor origin efficiently because one needs to lower the momentum threshold. Thus our motivation is to improve the rejection power by adding the trigger capability to FVTX as an additional matching requirement on the existing high momentum trigger provided by Muon Tracking Chambers. The FVTX trigger can be formed by pattern matching between the observed hits and preprogrammed hit patterns to be a track within the FVTX readout electronics (FPGA).

Fig. 1 Setup of the timing measurement using a scope and FVTX readout devices

An FVTX detector and its readout system have been set up at the test bench in RIKEN. It is important to measure the present FVTX readout time to know how much time window allowed (latency) for the new trigger in order to process signals before the trigger decision. The actual latency constraint is known to be 17 Beam Clocks (BCLKs) for all the trigger signals to be received by the Local Level-1 trigger system. As the first step of the trigger development, the signal process time in the readout system was measured using the setup shown in figure 1. As shown in figure 2, the time difference was 2.8 μs. Since 13 additional BCLK delay was inserted in the readout system for some purpose, the true time difference is expected to be about 15 BCLKs.

Fig. 2 Coincidence between calibration pulse (yellow) and trigger signal (pink)

As the next step, the timing measurement using a radiation source is being conducted to measure the latency, including the FVTX sensor.

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Common trigger firmware for GTO

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The data acquisition (DAQ) system at RIKEN RIBF1) utilizes the field programmable gate array (FPGA)-based logic modules of LUPO2) and GTO3). A common trigger firmware for the GTO has been introduced for experiments in BigRIPS, SHARAQ, EURICA, MINOS, and SAMURAI4). There are two versions of the common trigger firmware: 8-trigger/16-end-of-busy inputs version and 4-trigger/20-end-of-busy inputs version. Both versions provide the same functionality, and the only difference between them is the number of the trigger and busy inputs. Here, we report on the functionality and timing performance of the 8-trigger/16-end-of-busy inputs version of the common trigger firmware.

This firmware was developed to provide acceptable triggers, i.e., the common trigger, for all CAMAC and VME front-end systems. Previously, three logic fan-in/out, three latch and one coincidence NIM modules were used to generate the common trigger. However, the developed firmware can generate the common trigger using only one GTO module. In addition, the remote control capabilities via Ethernet of the GTO allow us to change the trigger configuration without inserting and removing cables. Common trigger firmware consists of trigger multiplexer, multi-channel latch, and trigger veto circuits. Figure 1 shows the functional schematic of the firmware. The trigger multiplexer circuit has 8 inputs, and these input signals are enabled by the remote control function. The multi-channel latch circuit produces the veto signal for the trigger when CAMAC/VME front-end systems are busy. There are 16 end-of-busy inputs; therefore, this firmware can accept up to 16 CAMAC/VME front-end systems. Each latch signal is triggered by the leading edge of the accepted trigger, and it is cleared by the trailing edge of the end-of-busy signal from the front-end system. The trigger veto circuit inhibits trigger signals when either DAQ is not started or at least one of the front-end systems is busy. Using these circuits, the GTO can provide the complete common trigger. The dead time of the DAQ system is determined by the slowest front-end system.

To evaluate the timing performance of the common trigger firmware, the propagation delay and time jitter are measured. The propagation delay is the time between the trigger input and the accepted-trigger output. These parameters are measured by an Agilent Technologies U1060A-002 TDC, which has a timing resolution of 5 ps; the results are shown in Tab. 1.

According to these results, the skew, that is, the maximum difference between the propagation delay of all channels, is 1.0 ns. This 1.0-ns skew is not small but does not present any difficulty to the function of the trigger multiplexer. The maximum time jitter is 8 ps, which is normal for a NIM logic module.

In summary, the common trigger firmware for the GTO has been successfully developed. It allow us to reduce the number of logic NIM modules and change the configuration remotely. Further, the timing performance of the firmware is sufficient for use as a trigger circuit.

References
Computing and network environment at the RIKEN Nishina Center

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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 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. Mailing list services are also supported. This is a core server for the RNC Linux/Unix cluster with approximately 600 registered user accounts. The hosts RIBF00/01 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.

In the April of 2013, a 39 TB RAID was added for data analysis for the EURICA experiment. The hosts RIBFSMT1/2 are the mail front-end servers, and they are used for tagging spam mails and isolating virus-infected mails. Two sets of HP ProLiant DL-145 G3 were installed in 2007, and they were replaced by DL-320e G8 in 2013. The latest version of the Sophos Email Protection-Advanced (PMX 6.0.3) has been installed on these. Figure 2 shows the Mail trends by the PMX for 30 days. Orange indicates the number of spam mails blocked by the IP blocker. Approximately 70 % of the incoming mails are blocked.

The Integrated Digital Conference (INDICO) system3) has been operated at the host indico.riken.jp since 2007. We replaced the hardware and software of this server in February 2013 in order to improve the function and reliability. The indico was updated from indico 0.94 to 0.99.

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The host NISHINA-PREPRINTS is an electric preprint server. Other servers installed in 2007 such as ribf00/01 and ribf-exp are planned to be replaced by DL-320e G8 in this fiscal year.

An anonymous ftp server, FTP.RIKEN.JP, is managed and operated at the RNC. Major Linux distributions, including Scientific Linux, Ubuntu, Debian, etc., are mirrored daily at the ftp server for the convenience of their users and for facilitating high-speed access. A 72 TB RAID system was installed in January 2014 to replace two old RAID systems to ensure the high reliability of the operation.

References
1) http://ribf.riken.jp/comp/
3) http://indico-software.org/

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*1 RIKEN Nishina Center
CCJ operation in 2013

Y. Ikeda,*1 H. En’yo,*1 T. Ichihara,*1 Y. Watanabe,*1 and S. Yokkaichi*1

1 Overview

The RIKEN Computing Center in Japan (CCJ1) 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 nano data summary tape (nDST) files, which is a term for a type of summary data files at PHENIX, from the RHIC Computing Facility (RCF4) to the CCJ. The transferred data files are first stored in a High Performance Storage System (HPSS)5 before performing the analysis. The CCJ maintains sufficient computing power for simulation and data analysis by operating a PC cluster running a PHENIX-compatible environment.

A joint operation with the RIKEN Integrated Cluster of Clusters (RICC6) was launched in July 2009. Twenty PC nodes have been assigned to us for dedicated use, sharing the PHENIX computing environment.

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 2013, CCJ has been contributed 31 published papers and more than 33 doctoral theses.

2 Configuration

2.1 Calculation nodes

In our machine room 258/260 in the RIKEN main building, we have 28 PC nodesa), and these nodes have been used for the analysis of the PHENIX nDST data. Table 1 lists the numbers of job slots, CPU threads, and CPU cores, and the number of nodes (there is no change in 2013). These nodes are operated using a data-oriented analysis scheme that carries out optimization using local disks7)8). The OS on the calculation nodes is Scientific Linux (SL) 5.39), and the same OS works on the 20 nodes at the RICC. As a batch-queuing system, LSF 8.0.010) and Condor 7.4.211) were run on the CCJ and RICC nodes, respectively, as of Dec 2013.

Table 2 lists the numbers of malfunctioned SATA or SAS disks in the HP servers (including NFS/AFS servers described in the next section).

Table 1. Limitation of number of job slots from LSF queue with cluster node.

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Cores</th>
<th>Threads</th>
<th>Jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCJ-hp1</td>
<td>18</td>
<td>144</td>
<td>180</td>
</tr>
<tr>
<td>CCJ-hp2</td>
<td>10</td>
<td>120</td>
<td>240</td>
</tr>
<tr>
<td>RICC</td>
<td>19</td>
<td>152</td>
<td>144</td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>416</td>
<td>524</td>
</tr>
</tbody>
</table>

Table 2. Malfunctioned HDDs in 2011, 2012, and 2013

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Total 2013</th>
<th>2012</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>SATA</td>
<td>1 TB</td>
<td>192</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>SAS</td>
<td>146 GB</td>
<td>38</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>300 GB</td>
<td>24</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2 Data servers

Two data servers (HP ProLiant DL180 G6 with 20 TB SATA raw disks) are used to manage the RAID framework of the internal hard disks, which contain the user data and nDST files of PHENIX. The disks are not NFS-mounted on the calculation nodes to prevent performance degradation by process and network congestion. These disks can be accessed only using the “rcpx” command, which is the wrapper program of “rcp” developed at CCJ, and it has an adjustable limit for the number of processes on each server.

The Domain Name System, Network Information System, Network Time Protocol, and Network File System servers are operated on the server ccjnfs20b) with a 10-TB FC-RAID, where the users’ home and work spaces are located. The home and work spaces are formatted with VxFS 5.012). The backup of home spaces on ccjnfs20 is saved to another disk server once a day and to HPSS once a week. The backups on HPSS are stored for three weeks.

2.3 HPSS

Since Dec 2008, the HPSS servers and the tape robot have been located in our machine room, although they are owned and operated by RICC. The specifications of the hardware used can be found in the literature13). The amount of data and the number of files archived in the HPSS were approximately 1.7 PB and 2.1 million files, respectively, as of Dec 2013. Table 3 lists the files and the current class of service (COS) in the HPSS. No new file has been added in 2013.

Table 3. Files and current class of service (COS) in HPSS

<table>
<thead>
<tr>
<th>Type</th>
<th>Total 2013</th>
<th>2012</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHENIX</td>
<td>1.7 PB</td>
<td>2.1 million</td>
<td></td>
</tr>
</tbody>
</table>

---

*1 RIKEN Nishina Center

a) HP ProLiant DL180 G5 with dual Xeon E5430 (2.66 GHz, 4 cores), 16 GB memory and 10 TB local SATA data disks for each node, and HP ProLiant DL180 G6 with dual Xeon X5650 (2.66 GHz, 6 cores), 24 GB/20 TB as above, for each node

b) SUN Enterprise M4000 with Solaris 10
3 Data transfer from BNL and the PHENIX software environment

Data collected during the PHENIX experiment was transferred from the RCF to the CCJ using grid-FTP through the science information network (SINET) with a 10 Gbps bandwidth. The data transferred from BNL is moved to local disks on the HP calculation nodes and the HPSS. The files are transferred using grid-FTP at a maximum speed of about 300 MB/s. Two PostgreSQL server nodes are operated for the PHENIX database, whose data size was 285 GB as of Dec 2013. The data are copied from the RCF everyday and made accessible to the users. One AFS server node is operated for the PHENIX AFS. The size of the libraries for the PHENIX analysis setup was 1.7 TB as of Dec 2013. The libraries are also copied from the RCF by AFS everyday.

3.1 Uninterruptible power-supply system (UPS)

The power consumption of the CCJ system, excluding the HPSS, is about 25 kW, and the power is supplied through five UPSs (10.5 kVA each) as of Dec 2013. For the HPSS, there is one 7.5-kVA UPS for 100 V and three 10.5-kVA UPSs for 200 V purchased by CCJ. The batteries of the three UPSs expire in 2014 (One have expired in 2013).

3.2 Login server upgrade

CCJ had two login servers, ccjsun (HP Proliant DL145) with SL 5.3 and ccjgw (Supermicro 5011E) with CentOS 3, in 2012. The ccjgw server was upgraded to the HP Proliant DL145 with SL 5.3 in 2013.

References
2) http://www.phenix.bnl.gov/
III. RESEARCH ACTIVITIES II
(Material Science and Biology)
1. Atomic and Solid State Physics (Ion)
Beta-NMR study of $^{58}$Cu in Si


Cu impurities in Si devices are considered serious contaminants. The short-lived $\beta$ emitter $^{58}$Cu ($I^+ = 1^+$, $T_{1/2} = 3.2$ s) is attractive for studying the behavior of Cu impurities in Si using the $\beta$-NMR technique, which will provide unique information on the mechanism of fast Cu diffusion\textsuperscript{1} or the property of Cu-dopant complex that is related to the gettering technique.\textsuperscript{2} The $N = Z$ odd-odd nucleus $^{58}$Cu, consisting of $^{56}$Ni plus one proton and one neutron, is also interesting in terms of the nuclear moment, from which we can study the proton-neutron interaction in $pf$-shell nuclei.\textsuperscript{3}

We detected an NMR signal of $^{58}$Cu in Si in 2010, and the magnetic dipole moment $|\mu|^{[58Cu]} = (0.46 \pm 0.03)$\mu$_B$ was obtained.\textsuperscript{4} In 2011, Vingerhoets et al. greatly improved the measurement accuracy using collinear laser spectroscopy, achieving $\mu^{[58Cu]} = +0.570 \pm 0.002$\mu$_B$,\textsuperscript{5} which is about 20% larger than ours. One possibility for the discrepancy is the existence of an electric field gradient (EFG) which could be generated if some defects are formed at a $^{58}$Cu site in Si, though a cubic symmetry site without EFG is expected in terms of the crystal structure of Si. If the EFG exists, the NMR spectrum should split into two lines with frequencies of $\nu_{\pm} = \nu_0 \pm \nu_Q/2$ in the case of $I = 1$, where $\nu_0$ and $\nu_Q$ are the carrier frequency and the quadrupole splitting frequency, respectively. In this case, our previous NMR line may have originated from $\nu_-$. In the present study, we have applied the multi-radiofrequency (RF) ($\beta$-NQR) technique\textsuperscript{6} to the $\beta$-NMR measurement of $^{58}$Cu in Si to search for a quadrupole splitting in order to verify the above picture and to solve the discrepancy problem.

The experimental method is similar to our previous one.\textsuperscript{4} Spin-polarized $^{58}$Cu nuclei were produced through the charge exchange reaction of $^{58}$Ni by implanting a $^{58}$Ni primary beam at 63 MeV/u, provided by the RIKEN ring cyclotron with a typical intensity of 100 particle nA, on a 0.5-mm thick Be target. Fully stripped $^{58}$Cu$^{29+}$ ions were separated by the RIKEN projectile fragment separator (RIPS) and were implanted into a single crystal sample of B-doped Si at 15 K with the crystal (001) orientation set parallel to the external magnetic field $B_0 = 0.93$ T, the same condition as in the previous experiment. A pair of resonance frequencies $\nu_{\pm}$ was searched for by changing both $\nu_0$ and $\nu_Q$, using the $\beta$-NQR technique in which two frequencies were applied in series as $\nu_- \rightarrow \nu_+ \rightarrow \nu_-$ during the RF duration to inverse spin polarization of $^{58}$Cu.

The resonance was found at $\nu_0 \sim 4.1$ MHz and $\nu_Q \sim 2.6$ MHz. The $\nu_Q$ spectrum at $\nu_0 = 4.00-4.15$ MHz is shown in Fig. 1, from which $\nu_Q = 4e\nu Q/3h(3\cos^2\theta - 1) = (2.6 \pm 0.4)$ MHz was obtained. The EFG $q$ will be obtained using the known $Q$ moment of $^{58}$Cu\textsuperscript{5} after determining the angle $\theta$ between the main axis of the EFG and $B_0$ from the crystal orientation dependence of $\nu_Q$. $|\mu|^{[58Cu]} = (0.58 \pm 0.01)$\mu$_B$ was obtained from $\nu_0$, which is in agreement with the data reported by Vingerhoets et al.\textsuperscript{5} The difference between the present $\mu^{[58Cu]}$ and the previous one\textsuperscript{4} is mostly explained by the quadrupole splitting.

Fig. 1. Beta-NQR spectrum of $^{58}$Cu in Si.

References

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\textsuperscript{*2} Department of Physics, University of Tsukuba
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\textsuperscript{*7} Department of Physics, Tokyo University of Science
\textsuperscript{*8} Department of Physics, Saitama University
\textsuperscript{*9} The University of Electro-Communications
\textsuperscript{*10} Meiji University
\textsuperscript{*11} Peking University
\textsuperscript{*12} IMSS, KEK
\textsuperscript{*13} GSI
\textsuperscript{*14} SUMCO, Co.
\textsuperscript{*15} ISIR, Osaka University
Observation of hyperfine resonance of $^{87}$Rb in superfluid helium toward laser spectroscopy of atoms with exotic nuclei

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We have developed a new nuclear laser spectroscopy technique called OROCHI (Optical RI-atoms Observation in Condensed Helium as Ion-catcher). OROCHI is a laser spectroscopy method based on the combination of the laser-microwave (MW)/radio frequency (RF) double resonance technique and superfluid helium (He II) as a host matrix.$^{11}$ In OROCHI, a highly energetic ion beam is injected into He II. The injected ion is decelerated, neutralized, and slowly floated in He II. We measure the Zeeman and hyperfine structure (HFS) splitting energy to determine nuclear spins and moments. So far, we have successfully deduced the nuclear spins and moments of stable $^{85,87}$Rb, $^{133}$Cs, $^{107,109}$Ag, and $^{197}$Au atoms introduced into He II using the laser ablation technique. Furthermore, we successfully observed the Zeeman resonance of $^{85}$Rb and radioactive $^{84}$Rb produced by the projectile fragmentation.$^{2,3}$ Since the transition probability of the HFS resonance is small than that of the Zeeman resonance, HFS splitting of the injected Rb atoms is not observed in He II. Recently, we observed for the first time the HFS resonance of an energetic ion beam of $^{87}$Rb atoms injected into He II.

Fig. 1. Schematic layout of the experimental setup.

Figure 1 shows the schematic layout of the experimental setup in the superfluid helium cryostat. The $^{87}$Rb beam from the RIPS separator was injected into He II. The stopping position of the genetic ion beam could be adjusted using two Al degraders of various thicknesses located in front of the cryostat.$^{4}$ The stopped $^{87}$Rb atoms were subjected to irradiation by circularly polarized CW Ti:S laser light (laser power: 100 mW, laser diameter: 2 mm). The laser wavelength was tuned to the D1 absorption line of Rb atoms in He II (780 nm)$^{5}$. The laser-induced fluorescence photons from laser-excited $^{87}$Rb atoms were collected, wavelength-separated, and detected using a photodetection system$^{6}$. To preserve the atomic spin polarization, we applied a static magnetic field of 2.2(1) G using a pair of Helmholtz coils placed along the laser beam axis. In addition, we irradiated MW (power: typically a few watts) generated by an oscillator and an amplifier through an MW loop antenna located above the detection region. By sweeping the MW frequency, we observed HFS resonance as shown in figure 2. The obtained spectra clearly show the effect of the HFS resonance. Since the resonance frequencies of the spectra shift depending on the polarization of the laser light, we observed the case for both $\sigma^+$ and $\sigma^-$ polarization. By taking the average of two frequencies, we could obtain the HFS splitting energy of $^{87}$Rb atoms in He II. The asymmetric shape of the spectra is mainly attributed to the inhomogeneity of the applied magnetic field.

![Fig. 2. Observed spectra with an applied static field of 2.2(1)G. The laser polarization is a) $\sigma^+$ and b) $\sigma^-$.](Image)

In conclusion, we have been developing OROCHI that can be applied to investigate the structure of unstable nuclei. We successfully performed double resonance experiments using energetic ion beams. From these results, we confirmed the feasibility of OROCHI, and we are now ready to extend our method to atoms with exotic nuclei.

References
5) A. Sasaki et al.: RIKEN. APR. 44, 204 (2011).
Search for efficient laser resonance ionization schemes for Ta and W in KISS


In KISS (KEK Isotope Separation System) 1), laser resonance ionization is employed for the element-selective ionization of multi-nucleon transfer reaction products. We searched for efficient laser resonance ionization schemes for tantalum ($Z = 73$) and tungsten ($Z = 74$), which are the elements that are studied in KISS.

Fig. 1 Two-color laser resonance ionization

Fig. 1 shows a schematic view of two-color laser resonance ionization. An atom is element-selectively excited by the first step laser with a wavelength of $\lambda_1$. Through the second step laser with a wavelength of $\lambda_2$, the atom then transits from the excited state to an auto-ionization state (AIS), which is located above the ionization potential. The AISs having ionization efficiencies that higher than that by means of the continuum by more than ten times are searched for in general. 2)

We used wavelength-tunable dye lasers pumped by excimer lasers to obtain laser beams of $2\lambda_1$ and $\lambda_2$. The wavelength $\lambda_1$ in the ultraviolet ray region is generated from the $2\lambda_1$ wavelength by using a second harmonic generator, which consists of a non-linear crystal of BBO. Both lasers are transported into a reference cell that was newly made to search for ionization schemes in off-line experiments. The lasers were focused on a spot of a few mm$^2$ between ion-acceleration electrodes. Neutral atoms were evaporated from a filament and ionized by laser irradiation between the electrodes. Ions were accelerated by the electrodes and detected by a channeltron at about 30 cm away from the ionization region. The ions were mass-analyzed by measuring the TOF. The mass resolving power was measured to be 12.3%.

We scanned $\lambda_2$ to search for AISs; then, we measured laser-ionized atoms by means of the AIS by changing the power of the respective lasers. The $\lambda_{1,8}$ were selected from the known excited states that had a high Einstein A coefficient. 3) We deduced the photon absorption cross section ($\sigma_{1,2}$, $\sigma_i$) of each transition by fitting the solution from rate equations 2, 4) to the laser power dependence of ion counts. The rate equations express the time evolution of the number of atoms in the ground state, the excited state, and the AIS. In addition to those states, we considered the intermediate states, where the atoms decay from the excited state, and are located above the ground state. The excitation rate (ionization rate) is proportional to the photon absorption cross section of the transition from the ground state (the excited state) to the excited state (the AIS). These rates are all proportional to the photon densities of the $\lambda_1$, laser and $\lambda_2$ laser. We deduced the laser powers required for the saturation conditions of ionization probability in the KISS gas cell from the determined photon absorption cross sections.

For tantalum, $\lambda_2$ was scanned from 410 to 425 nm with $\lambda_1 = 264.8258$ nm, so that four strong peaks were observed. The strongest peak at 421.652 nm yielded $\sigma_{12} = 4.8 \pm 0.5$ (stat.) $\pm 0.7$ (syst.) $\times 10^{-15}$ cm$^2$, $\sigma_i = 2.0 \pm 0.2$ (stat.) $\pm 0.8$ (syst.) $\times 10^{-16}$ cm$^2$. The laser powers required for the overlap in the gas-cell ($\phi$10 mm) were $P_1 \sim 0.5$ mJ/pulse, $P_2 \sim 29.3$ mJ/pulse. On the other hand, for tungsten, $\lambda_2$ was scanned from 404 to 414 nm with $\lambda_1 = 245.2737$ nm, so that two strong peaks were observed. The stronger peak at 404.393 nm yielded $\sigma_{12} = 4.5 \pm 0.6$ (stat.) $\pm 0.6$ (syst.) $\times 10^{-16}$ cm$^2$, $\sigma_i = 7.5 \pm 0.7$ (stat.) $\pm 1.6$ (syst.) $\times 10^{-17}$ cm$^2$. The laser powers required for the overlap in the gas-cell ($\phi$10 mm) were $P_1 \sim 5.5$ mJ/pulse, $P_2 \sim 241.9$ mJ/pulse. These powers required are too high for our laser system to achieve saturation. In our laser system, the maximum laser power is approximately 200 $\mu$J for the first step laser and about 2 mJ for the second step laser. The ionization probability achieved using our laser system is expected to be as low as 11% for tantalum and 0.33% for tungsten. We will search for other $\lambda_2$ values in different wavelength regions with the current $\lambda_1$ and also look for AISs with different $\lambda_1$ values.

The resonance structure of the AIS might be affected by the isotope shift of the wavelength. We are going to increase the mass resolving power of the reference cell by introducing electric lenses and a longer flight tube, which will provide us with further information on the AIS.

References

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*3 Seoul National University
Cold molecules and their ions are attractive subject of research in the fields of fundamental physics and cold chemistry. With regard to cold chemistry, the reaction-rate constants of cold ion-molecule reactions are important information for studying the chemical evolution of interstellar clouds. Recently, we have developed a combined Stark-velocity-filter–ion-trap apparatus for measuring the reaction rate between cold trapped ions and slow polar molecules under ultra-high vacuum conditions. We experimentally measured the reaction rates between sympathetically cooled N$_2$H$^+$ ions and velocity-selected polar molecules, namely CH$_3$CN.

The measurement procedure is as follows. First, we produce a Ca$^+$ Coulomb crystal in a linear Paul trap. Then a nitrogen gas of about 1 $\times$ 10$^{-7}$ Pa is introduced into the vacuum chamber, and an electron beam is incident to the center of the ion trap in order to produce N$_2^+$ ions by electron impact ionization. Because the mass of the nitrogen molecular ion is lighter than that of Ca$^+$, the molecular ions are more tightly bounded by the trapping potential and accumulate near the trap axis. After the preparation of cold N$_2^+$ ions, a hydrogen gas of about 6 $\times$ 10$^{-6}$ Pa is introduced into the vacuum chamber. All N$_2^+$ ions change into N$_2$H$^+$ ions via the reaction of N$_2^+$ + H$_2$ $\rightarrow$ N$_2$H$^+$ + H in a reaction time of 240 s.

After the preparation of cold N$_2$H$^+$ ions, we irradiated the velocity-selected CH$_3$CN molecules to the two-species Coulomb crystal containing Ca$^+$ and N$_2$H$^+$ ions. Figure 1(a) shows the snapshots of the laser-induced fluorescence (LIF) images of the Coulomb crystal at several reaction times. The dark area containing N$_2$H$^+$ progressively decreases with increasing reaction time owing to the progress of CH$_3$CN + N$_2$H$^+$ $\rightarrow$ CH$_3$CNH$^+$ + N$_2$ reactions. We also observed an increase in the sparse dark area in the outer peripheral region of the Ca$^+$ Coulomb crystal because a part of the reaction products (CH$_3$CNH$^+$) is trapped. Under the present experimental conditions, the average reaction energy is estimated to be approximately 3 K.

In order to obtain the reaction rate, we determine the relative number of molecular ions from the volume of the dark area in the observed fluorescence images under the assumption of a constant number density at 0 K. Figure 1(b) shows the decay curve of the relative number of N$_2$H$^+$ ions as a function of the reaction time. In this example, the reaction rate is determined to be 2.4(4) $\times$ 10$^{-3}$ s$^{-1}$. We performed 9 measurements and obtained an averaged reaction rate of 2.0(2) $\times$ 10$^{-3}$ s$^{-1}$. Using the number density of the velocity-selected CH$_3$CN, which was separately determined, the reaction-rate constant was also determined to be 1.7(6) $\times$ 10$^{-8}$ cm$^3$ s$^{-1}$. The main reason for the error is considered to be the uncertainty in the number density of CH$_3$CN. The present reaction-rate constant is consistent with the estimated capture rate, $k_{tas} = 3.6 \times 10^{-8}$ cm$^3$ s$^{-1}$, using the trajectory-scaling formula, which is considered to be the maximum value of the reaction-rate constant.

In the future, the present velocity filter combined with a cryogenic trap apparatus will enable us to perform systematic measurements of cold ion-polar molecule reactions, which are important problems from a fundamental viewpoint and contribute to astrochemistry.

References
Effects of 2.6-GeV uranium irradiation on (Ba,K)Fe$_2$As$_2$ single crystals

T. Tamegai,$^{*1}$ T. Taen,$^{*1}$ F. Ohtake,$^{*1}$ S. Pyon,$^{*1}$ T. Kambara,$^{*2}$ Y. Kanai,$^{*3}$ and A. Yoshida$^{*2}$

Through extensive studies on the recently discovered iron-based superconductors (IBSs), the transition temperature $T_c$ in rare-earth-based iron-oxyselenides has been increased up to ~55 K within a short period of time. However, the critical current density, $J_c$, at low temperatures is not large enough. Despite the lower $T_c$ in IBSs compared with that in cuprate superconductors, IBSs have smaller electromagnetic anisotropies and are considered to be attractive for practical applications. $J_c$ can be enhanced by introducing artificial pinning centers. It is well known that the most efficient way to improve the $J_c$ characteristics is to pin vortices with columnar defects (CDs) created by swift particle irradiations. In high-temperature superconductors, the existence of CDs enhances $J_c$ dramatically.\(^1\)

One of the most extensively studied IBSs, Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, with the highest $T_c$ (~24 K) is readily available in a large single crystal. Its $J_c$ reaches 1x10$^6$ A/cm$^2$ at $T = 2$ K, which is potentially attractive for technological applications. We expect that $J_c$ in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ can be enhanced by introducing CDs that can pin vortices. However, it is well known that morphologies of irradiation-induced defects strongly depend on various parameters such as ion energy, stopping power of incident ions, thermal conductivity, and perfection of the target crystal. Hence, it is still an open question as to what kind of defects can be created in IBSs under a specific condition. Our preliminary study using 200 MeV Au ions has successfully demonstrated that CDs can be introduced and $J_c$ is enhanced by a factor of 5 at low temperatures.\(^2\) In our previous irradiation in IBS performed at RIKEN, we have used heavier and more energetic 2.6 GeV Uranium (U) ions and found that U also enhances $J_c$ in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$.\(^3\) In this case, however, magnetic hysteresis loop shows an interesting dip structure at low magnetic fields; such a dip has not been observed in the case of Au irradiation. One of the possible origins for this dip is that pinning by CDs is not effective in the remnant state of a thin-plate superconductor, where flux lines have a strong curvature due to the strong demagnetization effect.\(^4\)

This year, we have explored similar irradiation effects on another promising IBS, (Ba$_{1-x}$K$_x$)Fe$_2$As$_2$. Figure 1 shows the magnetic hysteresis loops of the 2.6-GeV U-irradiated (Ba$_0$$_{0.6}$K$_{0.4}$)Fe$_2$As$_2$ at $B = 2$ T and at low temperatures. Except for temperatures close to $T_c$ and 2 K, the width of the hysteresis loop is diminished at lower fields, which is similar to the dip structure observed in the case of the U-irradiated Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$.\(^5\) In Fig. 2, we convert the width of the hysteresis loop into $J_c$ using the Bean model. After the irradiation, $J_c$ at $T = 2$ K under a self-field reaches 7x10$^6$ A/cm$^2$, which is larger than that in the case of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. It should be noted that $J_c$ at $T = 25$ K and $H = 45$ kOe is ~2x10$^5$ A/cm$^2$, which is larger than the technologically required value for superconducting wires.

Fig. 1. Magnetic hysteresis loops of 2.6-GeV U-irradiated (Ba$_0$$_{0.6}$K$_{0.4}$)Fe$_2$As$_2$ ($B = 2$ T) at several fixed temperatures.

Fig. 2. Magnetic field dependence of $J_c$ in 2.6-GeV U-irradiated (Ba$_0$$_{0.6}$K$_{0.4}$)Fe$_2$As$_2$ ($B = 2$ T).

References


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Site occupancies of hydrogen in Nb alloyed with oversized Ta atoms or undersized Mo atoms†

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An interaction of hydrogen with solute atoms is one of the fundamental problems on hydrogen in metals, because various hydrogen-related properties are strongly affected by alloying. In order to understand the interaction, the knowledge of the atomistic state of hydrogen in alloys is highly required. However, such information has been extremely limited, because of experimental difficulties. Therefore, the channelling method utilizing a nuclear reaction of $^4\text{He}^{(+1)}\text{B},\alpha\alpha\alpha$ with a $^{11}\text{B}$ beam of about 2 MeV had been developed.† This method has been demonstrated to be very useful to locate hydrogen dissolved in metals.1,2 In previous studies, the lattice location of hydrogen has been investigated systematically in detail in Nb alloyed with undersized Mo atoms up to 60 at. % by the channelling method at room temperature with a tandem accelerator. Their atomic radii are 1.43 Å for Nb and 1.36 Å for Mo atoms. This alloy system forms a solid solution over the entire Mo concentration ($C_{\text{Mo}}$) range, maintaining a bcc crystal structure, although the lattice parameter changes.

It has been demonstrated that the lattice location changes very sensitively with Mo concentration and, with the help of the measurement of width of X-ray reflection lines, that such change can be explained in terms of lattice distortion introduced by alloying with Mo atoms.3,4 At low $C_{\text{Mo}}$, lattice is strongly distorted around Mo atoms. Hydrogen is trapped by a Mo atom to be located at a $T$ site, which is displaced from an original tetrahedral ($T$) site by about 0.6 Å towards the Mo atom, so as to reduce the distortion around Mo atom. There exists a strong attractive interaction between hydrogen and Mo atoms.5,6 With increasing $C_{\text{Mo}}$, the lattice distortion is reduced owing to interference between strain fields around individual Mo atoms, and most of the H atoms occupy $T$ sites as in Nb. For $C_{\text{Mo}}$ higher than 39 at. %, the lattice distortion gradually increases again with increasing $C_{\text{Mo}}$ because of the increase in the number of undersized Mo atoms in a unit cell, but not so strongly as that at low $C_{\text{Mo}}$, i.e., up to an intermediate level. In this case, H atoms are distributed over $T$ and $d$-$T$ sites, which is displaced from $T$ sites to their nearest neighbour octahedral ($O$) sites by about 0.25 Å. The $T$-site occupancy is energetically more favourable than the $d$-$T$-site occupancy.

In the present study, the site occupancy of hydrogen in Nb alloyed with 2 or 5 at. % of oversized Ta atoms (atomic radius: 1.44 Å), Nb$_{0.98}$Ta$_{0.02}$H$_{0.01}$, Nb$_{0.98}$Ta$_{0.02}$H$_{0.02}$, and Nb$_{0.95}$Ta$_{0.05}$H$_{0.01}$, was investigated by the channelling method at room temperature. The objectives of the present study are to investigate a difference in an interaction of hydrogen with solute atoms between oversized Ta and undersized Mo atoms and to examine the above-described interpretation on the basis of the lattice distortion.

The following results were obtained. Taking account of the previously reported results on Nb$_{0.95}$Ta$_{0.05}$H$_{0.015}$ and Nb$_{0.95}$Ta$_{0.05}$H$_{0.025}$,7 in both Nb$_{0.98}$Ta$_{0.02}$ and Nb$_{0.95}$Ta$_{0.05}$ alloys, at low hydrogen concentration $C_H$, most of the H atoms are located at $T$ sites, while at high $C_H$, most of them are at $d$-$T$ sites displaced by 0.25 Å from $T$ sites towards their nearest neighbour $O$ sites, and the remains are at $T$ sites. This result is different from that in Nb alloyed with similar concentration of undersized Mo atoms, where hydrogen preferentially occupies $T_\alpha$ sites. It was deduced that, in both Nb$_{0.98}$Ta$_{0.02}$ and Nb$_{0.95}$Ta$_{0.05}$ alloys, the $T$ site occupancy is energetically more favourable than the $d$-$T$-site occupancy, but the concentration of available $T$ sites is limited. In these alloys, the lattice distortion is small and at an intermediate level, because of the smaller size difference between Nb and Ta atoms than between Nb and Mo atoms. This difference in lattice distortion is reflected in the X-ray line widths. Therefore, hydrogen preferentially occupies $T$ sites in the undistorted or very weakly distorted tetrahedra some distance away from Ta solutes and excess H atoms enter $d$-$T$ sites in the tetrahedra distorted at an intermediate level near Ta solutes. Therefore, the interaction between hydrogen and an oversized Ta atom is not attractive in Nb, in contrast to the attractive interaction between an undersized Mo atom and hydrogen inNb.

With the help of measurements of the half-widths of X-ray reflection lines in Nb-Mo and Nb-Ta alloys, the site occupancy of hydrogen in the Nb-Ta alloys is explained in terms of an effect of lattice distortion induced by alloying, as in the case of the site occupancy in Nb-Mo alloys with Mo concentration higher than about 39 at. %. The $d$-$T$ site is a stable site for hydrogen in a slightly distorted bcc lattice.

References
Evaluation of single-event damages on Silicon Carbide (SiC) power MOSFETs

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Silicon carbide (SiC) is the material used in next generation semiconductor devices that is applicable to higher voltage and temperature applications because of the inherent wide energy band-gap of 3.26 eV.1) In addition, saturated electron velocity is considerably fast in the SiC material. Therefore, SiC devices can operate in ultra-high frequency applications.2) If the SiC material is used in power devices instead of Si, these devices can achieve higher efficiency and lower loss.3) In our study, we investigated in detail the fatal destruction mode called Single-Event Burnout (SEBs) on commercial SiC power MOSFETs with the radiation effect during heavy-ion irradiations in space.

A single ion incidence into the device generates some amount of charge according to the Linear Energy Transfer (LET) value of the ion, and the charge can be amplified in the device using mechanisms such as avalanche multiplication. Finally, the charge is collected at the drain terminal and can be measured using a charge sensitive amplifier (CSA). The input charge range and the output voltage of CSA are 0.5 - 50 nC and 0.1 mV - 10 V, respectively. For the cases where the amplification level increases exponentially with the applied voltage to the sample device, the Energetic Particle Induced Charge Spectroscopy (EPICS) is more suitable. EPICS is specially designed for the pulse-height analyzer (PHA) system that is used to analyze the charge collection characteristics in semiconductor devices.4) It can measure a wide range of charges using a logarithmic scale. The block diagram of the EPICS system is shown in Fig. 1.

SiC power MOSFETs used in this study were commercial devices. The maximum ratings for the drain-Source breakdown voltage, continuous drain current, and the drain-source on-state resistance are 1200 V, 24 A, and 220 mΩ, respectively.

The test was performed at room temperature by irradiation with a Kr-ion beam of 713 MeV using the RIKEN RILAC+RRC. Fluence was set to 1×10⁵ ions/cm² at the chip surface. The drain bias voltage, V_{DS}, was increased at an interval of 50 V. The gate voltage, V_{GS}, was set to 0 V to force the devices to enter the OFF state.

![Fig. 1. Block diagram of EPICS system.](image)

![Fig. 2. Collected charge spectra by Kr ion irradiation using the EPICS system.](image)

Figure 2 shows the EPICS spectra on SiC power MOSFETs of Kr-ion irradiation. The cross marks Q_{max} indicate the maximum collected charge for each spectrum. There were two peaks on each spectrum similar to the one of Si power MOSFETs.4) At the drain voltage of 100 V, the device was damaged because the leakage current was more than the maximum rated zero gate voltage drain current of 10 μA. In Si power MOSFETs, a high energy collected charge peak Q_{max} of more than 10⁵ pC was observed when SEB occurs. However, in SiC power MOSFETs, permanent increase of the leakage current was observed at the drain voltage of 100 V; however, no high SEB peak was observed up to the voltage level, and the maximum collected charge was less than 100 pC. This behavior is the same as our previous study on SiC Schottky barrier diodes.5) This fact suggests that the mechanism of SEB was different between SiC power MOSFETs and Si power MOSFETs. Therefore, it is necessary to perform additional experiments to understand the SEB mechanism of SiC power MOSFETs.

References
2. Atomic and Solid State Physics (Muon)
**μSR study of the spin correlation in iron-chalcogenide superconductors \( \text{Fe}_{1-y}\text{M}_y\text{Se}_{0.3}\text{Te}_{0.7} \) (M = Co, Ni, Zn)**

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In recent years, much attention has been paid to the so-called iron-based superconductors due to their high superconducting (SC) transition temperatures, \( T_c \)'s, in the research field of superconductivity. Hsu et al. have discovered superconductivity with \( T_c = 8 \text{ K} \) in the iron-chalcogenide FeSe.\(^1\) It has been found that \( T_c \) of FeSe increases through the partial substitution of Te for Se, shows a maximum of 14 K at \( x \sim 0.7 \) in FeSe\(_{0.3}\)Te\(_{0.7}\), and the superconductivity disappears at \( x = 1 \), namely, in FeTe.\(^2\) The compound FeTe is not SC but develops an antiferromagnetic (AF) order at low temperatures below \( \sim 67 \text{ K} \).\(^3\) Therefore, one may guess the mechanism of superconductivity relating to the AF spin fluctuation in the iron-chalcogenide superconductors, which is similar to the case of high-\( T_c \) cuprate superconductors.

In order to investigate impurity effects on the SC properties, we have grown impurity-substituted single crystals of Fe\(_{1-y}\)M\(_y\)Se\(_{0.3}\)Te\(_{0.7}\) (M = Co, Ni, Zn) with \( y = 0 \sim 0.05 \) and have measured the in-plane electrical resistivity.\(^4\) Here, Co and Ni ions are expected to dope one and two electrons, respectively, while Zn is expected to dope no electrons. As a result, it has been found that \( T_c \) is reduced through the Co substitution and that the reduction of \( T_c \) is more significant in the Ni substitution than in the Co substitution. On the other hand, the decrease in \( T_c \) with the Zn substitution has been found to be negligibly small. Moreover, it has been found that both \( T_c \) and the residual resistivity depending on the impurity concentration cannot be explained by the Abrikosov-Gor’kov theory, suggesting that a glue to form electron pairs is not the spin fluctuations\(^5\) but the orbital fluctuations.\(^6\)

Therefore, in order to investigate the spin fluctuations directly, we have performed \( \mu \)SR measurements of Fe\(_{1-y}\)M\(_y\)Se\(_{0.3}\)Te\(_{0.7}\) (M = Co, Ni, Zn) with \( y = 0 \sim 0.05 \).\(^7\) Zero-field (ZF) and longitudinal-field \( \mu \)SR measurements were carried out using a Variox cryostat at temperatures down to 1.6 K at RIKEN-RAL.

For the impurity-free crystal of \( y = 0 \), it has been found that ZF \( \mu \)SR spectra are independent of temperature at low temperatures down to 1.6 K, indicating that the crystal is in a paramagnetic state. Figure 1 shows ZF spectra of the Zn-substituted crystal of Fe\(_{1-y}\)Zn\(_y\)Se\(_{0.3}\)Te\(_{0.7}\) with \( y = 0.05 \). At 29 K, the spectrum shows slow depolarization of muon spins similar to that observed in the impurity-free crystal. On the other hand, the depolarization becomes fast with decreasing temperature and the initial asymmetry is missing at 1.6 K. These results suggest significant development of the spin correlation through the Zn substitution. For the Co and Ni substitution, it has been found that the spin correlation is enhanced at \( y = 0.02 \) and that further substitution of impurities leads to weakening of the spin correlation at \( y = 0.05 \). These \( \mu \)SR results depending on the amount and kind of impurities strongly suggest that not the spin fluctuations but the orbital fluctuations may be a glue to form electron pairs in the iron-chalcogenide superconductors.

In summary, we have found impurity-induced development of the spin correlation in Fe\(_{1-y}\)M\(_y\)Se\(_{0.3}\)Te\(_{0.7}\) (M = Co, Ni, Zn) from \( \mu \)SR measurements. The present \( \mu \)SR results strongly suggest that the formation of electron pairs is mediated by the orbital fluctuations in iron-chalcogenide superconductors.

**Fig. 1.** Zero-field \( \mu \)SR time spectra of Fe\(_{1-y}\)Zn\(_y\)Se\(_{0.3}\)Te\(_{0.7}\) with \( y = 0.05 \).

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References
μSR re measurement of La$_2$CuO$_4$ to reinvestigate muon sites

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In a previous report,1) we have predicted a muon site in La$_2$CuO$_4$ (LCO) with the tetragonal structure (the structure above 550 K) by calculating the minimum potential energy for muons, according to the density functional theory (DFT), and the hyperfine field contribution from Cu spins. We predicted two possible muon sites in LCO, although a single muon site with an internal field between 410-430 G was experimentally achieved2). Because of this disagreement, we remeasured the internal field at the muon site using the μSR method with higher statistics. In addition to this experimental effort, we also continued a similar estimation to find all possible minimum potentials in the orthorhombic structure (the structure that occurs below 550 K).

Zero-field (ZF) μSR measurements were performed at the RIKEN-RAL Muon Facility and PSI using a single crystal of LCO in the magnetically ordered state at 10 K and 1.7 K, respectively. The DFT calculation was performed by using the RIKEN integrated cluster of clusters (RICC) system using the Vienna ab-initio simulation package (VASP). A supercell structure that contains 27 unit cells (3×3×3 unit cells) was adopted for calculation taking into account the effect of relaxations of the local lattice and muon positions. The minimum potential in the static case was used to determine the initial positions of lattice points prior to final calculations with relaxation effects. The dipole calculation was performed on the basis of the antiferromagnetic ordered state, which has been experimentally determined by Vaknin et al.3) The magnetic moment was traced from 0.10 to 0.70 μ$_B$/Cu until the dipolar fields fit the internal fields experimentally determined by ZF-μSR.

Fig. 1 Fourier spectra of La$_2$CuO$_4$ ZF-μSR obtained with high statistics in the RIKEN-RAL and PSI.

Fourier spectra of ZF-μSR are shown in Fig. 1. Three components of internal fields were found. We marked them as B$_1$, B$_2$, and B$_3$ from the lower field component.

B$_2$ has the largest amplitude while B$_1$ and B$_3$ have much smaller amplitudes that are less than 1/30 of that of B$_2$. The internal field of B$_2$ corresponds to that experimentally observed.2) In terms of DFT calculations, three minimum potentials were found in LCO from our current study, as shown in Fig. 2. This result is qualitatively explained by three muon positions in LCO.

We attempted to explain the observed internal fields on the basis of the dipole-dipole interaction by tuning the magnitude of the magnetic moment of the Cu spin. As a result, we found that the three observed components of the internal field can be explained if the magnetic moment of the Cu spin is reduced to be around 0.23 μ$_B$, as shown in Fig. 3. Such a local reduction of the Cu spin is currently being argued.4)

Fig. 2 (a) Minimum potential positions estimated from DFT and (b) shape of the potential energy between minima.

Fig. 3 Comparison between calculated dipolar field spectra and the internal field obtained from μSR experiments.

In conclusion, we found new additional muon sites in LCO from the ZF-μSR experiment with higher statistics. Our DFT calculation supported those three muon sites. Assuming only the dipole-dipole interaction, we suggest the possible local reduction of magnetic moment of the Cu spin to be approximately 50%. The reason for this reduction is currently being discussed.

References
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Magnetic ordering in Cu₆O₈TbCl probed during the μSR measurement

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The copper-oxide family of Cu₆O₈MCl (M = cation) has a caged structure (Cu₆O₈ cage) in its crystal structure (crystal system: cubic, space group: Fm-3m (No. 225)). The form of the surface of the Cu₆O₈ cage is similar to the CuO₂ plane in high-Tc cuprate superconductors. The Cu₆O₈ cage forms a three-dimensional network, sharing their face (left panel of Fig. 1).¹,² The Cl⁻ anions are located at the center of the Cu₆O₈ cage, and the M cations, which have a valence of 3⁺ or 4⁺, exist in the cuboid space located between Cu₆O₈ cages. The average valence of Cu ions in the Cu₆O₈ cage is 2.33⁺ for M³⁺.

For the M = Tb³⁺ compound (Cu₆O₈TbCl), the magnetic susceptibility data indicate a weak magnetic transition at approximately 40 K. Moreover, the electrical resistivity data exhibit a metal-insulator transition at approximately 40 K (right panel of Fig. 1). The effective Bohr magneton Pₑff is estimated to be ~6.74, which is close to the theoretical value for Tb³⁺, indicating that a localized magnetic moment exists at the Tb³⁺ site. However, whether the origin of the magnetic ordering state is long range (static) or not and the relationship between the magnetic state and other physical properties is not yet clear. In order to clarify these points, μSR measurement was performed at the RIKEN-RAL Muon Facility in U.K. using a polycrystalline sample of Cu₆O₈TbCl.

Figure 2 (a) shows the time dependence of asymmetry of the zero field (ZF) μSR spectra, A(t), of Cu₆O₈TbCl measured at various temperatures. These spectra were observed using the double-pulse muon beam. The spectra show exponential-like depolarized behaviors, and the muon-spin depolarization becomes faster with decreasing temperature above 40 K. Significant loss of initial asymmetry (at t = 0) is observed below 40 K. In order to observe the change of the spin dynamics in detail, all of the time spectra were analyzed using the following function:

\[ A(t) = A₀ \exp(-\lambda t) + A_b, \]

where A₀ is the initial asymmetry, \( \lambda \) is the depolarization rate of the muon spins, and A₀ is the background. The parameters obtained from the best fit of Eq. 1 to the data in Fig. 2(a) (solid line) are shown in Fig. 2(b). From Fig. 2(b), A₀ slightly decreases and \( \lambda \) increases above 40 K. Moreover, A₀ and \( \lambda \) values rapidly change at approximately 40 K, indicating that the spin state drastically changes at 40 K. The inset of Fig. 2(a) shows an early time region of the ZF μSR spectra at 5 K (lowest temperature of this measurement) measured using the single-pulse muon beam. Muon-spin precession behavior was observed, indicating the existence of a long-range magnetic-ordered state. Consequently, the weak magnetic transition confirmed in the magnetic susceptibility data of Cu₆O₈TbCl is generated by the development of long-range magnetic order of Tb³⁺. Moreover, it is suggested that the conducting carrier is trapped and that the ground state changes from metallic to semiconducting with the onset of long-range magnetic order.

References
Disappearance of gapped Mott insulating phase neighboring Bose glass phase in $\text{Tl}_{1-x}\text{K}_x\text{CuCl}_3$ detected by longitudinal-field muon spin relaxation†


TI CuCl$_3$ and K CuCl$_3$ are isostructural, and are three-dimensionally coupled Cu 3d $S = 1/2$ spin dimer systems. The ground states are spin singlets with excitation gaps of $\Delta = 7.5$ K in TI CuCl$_3$ and 31 K in K CuCl$_3$, originating from strong intradimer antiferromagnetic interaction $J$. Applying magnetic fields to the gapped state, the spin gap is collapsed, and a magnetically ordered state appears, which is qualitatively well described by the magnon Bose-Einstein condensation (BEC) theory. Describing the magnetic states by magnon motions, the spin singlet state corresponds to the gapped Mott Insulating (MI) phase.

By introducing randomness in the intradimer interaction, a new phase, Bose glass (BG) phase was theoretically predicted to appear at $T = 0$ neighboring the magnon BEC phase. In the mixed system $\text{Tl}_{1-x}\text{K}_x\text{CuCl}_3$, the randomness of the local chemical potential is introduced spatially, because the value of the dominant intradimer interaction $J$, which corresponds to the local potential of magnons, is different between TI CuCl$_3$ and K CuCl$_3$. Recently, Yamada et al. performed electron-spin resonance (ESR) measurements on $\text{Tl}_{1-x}\text{K}_x\text{CuCl}_3$ with $x = 0.22$ and 0.44 in resonance fields close to the critical field of BEC transition which is confirmed by specific heat measurements, and reported the change of the spectrum shape from Lorentzian shape to the intermediate shape between Gaussian and Lorentzian. This result suggests the localization of magnons at sufficiently low temperature, and suggest the appearance of the BG phase adjacent to the BEC phase. According to the theoretical prediction, the BG phase appears between the gapped MI phase and the BEC phase, and there exist a quantum phase transition point $H_B$ from the BG phase to the gapped MI phase with decreasing the magnetic field. However, magnetization measurements suggest $H_B = 0$. Thus, whether or not the gapped MI phase neighboring the Bose glass phase disappears in the zero-field limit is a controversial problem. The purpose of this study is to microscopically investigate this problem using LF - $\mu$SR technique.

Figure 1 shows temperature dependence of LF - $\mu$SR time spectrum of $\text{Tl}_{1-x}\text{K}_x\text{CuCl}_3$ with $x = 0.40$ down to 25 mK in various longitudinal fields. All time spectra are analyzed using the stretched exponential function $A(t) = A_0 \exp(-(\lambda t)^\beta)$, and are well fitted as shown with solid lines. $A_0$ is the initial asymmetry and $\lambda$ is the muon spin relaxation rate. Fitted results of $\beta$ are almost constant for all spectra in a range of $\beta = 0.8 \pm 0.06$, which is consistent with the previous data for $x = 0.40$ in longitudinal fields. LF-$\mu$SR time spectra shows an exponential like decay, and the muon spin-relaxation rate does not has a significant temperature dependence down to 25 mK. As a fitted result, $\lambda$, which corresponds to a low frequency dynamical susceptibility, is almost constant down to 25 mK although slight changes in $\lambda$ are observed. The low frequency spectrum seems to be a white spectrum, because $\lambda$ in each field is finite below 500 gauss. These results mean that internal magnetic fields at the muon sites are fluctuating by low frequencies below $\sim 1$ MHz down to 25 mK. When the spin system has a tendency toward a magnetic phase transition, $\lambda$ is expected to increase with decreasing temperature in the zero-field limit below 500 gauss. Thus, in this case, a magnetic ordered state is not experimentally expected, and the ground state is a spin fluctuating state. It is suggested that the theoretically predicted quantum phase transition point from the Bose glass phase to the gapped Mott insulating phase disappears, i.e. $H_B = 0$.

References

Fig. 1. Temperature dependence of LF-$\mu$SR time spectrum of $\text{Tl}_{1-x}\text{K}_x\text{CuCl}_3$ with $x = 0.40$.†
Magnetic order in pyrochlore iridate Nd$_2$Ir$_2$O$_7$ probed by employing muon spin relaxation†

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Pyrochlore iridates are highly suitable to investigate novel topological phases based on the network of corner-sharing tetrahedra structures and the relatively large spin-orbit coupling (SOC) inherent in Ir 5$d$ electrons.† The interplay between SOC and electron-electron correlations ($U$) produces characteristic electronic states. A series of R$_2$Ir$_2$O$_7$ ($R$-227, $R$ = Nd-Ho) compounds exhibit metallic or semi-metallic behavior and undergo metal-insulator transitions (MITs) at a temperature $T_{\text{MI}}$ while Pr-227 shows metallic behavior down to 0.3 K.†

In this study, we focus on Nd-227, which shows metallic behavior at high temperatures and undergoes a MIT at $T_{\text{MI}}$ of about 30 K, and the magnetic susceptibility shows the bifurcation below $T_{\text{MI}}$ in zero-field-cooling (ZFC) and field-cooling (FC) conditions.† Muon spin precession is observed below $T_{\text{MI}}$, and the spectra were fitted using the following function:

$$A(t) = A_1 e^{-\lambda_1 t} + A_2 \cos(\gamma \mu H_{\text{int}} t + \varphi) e^{-\lambda_2 t}$$  \hspace{1cm} (1)

where $H_{\text{int}}$ is the internal field at the muon site, $\lambda_1$ is the muon spin-lattice relaxation rate, and $\lambda_2$ and $\varphi$ are the damping rate and initial phase of the muon spin precession, respectively.

The temperature dependence of the extracted parameters is shown in Fig. 1. $H_{\text{int}}$ begins to increase below $T_{\text{MI}}$, following the Brillouin-type ordering and tends to saturate below about 20 K to a value of about 350 G. Below about 10 K, $H_{\text{int}}$ increases again. $\lambda_1$ continues to decrease below $T_{\text{MI}}$ and increases again from the same temperature at which $H_{\text{int}}$ exhibits an increase. From the inset of Fig. 1(a), it can be seen that $\lambda_1$ increases monotonically with decreasing temperature, reflecting the slowing down of the magnetic moments. A small increase is observed around $T_{\text{MI}}$. However, no critical slowing down behavior is observed, as shown in Fig. 1(b). $\lambda_1$ continues to increase below $T_{\text{MI}}$ and shows a broad peak at around 10 K.

The increase in $H_{\text{int}}$ below about 10 K is consistent with the results of the neutron scattering experiment that shows the ordering of Nd$_{3+}$ moments, so it is attributed to the ordering of Nd$_{3+}$ moments from our muon spin relaxation ($\mu$SR) experiment. The decrease in $\lambda_1$ below about 10 K is then accounted for by the freezing out of the magnetic fluctuations, and the increase in $\lambda_2$ suggests that the distribution of the internal field becomes larger at the vicinity of the magnetic ordering. The ordering below $T_{\text{MI}}$ is then attributed to the ordering of the Ir$^{4+}$ moments, suggesting its close relationship with the MIT.

According to a local spin-density approximation calculation including $U$ and SOC, the magnetic structure of the Ir sublattice is the all-in/all-out type, which does not break the lattice periodicity; therefore, the Slater transition is ruled out to account for the relationship between the MIT and the magnetic transition. On the other hand, the Lifshitz-like transition in which the hole band and electron band are moved downward and upward, respectively, due to the specific magnetic structure and the large SOC of Ir 5$d$ electrons may explain the mechanism of MIT. The saturated internal field from the ordered Ir$^{4+}$ moments is found to be much smaller than that in the case of the other pyrochlore iridates with a magnetic insulating ground state. This implies a stronger hybridization between the Ir 5$d$ and the O 2$p$ electronic orbitals in Nd-227.

References
Unconventional spin freezing in a highly two-dimensional spin-1/2 Kagome antiferromagnet \( \text{Cd}_2\text{Cu}_3(\text{OH})_6(\text{SO}_4)_2\cdot4\text{H}_2\text{O} \): evidences of partial order and co-existing spin singlet state on distorted Kagome lattice

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The magnetic phases of geometrically frustrated magnets have been rigorously studied both theoretically and experimentally in the last two decades. The Kagome antiferromagnet, a two-dimensional net of corner-sharing triangles, is an excellent choice for investigating spin liquid and other exotic states, because it is expected to be one of the most highly frustrated systems. However, the Kagome system is still not completely understood, leading to many unanswered questions. Even the most essential issue of whether the ground state is a gapped spin liquid or a gapless one remains undetermined. Besides the difficulties of theoretically dealing the quantum spins on the Kagome lattice (which is much more complicated than the simple triangular lattice), the lack of such compounds has been a major obstacle.

We have recently found a new Kagome antiferromagnet, \( \text{Cd}_2\text{Cu}_3(\text{OH})_6(\text{SO}_4)_2\cdot4\text{H}_2\text{O} \). It possesses a monoclinic crystal structure identical to that for the previously reported mineral Edwardsite [1]. It crystallizes in the space group \( P 21/c \) with lattice parameters of \( a = 10.8887(2) \) Å, \( b = 13.1745(2) \) Å, \( c = 11.2258(2) \) Å, and \( \beta = 112.994(1)^\circ \). As illustrated in Fig. 1, four \( \text{Cu}^{2+} \) sites exist, forming a Kagome lattice for the \( S = 1/2 \) spins. The structural information show that \( \text{Cd}_2\text{Cu}_3(\text{OH})_6(\text{SO}_4)_2\cdot4\text{H}_2\text{O} \) is a slightly distorted Kagome lattice with high two-dimensionality, which is a great advantage in studying the intrinsic spin behaviors on distorted Kagome lattices; it also serves as a reference system for undistorted Kagome lattices.

Fig. 1 Structure of \( \text{Cd}_2\text{Cu}_3(\text{OH})_6(\text{SO}_4)_2\cdot4\text{H}_2\text{O} \).

Fig. 2 Zero-field \( \mu \)SR asymmetry spectra at various temperatures.

\( \mu \)SR, having a large gyromagnetic ratio, is a sensitive microscopic probe for magnetic order and spin fluctuations. Figure 2 shows the zero-field (ZF) asymmetry spectra at various temperatures. The asymmetry spectra change obviously from \( T = 5 \) K. Detailed analysis showed the formation of static magnetism below \( 5 \) K. The magnetic behaviors are distinctly different from the spin liquid state on an undistorted Kagome lattice, demonstrating the critical role of lattice distortion.

References

Muon spin relaxation study of spin-glass freezing in the Heusler compound Ru$_{1.9}$Fe$_{0.1}$CrSi$^\dagger$

M. Hiroi, T. Hisamatsu$^\star$, T. Suzuki, K. Ohishi, Y. Ishii$^*,$ and I. Watanabe$^*$

The magnetic properties of the Heusler compounds Ru$_{2-x}$Fe$_x$CrSi have attracted interest. It has been revealed that Fe-rich compounds are ferromagnetic$^1$ and that the Ru-rich compound Ru$_2$CrSi shows an antiferromagnetic transition at $T_N = 14$ K.$^2$ Although the Ru-rich compound Ru$_{1.9}$Fe$_{0.1}$CrSi was found to show a peak in magnetic susceptibility at $T_N \sim 30$ K, which seemed to indicate an antiferromagnetic transition, no phase transition was found around $T_N$ or at any other temperatures in the specific heat.$^3$ In stead, the difference between the magnetic susceptibilities observed in a zero-field-cooling process and a field-cooling process increased significantly below $T_g \sim 15$ K, which was regarded as the onset of strong irreversibility.$^3$ This observation suggests the formation of a spin-glass (SG) state. In order to reveal the nature of the magnetic transitions, we have performed zero-field (ZF) and longitudinal-field (LF) muon-spin-relaxation ($\mu$SR) measurements for Ru$_{1.9}$Fe$_{0.1}$CrSi. The measurements were carried out at the RIKEN-RAL Muon Facility using a spin-polarized single-pulse positive surface muon beam. In these measurements, the time spectra of muon spin depolarization consisted of two components, and the asymmetry, $A_0(t)$, can be expressed as

$$A_0(t) = A_1 \exp(-\lambda_1 t) + A_2 \exp(-\lambda_2 t). \quad (1)$$

The first and second terms represent the fast and slow relaxation components, respectively, and $\lambda_1$ and $\lambda_2$ are the muon spin relaxation rates for each component. The initial asymmetry $A_0$ is $A_0(0) = A_1 + A_2$. The parameters in Eq. (1) were obtained from the fitting of the time spectra, and these temperature dependences in the ZF-$\mu$SR measurement are shown in Fig. 1. As shown in the figure, a peak of the relaxation rates was observed at $\sim 16$ K, and this suggests the onset of spin freezing at $\sim T_g$. Furthermore, LF-$\mu$SR measurement for different values of magnetic field was performed at 0.3 K, which confirmed the presence of a static internal magnetic field. The internal field was estimated to be approximately $0.1308 \pm 0.005$ T. From these results we conclude that SG freezing occurs at $T_g$.

On the other hand, an anomaly in the relaxation rate of ZF-$\mu$SR, indicating a phase transition, appeared to be absent around $T_N$, whereas with decreasing temperature a large decrease in the initial asymmetry and a gradual increase in the relaxation rates were observed starting at $\sim 40$ K, which is slightly higher than $T_N$. The loss of the initial asymmetry may have been caused by a static internal field. To investigate the origin of the large decrease in the initial asymmetry below $\sim 40$ K, we performed LF-$\mu$SR measurements as a function of magnetic field $H_{LF}$ between $T_g$ and $\sim T_N$. The $H_{LF}$ dependence of $A_2$ was analyzed, and it was found that at temperatures below 30 K, $A_2$ increases from approximately the same field as at 0.3 K. This analysis suggests that a static field arises at the muon site from temperatures higher than $T_N \sim 30$ K and the value of the static field does not change much below $\sim 30$ K. These results indicate an inhomogeneous magnetic state. It appears that the formation of independent spin-frozen regions begins at $\sim 40$ K. As the temperature decreases, these static regions extend gradually, and this results in the observed decrease in the initial asymmetry. The correlation between static regions becomes larger and eventually SG freezing occurs at $T_g$.

References


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Fig. 1. Temperature dependences of (a) $A_0 = A_1 + A_2$ and $A_2$, and (b) $\lambda_1$ and $\lambda_2$, for ZF-$\mu$SR. Solid lines are guides to the eye.
**μSR study of heavy fermion superconductor URu$_2$Si$_2$**

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Despite intensive studies for more than two decades, the order parameter of the mysterious phase transition at $T_o = 17.5$ K in URu$_2$Si$_2$ has not been identified yet, and thus the ordered phase is referred to as the hidden order (HO) phase.

The symmetry of the HO phase is crucial information for the identification of its order parameter. Recent Shubnikov-de Haas experiments have revealed that the Fermi surfaces in the HO phase are very similar to those of the pressure induced antiferromagnetic phase. This confirms that translational symmetry is broken in the HO phase, and the ordering vector is $Q_{\text{HO}} = (1, 0, 0)$. In addition, in the HO state, NMR and magnetic torque experiments have shown that the four-fold rotational symmetry in the (001) plane is broken. On the other hand, the time-reversal symmetry (TRS) is still a controversial issue, since we can find two types of very recent theoretical models for the HO transition: some of the theoretical models assume that the TRS is conserved in the HO phase, while the others assume that TRS is broken. Therefore, although the previous NMR and μSR studies have reported the development of tiny internal magnetic fields below $T_o$, and indicate the breaking of the TRS in the HO phase, further characterization of the internal magnetic field in the HO phase is required. In the present study, we performed zero-field (ZF) and longitudinal-field (LF) μSR experiments on a single crystal of URu$_2$Si$_2$ in order to characterize the internal magnetic fields in the HO state.

The inset of Fig. 1 shows ZF-μSR spectra at 11 and 19.5 K, which are below and above $T_o$. The ZF-spectra were well fitted by a single exponential function $A_0 \exp(-\lambda_{ZF}t)$ over the temperature range presently investigated. We observed an enhancement of $\lambda_{ZF}$ in the HO phase, which reflects a development of the TRS breaking magnetic field. Figure 1 exhibits the temperature dependence of $\lambda_{ZF}$, and a sharp increase is clearly observed at $T_o$. $\lambda_{ZF}$ shows a saturated feature around 10 K, but it exhibits an additional increase with further decreasing temperature and keeps increasing down to the lowest temperature.

In order to investigate the dynamics of the internal magnetic field in the HO phase, we performed LF-field experiments where LF was applied parallel to the $a$-axis. Figure 2 shows the LF-μSR spectra measured at 11 K. The long tails of relaxation spectra are strongly affected by applying tiny LFs. This is a characteristic feature in the presence of a static field distribution at muon sites. In this case, the exponential relaxation in the ZF experiments reflects the presence of a Lorentzian field distribution at muon sites. Since the relaxation rate under LFs is a measure of transverse components of field fluctuations at muon sites, the observed decoupling behavior implies the absence of measurable field fluctuations along both the $a$ and $c$ directions. Hence, we conclude that measurable magnetic fluctuations do not exist along any directions at muon sites, and the internal magnetic field developed in the HO phase is static on the time scale of μSR.

Fig. 1. Temperature dependence of the ZF-relaxation rate. The inset shows the ZF-μSR spectra measured at 11 and 19.5 K.

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References

Magnetic instability induced by Rh doping in the Kondo semiconductor CeRu$_2$Al$_{10}$

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The ternary compound CeT$_2$Al$_{10}$ (T = Fe, Ru, and Os) is a unique system that shows Kondo semiconducting behavior at low temperatures, and it exhibits an antiferromagnetically (AFM) ordered state at $T_0 \sim 30$ K for T = Ru and Os, while a nonmagnetic ground state is observed for T = Fe, as is usually the case for Kondo semiconductors (or insulators).$^{1–3}$ Since the magnetic susceptibility ($\chi$) systematically decreases on changing the transition metal element in the order from T = Ru to Os to Fe, the 4$f$ electron state is located in the vicinity of the boundary between localized and non-localized states, as expected from the Kondo semiconducting behavior. Thus, the c$\ell$ hybridization between d- and 4$f$-electrons must play a key role for their low-temperature properties involved in the origin of the AFM order.

The AFM order is very unusual. $T_0$ is quite high for a usual Ce-based intermetallic compound when taking into account, for instance, the long distance of 5.2 Å between neighboring Ce ions.$^2$ The magnetic anisotropy is also unusual. Although the easy axis is the $a$ axis with the large magnetic anisotropy ($a \gg b$), the AFM ordered moment ($m_{\text{AFM}}$) with a magnitude of $0.3–0.4 \mu_B$/Ce aligns in the $c$-axis direction.$^4$ Recently, the Rh-doping effect on CeRu$_2$Al$_{10}$ has been examined, where Rh ($4d^{10}$) has one electron more than Ru ($4d^9$).$^7,8$ On the basis of the results, we infer that $\chi$ becomes more Curie–Weiss like and decreases drastically below $T_0$ for $H||a$. These results imply that the Rh-doping breaks $m_{\text{AFM}}||c$ and $m_{\text{AFM}}||a$ is indeed realized instead. In order to clarify the spin alignment and the critical Rh concentration $x_c$, from a microscopic point of view, we performed zero-field $\mu$SR on Ce(Ru$_{1-x}$Rh$_x$)$_2$Al$_{10}$ ($x = 0, 0.03, 0.05,$ and 0.1).

Figure 1 shows the temperature dependence of the internal magnetic field ($H_{\text{small}}$, $H_{\text{large}}$) at the muon site for Ce(Ru$_{1-x}$Rh$_x$)$_2$Al$_{10}$. Here, $H_{\text{small}}$ ($H_{\text{large}}$) represents the smaller (larger) component of internal magnetic fields. For the undoped sample, $H_{\text{small}}$ shows non-mean-field-like behavior, while $H_{\text{large}}$ increases below $T_0$ and saturates to a value of about 180 G below about 15 K. On the other hand, for Rh-doped samples, $H_{\text{large}}$ reaches about 800 G at low temperatures. This suggests the spin-flop transition from $m_{\text{AFM}}||c$ to $m_{\text{AFM}}||a$ on the basis of our dipolar field calculation at the suggested muon site, which is consistent with the bulk properties.$^7,8$ Since there is no Rh-concentration dependence in $H_{\text{large}}$ for $x > 0.03$, the boundary of the different magnetic ground states is identified at around $x \sim 0.03$. The drastic change of the magnetic ground state by such a tiny Rh doping indicates that the magnetic structure in CeRu$_2$Al$_{10}$ is not robust and can be quite easily tuned using external perturbations such as $d$-electron doping. On the basis of previous experimental results from thermal electric power,$^9$ neutron scattering,$^4$ and NQR measurements,$^{10}$ the non-mean-field-like behavior of $H_{\text{small}}$ for the $x = 0$ sample is attributed to the Fermi contact field from the polarized electrons at the muon site, while the $T$ dependence of $H_{\text{large}}$ for the Rh-doped samples is still an unresolved question; whether it results from the Fermi contact field or from the unusual ordering of Ce$^{3+}$ moments should be clarified by future neutron scattering experiments.

References

**μSR study on CeRu$_2$Al$_{10}$ under pressure**

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CeT$_2$Al$_{10}$ ($T =$ Fe, Ru, and Os), which has the orthorhombic YbFe$_2$Al$_{10}$-type structure, can be categorized as a Kondo semiconductor and is of interest because of numerous anomalous electronic behaviors due to the $e - f$ hybridization effect.$^{1 - 3}$ For instance, the antiferromagnetic (AFM) transition temperature ($T_0$) is quite high compared to that usually expected for Ce-based intermetallic compounds,$^2$ and the spin alignment in the AFM ordered state is $m_{AF} \parallel c$, although the easy magnetization axis is the $a$-axis with the large magnetic anisotropy $a \gg c \gg b$.$^{4,5}$ In addition, the magnetic structure is easily changed from $m_{AF} \parallel c$ to $m_{AF} \parallel b$ or $m_{AF} \parallel b$ to $m_{AF} \parallel c$ by application of non-magnetic La doping, magnetic field, or external pressure.$^6$ Furthermore, tiny $d$-electron doping, such as Rh(4$d^5$)-doping in Ru(4$d^7$), easily breaks the $m_{AF} \parallel c$ ordering, and $m_{AF} \parallel a$ ordering is realized instead.$^7$ These results indicate that the magnetic structure of CeRu$_2$Al$_{10}$ is not robust and is easily tuned by such perturbations.

Regarding the effect of pressure on CeRu$_2$Al$_{10}$, $T_0$ is enhanced up to about $P = 2$ GPa, beyond which it exhibits a slight decrease; at approximately $P_c = 4$ GPa, CeRu$_2$Al$_{10}$ exhibits a first-order-like transition from the AFM Kondo semiconducting state to the non-magnetic Fermi liquid state.$^2$ Since $T_0$ is enhanced at low pressures, the bulk magnetization is expected to also be enhanced by pressure. However, the magnetization is strongly suppressed by pressure.$^8$ At $P = 1$ GPa, the magnetization becomes nearly half of that at ambient pressure. That is, the pressure enhances $T_0$ but suppresses the magnetization. These results seem to contradict each other. In order to verify whether $m_{AF}$ is suppressed on applying pressure, we performed μSR experiments on CeRu$_2$Al$_{10}$ under pressures up to about $P = 0.6$ GPa. From the μSR experiment, the pressure dependence of $m_{AF}$ can be clarified through the change in the internal magnetic field at the muon site. To our knowledge, this is the first attempt at investigating the effect of pressure on the $m_{AF}$ in CeT$_2$Al$_{10}$ ($T =$ Ru, Os).

Figure 1 shows the temperature dependence of the initial asymmetry of CeRu$_2$Al$_{10}$ at ambient pressure and at $P = 0.6$ GPa. The initial asymmetry is extracted from transverse field (TF) measurements by observing bulk properties. The temperature dependence of the initial asymmetry at ambient pressure is consistent with our previous μSR experiment.$^7$ As seen below for $T = 10$ K, the temperature dependence of the asymmetry is different between the data at ambient pressure and at those $P = 0.6$ GPa, indicating that the evolution of the $m_{AF}$ is different between these two cases. This would be attributed to a change in the hyperfine process through the Fermi contact field caused by pressure.$^7$ We aimed to clarify a change in the magnitude of $m_{AF}$ under pressure. However, owing to the fraction of stopping muons in the sample being less and the strong restriction of the time resolution of the double-pulsed muon beam, we could not observe the muon spin precession, and thus, from the zero field measurement, no quantitative information on $H_{int}$ could be achieved directly under ambient or high pressure. In order to obtain detailed information on $m_{AF}$, further studies are needed.

**Fig. 1.** Temperature dependence of the initial asymmetry of CeRu$_2$Al$_{10}$ at ambient pressure and at $P = 0.6$ GPa. 

- The initial asymmetry is extracted from transverse field (TF) measurements.
- The decrease in the initial asymmetry below $T_0$ is a good indicator of the appearance of a magnetically ordered state. We clarified that $T_0$ is enhanced by pressure.

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References
Muon LCR measurements for organic magnets based on [Pd(dmit)\textsubscript{2}] metal-complex molecules\textsuperscript{\textdagger}

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Magnetic ground states of quasi two dimensional (Q2D) triangular Heisenberg antiferromagnetic (AF) systems are of great interest. Magnetic frustration arising from the triangular exchange network suppresses the AF order. This kind of quantum-spin states without either long-range magnetic order or lattice symmetry breaking is named quantum spin liquid (QSL) state. Theoretically, this QSL state has been studied extensively and many classes of theoretical models such as $Z_2$ spin liquid, spinon fermi surface (SFS) and spin-bose metal are proposed. Although experimentalist have sought real model materials with QSL state for quite some time, only a few candidate materials are known to this date.

A series of organic salts, \((\text{Cation})[\text{Pd(dmit)}\textsubscript{2}]\) (dmit=1,3-dithiole-2-thione-4,5-dithiolate) has triangular exchange network \(S=1/2\) unit of molecular dimers\textsuperscript{1}). The strength of the spin frustration can be controlled by the choice of cation and most of materials belonging to this family undergo AF states. In such triangular magnets, geometrical frustration is though to play an important role on the magnetic states as the AF transition temperatures is found to increase proportionally to the deviation from the regular triangular exchange networks. It is thought that EtMe\textsubscript{3}Sb[\text{Pd(dmit)}\textsubscript{2}] do not show any AF order due to strong spin frustrations. These materials have almost regular triangular exchange networks with exchange interaction \(J\) of the order of 200 to 300 K.

Recently, we have performed longitudinal field (LF) \(\mu\)SR measurements on EtMe\textsubscript{3}Sb[\text{Pd(dmit)}\textsubscript{2}] a QSL candidate. Preliminary analysis suggest that field dependence of muon relaxation rate, \(\lambda\) is proportional to \(1/\sqrt{B}\) behaviour in a field range of \(1 \le B_{\text{ext}} \le 1000\) Gauss at low-temperatures. Such a behaviour is expected from spins diffusing along a one-dimensional direction. In an ideal 1D spin system model, the field dependence of \(\lambda\) is approximately described as follows:

\[
\lambda(\omega) = \frac{A^2}{4} \frac{1}{\sqrt{2D_\parallel} \omega}
\]

where \(D_\parallel\) is the diffusion rate of spinon, \(\omega = \gamma_eB\) is the Larmor frequency and \(A\) is the scalar hyperfine coupling constant\textsuperscript{3}). In order to determine \(D_\parallel\) and its temperature dependence quantitatively, a Muon level-crossing resonance measurements (LCR) of the \(\text{Pd(dmit)}\textsubscript{2}\) molecule was made. For this purpose, we used (EtMe\textsubscript{3}Sb)[\text{Pd(dmit)}\textsubscript{2}], a non-magnetic material, instead of the neutral \(\text{Pd(dmit)}\textsubscript{2}\) molecule due to chemical stability issues.

Results of the longitudinal field dependence in (EtMe\textsubscript{3}Sb)[\text{Pd(dmit)}\textsubscript{2}] at 10K and 300K together with fitted repolarization curves.\textsuperscript{\textdagger}

Further LCR measurements, in magnetic fields up to 5 Tesla in the Hi-Fi magnet at the ISIS muon facility have recently been awarded and will complete this study to understand the Muonium sites on a \(\text{Pd(dmit)}\textsubscript{2}\) molecule and the hyperfine coupling constant associated with such sites.

References
Study on static and dynamic spin-crossover tripyrazolylmethane iron(II) complexes by using μSR spectroscopy

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Transition-metal complexes have attracted much attention from the viewpoints of magnetic, redox, and optical properties originating from d spins. In particular, complexes with a $d^{5}-d^{1}$ configuration have the possibility of undergoing spin crossover transitions between low-spin (LS) and high-spin (HS) states, showing bistability with color and magnetic susceptibility changes. Spin-crossover phenomena can be classified into two types according to the time window of a measurement, (i) static spin crossover, which is often observed with a thermal hysteresis, and (ii) dynamic spin crossover, which sometimes shows an equilibrium obeying the van’t Hoff equation (i.e., spin equilibrium).

A large number of spin-crossover iron(II) complexes have been developed and their spin dynamics has been investigated by means of Mössbauer spectroscopy, nuclear equilibrium obeys the van’t Hoff equation (i.e., spin equilibrium). However, the μSR spectroscopy has scarcely been applied to the study of dynamic spin-crossover systems. To investigate the rapid spin equilibrium in detail, we selected iron(II) complexes containing tripyrazolylmethane ligands (Fig. 1), [Fe{(pz)$_3$CH}$_2$](BF$_4$)$_2$ (I; pz = 1-pyrazolyl) and [Fe{(pz)$_3$CH}$_2$]{(3,5-Me$_2$pz)$_3$CH}](BF$_4$)$_2$ (2), which show dynamic and static spin crossover, respectively, on $^{57}$Fe Mössbauer spectroscopy.1,2) Similar molecular structures of 1 and 2 facilitate μSR study. Thus, we can expect that positive muons would be trapped at the same sites in their compounds.

Polycrystalline samples of 1 and 2 were wrapped in silver foil and stuck to a silver plate. We used He-flow cryostats in the entire temperature range. Such a decay is presumably caused by the spin fluctuation of the equilibrium between the HS and LS. The detailed analysis is now in progress.

![Fig. 1. Structural formula of [Fe{(pz)$_3$CH}$_2$](BF$_4$)$_2$ (1) and [Fe{(pz)$_3$CH}$_2$]{(3,5-Me$_2$pz)$_3$CH}](BF$_4$)$_2$ (2).](image)

decoupled by a field of 1000 Oe. The behavior indicates the formation of paramagnetic muonium species in pyrazolyl rings. The fluctuation can be completely decoupled at 3000 Oe.

On the other hand, the initial asymmetry in the HS states (1: 475 K; 2: 300 K) is lower, even above 1000 Oe, compared to those in the LS states, suggesting the existence of other strong fluctuations. The temperature spectra of 1 and 2 in LF = 3000 Oe drastically changed with a change of temperature, and the relaxation rates ($\lambda_f$) derived from strong fluctuations increased on heating. We found that the temperature dependences of $\lambda_f$ strongly correlate with $\chi_mT$ vs $T$ profiles (Fig. 2). Thus, the results clarified that μSR spectroscopy using a high LF can detect spin transitions in both dynamic and static spin-crossover complexes.

In the ZF-μSR spectra, there is an apparent difference between temperature dependences of the initial asymmetries of 1 and 2. The initial asymmetry of 1 decreased around the spin transition, although that of 2 was constant over the entire temperature range. Such a decay is presumably caused by the spin fluctuation of the equilibrium between the HS and LS.

![Fig. 2. Temperature dependences of relaxation rates ($\lambda_f$) under LF = 3000 Oe for (a) 1 and (b) 2. The $\lambda_f$ plots are superimposed on $\chi_mT$ vs $T$ plots.](image)

References
Na dynamics in the quasi-one-dimensional ionic conductor NaM$_2$O$_4$ ($M$=Ti and V)

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Fig. 1. Crystal structure of NaM$_2$O$_4$.

In the NaM$_2$O$_4$ lattice with a CaFe$_2$O$_4$-type orthorhombic structure, the Na$^+$ ions are located at the center of a one-dimensional (1D) tunnel along the $b$-axis, which is formed by 1D double chains consisting of edge-sharing MO$_6$ octahedra ($M$: transition metal) (see Fig. 1). The physical properties of NaM$_2$O$_4$ are reported to strongly depend on $M$. In particular, it is very important to clarify their Na$^+$-ion conductivity ($\sigma$$_{Na}$) and/or Na$^+$-ion diffusion coefficient ($D$$_{Na}$) when using NaM$_2$O$_4$ as a solid electrolyte in an all-solid-state Na-ion battery.

Following the preliminary report on NaV$_2$O$_4$)1), we explain here in the results of $\mu^+$SR measurements on NaM$_2$O$_4$ ($M$=Ti and V). The former is a semiconductor with a small band gap$^3)$, while the latter is a half metal with anisotropic electric conductivity$^4)$. Both ZF- and LF-$\mu$SR spectra were measured in the temperature ($T$) range between 145 and 500 K. The obtained spectra were fitted by a combination of an exponentially relaxing dynamic Kubo-Toyabe signal from a sample and a non-relaxing background signal from a titanium sample holder.

Figure 2 shows the $T$-dependences of field fluctuation rate ($\nu$), field distribution width ($\Delta$), and exponential relaxation rate ($\lambda$) for (a) NaTi$_2$O$_4$ and (b) NaV$_2$O$_4$. For NaM$_2$O$_4$, $T$ increases from 150 K, $\Delta$ slowly decreases, while $\nu$ increases rapidly particularly above 350 K. This indicates that the local nuclear magnetic field experienced by $\mu^+$ starts to fluctuate because of Na$^+$ diffusion. For NaV$_2$O$_4$, on the other hand, even at 150 K $\nu$ is comparable to that for NaTi$_2$O$_4$ at 450 K. This indicates that Na$^+$ ions diffuse even at 150 K in NaV$_2$O$_4$. The anomaly around 450 K in the $\nu(T)$ curve is probably caused by a structural phase transition.

If we assume a thermal activation process for the $T$ dependence of $\nu$, the activation energy ($E_a$) is estimated to be 350 meV for NaTi$_2$O$_4$ and 48 meV for NaV$_2$O$_4$. Since the simple Nernst-Einstein equation states that $\sigma$$_{Na}$ $\propto$ $D$$_{Na}$, where $D$ $\propto$ $\nu$, NaV$_2$O$_4$ is expected to be a good candidate for a Na$^+$-ionic conductor.

References

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Lithium-ion diffusion in novel battery materials

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Diffusion coefficient of Li+ ions ($D_{Li}$) in solids is usually evaluated by $^7$Li-NMR. However, for materials containing magnetic ions, Li-NMR provides very limited information on $D_{Li}$, because of the effect of electron spins on the spin-lattice relaxation rate ($1/T_1$). Note that positive electrode materials of Li-ion batteries all include transition metal ions to compensate charge neutrality during the Li+ intercalation and deintercalation reaction. On the contrary, $\mu^+$ sees an internal magnetic field caused by both electrons and nuclei in a zero field (ZF). Thus, $\mu^+$SR extracts the nuclear field even in such positive electrode materials by combining with weak longitudinal field (LF) measurements. For the positive electrode materials, since Li ions are known to be more mobile than $\mu^+$ due to a strong $\mu^+$-O bond, the hopping rate ($\nu$) estimated by $\mu^+$SR reflects the dynamics of the Li ions.

A solid solution system between LiCoO$_2$ and LiNiO$_2$, i.e. Li(Co$_{1-x}$Ni$_x$)$_2$O$_2$ in the rhombohedral symmetry with space group $R_3m$ is widely used in commercial Li-ion batteries. According to the previous experiment on Li(Co$_{1-x}$Ni$_x$)$_2$O$_2$ with $x = 0, 0.33, 0.67$, and $1$, $\nu$ above ambient $T$ drastically increased with increasing $x$. Since the $\nu(T)$ curve for the $x = 0.67$ sample is clearly different from that for LiNiO$_2$, we have measured ZF- and LF- spectra for the samples with $x = 0.85$, $0.90$, and $0.95$.

Figure 1 shows the $T$ dependences of the field distribution width ($\Delta$) and $\nu$ for the $x = 0.67 - 1$ samples. For all the samples, as $T$ increases from 50 K, $\Delta$ decreases linearly up to $\sim 250$ K, then looks to be $T$-independent until $\sim 400$ K, and finally decreases with further increasing $T$. Here, $\Delta$ is mainly determined by the nuclear field of Li, because $\mu^+$ locates at the vicinity of the O$^{2-}$ ion with $d_{\mu-O} = 1$ Å, but not in the Co$_{1-x}$Ni$_x$O$_6$ octahedron. As a result, $\Delta$ is not sensitive to $x$. On the other hand, for the present three samples, $\nu$ increases with $T$ until 225 K, then decreases with $T$ until 450 K, and then increases again with $T$.

Note that a stoichiometric LiNiO$_2$ has never been obtained by a solid state reaction technique. A small amount of Ni ions are always located in the Li plane due to the similarity in ionic radii between Li$^+$ and Ni$^{3+}$ (see Fig. 2). Thus, the correct formula of LiNiO$_2$ is (Li$^{1-y}$Ni$_y^{3+}$)(Ni$^{3+}$)$^{y}_y$O$_2$ with $y \leq 0.02$. The Ni ions in the Li plane suppress Li-diffusion. But, Co substitution for Ni is known to reduce $y$. Thus, it is expected that Li-diffusion increases with the Co content, against to the present result. In order to further understand the diffusion nature, it is highly required to investigate the Li-deficient samples, which is prepared by the Li$^+$ deintercalation reaction, with $\mu^+$SR, because the direct jump of Li$^+$ from the regular site to the nearest deficient site is predominant for Li-diffusion.

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Muon Detection of Spin-Polarized Conduction Electrons Induced by Circularly-Polarized Direct Band Excitation in n-type Si

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We investigated the possibility that muon spin-relaxation can be used to detect the spin-polarization of conduction electrons in the indirect bandgap semiconductor Silicon. Spin-polarized conduction electrons can be detected optically in direct bandgap semiconductors (i.e., GaAs) through known selection rules at the bandgap. However, Silicon, arguably the most technologically important semiconductor, has no optical analog due to its indirect bandgap. μSR has intrinsic spin-polarization sensitivity and, if able to detect spin polarization in Silicon, may advance Si spintronics. Implanted muons in Si interact with electrons to form bound muonium states. In a mechanism originally proposed by Torikai1), anti-parallel conduction electrons may exchange with parallel bound electrons in triplet muonium converting it to singlet muonium which would be detectable by enhanced depolarization of the muon spin.

Earlier we demonstrated that μSR was sensitive to laser-injected spin-polarized electrons in n-GaAs2). Circularly-polarized, 7 ns duration, laser pulses with photon energy tuned below bandgap injected 50% spin-polarized electrons throughout the bulk of a 350 micron thick wafer. Experiments at all B-field and wavelengths are consistent with the laser-excitation enhancing spin-relaxation of muons in only one species, Mu-. The amplitude reduction is larger for anti-parallel polarized conduction electrons consistent with the proposed exchange mechanism.

We performed similar experiments on n-Si. Although it is generally accepted that optical spin-injection is forbidden by the indirect bandgap of Si, a recent density functional theory calculation by Nastos, et al.3) shows that at the direct bandgap, the degeneracy factors for the transitions are as shown in Fig. 1 (left) and lead to a degree of spin polarization vs photon energy shown in Fig. 1 (right).

Samples were 300 μm thick wafers of n-Si with evaporated Au and ITO (Indium Tin Oxide) electrodes for voltage-biased transport of the injected electrons. Muons were implanted in the 100 μm region closest to the laser-excitation side of the sample. Typical data are as shown in Fig. 2 (Left), for the case of B=1000 G at 20K. The laser pulse arriving at 0.8 μs induces a step-like change in the F-B asymmetry that can reduce as much as 50% of the total F-B asymmetry in <300 ns. Unlike GaAs, however, the laser-induced change affects multiple species. Three species are known in n-Si: Tetrahedral (T) muonium, bond-centered (BC) muonium, and the negative ion (T) Mu-.

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Fig. 1: Ref [4], (L) Si interband transition degeneracies for σ+ excitation. (R) Degree of Spin Polarization vs photon energy in LDA and k-p approximations.

Fig. 2. (Left) n-Si F-B Asymmetry change induced by 372 nm laser excitation. σ+ and σ− changes and best fit. (Right) σ−-σ+ best fit difference.

F-B Asymmetry vs time without laser excitation shows a fixed component and an exponentially decaying component, fitting A+Bexp(-γt). The laser-induced change (σ+Laser on) and (σ−Laser off) can be fit by ΔA+ΔB exp(-γt). Here ΔA and ΔB are both ~ -2.5%. The solid blue and red lines are the best fits to the data for σ+ and σ−. The difference between the best fit lines (σ+−σ−) is shown in Fig. 2 (right). Spin-dependent ΔA=0.073±0.082 and ΔB=−0.13±0.13 with 25M events for each laser helicity (100M events total, 50M laser off). We will need significantly higher statistics (15X) to resolve this effect at -0.02% F-B asymmetry. We repeated this measurement at 12 photon energies spanning 3.32 to 3.64 eV, the spectral range in Fig. 1. The signs of ΔA− and ΔB− are opposite to each other within experimental uncertainty for all 12 photon energies although the sign of ΔA− was not always positive. The opposing signs are experimentally significant for the data set as a whole, but we have no explanation presently.

Future followup experiments will require finding ways to restrict the μSR signal to one species such as via ALC resonance, increasing signal to noise and statistics, and/or finding the optical wavelength of maximum spin-injection by some other technique (e.g. spin-polarized fluorescence).
Response of muonium to oxygen impurities in hemoglobin and other biological aqueous solutions for application to studies on hypoxia


Hypoxia, or low oxygenation, is known as an important factor in tumor biology; in cancer patients, an accurate measurement of $O_2$ concentration in specific regions may prove important in the management of treatment and outcome of the disease1). For this purpose, improved $O_2$ detection methods are required. Several trials that employ PET, MRI and EPR have been conducted1).

In this article, we propose the use of $\mu^+$ as a new sensitive method to probe the existence of paramagnetic $O_2$ in cancerous tumors in the human body. The $\mu^+$ in water is known to take the states of diamagnetic $\mu^+$ such as $\mu^+\text{OH}$ (60%), paramagnetic muonium (Mu, $\mu^+ + e^-$) (20%), and a missing fraction (20%). In Mu, a half becomes an ortho state with spin 1, providing a spin rotation signal with a precession pattern (1.39 MHz/G) that is 100 times faster than that of diamagnetic $\mu^+$. There have been experimental studies on the oxygen-dissolving effects of the spin relaxation rate ($\lambda_{\text{Mu}}$) of paramagnetic Mu in pure water due to electron spin exchange interactions with paramagnetic $O_2$ in water; the rate change of $\lambda_{\text{Mu}}$ against $O_2$ concentration is $(1.8 \pm 0.1) \times 10^{10} \text{ (litr/mol) } s^{-1}$2). The sensitivity for $O_2$ to $\mu$ in pulsed $\mu$SR becomes 0.5 $\times 10^{-6}$ ~ 0.5 $\times 10^{-4} \text{ (mol/litr)}$. The $\lambda_{\text{Mu}}/(\text{mol/sL})$ becomes 0.4 $\times 10^{-3}$ ~ 0.4, which perfectly corresponds to the condition in hypoxia. The unsolved problem regarding the muon method is the background factor in tumor biology; in cancer patients, an accurate measurement of $O_2$ concentration in specific regions may prove important in the management of treatment and outcome of the disease.

Before measuring the $O_2$ dependence of $\lambda_{\text{Mu}}$, its dependence on the concentration of each biological molecule was systematically measured. The decreasing rate of $\lambda_{\text{Mu}}$ was obtained as 25 MHz/(g/litr) for albumin, 1 MHz/(vol. %) for serum and 3.1 MHz/(g/litr) for Hb.

Then, by determining the relevant concentration for each molecule, the $O_2$ dependence of $\lambda_{\text{Mu}}$ was measured. The results for these three aqueous solutions are summarized in Fig. 1. The $\lambda_{\text{Mu}}$ in these biological aqueous solutions was found to experience an almost similar change in relaxation against increasing $O_2$ concentration as that for pure water. For Hb, $\lambda_{\text{Mu}}$ was expected to exhibit a different behavior since the increase in $O_2$ makes decrease of magnetic Deoxygenated-Hb and increase of non-magnetic Oxygenated-Hb causing the decrease in $\lambda_{\text{Mu}}$. By solving Hill’s equation3), such an effect can be predicted. The obtained result is very encouraging for application to hypoxia; there is one-to-one correspondence between $\lambda_{\text{Mu}}$ and $O_2$ concentration, which allows the unique determination of $O_2$.

Before carrying out the clinical application of the proposed method to studies on hypoxia, it is important to conduct systematic studies on the behavior of $O_2$ impurities in various other biological aqueous systems, especially with high-concentration Hb. On the other hand, by using the concept of the advanced $\mu^+$ beam, which is an accelerated beam of ultra-slow muon, one can expect the stopping region confinement to be 10 $\mu$m at cm-region depth of the human body. Thus, we are approaching a realization of the advanced cancer inspection by using muons appears possible.

Fig. 1 Summary of dependence on $O_2$ concentration of muonium relaxation rates in pure water and water solution of 0.04 wt. % albumin, 0.5 vol. % serum and 0.07 wt. % hemoglobin.

References
Development of room-temperature thermal-muonium-emitting material for ultra-slow muon production


Ultra-slow muons, which are positive muons having an energy of a few electron volts, are useful tools for producing variable-energy muon beams with extraordinarily small energy spread by accelerating them through an electrostatic field. This technique will extend \( \mu \)SR (muon spin rotation and relaxation) studies to thin films, surfaces and interfaces, and nano-structures, which has yet been achieved by the conventional \( \mu \)SR technique using surface muons. This technique has also attracted attention for use in measuring the muon anomalous magnetic moment \( g-2 \) and electric dipole moment at J-PARC\(^1\), which requires an intense muon beam having an extremely small transverse momentum.

Ultra-slow muon production has been realized by two-photon resonant laser ionization of thermal muonium atoms (\( \mu^+ e^- \), Mu) emitted into vacuum, where tungsten foils heated to 2300 K have been employed as a Mu-emitting material\(^2\).

On the other hand, silica (\( \text{SiO}_2 \)) powder is known as a Mu-emitting material at room temperature\(^3\). The room-temperature target resulting in even lower Mu energies than that from a hot tungsten target (2300 K → 300 K) has the following significant merits:

- Experimentally easy to handle in terms of the operation temperature (no large radiant heat)
- Smaller emittance of the ionized source due to the lower energies
- Smaller spatial spread and smaller Doppler broadening of the resonant line for Mu excitation (as a result of the lower Mu energy distribution), leading to a more efficient use of the available laser power

Despite the many advantages, silica powder has not yet been employed for ultra-slow muon production. This is simply because powdery materials are not self-standing and are generally unfavorable in terms of handling and vacuum pumping.

In the TRIUMF S1249 experiment, we have investigated the possible use of a silica aerogel that has the same chemical composition as silica powder but is a self-standing solid with extremely low density.

In the earlier measurement of S1249, Mu emission from silica aerogel into vacuum has been successfully observed\(^4\), and the recent measurement (in Oct 2013) yielded promising results in terms of the Mu emission yields with aerogels having a surface with sub-millimeter structures such as pores (which increase surface area), e.g., laser-drilled aerogel, as shown in the insets of Fig. 1. This result indicates that Mns produced near the surface of the aerogel are essential for vacuum emission. Detailed data analysis is now in progress.

For practical-scale development, we are now preparing an ultra-slow muon beamline dedicated to the research and development of practical ultra-slow muon production with room-temperature targets at RIKEN RAL port3.

![Fig. 1. Photograph of the experimental setup of the recent TRIUMF S1249 experiment. The insets show a laser-drilled aerogel used as a Mu-emitting material (right) and the surface (left).](image)

References
Precision measurement of muonium hyperfine splitting at J-PARC; development of high-rate positron detector

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Muonium is the bound state of a positive muon and an electron. In the standard model of particle physics, muonium is considered as the two-body system of structureless leptons.

At J-PARC, we plan to measure muonium’s hyperfine splitting precisely. Our experiment has three major objectives: test of QED with the highest accuracy, precision measurement of the ratio of muon’s magnetic moment to proton’s magnetic moment, and search for CPT violation via the oscillation with sidereal variations.

The experimental methodology is microwave spectroscopy of muonium. Figure 1 shows the conceptual overview of the experiment. Spectroscopy of the energy states can be performed by measurement of positron decay asymmetry.

The uncertainty of the most recent experimental result[1] was mostly statistical (more than 90% of total uncertainty). Hence, improved statistics is essential for higher precision of the measurement. Our goal is to improve accuracy by an order of magnitude compared to the most recent experiment. For the improvement of precision, we use the J-PARC’s highest-intensity pulsed muon beam and highly segmented positron detector with SiPM (Silicon PhotoMultiplier). After the improvement of statistical precision, reduction of systematic uncertainty becomes more important to reduce systematic uncertainty. Thus, we reduce the systematic uncertainty by using a longer cavity, a high-precision superconducting magnet, and an online/offline beam profile monitor.

The detector system consists of several layers of hodoscopes and fast readout circuits with custom ASIC and FPGA-based multi hit TDC. Important requirements of the positron detector are high event rate capability and high detection efficiency. The designed muon beam intensity at J-PARC MUSE H-Line is $1 \times 10^8 \, \mu^+$/s.

To establish the optimal design of the positron detector, we developed GEANT4-based Monte-Carlo simulation tools. Figure 2 shows a simulated muon stopping distribution in the target gas chamber. Under realistic conditions, the highest instantaneous event rate is about 3 MHz/cm². The resonance lineshape was calculated numerically, and the systematic uncertainty of the resonance frequency due to the detector specification was evaluated as a function of the detector performance. Based on the results of the simulation study, a new prototype of the detector is under development and a test experiment with high-intensity pulsed muon beam at J-PARC was performed in February of 2014.

Fig. 1. Experimental overview

Fig. 2. Simulated muon stopping distribution

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Cross-section measurement of the $^{248}$Cm($^{19}$F,$5\alpha$)$^{262}$Db reaction

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The isotope $^{262}$Db ($T_{1/2} = 33.8$ s$^{1}$) is used in the chemical studies of element 105, Db. One of the commonly used direct synthetic routes of $^{262}$Db is the reaction of $^{19}$F with $^{248}$Cm. Few cross sections are available for this reaction, but there is a large discrepancy among these data. Dressler et al.$^{2}$ reported a production cross section of 0.26 ± 0.15 nb at 106.5 MeV. Nagame et al.$^{3}$ reported a cross section of 1.3 ± 0.4 nb at nearly the same energy, 106 MeV. The same group also reported a maximum cross section of 1.5 ± 0.4 nb at 103 MeV.$^{4}$ Thus, the cross-section data are inadequate, and the optimal beam energy to produce $^{262}$Db is not clear. Therefore, we plan to measure the excitation function of the $^{248}$Cm($^{19}$F,$5\alpha$)$^{262}$Db reaction to effectively produce $^{262}$Db for the future chemical experiments of Db. First, in this work, we produced $^{262}$Db at 102 MeV.

A $^{248}$Cm$_2$O$_3$ target of 460-µg/cm$^2$ thickness and 9-mm diameter was prepared by electrodeposition onto a Be foil of 1.8-µg/cm$^2$ thickness. $^{nat}$Gd$_2$O$_3$ of 23-µg/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,$x\alpha$)$^{170}$Ta reaction. A $^{19}$F$^+\gamma$ beam of 124.9 MeV supplied by the AVF cyclotron was passed through a 3.2-µg/cm$^2$ Be vacuum window, 0.10 mg/cm$^2$ of He cooling gas, and the Be backing foil before it entered the target. The primary beam energy was measured using time-of-flight apparatus. The beam energy at the middle of the target was 101.9 MeV, and the energy degradation in the target was estimated to be 1.0 MeV. The average beam intensity was approximately 440 pA.

The reaction products recoiling out of the target were stopped in 102.0-kPa He gas in the recoil chamber, attached to KCl aerosols generated by sublimation of KCl powder at 640°C, and continuously transported with a flow rate of 2.5 L/min to the rotating wheel detection system MANON (Measurement system for Alpha-particle and spontaneous fission ON-line) through a 8.6-m Teflon capillary with 1.59-mm inner diameter. MANON has 7 pairs of Si PIN photodiodes, and the counting efficiency of each photodiode was 38%. In MANON, the aerosols were deposited on Mylar foils of 0.5-µm thickness, 40 of which were set on the periphery of a rotating wheel 420 mm in diameter. The gas-jet transport efficiency was estimated to be 53.5 ± 2.0% by comparing the collected yields of $^{170}$Ta on the 10-µm Be catcher foil placed immediately behind the target and on the Al foil set to the position of the Mylar foil in MANON. After the aerosol collection, the wheel was stepped at 20-s nominal interval to move the foils between the detector pair. Because the long-lived activities were accumulated during the irradiation, the wheels containing the Mylar foils were replaced every 6 h. While exchanging the wheels, the aerosols were collected on the glass filters in the collection chamber, and the glass filters were subjected to γ-ray spectrometry to verify whether the yields of $^{170}$Ta were stable.

Figure 1 shows the sum of the measured α-spectra in the 2nd-7th top detectors, corresponding to a time interval of 20–140 s. A beam dose of 1.91 × 10$^{17}$ was accumulated. In Fig. 1, α events of $^{262}$Db (α branch $b_\alpha = 48\%$, α energies $E_\alpha = 8.46$ MeV (70%) and 8.68 MeV (30%$^{1}$)) and its daughter nuclide $^{258}$Lr ($T_{1/2} = 3.9$ s, $b_\alpha = 97.4\%$, $E_\alpha = 8.565, 8.595, 8.621$, and 8.654 MeV$^{2}$) are clearly recognized. However, α lines of by-products such as Po isotopes are also observed in the α-energy region of $^{262}$Db and $^{258}$Lr. Analyses of the time-correlated α-α pairs are needed to extract the decay chains of $^{262}$Db →$^{258}$Lr →. Further analyses of the obtained data are in progress.

![Figure 1](image-url)

**Fig. 1.** Sum of α spectra measured in the 2nd–7th top detectors of MANON.

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Excitation functions for production of Nb and Ta isotopes in the $(d,x)$ reactions on $^{nat}Zr$ and $^{nat}Hf$ up to 24 MeV

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The isotopes $^{95\alpha}Nb$ ($T_{1/2} = 34.991$ d) and $^{179}Ta$ ($T_{1/2} = 1.82$ y) are useful radiotracers for the basic studies of the element 105, Db. We have investigated the production of these radiotracers by the activation of $^{nat}Zr$ and $^{nat}Hf$ with a 14-MeV proton beam supplied by the RIKEN AVF cyclotron.1 From the AVF cyclotron, a deuteron beam is also available.2,3 Activation by the deuteron beam is one of the widely used and well-studied methods to produce the radiotracers. However, the production cross sections of $^{95\alpha}Nb$ by the $(d,x)$ reaction are scanty compared to those of the $(p,x)$ reactions. Furthermore, the cross sections of $^{179}Ta$ in the $(d,x)$ reaction have not been reported. In this work, we measured the excitation functions for the production of $^{95\alpha}Nb$ and $^{179}Ta$ as well as other isotopes in the $(d,x)$ reactions on $^{nat}Zr$ and $^{nat}Hf$.

The excitation functions were measured with a stacked-foil technique. For the measurement of the cross sections of Nb isotopes, thin foils of $^{nat}Zr$ (20 $\mu m$ thickness), $^{nat}Ti$ (20 $\mu m$ thickness), and $^{nat}Ta$ (20 $\mu m$ and 10 $\mu m$ thickness) were stacked alternately and used as a target. The $^{nat}Ti$ foils were used to determine the beam energy and intensity by measuring the excitation function of the $^{nat}Ti(d,x)^{18}V$ reaction, and the $^{nat}Ta$ foils were also used as the energy degrader. For measurement of the cross sections of Ta isotopes, thin foils of $^{nat}Hf$ (25 $\mu m$ thickness) and $^{nat}Ta$ (20 $\mu m$ thickness) were stacked alternately. The size of all the foils was $15 \times 15$ mm$^2$. Both stacks were irradiated by the 24-MeV deuteron beam supplied by the AVF cyclotron for 30 min. The beam was collimated to a diameter of 9 mm, and the average beam currents were 0.48 $\mu A$ and 0.46 $\mu A$ for the Zr/Ti/Ta and Hf/Ti stacks, respectively. After irradiation and proper cooling, $\gamma$- and X-rays of each foil were measured by the Ge detectors.

The production cross sections were derived by the well-known activation formula.4 The beam energies in the individual target foils were calculated with the SRIM-2008 program.5 The experimental data were compared with the cross section data calculated by the TALYS-1.4 code.6

The cross sections of $^{90g,91m,92m,95m,95\alpha}Nb$, $^{95,97}Zr$, and $^{87m,87g,88}Y$ were measured in the $^{nat}Zr(d,x)$ reactions, whereas the production cross sections of $^{175,176,178,179,180}Ta$ and $^{175,179m,2,180m,181}Hf$ were measured in the $^{nat}Hf(d,x)$ reactions. Figure 1(a) shows the excitation function of the $^{nat}Zr(d,x)^{95m+\alpha}Nb$ reaction. In Fig. 1(a), the cross sections reported by Gonchar et al.7, those reported by Tárkányi et al.8, and those calculated by the TALYS code9 are compared. The data reported by Gonchar et al.7 and Tárkányi et al.8 show a similar shape of the excitation function with a systematically higher magnitude. The TALYS code also indicates a similar shape of the excitation function but lower values than the measured ones. The cross sections of the $^{nat}Hf(d,x)^{179}Ta$ reaction were measured for the first time, as shown in Fig. 1(b). The measured excitation function exhibits the maximum cross section of $489 \pm 50$ mb at $21.1 \pm 0.4$ MeV. Again, the calculated cross sections by TALYS indicate lower values, though the shape of the excitation function is similar.

Thick-target yields of $^{95m,96}Nb$ and $^{179}Ta$ were deduced from the measured cross sections and the stopping power given by the SRIM-2008 program.5 The deduced yields for beam energies up to 24 MeV were 1.3, 0.40, and 0.21 MBq/(µA-h) for $^{95m}Nb$, $^{95\alpha}Nb$, and $^{179}Ta$, respectively.

Fig. 1. Excitation functions of (a) $^{nat}Zr(d,x)^{95m+\alpha}Nb$ reaction and (b) $^{nat}Hf(d,x)^{179}Ta$ reaction.

References
Production cross sections of \((d,x)\) reactions on natural irons†

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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 the production cross sections of deuteron-induced radionuclides from various target elements because measured data of the \((d,x)\) processes are limited compared to those of \((p,x)\) processes. A survey of existing literature shows that several investigations have been conducted for the \(^{56}\text{Fe}(d,x)\) reactions, leading to various applications. The formation of the \(^{55}\text{Co}\) radionuclide via the \(^{56}\text{Fe}(d,x)\) reaction is useful in PET imaging procedures, especially for diagnosing slower metabolic processes. It also plays an important role as a label for bleomycin in diagnostic nuclear medicine, and more recently, in some cardiac and cerebral studies. Several authors successfully applied \(^{55}\text{Co}\) as a PET imaging agent in studies of ischemic stroke for quantifying cerebrospinal fluid kinetics in the brain, and they suggested that its effective clinical use is limited up to 48 h because of the production of the \(^{56}\text{Co}\) contaminant. \(^{55}\text{Co}\) was also applied as a potential renal imaging agent through the dynamic PET imaging of animal renal functions. Therefore, accurate determination of the production cross sections of the \(^{56}\text{Fe}(d,x)\) \(^{55}\text{Co}\) reaction is required because of its great importance in various practical applications, especially in nuclear medicine.

The objective of the present study was to report the latest cross sections of the \(^{56}\text{Fe}(d,x)\) \(^{55}\text{Co},\,^{56,58}\text{Mn},\,^{51}\text{Cr},\,^{53}\text{Fe}\) 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.3. A brief description of the model codes used in this work is also available elsewhere. Owing to the space limitation of this report, we present only the \(^{nat}\text{Fe}(d,x)\) \(^{55}\text{Co}\) cross sections and the deduced yield in Figs. 1 and 2, respectively. Measured cross sections with an overall uncertainty of about 12% are listed in Ref.3. The cross-sections were normalized by using the \(^{nat}\text{Ti}(d,x)\) \(^{48}\text{V}\) monitor cross sections recommended by IAEA. Measured data were critically compared with the available literature data, and an overall good agreement was found. However, only partial agreements were obtained with the data extracted from the TENDL-2012 library based on the TALYS code. The deduced thick-target yields indicate that a low-energy (<13 MeV) cyclotron and a highly enriched \(^{56}\text{Fe}\) target could be used to obtain the high purity product \(^{55}\text{Co}\), which is a long-lived positron emitter used in clinical applications.

Fig. 1. Excitation function of the \(^{nat}\text{Fe}(d,x)\) \(^{55}\text{Co}\) reaction.

Fig. 2. Physical thick target yields for the \(^{55}\text{Co}\) radionuclide.

References

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Deuteron activation cross sections for monitor reactions

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Structural materials in fusion energy devices like ITER are expected to be exposed to intense neutron flux. Therefore, material tests are important in fusion energy technology. The International Fusion Material Irradiation Facility (IFMIF) is a candidate facility for material tests. Intense neutrons consisting of a peak around 15 MeV are planned to be produced in IFMIF using the $^7\text{Li}(d,n)$ reaction with intense (125 mA + 125 mA) deuteron beams that are accelerated to 35 to 40 MeV by two linear accelerators1). The prototype is under construction in Rokkasho, Japan within IFMIF Engineering Design Activities (IFMIF/EVEDA). In addition to generating high energy tail $(d,n)$ neutrons up to 55 MeV, the deuteron beams also activate the surrounding materials of the test facility. To perform activation calculations2) for radiation safety, it is necessary to measure the radioisotope production cross sections for deuteron induced reactions. Accordingly, a deuteron induced reaction sublibrary was added to the latest version of the Fusion Evaluated Nuclear Data Library (FENDL-3.0)3). Deuteron-induced reactions could also be useful for efficient radioisotope production. For various applications, we have started the measurements of radioisotope production cross sections for various deuteron-induced reactions by the AVF cyclotron of the RIKEN RIBF.

Radioisotope production cross sections for charged-particle induced reactions are often measured through monitor reactions. Recommended cross sections of various monitor reactions are distributed from the IAEA Nuclear Data Section4,5), and we have also adopted their recommended $^{27}\text{Al}(d,x)^{24}\text{Na}$ and $^{nat}\text{Ti}(d,x)^{18}\text{V}$ cross sections in our experimental studies6,7).

In addition to the best estimate of the cross sections, their uncertainties also become important for modern applications of nuclear reaction cross sections. This point has been stressed on for many decades for low energy neutron-induced reaction applications in relation to critical and radiation safety, and experimentalists are urged to perform error propagation and its documentation properly8). This is also a common issue for people who report charged-particle induced reaction cross sections for applications. The recommended cross section for the monitor reaction is a major source of the correlated uncertainty in various experimental works, and its uncertainty must be well-known prior to the error propagation. For the standard neutron-induced reactions like $^{235}\text{U}(n,f)$, IAEA standard cross sections are provided with their uncertainties and covariance matrices9). However, we currently assume an uncertainty of 5% in the IAEA recommended cross sections in its error propagation to our measured cross sections because their uncertainties are not provided. This issue is currently being discussed in an IAEA Co-ordinated Research Project10). However, we decided to determine the uncertainties in the monitor reaction cross sections by ourselves for more appropriate error propagation in our future deuteron-induced isotope production cross section experiments. The purpose of this work is to determine the cross sections and their uncertainties for three monitor reactions $^{27}\text{Al}(d,x)^{24}\text{Na}$, $^{nat}\text{Ti}(d,x)^{18}\text{V}$, and $^{nat}\text{Cu}(d,x)^{65}\text{Zn}$ by using the stacked target activation technique.

A target stack consisting of Al foils (25 µm and 50 µm thick), Ti foils (20 µm thick), and Cu foils (12.5 µm and 25 µm thick) was prepared and irradiated by a deuteron beam (about 200 nA) extracted from the AVF cyclotron of the RIKEN RIBF for two hours. In order to determine the cross sections without reference cross sections for the monitor reactions, we provided an electric current of exactly 200 nA to the target holder and measured the electric current by a current integrator. We have confirmed that the current integrator may be calibrated by a very small correction factor (about 0.995). After the irradiation, the target stack was disassembled, and the gamma activity measurement was started 4.25 hours after the end of irradiation by using a germanium detector calibrated by a multiple gamma ray emitting point source covering the gamma energy range between 60 and 1836 keV. The off-line measurement is ongoing, and we plan to report the cross sections with well-determined uncertainties for the three monitor reactions $^{27}\text{Al}(d,x)^{24}\text{Na}$, $^{nat}\text{Ti}(d,x)^{18}\text{V}$, $^{nat}\text{Cu}(d,x)^{65}\text{Zn}$ as well as other useful reactions like $^{nat}\text{Cu}(d,x)^{64}\text{Cu}$ for positron-emitter production application.

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Solvent extraction of tungsten from oxalic acid solution with Aliquat 336 toward chemical studies of seaborgium


The aqueous chemical experiments of element 106, seaborgium (Sg), have been reported by Schädel et al. in 19971) and 19982). In these experiments, the cation exchange chromatography of Sg was conducted in HF/HNO33) and HNO32) solutions. However, no chemical experiments for Sg have been reported since these experiments. Therefore, further experimental results are required for detailed discussion of chemical properties of Sg in aqueous solutions. We are planning to investigate solvent extraction behavior of Sg. Oxalic acid is a typical organic acid used as ligand for transition metals. It is reported that molybdenum (Mo) and tungsten (W), which are lighter homologs of Sg, form anionic oxalate complexes and are extracted into an organic phase with ion-pair extractant. In this work, we investigated the extraction behavior and extracted species of W from oxalic acid solution into toluene with Aliquat 336 toward the chemical studies of Sg. The experiments were performed using 181W in tracer scale to prevent the formation of polyoxometalate complexes of W.

The radiotracer 181W (T1/2 = 121.2 d) was produced in the bombardments of 24-MeV deuteron beam supplied by the RIKEN AVF cyclotron on natTa target foils. The 181W tracer was chemically separated from the target material by an anion exchange method and stored in 1 M HCl solution.

The solvent extraction of 181W was carried out as following procedure. One µL of the tracer solution was pipetted to a 1.5 mL polypropylene tube. Then, 700 µL of the oxalic acid solution containing 0.1 M HCl/0.9 M LiCl for keeping ionic strength constant was added. The same volume of Aliquat 336/toluene solution was mixed to the aqueous solution, and the mixture was shaken by a mechanical shaker for 5 min. After centrifuging for 30 s, 500 µL aliquot of each phase was separately taken into vials, and radioactivities of both phases were measured with a Ge detector. The distribution ratio (D) of 181W was calculated using the following equation:

\[ D = \frac{(A_{\text{org}} / V_{\text{org}})}{(A_{\text{aq}} / V_{\text{aq}})} \]

where \( A_{\text{org}} \) and \( A_{\text{aq}} \) are the radioactivities of organic and aqueous phases, respectively, and \( V_{\text{org}} \) and \( V_{\text{aq}} \) are the volumes of organic and aqueous phases, respectively. The extraction kinetics was also investigated from 1.0 × 10-2 M oxalic acid with 0.1 M HCl/0.9 M LiCl into 2.0 × 10-3 M Aliquat 336/toluene solution by changing the shaking time from 3 to 3600 s.

In the experiment of the investigation of extraction kinetics, the D value of 181W became constant in shaking time longer than 30 s. This result shows that the extraction of W from oxalic acid solution with Aliquat 336 is fast. The dependence of the D values of 181W on the Aliquat 336 concentration from 1.0 × 10-2 M oxalic acid with 0.1 M HCl/0.9 M LiCl is shown in Fig. 1. The D value of W increases with increasing [Aliquat 336]. The slope of the D value of W vs. [Aliquat 336] plot in logarithmic scale is estimated to be 0.95 ± 0.08 with a weighted least-squares fitting. This indicates that extracted anionic oxalate complex of W is associated with one molecule of Aliquat 336. However, in macro scale, it was reported that W is extracted as (R3NH)2WO2(C2O4)2, where R3N shows a trioctylamine (TOA) molecule, when the mole ratio (Oxalate / WO42-) in the aqueous phase was higher than 4.54. This discrepancy might be caused by the protonation to the W complex in the present experimental condition. Further experiments such as an investigation of dependence of D value on H+ concentration would be performed for the speciation of the extracted species.

Fig. 1. Variation of the distribution ratio of 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.

References
Solvent extraction behavior of $^{95}$Nb and $^{179}$Ta in HF medium with tributyl phosphate

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In a previous study, a long-lived isotope with a half-life of 27 h, $^{268}$Db, was assigned as the descendant nucleus of $^{288}$115 because of its similar chemical behavior to group-5 elements. It was also reported that the chemical behavior of Db was similar to that of Ta rather than of Nb. Recently, a chemical experiment on $^{262}$Db ($T_{1/2} = 34$ s) has been carried out in a mixed HF/HNO$_3$ solution. In contrast, this experiment showed a contrary result that the chemical behavior of Db is similar to that of Nb. Therefore, more detailed studies on the chemical properties of Db are required for the clear identification of element 115. In this study, extraction behaviors of the lighter homologs of Db, Nb and Ta, and the extraction kinetics is investigated toward the chemical identification of Db. To carry out chemical experiments of Db on a atom-at-a-time scale, the chemical studies of Nb and Ta should be conducted on a tracer scale. Moreover, in the experiment on Db, rapid kinetics for the extraction equilibrium is required because only short-lived radioisotopes of Db can be produced directly by heavy-ion induced nuclear reactions. We tried solvent extraction with $^{95}$Nb ($T_{1/2} = 34.991$ d) and $^{179}$Ta ($T_{1/2} = 1.82$ y) with tributyl phosphate (TBP), which is widely used in the industrial separation of Ta from Nb,3,4) and organic phases, respectively.

We also studied the extraction kinetics of this system by changing the shaking time $t$ ($t = 0.2$, 0.5, 1, 5, 10, 90, and 180 min). In the experiment for investigating extraction kinetics with 1.8 M TBP in 1, 2-dichloroethane and 5.4 M HF solutions, the $D$ values of $^{95}$Nb and $^{179}$Ta were almost constant in the studied range of shaking time studied, suggesting that the extraction equilibrium is very fast.

Figure 1 shows HF concentration dependences of the distribution ratios of $^{95}$Nb and $^{179}$Ta in 1.8 M TBP in 1, 2-dichloroethane. When [HF]$_{ini} = 0.27$ M, the $D$ value of $^{179}$Ta has a maximum of 346 ± 58, while the value of $^{95}$Nb is approximately 10$^{-2}$. This indicates that Ta can be clearly separated from Nb in the 0.27 M HF solution and the predominant complex of Ta in HF solution varies near this concentration. Therefore, this experimental condition would be suitable to investigate whether Db behaves like Nb or Ta.

For chemical experiments on short-lived Db, an on-line rapid extraction apparatus is required. The development of an apparatus utilizing a flow injection analysis system is in progress. The on-line extraction of Nb and Ta from HF solution into TBP will be performed using the apparatus.

$D = (A_{org}/V_{org})/(A_{aq}/V_{aq})$

where $A$ is the radioactivity of the metals, and $V$ is the volume of each phase. The subscripts aq and org denote the aqueous and organic phases, respectively.

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Extraction behavior of Nb and Ta with Aliquat 336 in HF solutions

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Studies on the chemical properties of transactinide elements with atomic numbers Z ≥ 104 are extremely interesting. It is suggested that the chemical properties of these elements are different from those of their lighter homologs because of the strong relativistic effects on the valence electrons3). Therefore, comparative studies on the chemical behaviors of transactinide elements and their lighter homologs are very important.

We are planning to investigate the chemical properties of Db, which is the 105th element in the periodic table. Because a fluoride ion is known as a strong complexing reagent for group 5 elements3), ion-pair extractions of Nb and Ta, which are the lighter homologs of Db, with quaternary ammonium (Aliquat 336) in HF solutions were carried out to study complex formations of these elements with fluoride ions.

Long-lived radiotracers, 95gNb (T1/2 = 34.97 d) and 179Ta (T1/2 = 665 d), were produced during proton bombardments of Zr and Hf metallic foil targets with natural isotopic abundances, respectively, using the RIKEN AVF Cyclotron. These radiotracers in the targets were chemically isolated by ion-exchange separation. The tracers were dissolved in 600 μL of 1 M HF and then mixed with the same volume of 10⁻³–10⁻² M Aliquat 336-1,2-dichloroethane solutions in a polypropylene tube. After shaking the solutions for 5 min, followed by centrifugation, the two phases were separately pipetted into sample tubes. The radioactivities of the two samples were assessed with a Ge detector. Distribution ratios (D) of Nb and Ta were obtained from the ratio of the radioactivities of the two phases.

The dependence of the distribution ratios of 95gNb and 179Ta in 1 M HF on the concentrations of Aliquat 336 are shown in Fig. 1. The results show a linear relation with a slope of ≈1 for both Nb and Ta, which indicates that univalent anionic fluoride complexes are extracted by Aliquat 336.

The dependences of D values of 95gNb and 179Ta on the HF concentration were also investigated for varying HF concentrations (10⁻²–10 M) with 10⁻³ M Aliquat 336-1,2-dichloroethane solution (Fig. 2). The maximum D value of Ta is obtained in 0.27 M HF. On the other hand, the D value of Nb decreases gradually with HF concentration from 10⁻² M to 10 M, thus, there was a clear differences in the extraction behaviors of Nb and Ta. The large difference in the D values of Nb and Ta is probably due to the fact that Ta forms fluoro-complexes TaF₆⁻, while Nb is predominantly present as oxo-fluoro complexes NbOF₃⁻. As mentioned above, the results obtained from Fig.1 show that the extracted species of Nb and Ta are both univalent anionic complexes. Therefore, Nb and Ta exist as TaF₆⁻ and NbOF₃⁻ under these experimental conditions.

The fluoro-complex formation of Db needs to be investigated from the experimental result to determine whether the extraction behavior of Db from HF solutions into Aliquat 336-1,2-dichloroethane solution is closer to that of Nb or Ta.

Fig. 1: Variation of the distribution ratio D of 95gNb and 179Ta vs. concentration of Aliquat 336 in 1 M HF

Fig. 2: Variation of the distribution ratio D of 95gNb and 179Ta vs. initial concentration of HF

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Online coprecipitation experiment of $^{85}$Zr and $^{169}$Hf with Sm hydroxide for chemical study of Rf

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Elucidating chemical properties of transactinide elements with atomic numbers $Z \geq 104$ is an intriguing and important topic. Transactinide elements are produced at accelerators using heavy-ion-induced nuclear reactions. The production rates of these elements are low and their half-lives are short ($T_{1/2} \leq \sim 1$ min). Thus, chemical studies on these elements are conducted on a one-at-a-time basis using rapid chemical separation techniques, and products transported online by a gas-jet system from a nuclear reaction chamber are used. For unambiguous identification of a single atom, detection of $\alpha$ or spontaneous fission decay is required. Owing to these difficulties, so far, simple partition methods such as gas-phase and aqueous-phase chromatographic experiments have been applied to the studies of transactinide elements.

Recently, the anion- and cation-exchange behaviors of rutherfordium (Rf, $Z = 104$) in HF and HF/HNO$_3$ solutions were successfully investigated at the Japan Atomic Energy Agency Tandem Facility, the behaviors of Rf was reported to be different from those of its homologues Zr and Hf. Detailed studies on Rf in various chemical systems are needed for a further understanding of its chemical properties. To establish a new chemical experiment for superheavy elements, thus far, we have developed a method to rapidly prepare a coprecipitated sample, which has good energy resolution in alpha spectrometry. For the coprecipitation study of Rf, we have studied coprecipitation properties of group-4 elements, Zr, Hf, and Th with Sm(OH)$_3$ and also developed an apparatus for rapid preparation of precipitate samples. In this study, we performed online coprecipitation experiments of $^{85}$Zr and $^{169}$Hf using the developed apparatus, and determined the experimental conditions for Rf.

We produced carrier-free radiotracers $^{85}$Zr ($T_{1/2} = 7.9$ min) and $^{169}$Hf ($T_{1/2} = 3.25$ min) in the $^{26}$Ge($^{18}$O, $\alpha n$) reactions using the RIKEN K70 AVF cyclotron. The reaction products were transported online by a He/KCl gas-jet system to the chemistry laboratory. They were deposited on the collection site of a dissolution apparatus, and then dissolved in 120 $\mu$L of a 0.46 M HNO$_3$ solution containing Sm ions (460 mg/L). Various compositions of basic solutions (dilute and concentrated aqueous NH$_3$, 0.15, 1, 6, and 12 M NaOH) were added into the sample solution. The resultant concentrations were 0.28 and 13 M NH$_3$, and 0.08, 0.84, 5.3, and 11 M NaOH, respectively. After stirring the sample for 10 s, the coprecipitate sample was prepared by suction filtration on a polypropylene membrane filter (0.1 $\mu$m, $\phi$20, Eichrom) using a semiautomatic filtration apparatus for repetitive experiments. The sample was dried using a heater at 100 $^\circ$C and was subjected to $\gamma$-ray measurement using a Ge detector. On the other hand, radioactivities of the products dissolved using the dissolution apparatus were also determined. From the ratio of the measured radioactivities of the precipitate to those of the dissolved solution, precipitation yields of Zr and Hf were determined.

The dependence of the yield on the composition of the added basic solution is depicted in Fig. 1. It was found that almost the entire amounts of Zr and Hf were coprecipitated with Sm hydroxide when aqueous NH$_3$ and 0.1 M NaOH were used. This suggests that Zr and Hf form a neutral hydroxide complex and coprecipitate with Sm(OH)$_3$ precipitate in these basic solutions. For more concentrated NaOH solutions, the yields decreased as the concentration of the hydroxide ion increased, indicating that the Zr and Hf form anionic hydroxide complexes. These results are consistent with those obtained in the offline coprecipitation experiment using $^{85}$Zr and $^{175}$Hf. It was found that the coprecipitation yields of Zr and Hf with Sm hydroxide in the rapid and online precipitation experiment can be obtained using the developed apparatus connected to the accelerator at RIKEN; the present experimental systems are applicable to Rf experiments.

Very recently, we indeed produced $^{26}$Rf in a $^{248}$Cm($^{18}$O, 5$n$)$^{260}$Rf reaction and performed the first trial of coprecipitating Rf with Sm(OH)$_3$. Approximately 43 alpha events were detected in the energy region of $^{26}$Rf.

References

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Fig. 1. Coprecipitation yields of $^{85}$Zr and $^{169}$Hf.
Adsorption behavior of Zr and Hf to TTA-resin in microcolumn for determining the forming ability of Rf monofluoride complex

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The present study aims to elucidate the relevant chemical species of Rf by reversed-phase extraction chromatography with 2-thienyltrifluoroacetone (TTA) as a stationary phase. Because TTA has been suggested to extract quadrivalent metallic ions, the distribution ratios of the system may make it possible to determine the specific complex-formation constant of Rf. We have so far performed several experiments for the chemical systems with Zr and Hf ions, but failed to find an experimental condition appropriate for measuring the adsorption of Rf.1,2,3

In order to optimize an appropriate experimental condition for Rf, in the present study, the equilibration time and distribution ratios for extraction have been measured by batch method experiments with carrier-free radioisotopes of Zr and Hf on TTA-resin in the 1.0×10^{-4}–1.0×10^{-3}\text{ M} HF/1.0×10^{-2}\text{ M} HNO_{3} solutions. An online experiment has been also performed for investigating the reversed-phase chromatographic behaviors of Zr and Hf on the TTA resin with Automated Rapid Chemistry Apparatus (ARCA)\textsuperscript{9} to simulate the Rf experiments.

The radioisotopes of 88\textsuperscript{Zr} (t_{1/2} = 83.4 \text{ d}) and 175\textsuperscript{Hf} (t_{1/2} = 70.0 \text{ d}) used in the batch experiments were produced by the \textsuperscript{89}\text{Y}(p, 2n) and \textsuperscript{175}\text{Lu}(p, n) reactions, respectively, at the RIKEN K70 AVF Cyclotron. The short-lived 85\textsuperscript{Zr} and 169\textsuperscript{Hf} isotopes were also produced by the \textsuperscript{78}\text{O}-induced reaction with the \textsuperscript{112}\text{Ge} and \textsuperscript{155}\text{Gd} targets, respectively, for the on-line experiments. The TTA-resin was simultaneously produced by mixing the CHP20/P20 resin with a TTA-octanol solution of 50 or 30 wt.\%, which includes 50 or 20 wt.\% of TTA in n-octanol, respectively. The prepared TTA-resin was used for the batch experiments, as well as for the on-line reversed-phase extraction chromatography. The details of the procedures can be found elsewhere.\textsuperscript{5}

In the batch experiments, the D value of 50 wt.\% resin was found to be higher than that of the other resin, while the time for chemical equilibration of the former is almost the same as that of the other. The elution curves of Zr and Hf at a flow rate of 0.15 mL/min in the range 1.0×10^{-4}–1.0×10^{-3}\text{ M} of HF concentration on the former resin are shown in Fig. 1; the peaks of the curves are clearly visible in the figure for all the conditions of HF concentration.

The D values for the on-line experiments are evaluated from the elution curves by using the following equation, D = \frac{V_{e}}{m} [\text{ mL/g }], where \textit{V}_{e} is the peak volume of an elution curve, and \textit{m} is the resin weight in a microcolumn. The D values of Zr tend to be higher than those of Hf in the on-line experiments, although, based on the batch experiments, the D value of Hf should be higher than that of Zr at the chemical equilibrium. For instance, in Fig.1(a) the D value of Zr was found to be higher than that of Hf by a factor of 1.2, although in the batch experiments the D value of Zr was found lower than that of Hf by a factor of 2.8. These results in the on-line experiments show that the chemical equilibrium time of Zr is shorter than that of Hf, which agrees with the results of the present batch experiments measured as a function of shaking time. The kinetic behavior observed here should be clarified in order to perform the Rf experiment in the expected project.

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References

\textbf{Fig. 1.} Elution curves of Zr and Hf against the HF concentration, (a) 1.0×10^{-4}\text{ M}, (b) 6.0×10^{-4}\text{ M}, (c) 1.0×10^{-3}\text{ M}, in the HF/0.010-M HNO_{3} solution, at a flow rate of 0.15 mL/min. The radioactivity values in the figure represent the values relative to the total eluted radioactivity. Solid lines are curves fitted to a theoretical equation derived by Glückauf model\textsuperscript{4}.

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Coperiprecitation experiment of various elements with Sm hydroxide using multitracer

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Chemical studies on transactinide elements with atomic numbers \( Z \geq 104 \) are currently at the frontier in nuclear chemistry. The transactinide elements are produced at accelerators using heavy-ion-induced nuclear reactions. Rapid chemistry on a one-atom-at-a-time basis is applied to these elements because of their low production rates and short half-lives. In addition, for unambiguous identification of these elements, it is necessary to detect \( \alpha \) or spontaneous fission decays. Therefore, chemical experiments of transactinides are not abundant. In the ion-exchange chromatography, the fluoride complex formation of \( \text{Rf} (Z = 104) \) was successfully investigated, and the behavior of \( \text{Rf} \) was reported to be clearly different from those of the homologues \( \text{Zr} \) and \( \text{Hf} \). Chemical studies on transactinides in various chemical systems should be conducted to understand their characteristic chemical properties.

The purpose of the present study is to establish a coperiprecipitation method as a new method for the chemistry of transactinide elements. Because these elements can be treated as only one atom at a time, we must study their coperiprecipitation behaviors with a carrier element. For this, a preparation method of coperiprecipitated samples with \( \text{Sm} \) hydroxide, which facilitated the \( \alpha \) spectrometry with a high energy resolution, was established.\(^{11}\) We are planning to apply this method to transactinide chemistry and to investigate the coperiprecipitation behaviors of transactinides. In the chemistry of transactinides, model experiments with their homologues are usually performed to establish the experimental method and to determine the conditions. In this work, we investigated the coperiprecipitation behaviors of various elements with \( \text{Sm} \) hydroxide using a multitracer produced by nuclear spallation reactions in RIKEN.

A multitracer was produced by irradiating the \(^{186}\text{Ta}\) foil targets by 135-MeV/nucleon \(^{14}\text{N} \) ions accelerated by RIKEN Ring Cyclotron\(^ {21}\). Various nuclides, namely various elements, with \( Z < 73 \) (\( \text{Ta} \)) were produced by nuclear spallation reactions. Only the nuclear reaction products recoiling out of the target foils were transported from the reaction chamber to the chemical laboratory by the \( \text{He/KCl} \) gas-jet system.\(^ {23}\) The products collected on a glass filter paper for about 40 h were dissolved in 1 mL of 0.01 M \( \text{HCl} \) solution, and the solution sample was filtrated with a filter paper to remove the glass chips from the solution.

The \( \text{Sm} \) standard solution (20 \( \mu \text{L} \)) containing 20 \( \mu \text{g} \) of \( \text{Sm} \) was added into 220 \( \mu \text{L} \) of the multitracer solution. The solution was stirred, and then 2 mL of the basic solution (dilute and concentrated aqueous \( \text{NH}_3 \), and 0.1, 1, 6, and 12 M \( \text{NaOH} \) solutions) was added. The solution was stirred for 10 s or 10 min. Then, the solution containing the precipitate was filtrated by suction with a polypropylene membrane filter (0.1 \( \mu \text{m} \), \( \#20 \), Eichrom). The filtrate was collected in a vial. Both the precipitate and filtrate were dried using a heater at 100°C and then subjected to \( \gamma \)-ray spectrometry with a \( \text{Ge} \) detector. The precipitation yields (\( Y_1 \)) were determined from these radioactivities. The reference radioactivities of the radionuclides were also determined. The precipitation yield (\( Y_2 \)) as a relative value to the reference was also determined to check the accuracy of the obtained precipitation yields.

The product nuclides were identified from the energies and half-lives of the observed \( \gamma \)-ray peaks. We found the following nuclides: \(^{24}\text{Na} \), \(^{42}\text{K} \), \(^{82}\text{Rb} \), \(^{127,129}\text{Cs} \) (alkali metals), \(^{47}\text{Ca} \), \(^{128}\text{Ba} \) (group 2), \(^{44,47,48}\text{Sc} \), \(^{87}\text{Y} \) (group 3), \(^{132,135}\text{Ce} \), \(^{145,146,147,149,150}\text{Eu} \), \(^{149-153}\text{Gd} \), \(^{155,157}\text{Dy} \), \(^{160}\text{Ho} \), \(^{161}\text{Er} \), \(^{165,167}\text{Tm} \), \(^{166,169}\text{Yb} \), \(^{169,171,172}\text{Lu} \) (lanthanides), \(^{89}\text{Zr} \), \(^{170,172}\text{Hf} \) (group 4), \(^{90}\text{Nb} \), \(^{176}\text{Ta} \) (group 5), \(^{93}\text{Mo} \) (group 6), \(^{96}\text{Tc} \) (group 7), \(^{99}\text{Rh} \), \(^{100}\text{Pd} \), \(^{106}\text{Zn} \), \(^{110,111}\text{In} \) (group 13), \(^{71,72}\text{As} \), \(^{118,120}\text{Sb} \) (group 15), \(^{71}\text{Se} \), and \(^{119}\text{Te} \) (group 16).

For these elements, the precipitation yields and their dependences on the composition of the basic solution were obtained. Overall, the yields reflecting the properties of each element in the hydroxide precipitation were observed. For example, the yields of alkali metal elements were almost 0% under all the conditions. The yields of lanthanides were almost 100%, and decreased in the case using 6 and 12 M \( \text{NaOH} \). In addition, the precipitation yield of \( \text{Zn} \) was decreased to almost 0% in adding concentrated aqueous \( \text{NH}_3 \), indicating the well-known properties that \( \text{Zn} \) forms a cationic ammine complex in such a solution. The yields of \( \text{Zr} \) and \( \text{Hf} \), the homologues of \( \text{Rf} \), were close to 100% and decreased with an increase in the hydroxide-ion concentration, while those of \( \text{Nb} \) and \( \text{Ta} \), the homologues of \( \text{Db} \), were always high. In contrast, the yields of \( \text{Mo} \), the homologue of \( \text{Sg} \), were 0% under all the conditions. It would be interesting to study the precipitation behaviors of these transactinides. The \( Y_1 \) values were consistent with the \( Y_2 \) values. In comparison between the results with 10-s and 10-min stirring, both the yields agreed with each other for many elements, suggesting rapid chemical reactions; only exception was the result using 12 M \( \text{NaOH} \). We believe that the coperiprecipitation properties of transactinides with \( \text{Sm} \) hydroxide could be investigated by the present method.

References


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Development of rapid solvent extraction technique with flow injection analysis for superheavy element chemistry

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For the chemical investigation of superheavy elements with atomic numbers $\geq 104$, rapid chemical separation is needed because they have relatively short half-lives. We developed a solvent extraction system applying flow injection analysis (FIA). This FIA system consists of solvent extraction and phase separation parts (Fig. 1). In the solvent extraction part, aqueous and organic phases are mixed in a tube with a very small inner diameter of 100–200 μm. Because of the large specific interfacial area and short diffusion length in the tube, extraction equilibrium is rapidly attained. In the phase separation part, on-line liquid-liquid phase separation is achieved with a hydrophobic poly(tetrafluoroethylene) (PTFE) membrane. In this work, solvent extraction of $^{95}$Nb ($T_{1/2} = 35$ d) using this system was investigated as a model experiment for element 105, Db.

The $^{95}$Nb tracer was produced through the bombardment of a $^{187}$Zr metal target foil with a 14-MeV proton beam supplied by the RIKEN AVF cyclotron. The carrier-free $^{95}$Nb tracer was prepared by the chemical separation from the target using an anion-exchange technique.1)

In the solvent extraction experiment using the FIA system, 5 M HCl solution containing $^{95}$Nb tracer and 0.1 M Aliquat 336 in 1,2-dichloroethane solution were used as aqueous and organic solutions, respectively. The aqueous and organic solutions were pumped using double-plunger pumps and mixed in a T-connector. The mixture was fed into the extraction coil of the PTFE tube of inner diameter 0.17 mm, and on-line liquid-liquid phase separation was performed using the membrane phase separator of thickness 75 μm and a 0.8-μm pore size PTFE filter.

In order to evaluate the time needed for attaining extraction equilibrium, the flow rate and extraction coil length were varied. After extraction, both solutions eluting from the phase separator were collected in polypropylene tubes. Experiments without the phase separator were also performed. Batch extraction experiments of $^{95}$Nb using 0.6 mL of each phase were also performed for comparison with the results obtained using the FIA system. The two separated phases were then subjected to $\gamma$-ray spectrometry using a Ge detector in all experiments. The distribution ratio ($D$) was calculated as the radioactivity ratio of each phase by using the same flow rate (Eq.1).

$$ D = \frac{A_{\text{org}}}{A_{\text{aq}}} \quad (1) $$

The results of using the FIA system and the shaking time in the batch experiments are shown in Figs. 2 (a) and (b), respectively. In the experiment using the FIA system, the extraction equilibrium was attained within a contact time of approximately 2 s. On the other hand, a shaking time of 40 min was needed to attain extraction equilibrium in the batch experiment. This result shows that extraction equilibrium can be rapidly attained using the FIA system. On-line liquid-liquid phase separation was successfully performed using the membrane phase separator in the FIA system.

Thus, the developed FIA system is applicable for the solvent extraction experiments of superheavy elements with half-lives of several tens of seconds considering other time-consuming steps such as dissolution and sample preparation for $\alpha$-particle measurement.

Fig. 1. Schematic view of the FIA system.

Fig. 2. The dependence of $D$ value of $^{95}$Nb on the contact time in the FIA system (a) and the shaking time in the batch experiment (b).

References

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We are developing a CO gas-jet technique and plan to apply it to the separation of neutron-rich isotopes of Sg produced in the transfer reaction $^{248}\text{Cm} + ^{48}\text{Ca}$. In this preliminary investigation, we successfully separated $^{179m}\text{W}$, the lighter homologue element of Sg, from other heavy ions ($^{89m}\text{Zr}$, $^{28}\text{Al}$ et al.) in the form of a volatile carbonyl complex.

A 24-MeV d beam was extracted from the AVF cyclotron of the RIKEN RI Beam Factory. Five $^{nat}\text{Ta}$ targets were stacked with one $^{nat}\text{Nb}$ target in the sequence Ta/Nb/Ta/Ta/Ta/Ta. All targets were fixed in an Al holder with 5-mm distance between each other. The thicknesses of $^{nat}\text{Ta}$ and $^{nat}\text{Nb}$ target were 7.62 and 0.917 mg/cm$^2$, respectively. Reaction products emitted from the targets were thermalized and stopped in the He/CO mixed gas. Elements that could form volatile complexes with the CO reagent, e.g. W(CO)$_6$, were flushed out from the target chamber and extracted along capillaries of inner diameter (i.d.) 1.59 or 2.0 mm. After the volatiles were passed through a PTFE filter (SMC SFB 300-02) mounted at the outlet of the target chamber and a 2.1-m quartz column (2.0-mm i.d.) immersed in a chiller, they were collected using a charcoal filter (ADVANTEC CP20) and subjected to γ-ray spectrometry with a Ge detector. Because of the beam irradiation, CO molecules would be decomposed into carbon and oxygen. Most products adhered to the carbon particles and were removed by the PTFE filter. The length from the PTFE filter to the collection site was about 17 m. Flow rates of He and CO were controlled independently to adjust their concentrations in the target chamber. The lowest flow rate controlled by the mass-flow meter was 0.2 L/min.

As explained above, reaction products could be transported out in the form of volatile molecules or by using aerosols. First, to check all the products, a high-intensity beam with 2.9 particle μA (pμA) as well as 1.2(He)+0.2(CO) L/min mixed gas was used to generate many carbon aerosols. All nuclear products were efficiently carried to the charcoal filter by carbon particles without selectivity when the PTFE filter was removed. The 6.4-min $^{179m}\text{W}$ and 4.16-min $^{89m}\text{Zr}$ were identified by their γ-energies and decay curves. The production yields after 1-min collection were deduced to be 9.86±0.84 and 0.40±0.04 kBq/pμA for $^{179m}\text{W}$ and $^{89m}\text{Zr}$, respectively. By changing the i.d. of the capillary and increasing the He gas flow rate, the yield could not be improved further.

After the PTFE filter was installed, the 221.5-keV γ-line of $^{179m}\text{W}$ was observed subsequent to 7-min beam irradiation under 0.03 pμA (See Fig.1). Other nuclides, which could not form volatiles in a CO atmosphere, were removed, such as $^{89m}\text{Zr}$. The transport efficiency for $^{179m}\text{W}$ in the carbonyl form was decreased with the beam intensity and CO flow rate, but it could be improved by increasing the He gas flow rate. By changing the i.d. of capillary from 1.59 to 2.0 mm, the maximum flow rate of He gas was increased from 1.2 to 4.0 L/min, corresponding to about 1 atm in the target chamber. Under 4.0 L/min He flow rate, the count of 221.5-keV γ-line was improved by a factor of 4 (see Fig. 1). The optimal relative transport efficiency for $^{179m}\text{W}$ was 13.1±2.2%, which was obtained by normalizing to the production yield of using carbon aerosols as the transmission medium under 2.9-pμA beam intensity. The yield of $^{179m}\text{W}$ that passed through an isothermal column at different temperatures was measured, and the results are displayed in Fig. 2. By fitting the breakthrough curve with a Monte-Carlo simulation1), the adsorption enthalpy of the carbonyl complex was determined to be -47±1 kJ/mol, which agrees well with the 46.5±2.5 kJ/mol reported for W(CO)$_6$ in Reference2).

![Fig. 1. γ-ray spectra obtained for $^{179}\text{W}$ in the form of a volatile carbonyl complex.](image)

![Fig. 2. Yields of $^{179m}\text{W}$ passing through the quartz column.](image)

References
Recovery of $^{248}$Cm material from mixed Cm/Gd target

M. Murakami$^{1,*1}$ and H. Haba$^1$

In the chemical experiments on superheavy elements (SHEs), the lighter homologue elements in the periodic table are simultaneously produced, and their chemical behaviors are compared to those of SHEs under identical experimental conditions. For this purpose, a mixed $^{248}$Cm/Gd target deposited on a thin metallic backing foil has been often used.$^{1,2}$ The target as well as the backing material are gradually damaged by the irradiation with the intense heavy-ion beams. Since the available amount of $^{248}$Cm is limited, its recovery, which involves purification from the used target, is essential to produce a new target.

Bis(2-ethylhexyl)phosphoric acid (HDEHP) is one of the widely used extractants for separating lanthanide ions.$^3$ Separation of lanthanide and actinide through extraction chromatography using an HDEHP-laden resin has been studied.$^4,5$ Using the HDEHP resin, one can perform stepwise separation of lanthanide and actinide elements by simply changing the concentration of the HNO$_3$ eluents. The distribution coefficients ($K_d$) of these elements strongly depend on the HNO$_3$ concentration: The $K_d$ values for $+3$ ions are inverse third power dependent on the mean activity of the hydrogen ion.$^4$ Therefore, in this work, we investigated several schemes to effectively separate Cm and Gd with the HDEHP resin using a multitracer of lanthanide elements. Further, we separated the $^{248}$Cm material from $^{nat}$Gd with the optimized scheme.

The commercially available Ln Resin (Eichrom), the HDEHP-laden hydrophobic resin with the particle size of 100–150 µm, was packed into a polyethylene column (5 mm i.d. $\times$ 50 mm height; column volume: $\approx$ 1 mL). The multitracer was produced by bombarding a $^{nat}$Hf target with a 135-MeV/nucleon $^{14}$N beam from the RIKEN Ring Cyclotron. After the irradiation, the rare earth elements were separated from the target material by an established procedure, detailed in Ref. 6. The multitracer including $^{133}$Ba, $^{139}$Ce, $^{143}$Pm, $^{145}$Sm, and $^{153}$Gd in 0.1 M HNO$_3$ was stocked in a polypropylene (PP) tube. The $K_d$ values are reported to be in the order Ba $\ll$ Ce $<$ Sm $<$ Gd $< Pm$ in the Ln Resin–HNO$_3$ system.$^5$ After the conditioning of the column with 3.0 mL of 0.1 M HNO$_3$ solution, 1 mL of the stock solution was loaded onto the column. 4 mL of 0.1 M HNO$_3$ was then fed onto the column as a first eluent. According to the reported $K_d$ values, $^5$ most of the $+1$ and $+2$ metal ions such as $^{133}$Ba elute in this fraction. As a second eluent, 0.2–0.5 M HNO$_3$ solutions were fed until $^{143}$Pm was completely eluted from the column. Finally, 6 mL of 1.0 M HNO$_3$ was fed to elute $^{153}$Gd completely. The flow rate was 230–240 µL/min at room temperature. Each 1 mL of the effluent was collected in a separate PP tube and subjected to $\gamma$-ray spectrometry at fixed geometry.

Figures 1(a)–(d) show the elution curves of the multitracer with 0.2, 0.3, 0.4, and 0.5 M HNO$_3$ as the second eluent. $^{133}$Ba was eluted with 5 mL of 0.1 M HNO$_3$ with a recovery of 100.3 ± 2.5%. 30 mL of 0.2 M HNO$_3$ (Fig. 1(a)) was used to elute $^{139}$Ce and then $^{143}$Pm, as expected from the difference in the $K_d$ values.$^5$ $^{143}$Sm and $^{153}$Gd were not eluted in these fractions. Owing to the increase in the concentration of the second eluent, the peaks of the elution curves of $^{139}$Ce and $^{143}$Pm get shifted to lower volumes and approach to each other. In the case of 0.5 M HNO$_3$, 6.2 ± 0.6% of $^{153}$Gd was eluted until $^{139}$Ce was completely eluted. Since Cm is expected to be found between Ce and Pm from the order of the $K_d$ values,$^5$ Cm and Gd can be separated with the schemes shown in Fig. 1(a)–(c). However, the scheme shown in Fig. 1(a) takes a large amount of eluent, and in the case of 0.4 M HNO$_3$, the condition for separation is stricter than that in the case of 0.2 M and 0.3 M HNO$_3$, owing to the close peaks of the elution curves. Therefore, we selected the scheme in Fig. 1(b) for the separation of $^{248}$Cm and $^{nat}$Gd.

By applying the scheme of Fig. 1(b) to the purification of $^{830-\mu g}$ $^{248}$Cm target material containing $^{nat}$Gd (about 10 wt%), 99.3 ± 4.1% of $^{248}$Cm was collected in the fraction of the 12-mL 0.3 M HNO$_3$ solution.

![Fig. 1. Elution curves of $^{133}$Ba, $^{139}$Ce, $^{143}$Pm, $^{145}$Sm, and $^{153}$Gd. The concentrations of the second eluents are (a) 0.2 M, (b) 0.3 M, (c) 0.4 M, and (d) 0.5 M.](image_url)

References
Method for preparing ultra-thin sources for low-energy particle spectrometry

H. Kikunaga,*1,*2 H. Haba,*1 and J. Kanaya*1

Generally, internal conversion electrons originate from the K shell. If the decay energy of a nuclear isomer is less than the binding energy of an inner-shell electron, the emission of an electron from the shell is forbidden, in which case the isomer interacts with outer-shell electrons. As a result, the probability of internal conversion is affected by the outer-shell electron state, namely the chemical state. Examples of this type of nuclides are $^{99}$Tcm (2.17 keV) and $^{229}$Thm (7.6 eV). The goal of our research is to measure such low-energy internal conversion electrons of various chemical states. For high-resolution energy spectrometry, it is necessary to prepare radionuclides as a thin source. In this report, we attempt to prepare a ultra-thin source using the Self-assembled Molecular (SAM) technique. The performance of the SAM substrate was investigated through radio-tracer experiments.

RIKEN Ag-based multi-isotope tracers and single-isotope tracers were used for the experiments. The multi-tracers were produced by irradiation of a Ag metal plate with a $^{14}$N ion beam accelerated by the RIKEN Ring Cyclotron. Ag target material was removed by a precipitation method with the use of hydrochloric acid. Single-isotope tracers were prepared using the AVF cyclotron at CYRIC, Tohoku University.

The procedure for the preparation of SAM substrates was similar to that described in Ref[1]. An Al plate 25 mm in diameter was polished and rinsed with distilled water. After drying, the Al plate was treated with 1 vol.% 3-aminopropyltriethoxysilane (APTES) in absolute toluene through chemical vapor deposition in a self-made PTFE cell at 100 °C for 2 h; subsequently, it was rinsed with methanol and absolute toluene. Phosphonation of the terminal amino groups of APTES was performed with phosphoryl chloride and γ-collidine in absolute acetonitrile, and the sample was then rinsed with absolute acetonitrile and distilled water. The coupling of the SAM substrate and radionuclides was carried out in an aqueous solution or an isopropyl alcohol solution.

The bound radionuclides were assayed by γ-ray spectrometry with an HPGe semiconductor detector. A γ-ray spectrum of a multitracer-SAM sample is shown in Fig. 1. The γ-peaks of $^{46}$Sc, $^{54}$Mn, $^{65}$Zn, $^{75}$Se, $^{83}$Rb, $^{85}$Sr, $^{88}$Zr, $^{88}$Y, $^{101}$Rh, and $^{102}$Rh$^{m}$ are observed in the spectrum. By comparison of γ-peak counts of each nuclide, we found that the yield of nuclides with oxidation states +3 and +4 is relatively high. On the other hand, $^{22}$Na and $^{57}$Co were not detected, although these nuclides were included in the multi-tracer solution. This tendency was found regardless of the reaction solvent to be combined with radionuclides.

To confirm the uniformity of the SAM source, the α source was prepared with $^{241}$Am tracer and subjected to autoradiography. A photograph taken using an imaging plate is shown in Fig. 2. The deviation of α activity is observed at the upper-left part of the image. This deviation probably originates from fine scratches on the Al plate. With the exception of this part, the α activity is spread uniformly over the entire SAM substrate. Although there are still some problems, the present method will provide us with a reliable ultra-thin source after some improvements.

![Fig. 1. An example of a γ-ray spectrum of a multitracer-SAM sample.](image)

![Fig. 2. Photographic image of a $^{241}$Am-SAM sample taken using an imaging plate.](image)

References


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Production of purified $^{85}$Sr solution

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Since 2007, we have distributed purified radioisotopes such as $^{65}$Zn, $^{88}$Y, and $^{109}$Cd to the general public.1) After the Fukushima Dai-ichi Nuclear Power Plant accident in 2011, the demand for $^{85}$Sr solutions having a high specific radioactivity has been growing. In this work, we investigated the production of $^{85}$Sr in the $^{85}$Rb($d$,2$n$)$^{85}$Sr reaction using a 24-MeV deuteron beam from the RIKEN AVF cyclotron. We also studied a chemical procedure to obtain a purified $^{85}$Sr solution.

$^{85}$Sr ($T_{1/2} = 64.853$ d) was produced by irradiating an 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. $^{85}$Sr was chemically separated in accordance with the scheme shown in Fig. 1. The irradiated RbCl target was dissolved in 2 mL of H$_2$O and 2 mL of 8 M HNO$_3$. After evaporating the solution almost to dryness, the residue was again dissolved in 2 mL of 8 M HNO$_3$. The resulting solution was evaporated to dryness to remove chloride ions, and the residue was dissolved in 4 mL of 8 M HNO$_3$ and loaded onto a reversed-phase extraction chromatography column (5 mm×50 mm height) packed with Sr Resin (Eichrom; 100–150 mesh). The column was then washed with 12 mL of 8 M HNO$_3$. In this process, $^{85}$Sr was absorbed on the Sr Resin, and the target material of Rb was completely eluted, as traced by byproducts of $^{84}$Rb and $^{86}$Rb. $^{85}$Sr was then eluted with 8 mL of 0.05 M HNO$_3$. The activity of $^{85}$Sr was determined through $\gamma$-ray spectrometry using a calibrated Ge detector.

The $\gamma$-ray spectra of the produced $^{85}$Sr are shown in Fig. 2. The produced activity of $^{85}$Sr was 145 kBq, and the radionuclidic purity was $>99.9\%$. The production yield of $^{85}$Sr under the present experimental condition was about 3 MBq h$^{-1}$ A$^{-1}$. The chemical yield was 89%.

The chemical impurity in the purified solution will be evaluated by using ICP MS for a control sample, which was treated using the same procedure as that used for the irradiated sample, in further studies.

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References
1) T. Kambara et al.: a separate paper in this issue.
4. Radiation Chemistry and Biology
Linear-energy-transfer dependence of polymer gel dosimeters under carbon beam irradiation

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Polymer gel dosimeters are widely used for quality assurance in the treatment planning of cancer therapy using low linear-energy-transfer (LET) radiations such as X-rays, and γ -rays. They consist of gel-fixed radiation-sensitive compounds, and the amount of the reaction products after irradiation depends on the dose accumulated at each position in the gel. The proton NMR is sensitive to the reaction products, and its three-dimensional map can be read out by using the magnetic resonance imaging (MRI) technique [1]. With regard to the application of gel dosimeters to heavy-ion beams that have higher biological effectiveness than low-LET radiations, it has been reported that the dose response of all the gel dosimeters except for the nanocomposite Fricke gel developed recently [2] changes with radiation quality, which depends on the charge and velocity of the ion in the case of heavy-ion beams. The dose distribution hence cannot be evaluated directly from the measured MRI signal strength in these gel dosimeters.

In this study, we investigated the dose response of the VIP polymer gel dosimeters [3] for carbon beams having a wide LET range, by comparing the relaxation rate (R2 [s−1]) obtained by MRI with the dose estimated by the Particle and Heavy Ion Transport code System (PHITS) [4]. The LET is a representative index of radiation quality, and a reliable estimation of the LET and the dose is now available by PHITS. VIP polymer gel dosimeters were prepared following the prescription [3] and sealed into containers, the length of which is sufficient to stop the ions injected into the gel dosimeters. They were irradiated with 135-AMeV and 290-AMeV 12 C 6 ions accelerated by the RIKEN Ring Cyclotron and the Heavy Ion Medical Accelerator in Chiba, respectively. The dose response of irradiated samples was obtained from 1.5-T MRI (Philips).

Results of the dose response [s−1 Gy−1] are plotted as functions of the dose-weighted average of the LET (hereafter, dose-averaged LET) where the projectile ions and all the secondary particles produced by the nuclear reaction are included. The dose response decreases with increasing LET, as reported in the literature. In addition, the dose response is approximately 10% higher for the 290-AMeV beam than for the 135-AMeV beam at the same dose-averaged LET (Fig 1, symbols). This sizable difference can be explained by the different contributions from secondary particles. Ions with higher injection energy pass the thicker gel before reaching the given dose-averaged LET, and yield mode of secondary particles, mainly light fragments of the projectile. Furthermore, low-LET fragments contribute more effectively to R2 than high-LET particles. Hence, the 290-AMeV beam has higher dose response than 135-AMeV beam. For the above effects, we are investigating the contribution of minor ions such as target fragments.

To confirm the present explanation quantitatively, we investigated whether the observed 10% difference can be reproduced by assuming that the dose response of the gel dosimeter depends only on the LET value for all the relevant ions. As a result, we found a universal dose response function of the LET (R(LET), blue-dashed line in Fig. 1) that reproduced well the measured dose response for both the 135-AMeV and 290-AMeV carbon beams. The dose-averaged responses R ave defined in Eq. 1 are shown in Fig. 1.

\[
R_{\text{ave}} = \frac{\int R(\text{LET}) \cdot \text{Dose(LET)} \, \text{dLET}}{\int \text{Dose(LET)} \, \text{dLET}}
\]  

(1)

The dose response obtained here was used for predicting a geometrically more complicated R2 map measured by the VIP gel under a heterogeneous irradiation condition. The calculated R2 distributions reproduced the measured ones with the accuracy of ±5% except for the end of the ion range, the position of which was also reproduced within 1-2 mm.

![Image](image_url)

**Fig. 1.** Comparison of dose response of VIP gel obtained at different incident energies. Symbols represent experimental results, continuous lines represent dose-averaged response calculated by PHITS, and the dashed line represents the assumed fitting function.

References


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Observation of unrepairable lesions in DNA by using 3-MeV proton microbeams produced by glass capillaries

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Microbeams allow extremely efficient alteration of or damage to a small region in the target with minimum beam intensity. To date, X-ray, UV, and visible light laser have been used as microbeams. However, to create double strand breaks (DSBs) in DNA, which are difficult to repair, multiple photons are required and have to be focused on the DNA. Because of the finite size of the focal spot, the beam intensity needs to be high. This intense beam creates multiple photons are required and have to be focused on the DNA. Damage to a small region in the target with minimum beam intensity. To date, X-ray, UV, and visible light laser have been used as microbeams. However, to create double strand breaks (DSBs) in DNA, which are difficult to repair, single cells or a small region of tissue can be targeted. The capillary is known as glass pipet for micromanipulation. The beam used for irradiation was composed of 3-MeV protons that were generated by a RIKEN Pelletron accelerator and transported to the cell irradiation port, which uses an inverted microscope (OLYMPUS IX-71). A glass capillary optics system with a thin plastic end-window (diameter, 2 µm) was mounted at the beam port at 45° so that a petri dish filled with solution can be used. The capillary tip can go close to the cells which is advantageous for suppressing multiple scattering of ions before they reach the target. To adjust the number of protons, which is proportional to the dose, the time window of the beam pulse, which included a maximum of 10 ions, was set at 1 - 5 µs, wherein the number of ions in a pulse follows Poisson distribution. We irradiated 50-1,000 ions per cell to reduce statistical error.

Figure 1(a) is a microscopic view of HeLa cells during irradiation. Cell nuclei marked by yellow circles were selected. The capillary tip, which was above the cells, is at the lower left in Fig. 1(a). It took ~20 min to irradiate 60 cells in one dish. After the irradiation, cells grown in glass-bottom dishes 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).

We obtained clear fluorescence distributions only in the irradiated nuclei. The brightness of the foci (determined in terms of Alexa488 fluorescence) in each irradiated nucleus was proportional to the number of unrepairable lesions in DNA at the time cell fixation was initiated. The brightness data were displayed in a histogram by using the software, Image-J3 After subtracting the low background level of foci seen for the non-irradiated cells, histogram integration was compared according to the microbeam intensities (Table 1). The brightness increased with but was not proportional to microbeam intensity, perhaps because of saturated damage due to the large number of ions.

The linear energy transfer (LET) of 3-MeV proton was ~10 keV/µm [Fig. 1(b)]. When heavier ion pieces are selected, higher LETs will be obtained. Moreover, the ion stopping positions can be localized at a certain depth inside a cell because of their short ranges. In this case, extremely high energy deposition corresponding to the Bragg peak is available for destroying a single cell or a small region of tissue.

Table 1. Integrated brightness of the foci.

<table>
<thead>
<tr>
<th>Microbeam intensity (ions/cell)</th>
<th>Brightness of Alexa488 (arbitrary unit)</th>
</tr>
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<tbody>
<tr>
<td>50</td>
<td>733</td>
</tr>
<tr>
<td>200</td>
<td>875</td>
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References
Effects of trichostatin A on radiosensitivity to high-linear energy transfer (LET) radiation in mammalian cells with defects in DNA repair proteins

M. Izumi*1 and T. Abe*1

In eukaryotes, DNA is associated with histones and packaged into nucleosomes, which are arranged into higher order structures to form chromatin. The chromatin structure contributes to various aspects of DNA metabolism including replication, recombination, and transcription. However, it is still unclear how repair reactions and checkpoint responses caused by heavy-ion irradiation are regulated by chromatin structures. To investigate the roles of chromatin structures in DNA repair after heavy-ion irradiation, we have been focusing on the damage response observed after cells are treated with a potent histone deacetylase inhibitor, trichostatin A (TSA).

To analyze the effects of TSA on repair pathways, we investigated the X-ray sensitivity of wild-type CHO-AA8 cells and CHO mutant lines deficient in homologous recombination (irs1SF cells)1, non-homologous end-joining (V3 cells)2, and base excision repair (EM9 cells)3 in the absence or presence of TSA in a previous study4. All three mutant cell lines showed increased X-ray sensitivity (Fig. 1a). TSA treatment enhanced the X-ray sensitivity of wild-type CHO cells. In contrast, TSA enhanced the X-ray radioresistance of irs1SF cells, suggesting that the homologous recombination pathway is involved in radiosensitivity enhancement by TSA. However, TSA did not affect V3 and EM9 survival. These results suggest that non-homologous end-joining and/or base excision repair are stimulated by TSA.

In this study, we investigated argon-ion (LET = 300 keV/µm) sensitivity using the same cell lines. We compared the radiosensitivity of the four cell lines without TSA treatment (Fig. 1a). We found that CHO and V3 cells showed nearly identical dose-response profiles after argon-ion irradiation. We obtained the same results after carbon-ion (LET = 80 keV/µm) irradiation (data not shown), suggesting that non-homologous end-joining is not involved in the repair pathway induced by high-LET ionizing radiation. EM9 and irs1SF cells showed increased sensitivity to argon ions. These results are comparable with those of several recent studies5,6.

We investigated the effect of TSA on cell line survival (Fig. 1b). TSA treatment enhanced CHO cell sensitivity to argon ions. However, TSA did not affect irs1SF cell sensitivity, which is compatible with the conclusion that non-homologous end-joining is not involved in the repair pathway induced by high-LET irradiation. In contrast, TSA slightly enhanced V3 and EM9 cell radiosensitivity, which seems to be due to the inhibitory effect of TSA on homologous recombination.

Although our survival assay suggests that the non-homologous pathway is not involved in repair after heavy-ion irradiation, we observed that DNA-PK was recruited to the DNA damage sites (data not shown). Currently, we are investigating the localization of repair proteins by indirect immunofluorescence and studying the mechanism underlying the suppression of non-homologous end-joining after heavy-ion irradiation.

Fig. 1 (a) X-ray and argon-ion sensitivity of CHO, irs1SF, V3, and EM9 cells. Cells were irradiated with X-rays or argon ions (LET = 300 keV/µm), and radiosensitivity was estimated by the clonogenic survival assay. (b) Effects of trichostatin A (TSA) on the radiosensitivity of CHO, irs1SF, V3, and EM9 cells. Cells were pretreated with TSA (0.1 µM) for 10 h and irradiated with argon ions. Subsequently, the cells were cultured for an additional 14 h in the presence of TSA, and radiosensitivity was estimated by the clonogenic survival assay.

References

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Cell-killing effect of low doses of high-LET heavy ions (VI)

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Non-DNA-targeted effects are not a direct consequence of radiation-induced initial lesions produced in cellular DNA, but are an indirect consequence of intra- and intercellular communication involving both irradiated and nonirradiated cells. These effects include low-dose hyper-radiosensitivity (HRS) and radiation-induced bystander response (RIBR).1,2) RIBR is a cellular response induced in nonirradiated cells that receive bystander signals from directly irradiated cells within an irradiated cell population.1,2) 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 RIBR induced by such low doses of high-LET radiations. We previously found that HRS was induced in normal human fibroblast WI-38 cells that were irradiated with low doses of high-LET argon (Ar) and iron (Fe) ions, suggesting that RIBR was induced.3–5) Nitric oxide (NO) was found to be involved in this process.3–5) Furthermore, we found that reactive oxygen species (ROS), gap-junction intercellular communication (GJIC), and cyclooxygenase-2 (COX-2) protein as well as NO may be involved in Ar-ion-induced bystander signal transfer.4) Here, we examined the effects of a scavenger of ROS (DMSO) and an inhibitor of GJIC (lindane) or COX-2 (NS-398) on Fe-ion-induced RIBR.

Here, we have shown the revised clonogenic survival curve of WI-38 cells irradiated with Fe ions; the curve was obtained by adding new data to previous results3) [Fig.1]. HRS could be clearly observed in cells irradiated with Fe ions at doses lower than 0.2 Gy and was partly suppressed by pretreatment with carboxy-PTIO (c-PTIO), an NO scavenger.

Next, we examined HRS suppression at 0.1 Gy by DMSO, lindane, c-PTIO or NS-398 pretreatment [Fig. 2]. Lindane and NS-398 were dissolved in DMSO. DMSO did not significantly suppress the HRS, although the standard errors of the mean (SEM) were large. In contrast, lindane, NS-398, and c-PTIO significantly suppressed HRS to similar levels. These results suggested that the GJIC and COX-2 mediated pathway as well as NO was also involved in Fe-ion-induced bystander signal transfer. Currently, we are examining the role of the NF-κB/Cox-2/prostaglandin E2 and NF-κB/iNOS/NO pathways,2) which may be activated in bystander cells that have been subjected to ROS and NO, in HRS induced by high-LET radiations.

The electronic supplementary material is available online at: http://www.riken.jp/.../398.pdf

References

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Heavy-ion beam mutagenesis is an effective mutation breeding method \(^1\, ^2\). Although this method has been highly successful with plants, its use for animals has been limited. To extend its application to animals, we plan to acquire more basic data to determine optimal conditions for heavy-ion-beam irradiation using *Drosophila melanogaster* (fruit fly) as a useful model system.

Over the past century, several unique genetics tools have been developed using the fruit fly. A balancer chromosome is one such popular tool and is known to prevent homologous recombination during meiosis. A single balancer line was previously found to be more suitable for stabilizing the mutant isolation system than a double balancer line \(^3\). Therefore, we focused only on third-chromosome events and re-established a third chromosome balancer line before starting the irradiation experiment.

To overcome the instability problem of a graphic record at previous data \(^3\), we decided to use commercial cuvettes with a plane surface [Fig. 1a]. Because most of the vials commonly used for fly maintenance have a curved surface, heavy-ion-beam irradiation condition is uneven in the vials depending on the thickness of curved plastic. To decrease the opportunity of the energy loss in heavy-ion beam by flies overlapping, only two flies were put into each cuvette. Then, six cuvettes were arranged in a commercial container in order to use a uniform irradiation range with an automatic sample changer [Fig. 1b]. To evaluate the stability of the improved mutant isolation system, we subjected the fruit flies to a carbon-ion beam with linear energy transfer (LET) values of \([80\text{keV} / \mu \text{m}]\) at several dose levels \((1.0, 3.0, 10.0, 30.0, \text{and } 60.0 \text{ Gy})\).

To estimate the effect of heavy-ion-beam irradiation, we measured the number of F1 progeny as a biological effect. In this study, males and females were immediately separated after eclosion and were bred for 3 days. Then every two males were put into each cuvette for irradiation [Fig. 1b]. It was performed in the females equally. After irradiation with different heavy-ion-beam doses, the males were provided fresh hares of virgin females every 2–3 days. The females were provided with males and the medium was replaced every 2–3 days. The oviposited eggs were bred, and the number of progeny that survived to the adult stage was determined.

Decrease in the reproductive ability of males was found to be caused by aging and not irradiation. In contrast, the reproductive ability of females did not change during the observation period [Fig.2]. The results for the males showed a linear correlation between the number of progeny and irradiation dose. In contrast, a non-linear curve was observed for the females [Fig. 2]. These data suggest that a radiosensitivity is different between males and females.

We have developed a stable mutant isolation system using fruit flies by using heavy-ion-beam irradiation. Currently, we are establishing various mutants and will be analyzing DNA damage in homozygotes. These data will be helpful for optimizing the irradiation system in the future.

References

Detection of deletions induced by Fe-ion irradiation in *Arabidopsis thaliana* using array comparative genomic hybridization†

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Heavy-ion irradiation mainly induces deletions. The size of deletions increases with increasing linear energy transfers (LETs). Because large deletions are useful for producing null mutations as well as disrupting multiple genes arrayed in tandem, high-LET ion beams are considered powerful mutagens in the field of genome science. However, the determination of deleted chromosomal region(s) in a mutant by using classical PCR-based methods is difficult because designing primers at both sides of a large unidentified deletion is quite difficult. Thus, a method for rapidly detecting deletions at the whole-genome level is desired.

Array comparative genomic hybridization (array CGH) is a powerful tool for detecting deletions at the whole-genome level. In the present study, we herein optimized the array CGH experiment to develop a method for investigating large heavy-ion induced deletions at the whole-genome level. For the array CGH, we used an *Arabidopsis* mutant having downward-pointing flowers (Fe-148-pg1) as an example of a mutant harboring large deletions, which was induced by Fe-ion beam irradiation (90 MeV/nucleon, 640 keV/μm) at a dose of 50 Gy. Through the phenotypic characterization and PCR confirmation, Fe-148-pg1 was found to have a large deletion around the *BREVIPEDICELLUS* (*BP*) gene.

*Arabidopsis thaliana* ecotype Columbia (Col-0) was used as a wild-type plant. The whole-genome sequence of Col-0 was tiled with oligonucleotides that started every 50 bp. Probe lengths were constrained to a minimum of 50 and a maximum of 75 bp. Considering this design, our array was expected to detect deletions of more than 200 bp at the whole-genome level.

The DNA of the wild-type and the mutant plant (Fe-148-pg1) were labelled with Cy5 and Cy3, respectively. Hybridization, washing, and scanning were conducted by Roche NimbleGen Inc (Madison, WI, USA). Raw fluorescence intensity data were obtained from scanned images of the oligonucleotide tiling arrays by using NimbleScan 2.4 extraction software (Roche NimbleGen Inc.). For each spot on the array, log2 ratios of the Cy3-labelled sample to the Cy5 reference sample were calculated.

Candidate deletions were identified as follows. First, regions supported by more than 4 consecutive probes with log2 ratios of over 1.0 were listed as candidate deletions. Then, the candidate deletions were confirmed by performing PCR. For the PCR test, 7 individual M3 plants were tested; when some of the plants showed amplification in the candidate deletion region, the candidate deletion was determined as being heterozygous in the M2 generation. Finally, we detected 7 deletions (Table 1). Candidate deletions supported by the higher log2 ratio tended to be homozygous. However, candidate deletions supported by log2 ratios lower than 1.209 were false positives. As expected, the Fe-148-pg1 had a large deletion covering the *BP* gene; the size of deletion was found to be 90,307 bp by conducting PCR-based confirmation and sequencing. The results suggest that our array platform can detect both homozygous and heterozygous deletions at the whole genome level, although the estimated deletion size is not completely consistent with the actual one.

### Table 1 List of deletion peaks estimated by array CGH in Fe-148-pg1.

<table>
<thead>
<tr>
<th>Chr.</th>
<th>Position</th>
<th>Estimated deletion size</th>
<th>Signal*</th>
<th>Detected deletion</th>
<th>Genetic homogeneity in M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5,129,711</td>
<td>88069</td>
<td>1.500–6.097</td>
<td>○ homogeneous</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7,875,508</td>
<td>81108</td>
<td>3.375–6.047</td>
<td>○ homogeneous</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>17,030,769</td>
<td>467</td>
<td>2.289</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>17,831,368</td>
<td>450</td>
<td>2.076</td>
<td>○ homogeneous</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8,550,408</td>
<td>264</td>
<td>1.992</td>
<td>○ homogeneous</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8,060,900</td>
<td>84816</td>
<td>1.744–1.930</td>
<td>○ heterogeneous</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2,179,908</td>
<td>859</td>
<td>1.777</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2,177,558</td>
<td>814</td>
<td>1.767</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2,185,508</td>
<td>723</td>
<td>1.743</td>
<td>○ heterogeneous</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2,181,208</td>
<td>469</td>
<td>1.209</td>
<td>○ heterogeneous</td>
<td></td>
</tr>
</tbody>
</table>

*When several peaks were detected in a neighborhood, the peaks were combined and the range of signal values were considered.

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References

Exome resequencing reveals mutations in rice induced by heavy-ion beam with LETmax

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Heavy-ion beam irradiation induces mutations at a high rate without severely inhibiting growth at a relatively low dose. Heavy-ion beam with high linear energy transfer (LET) cause greater biological effects than low-LET radiation such as gamma rays and X-rays. LET can be controlled by adjusting the speed of the ions or choosing appropriate ion species. We found that the highest mutation rate is obtained at an LET of 30 keV/μm in Arabidopsis thaliana1). This high-efficiency LET (termed LETmax) mostly induced small deletions2). In rice, the LETmax value was determined as 50-70 keV/μm. However, the mutations induced in rice when we irradiated heavy-ion beams with LETmax were unclear. We performed exome-resequencing analysis to reveal the nature of the mutations in rice induced by heavy-ion beams with LETmax in rice.

We selected seven rice (Oryza sativa L. cv. Nipponbare) mutants induced by LETmax irradiation to perform exome-resequencing analysis. Paired-end libraries were constructed using SeqCap EZ developer library (Roche). Sequencing was performed using Hiseq 2000 (Illumina). Mutations were detected by using SAMtools and BEDTools software. We detected 16 deletions and 14 base substitutions among seven mutants (Table 1). Of the 16 deletions, 14 were small deletions (1-18 bp) and two were large deletions (739 bp and 102158 bp). Of the 16 deletions, 14 were located in coding regions. Two were located in the 5’ untranslated region and intron. Of the 14 base substitutions, 9 induced alteration of the amino-acid sequence of each gene, such as missence mutation, nonsense mutation, and START gain mutation. Four base substitutions were located in 3’ untranslated region. The one remain was a silent mutation. Of the 14 deletions located in coding regions, 1-18 bp deletions constituted 85.7% (12/14) of the total deletions. These findings indicate that heavy-ion beams with LETmax induce small deletions suitable for single-gene disruption in rice.

Table 1. Homozygous deletion and base substitution detected by Exome resequencing

<table>
<thead>
<tr>
<th>Line</th>
<th>Ion / Dose / LET (Gy) (keV/μm)</th>
<th>Deletion size (bp)</th>
<th>Remarks</th>
<th>Base substitution change base</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>3-14</td>
<td>C / 15 / 50</td>
<td>1*</td>
<td></td>
<td>A→G*</td>
<td>Missense mutation (KR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-12</td>
<td>C / 15 / 50</td>
<td>10</td>
<td>intron</td>
<td>A→G*</td>
<td>Missense mutation (Q/R)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-13</td>
<td>C / 15 / 60</td>
<td>9*</td>
<td></td>
<td>A→T</td>
<td>3’UTR</td>
</tr>
<tr>
<td>7-38</td>
<td>Na / 10 / 63</td>
<td>2+1*</td>
<td>Filler DNA</td>
<td>G→T*</td>
<td>START gain mutation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>S’ UTR</td>
<td>T→G</td>
<td>Silent mutation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>739*</td>
<td>disruption of 2 genes</td>
<td>G→T*</td>
<td>Nonsense mutation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C→T*</td>
<td>Missense mutation (G/S)</td>
</tr>
<tr>
<td>6-62</td>
<td>Na / 15 / 63</td>
<td>1*</td>
<td></td>
<td>G→T*</td>
<td>Missense mutation (Q/K)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1*</td>
<td></td>
<td>C→A*</td>
<td>Missense mutation (P/T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13*</td>
<td></td>
<td>A→T</td>
<td>3’UTR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>102158*</td>
<td>disruption of 7 genes</td>
<td>A→T</td>
<td>Nonsense mutation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T→A*</td>
<td>Missense mutation (L/H)</td>
</tr>
<tr>
<td>Ne-1779</td>
<td>Na / 15 / 63</td>
<td>14*</td>
<td></td>
<td>T→A*</td>
<td>Missense mutation</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T→A*</td>
<td>Nonsense mutation</td>
</tr>
<tr>
<td>7-30</td>
<td>Na / 15 / 70</td>
<td>12+1*</td>
<td>Filler DNA</td>
<td>C→T</td>
<td>3’UTR</td>
</tr>
</tbody>
</table>

* Mutations that change the aino-acid sequences

References
mPingSCAR marker, a powerful tool for genetic analysis of agricultural traits in rice mutants induced using ion-beam irradiation

H. Saito,*1 R. Morita,*2 Y. Okumoto,*1 K. Ishii,*2 Y. Hayashi,*2 S. Kogure,*2 K. Ichinose,*2 and T. Abe*2,3

Rice is a major cereal crop that is the dietary staple for more than half of the world’s population. For sustainable production and increased yield, it is important to perform molecular regulation of various agricultural traits. Mutagenesis study is an effective approach to identify novel genes that impart desired agricultural traits and to investigate their functions. Many of the agricultural traits, however, are quantitative traits and controlled by complex multiple genetic networks. Therefore, it is difficult to identify the mutant gene(s) when the F2 population derived from the crosses between distantly related varieties is used to develop several available DNA markers. On the other hand, it is difficult to develop available DNA markers for genetic linkage analysis when using the F2 population derived from the crosses between closely related varieties, to make it easy to identify the mutant gene(s) without multiple genetic segregations.

mPing is reported as the first active miniature inverted-repeat transposable element as well as the first active DNA transposon in rice1). Our previous study revealed that the japonica rice variety Gimbozu harbored over 1000 copies of mPing, whereas most of the closely related japonica varieties harbored less than 50 copies2). Therefore, polymorphic insertions of mPing are available for genetic analysis by using the F2 population crossed between the closely related japonica varieties and Gimbozu3). Here, we evaluate the availability mPingSCAR (sequence characterized amplified region) marker based on the polymorphic insertions of mPing in Gimbozu and mutants derived from closely related varieties.

The imbibition seeds of japonica rice variety (cv. Nipponbare) were exposed to C, Ar, and Ne ions accelerated at 135, 95, and 135 MeV/nucleon, respectively. M1 plants were grown in a paddy field, and M2 seeds were harvested separately from each M1 plant. In our paddy field research of the M2 lines, we isolated a total of 11 mutants in which we observed mutations in the agricultural traits (Table 1). These mutants were crossed with Gimbozu and then the F2 populations were applied to the genetic analysis for mapping the candidate region of the mutant genes by using the mPingSCAR markers.

All the F2 populations, comprising 24–96 plants, showed bimodal distribution within the parental ranges. The mutant type to wild type ratio fit the 1:3 ratio expected for one-locus segregation. These results indicate that each mutant phenotype is conferred by a single recessive mutant gene. The linkage analyses by using 50 selective mPingSCAR markers, which are evenly distributed in all chromosome, identified markers that are closely linked with the mutant phenotypes. Further analyses by using additional mPingSCAR markers around the closely linked marker showed that the mutant genes were located in the region at physical distances of 1.13–13.82 Mb on chromosome 1, 3, 4, 5, 8 and 9 (Table 1). The rice annotation project database (RAP-DB: http://rapdb.dna.affrc.go.jp) showed that 195–973 genes were located in each region. Further, we extracted and isolated the DNA segments, including the exon regions of over 30,000 genes from the five mutant lines, and performed exome analysis by using the next-generation sequencing analyzer, Hiseq2000 (illumina, San Diego, CA, USA). The experimental results showed that a single genomic mutation responsible for the mutant phenotype was identified in the candidate gene (or region) of the four mutant lines.

Although the current progress of next-generation sequencing techniques is remarkable, obtaining the sequence information of the whole genome alone is not enough to identify the candidate gene responsible for the mutant phenotype. Delimiting the candidate genes by using mPingSCAR markers in combination with the sequencing techniques and well developed database information would ensure further efficiency in detecting the mutant gene. Thus, we are confident that mPingSCAR marker is a powerful tool for the genetic analysis of the agricultural quantitative traits.

Table 1 The mapping summary of mutants in this study.

<table>
<thead>
<tr>
<th>Number of analyzed mutants</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromosomes for locating the mutant genes</td>
<td>1, 3, 4, 5, 8, 9</td>
</tr>
<tr>
<td>The size range of the candidate region</td>
<td>1.13–13.82 Mb</td>
</tr>
<tr>
<td>Number of genes located in the candidate region</td>
<td>195–973</td>
</tr>
</tbody>
</table>

References
Identification of mutated sites induced by Ar-ion-beam irradiation in rice


Our team has studied the mutation induction in rice as an effect of heavy-ion-beam irradiation. Rice is a model plant of monocots, and it is useful for identifying mutation sites because its entire genome sequences are available. In previous studies, we showed that C-ion beams (15 Gy, LET 50 keV/\( \mu \)m) and Ne-ion beams (15 Gy, LET 63 keV/\( \mu \)m) cause small size deletion (6 mutant lines include 2 to 12 bp, 1 mutant line include 72348 bp) in rice genome.1)-4) In this study, we report the screening and identification of mutated genes and sites induced by Ar-ion beams.

Last year, we grew 1370 lines of M2 generation obtained by irradiation of imbibed rice seeds with Ar-ion beams (2.5 or 5 Gy, LET 290 keV/\( \mu \)m) in both a greenhouse and a field. Over 100 mutant lines were isolated by screening, and some were suitable for PCR and sequence analysis.

Two mutant lines were selected in a greenhouse 2–3 weeks after germination and identified as mutated sites. Ar5-587 showed the phenotype of plastochron (PLA) mutants, which cause the rapid initiation of vegetative leaves without affecting phyllotaxy5) (Fig. 1a). A sequence analysis revealed that it contained 176-bp deletion and 7-bp insertion in the 1st exon of \( PLA1 \). Ar5-672 showed the phenotype of rice gibberellin (GA)-related mutants, which cause severe dwarfness with wide leaf blades and dark green leaves6) (Fig. 1b). It contained 2,627-bp deletion in the GA positive regulator, \( GIBBERELLIN-INSENSITIVE DWARF 2 \) (\( GID2 \)).6)

Three mutant lines were selected in a field, and identified as mutated sites. Ar5-62 exhibited heading 20 days earlier than wild type (Nipponbare). It contained 65,534-bp deletion and 2-bp (TG) insertion in chromosome 7, and lacked whole \( GRAIN NUMBER, PLANT HEIGHT AND HEADING DATE 7 \) (\( Ghd7 \)).7) which is an important regulator of heading date and yield potential in rice. Ar5-154 exhibited tall phenotype at the heading stage. It contained 47,930-bp deletion in chromosome 5, and lacked whole \( ELONGATED UPPERMOST INTERNODE 1 \) (\( EU1 \)).8) Ar5-90 showed short grains (Fig. 1c) and semi-dwarfness. TAIL-PCR and several sequence analyses revealed that it contained 22,148-bp deletion in chromosome 1, and lacked whole \( DAIKOKU DWARF1 \) (\( D1 \)).9)

The data from these five mutant lines show that Ar-ion beams (5 Gy, LET 290 keV/\( \mu \)m) cause large deletions (>100 bp) in the rice genome.

It is necessary to identify more mutated regions of rice mutants for characterizing the mutations induced by heavy-ion-beam irradiation. We have isolated various rice mutants, and the research is in progress.

Table 1. Isolated mutants by Ar-ion-beam irradiation

<table>
<thead>
<tr>
<th>Line</th>
<th>Phenotype</th>
<th>Gene</th>
<th>Mutation size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar5-62</td>
<td>Early heading</td>
<td>( Ghd7(\text{Os07g0261200}) )</td>
<td>65534-bp + 2-bp</td>
</tr>
<tr>
<td>Ar5-90</td>
<td>Short grain</td>
<td><strong>DAIKOKUDWARF1(\text{Os05g0333200})</strong></td>
<td>22148-bp del</td>
</tr>
<tr>
<td>Ar5-154</td>
<td>Elongation at heading stage</td>
<td>( EU1(\text{Os05g0482400}) )</td>
<td>47930-bp del</td>
</tr>
<tr>
<td>Ar5-587</td>
<td>Plastochron</td>
<td>( PLA1(\text{Os10g0403000}) )</td>
<td>176-bp del = 7-bp del</td>
</tr>
<tr>
<td>Ar5-672</td>
<td>Severe dwarf</td>
<td>( GID2(\text{Os02g0580300}) )</td>
<td>2627-bp del</td>
</tr>
</tbody>
</table>

del: deletion, in: insertion

References

Fig. 1. Photograph of 4-weeks-old seedlings of Ar5-587 (a), 2-weeks-old seedlings of Ar5-672 (b), and seeds of Ar5-90 (c). Bar = 1 cm.

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Relationship between gene expression level and LET immediately after heavy-ion beam irradiation in rice

K. Ishii,*1 R. Morita,*1 T. Hirano,*2 Y. Kazama,*2 T. Ikeda,*1 Y. Nagamura,*1 and T. Abe*1,2

In plant mutagenesis by heavy-ion beam irradiation, linear energy transfer (LET) is one of the most important factors that determines the mutation rate. The most effective linear energy transfer (LETmax) has been defined and reported for Arabidopsis thaliana and rice. In wet seeds of rice, the mutation rate was low at low LET (22.5 keV/μm) and high at LETmax (50–70 keV/μm). The relationship between the mutation rate and LET curved sigmoidally, however, the reason is still unknown. In this study, we tried to reveal the relationship between the gene expression level and LET after heavy-ion beam irradiation and to show whether the change of gene expression corresponds to that of the mutation rate.

Wet seeds of rice (Oryza sativa L. cv. Nipponbare) were imbibed for three days and used as samples. Heavy-ion beam irradiation (C-ions for LETs of 22.5 and 50 keV/μm and Ne-ions for LETs of 63 and 80 keV/μm), RNA extraction, and gene expression analysis were conducted as previously described. All the analyses in this study were conducted on the samples sampled two hours after irradiation.

Out of 45,221 probe sets, 81 probe sets showed significantly (p < 0.01) higher expression levels when irradiated at all LETs (22.5, 50, 63, and 80 keV/μm) than when not irradiated (control). These probe sets contained the homologs of Rad51, Rad21/Rec8, and Artemis, which are the genes involved in DNA double-strand break repair. It was shown that the gene expression analysis successfully reflected the immediate response to the heavy-ion beam irradiation.

It was found that 1575 probe sets showed significantly (p < 0.05) higher expression levels when irradiated at 63 or 80 keV/μm of LET than when not irradiated. On each probe set, the relationship between the expression level and LET was fitted to both the linear and sigmoid functions (Fig. 1).

Moreover, 826 probe sets were significantly (R^2 ≥ 0.8) fitted to either function. Among these 826 probe sets, the relationships between the expression level and LET of 594 probe sets (72%) were fitted better to linear function, whereas those of the remaining 232 probe sets (28%) were fitted better to sigmoid function [Table 1]. In these 232 probe sets, the relationships between the expression level and LET of only three probe sets (0.4%) were coincident with the relationship between the mutation rate and LET.

This is the first observation of the relationship between the gene expression level and LET immediately after heavy-ion beam irradiation. On almost all the researched genes, the relationship between the gene expression level and LET was not coincident with that between the mutation rate and LET. The three exceptional genes can be used as the indicators of LETmax.

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**References**

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**Table 1. Classification of probe sets based on the nature of relationship between their expression level and LET.**

<table>
<thead>
<tr>
<th>Classification</th>
<th>80 keV/μm &gt; ctrl.*</th>
<th>63 keV/μm &gt; ctrl.**</th>
<th>Subtotal</th>
<th>(%)</th>
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<tr>
<td>Fitted to linear function</td>
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<td>35</td>
<td>594</td>
<td>72</td>
</tr>
<tr>
<td>Fitted to sigmoid function</td>
<td>197</td>
<td>35</td>
<td>232</td>
<td>28</td>
</tr>
<tr>
<td>LETmax &gt; 22.5 keV/μm†</td>
<td>(2)</td>
<td>(1)</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>Sum total</td>
<td>756</td>
<td>70</td>
<td>826</td>
<td></td>
</tr>
</tbody>
</table>

*Expression level when irradiated at 80 keV/μm was significantly higher than that of control.
**Expression level was not significantly higher than control when irradiated at 80 keV/μm but significantly higher when irradiated at 63 keV/μm.
†Expression levels when irradiated at 50 and 63 keV/μm were significantly higher than that when irradiated at 22.5 keV/μm.

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Isolation of early-heading mutants induced by heavy-ion radiation in an Indonesian native rice cultivar

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Rice is cultivated as far as 50° N in China and 40° S in Argentina.1) The period from seeding to heading is important for cultivation over a wide latitude. The heading time can be determined by the period of vegetative growth phase, from seedling to panicle primordium initiation, and reproductive phase, from panicle initiation to heading.2) The vegetative growth phase consists of the basic vegetative phase (BVP) and photoperiod sensitive phase (PSP). Cultivated rice is classified as a short-day plant, and it exhibits a wide genetic diversity with respect to sensitivity to photoperiod.3) Tanisaka et al. isolated a longer BVP mutant line induced by γ-irradiation of seeds of the Japanese lowland rice cultivar ‘Ginbozu’ with a longer PSP and shorter BVP.3) Indonesian rice cultivars belonging to the ecotype bulu have a shorter PSP and longer BVP.4) The aim for this study was to isolate a shorter BVP mutant line induced by heavy-ion radiation.

Dry seeds of an Indonesian native rice cultivar (Oryza sativa L. ‘Gemdjah Beton’ belonging to the ecotype bulu) were irradiated with C-ions accelerated to 135 MeV/nucleon by (RRC) at a dose of 125 Gy in April 2011. LET values of the C-ions corresponded to 22.5 keV/μm.

In 2011, the M1 seeds were sown in seedling trays at the end of April and grown in a greenhouse for 4 weeks. Field experiments were conducted in the paddy fields of the Experimental Farm Station, Graduate School of Life Sciences, Tohoku University, in Kashimadai, Osaki, Miyagi, Japan (37º28’, 141º06’). A fertilizer was applied to the paddy fields at rates of 30 kg of N, P, and K/ha. We transplanted 3,000 seedlings (age, four weeks) into a single lot at the end of May. Plants were grown at a density of a plant per hill, with 30-cm spacing between hills. In the middle of September, more than 15 M1 plants flowered one week earlier than the other M1 plants and the wild-type ‘Gemdjah Beton’. We sampled the M2 seeds of these M1 plants in the beginning of November.

In 2012, we planted the M2 seeds of these selected lines at the end of April and then transplanted 50 seedlings per each line in a paddy field at the end of May. One mutant line flowered over about ten days earlier than the other M2 lines and the wild-type ‘Gemdjah Beton’. We sampled the M3 seeds of these M2 plants in the beginning of November.

In 2013, we randomly selected 10 M3 lines from 26 M3 lines and grew 50 plants of each M3 line. The period from transplanting to the heading of wild-type was 17 weeks. Six M3 lines exhibited the segregation from 15 to 17 weeks. The heading day of two M3 lines was the same as that of the wild-type. All plants of another two M3 lines showed heading two weeks earlier than the wild-type. Therefore, we succeeded in isolating early-heading mutant lines induced by heavy-ion radiation.

Seven loci that control the period of BVP were detected in cultivated rice.5) We are currently attempting to determine the locus of the mutant gene that shortens the period of BVP in the mutant lines isolated in this study.

Fig. Early-heading M3 mutant line (left) and wild-type (right) grown in a paddy field on October 18, 2013

References
The wheat plastochron mutant, *fushi-darake*, produced by heavy-ion beam mutagenesis†


Grasses such as wheat (*Triticum aestivum*) are the major source of carbohydrates for humans, and the yield of grain from these crops is largely dependent on inflorescence architecture. A detailed understanding of development in wheat plants is of value not only to wheat breeding but also for basic scientific research. From the large scale mutant panel of diploid einkorn wheat (*Triticum monococcum*) developed by heavy-ion beam irradiation, we identified a mutation that had an abnormally large number of nodes; we termed this mutation *fushi-darake* (*fdk*), which means too many nodes in Japanese.

The *fdk* showed drastic changes to their structural organization compared to wild type (WT) plants in the field (Fig. 1). Contrary to WT, *fdk* plants had 1/2 alternate phyllotaxy with rapid leaf emergence. Consequently, the *fdk* plants had a larger number of nodes and leaves compared to the WT plants. In the *fdk* plants, vegetative shoot branches emerged from the nodes in the upper part of the culm of most tillers (Fig. 1). In these ectopic shoots, normal leaves were produced with 1/2 alternate phyllotaxy. The culms of *fdk* plants were unable to support the heavy upper vegetative shoots, with the result that the plants collapsed onto the ground (Fig. 1).

We examined the timing of leaf unfolding in WT and *fdk* seedlings grown in a growth chamber. The rate of leaf emergence was more rapid in *fdk* compared to WT after the 3-leaf stage. This indicates that rapid leaf emergence in *fdk* resulted from a rapid rate of leaf initiation: the plastochron of *fdk* plants was estimated to be half of that in WT.

To investigate further the morphological differences between WT and *fdk* plants, we carried out an SEM (scanning electron microscope) analysis of shoot apical meristem (SAM) development. SAM development in *fdk* plants was very different to that of WT plants. The SAM elongated but its branch meristems (BMs) resembled leaf primordia rather than spikelet meristems (SMs). Ectopic flat dome-like BMs that were similar to leaf primordia were initiated with 1/2 alternate pattern. These observations, together with those on the morphology of the *fdk*, suggest that the flat dome-like BMs develop into vegetative shoots.

The inflorescence of grass species is composed of a unique unit called the spikelet. When the wheat plant transits from the vegetative to reproductive growth phase (flowering), the SAMs are elongated and spikelet meristems (SMs) initiate as lateral branches. Our SEM analysis of the *fdk* mutant indicated that differentiation of SMs was delayed and the leaf primordia were initiated from branch meristems (BMs) with 1/2 alternate phyllotaxy. These observations suggest that 1/2 alternate phyllotaxy with rapid leaf emergence produced the shortened plastochron in the *fdk* mutant. The SAMs further elongated and produced flat dome-like BMs at the position of the original SMs. We also found that *fdk* plants had vegetative shoot branches emerging from the nodes of upper part of culm of almost all tillers. Thus, our results suggest that these vegetative shoots are likely to be developed from the BMs of elongated SAMs. In conclusion, our findings indicate that the abnormal phenotype of the *fdk* mutant resulted from transformation of SMs into vegetative shoots.

Three plastochron mutants, *plastochron 1* (*pla1*) *2), *pla2* *3, and *pla3* *3), have been identified in rice (*Oryza sativa*). Among them, we found that wheat *fdk* and rice *pla1* mutants show similar phenotypes. These facts indicate that some common genetic cascades are involved in the phenotype of wheat *fdk* and rice *pla1*. The WT gene, *PLASTOCHRON 1* (*PLA1*), encodes a member of a plant-specific subfamily of cytochrome P450, CYP78A11, which potentially catalyzes substances controlling plant development. The similar phenotypes of the *fdk* with *pla1*, suggest that *PLA1* or related genes may be candidates for the *fdk* mutation in wheat.

References

† Condensed from the article in American J. Plant. Sci. 4, 28 (2013)
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![fdk](image1.png) WT

Fig. 1. *fushi-darake* (*fdk*) mutant plant grown in the field and green house. WT: wild-type wheat strain KU104-1.
Constructing $S$-locus deletion mutant in common buckwheat by using heavy-ion-beam irradiation


In *Fagopyrum esculentum* (common buckwheat), the plants exhibit short-styled or long-styled flowers, showing distyly. The floral morphology and intra-morph incompatibility are both determined by a single genetic complex named $S$-locus. Plants with short-styled flowers are heterozygous ($S/s$) and plants with long-styled flowers are homozygous recessive ($s/s$) at $S$-locus. Previously we discovered a new gene, $S$-LOCUS EARLY FLOWERING 3 ($S$-ELF3), which is a candidate gene for short-styled phenotypes of distyly, and its flanking region of about 500 kbp has already been sequenced. Recombination around the $S$-locus is supposed to be restricted, because no recombination between floral morphology and intra-morph incompatibility was observed. Thus, genetic mapping is not possible to determine the genomic region containing the $S$-locus. The purpose of this study is to construct mutants that lack the genomic region around the $S$-locus by heavy-ion-beam irradiation, in order to use the mutants for narrowing down the $S$-locus in the future.

For obtaining an $S$-locus-deletion plant, buckwheat seeds were irradiated with accelerated $^{12}C^{6+}$ ions in doses ranging from 100 Gy to 125 Gy. The linear energy transfer (LET) range of $^{12}C^{6+}$ was from 22.5 keV/µm to 30 keV/µm. The total DNA was extracted from 1,152 plants of $M_2$ growing in the experimental room, and their flower types were investigated. For screening of the $S$-locus-deletion plant, PCR was performed using an $S$-haplotype specific primer set ($Y_{#3}$) obtained using cDNA-Amplified Fragment Length Polymorphism (AFLP) analysis (Yasui et al., in preparation). The $Y_{#3}$ PCR marker showed perfect linkage with the $S$-locus in 1,400 mapping population and was amplified only with short-styled buckwheat plants collected from all over the world. $S$-ELF3 and $Y_{#3}$ marker were located physically distant to each other, because the DNA sequence of $Y_{#3}$ marker could not be found on the 500 kbp BAC contig flanking of $S$-ELF3 (Yasui et al., in preparation). Further, if short-styled plants lack genomic region only around the $S$-locus, the flower type of the plant is expected to become long-styled, but must possess the $Y_{#3}$ marker (Fig. 1).

In 1,152 plants investigated, one showed both positive $Y_{#3}$ PCR amplification and long-styled flowers and was named $S$-del1. Furthermore, $S$-ELF3 and six dominant PCR markers covering the 500 kbp sequence flanking $S$-ELF3 produced no PCR products with $S$-del1 DNA. It is considered that the large genomic region (>500 kbp) harboring the $S$-locus was deleted in the $S$-del1 mutant and that the flower type of $S$-del1 changed from short-styled to long-styled (Fig. 1). These results imply that $S$-ELF3 or its flanking gene controlled short-styled phenotypes.

It is expected that combining PCR amplification with $S$-linked maker ($Y_{#3}$) and phenotyping of flower type on $M_2$ plants is effective in the screening of $S$-locus-deletion plants. We are planning to screen other sets of $M_2$ population. In the near future, we will be able to construct a fine deletion map such as that of the $Y$ chromosome of *Silene latifolia*.

In this study, we observed a phenotypic change from short-styled to long-styled flowers in the mutant progeny. This makes the creating of $S$-del homozygous ($S$-del/$S$-del) plant possible, and the resulting plants will enable us to estimate the role of $s$-haplotype genes and to narrow down the genomic region harboring these genes.

References
DNA marker analysis revealed that the deletion is relatively small in loss-of-apomixis mutants

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Apomixis produces seed progeny that are genetically identical to the mother plant. This process is widely observed among wild plant species but is almost completely absent in major crop species. Apomixis will have a great impact on agriculture through clonal seed production. As the first step of the agricultural use of apomixis, we aimed to isolate the gene(s) controlling apomixis for application in major crops. Guinea grass (Panicum maximum Jacq.), a major tropical forage grass, has some characteristics suitable for the study of apomixis. However, recent studies have suggested that recombination is suppressed at the apomixis-controlling locus in guinea grass. To narrow down the apomixis-controlling genomic region, we developed deletion mutants for this region by using irradiation with heavy-ion beams.1), 2), 3) In a previous study, we found that two mutant lines (SM-1 and SM-2) showed different AFLP patterns between M2 progenies within each line.3) This result suggested that they lost the apomictic pathway of reproduction and propagated using the sexual mode of reproduction. In the present study, we analyzed the deletion size of these loss-of-apomixis mutants with apomixis-specific sequence-tagged site (STS) markers.

The M1 plants of SM-1 and SM-2 were generated from dry seeds (an apomictic cultivar ‘Natsukaze’) irradiated with 20Ne10+ (63 keV/μm) ions at 20 Gy, respectively.2) Approximately ten M2 plants of each line were grown in a field. DNA from five M2 plants of each line were extracted from leaves and analyzed using polymerase chain reaction (PCR) with 83 apomixis-specific STS markers. The SM-1-1, SM-1-4, and SM-1-6 plants were blighted before analysis.

Fig. 1 shows that SM-1 lost four markers (CA-A14-252, CI-A1-296, CI-T1-217, and CK-T2-374) among the 83 analyzed markers (4.8%). In case of the SM-2 line, two markers (CA-A3-354 and CA-A11-355) among the 83 analyzed markers (2.4%) were lost in only three M2 plants (SM-2-3–5). Fig. 1 also shows that SM-2-1 possessed all markers, suggesting that it had an intact apomixis chromosome. In contrast, SM-2-2 lost all markers, suggesting that it lost the entire apomixis chromosome. These results can be explained by the exchange of chromosomes during the process of sexual reproduction in SM-2. SM-2-3–5 were suggested to have a partially deleted apomixis chromosome.

These results suggested that the size of the deletion in SM-1 and SM-2 was relatively small, probably several percent of the apomixis-controlling genomic region. Previously, we obtained 22 other mutants in which the apomixis-controlling genomic region was partially deleted, and these mutants lost 2–12 STS markers out of a total of 48 markers (4.2–25%).3) Compared to these mutants, the size of the deletion in SM-1 and SM-2 were suggested to be relatively small. However, we could not estimate the exact physical size of these deletions because the whole DNA sequence of this region has not been obtained. Sequencing and scaffolding of BAC clones of this region is currently in progress. This result will be useful in estimating the exact size of the deletions and in searching for the genes within these deletion regions.

![Fig. 1](image.png)

Fig. 1  PCR analysis using STS markers lost in SM-1 or SM-2 mutant line. Five M2 individuals were analyzed in each mutant line. An apomictic cultivar ‘Natsukaze’ (NK) and a sexual line ‘Noh PL1’ (Noh) were used as the positive and negative controls, respectively.

References

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Effect of C-ion beam irradiation on survival rates and flower color mutations in statice (*Limonium sinuatum* Mill.)

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Statice (*Limonium sinuatum* Mill.) is one of the popular cut flowers for flower arrangement or flower tribute because of the long-term keeping quality of the flower and wide variety of flower color. Generally, flower color of statice, which is defined by the color of the calyx, can be classified into five groups: purple, pink, blue, yellow, and white. Wakayama Prefecture, which is the major statice-producing region of Japan, has developed 7 cultivars by cross-breeding. However, a superior pink cultivar has not been developed. Therefore, we aimed to obtain statice mutants with pink calyx by heavy-ion beam irradiation. In this study, we investigated the suitable doses of heavy-ion beam irradiation for statice and flower color mutations.

Multiple-shoot cultures of statice Kishu Fine Grape were irradiated using C-ion beam (LET 23 keV/μm) at doses of 5–30 Gy. After irradiation, the samples were cut into single shoot segments and transferred to a medium supplemented with 0.2 mg/l α-naphthaleacetic acid for root induction. Eight weeks after irradiation, the surviving shoots and rooted shoots were counted (Fig. 1). The survival frequency of the shoots was found to be 95.5% when the irradiation dose was 5 Gy. On the contrary, at doses of over 10 Gy, the survival frequency apparently decreased. The rooting frequency of the shoots decreased from 87.7% at 0 Gy to 29.9%. No root formation was observed at 5 and 10 Gy. These results suggest that the suitable dose of C-ion irradiation for statice is less than 5 Gy.

Thus, for the improvement of flower color, we irradiated one purple cultivar (Kishu Fine Grape) and two light purple cultivars (Kishu Fine Lavender and Kishu Star) with C-ion beams at doses of 2 and 5 Gy in our further experimentation. Four weeks after the irradiation, the rooting rates of Kishu Star were 87.5%, 87.3%, and 67.7% at 0, 2, and 5 Gy, respectively. Similar results were obtained for the other cultivars Kishu Fine Grape and Kishu Fine Lavender (data not shown). The rooted plants were acclimated to outside conditions and subsequently transplanted to pots containing soil.

Table 1 shows the flower-color mutants obtained in this study. Among the 3 cultivars, Kishu Fine Lavender and Kishu Star showed flower color mutations. However, we failed to obtain the mutants from Kishu Fine Grape. Six mutants were induced from Kishu Fine Lavender. All six mutants exhibited paler flower color (e.g., Royal Horticulture Society [RHS] Color Chart value N91D) than that of the original cultivar (RHS Color Chart value N87D). Ten mutants were induced from Kishu Star. Among them, 5 and 2 were pale and deep color mutants, respectively (Fig. 2). The other 2 mutants changed to reddish color (e.g., RHS Color Chart value N81C).

Although a pink-colored mutant was not obtained in this study, we confirmed that flower color mutants of statice could be obtained by heavy-ion beam irradiation. Furthermore, other interesting mutations were found, such as small flower, variations in the calyx shape, and no hair on the peduncle (data not shown). These results suggest that heavy-ion beam irradiation is effective for developing various useful mutants in statice. Mutant screening for the above-mentioned aim are currently in progress.

### Table 1. Type and number of flower color mutants obtained by C-ion beam irradiation.

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>Dose (Gy)</th>
<th>No. of plants investigated</th>
<th>Pale color</th>
<th>Deep color</th>
<th>Reddish color</th>
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<tr>
<td>Kishu</td>
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</table>

Fig. 1. Effect of C-ion beam irradiation on the survival and rooting rates in statice Kishu Fine Grape. Data were recorded 8 weeks after the irradiation.

Fig. 2. Flower color mutants of statice Kishu Star. Royal Horticulture Society Color Chart values are indicated in parentheses.

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Flower color mutants of chrysanthemum obtained using C-ion beam irradiation

K. Tamaki,*1 M. Yamanaka,*1 Y. Mizutani,*1 Y. Hayashi,*2 T. Hirano,*1 and T. Abe*2,*3

Chrysanthemum is a major agricultural product in Hyogo Prefecture. We tried to use ion beams to induce flower color variation in chrysanthemum. We irradiated 53 cultivars of chrysanthemum with carbon beams. We have previously reported their mutant frequency and flower color mutants.1) We tried to increase variation in flower color by using a single origin. We irradiated flower color mutants from ‘Benitsubaki’ with C-ion beams and obtained more mutants. ‘Benitsubaki’ is a purplish red small mum that blooms at the end of November (Fig. 1). In 2009, we irradiated cuttings with C-ion beams (energy, 135MeV/nucleon; LET, 23 keV/μm) at doses of 4 and 6 Gy. After irradiation, herbaceous cutting was performed, and four weeks later, fixed planting was carried out in a glass house. Cultivation conditions were no pinching and no picking the bud. Other conditions for cultivation were standard. At the time of full bloom, we observed the mutation rate with respect to flower shapes. Stability of the mutation was confirmed in 2010. We irradiated the cuttings of VT4Pi and VT6RB mutants with C-ion beams at doses of 4 and 6 Gy in 2011. Other conditions were the same in 2009. Relative DNA contents of somatic nuclei in ‘Benitsubaki’ and mutants derived after re-irradiation were compared using flow cytometry.

The mutation frequencies of ‘Benitsubaki’ were 6.3% at 4 Gy and 4.3% at 6 Gy. We obtained two flower color mutants, deep pink (VT4Pi) and red (VT6RB), that bloomed at the end of November. These mutations were stable in 2010. Since the flower color of VT4Pi was not different from that of the original ‘Benitsubaki’, we tried re-irradiation to obtain more varied mutants.

The mutation frequencies of VT4Pi were 7.8% at 4 Gy and 3.9% at 6 Gy. We obtained 4 flower color mutants from VT4Pi (Fig. 1). One of them was double-colored, purplish red outside and white inside (VT4Pi6WT-Wh), that bloomed at the middle of December. Two mutants were also double-colored flowers that bloomed at the end of December and were deep pink outside and white inside (VT4Pi6Pi-Wh) and light pink outside and white inside (VT4Pi6LtPi-Wh). The fourth mutant was also double-colored, orange outside and yellow inside (VT4Pi6Or-Yr) and bloomed at the middle of December. The difference among three mutants, VT4Pi6WT-Wh, VT4Pi6Pi-Wh and VT4Pi6LtPi-Wh, was the strength of the color. The mutation frequencies of VT6RB were 7.3% at 4 Gy and 14.3% at 6 Gy. The yellow mutant (VT6RB6Yr-RB) bloomed in the middle of December (Fig. 1).

Although this mutant had a reddish bud, the flowers were bright yellow with green core.

Flower color changes under the influence of cultivation temperature. We are currently carrying out cultivation experiments to reveal the effect of temperature on the blooming period and flower color of these mutants. In terms of blooming period, all the obtained mutants bloomed late. The mutation frequency by re-irradiation was higher than that after a single irradiation. The relative DNA contents in the mutants obtained after re-irradiation did not decrease to that in ‘Benitsubaki’. These results indicate that ion-beam re-irradiation of mutants is effective in increasing the variety of mutants.

Fig. 1 ‘Benitsubaki’ and its flower color mutants

References

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Effects of heavy-ion-beam irradiation on flower-color mutation in chrysanthemum


Kagoshima Prefecture is a leading spray-mum production region in Japan. Until date, we have developed more than 50 spray-mum cultivars by cross breeding; in addition, we also performed mutation breeding by using heavy-ion-beam irradiation. In this study, we investigated the effects of heavy-ion-beam irradiation on flower-color mutation of spray-mum.

We irradiated cuttings of the spray-mum cultivar ‘Southern Chelsea’, which was developed in Kagoshima Prefecture, with C-ion (LET 23 keV/μm) at doses of 2–5 Gy, Ne-ion (LET 62 keV/μm) at doses of 2 and 5 Gy, Ar-ion (LET 280 keV/μm) at doses of 2 and 5 Gy, and X-ray at doses of 5–20 Gy. After the irradiation, we planted the cultivars in a greenhouse and investigated the variations in flower-color mutation.

Among 4,741 irradiated branches, we obtained 468 branches with flower-color mutations (Table 1). The mutants from ‘Southern Chelsea’ with pink flower showed flower colors of white, light pink, deep pink, yellow, light reddish yellow, and deep reddish yellow (Fig. 1).

On the basis of the analysis of flower pigments in the mutants, the relationship between the variations in the amount of the pigments and colors was considered, as shown in Figure 2. The mutants with deep pink flowers had higher anthocyanin content in their flowers than that in ‘Southern Chelsea’, and the mutants with white, yellow, and light pink flowers had low anthocyanin content. The light reddish yellow, deep reddish yellow, and yellow flowers were because of increased carotenoid content. The flower-color mutation was high in the order of deep reddish yellow, white, and light reddish yellow.

Table 1. Flower-color mutation induced by heavy-ion-beam and X-ray irradiations.

<table>
<thead>
<tr>
<th>Variation source</th>
<th>Deep reddish yellow</th>
<th>Light pink</th>
<th>Light reddish yellow</th>
<th>Yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line class and dose (Gy)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4.8</td>
</tr>
<tr>
<td>C</td>
<td>2</td>
<td>84</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Ne</td>
<td>2</td>
<td>354</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Ar</td>
<td>2</td>
<td>354</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>X-ray</td>
<td>2</td>
<td>354</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

In the irradiations at 5 Gy, the flower-color mutation rate was high in the order of Ne-ion, C-ion, Ar-ion, and X-ray (Table 1), indicating that the heavy-ion-beam irradiations were more effective for the induction of flower-color mutation than that by X-ray irradiation. Since the majority of the shoot tips died after Ar-ion irradiation at 5 Gy, mutant screening should be performed at low-dose irradiations such as 2 Gy.

The mutation rate for yellow flowers was 0–0.2% after C-ion, Ne-ion, and X-ray irradiations. On the other hand, the mutation rate after Ar-ion irradiation was 0.9% and was higher than that after the other irradiations (Table 1). In addition, some mutants showed flower-shape and color variations at the tips of the petals, such as to yellow or white (Fig. 1-B). These variations were only observed in the Ar-ion irradiation, suggesting that the Ar-ion beam at a LET of 280 keV/μm might have more different effects on mutation induction than that by the lower LET Ar-ion-beam irradiation.

The results in this study indicated that heavy-ion-beam irradiation can induce a broad spectrum of mutant phenotypes in chrysanthemum. Currently, we are screening the mutants derived from Ar-ion irradiation.

![Fig. 1 Spectrum of mutant phenotypes. (A) Flower-color mutations. (B) Color variations at the tips of the petals and variations in the flower shape.](image)

![Fig. 2 Relationship between the amount of pigments and color variations in the mutants.](image)
Effect of heavy-ion beam irradiation on seeds reduction of ‘Konta’ kumquat fruit

K. Tomura,1 T. Teraoka,2 T. Nakajima,1 Y. Kobayashi,1 I. Sawano,3 Y. Hayashi,4 N. Fukunishi,4 T. Abe4

‘Konta’ kumquat was found as a bud mutant in the field by a farmer in Shizuoka Prefecture. ‘Konta’ has some unique characteristics compared with ‘Neiha’ kumquat. It has higher sugar content and lesser citric acid content than ‘Neiha’ kumquat, which tastes extremely good. On the other hand ‘Konta’ has more seeds (6-7) than ‘Neiha’ (5-6).1 If we can develop seedless ‘Konta’, it will be a valuable cultivar. Especially since ‘Konta’ has multi-embryonic seeds, it is difficult to breed this cultivar.

In this study, we investigated the effect of heavy-ion beam irradiation on seed reduction and attempted to obtain a mutant of ‘Konta’ kumquat fruit with reduced number of seeds. In 2007 and 2008, dormant scions from the hard branches of ‘Konta’ kumquat were irradiated with 12C and 20Ne at a dose of 10Gy (135 MeV/u, 61.1 keV/μm). After irradiation, the scions were grafted on Poncirus trifoliata to create the vegetative mutant (vM1) generation. After sprouting, the treetops were subjected to cutting back at least 3 times. As the control, original ‘Konta’ was grafted on P. trifoliata. These plants are pollinated naturally, and superfluous fruits were not removed for securing the number of fruits.

We counted the number of perfect seeds on the equatorial cut surface of all the fruits obtained from Ne-ion irradiated vM1 and C-ion irradiated vM1 in 2011 and 2012. We considered fruits with 0-2 perfect seeds as “seeds reduced fruit” (Fig. 1) and calculated the ratio of seeds reduced fruits (i.e., number of fruits with two or less seeds/number of examined fruits).

For Ne-ion beam irradiation, the appearance ratio of seeds reduced fruit in vM1 plants was 6%, while that in the control was 1% (Table 1). One of thirty-six vM1 plants bore more than 80% seeds reduced fruits by Ne-ion beam irradiation. For C-ion beam irradiation, the appearance ratio of seeds reduced fruit in vM1 plants was 13%, while that in the control was 8% (Table 2). In four plants, the ratio of seeds reduced fruit per vM1 plant exceeded 70% by C-ion beam irradiation. The ratios of seeds reduced fruit per control plant were less than 10% in both the irradiation studies. These results indicate that heavy-ion beam irradiation is effective for seed reductions in ‘Konta’ fruit.

We selected the vM1 plants with high seeds reduced fruits rate (Fig. 2). Furthermore, we isolated the branches bearing more seeds reduced fruits from these selected vM1 plants. The fixation of seeds reduction is currently under investigation.

![Fig. 1 fruit surfaces after equatorial cuts. Perfect seeds (left) and reduced seed (right)](image)

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Number of vM1</th>
<th>Number of total fruits</th>
<th>Number of perfect seeds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>36</td>
<td>2125</td>
<td>128(6%) 1997(94%)</td>
</tr>
<tr>
<td>Control</td>
<td>29</td>
<td>1651</td>
<td>21(1%) 1630(99%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Irradiation</th>
<th>Number of vM1</th>
<th>Number of total fruits</th>
<th>Number of perfect seeds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>128</td>
<td>7307</td>
<td>962(13%) 6345(87%)</td>
</tr>
<tr>
<td>Control</td>
<td>5</td>
<td>208</td>
<td>17(8%) 191(92%)</td>
</tr>
</tbody>
</table>

![Fig. 2 Examples of vM1 plant with high seeds reduced fruits rate. Vertical bars represent ± SD (Ne: n = 29, C: n = 5).](image)

References


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1 Fruit Tree Res. Center, Shizuoka Res. Inst. of Agric. and For.
2 present: Shizuoka Agric. Promotion div.
3 present: Shizuoka Toubu Agric. and For. Office
4 RIKEN Nishina Center

Table 1. Appearance of seeds reduced fruits of ‘Konta’ by Ne-ion beam irradiation

Table 2. Appearance of seeds reduced fruits of ‘Konta’ by C-ion beam irradiation
Rapid evaluation of mutational effects resulting from heavy-ion irradiation of *Undaria pinnatifida*


*Undaria pinnatifida*, called wakame in Japan, is a major commercial seaweed. Recently, there has been a demand for new cultivars with enhanced properties, such as high yield, high environmental adaptability, or high concentration of available contents for human health, to expand the market for wakame. Therefore, we performed the mutation breeding of *U. pinnatifida* through heavy-ion-beam irradiation.\(^1\) Optimization of the dose and linear energy transfer (LET) in heavy-ion mutagenesis is essential for efficient mutant induction.\(^2\) However, a method for evaluating mutation frequency has never established in *U. pinnatifida*, and the optimization is still difficult. Moreover, in macroalgae, the analysis of mutation frequency in M\(_2\) generation consumes much time and requires large space. In the present study, we irradiated zoospores with heavy-ion beams. Because the female and male gametophytes developed from the zoospores are in the haploid stage of its life cycle, mutant screening can be performed in M\(_1\) generation. Through the mutant screening and investigation of the mutant phenotypes, we tried to develop a method for the effectiveness of heavy-ion mutagenesis.

Samples (3 cm × 3 cm) of sporophylls of *U. pinnatifida* were irradiated with C ions (LET: 30.0 keV/μm) at a dose of 0–25 Gy or Ar ions (LET: 280 keV/μm) at a dose of 0–10 Gy. The irradiated pieces were placed in beakers filled with sterilized seawater, and zoospores were induced. The method for evaluating mutation frequency has never established in *U. pinnatifida*, and the optimization is still difficult. Moreover, in macroalgae, the analysis of mutation frequency in M\(_2\) generation consumes much time and requires large space. In the present study, we irradiated zoospores with heavy-ion beams. Because the female and male gametophytes developed from the zoospores are in the haploid stage of its life cycle, mutant screening can be performed in M\(_1\) generation. Through the mutant screening and investigation of the mutant phenotypes, we tried to develop a method for the effectiveness of heavy-ion mutagenesis.

Fig. 1 Effect of heavy-ion irradiation on gametophyte development. The formation rates after 3 weeks of culture are expressed as the mean of two individual experiments.

![Fig. 1 Effect of heavy-ion irradiation on gametophyte development.](image)

When we investigated the growth of the gametophytes developed from the irradiated zoospores, the number of developed gametophytes decreased with increasing irradiated dose (Fig. 1). A comparison between C-ion and Ar-ion irradiation revealed that the Ar-ion irradiation has high biological effect to the cell division or cell growth. After 5 weeks of culture, some mutants in cell shape, cell size, and intracellular structure were observed. One of the mutants showed a reduction in cell elongation (Fig. 2C, D). In the untreated control, the female gametophyte cells were larger than the male gametophyte cells (Fig. 2A, B). There were at least two types of cell elongation mutants: 

- small-cell type (Fig. 2C) and large-cell type (Fig. 2D). One possible interpretation is that the small-cell type and the large-cell type cells were induced in male and female gametophytes, respectively. The mutation frequency for the cell elongation mutant tended to increase in a dose-dependent manner (data not shown). Therefore, the mutants can be used as an indicator for investigating the effectiveness of heavy-ion mutagenesis. We will evaluate LET-dependent effects for mutation induction in *U. pinnatifida* using this method.

Fig. 2 Morphological mutants induced by C-ion irradiation. The male (A) and female gametophytes (B) from unirradiated zoospores were cultured for 5 weeks. The cell elongation mutants after 5 weeks of culture derived from the C-ion irradiation at 5 Gy (C) and 12.5 Gy (D). Bars indicate 20 μm.

References
**Effects of heavy-ion beam irradiation on sporophyte survival and growth in Undaria pinnatifida**

Y. Sato,*1,*2 T. Hirano,*3 Y. Hayashi,*4 M. Kasahara,*1 N. Fukunishi,*4 T. Abe*3,*4 and S. Kawano*2

Undaria pinnatifida, called wakame in Japanese, is one of the most popular seaweed in Japan, Korea, and China. It is the most important cultivated seaweed in Iwate and Miyagi Prefectures in Japan. In recent years, the wakame yield has been decreasing because of changing environment, unimproved productivity, and damage due to Tsunami. For the purpose of yield restoration and sustainable growth market of U. pinnatifida, the development of new cultivars with properties such as high yield or high environmental adaptability is necessary. We used heavy-ion-beam irradiation to induce mutagenesis in U. pinnatifida for the production of new cultivars.1) However, since not enough studies have been conducted in the mutagenesis of marine algae, it is important to produce efficient mutation breeding in U. pinnatifida to assess the relationship between survival rate after irradiation and mutation frequency. In this study, we irradiated U. pinnatifida sporophytes with C-ion and Ar-ion beam and analyzed the effects on sporophyte survival and growth in the M1 generation toward successful mutant screening in M2 generation.

Sporophytes of U. pinnatifida were obtained after fertilizing the male and female gametes. The sporophytes of 1-mm length were transferred into 15-ml plastic tubes for C-ion irradiation and hybribags for Ar-ion irradiation, both containing sterilized seawater, and were irradiated at dose ranges of 0–25 Gy (C ions) or 0–10 Gy (Ar ions). Each tube or hybribag contained 50 sporophytes. After the irradiation, the sporophytes were cultivated in 500-ml Erlenmeyer flasks containing 1/4 PESI medium, 2) with aeration, at 15°C, photoperiod of 12 h/12 h (light/dark), and a light intensity of 90 μmol photons m⁻² s⁻¹. The survival rate was measured after 3 weeks of culture. The plants surviving and reaching 20-mm with in the culture period were further cultivated in the Rotating and Flowing Land Tank System (PAT.P) at 10°C, photoperiod of 12 h/12 h (light / dark), and a light intensity of 180 μmol photons m⁻² s⁻¹ for 8 weeks. The total length and fresh weights of all the sporophytes were measured after blotting them dry.

In the flask cultivation after irradiation, dead sporophytes were observed. Almost all the dead sporophytes had formed within 1 week of cultivation and had wrinkled leaves (data not shown). The survival rates after 3 weeks of cultivation were decreased with increasing irradiation dose (Fig. 1). The survival rates in sporophytes irradiated using C-ion beam in sporophytes irradiated using C-ion beam were almost similar to those in female gametophytes derived from sporophylls irradiated using C-ion beam.1)

The surviving sporophytes of 20-mm length were transferred to the land tanks. The total length and individual weight differed between the doses and ion species. The sporophytes irradiated with 2 Gy of C-ion beam were the largest: the maximum length and weight were 75 cm and 45.6 g, respectively. These values were approximately two times higher than those for the largest sporophytes in the control. The sporophytes irradiated with 25 Gy of C-ion and 2.5–10 Gy of Ar-ion remained withered for up to 2 weeks after culturing in the tanks.

The sporophytes irradiated with 2-12.5 Gy of C-ion and 1 Gy of Ar-ion formed sporophylls after cultivation for 2 months. Currently, we have cultured and performed mutant screening of the sporophytes in the M2 generation. We will analyze the next generation of the large sporophytes obtained after C-ion irradiation at 2 Gy to confirm whether the phenotype is inheritable.

![Fig. 1 Survival rates of young sporophytes irradiated with C-ion and Ar-ion beams.](image1)

![Fig. 2 Total length and individual weight of Undaria pinnatifida sporophytes measured 8 weeks after the irradiation with C-ion and Ar-ion beams.](image2)

**References**

2) M. Takewaki: Phycologia 6, 62 (1966)
**Mutation rates of Parachlorella kessleri** by heavy-ion-beam irradiation and classification of their genomic deletion types

T. Yamazaki,*1,*2 S. Ota,*1,*2 K. Oshima,*1 M. Hattori,*1 Y. Kazama,*1 T. Abe,*3,*4 S. Kawano,*1,*2

Consumption of fossil fuels such as petroleum oil not only depletes a finite resource but also increases carbon dioxide levels, which causes global warming. Because of carbon fixation, plants can contribute to the reduction of carbon dioxide levels. Moreover, biofuels from plants have been considered as substitutes for fossil fuels. Microalgae, which perform photosynthesis like terrestrial plants, have been attracting attention as a feedstock of biodiesel production in recent years. To increase the production of biomass and improve the amount of biofuel from microalgae, the common process used is the isolation of strains with high biomass productivity and/or high oil content from the natural environment and optimization of culture conditions for the isolated strains. However, this strategy does not necessarily obtain the best strains. Therefore, we artificially modified the genome of microalgae by using the heavy-ion-beam irradiation. The heavy-ion beam is considered a mutagen that causes the partial deletion of genomic DNA very effectively, and it can also be used to breed a variety of organisms, including flowering plants. Because little is known about breeding of unicellular microalgae by using heavy-ion-beam irradiation, evaluation of its effectiveness is necessary.

In this study, we used a green microalga, Parachlorella kessleri, the draft genome of which has been determined by our group. A search for the draft genome sequence revealed that NR, NRT, and NIR are single-copy genes, and NAR is duplicated into two genes (NAR1-1, NAR1-2). The transcript of NAR1-1 was not detected in transcriptome data, suggesting that nitrate is metabolized to ammonia through a single pathway (NRT-NR-NAR-NIR pathway) in P. kessleri (Fig. 1A). Therefore, a P. kessleri mutant that can grow in an ammonia-containing medium but not in a nitrate-containing medium is considered to have a defective nitrate assimilation pathway.

P. kessleri cells were irradiated by heavy-ion beams of different doses and nuclear species, and then screening was performed using following steps: (1) a single clone derived from irradiated P. kessleri cells was inoculated in a TAP medium containing ammonia; (2) After the P. kessleri cells were grown, they were inoculated in both TAP medium and a modified TAP medium containing only nitrate as a nitrogen source; (3) a putative mutant grow in the TAP medium, but not in the modified TAP medium. Doses and nuclear species used for the screening are carbon ions the

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**Table 1. Mutation frequency by heavy-ion-beam irradiation**

<table>
<thead>
<tr>
<th>Nuclear species</th>
<th>Dose (Gy)</th>
<th>Isolated clone number</th>
<th>Positive clone number</th>
<th>Frequency (%)</th>
<th>Survival rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>25</td>
<td>4005</td>
<td>0</td>
<td>0.00</td>
<td>n.d.</td>
</tr>
<tr>
<td>Ar</td>
<td>25</td>
<td>4007</td>
<td>4</td>
<td>0.10</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>4007</td>
<td>3</td>
<td>0.07</td>
<td>50</td>
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<tr>
<td></td>
<td>50</td>
<td>4012</td>
<td>4</td>
<td>0.10</td>
<td>28</td>
</tr>
</tbody>
</table>

*Ota et al. (2013)*

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Next, the PCR fragment analysis and restriction fragment length polymorphism-PCR analysis were performed for the NR gene. However, there was no difference between the wild-type and all mutants, suggesting that the deletions of genomic DNA by heavy-ion-beam irradiation are very small in microalgae. Currently, we are performing re-sequence analysis using the next generation sequencer IonProton for the 11 mutants, expecting a detailed comparison of the deletion pattern of a set of genes involved in nitrate metabolism, including the NR gene.

This study was supported by JST, CREST (to SK).

**References**

IV. OPERATION RECORDS
Program Advisory Committee meetings for nuclear physics and for material and life science

K. Yoneda, K. Ishida, H. Ueno, and H. Sakai

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 2013, 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 RAL and RIBF.

NP-PAC

The 12th and 13th NP-PAC meetings were held on June 28 and 29, 2013, and December 13 and 14, 2013, respectively. The outcome of these NP-PAC meetings is summarized in Table 1.

After the 12th NP-PAC meeting, eight NP-PAC members were renewed. The PAC members of the 12th and 13th NP-PAC meetings are as follows:
12th NP-PAC meeting: R. Tribble (Texas A&M, the chair), R.F. Casten (Yale Univ.), H. Emling (GSI), T. Glasmacher (MSU), M. Huyse (KU Leuven), T. Kishimoto (Osaka Univ.), M. Lewitowicz (GANIL), M. Huyse (KU Leuven), T. Nakamura (Tokyo Tech.), T. Nakatsukasa (RNC), A. Ono (Tohoku Univ.), C. Scheidenberger (GSI), T. Shimoda (Osaka Univ.), F.-K. Thielemann (Univ. of Basel), M. Yahiro (Kyushu Univ.), and Y. Ye (Peking Univ.).
13th NP-PAC meeting: M.N. Harakeh (KVI, the chair), R.F. Casten (Yale Univ.), H. Emling (GSI), H. Iwasaki (Michigan State Univ.), C.J. (Kim) Lister (UMass Lowell), T. Nakamura (Tokyo Tech.), T. Nakatsukasa (RNC), A. Ono (Tohoku Univ.), C. Scheidenberger (GSI), T. Shimoda (Osaka Univ.), F.-K. Thielemann (Univ. of Basel), M. Yahiro (Kyushu Univ.), and Y. Ye (Peking Univ.).

ML-PAC

The 10th ML-PAC meeting was held on July 2 and 3, 2013. Before the meeting, one of the PAC members from RAL was renewed. In this meeting, twenty-four RAL proposals and seven RIBF proposals were reviewed. The summary of the outcome of the meeting is given in Table 2.

The 10th ML-PAC members are J.-M. Poutissou (TRIUMF, the chair), A. Amato (PSI), T. Azuma (RIKEN), A. Miller (ISIS, RAL), R. Kadono (KEK), A. Kawamoto (Hokkaido Univ.), N. Kojima (Univ. of Tokyo), K. Kubo (ICU), D.E. MacLaughlin (UC Riverside), S. Maekawa (JAEA), P. Mendels (Univ. Paris, Orsay), H. Yamase (NIMS), S. Yoshida (Yokohama City Univ.), 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
Beam-time statistics of RIBF experiments

K. Yoneda, H. Ueno, and H. Sakai

This report describes the statistics of the beam times (BTs) at the RIBF facility in Fiscal Year (FY) 2013. In the following, the BTs are categorized into two groups: high-energy-mode and low-energy-mode BTs. In the former, beams were delivered in the acceleration scheme of AVF, RILAC, or RILAC2 → RRC → (IRC → IRC →) SRC, where the accelerators in parentheses can be skipped in the cascade acceleration, depending on the beam species used. In the latter, the acceleration scheme is AVF or RILAC (→ RRC).

BTs in the high-energy mode were scheduled in April – July 2013 and in the latter half of March 2014, 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 particular, we skipped the October – December period in FY2013, where we regularly assigned high-energy-mode BTs so far. This is mainly due to the rise in electricity costs and lack of operation budget. Big demand of large-scale maintenances, including replacement of the RRC main colis, is also the reason. In the high-energy-mode BTs in FY2013, the primary beams of $^{18}$O, $^{124}$Xe, and $^{238}$U were delivered to users, for $T_{BT} = 60.5$ days to conduct 13 experimental programs approved by the RIBF Program Advisory Committees$^1$. Including $T_{BT} = 14.3$ days used by RIKEN for facility development programs, defined as machine study (MS) experiments, $T_{BT} = 74.8$ days was used in total for the experiments in the high-energy mode. The data summary of the high-energy-mode BTs in FY2013 is shown in Fig. 1 as a bar chart, where the total BTs provided for the users’ experiments and those provided for the MS experiments are indicated by blue and orange bars, respectively.

The data summary of FY2013 BTs conducted in the low-energy mode is shown in Fig. 2. The BTs are classified by the accelerator operation modes AVF, RILAC, and RRC. Experiments in which the AVF or RILAC was operated in the stand-alone mode were able to be conducted in parallel with the high-energy-mode BTs. As seen in Fig. 2, the total low-energy-mode BT in FY2013 was reduced by 50 days compared with that in FY2012. This reduction is simply due to the long-term maintenances of RILAC and RRC scheduled in FY2013. $T_{BT} = 140.7$ days was used for 75 experiments in FY2013, which is more than 68 experiments conducted in FY2012.

References

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IV. OPERATION RECORDS

Fee-based distribution of radioisotopes

T. Kambara,*1 A. Yoshida,*1 H. Haba,*1 J. Kanaya,*1 S. Shibata,*1 Y. Wakitani,*1,*2 and S. Yanou*1,*2

RIKEN distributes radioisotopes (RIs) produced at RIBF to users in Japan for a fee. This project was started in October 2007 in collaboration with the Japan Radioisotope Association1) (JRIA), an organization established to support the utilization of RIs in Japan. According to a material transfer agreement (MTA) drawn between JRIA and RIKEN, JRIA mediates the transaction of the RIs and distributes them to users for a fixed fee. 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 and 88Y are produced through (p,n) reactions with natural Cu and SrO targets, respectively. 109Cd is produced through the 109Ag(d,2n)109Cd reaction with a 24-MeV deuteron beam since the (d,2n) reaction is more efficient than the conventional (p,n) reaction and the produced RI has almost the same specific activity.2)

The prices of the distributed RIs listed in the MTA were determined on the basis of the production costs and efficiencies before the start of the distributions and have been unchanged for more than five years. The production costs and efficiencies were reviewed in 2012, and new prices were set effective in 2013. The price of 65Zn has been increased except for quantities smaller than 1 MBq. The prices for 109Cd and 88Y have been reduced, reflecting an improvement in the production yields. In particular, the use of the (d,2n) reaction for the 109Cd production has contributed to the price reduction.

In 2013, we delivered five shipments of 109Cd with a total activity of 14.15 MBq, 14 shipments of 65Zn with a total activity of 72.7 MBq, and one shipment of 88Y with an activity of 0.03 MBq. The shipment of 88Y was the first one since February 2010 when the distribution of this radioisotope was formalized. The final recipients of the RIs were eight universities, two research institutes, and one private company. Compared with 2012, the amount of 109Cd distributed in 2013 was lower by about 30% (20 MBq in 2012) and the amount of 65Zn was higher by about 24% (58.4 MBq in 2012). Figure 1 shows the yearly trends in the number of orders, and Fig. 2 shows the amounts of the distributed RIs. Data for 88Y are not included in Fig. 2 because the amount of 0.03 MBq is too small to be displayed.

Information on the RIs can be obtained from JRIA through their dedicated website (https://www.j-ram.net/jram/DispatchTopPage.do; in Japanese), FAX (03-5395-8055), or E-mail (gyomu1@jrias.or.jp).

References
1) http://www.jrias.or.jp/ (Japanese), http://www.jrias.or.jp/e/ (English).

Fig. 1. Number of orders of 65Zn, 109Cd, and 88Y distributed yearly from 2007 to 2013.

Fig. 2. Amounts of 65Zn and 109Cd distributed yearly from 2007 to 2013.
Electric power condition of Wako campus in 2013


The monthly electrical power consumption data for RIKEN Wako campus (Wako) and RIKEN Nishina Center (RNC) and the energy supply by the cogeneration system (CGS) are shown in Fig.1. The hourly electrical power consumption of RNC in 2013 is shown in Fig.2. The annual data of energy supply and consumption in 2013 is listed in Table 1. The total electrical power consumption of Wako in 2013 was 143,508 MWh, which was 14% lower than that in 2012. On the other hand, the total electrical power consumption of RNC in 2013 was 55,820 MWh, which was 32% lower than that in 2012. When the RIK 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 21.00 MW with a CGS output of 4.00 MW on May 24, 2013, and the maximum electrical power consumption of RNC reached 16.8 MW on April 26, 2013.

A complete overhaul of the gas turbine of the CGS #1 after 24,000 h of operation was carried out between February and March 2013. After that, an inspection of the gas turbine of the CGS #1 after 4,000 h of operation was carried out in August 2013.

We experienced the following problems during the reporting period. The absorption chillers of the CGS #1 had problems, such as corrosion of the surface of the heat transfer tube. Therefore, work for replacing two markedly impaired absorption chillers is currently in progress by the manufacturer since December 2013, and the work is to be completed by the middle of February 2014. We had a short interruption in power twice, in July and August 2013, due to thunderbolts. Earth leakages also occurred 21 times. However, the origin of most of those leakages was unexplained.

Table 1 Annual data of energy supply and consumption in 2013.

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Unit</th>
<th>Note</th>
<th>% of 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wako purchase</td>
<td>125,923</td>
<td>MWh</td>
<td>Total electrical power supply to Wako from TEPCO</td>
<td>91%</td>
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<tr>
<td>Wako consumption</td>
<td>143,508</td>
<td>MWh</td>
<td>Wako electrical power consumption (CGSs + TEPCO)</td>
<td>86%</td>
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<tr>
<td>RNC purchase</td>
<td>43,278</td>
<td>MWh</td>
<td>Total electrical power supply to RNC from TEPCO</td>
<td>76%</td>
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<tr>
<td>CGS #1</td>
<td>12,542</td>
<td>MWh</td>
<td>CGS #1 total electrical power output</td>
<td>49%</td>
</tr>
<tr>
<td>RNC consumption</td>
<td>55,820</td>
<td>MWh</td>
<td>RNC total electrical power consumption</td>
<td>68%</td>
</tr>
<tr>
<td>CGS #1 thermal</td>
<td>32,696</td>
<td>tons</td>
<td>RNC total thermal power</td>
<td>74%</td>
</tr>
</tbody>
</table>

*1 RIKEN Nishina Center
Radiation safety management at RIBF

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H. Fukuda,*1 S. Hashiguchi,*3 M. Takekoshi,*3 Y. Yamauchi,*3 S. Fujita,*1 K. Nakano,*1 H. Aiso,*1 K. Igarashi*1
and S. Iizuka*1

Since 1986, residual radioactivity at the deflectors of cyclotrons has been measured regularly just before
maintenance work. The variations in the dose rates are shown in Fig. 1. New measurements in 2013 were
conducted only at AVF and RRC owing to their maintenance work. The beam intensity of AVF has been
increased since 2006 for the radioisotope production, and the dose rate has also increased. Because the high intense
beam was not provided to RRC in 2013, there was a reduction in the dose rates as shown in Fig. 1. The change
in the dose rate at RRC from 1990 to 2006 is not large, and the value is typically around 20 mSv/h. After 2006, large
variations in the dose rate are observed. It depends on the beam intensity of RIBF and the cooling time. The dose rate
of SRC increased in 2011, and the value became similar to those of AVF and RRC. The dose rates of IRC1 and fRC
were measured in 2012 only.

The residual radioactivity was measured along the beam lines after almost every experiment. Points 1–26, marked
with solid circles in Fig. 2, are the 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 maximum dose rate was found to be 7 mSv/h at point 25, which is below the beam dump chamber of BigRIPS.
The dose rates on the site boundary in 2013 have been monitored to prevent it be over legal limit of 1 mSv/y.

Fig. 1. Dose rates of residual radioactivity at the deflectors of 5 cyclotrons.

Fig. 2. Layout of beam lines at RIBF. Locations where high dose rates were observed are indicated by solid circles
1–26.

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We continuously monitor the radiation in and around the RIBF facility using neutron and gamma area monitors. The background dose rates were evaluated and the measured values were corrected. The background data have been acquired over a period of a month in August 2013 when all the accelerators were not in operation. The background of gamma-ray dose is currently about 2 times higher than the natural dose rate because of the fallout due to the accident at the Fukushima Dai-ichi power station. Before the accident, the natural background of the gamma-ray dose at the site boundary near the BSI East Bldg. was 0.039 μSv/h in January 2011. The background of gamma-ray dose in 2013 was 0.062 μSv/h. Just like before, all of the corrected dose rates monitored at 2013 were below the detection limit, corresponding to 2 μSv/y for neutrons and 8 μSv/y for gamma-rays. The total dose rate was less than 10 μSv/y and was considerably lower than the legal limit.

The radiation dose on the boundary of the radiation-controlled area have also been monitored. The monitors of gamma-rays and neutrons are placed at the three points on the boundary. One is in the computer room of the Nishina building, and the two other are on the roofs of the IRC and BigRIPS in the RIBF accelerator building. The highest value was observed on the IRC roof as a result of the beam loss at the transport line between SRC and BigRIPS. The annual neutron doses at these locations since 1999, which are sufficiently lower than the legal limit, are shown in Fig. 3. The value of the BigRIPS roof was similar to the background level and is not shown in Fig. 3. The legal limit of a boundary of a radiation-controlled area is 1.3 mSv/3month, and all the measured doses were low enough.
The RIKEN heavy-ion linac (RILAC) has been operating steadily throughout the reporting period and has been supplying various ion beams for different experiments. Some statistics regarding the RILAC operation from January 1 to December 31, 2013, are given in Table 1. The total beam-service time of the RILAC accounted for 75.4% of its operation time. The two operation modes of the RILAC, namely, the stand-alone mode and the injection mode, in which the beam is injected into the RIKEN Ring Cyclotron (RRC), accounted for 62.2% and 37.8% of the total beam-service time of the RILAC, respectively. For the beam experiment and the machine study of the RI Beam Factory (RIBF), a 2.648-MeV/nucleon $^{18}$O-ion beam and a 2.932-MeV/nucleon $^{40}$Ar-ion beam accelerated by the RILAC was injected into the RRC between April and June 2013. Table 2 lists the beam-service times in the stand-alone mode of the RILAC allotted to each beam course in the RILAC target rooms in 2013. The $e_2$ beam course in target room no. 1 was used in the machine study of a new gas-filled recoil ion separator (GARIS-II). The $e_3$ beam course in target room no. 1 was used in experiments involving the heaviest elements and the study of the physical and chemical properties of these elements using the GARIS. The $e_6$ 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 2013.

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. In addition, the major components of mechanical parts were subjected to simple inspection.

2) Two water pumps of the cooling tower circuits 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. Eight cryogenic pumps used for the RILAC and CSM cavities were overhauled.

We experienced the following mechanical problems during the reporting period.

1) Water was found to have splashed in the 18G-ECRIS because of leakage from a cooling water jacket; it took approximately twelve days to repair it.

2) A section of the cooling pipe of stem-2 in the FC-RFQ cavity had a vacuum leak; it took approximately four days to repair it.

3) Water was found to have splashed in the RF power amplifier no. 3 because of leakage from a water joint outside the plate stub; it took approximately two days to repair it.

4) Water was found to have splashed in the CSM-A3 cavity because of leakage from a cooling pipe on the outside wall of the cavity; it took approximately two days to repair it.

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**Table 1. Statistics on RILAC operation from January 1 to December 31, 2013.**

<table>
<thead>
<tr>
<th>Operation time of RILAC</th>
<th>2779.4 h</th>
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<tbody>
<tr>
<td>Mechanical trouble</td>
<td>42.9 h</td>
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</table>

<table>
<thead>
<tr>
<th>Stand-alone RILAC</th>
<th>1304.0 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection into RRC</td>
<td>791.3 h</td>
</tr>
</tbody>
</table>

| Total beam service time of RILAC | 2095.3 h |

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**Table 2. Beam service time of the stand-alone RILAC allotted to each beam course in target rooms no. 1 and no. 2 in 2013.**

<table>
<thead>
<tr>
<th>Beam course</th>
<th>Total time (h)</th>
<th>%</th>
</tr>
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<tbody>
<tr>
<td>$e_2$</td>
<td>110.8</td>
<td>8.5</td>
</tr>
<tr>
<td>$e_3$</td>
<td>1151.3</td>
<td>88.3</td>
</tr>
<tr>
<td>$e_6$</td>
<td>33.2</td>
<td>2.5</td>
</tr>
<tr>
<td>RRC injection course</td>
<td>8.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Total</td>
<td>1304.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

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**Table 3. Operation time of the 18G-ECRIS in 2013.**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Mass</th>
<th>Charge state</th>
<th>Total time (h)</th>
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<tbody>
<tr>
<td>N</td>
<td>15</td>
<td>3</td>
<td>72.0</td>
</tr>
<tr>
<td>O</td>
<td>18</td>
<td>6</td>
<td>252.1</td>
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<tr>
<td>F</td>
<td>19</td>
<td>6</td>
<td>105.0</td>
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<tr>
<td>Ne</td>
<td>22</td>
<td>6</td>
<td>599.9</td>
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<tr>
<td>Mg</td>
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<td>7</td>
<td>338.7</td>
</tr>
<tr>
<td>Al</td>
<td>27</td>
<td>6</td>
<td>300.8</td>
</tr>
<tr>
<td>Ar</td>
<td>40</td>
<td>11</td>
<td>238.2</td>
</tr>
<tr>
<td>Ca</td>
<td>40</td>
<td>11</td>
<td>61.7</td>
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<tr>
<td>Ca</td>
<td>48</td>
<td>11</td>
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</tr>
<tr>
<td>Ni</td>
<td>58</td>
<td>13</td>
<td>215.4</td>
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<tr>
<td>Kr</td>
<td>82</td>
<td>18</td>
<td>144.0</td>
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<tr>
<td>Kr</td>
<td>86</td>
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<td>162.3</td>
</tr>
<tr>
<td>Xe</td>
<td>136</td>
<td>20</td>
<td>12.5</td>
</tr>
<tr>
<td>U</td>
<td>238</td>
<td>35</td>
<td>128.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3229.6</td>
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</table>

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*1 RIKEN Nishina Center
*2 SHI Accelerator Service Ltd.
Radiation monitoring in the RIBF using ionization chambers

M. Nakamura,*1 K. Yamada,*1 A. Uchiyama,*1 H. Okuno,*1 and M. Kase*1

In recent years, we attempted to monitor radiation due to beam loss at several important components in the RIBF by using self-made ionization chambers (ICs)1-5). Furthermore, we input an alarm signal from the IC to the RIBF beam interlock system (BIS)6). The next focus of this study is the detection of the most suitable alarm level for acceleration operations. Firstly, we attempted to calibrate the alarm level by using an IC near the acceleration operations, many ions, such as N, O, Ar, Ca, Zn, Xe, and U, were used. In the present study, we investigated beam-loss calibration for the N, O, Ca, and U beams. In this report, we summarize the results and consider the suitable alarm levels for the BIS.

The experimental conditions of IC measurements have been described in the previous papers 2)-4). When we attempted the calibrations, 18O8+ beams were observed for the calibration curve of the 18O8+ beam, we could collect only three data. However, the dispersion of the data was low, and a favorable calibration curve could be drawn. In the case of the 14N7+ beam, we collected only four data at this stage, and the dispersion of the data was significant. Hence, the 14N7+ beam should be studied further in the near future. Furthermore, among the calibration curves of 14N7+, 18O8+, 48Ca20+, and 238U86+ beams, the sharpest slope was observed for the calibration curve of the 18O8+ beam. This result showed that the intensity of radiation caused by the 18O8+ beam loss is the largest, at least in the present calibrations. Conversely, the calibration curve of the 238U86+ beam showed the lowest slope, indicating that the intensity of radiation caused by the 238U86+ beam loss is the smallest among these ion beams.

We investigated the alarm signal for the BIS using these data. In a previous paper 6), we reported that problems with 48Ca20+ ion beam in the EDC of SRC frequently occurred when the IC output had risen to about 4 V. On comparing the values in the previous paper with the values in Fig. 1, problems occurred in the EDC when the 48Ca20+ beam loss at the EDC increased beyond about 130 W. The exact value of this threshold is still under investigation. Furthermore, the thresholds of the beam loss at which problems begin to occur in the EDC have to be studied for each ion. However, from these estimations, suitable alarm levels can be determined and input to the BIS.

At present, in addition to the elements estimated in this paper, Zn, Ar, and Xe ion beams were accelerated in the experiments using SRC. We plan to investigate the beam loss and alarm levels for these elements in the near future.

References

*1 RIKEN Nishina Center
Operations of RIBF ring cyclotrons (RRC, fRRC, IRC, and SRC)

R. Koyama,*2 T. Dantsuka,*1 M. Fujinami,*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,*1 M. Komiyama,*1 Y. Kotaka,*1 H. Kuboki,*1 K. Kumagai,*1 T. Maie,*1 M. Nagase,*1 T. Nakagawa,*1 M. Nakamura,*1 T. Nakamura,*1 M. Nishida,*2 M. Nishimura,*2 J. Ohnishi,*1 H. Okuno,*1 K. Ozeki,*1 N. Sakamoto,*1 J. Shibata,*1 K. Suda,*1 N. Tsukiori,*2 A. Uchiyama,*1 S. Watanabe,*1 T. Watanabe,*1 Y. Watanabe,*1 K. Yadomi,*2 K. Yamada,*1 and H. Yamazawa*1

The yearly report on the operation of the four RIBF ring cyclotrons RRC, fRRC, IRC, and SRC, including statistics of beam service time as well as developments and troubles in the January–December 2013 period, is presented.

The yearly operation status of the RIBF ring cyclotrons is summarized in Table 1. The medium-energy beams accelerated by the RRC in the last stage were used for the experiments and machine studies (MS) for 1166 h in total. Similarly, the high-energy beams accelerated by the RRC in the last stage were used for 124 Xe acceleration in December. The acceleration stream of the RRC and fRRC, respectively, in June for the first time. Owing to the gas strippers and other continuous efforts, a 345 MeV/nucleon-124 Xe beam of 38 particle nA was provided to the beam users with an availability as high as 91%.

c) Layer short of the RRC main-coil of the west-sector magnet was fixed by replacing it with a new one in August. Its soundness was confirmed in the MS of 50.5 MeV/nucleon-40 Ca acceleration in September.

d) The improvement of efficiency of injection to the RRC from RILAC2 was confirmed when a saw-tooth wave was used for the prebuncher instead of a usual sine wave in the MS of 11 MeV/nucleon-124 Xe acceleration in December. The acceleration at harmonic numbers \( h = 12 \) and \( h = 18 \) instead of the usual \( h = 9 \) was also tested for the future upgrade of the RRC in the same MS. The obtained data is now under analysis.

For more details of those operations and others, refer to Ref. 1.

References

Table 1. Yearly operation results of the RIBF ring cyclotrons. For notable events a)–d), see text.

<table>
<thead>
<tr>
<th>Last stage cyclotron</th>
<th>Preaccelerators</th>
<th>Particle</th>
<th>Energy (MeV/nucleon)</th>
<th>Experimental course</th>
<th>Intensity [particle nA]</th>
<th>Actual</th>
<th>Beam time [h]</th>
<th>Temporary suspension [h]</th>
<th>Availability [%]</th>
<th>Notable events</th>
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</thead>
<tbody>
<tr>
<td>RILAC</td>
<td>(^40)Ca</td>
<td>50.5</td>
<td>RRC</td>
<td>MS</td>
<td>143</td>
<td>84.0</td>
<td>84.0</td>
<td>0.0</td>
<td>100</td>
<td>c)</td>
</tr>
<tr>
<td>RILAC</td>
<td>(^40)Ca</td>
<td>63</td>
<td>E3</td>
<td>1</td>
<td>38</td>
<td>12.0</td>
<td>12.7</td>
<td>0.0</td>
<td>100</td>
<td>d)</td>
</tr>
<tr>
<td>RILAC2</td>
<td>(^124)Xe</td>
<td>10.75</td>
<td>E6</td>
<td>1</td>
<td>29</td>
<td>24.0</td>
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<td>100</td>
<td>d)</td>
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<tr>
<td>AVF</td>
<td>(^63Ni)</td>
<td>70</td>
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<td>100</td>
<td>d)</td>
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<td>250</td>
<td>SAMURAI</td>
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<td>BigRIPS</td>
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<td>d)</td>
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<td>RILAC2-IRC</td>
<td>(^86Kr)</td>
<td>36</td>
<td>BigRIPS</td>
<td>16</td>
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Subtotal of medium-energy experiment at old facility: 1137.5 1166.1 49.0 98

<table>
<thead>
<tr>
<th>Last stage cyclotron</th>
<th>Preaccelerators</th>
<th>Particle</th>
<th>Energy (MeV/nucleon)</th>
<th>Experimental course</th>
<th>Intensity [particle nA]</th>
<th>Actual</th>
<th>Beam time [h]</th>
<th>Temporary suspension [h]</th>
<th>Availability [%]</th>
<th>Notable events</th>
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<td>RILAC</td>
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Subtotal of high-energy experiment at new facility: 1517.5 1646.1 255.2 92

Total: 2655.0 2012.2 364.1 94

*1 RIKEN Nishina Center
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Operation of the superconducting ring cyclotron cryogenic system


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 six months in 2013, with a five-month maintenance shutdown in summer (July–December) and a shutdown to conserve electrical power in January, as shown in Fig. 1. The trend observed for the main coil current of the SRC sector magnet is also shown in this figure. During system operation, there was no major hindrance to stop the He refrigerator and compressor. Because of the extensive He leak during operation in 2012, approximately 200 m³ of He gas had to be refilled once in two months.1) The leak was found to occur in the flange connection between the power lead and He gas pipes used for their cooling. The connection mainly consists of an insulation flange and O-ring as shown in Fig. 2. The main parts were replaced with new ones. The replacement was successfully accomplished in the August. Furthermore, the heater system for the power lead was also upgraded to moderate the heat cycle on parts of the flange connection.

References

Fig. 1. Trend observed in liquid He level in the dewar and main coil current for the SRC superconducting sector magnet.

Fig. 2. Photograph and structural schematic of the current leads at which the leak occurred.

*1 RIKEN Nishina Center
*2 Nippon Kicho Service Co., Ltd
Present status of the BigRIPS cryogenic plant

Periodic maintenance of the BigRIPS cryogenic plant is essential to ensure long-term continuous operations of BigRIPS. In addition to periodically calibrating the pressure and temperature sensors installed in the system, maintaining the oil-removal module in the helium compressor unit is crucial. The oil-removal module comprises an oil vessel with a demister, which is used as a bulk oil separator (1SP), three coalescer vessels (2SP, 3SP, and 3.5SP), and two adsorbent vessels (4SP and 5SP) that contain activated charcoal and molecular sieves. The periodic replacement of coalescer filters and adsorbents ensure the small oil contamination in helium gas. The contamination ranges between 0.008 - 0.02 weight ppm (wt. ppm), depending on the quality of the coalescers used.

We replaced all the coalescer filters in three coalescer vessels during the summer maintenance in 2008, 2010, and 2012. Each coalescer vessel contains four coalescer filters, manufactured by Domnick Hunter, and 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 vessel. The expected oil contamination levels at the exit 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 be easily measured with an oil check kit.

Figure 1 shows the contamination measured at the entrance of 3SP as a function of the coalescer filter operation time. The oil check kit values are shown as open symbols in Fig. 1. The open triangles, squares, and circles represent results for the 2008-2009, 2010-2011, and 2012 operations, respectively. An estimate from the oil drain from the 3SP is also shown in Fig. 1. We estimate the oil contamination level by measuring the operation interval of the solenoid valve installed in 3SP. The navy blue, green, and yellow diamonds represent the estimates for the 2008-2009, 2010-2011, and 2012 operations, respectively. The estimates of oil drain increase to 50~75 wt. ppm up to an operation time of 2000 h for the period of 2008-2009 and 2010-2011 and then stays constant. Corresponding oil check kit results show a similar increasing tendency. On the other hand, the estimate from the oil drain for the period of 2012 shows monotonous increasing tendency and does not stay constant for any long period. We shall continue observations in the next operation. This difference indicates the performance efficiency of different coalescer filters.

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 less oil contamination at the entrance of the 3SP, the results for the period of 2010-2011 are approximately half of that of the other period. However, the oil contamination estimated from the oil drain for the period of 2012 unexpectedly increased faster than other periods. We shall continue observations in the next operation and investigate the coalescer filters in the maintenance planned in the summer of 2014.

References
3) http://www.parker.com/


Fig. 1. Oil contamination at the entrance of the second coalescer vessel (3SP).

Fig. 2. Oil contamination at the entrance of the third coalescer vessel (3.5SP).
Present status of liquid-helium supply and recovery system

T. Dantsuka, H. Okuno, M. Nakamura, K. Ikegami, M. Kase, S. Tsuruma,
M. Ohshima, H. Miura, Y. Tezuka, H. Hazama and H. Shiba

The liquid-helium supply and recovery system\(^1\), which can produce liquid helium from pure helium gas at a rate of 200 L/h from pure helium gas, has been stably operated since the beginning of April 2001. The volumes of liquid helium supplied each year from 2001 to 2012 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 extended the recovery line at one place. A new recovery line was connected to the existing line at the RIBF Building at B3F.

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 is rarely more than 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%. The average recovery efficiency from January 2008 to July 2013 is shown in Fig. 2. This value also increased to over 90%.

Fig.1. Volumes of liquid helium supplied to laboratories for each fiscal year from 2001 to 2012

Fig.2. Average recovery efficiency measured from January 2008 to July 2013

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\(^1\) RIKEN Nishina Center
\(^2\) Nippon Air Conditioning Service K.K

References
V. EVENTS
The 7th Nishina School

T. Kishida *1

The Nishina School was held from Aug. 6 to 16. The School was for the students of Peking University (11 M0 students), Seoul National University (8 undergraduate students) and the University of Tokyo (4 graduate students). Although the School was held every year for each university, this was the first one which was held together for these three universities.

The first week program consisted of lectures and basic trainings. The second week program consisted of several experiments. On the last day of the School, the presentation session by the students was held.

As well as the Nishina School, the Summer School for Phillips Exeter Academy (a high school in the United States) was held from Jul. 30 to Aug. 16. Two high school students attended the school. They also joined the first program and the presentation session of the Nishina School.

Thus, the Nishina School became a real international school where international cultural exchange was made among China, Korea, U.S. and Japan. All the students enjoyed the School fully. Figure 1 shows a photograph taken at the opening ceremony on Aug. 6.

*1 RIKEN Nishina Center, the Principal of the Nishina School

Fig. 1. Opening Ceremony of the Nishina School.
VI. ORGANIZATION AND ACTIVITIES
OF RIKEN NISHINA CENTER
(Activities and Members)
VI. RNC ACTIVITIES

1. Organization

1.1 Organization Chart as of April 1, 2013

![Organization Chart Image]
1.2 Topic in FY2013

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 1, 2013</td>
<td><strong>Start of Nuclear Spectroscopy Laboratory</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Start of Research Group for Superheavy Element</strong>, taking over Superheavy Element Laboratory, associated with following two teams</td>
</tr>
<tr>
<td></td>
<td><strong>Superheavy Element Production Team</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Superheavy Element Device Development Team</strong></td>
</tr>
<tr>
<td>Nov. 1, 2013</td>
<td><strong>Personnel Change</strong></td>
</tr>
<tr>
<td></td>
<td>Deputy Director of RNC: Hiroyosi SAKURAI</td>
</tr>
<tr>
<td></td>
<td>Director of RBRC: Samuel H. ARONSON</td>
</tr>
<tr>
<td></td>
<td>Team Leader of User Support Office: Ken-ichiro YONEDA</td>
</tr>
<tr>
<td></td>
<td>Team Leader of SAMURAI Team: Hiromi SATO</td>
</tr>
<tr>
<td></td>
<td><strong>New Appointment</strong></td>
</tr>
<tr>
<td></td>
<td>Deputy Group Director of Accelerator Group (Energy Efficient Management): Masayuki KASE</td>
</tr>
<tr>
<td></td>
<td>Senior Adviser: Walter F. HENNING</td>
</tr>
<tr>
<td></td>
<td><strong>New Appointment</strong></td>
</tr>
<tr>
<td></td>
<td>Deputy Director of RBRC: Robert PISARSKI</td>
</tr>
</tbody>
</table>

2. Finances

Breakdown expenses of the RNS FY2013 budget and transition for past five years are shown in following figures. Due to the budgetary limitation caused by the aftermath of Tohoku earthquake and Fukushima nuclear disaster, beam time for the RIBF users as recommended in NCAC2011 is not able to be provided sufficiently at present. For FY2013, RNC managed to realize 3.5 month operation by receiving additional President’s Discretionary Fund and cancelling accelerator operation in autumn which was replaced by a consecutive operation from the year-end to the next fiscal year.
3. Staffing

Having reached a consensus within RIKEN on the issue of supplementing additional permanent staff to the Accelerator Group, RNC now have a better outlook for solving personnel shortage problem. RNC eagerly anticipate additional permanent staff to join the Accelerator Group in the near future, with one new arrival in FY2013, another one to be selected for FY2014. On the other hand, while there is several permanent staffs that underwent career shift from research to research support, the number is still not enough. To further promote an increase in permanent research support staff, RNC are recruiting from entire RIKEN for qualified candidates.

Breakdown to six personnel categories in FY2013 and transition for past five years are shown in following figures.

4. Management

RIKEN Nishina Center for Accelerator-Based Science (RNC) is now composed of, under RNC Director Hideto En'yo,
10 Laboratories,
1 Research unit,
7 Groups with 20 Teams,
2 overseas research center with 3 Groups.

There are also three 'Partner Institutes' which conduct research in the laboratories arranged in RNC.
RNC is managed by its Director through the majority decision in the RNC Coordination Committee. Accelerator Research Promotion Section which carries out administrative function of RNC under the President of RIKEN is set close to RNC.

In order to support the management of RNC, there are
Scientific Policy Committee,
Program Advisory Committee,
Safety Review Committee,
RIBF Machine Time Committee, and
Public Relations Committee.

There are also committees to support the President of RIKEN or the Director of RNC.
RBRC Management Steering Committee (MSC) and Nishina Center Advisory Council, which has 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, 2014)

<table>
<thead>
<tr>
<th>Name</th>
<th>Role and Laboratory</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</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

Following subjects relating to RNC management are deliberated under the chairmanship of 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 as to the management of RNC and the response to recommendations by external evaluation.

RNC Coordination Committee is held monthly.

Members (as of March 31, 2014)

<table>
<thead>
<tr>
<th>Name</th>
<th>Role and Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Hiroyoshi SAKURAI</td>
<td>Deputy Director, RNC; Chief Scientist, Director of Theoretical Nuclear Physics Laboratory</td>
</tr>
<tr>
<td>Tetsuo HATSUDA</td>
<td>Deputy Director, RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory</td>
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<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>Koseke 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</td>
</tr>
<tr>
<td>Hideyuki SAKAI</td>
<td>Group Director, User Liaison and Industrial Cooperation Group</td>
</tr>
<tr>
<td>Hiroki OKUNO</td>
<td>Deputy Group Director, Accelerator Group; Team Leader, Accelerator R&amp;D Team; Team Leader, Cryogenic Technology Team</td>
</tr>
<tr>
<td>Nobuhisa FUKUNISHI</td>
<td>Deputy Group Director, Accelerator Group; Team Leader, Beam Dynamics &amp; Diagnostics Team</td>
</tr>
<tr>
<td>Masayuki KASE</td>
<td>Deputy Group Director, Accelerator Group; Team Leader, Infrastructure Management Team</td>
</tr>
<tr>
<td>Tomoko ABE</td>
<td>Group Director, Accelerator Applications Research Group; Team Leader, Radiation Biology Team</td>
</tr>
<tr>
<td>Yoshitomo UWAMINO</td>
<td>Group Director, Safety Management Group</td>
</tr>
<tr>
<td>Toshiyuki KUBO</td>
<td>Group Director, Research Instruments Group; Team Leader, Detector Team</td>
</tr>
<tr>
<td>Masanori WAKASUGI</td>
<td>Group Director, Instrumentation Development Group; Team Leader, Rare RI-ring Team; Team Leader, SCIT Team</td>
</tr>
<tr>
<td>Eiji IKEZAWA</td>
<td>Team Leader, RILAC Team</td>
</tr>
<tr>
<td>Takashi ICHIHARA</td>
<td>Team Leader, Computing and Network Team</td>
</tr>
<tr>
<td>Naruhiko SAKAMOTO</td>
<td>Team Leader, Cyclotron Team</td>
</tr>
<tr>
<td>Hiromi SATO</td>
<td>Team Leader, SAMURAI Team (-Mar. 2014), Team Leader, Detector Team (Apr. 2014-)</td>
</tr>
<tr>
<td>Takahide NAKAGAWA</td>
<td>Team Leader, Ion Source Team</td>
</tr>
<tr>
<td>Hiromitsu HABA</td>
<td>Team Leader, RI Applications Team</td>
</tr>
<tr>
<td>Koji MORIMOTO</td>
<td>Team Leader, Superheavy Element Device Development Team</td>
</tr>
<tr>
<td>Atsushi YOSHIDA</td>
<td>Team Leader, Industrial Cooperation Team</td>
</tr>
<tr>
<td>Koichi YOSHIDA</td>
<td>Team Leader, BigRIPS Team</td>
</tr>
<tr>
<td>Ken-ichiro YONEDA</td>
<td>Team Leader, User Support Office</td>
</tr>
<tr>
<td>Michiharu WADA</td>
<td>Team Leader, SLOWRI Team</td>
</tr>
<tr>
<td>Yasuyuki Akiha</td>
<td>Vice Chief Scientist, Radiation Laboratory; Group Leader, Experimental Group, RIKEN BNL Research Center</td>
</tr>
<tr>
<td>Katsuhiko ISHIDA</td>
<td>Vice Chief Scientist, Advanced Meson Science Laboratory</td>
</tr>
<tr>
<td>Tsukasa TADA</td>
<td>Vice Chief Scientist, Quantum Hadron Physics Laboratory</td>
</tr>
<tr>
<td>Yuko MOTIZUKI</td>
<td>Research Unit Leader, Astro-Glaciology Research Unit</td>
</tr>
<tr>
<td>Akihiko UEDA</td>
<td>Senior Manager; Director, Head of Accelerator Research Promotion Section</td>
</tr>
</tbody>
</table>
Accelerator Research Promotion Section

The scope of business of Accelerator Research Promotion Section is Planning and coordination as to research program and research system of RNC, Planning and management of budget use of RNC, Public relations activity.

Members (as of March 31, 2014)

Akihiko UEDA Senior Manager; Director, Head of Accelerator Research Promotion Section
Mitsuru KISHIMOTO Manager, Accelerator Research Promotion Section
Hayato NISHIMURA Deputy Manager (May 2014)
Kazunori MABUCHI Deputy Manager
Yukari ONISHI Chief
Kuniko SUGITA Special Administrative Employee
Yuko OKADA Task-Specific Employee
Yukiko SATO Task-Specific Employee
Kyoji YAMADA Special Temporary Employee
Yoshio OKUIZUMI Temporary Employee
Masatoshi MORIYAMA Consultant for Advisory Committee, Research Review, etc.
Rie KUWANA Temporary Staff

Scientific Policy Committee

Scientific Policy Committee deliberates on Research measures and policies of RNC, Administration of research facilities under RNC’s control. Committee members are selected among professionals within and without RNC. The Committee is held annually.

Members (as of March 31, 2014)

Hirokazu Tamura Chair
Prof., Graduate School of Science, Tohoku University
Yujiro IKEDA Director, J-PARC Center
Akira UKAWA Prof., Faculty of Pure and Applied Sciences, University of Tsukuba
Takaharu OTSUKA Director, Center for Nuclear Study (CNS), University of Tokyo
Hideo OHNO Research Advisor, Japan Synchrotron Radiation Research Institute (JASRI)
Ryosuke KADONO PI, Muon Science Laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK)
Takashi NAKANO Director of Research Center for Nuclear Physics (RCNP), Osaka University
Hirohiko TSUJII Fellow, National Institute of Radiological Sciences (NIRS)
Tomofumi NAGAE Prof. Graduate School of Science, Kyoto University
Hitohiko TSUJII Fellow, National Institute of Radiological Sciences (NIRS)
Takashi NAKANO Director of Research Center for Nuclear Physics (RCNP), Osaka University
Hirohiko TSUJII Fellow, National Institute of Radiological Sciences (NIRS)
Tomofumi NAGAE Prof. Graduate School of Science, Kyoto University
Hitohiko TSUJII Fellow, National Institute of Radiological Sciences (NIRS)
Masanori YAMAUCHI Director, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)
Kazuyoshi YAMADA Director, Institute of materials Structure Science, High Energy Accelerator Research Organization (KEK)
Kazuo SHINOZAKI Director, Center for Sustainable Resource Science, RIKEN
Ryutaro HIMEINO Director, Advanced Center for Computing and Communication, RIKEN

The meeting of FY2013 was held on July 11, 2013 at Tokyo Liaison Office of RIKEN.

Program Advisory Committee

Program Advisory Committee reviews experimental proposals submitted by researchers and reports the acceptance or the denial of the adaptation of proposals to RNC Director. The Committee also reports to RNC Director the available period (days) of RIBF or Muon Facility at RAL allotted to researchers.

The name and scope of the Committees are follows;

(1) Nuclear Physics Experiments at RIBF (NP-PAC): academic research for nuclear physics,
(2) Materials and Life Science Researches at RNC (ML-PAC): academic research for material 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

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, Chaina
Christoph SCHEIDENBERGER  Head, NuSTAR/ENNA Department, GSI, Germany
Friedrich-K. THIELEMANN  Prof. Department of Physics, University of Basel, Switzerland
Rick F. CASTEN  Physics Department, Yale University, USA
Christopher J. (KIM) LISTER  Prof. Department of Physics and Applied Physics, University of Massachusetts, Lowell, USA
Hans EMLING  GSI, Germany
Hironori IWASAKI  Assistant Professor of Physics, National Superconducting Cyclotron Laboratory, Michigan State University, USA
Walter D. LOVELAND  Full Prof. Department of Chemistry, Oregon State University, USA
Thomas NILSSON  Prof. Department of Fundamental Physics, Chalmers Univ. of Technology, Sweden
Chair of BFC (Board of FAIR Collaborations)
Bradley. M.SHERRILL FRIB Chief Scientist, Michigan State University, USA
Olivier SORLIN  Grand Accélérateur National d’Ions Lourds (GANIL), France
Satoshi N. NAKAMURA  Associate Prof. Nuclear Experiment Group, Faculty of Science, Tohoku University
Atsushi TAMII  Associate Prof. Experimental Nuclear Physics Division, Research Center for Nuclear Physics, Osaka University
Yutaka UTSUNO  Frontier Research on Heavy Element System, Advanced Science Research Center, JAEA
Masanobu YAHiro  Prof. Fundamental particle physics, Department of Physics, Faculty of Sciences, Kyushu University
Takashi NAKATSUKASA  Associate Chief Scientist, Director of Theoretical Nuclear Physics Laboratory, RNC, RIKEN

Program Advisory Committee for Materials and Life Science Researches at RIKEN Nishina Center (ML-PAC)

Members
Jean-Michel POUTISSOU  Chair
Senior research scientist Emeritus, TRIUMF, Canada
Alex AMATO  Muon Spin Spectroscopy, Paul Scherrer Institute, Switzerland
Douglas E. MACLAUGHLIN (University of California, Riverside, USA)
Sadamichi MAEKAWA  (JAEA, JAPAN)
Kenya KUBO  Prof. The College of Liberal Arts, International Christian University
Adrian HILLIER  ISIS, RAL, UK
Philippe MENDELS  Laboratoire de Physique des Solides, Universite Paris-SUD, France
Xu-Guang ZHENG  Saga University
Hiroyuki YAMASE (NIMS, JAPAN)
Ryosuke KADONO  PI, Muon Science Laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK)
Norimichi KOJIMA  University of Tokyo, JAPAN
Toshiyuki AZUMA  Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN
Atsushi KAWAMOTO  (Hokkaido University, JAPAN)
Shigeo YOSHIDA  (Yokohama City University, JAPAN)

Industrial Program Advisory Committee (In-PAC) Members (July 1, 2012–March 31, 2014)

Members
Akihiro IWASE  Chair
Prof. Graduate School of Engineering, Osaka Prefecture University
Kenya KUBO  Prof. The College of Liberal Arts, International Christian University
Hitoshi NAKAGAWA  Auditor, Japan International Research Center for Agricultural Sciences
Nobuhiko NISHIDA  Chief Engineer, Quantum Equipment Division, Sumitomo Heavy Industries, Ltd
Toshihito MITSUMOTO  Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN
Toshiyuki AZUMA  Chief Scientist, Atomic, Molecular & Optical Physics Laboratory, RIKEN

Safety Review Committee

Safety Review Committee is composed of two sub committees, Safety Review Committee for Accelerator Experiments and Hot-Labo Safety Review Committee. These Committees review the safety of the usage scenario about radiation generating equipment submitted to RNC Director from the spokesperson of the approved experiment.

Safety Review Committee for Accelerator Experiments

Members
Takashi KISHIDA  Chair, Sakurai Radioactive Isotope Physics Laboratory
Kouji MORIMOTO  Superheavy Element Research Device Development Team
Eiji IKEZAWA  RILAC Team
Hiromitsu HABA  RI Applications Team
Shinichiro MICHIMASA  Assistant Prof., Center for Nuclear Study, University of Tokyo
Hidetoshi YAMAGUCHI  Lecturer, Center for Nuclear Study, University of Tokyo
Hirosi WATANABE  Lecturer, KEK
Hiromi SATO  Detector Team
VI. RNC ACTIVITIES

Atsushi YOSHIDA  Industrial Cooperation Team
Koichi YOSHIDA  BigRIPS Team
Naoki FUKUDA  BigRIPS Team
Naruhiko SAKAMOTO  Cyclotron Team
Hisao SAKAMOTO  Safety Management Group
Yoshitomo UWAMINO  Safety Management Group
Kanenobu TANAKA  Safety Management Group

Hot-Labo Safety Review Committee
Members
Masako IZUMI  Chair, Radiation Biology Team
Yoshitomo UWAMINO  Safety Management Group
Hisao SAKAMOTO  Safety Management Group
Hiroki MUKAI  Safety Management Group
Kanenobu TANAKA  Safety Management Group
Hiromitsu HABA  RI Applications Team

RIBF Machine Time Committee
Upon request of RNC Director, RIBF Machine Time Committee deliberates the operating program of RIBF and returns the results to him.

Members
Hideoyuki SAKAI  Chair, 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, Sakurai 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
Hidetoshi YAMAGUCHI  Lecturer, Center for Nuclear Study, University of Tokyo
Hiroshi MIYATAKE  Professor, KEK

Public Relations Committee
Upon request of RNC Director, Public Relations Committee deliberates and coordinates following matters.
(1) Construction of the public relation system of the overall RNC,
(2) Prioritization of the public relation activities of the overall RNC,
(3) Other basic matters and important matters concerning the public relations of the overall RNC.

Members
Akihiko UEDA  Chair, Senior Manager; Director, Head of Accelerator Research Promotion Section (-Mar. 2014)
Hiroyoshi SAKURAI  Deputy Director, RNC; Chief Scientist, Director of Radioactive Isotope Physics Laboratory
Tetsuo HATSUDA  Deputy Director, RNC; Chief Scientist, Director of Quantum Hadron Physics Laboratory
Tohru MOTOBAYASHI  RIBF synergetic-use coordinator
Walter F. HENNING  Senior Advisor
Yusuhide YANO  Senior Advisor
Masahiko IWASAKI  Chief Scientist, Director of Advanced Meson Science Laboratory
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Hideki UENO  Chief Scientist, Director of Nuclear Spectroscopy Laboratory; Deputy Group Director, User Liaison and Industrial Cooperation Group
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Emiko HIYAMA  Associate Chief Scientist, Director of Strangeness Nuclear Physics Laboratory
Koji HASHIMOTO  Associate Chief Scientist, Director of Mathematical Physics Laboratory
Kosuke MORITA  Group Director, Research Group for Superheavy Element; Team Leader, Superheavy Element Production Team
VI. RNC ACTIVITIES

Osamu KAMIGAITO  
Group Director, Accelerator Group

Hideyuki SAKAI  
Group Director, User Liaison and Industrial Cooperation Group

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RBRC MSC is set up according to Memorandum of Understanding Between RIKEN and BNL concerning the collaboration on the Spin Physics Program at the Relativistic Heavy Ion Collider (RHIC).

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5. International Collaboration

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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. Nucleon structure and nuclear force from QCD
2. Theory of spontaneous symmetry breaking
3. QCD under extreme conditions
4. Non-perturbative study of supersymmetric quantum field theories and string theories
5. QED calculation of the lepton anomalous magnetic moments
6. Physics of particles with resonant interactions

3. Summary of Research Activity

1. Nucleon structure and nuclear force from QCD

1-1. Nucleon structure from lattice QCD

The structure of nucleon is a crucial quantity to understand the low energy behaviors of QCD, and to detect the possible sign of physics beyond the standard model. In particular, the precise values of scalar matrix elements are required for the dark matter search experiments, and we performed the lattice QCD calculation for strangeness and charmness scalar matrix elements using chiral fermions. The so-called "spin crisis" is one of the most challenging issues in nucleon structure. Its lattice QCD study is also challenging since the computation of the disconnected insertions and glue matrix elements are required. We developed a novel method to calculate these components and performed the first complete lattice calculation for the nucleon spin.

1-2. Lattice nuclear force

While the nuclear force serves as the cornerstone in nuclear physics, theoretical understanding of them from the underlying theory, QCD, has not been established yet. Our HAL QCD Collaboration has been developing the lattice QCD method to determine the nuclear forces. The method has been successfully applied to various hadron-hadron interactions including the hyperon forces. The physical origin of the repulsive core was revealed as the quark Pauli blocking effect. The equation of state based on lattice nuclear forces was studied and the saturation of nuclear matter was observed for the first time. Of particular interest is the determination of the three-nucleon forces from lattice QCD. Facing the challenge of the enormous computational cost for this study, we developed a novel algorithm which reduces the cost by a factor of 192. The lattice QCD results indicate that repulsive three-nucleon forces exist at short distance.

2. Theory of spontaneous symmetry breaking

The general counting rule for Nambu-Goldstone (NG) modes is derived using Mori's projection operator method in non-Lorentz invariant systems at zero and finite temperatures. We classified NG modes into two types: One is the same type (Type-I or A) as that in relativistic systems. The other is type-II or B NG mode that is characterized by the expectation value of \([Q_a, Q_b]\), where \(Q_a\) and \(Q_b\) are broken charges. The motion of the type-II NG mode is precessional, while that of type-I NG mode is harmonic. The total number of Nambu-Goldstone modes is equal to the number of broken charges minus half the rank of the expectation value of \([Q_a, Q_b]\).

3. QCD under extreme conditions

3-1. QCD under strong magnetic field

We discussed the fate of chiral symmetry in an extremely strong magnetic field \(B\), taking into account not only quark fluctuations but also neutral meson effects. The former would enhance the chiral-symmetry breaking at finite \(B\) according to the Magnetic Catalysis, while the latter would suppress the chiral condensate once \(B\) exceeds the scale of the hadron structure. Using a chiral model we demonstrate how neutral mesons are subject to the dimensional reduction and the low dimensionality favors the chiral-symmetric phase. We pointed out that this effect, the Magnetic Inhibition, can be a feasible explanation for recent lattice QCD data indicating the decreasing behavior of the chiral-restorement temperature with increasing \(B\). We also discussed the behavior of vector-meson mass and the possibility of its condensation in a strong magnetic field. Several hadronic models show that the mass of the charged vector meson decreases as the magnetic field increases, and at some critical magnetic field, the charged vector meson condenses. We, however, showed, by using the Vafa-Witten theorem, that the vector meson condensation does not happen in QCD. We also performed the numerical analysis for the meson mass and condensation in lattice QCD. The lattice QCD data confirmed no charged vector meson condensation in a magnetic field.

3-2. Relativistic hydrodynamics

We studied relativistic hydrodynamics in the linear regime, based on Mori's projection operator method. In relativistic hydrodynamics, it is considered that an ambiguity about the fluid velocity occurs from a choice of a local rest frame: the Landau and Eckart frames. We derived hydrodynamic equations in the both frames by the projection operator method. We found that the difference of the frames was not the choice of the local rest frame, but rather that of dynamic variables in the linear regime.
(4) Non-perturbative study of supersymmetric quantum field theories and string theories

(4-1) Lattice formulation of the N=2 supersymmetric Landau-Ginzburg model and numerical simulation

Noting the fact that a simple momentum cutoff applied to an off-shell supersymmetric multiplet does not break supersymmetry (SUSY), we constructed a lattice formulation of the two-dimensional N=2 supersymmetric Wess-Zumino (WZ) model that preserves manifest SUSY. Although the locality is broken with this lattice formulation, one can argue that the locality is restored in the continuum limit because of the preserved SUSY. Using this formulation, we further carried out a numerical simulation of a massless WZ model with a cubic superpotential, which is believed to become an N=2 superconformal field theory in the infrared limit. We measured a scaling dimension and the central charge in the infrared limit and obtained values consistent with the theoretical conjecture.

(4-2) Theoretical basis for a lattice formulation of the four-dimensional N=1 supersymmetric Yang-Mills (SYM) theory

Since there is no lattice formulation of the four-dimensional N=1 SYM theory that can preserve manifest SUSY, it is important to understand how SUSY is restored in the continuum limit. In a precise theoretical treatment, this issue should be addressed in terms of the Ward-Takahashi (WT) relation associated with SUSY. We pointed out there was a flaw in past treatments of the WT relation and provided a proper analysis of the WT relation by using a generalized BRS transformation that treats the chiral symmetry, SUSY and the translational invariance in a unified way. Since the lattice regularization breaks the infinitesimal translation, it is not straightforward to construct the EMT, a Noether correct associated with the translational invariance. We pointed out that in lattice formulations of the four-dimensional N=1 SYM theory, there is a natural method to define an EMT in view of the Ferrara-Zumino supermultiplet, a supermultiplet that contains the supercurrent and the EMT. In the continuum limit, because of the restored SUSY, the EMT also restores the conservation law.

(4-3) Lattice EMT using the Yang-Mills gradient flow

Although the EMT is a fundamentally important object in quantum field theory, its construction in lattice field theory is not straightforward because there the translational invariance is explicitly broken. The difficulty of the problem comes from the fact that a composite operator generally contains the ultraviolet (UV) divergence and its definition inevitably depends on the UV regularization adopted. Here, noticing the UV finiteness of composite operators defined through the so-called Yang-Mills gradient flow, we construct a formula for the EMT in the lattice formulation of the pure Yang-Mills theory. The formula reproduces a correctly-normalized conserved EMT in the continuum limit.

(4-4) Matrix model for a type-IIA superstring and the non-perturbative SUSY breaking

We studied analytically and numerically a matrix model that is supposed to provide a non-perturbative definition of a type IIA superstring in a two-dimensional spacetime. We found that the spacetime SUSY in the system, although it does not contain the translations, is spontaneously broken as a result of a non-perturbative dynamics. This is the first example in which one can concretely address a non-perturbative spontaneous breaking of the spacetime SUSY in superstring theory.

(4-5) Novel quantum effects on non-perturbative dynamics of string theory

While perturbative aspects of string theories are well understood by the worldsheet calculations applying powerful techniques of conformal field theories, non-perturbative dynamics are difficult to comprehend. An exception would be the non-critical string in less-than one-dimension, which can be formulated non-perturbatively with matrix models. Therefore, studies of matrix models are potentially important to the understanding of non-perturbative dynamics of string theory, in this regard. To represent the dynamics of non-critical string, the potential of the corresponding matrix model is tuned so that it exhibits the second-order critical point. Thus, the matrix model which composes discretized strings becomes continuous smooth string theory. It is found, however, with a certain type of the potential, a matrix model can manifest the first order transition. This phenomenon is due to the quantum effect known as the resonant tunneling. This effect has not been considered in the studies of matrix models so far. Incorporating these kinds of quantum effects into the study of matrix models may reveal novel dynamics of string theory.

(4-6) Investigations of string duality through worldsheet dynamics

String duality is a powerful concept that has been leading us to better understandings of the non-perturbative aspects of string theory. One type of duality is particularly of interest, namely open-closed duality. Open string corresponds to gauge theories while closed one shows gravity. Thus, open-closed duality suggests relation between gauge theories and the theory of gravity. This relation could be behind another duality, AdS/CFT correspondence. The difference between open string and closed string is, from the view point of the world sheet of string theory, nothing but the difference of the boundary condition of the worldsheet field theory. Since the difference is predetermined by the boundary condition, investigating directly the relation between open and closed string is a difficult task. Recently, it is found that certain quantum systems exhibit the change from the closed-boundary vacuums to open-boundary ones through the spatial modulation of the couplings. This procedure is called Sine-Square Deformation (SSD). Since open string may become closed one through SSD, it is interesting to investigate SSD in the context of string theory. We found a divergence in the worldsheet metric and also degenerated vacua other than the ordinary sl(2,C) invariant vacuum.

(5) QED higher-order calculation of lepton anomalous magnetic moments

The electron and muon anomalous magnetic moments (g-2) were precisely measured at Harvard and at Brookheaven, respectively. Comparing the measurements to the theoretical predictions of g-2, we are able to test the standard model of elementary particles in rigorous ways and find a possible window to new physics. To carry out such tests the tenth-order contribution of the perturbation theory of Quantum Electrodynamics (QED), which consists of 12,671 Feynman diagrams, must be known. About ten years ago we started the project calculating all QED contributions of the tenth order by numerical means. With help of the code-generator developed by ourselves, we made all computer programs necessary to determine the tenth-order g-2. In 2012 we have finally obtained the preliminary values of the tenth-order g-2 for both electron and muon and announced them publicly. Improvement of numerical calculation has also been attempted to meet the precision proposed by the ongoing new experiments of both electron and muon g-2’s.

(6) Physics of particles with resonant interactions

(6-1) Universal physics of particles with resonant interactions

We investigated the universal physics that arises in presence of resonant interactions, in particular the Efimov effect for three particles.
which can bind them into a trimer. Efimov trimers are characterised by a parameter called the three-body parameter. Performing calculations using realistic helium-4 atomic interactions, we have shown that helium-4 atoms follows the van der Waals universality of the Efimov three-body parameter previously observed in ultracold atom experiments. This universality has then been explained by the universality of the atomic pair correlation, using pair models and separable potentials. It has been generalized to other short-range interactions, such as interactions in nuclear physics and condensed matter, making predictions for the trimer energies in these systems. It was also investigated the case of mass-imbalanced three-body systems where one particle is significantly lighter than the other two. Depending on the mass ratio and scattering length, the three-body system can form universal trimers determined solely by the scattering length, or Efimov trimers determined by the three-body parameter. Using numerical calculations, we have mapped out the crossover between these two limits.

(6-2) **Coherent photoassociation of a Bose-Einstein condensate**

Photoassociation is the process of binding a pair of atoms by shining light onto it. It usually results in incoherent losses, but some years ago we predicted the conditions for the observation of coherent oscillations when a Bose-Einstein condensate of atoms is photoassociated. This prediction has been successfully observed by experimentalists at Rice University with whom we have collaborated to analyze the experimental data.

**Head**
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Yoshimasa HIDAKA (Research Scientist)
Pascal Raphaël Gabriel NAIĐON (Research Scientist)

**Nishina Center Research Scientist**
Makiko NIO

**Special Postdoctoral Researchers**
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Arata YAMAMOTO ( - Mar. 31, 2014 )
Kanabu NAWA
Yuji SAKAI
Kazuhiko KAMIKADO ( Apr. 1, 2013 - )
Takashi SANO ( Apr. 1, 2013 - )

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**Postdoctoral Researchers**
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Taichi KAWANAI ( Apr. 1, 2013 - )
Shinsuke YOSHIDA ( Apr. 1, 2013 - )
Daisuke SATO ( Apr. 1, 2013 - )
Koich HATTORI ( Feb. 1, 2014 - )

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Toichiro KINOSHITA (Physics Department, Cornell University)
Sinya AOIKI (Yukawa Institute for Theoretical Physics, Kyoto University)
Taichi KAWANAI (Graduate School of Science, University of Tokyo) - Mar. 31, 2013
Masahito UEDA (Graduate School of Science, University of Tokyo)
Tatsuyuki TAKATSUKA (Faculty of Humanities and Social Science, Iwate University)
Hong MAO (Hangzhou Normal University, China)
Sho OZAKI (Yonsei University, Korea)
Kazuyuki KANAYA (Graduate School of Pure and Applied Science University of Tsukuba)
Makoto TAKIZAWA (Showa Pharmaceutical University)
Sachiko TAKEUCHI (Faculty of Social Welfare, Japan College of Social Work)
Yuji HIRONO (Graduate School of Science, University of Tokyo)
Hiroshi TOKI (RCNP, Osaka University)  Apr. 1, 2013 -
Masashi HAYAKAWA (Graduate School of Science, Nagoya University)
Kenji SASAKI (Center for Computational Sciences, University of Tsukuba)
Takayuki MATSUKI (Department of Environmental Science and Education, Tokyo Kasei University)
Daisuke KADOH (IPNS, KEK) - Apr. 30, 2013
Hiroshi SUZUKI (Faculty of Sciences, Kyushu University)  Sep. 1, 2013 -

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Hiroshi TOKI (RCNP, Osaka University)  - Mar. 31, 2013

Junior Research Associate
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Short-term Program for International Program Associate
Robert Friedrich LANG (Department of Physics, Technical University of Munich)  Oct. 7, 2013 – Feb. 12, 2014

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Akihiko MONNAI (Graduate School of Science, University of Tokyo)  - Mar. 31, 2013
Yasufumi ARAKI (Graduate School of Science, University of Tokyo)
Yusuke HAMA (Graduate School of Science, University of Tokyo)
Tomoya HAYATA (Graduate School of Science, University of Tokyo)
Yasuki TACHIBANA (Graduate School of Science, University of Tokyo)
Kota MASUDA (Graduate School of Science, University of Tokyo)
Masaru HONGO (Graduate School of Science, University of Tokyo)  - Mar. 31, 2013
Yuya TANIZAKI (Graduate School of Science, University of Tokyo)
Ryuichi KURITA (Graduate School of Science, University of Tokyo)
Sho KAMATA (Graduate School of Science, Rikkyo University)
Masanori YAMADA (Graduate School of Pure and Applied Science, University of Tsukuba)
Koichiro HIRANUMA (Graduate School of Science & Engineering, Tokyo Institute of Technology)
Simpei ENDO (Graduate School of Science, University of Tokyo)

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Theoretical Research Division
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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) Energy-density-functional calculation including proton-neutron mixing
We have performed mean-field calculation based on the Skyrme energy density functional (EDF) including arbitrary mixing between protons and neutrons. Isobaric analogue states (IASs) were calculated using the iso-mixing method. Through the calculations for IASs in A=14 and 40-56 isobars, we demonstrated that our model is capable of qualitative description of the excited IASs. The $T_z$=1 IAS in the $A$=14 exhibits asymmetry between the relative energy of the $T_z$=1 state and that of the $T_z$=1 states measured from the $T_z$=0 state, which may be related to charge asymmetry and independence of the $NN$ interaction. To investigate this point, we also started a systematic calculation of the $T_z$ = 1 triplets in the $A$=10-58 region. We also performed a benchmark calculation by comparing the results obtained with our 3D EDF solver and those obtained with an axial EDF solver.

(2) Finite amplitude method in covariant density functional theory
The $^{22}$C nucleus is currently of significant interest, since its halo structure with extremely weak binding was suggested by experiments. We have performed the Glauber analysis on this nucleus based on the density distribution calculated with the Skyrme energy density functional. To reproduce the large experimental cross section, we need to readjust the $t_0$ parameter of the Skyrme functional. It is desirable to have new experimental data on the reaction cross section with higher bombarding energy which should be available in current RIBF. In addition, we calculated the electric dipole modes of excitation with the RPA using the finite amplitude method (FAM). The computer code was previously developed, however, we need a very large space to treat such a weakly bound nucleus. The calculation with the 3D coordinate space of radius of 100 fm has been carried out, thanks to available high performance computing systems. It suggests that a very strong low-energy peak does not consist only of weakly bound s-wave neutrons, but also of sizable amount of d-wave components.

(3) Reaction cross section and electric dipole excitations in $^{22}$C
The $^{22}$C nucleus is currently of significant interest, since its halo structure with extremely weak binding was suggested by experiments. We have performed the Glauber analysis on this nucleus based on the density distribution calculated with the Skyrme energy density functional. To reproduce the large experimental cross section, we need to readjust the $t_0$ parameter of the Skyrme functional. It is desirable to have new experimental data on the reaction cross section with higher bombarding energy which should be available in current RIBF. In addition, we calculated the electric dipole modes of excitation with the RPA using the finite amplitude method (FAM). The computer code was previously developed, however, we need a very large space to treat such a weakly bound nucleus. The calculation with the 3D coordinate space of radius of 100 fm has been carried out, thanks to available high performance computing systems. It suggests that a very strong low-energy peak does not consist only of weakly bound s-wave neutrons, but also of sizable amount of d-wave components.

(4) Systematic study on pygmy dipole strength in heavy isotopes
We have systematically studied the low-lying electric dipole mode, so-called the pygmy dipole resonances (PDR) in neutron-rich isotopes in a region of nuclei with N<90, using the linear response calculation with the Skyrme energy density functional. The strong neutron shell effects have been found, which suggest several magic numbers for the enhancement of the PDR strength. We also investigate the deformation effect on the PDR. The K=0 component of E1 strength become dominant in Sr and Zr isotopes with prolate deformation. However, it is not associated with the orientation dependence of the neutron skin thickness. In fact, it is opposite, namely, the neutron skin thickness along the symmetry axis is smaller than that in the perpendicular directions. The close examination of the PDR strength in nuclei beyond N=82 indicates different characters for the peaks at E > 5 MeV and those at E < 5 MeV. The low-energy dipole states appearing at very low energies (E < 5 MeV) indicates no hindrance of the E1 strength from the pure single-particle strength. This suggests that these PDR peaks are completely decoupled from the giant dipole resonance (GDR).

(5) Deformed nuclei in the black-sphere approximation
In order to study the value of the density derivative $L$ of the symmetry energy of nearly symmetric nuclear matter, the total reaction cross section, $\sigma_{tot}$ of neutron-rich nuclei is one of the most important observables. We focus on the reactions involving the isotopes of Ne and Mg using the black-sphere approximation of nuclei. In this region of nuclei, we have to face the nuclear deformation. We change the black sphere into a spheroid of the same volume in order to take into account nuclear deformation before the discussion of $L$ dependence. The values of the deformation parameter, $\beta$, are taken from microscopic nuclear structure models. Before drawing conclusion, we have to check the interaction dependence by adopting SkM*, SLy4, KTUY etc. The study is now in progress.
(6) Giant dipole resonance in $^{96}$Mo at finite temperature and angular momentum

The line shapes of giant dipole resonance (GDR) in the decay of the compound nucleus $^{88}$Mo, which is formed after the fusion-evaporation reaction $^{48}$Ti + $^{40}$Ca at various excitation energies $E^* \text{s}$ from 58 to 308 MeV, are generated by averaging the GDR strength functions predicted within the phonon damping model (PDM) using the empirical probabilities for temperature and angular momentum. The average strength functions are compared with the PDM strength functions calculated at the mean temperature and mean angular momentum, which are obtained by averaging the values of temperature and angular momentum using the same temperature and angular-momentum probability distributions, respectively. It is seen that these two ways of generating the GDR linear line shape yield very similar results. It is also shown that the GDR width approaches a saturation at angular momentum $J \geq 50\hbar$ at $T= 4$ MeV and at $J \geq 70\hbar$ at any T.

The evolution of the GDR width and shape at finite temperature T and angular momentum J is described within the the 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 $^{88}$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.

(7) Study of pygmy dipole resonance with the exact treatment of the pairing

The strength functions of giant dipole resonance (GDR) in oxygen $^{18}$–$^{24}$O, calcium $^{50}$–$^{60}$Ca, and tin $^{120}$–$^{130}$Sn isotopes are calculated within the phonon damping model under three approximations: without superfluid pairing, including BCS pairing, and exact pairing gaps. The analysis of the numerical results shows that exact pairing decreases the two-neutron separation energy in light nuclei, but increases it in heavy nuclei as compared to that obtained within the BCS theory. In neutron-rich medium and heavy nuclei, exact pairing significantly enhances the strength located at the low-energy tail of the GDR, which is usually associated with the pygmy dipole resonance (PDR). The line shape of the GDR changes significantly with increasing the neutron number within an isotopic chain if the model parameter is kept fixed at the value determined for the stable isotope.

(8) Microscopic analysis of fusion hindrance in heavy systems

We study the reaction mechanism of fusion reactions and analyze origins of fusion hindrance in heavy systems with microscopic time-dependent Hartree-Fock (TDHF) theory. We have developed a method to directly extract nucleus-nucleus potential and energy dissipation from the relative motion of colliding nuclei to nuclear intrinsic excitations in fusion reactions from TDHF trajectories. We show that the Coulomb barrier disappears in potentials obtained in heavy systems and they monotonically increase as relative distance decreases, which are different from those of light, medium-mass systems. Further analysis shows that main origin of fusion hindrance is a dynamical change of extracted potential at short relative distance.

(9) Nuclear β-decay half-lives and r-process matter flow

Nucleosynthesis via rapid neutron capture, i.e., the r-process, is a major mechanism for producing the elements heavier than Fe in Universe. Understanding this process requires knowledge of properties such as masses, β-decay half-lives, and neutron-capture cross sections for a large number of extremely neutron-rich nuclei far from the stability line. In order to reliably predict the β-decay half-lives of thousands of unknown nuclei relevant to the r-process, the full self-consistency of the quasi-particle RPA (QRPA) approach is essential. Meanwhile, the proton-neutron pairing correlations in both isovector ($T = 1$) and isoscalar ($T = 0$) channels must be taken into account properly. In a very recent work, we established a fully self-consistent charge-exchange QRPA with both $T = 1$ and $T = 0$ proton-neutron pairing, based on the relativistic Hartree-Fock-Bogoliubov (RHFβ) framework. Then, we systematically investigated the β-decay half-lives of neutron-rich even-even nuclei with $20 \leq Z \leq 50$. It is shown that the available data are well reproduced, where the isospin-dependent $T = 0$ proton-neutron pairing is one of the most important ingredients. With the calculated β-decay half-lives, a classical r-process calculation has been performed with neutron density $n_n = 1022$–$1024$ cm$^{-3}$ and temperature $T = 1.5 \times 10^9$ K, and a remarkable speeding up of r-matter flow is predicted. This leads to enhanced r-process abundances of elements with $A \geq 140$, an important result for understanding the origin of heavy elements in Universe.

(10) Pseudospin symmetry in nuclear single-particle spectra

In nuclear single-particle spectra, pairs of single-particle states with quantum numbers $(n-1, \ell+1/2, j=\ell+3/2)$ and $(n, \ell, j=\ell+1/2)$ are always found to be quasi-degenerate. Arima et al. and Hecht et al. introduced in 1969 the so-called pseudospin symmetry (PSS) to explain this phenomenon. Although it has been already more than 40 years since the suggestion of PSS in atomic nuclei and comprehensive efforts have been made, the origin of PSS is still a puzzle. Recently, we suggested that it is promising to understand PSS and its breaking mechanism in a fully quantitative way by combining the similarity renormalization group technique, supersymmetric (SU(3)Y) quantum mechanics, and perturbation theory. We took the Schrödinger equation as an example, which corresponds to the lowest-order approximation in transforming a Dirac equation into a diagonal form by using the similarity renormalization group. It is shown that while the spin symmetry-conserving term appears in nuclear single-particle Hamiltonian, the PSS-conserving term appears naturally in its SUSY partner Hamiltonian. The eigenstates of these two Hamiltonians are exactly identical except for the so-called intruder states, which have no pseudospin partners. In such a way, the origin of PSS deeply hidden in the original Hamiltonian can be traced in its SUSY partner.
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Kenichi MATSUYANAGI ( - Mar. 31, 2014)

**Visiting Researcher**
Haozhao LIANG (JSPS) ( - Dec. 31, 2013)

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Naoyuki ITAGAKI (Kyoto Univ.)
Kaori KAKI (Shizuoka Univ.)
Lu GUO (Univ. of Chinese Academy) - Mar. 31, 2013
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Kazuhiko OYAMATSU (Aichi Shukutoku Univ.)
Yasuyuki SUZUKI (Niigata Univ.)
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**Assistants**
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Strangeness nuclear physics Laboratory

1. Abstract
We proposed 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) By addition of \(\Lambda\) particle to neutron-rich \(\Lambda\) hypernuclei, we found that states of the \(^7\Lambda\)He and \(^6\Lambda\)H became more stable. Especially, in \(^7\Lambda\)He, our prediction for the ground state is not inconsistent with the observed data within the error bar. The calculated result in \(^6\Lambda\)H did not find any bound state, which is inconsistent with the observed data. To understand the observed data for \(^6\Lambda\)H, theoretically it is requested to calculate reaction cross section of \(^4\)Li(\(\pi^+\),K\(^+\)) \(^6\Lambda\)H.

(2) As one of nuclear response by addition of \(\Lambda\) particle, we found that \(\Lambda\)-separation energy was dependent on the degree of deformation of core nuclei. Especially, energy gain by the \(\Lambda\)-particle addition in super-deformed state is much smaller than that in normal-deformed state in \(^{10}\Lambda\)Be and \(^{41}\Lambda\)Ca.

(3) By solving \(^4\)He trimer and tetramer systems accurately, we succeeded in exploring their level structure and a universality between those atomic systems and few-nucleon systems. Furthermore, we succeeded in explaining some fundamental results of the cold atom experiments using alikali atoms (Li, K, Rb, Cs) on account of the universality between \(^4\)He atoms and the alkali atoms.

Head
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Researcher (appointment across AICS)
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Foreign Postdoctoral Researcher
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Special Postdoctoral Researcher
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Daisuke JIDO (Tokyo Metropolitan University)
Hidekatsu NEMURA (University of Tsukuba)
Soichi ISHIKAWA (Hosei University)
Takenori FURUMOTO (Ichinoseki National College of Technology) -Mar. 31,2014
Atsushi HOSAKA (RCNP, Osaka University)
Shoji SHINMURA (Gifu University)
Akinobu DOTE (High Energy Accelerator Research Organization, KEK)
Thomas RIJKEN (Radboud University Nijmegen)
Kazama NAKAZAWA (Gifu University)
Atsushi UMEYA (Nihon Institute of Technology)
Toru SATO (Osaka University)
Satoru HIRENZAKI (Nara Women's University)
Masayuki ASAKAWA (Osaka University)
Masakiyo KITAZAWA (Osaka University)
Wolfram WEISE (Technical University of Munich)
Keiko MURANO (YITP, Kyoto University)
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Yoshikazu FUJIWARA (Kyoto University)  -Mar. 31, 2014
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VI. RNC ACTIVITIES

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) AdS/CFT correspondence and nuclear physics
   The renowned AdS/CFT correspondence, which was initiated in superstring theory, is a useful and powerful tool for analyzing strongly-coupled gauge theories. This has been applied to QCD, the dynamics of quarks. We studied how this powerful tool can have an impact on nuclear physics. We computed an effective action of multi-baryon systems, which should serve as a basic quantum action for nuclear physics. This turned out to reproduce nicely nuclear forces and baryon spectrum. In addition, three-body nuclear force was computed.

2) Vacuum Instability in Electric Fields via AdS/CFT: Euler-Heisenberg Lagrangian and Planckian Thermalization
   We analyze vacuum instability of strongly coupled gauge theories in a constant electric field using AdS/CFT correspondence. The model is the N=2 1-flavor supersymmetric large N_c QCD in the strong 't Hooft coupling limit. We calculate the Euler-Heisenberg effective Lagrangian L(E), which encodes the nonlinear response and the quantum decay rate of the vacuum in a background electric field E, from the complex D-brane action in AdS/CFT. We find that the decay rate given by Im L(E) becomes nonzero above a critical electric field set by the confining force between quarks. A large-E expansion of Im L(E) is found to coincide with that of the Schwinger effects in QED, replacing its electron mass by the confining force. Then, the time-dependent response of the system in a strong electric field is solved non-perturbatively, and we observe a universal thermalization at a short timescale "Planckian thermalization time" t ~ 1/T ~ E^{-1/2}. Here, T is an effective temperature which quarks feel in the nonequilibrium state with nonzero electric current, calculated in AdS/CFT as a Hawking temperature. Stronger electric fields accelerate the thermalization, and for a realistic value of the electric field in RHIC experiment, we obtain t ~ 1 [fm/c], which is consistent with the believed value.

2) Cosmology
   1) Primordial spectra from sudden turning trajectory
      Effects of heavy fields on primordial spectra of curvature perturbations are discussed in inflationary models with a sudden turning trajectory. When heavy fields are excited after the sudden turn and oscillate around the bottom of the potential, the following two effects are generically induced: deformation of the inflationary background spacetime and conversion interactions between adiabatic and isocurvature perturbations, both of which can affect the primordial density perturbations. In this paper, we calculate primordial spectra in inflationary models with sudden turning potentials taking into account both of the two effects appropriately. We find that there are some non-trivial correlations between the two effects in the power spectrum and, as a consequence, the primordial scalar power spectrum has a peak around the scale exiting the horizon at the turn. Though both effects can induce parametric resonance amplifications, they are shown to be canceled out for the case with the canonical kinetic terms. The peak feature and the scale dependence of bispectra are also discussed.

2) A Parallel World in the Dark
   The baryon-dark matter coincidence is a long-standing issue. Interestingly, the recent observations suggest the presence of dark radiation, which, if confirmed, would pose another coincidence problem of why the density of dark radiation is comparable to that of photons. These striking coincidences may be traced back to the dark sector with particle contents and interactions that are quite similar, if not identical, to the standard model: a dark parallel world. It naturally solves the coincidence problems of dark matter and dark radiation, and predicts a sterile neutrino(s) with mass of (0.1–1) eV, as well as self-interacting dark matter made of the counterpart of...
ordinary baryons. We find a robust prediction for the relation between the abundance of dark radiation and the sterile neutrino, which can serve as the smoking-gun evidence of the dark parallel world.

(3) Lattice gauge theory

1) Phase structure of 2-dimensional topological insulators by lattice strong coupling expansion

The phase structure of 2-dimensional topological insulators under a sufficiently strong electron-electron interaction is investigated. The effective theory is constructed by extending the idea of the Kane-Mele model on the graphenelike honeycomb lattice, in terms of U(1) lattice gauge theory (quantum electrodynamics, QED). We analyze the phase structure by the techniques of strong coupling expansion of lattice gauge theory. As a result, we find that the topological phase structure of the system is modified by the electron-electron interaction. There evolves a new phase with the antiferromagnetism not parallel to the direction pointed by the spin-orbit coupling, in between the conventional and the topological insulator phases. We also discuss the physical implication of the new phase structure found here, in analogy to the parity-broken phase in lattice quantum chromodynamics (QCD), known as "Aoki phase".

(4) Mathematical physics

1) Non-Lagrangian Theories from Brane Junctions

In this article we use 5-brane junctions to study the 5D $T_N$ 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, Bonventuri 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 q-point functions of the q-deformed $W_N$ Toda theories.

2) SUSY breaking by nonperturbative dynamics in a matrix model for 2D type IIA superstrings

We explicitly compute nonperturbative effects in a supersymmetric double-wall matrix model corresponding to two-dimensional type IIA superstring theory on a nontrivial Ramond-Ramond background. We analytically determine the full one-instanton contribution to the free energy and one-point function, including all perturbative fluctuations around the one-instanton background. The leading order two-instanton contribution is determined as well. We see that supersymmetry is spontaneously broken by instantons, and that the breaking persists after taking a double scaling limit which realizes the type IIA theory from the matrix model. The result implies that spontaneous supersymmetry breaking occurs by nonperturbative dynamics in the target space of the IIA theory. Furthermore, we numerically determine the full nonperturbative effects by recursive evaluation of orthogonal polynomials. The free energy of the matrix model appears well-defined and finite even in the strongly coupled limit of the corresponding type IIA theory. The result might suggest a weakly coupled theory appearing as an S-dual to the two-dimensional type IIA superstring theory.

3) Conditionally valid uncertainty relations

It is shown that the well-defined unbiased measurement or disturbance of a dynamical variable is not maintained for the precise measurement of the conjugate variable, independently of uncertainty relations. The conditionally valid uncertainty relations on the basis of those additional assumptions, which include most of the familiar Heisenberg-type relations, thus become singular for the precise measurement. We clarify some contradicting conclusions in the literature concerning those conditionally valid uncertainty relations: The failure of a naive Heisenberg-type error-disturbance relation and the modified Arthurs-Kelly relation in the recent spin measurement is attributed to this singular behavior. The naive Heisenberg-type error-disturbance relation is formally preserved in quantum estimation theory, which is shown to be based on the strict unbiased measurement and disturbance, but it leads to unbounded disturbance for bounded operators such as spin variables. In contrast, the Heisenberg-type error-error uncertainty relation and the Arthurs-Kelly relation, as conditionally valid uncertainty relations, are consistently maintained.

4) $W_3$ irregular states and isolated $N=2$ superconformal field theories

We explore the proposal that the six-dimensional (2,0) theory on the Riemann surface with irregular punctures leads to a four-dimensional gauge theory coupled to the isolated $N=2$ superconformal theories of Argyres-Douglas type, and to two-dimensional conformal field theory with irregular states. Following the approach of Gaiotto-Teschner for the Virasoro case, we construct $W_3$ irregular states by colliding a single SU(3) puncture with several regular punctures of simple type. If simple punctures are colliding with the SU(3) puncture, the resulting irregular state is a simultaneous eigenvector of the positive modes $L_n$, ..., $L_{2n}$ and $W_{[2n]}$, ..., $W_{[3n]}$ of the $W_3$ algebra. We find the corresponding isolated SCFT with an SU(3) flavor symmetry as a nontrivial IR fixed point on the Coulomb branch of the SU(3) linear quiver gauge theories, by confirming that its Seiberg-Witten curve correctly predicts the conditions for the $W_3$ irregular states. We also compare these SCFT's with the ones obtained from the BPS quiver method.

5) A Landscape in Boundary String Field Theory: New Class of Solutions with Massive State Condensation

We solve the equation of motion of boundary string field theory allowing generic boundary operators quadratic in X, and explore string theory non-perturbative vacua with massive state condensation. Using numerical analysis, a large number of new solutions are found. Their energies turn out to distribute densely in the range between the D-brane tension and the energy of the tachyon vacuum. We discuss an interpretation of these solutions as perturbative closed string states. From the cosmological point of view, the distribution of the energies can be regarded as the so-called landscape of string theory, as we have a vast number of non-perturbative string theory solutions including one with small vacuum energy.
VI. RNC ACTIVITIES

Head
Koji HASHIMOTO (Associate Chief Scientist)

Special Postdoctoral Researchers
Toshifumi NOUMI
Masato TAKI
Shingo TORII

Postdoctoral Researchers
Johannes SCHMUDE (- Sep. 30, 2013)
Taro KIMURA (JSPS)
Yuki MINAMI

Senior Visiting Scientist
Koichi YAZAKI

Visiting Scientists
Tatsumi AYOYAMA (Nagoya Univ.) Aug. 1, 2013 -
Minoru ETO (Yamagata Univ.) -
Kazuo FUJIKAWA (Univ. of Tokyo)
Masanori HANADA (KEK)
Masashi HAYAKAWA (Nagoya Univ.) - Mar. 31, 2013
Tetsutaro HIGAKI (KEK) Jan. 1, 2014 -
Keiji IGI (Univ. of Tokyo)
Hideaki IIDA (Kyoto Univ.) - Mar. 31, 2013
Norhiro IIZUKA (CERN) - Mar. 31, 2013
Nobuyuki ISHIBASHI (Univ. of Tsukuba)
Hiroshi ITOYAMA (Osaka City Univ.)
Yu MAEZAWA (Universität Bielefeld)
Shoichi MIDORIKAWA (Aomori Univ.)
Muneto NITTA (Keio Univ.) - Mar. 31, 2013
Noriaki OGAWA (KIAS) - Mar. 31, 2013
Kazutoshi OHTA (Meiji Gakuin Univ.)
Makoto SAKAGUCHI (Keio Univ.)
Norisuke SAKAI (Tokyo Women's Christian Univ.)
Yuichi Hiroshi SHIBUSA (Nagasaki Inst. of Applied Science)
Asato TSUCHIYA (Shizuoka Univ.)
Yoshio YAMAGUCHI (Univ. of Tokyo)
Tamiaki YONEYA (The Open Univ. of Japan) - Mar. 31, 2013

Assistants
Keiko SUZUKI
Noriko KIYAMA (- Aug. 31, 2013)
Mitsue YAMAMOTO (Sep. 1, 2013 -)
VI. RNC ACTIVITIES

Sub Nuclear System Research Division
Radiation Laboratory

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 N. Samios, and recently by S. Aronson carries our core team at BNL for those exciting researches using the PHENIX detector. 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, we measured direct photons in d+Au collisions. The results show that there is little cold nuclear effects in the first thermal photon measurement, we measured direct photons in heavy ion collisions. The measurement indicates that the initial temperature reached in the central Au+Au collisions is about 350 MeV, far above the expected transition temperature $T_c \approx 170$ MeV, 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.

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]

After the establishment of small gluon polarization inside the proton, we are investigating the antiquark spin and partonic orbital motion inside the proton with polarized proton collisions at RHIC using the PHENIX detector in order to understand the last piece of the proton-spin puzzle. We have collected W-boson production data to extract flavor-separated antiquark polarizations. The data analysis is ongoing to obtain the final results of the antiquark polarization. The Drell-Yan process (quark-antiquark annihilation) with polarized proton collisions is one of the key measurements to investigate the orbital motion in the proton. We are proposing to perform such measurement by upgrading the PHENIX detector. As a pilot measurement, some of us are participating in the Fermilab SeaQuest experiment which has been collecting $\mu^+\mu^-$ pairs using a 120-GeV unpolarized proton at Fermilab. By measuring 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 350 MeV, far above the expected transition temperature $T_c \approx 170$ MeV, 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, $v_2$, of direct photons in Au+Au collisions. The results show surprisingly large $v_2$, 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 $p_T$ suppression in Au+Au collisions show that the suppression reduces at very high $p_T$ ($p_T > 20$ GeV). 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.

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.

(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 (MEET). 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 cooperation with Japanese industries, GEM foils with a world-largest size (30cm x 30cm) are newly developed.

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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 detector components is just finished and we are moving to the production phase. For the electronics, 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 finally completed and 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 the 2011 of RHIC. Subsequently, we collected 5 billion Au+Au events in the 2011 run, 11/pb of p+p data at 510 GeV, 3/pb of p+p data at 200 GeV, 110/μb of U+U data at 193 GeV, and 2.9/nb of Cu+Au at 200 GeV. We are now analyzing those datasets to study the interaction between heavy quarks and the quark-gluon plasma.

During the 2011 run, part of the pixel detector was damaged due to thermal stress on the detector. We improved the operation procedure and there is no additional damage on the detector since 2012. We repaired the damaged pixel detectors in 2012 to 2013, and this repair work has been completed. The detector was re-installed in PHENIX before the 2014 run and has been successfully re-commissioned. We will have a long (~15 weeks) of Au+Au run at 200 GeV and we expect that we have high quality data with much higher statistics than the 2011 Au+Au 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 250pb⁻¹ in Run13 and almost achieved our goal. The intensive analysis is underway towards the publication.

(5) Neutron optics

Cold or thermal neutron beam is a high-sensitivity probe to study not only the structure of condensed matter, but also fundamental physics. Recently interests arise to apply those neutrons for the internal imaging of industrial material, sometimes at the fabrication stage or sometimes after aging. RANS (RIKEN Accelerator-driven compact neutron source) has been developed at the K1 space of RIBF building, and became operational in January 2013. By bombarding protons accelerated to 7MeV onto the beryllium target, neutrons are produced in low-energy nuclear reactions, Be(p,n)B. Fast and slow neutrons are detected at the end of the beam line, 5m away from the target. The large-area neutron imaging detectors, the combination of plastic scintillators and MPPCs, have been developed for the non-destructive inspections of the large scale structures such as bridges. Initial imaging experiments were successful with thermal and cold neutrons, and also in neutron-induced prompt gamma-ray analysis. Instrumentations for the polarized-neutron imaging and pulsed-neutron imaging are under construction.

The technology for a neutron interferometer using multilayer mirrors is adopted for differential phase imaging, to see an internal structure of a bulk. We have demonstrated that an internal crack in an acrylic plate is observable.

These activities were transferred to Neutron Beam Technology Team in RIKEN Center for Advanced Photonics.

(6) Development of beam source

Under the collaboration with BNL, 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. We have demonstrated the instantaneous beam intensity of more than 70 mA with highly-charged carbon and aluminum. This is the highest-current heavy-ion beam produced by any methods. The technical developments are well accumulated and now being applied to the DIGITAL accelerator in KEK. The beam commissioning of this new system is expected in 2014 with fully-stripped carbon beam. We have also established stable operation of low charge state heavy ion beams with an extremely low emittance.

We just installed another new LIS at the most upstream of the RHIC accelerator complex in BNL. The new LIS allows rapid switching among a wide variety of beam species so that the complex can be operated with large flexibility.

At Wako, the development of a next-generation electron beam source was performed using the novel photocathode based on a super-lattice semiconductor with negative electron affinity (NEA) surface. This activity was transferred to Nagoya University.
VI. RNC ACTIVITIES

Head
Hideto EN’YO (Chief Scientist; Director, RNC)

Members
Yasuyuki AKIBA (Vice Chief Scientist)
Yuji GOTO (Senior Research Scientist)
Itaru NAKAGAWA (Senior Research Scientist)
Yoshie OTAKEY (Senior Research Scientist) ( - Mar. 31, 2013)
Yasushi WATANABE (Senior Research Scientist)
Satoshi YOKKAICHI (Senior Research Scientist)
Ralf SEIDL (Senior Research Scientist)
Hiroaki ONISHI (concurrent; Senior Research Scientist)

Special Postdoctoral Researcher
Yoshichika SEKI

Contract Researchers
Takashi HACHIYA
Hisayuki TORII (May 1, 2013 – Mar. 31, 2014)

Postdoctoral Researchers
Yuki ARAMAKI ( - Mar. 31, 2014 )
Yoshimasa IKEDA ( - Mar. 31, 2014 )
Yoshimitsu IMAZU ( - Jun. 30, 2013 )
Daisuke KAWAMA (JSPS)
Takayuki SUMITA ( May 1, 2013 - )
Tomonori TAKAHASHI ( - Mar. 31, 2014 )
Yuhei MORINO ( May 1, 2013 - )

Senior Visiting Scientists
Toshiaki SHIBATA (Grad. Sch. of Sci. and Eng., Tokyo Inst. of Tech.)
Takashi NAKANO (RCNP, Osaka University)

Visiting Scientists
Kazuya AOKI (Inst. of Particle and Nuclear Studies, KEK)  Jun. 1, 2013 -
Alexander BAZILEVSKY (BNL, USA)  Jul. 15, 2013 -
Wolfgang BENTZ (Tokai Univ.)
Akihiro ENOKIZONO (Grad. Sch. of Sci., Rikkyo Univ.)
Hirotugu FUJII (Grad. Sch. College of Arts and Sciences, Univ. of Tokyo)  - Mar. 31, 2013
Yoshinori FUKAO (Inst. of Particle and Nuclear Studies, KEK)
Kenji FUKUSHIMA (Keio Univ.)
Haruhiko FUNAHASHI (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Taku GUNJI (CNS, Univ. of Tokyo)  Jul. 1, 2013 -
Noriyosu HAYASHIZAKI (Tokyo Inst. Tech.)
Masanori HIRAI (Tokyo Univ. of Science)
Kensuke HOMMA (Grad. Sch. of Sci., Hiroshima Univ.)  - Mar. 31, 2013
Ryo ICHIMIYA (KEK)  Jun. 1, 2013 -
Noriyoshi ISHII (Grad. Sch. of Pure and Applied Sci., Univ. of Tsukuba)
Robert JAMESON (Goethe Universitat Frankfurt, Germany)  - Mar. 31, 2013
Masashi KANETA (Tohoku Univ.)  Oct. 1, 2013 -
Hirotugu KASHIWAGI (Takasaki Advanced Radiation Res. Inst., JAEA)
Shunzo KUMANO (Inst. of Particle and Nuclear Studies, KEK)
Teiji KUNIHIRO (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Makoto KUWAHARA (Nagoya Univ.)
Youngil KWON (Yonsei Univ., Korea)  Jul. 22, 2013 -
Yoshikazu MAEDA (RCNP, Osaka Univ.)  - Mar. 31, 2013
Yajun MAO (Peking Univ., China)  - Mar. 31, 2013
Tsumoto MIBE (KEK)
Norihito MURAMATSU (RCNP, Osaka Univ.)  - Mar. 31, 2013
Ryotaro MUTU (KEK)
Tomofumi NAGAE (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Atsushi NAKAMURA (Information Media Center, Hiroshima Univ.)  May 1, 2013 -
Tomoaki NAKAMURA (ICEPP, Univ. of Tokyo)  - Mar. 31, 2013
Kenichi NAKANO (Tokyo Inst. Tech.)
Megumi NARUKI (KEK)  Jul. 1, 2013 -
Masayuki NIYAMA (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Tomohiro NISHITANI (Nagoya University)
VI. RNC ACTIVITIES

Munehisa OHTANI (Kyorin Univ.)
Masahiro OKAMURA (BNL, USA)
Kyoichiro OZAWA (KEK)
Petra RIEDLER (CERN, Switzerland) - Mar. 31, 2013
Nashito SAITO (J-PARC, KEK) - Mar. 31, 2013
Hiroyuki SAKO (JAEA) - Mar. 31, 2013
Murad SARSOUR (Georgia State University) - Mar. 31, 2013
Susumu SATO (JAEA)
Shin-ya SAWADA (Inst. of Particle and Nuclear Studies, KEK)
Michiko SEIKIMOTO (Inst. of Particle and Nuclear Studies, KEK)
Maya SHIMOMURA (Iowa State University)
Kazutaka SUDO (Inst. of Particle and Nuclear Studies, KEK) - Mar. 31, 2013
Mizuki SUMIHAMA (RCNP, Osaka Univ.) - Mar. 31, 2013
Taneja SWADHIN (SUNY at Stony Brook) - Mar. 31, 2013
Masao TABUCHI (Nagoya Univ.) - Mar. 31, 2013
Junpei TAKANO (KEK)
Kiyoshi TANIDA (Seoul National Univ., Korea)
Yorito YAMAGUCHI (CNS, Univ. of Tokyo)
Satoru YAMASHITA (ICEPP, Univ. of Tokyo) - Mar. 31, 2013
Imuran YOUNUS (Univ. of New Mexico, USA) - Mar. 31, 2013

Student

Junior Research Associates
Yasuhiro FUWA (Grad. Sch. of Sci., Kyoto Univ.) Apr. 1, 2013 -
Shinichi HAYASHI (CNS, Univ. of Tokyo)
Tomoya HOSHINO (Grad. Sch. of Sci., Hiroshima Univ.) Apr. 1, 2013 -
Shunsuke Ikeeda (Tokyo Inst. Tech.) Apr. 1, 2013 -
Kouki KANNO (Fac. Sci., Univ. of Tokyo) Apr. 1, 2013 -
Yuya KOMATSU (Fac. Sci., Univ. of Tokyo)
Masafumi KUMAKI (Fac. Sci. and Eng., Waseda Univ.) Apr. 1, 2013 -
Sanshiro MIZUNO (Grad. Sch. of Pure and Applied Sci., Univ. of Tsukuba)
Hirosi NAKAGOMI (Grad. Sch. of Pure and Applied Sci., Univ. of Tsukuba) Apr. 1, 2013 -
Wataru NAKAI (Fac. Sci., Univ. of Tokyo) Apr. 1, 2013 -
Masaya NIHASHI (Grad. Sch. of Sci., Hiroshima Univ.) - Mar. 31, 2013
Yuko SEKIGUCHI (CNS, Univ. of Tokyo) Apr. 1, 2013 -
Megumi SEKINE (Tokyo Inst. Tech.)
Takahito TODOROKI (Grad. Sch. of Pure and Applied Sci., Univ. of Tsukuba) - Mar. 31, 2013
Tomoya TSUJI (CNS, Univ. of Tokyo)
Daisuke WATANABE (Grad. Sch. of Sci., Hiroshima Univ.) Apr. 1, 2013 -
Satoshi YANO (Grad. Sch. of Sci., Hiroshima Univ.) Apr. 1, 2013 –

International Program Associates
Chong KIM (Korea Univ., Korea) Dec. 10, 2013 -
Taehong MOON (Yonsei Univ., Korea) Jul. 1, 2013 -
Sanghwa PARK (Seoul National Univ., Korea)
Inseek YOON (Seoul National Univ., Korea)

Student Trainees
Nobuaki AMANO (Grad. Sch. of Sci., Kyoto Univ.) - Mar. 31, 2013
Nerangika Sadeera BANDARA (Univ. of Massachusetts, Amherst, USA) Jul. 1, 2013 – Jul. 23, 2013
Michael BEAUMIER (Univ. of California, Riverside, USA) Jul. 8, 2013 – Aug. 4, 2013
Kazuya HAYASE (Tokyo Univ. of Science) - Mar. 31, 2013
Daniel JUMPER (Univ. of Illinois at Urbana Champaign, USA) Jul. 8, 2013 – Jul. 26, 2013
Sotaro KANDA (Fac. Sci., Univ. of Tokyo) - Mar. 31, 2013
Aaron KEY (Univ. of New Mexico, USA) Jul. 1, 2013 – Jul. 21, 2013
Paul KLINE (Dept. of Physics, SUNY at Stony Brook, USA) - Mar. 31, 2013
Yukiyoshi KON (RCNP, Osaka Univ.) - Mar. 31, 2013
Andrew MANION (Dept. of Physics, SUNY at Stony Brook, USA) - Mar. 31, 2013
Shinichi MASUMOTO (Fac. Sci., Univ. of Tokyo) - Mar. 31, 2013
Abraham MELES (New Mexico State Univ., USA) Jul. 1, 2013 – Jul. 20, 2013
Pedro MONTUENGA (Univ. of Illinois at Urbana Champaign, USA) Jul. 8, 2013 – Jul. 29, 2013
Hikari MURAKAMI (Fac. Sci., Univ. of Tokyo) Nov. 1, 2013 -
Kazuya NAGASHIMA (Grad. Sch. of Sci., Hiroshima Univ.)
Shoichiro NISHIMURA (Fac. Sci., Univ. of Tokyo) - Mar. 31, 2013
Yuki OBARA (Fac. Sci., Univ. of Tokyo)
VI. RNC ACTIVITIES

Hideyuki OIDE (Fac. Eng., Univ. of Tokyo)  - Mar. 31, 2013
Yusuke OYA (Grad. Sch. of Sci., Hiroshima Univ.)
Gonaduwage PERERA (New Mexico State Univ., USA)  Jul. 1, 2013 – Jul. 20, 2013
Dai SAKURAI (Grad. Sch. of Eng., Tokyo Univ. of Science)  - Mar. 31, 2013
Takahiro SAWADA (RCNP, Osaka Univ.)  - Mar. 31, 2013
Takuya SHIBUKAWA (Fac. Sci., Univ. of Tokyo)  Apr. 1, 2013 -
Akihisa TAKAHARA (CNS, Univ. of Tokyo)  - Mar. 31, 2013
Yosuke WATANABE (Fac. Sci., Univ. of Tokyo)  - Mar. 31, 2013
Yuki WATANABE (Tokyo Univ. of Science)  - Mar. 31, 2013

Interns
Hidemitsu ASANO (Fac. of Sci., Kyoto Univ.)  - Mar. 31, 2014
Ciprian GAL (Dept. of Physics, SUNY at Stony Brook)  Jun. 28, 2013 – Aug. 4, 2013
Katsuro NAKAMURA (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Masako YAMADA (Grad. Sch. of Sci., Kyoto Univ.)  - Mar. 31, 2013
Takayuki YAMAMOTO (Waseda Univ.)  - Mar. 31, 2013

Part-time Staff (Research Assistance)
Ryoji AKIMOTO (CNS, Univ. of Tokyo)
Kimiaki HASHIMOTO (Fac. of Sci., Rikkyo Univ.)
Takeru IGURI (Rikkyo Univ.)
Toru NAGASHIMA (Rikkyo Univ.)
Wataru SAITO (Rikkyo Univ.)

Assistants
Keiko SUZUKI
Noriko KIYAMA ( - Aug. 31, 2013 )
Mitsue YAMAMOTO ( Sep. 1, 2013 - )
VI. RNC ACTIVITIES

Advanced Meson Science Laboratory

Sub Nuclear System Research Division

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 which has strange-quark as a constituent quark. 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).

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 recent 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 K\textsuperscript{b}N 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 ο 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 K\textsuperscript{b}N 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 \textsuperscript{3}He(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 6x10\textsuperscript{9} kaons on \textsuperscript{3}He target, corresponding to a ~1% of the approved proposal. We successfully obtained semi-inclusive \textsuperscript{3}He(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 \textsuperscript{3}He(K⁻, Ap) events. To derive more information on the K\textsuperscript{b}N 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. Many Kaonic atom x-rays are measured and most of them can be explained by theoretical calculation, however, very large deviation exist on kaonic helium (and the oxygen) which can never been explained in the present theoretical scheme. Therefore, a new and high precision data have been long awaited for. This large deviation could be due to the existence of deeply bound kaonic states in nuclei, well below the atomic levels of kaons in energy. Very recently, we performed a kaonic helium X-ray measurement. We have achieved much more precise X-ray measurement, resulting in the shift to be 2 ± 2 (stat.) ± 2 (syst.) eV, which is in good agreement with the theoretical calculation. Therefore, previous data should be replaced by the present value, and the so called “kaonic helium puzzle” has been dissolved.

Another important X-ray measurement of kaonic atom would be 2p→1s transition of kaonic deuterium. We have measured same transition of kaonic hydrogen, but the width and shift from electro-magnetic (EM) value reflect only isospin average of the K\textsuperscript{b}N
interaction. We can resolve isospin dependence of the strong interaction by the measurement. We are presently preparing a proposal to J-PARC PAC to measure kaonic deuteron X-ray.

(1-C) Deeply bound pionic atoms and \(\eta^-\) 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 conducting the precision measurement at RIBF. The first measurement is aiming at pionic tin 121 as the first step for the systematic spectroscopy. A pilot experiment was performed in 2010, and the first main experiment was performed in 2014 showing 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 \(\eta^-\) mesic nuclei in GSI/FAIR. Theoretically, peculiarly large mass of \(\eta^-\) is attributed to UA(1) symmetry and chiral symmetry breaking. As a result, large binding energy is expected for \(\eta^-\) meson bound states in nuclei (\(\eta^-\)-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 \(\eta^-\)-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 \(\eta^-\) in nuclei. Especially \((\gamma, p)\) is most important reaction channel, where we can perform missing mass spectroscopy by detecting forward going proton. One of the big advantages 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 \(4\pi\) Electro-Magnetic calorimeter has been constructed and proton counter to detect forward going proton produced via \((\gamma, p)\) reaction was partially 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 beam. 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 (\(\mu\)SR).

(2-A) Condensed matter/materials studies with \(\mu\)SR

We are going to serve new \(\mu\)SR spectrometer named CHRONUS to collaborative experiments from the May-June cycle in 2014. To have higher affinity on \(\mu\)SR studies with ISIS muon facility, common data acquisition (DAQ) system with ISIS standard DAQ (DAEIII) and front-end control system (SEKI) have been installed and optimized along with other equipment in Port-4. Installations of an experimental platform over Port-4 and a pillar crane have been completed. Thus, we can perform two independent \(\mu\)SR experiments in Port-2 and Port-4 at the same time, switching double-pulse to share beam between the two.

Among our scientific activities on \(\mu\)SR studies from year 2011 to 2013, following six subjects of material sciences are most important achievements at the RIKEN-RAL muon facility:

1) One-dimensional diffusive motion of spin-excited states in the spin liquid of molecular magnet, EtMe3Sb[Pd(dmit)2]3, has been found. The data shows that this material could be the first example that realized one-dimensional resonating valence bond state.

2) 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.

3) A static ordering of Yb moment in pyrochlore structure of Yb:TiO3 crystal has been confirmed. This ordering can be explained by the Higgs mechanism.

4) 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.

5) The universality class of the Mott transition in EtMe3P[Pd(dmit)2]2 has been confirmed by pressure dependences of transportation properties.

6) Muon sites in La2CuO4 crystal have been evaluated based on ab-initio calculation on spatial distribution of the potential energy, taking into account the Cu spin spatial distribution effect.

(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 \(\mu\)SR study will be drastically improved. The ultra-slow muon beam can be stopped in thin foils, multi-layered materials and artificial lattices and we can apply the \(\mu\)SR 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 \(\mu^-\) 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 decided to start 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. 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-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 are designing a new beam line based on microscope optics.

**(3) Theoretical Researches**

**3-A) Physics of Quantum Hall system**

We have investigated the interlayer phase coherence and the Josephson currents in the bi-layer quantum Hall system based on the non-commutative geometrical approach. We have demonstrated that the Josephson in-plane current provokes anomalous behaviors in the Hall resistance in counter flow and drag experiments. Furthermore, we investigate the condition on the input current for the tunneling current to be coherent and dissipation less. Our results explain quite well the experimental report on the input current due to the von Klitzing group [Phys. Rev. Lett. 104 (2010) 116802]. We have predicted also how the condition changes when the sample is tilted in the magnetic field.

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Yuki NOZAWA (Grad. Sch. Sci., Kyoto Univ.)  - Mar. 31, 2013
Yuta SADA (Grad. Sch. Sci., Kyoto Univ.)  - Mar. 31, 2013

**International Program Associates**

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Budi ADIPERDANA (UNPAD, Indonesia)  - Nov. 29, 2013
Hanjie GUO (Zhejiang Univ., China)  - Dec. 20, 2013
Zhang QI (Lanzhou Univ., China)  Apr. 1, 2013 -

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Assistants
Yoko FUJITA
Yuri TSUBURAII
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.
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.
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Pamela ESPOSITO (Theory Group Secretary)
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 particle 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 CKM 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 ($K \to \pi \pi, \epsilon'/\epsilon$, etc) 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.
Ⅵ. RNC ACTIVITIES

Fig. The rack, motherboard, and chips of QCDCQ

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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 170 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, AG.

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 π^0 ALL 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→μ 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.

Figure 2 show the results of the AL measurement from the 510 GeV polarized proton run in 2012. This is approximately 1/5 of the data that was recorded in the 2013 run. Much improved results are expected in the combined data set. The analysis of the data is in progress.
VI. RNC ACTIVITIES

Figure 1 Double spin asymmetry $A_{LL}$ in $\pi^0$ production as a function of transverse momentum $p_T$ compared with expectations for different gluon polarization $\Delta G(x)$. Submitted to Physical Review D (arXiv:1402.6296 (2014)).

Figure 2 Single spin asymmetry $A_L$ of $W\rightarrow e$ and $W\rightarrow \mu$ measured by PHENIX in the 2012 polarized proton run

(2) Experimental study of Quark-Gluon Plasma using RHIC heavy-ion collider

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:
VI. RNC ACTIVITIES

- 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 1700 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/Ψ 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 T_{init} = 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.

![Figure 3 Invariant cross section (p+p) and invariant yield (Au+Au) of direct photons as function of p_T.](image)

(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.

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.
Figure 4 Left: a picture of West half of VTX detector installed in PHENIX experiment. The interior of the detector can be seen. Right: The VTX detector completed with all cables, cooling tubes and dry gas connections.

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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 beam. 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 newly fabricated materials. Muons reveal static and dynamic properties of electronic state of materials in the zero-field condition which is the ideal magnetic condition for reasearches on the magnetism. We have carried out μSR investigations on frustrated organic system which has a triangular spin network. We found the one dimensional properties of the spin-spin correlations in the system. This proves the first example which has the one-dimensional resonating spin state in real materials.

Positive muon beam with thermal energy has been produced by laser ionization of muoniums (bound system of mu+ and electron) emitted from hot tungsten surface with stopping surface 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 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 laser 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 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 newly fabricated materials. 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 medium region between neutron scattering method ($10^{-10}$-10$^{-12}$ second) and Nuclear Magnetic Resonance (NMR) (longer than $10^{-6}$ second). At port-2 of the RIKEN-RAL Muon Facility, we have been performing μSR researchs 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 2011 to 2013, we have obtained excellent results, and the highlights are listed in the following,

1) One-dimensional diffusive motion of spin-excited states in the spin liquid state of molecular magnet, EtMe₃Sb[Pd(dmit)₂]_2
2) Static ordering of small Ir moments in the pyrochlore iridate, NdIr₂O₅
3) Static ordering of Yb moment on the corner of the pyrochlore structure of Yb₂Ti₂O₇ which can be explained by the Higgs mechanism.
4) Spontaneous small static internal fields in the superconducting state of URu₂Si₂.
5) Universality class of the Mott transition in EtMe₃[Pd(dmit)₂]_2.
6) Finding new muon sites in La₂CuO₄ and success to explain those sites from the potential view point on the basis of a newly developed calculation method taking into account an effect of the special distribution of Cu spin.
7) International collaborations to organize new μSR experiments and to develop a group to work on muon-site calculations by using computational technique.

Soft matters with small spins like organic molecules are now good target for the pulsed muon beam to be applied. The one-dimensional diffusive motion in the two-dimensional crystal structure has been observed. This indicates a strong possibility to observe the one-dimensional RVB state appears in the frustrated spin liquid state in organic molecules (result-1). Solid observations of a statically magnetically ordered state of corner-shared magnetic moments on pyrochlore systems gave us new interpretations to understand exotic phenomena (result-2 and 3). 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 give a light on the mechanism of the superconductivity which has been a long-standing problem of this system (result-4). We have been developing gas-pressurized high-pressure apparatus which can be not only be used for μSR but also other purposes. We have applied this pressure system to EtMe₃[Pd(dmit)₂]_2 and have found that pressure dependent resistivity and thermoelectric effect measurements have shown that the Mott transition belongs to the Ising universality class even in two-dimensional states (result-5). Well known and deeply investigate La₂CuO₄ did open a new scheme of the Cu spin. Taking into account the effect of the distribution of Cu spin, we succeeded to explain newly found muon sites and hyperfine fields at those sites (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 the student acceptance (result-7).

A new µSR spectrometer “Chronus” which has finely multi-segmented forward and backward µ-e counter arrays (303 counters each) is now being used for real muon experiments. Software systems which control the data acquisition and experimental conditions are well working in Port-4. The same data acquisition system with that being used in the ISIS muon facility (DAE-III) was adopted. Muon signals more than 70 million events per hour have been recorded even in the single-pulse mode by using DAE-III system in Port-4.

(2) Ultra Slow (low energy) Muon Beam Generation and Applications

Positive muon beam with thermal energy has been produced by laser ionization of muoniums (bound system of μ⁻ and electron) emitted from hot tungsten surface with stopping surface muon beam at Port-3. The method generates positive muon beam with acceleration energy from several 100 eV to several 10 keV, small beam size (a few mm) and good time resolution (less than 8 nsec). By stopping the ultra-slow muon beam in thin foils, multi-layered materials and artificial lattices, we can precisely measure local magnetic field in the materials, and apply the µSR techniques to surface and interface science. Since there has been no appropriate probe to study magnetism at surface and interface, the ultra-slow muon beam will open a new area of these research fields. In addition, the development of ultra-slow muon beam is very important as the source of ultra-cold (pencil-like small emittance) muon beam for muon g-2 measurement.

It is essential to increase the slow muon beam production efficiency by 100 times for these applications. 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 2013, we developed a high power Lyman-alpha laser in collaboration with laser 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. Therefore, the new laser system should be installed to J-PARC slow muon beam line. On the other hand, we succeeded to synthesize novel ceramic-based Nd:YGAG crystal in this development, 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 2011-2013 was to achieve drastic improvements in 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. Very recently, 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 group. Analysis is in progress and the result will be published soon. 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, will be rebuilt to use advantage of the new room temperature target, such as no need of thermal shielding etc. Also, we adopt an all-cylindrical beam-transport design, because of its simpler optics and better manufacture precision, which will contribute to the ultimate cold muon source required for muon g-2. We plan the construction and testing be finished in time for the RIKEN-RAL muon beam recovery in Feb 2015 after ISIS shutdown.

(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 funds and human resources maintaining the tritium facility, we plan the safe closure of the tritium facility well before 2018. We have started discussion of safe removal of the tritium handling facility. The decommissioning is planned in early 2015.

New demand is emerging 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. Measurements are being performed at RIKEN-RAL to measure such an error rate. There is also measurement to test the electronics chips in a condition equivalent to the high radiation environment in accelerator experiment.

A new proposal was submitted recently 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 2S-2P energy splitting. The hyperfine transition measurement needs a high intensity laser so it needs to be matched with pulsed muon beam. Design of the hydrogen target, the laser, and the detector is in progress.
VI. RNC ACTIVITIES

RIBF Research Division
Radioactive Isotope Physics Laboratory

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 C-16. 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 first campaign will be organized in April 2014 to study neutron-rich Cr, Fe and Ni 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 foci 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 and two PLB. One of the PRL papers was associated to the r-process path where half-lives for 18 neutron-rich nuclei were determined for the first time. The other PRL report paper found 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, three papers, two PRL’s and one PRC, 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 physics proposals will be discussed at the 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 “SPIRIT”. Construction proposal was submitted at the PAC 2012, and physics proposals were approved at the PAC 2012 and 2013. Physics runs are scheduled in 2015.

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 –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 will make the first attempt to measure fragmentation reaction data with Cs-137 and Sr-90 beams at 200A MeV.

(6) Missing mass method

Missing mass technique is one of fundamental spectroscopy methods at RIBF. Detection of recoil particles from target is essential in excitation energy determination of particle unbound states without any assumption of particle- and gamma-decay processes, and also giving transfer angular momentum from the angular distribution measurement. We have developed a solid hydrogen target as well as a detector system called ESPRI for proton-(in)elastic scattering. In 2010, the ESPRI system was placed at GSI to measure proton elastic scattering with Ni isotope beams. In addition, the first missing mass spectroscopy was performed at RIBF, where the start-of-art detector MUST2 was invited from France to investigate O-24 and its neighboring nuclei. The (p,2p) reaction study for the light neutron-rich nuclei was carried out with the Kappa spectrometer installed at the new facility of RIBF.

The missing mass activity based on direct reactions has been moved to Spin-Isospin Laboratory in RNC since Uesaka was appointed as a chief scientist in April 2011.

(7) Interdisciplinary study for nuclear astrophysics

To understand the origin of elements beyond ion, interdisciplinary works are important in linking data from nuclear physics programs. In this respect, we did promote the ice core analysis activity to find out historical supernovae and to estimate event rates of supernovae.

This activity has been moved to Astro-Glaciology Research Unit in RNC since Motizuki was appointed as a unit leader in July 2011.

(8) Laser spectroscopy of radioactive isotope atoms

Electromagnetic moment is one of the most important quantities for studying nuclear structures because they are directly correlated with the quantum states and configurations of valence nucleons. Precision laser spectroscopy of radioisotope atoms (RI atoms) reveals these nuclear properties through the measurement of atomic level structures affected by hyperfine interactions. We have been developing a novel laser spectroscopic method for RI atoms named “OROCHI (Optical RI-atom Observation in Condensed Helium as Ion-catcher).” It is a combination of superfluid helium (He II) as a stopper of energetic RI beam with several tens MeV/u and in situ laser-microwave-RF double resonance spectroscopy of stopped RI atoms. We expect that this method is applicable to a wide variety of atomic species whose yields are as low as 10 pps.

The laser spectroscopy activity has been moved to Nuclear Spectroscopy Laboratory in RNC since Ueno was appointed as a chief scientist in April 2013.
VI. RNC ACTIVITIES

Head
Hiroyoshi SAKURAI (Chief Scientist; Deputy Director, RNC)

Members
Takashi ICHIHARA (Vice Chief Scientist)
Yoichi NAKAI (Senior Research Scientist)
Hideaki OTSU (Senior Research Scientist)
Takashi KISHIDA (Senior Research Scientist)
Shunji NISHIMURA (Senior Research Scientist)
Huu Ching LEE (Research Scientist)
Tadaaki ISOBE (Research Scientist)
Pieter DOORNENBAL (Research Scientist)

Contract Researcher
Satoshi TAKEUCHI (Apr. 1, 2013 - )

Foreign Postdoctoral Researchers
Giuseppe LORUSSO
Paer-Anders SOEDERSTROEM (Feb. 1, 2014 - )

Postdoctoral Researchers
Paer-Anders SOEDERSTROEM (JSPS) ( - Oct. 17, 2013)

Senior Visiting Scientists
Shigeru KUBONO (University of Tokyo)
Kengo OGAWA (Chiba Univ.)

Visiting Scientists
Nori AOI (RCNP, Osaka University)
Dam Nguyen BINH (Institute of Physicks, Vietnam Academy of Science and Technology) - Mar. 31, 2013
Silvio CHERUBINI (University of Catania, Italy)
Daiki NISHIMURA ( Tokyo University of Science )
Mitsunori FUKUDA (Osaka University)
Adrian GELBERG (Universitat zu Köln, Germany) - Aug. 12, 2013
Mikhail GOLOVKOV (Flerov Lab. of Nuclear Reaction, JINR ) - Mar. 31, 2014
Andrey FOMICHEV (Flerov Lab. of Nuclear Reaction, JINR ) - Mar. 31, 2014
Atsushi HATAKEYAMA (Tokyo University of Agriculture and Technology) - Mar. 31, 2014
Chuangye HE (China Institute of Atomic Energy) - Mar. 31, 2013
Byungsik HONG (Korea University ) Feb. 24, 2014 -
Kazuo IEKI (Rikkyo University)
Hyo Soon JUNG (University of Notre Dame)
Le Hong KHIEM (Institute of Physicks, Vietnam Academy of Science and Technology)
Mehuyaki KOBAYASHI (School of Science, the University of Tokyo)
Yosuke KONDO (Tokyo Institute of Technology) - Mar. 31, 2013
Nikolaus Ludwigs KURZ (GSI) - Mar. 31, 2013
Yukari MATSUO ( Hosei University )
Indranil MAZUMDAR (GSI)
Takamasa MOMOSE (The University of British Columbia, Canada)
Tetsuya MURAKAMI (Graduate School of Science, Kyoto University)
Takashi NAKAMURA(Tokyo Institute of Technology ) - Mar. 31, 2013
Megumi NIKIJURA ( the University of Tokyo )
Evgeni NIKOLSKI (RRC Kurchatov Institute, Institute of General and Nuclear Physics, Russia)
Alexey OGOBLIN (RRC Kurchatov Institute, Institute of General and Nuclear Physics, Russia)
Hooi Jing ONG (RCNP)
Naohiko OTSUKA (International Atomic Energy Agency, Austria)
Toshiyuki SUMIKAMA (Tohoku University)
Mays TAKECHI (GSI) - Mar. 31, 2013
Xiaolong WANG (Kyoto Univ.) - Mar. 31, 2014
Hirotoshi WATANABE ( Beihang University )

Visiting Technician
Andrey BEZBAKH (Flerov Lab. of Nuclear Reaction, JINR) Sep. 1, 2013 - Mar. 31, 2014
Alexander KNAYAZEV (Flerov Lab. of Nuclear Reaction, JINR) Sep. 1, 2013 - Mar. 31, 2014
Ⅵ. RNC ACTIVITIES

Ivan KOJOUHAROV (GSI Helmholtzzentrum fuer Schwerionenforschung GMBH)
Sergey KRUPKO (Flerov Lab. of Nuclear Reaction, JINR) Sep. 1, 2013 - Mar. 31, 2014
Sergey SIDORCHUK (Flerov Lab. of Nuclear Reaction, JINR) Sep. 1, 2013 - Mar. 31, 2014
Roman SLEPNEV (Flerov Lab. of Nuclear Reaction, JINR) Sep. 1, 2013 - Mar. 31, 2014

Research Associates
Mizuki NISHIMURA (- Mar. 31, 2014)
Satoshi TAKEUCHI (- Mar. 31, 2013)

Junior Research Associates
Shintaro GO - Mar. 31, 2014
Yoshiaki SHIGA

International Program Associates
Xiaofei YANG (Peking Univ., China) -Feb. 16, 2014
Hongna LIU (Peking Univ., China)
Jin WU
Frank BROWNE - Sep. 30, 2013
Zena PATEL Mar. 21, 2013 - Sep. 30, 2013
William POWELL

Research Consultant
Masayasu ISHIHARA

Consultant
Tateaki TORII

Part-time worker
Zhengyu XU (- Mar. 31, 2014)

Intern

Student Trainees
Jin-hee CHANG (Korea University)
Rie DAIDO (Osaka University)
Justin ESTEE (Michigan State University)
Yifan FANG (Osaka University)
Tomomi FUJITA (Osaka University)
Lauren HEILBORN (Texas A&M University)
Hisaya HOTAKA (Tohoku Univ.)
Tomoki ISHIHAKI (Osaka University)
Rachel HODGES (Michigan State University)
Akira HOMMA (Niigata University)
Jongwon HWANG (Seoul National Univ.)
Kei IMAMURA (Meiji University)
Yasuto KAMISHOU (Osaka Univ.)
Masanori KANEKO (Kyoto University)
Sunji KIM (Soul Univ., Korea)
Shumpei KINNO (The Tokyo University of Science)
Kazuma KOBAYASHI (Rikkyo University)
Akihiro KOJIMA (Tohoku Univ.)
Jungwoo LEE (Korean University)
Keishi MATSUI (The University of Tokyo)
Hideyuki MATSUZAWA (Rikkyo University)
Takuya MIYAZAKI (The University of Tokyo)
Yosuke MITSUYA (Meiji Univ.)
Satoru MOMIYAMA (The University of Tokyo)
Shouta MORIMOTO (Osaka University)
Yosuke MORITA (Osaka University)
Motoki MURATA (Kyoto University)
Daiki MUROOKA (Niigata University)
Kotomi MUTO (Tohoku University)
Masayuki NAGASHIMA (Niigata University)
Junichi OHNO (Osaka University)
VI. RNC ACTIVITIES

Noritsugu NAKATSUKA (Kyoto University)
Hiroki NISHIBATA (Osaka University)
Ippei NISHIZUKA (Tohoku University)
Masami SAKO (Kyoto University)
Philipp SCHROCK (Technical University Darmstadt)
Hirotaka SUZUKI (Osaka University)
Tadashi TAKO (Tohoku University)
Kohei TAKENAKA (Kyoto University)
Mana TANAKA (Osaka University)
Suwat TANGWANCHAROEN (Michigan State University)
Ryo TANIUCHI (The University of Tokyo)
Keisuke TASHIRO (Nigata University)
Takumi USUKURA (Rikkyo University)
He WANG (Peking University)
Daisuke WATANABE (The Tokyo University of Science)
Kouta WATANABE (Osaka University)
Jack WINKELBAUER (Michigan State University)
Zhengyu XU (The University of Tokyo)
Ayumi YAGI (Osaka University)
Tetsuya YAMAMOTO (Osaka University)
Shintaro YAMAOKA (Osaka University)
Takamasa YOSHIDA (Rikkyo University)
Kenta YOSHINAGA (The Tokyo University of Science)
Andrew ZARRELLA (Texas A&M University)
Yifan ZHU (The Tokyo University of Science)

Assistant
Yu NAYA
Tomoko FUJII (Mar. 31, 2013)
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.

(1-a) 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.

(1-b) Asymmetry terms in nuclear incompressibility
Nuclear incompressibility represents stiffness of nuclear matter. Incompressibility of symmetric nuclear matter is determined to be 230±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.

(1-c) Multi-neutron and-cluster correlations at low densities
Occurrences of multi-neutron and-cluster correlations are other interesting aspects of nuclear matter and define its low-density behavior. The multi-neutron and-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).

(1-d) 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 $(p,\alpha)$ experiments at the RI Beam Factory. We have already applied WINDS to the $(p,\alpha)$ 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 $\beta^+$ type isovector spin monopole resonances (IVSMR) in $^{208}$Pb and $^{96}$Zr via the $(1,^3$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$(^1$H, $^1$H)$^{12}$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-d$_{14}$ 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 $^6$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 polarized 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)

Head
Tomohiro UESAKA (Chief Scientist)

Members
Masaki SASANO (Research Scientist)
Juzo ZENIHIRO (Research Scientist)

Postdoctoral Researchers
Masanori DOZONO  - Mar. 31, 2014
Valerii PANIN  Dec. 1, 2013-

Senior Visiting Scientists
Hiroyuki SAGAWA (Aizu University)  - Mar. 31, 2014
Didier BEAUMEL (IPN)  Apr. 1, 2013 -

Visiting Researcher
Alexandre OBERTELLI (JSPS)  Sep. 2, 2013 -

Research Associate
Kenichiro TATEISHI  Apr. 1, 2013 -

Junior Research Associates
Keiichi KISAMORI
Yuki KUBOTA  Apr. 1, 2013 -
CheongSoo LEE  Apr. 1, 2013 -
Fumi SUZAKI  Apr. 1, 2013 -

International Program Associates
Sergey S. CHEBOTARYOV  Jun 1, 2013 -
Evgeniy V. MILMAN  Apr. 1, 2013 -
Chao WEN  Oct. 25, 2013 -

Visiting Scientists
Anna CORSI (CEA Saclay)  Jun. 24, 2013 -
Alain GILLIBERT (CEA Saclay)  Feb. 24, 2014 -
Yosuke KONDO (Graduate School, Tokyo Institute of Technology)
VI. RNC ACTIVITIES

Attila KRASZNAHORKAY (ATOMKI)  Mar. 15, 2014 -
Yohei MATSUDA (RCNP)  May 1, 2013 -
Kenjiro MIKI (RCNP)  Apr. 1, 2013 -
Dennis MUECHER (TU Munchen)  Dec. 15, 2013 -
Takashi NAKAMURA (Graduate School, Tokyo Institute of Technology)
Kimiko SAKAGUCHI (Graduate School, Tohoku University)
Satoshi SAKAGUCHI (Kyusyu University)
Yasuhiro TOGANO (Graduate School, Tokyo Institute of Technology)
Takashi WAKUI (Tohoku University)
Takayuki YAMAGUCHI (Saitama University)

Visiting Technicians
Gilles AUTHELET (CEA Saclay)  Jun. 25, 2013 -
Denis CALVET (CEA Saclay)  Oct. 14, 2013 -
Frederic CHATEAU (CEA Saclay)  Oct. 14, 2013 -
Alain DELBART (CEA Saclay)  Oct. 14, 2013 -
Arnaud GIGANON (CEA Saclay)  Oct. 14, 2013 -
Caroline LAHONDE-HAMDOUN (CEA Saclay)  Oct. 14, 2013 -
Jean-Marc GHELLE (CEA Saclay)  Jun. 25, 2013 -
Cedric PERON (CEA Saclay)  Jun. 25, 2013 -

Research Consultant
Harutaka SAKAGUCHI

Interns
SungHan BAE  Aug. 6, 2013 - Aug. 16, 2013
Sungha BAEK  Aug. 6, 2013 - Aug. 16, 2013
JiHwan BHYUN  Aug. 6, 2013 - Aug. 16, 2013
ZhenXing CHEN  Aug. 6, 2013 - Aug. 16, 2013
Seungbum CHUNG  Aug. 6, 2013 - Aug. 16, 2013
BaoShan HU  Aug. 6, 2013 - Aug. 16, 2013
ZhiMeng HU  Aug. 6, 2013 - Aug. 16, 2013
Wei JIANG  Aug. 6, 2013 - Aug. 16, 2013
WeiGuang JIANG  Aug. 6, 2013 - Aug. 16, 2013
JaeSung KIM  Aug. 6, 2013 - Aug. 16, 2013
JinHa KIM  Aug. 6, 2013 - Aug. 16, 2013
YoungHoon LIM  Aug. 6, 2013 - Aug. 16, 2013
LanDiao LIU  Aug. 6, 2013 - Aug. 16, 2013
FaFu NIU  Aug. 6, 2013 - Aug. 16, 2013
Seongho SHIN  Aug. 6, 2013 - Aug. 16, 2013
YiWen WEN  Aug. 6, 2013 - Aug. 16, 2013
ZhaoRu ZHANG  Aug. 6, 2013 - Aug. 16, 2013
TongKe ZHAO  Aug. 6, 2013 - Aug. 16, 2013

Student Trainees
Naruki INABA (University of Tsukuba)  Apr. 1, 2013 -
Yuki ISHII (Kyoto University)  Apr. 25, 2013 -
Tomomi KAWAHARA (Toho University) - Mar. 31, 2013
Tatsuo BABA (Kyoto University)  Apr. 1, 2013 - Mar. 31, 2014
Takuo FUKUNAGA (Kyusyu University)  Apr. 1, 2013 - Mar. 31, 2014
Shota FUKUOKA (University of Tsukuba)  Apr. 1, 2013 -
Tatsuya FURUNO (Kyoto University)  Apr. 1, 2013 - Mar. 31, 2014
Shuhei GOTANDA (University of Miyazaki)  Apr. 1, 2013 -
Tomosuke KADOYA (Tohoku University) - Mar. 31, 2013
Yoshihisa KANAYA (University of Miyazaki)  Apr. 1, 2013 -
Junpei KOUNO (Saitama University)  Apr. 1, 2013 - Mar. 31, 2014
Satoshi MATSUOKA (Saitama University)  Apr. 1, 2013 -
Ryogo MINAKATA (Tokyo Institute of Technology)  Apr. 1, 2013 - Mar. 31, 2014
Hiroshi MIURA (Saitama University)  May 27, 2013 -
Takuma NISHIMURA (Saitama University)  May 27, 2013 -
Syunichiro OHMIKA (Saitama University)  May 27, 2013 -
Muduki ONO (Saitama University)  May 27, 2013 - Mar. 31, 2014
Kazuki SAWAHATA (Tokyo Institute of Technology)  May 1, 2013 -
Mizuki SHIKATA (Tokyo Institute of Technology) May 1, 2013 -
Chihiro SHIMURA (Saitama University) May 27, 2013 - Mar. 31, 2014
Yuuta SHIOKAWA (Tohoku University) Apr. 1, 2013 - Mar. 31, 2014
Takahiro TAGUCHI (Tohoku University) - Mar. 31, 2014
Megumi TAKAHASHI (Tohoku University) - Mar. 31, 2013
Yuuki TAKEUCHI (Saitama University) May 27, 2013 -
Zhengyang TIAN (Peking University) - Mar. 31, 2014
Junichi TSUBOTA (Tokyo Institute of Technology) May 1, 2013 -
Miho TSUMURA (Kyoto University) Apr. 1, 2013 - Mar. 31, 2014
Yusunori WADA (Tohoku University) Apr. 1, 2013 - Mar. 31, 2014
Hidetomo WATANABE (Tohoku University) Mar. 31, 2013 -
Junpei YASUDA (Kyusyu University) Apr. 1, 2013 -

Part-time workers
Tomomi KAWAHARA Apr. 1, 2013 -
Reiko KOJIMA May 31, 2013

Assistant
Emiko ISOGAI
Yu Naya
Tomoko FUJII (Mar. 31, 2013)
1. Abstract

The group has conducted nuclear-physics studies utilizing stopped/slowed-down radioactive-isotope (RI) beams at the RIKEN RIBF facility based on the technique of nuclear spectroscopy that takes advantage of intrinsic nuclear properties such as nuclear spins, electromagnetic moments, and decay modes. In particular, by combining the techniques and devices for the production of spin-controlled RI beams to spectroscopic studies, high-sensitivity measurements to spin precessions/resonances have been conducted through a change in the angular distribution of radiations. The nuclear structures and properties of far-unstable nuclei are discussed based on thus determined spin-related observables. The methods are also applied to condensed matter studies, such as semiconductors, ferromagnets, fullerenes, and systems with dilute magnetic impurities, by exploiting RIs as microscopic 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 $\beta$-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 $\beta$-ray-detected nuclear magnetic resonance ($\beta$-NMR) and $\gamma$-ray time differential perturbed angular distribution ($\gamma$-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 $\beta$-NMR/nuclear quadrupole resonance (NQR) methods, in-beam Mössbauer spectroscopy and the $\gamma$-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.

Head
Hideki UENO (Chief Scientist)

Members
Yuichi ICHIKAWA (Oct. 1, 2013-) (Research Scientist)
Aiko NAKAO (May 1, 2013-) (Senior Research Scientist)

Research Consultant
Takuya OKADA

Visiting Scientists
Hisazumi AKAI (Osaka Univ.)
Koichiro ASAHI (Tokyo Tech)
Dimiter BALABANSKI (Bulgarian Academy of Sciences)
Takeshi FURUKAWA (Tokyo Metropolitan Univ.)
Atsushi HATAKEYAMA (Tokyo Univ. of Agriculture and Technology)
Yuichi ICHIKAWA (Tokyo Institute of Technology) - Sep. 30, 2013
Radomira LOZEV A (CNRS/IN2P3)
Yukari MATSUO (Hosei Univ.)
Kensaku MATSUTA (Osaka Univ.)
Takamasa MOMOSE (Kyoto Univ.)
Jiro MURATA (Rikkyo Univ.)
Wataru SATO (Kanazawa Univ.)
Makoto UCHIDA (Tokyo Tech)
Xiaolong WANG (Kyoto Univ.) - Mar. 31, 2014
Akihiro YOSHIMI (Okayama Univ.)

Junior Research Associates
Yoko ISHIBASHI (Univ. of Tsukuba) - Mar. 31, 2014
Kei IMAMURA (Meiji Univ.)

Student Trainees
Aleksey GLADKOV (Kyungpook National University) - Mar. 31, 2014
Miki HAYASAKA (Tokyo Gakugei Univ.)
Ryosuke KANBE (Osaka Univ.) - Mar. 31, 2014
Yuki KANNO (Tokyo Tech)
Shota KISHI (Tokyo Gakugei Univ.) - Mar. 31, 2014
Shuichiro KOJIMA (Tokyo Tech) - Mar. 31, 2014
Yuichi OHTOMO (Tokyo Tech) - Mar. 31, 2014
Tsubasa SAGAYAMA (Tokyo Gakugei Univ.) - Mar. 31, 2014
Yu SAKAMOTO (Tokyo Tech)
Tomoya SATO (Tokyo Tech)
Yonggeun SEON (Kyungpook National University)
Hazuki SHIRAI (Tokyo Tech) - Mar. 31, 2014
Takahiro SUZUKI (Tokyo Tech)
Masaomi TANAKA (Osaka Univ.)
Masato TSUCHIYA (Tokyo Tech)

Assistant
Emiko ISOGAI
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.

Head
Toru TAMAGAWA (Associate Chief Scientist)

Contract Researcher
Goro SATO

Special Postdoctoral Researchers
Satoru KATSUDA
Shin'ya YAMADA
Asami HAYATO
Kumi ISHIKAWA

Postdoctoral Researcher
Takao KITAGUCHI

Visiting Scientists
Aya BAMBA (ISAS/JAXA)
Naohisa INADA (Univ. of Tokyo)
VI. RNC ACTIVITIES

Madoka KAWAHARADA (ISAS/JAXA)
Atsushi SENDA (JST)
Poshak GANDHI (ISAS/JAXA)
Ken OHSUGA (NAOJ)
Toru MISAWA (Shinshu Univ.)
Yujin NAKAGAWA (Waseda Univ.)
Rohita TAKAHASHI (Tomakomai Nat'l College of Tech.)
Yukikatsu TERADA (Saitama Univ.)
Harufumi TSUCHIYA (JAEA)
Masaki WAKABAYASHI (Jakulin commercial company LC)
Hiroya YAMAGUCHI (CfA/Harvard Univ.)

Visiting Researchers (JSPS)
Teruaki ENOTO (Stanford Univ.)
Wataru IWAKIRI (Saitama Univ.)

Part-time Workers
Shigeru ENDO
Megu KUBOTA
Rie YOSHII

Student Trainees
Takanori IWAHASHI (Tokyo Univ. of Science)
Saori KONAMI (Tokyo Univ. of Science)
Wataru IWAKIRI (Saitama Univ.)
Fumi ASAMI (Tokyo Univ. of Science)
Kenta KANEKO (Kogakuin Univ.)
Kenichi IWATA (Shibaura Institute of Technology)
Megu KUBOTA
Yoko TAKEUCHI (Tokyo Univ. of Science)
Rie YOSHII (Tokyo Univ. of Science)
Akifumi YOSHIKAWA (Tokyo Univ. of Science)

Assistant
Yu NAYA
Our Astro-Glaciology Research Unit, organized in July 2011, 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 the ice cores drilled at the Dome Fuji station in Antarctica in collaboration with the 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 ($\text{NO}_3^-$) 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 ($^{18}\text{O}$ and $^2\text{H}$) in the ice cores, in order to reconstruct past temperature changes on the earth, and
5. Variations in the nitrate isotope ($^{15}\text{N}$) 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.

**Head**
Yuko MOTIZUKI (Research Unit Leader)

**Members**
Kazuya TAKAHASHI (Concurrent: Senior Research Scientist)
Yoichi NAKAI (Concurrent: Senior Research Scientist)

**Contract Researcher**
Kentaro SEKIGUCHI (- Mar. 31, 2013)

**Postdoctoral Researcher**
Sachiko OKAMOTO (- Mar. 31, 2014)

**Visiting Scientists**
Hidehara AKIYOSHI (National Institute for Environmental Studies) - Mar. 31, 2013
Bradley MEYER (Clemson Univ., USA) - Mar. 31, 2013
Sachiko AMARI (Washington Univ., USA) - Mar. 31, 2013
Akira HORI (Kitami Institute of Technology)
Hiroyuki KOURA (Japan Atomic Energy Agency) - Mar. 31, 2013
Hideki MADOKORO (Mitsubishi Heavy Industries, Ltd.)
Takahiro TACHIBANA (Waseda High Sch., Waseda Univ.) - Mar. 31, 2013
Kohji TAKAHASHI (Universite Libre de Bruxelles) - Mar. 31, 2013

**Junior Research Associate**
Satomi KIKUCHI (Saimata University) - Mar. 31, 2013

**Student Trainees**
Daiti SUZUKI - Mar. 31, 2013

**Part-time Workers**
Keiko FUKUSHIMA
Manami MARUYAMA
Yuri OBI
Ⅵ. RNC ACTIVITIES

Ai TANEICHI

Assistants
Yoko FUJITA
Yuri TSUBURAI
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 Helmholtz Zentrum für Schwerionenforschung GmbH (GSI), Germany by using \(^{208}\text{Pb} \) or \(^{209}\text{Bi} \) based complete fusion reactions, so called “cold fusion” reactions. We have made independent confirmations of the productions of isotopes of \( 108\text{Hs} \), \( 110\text{Hs} \), \( 111\text{Hs} \), and \( 112\text{Hs} \) elements by using the same reactions performed at GSI. After these work, we observed an isotope of the \( 113\text{Hs} \) element, \(^{279}\text{Hs} \), in July 2004, in April, 2005, and in August 2012. The isotope, \(^{279}\text{Hs} \), 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 2009. 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, \(^{264}\text{Hs} \) \((Z=108)\), which has the smallest atomic mass number ever observed among the Hassium isotopes, has discovered in the study. New spectroscopic information for \(^{264}\text{Hs} \) and its daughters have obtained also. The spectroscopic study of Rutherfordium isotope \(^{261}\text{Rf} \) \((Z=104)\) 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 \(^{248}\text{Cm}(^{48}\text{Ca}, xn)^{296-378}\text{Lv} \) (\( Z = 116 \)) previously studied by Frelon Laboratory of Nuclear Reaction, Russia, and GSI.
We observed 5 isotopes in total which tentatively assigned to $^{293}\text{Lv}$, and $^{292}\text{Lv}$.

**Head**
Kosuke MORITA (Group Director)

**Visiting Scientist**
Kunihiro FUJITA (Kyushu University) Nov. 1, 2013-

**Student Trainees**
Yoshihiro NARIKIYO
Taiki TANAKA - Mar 31, 2014
Shoya YAMAMOTO - Mar 31, 2014

**Assistant**
Yu NAYA
For this year, see the section of Research Group for Superheavy Element.

**Head**  
Kosuke MORITA (Group Director)

**Member**  
Kouji MORIMOTO (concurrent)

**Nishina Center Research Scientist**  
Daiya KAJI (concurrent)

**Nishina Center Technical Scientist**  
Akira YONEDA

**Special Postdoctoral Researcher**  
Yasuo WAKABAYASHI

**Visiting Scientist**  
Hiroyuki KOURA (JAEA)

**Research Consultant**  
Kenji KATORI ( - Mar. 31, 2014)

**Part-time Worker**  
Kengo TANAKA

**Students**

**Junior Research Associate**  
Mirei TAKEYAMA

**Student Trainees**  
Yukiko KOMORI (Osaka Univ.) - Mar 31, 2014  
Takuya YOKOKITA (Osaka Univ.) - Mar 31, 2014  
Kengo TANAKA (concurrent)
RIBF Research Division
Research Group for Superheavy Element
Superheavy Element Device Development Team

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 related 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 $^{278}_{113}$ were produced by $^{70}$Zn + $^{209}$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.

Head
Kouji MORIMOTO (Team Leader)

Nishina Center Research Scientist
Daiya KAJI

Nishina Center Technical Scientist
Akira YONEDA (concurrent)

Visiting Scientist
Fuyuki TOKANAI (Yamagata University)

Part-time Worker
Sayaka YAMAKI (- Mar. 31, 2014)

Student Trainee
Sayaka YAMAKI (concurrent)
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 projects (Kamigaito, Fukunishi, Okuno)

3. Summary of Activity

(1) The stripping schemes for Xe and U beams have been renewed.
(2) The intensity of the xenon beam reached 38 pnA.
(3) The beam availability exceeded 90%.
(4) The large infrastructure was properly maintained based on a well-organized cooperation among the related sections.
(5) A new upgrade plan was proposed for further enhancement of the beam intensity. Basic study is in progress.

Group Director
Osamu KAMIGAITO (Chief Scientist)

Deputy Group Directors
Hiroki OKUNO (Intensity upgrade)
Nobuhisa FUKUNISHI (Stable and efficient operation)
Masayuki KASE (Energy-efficiency management)

International Program Associate
Vasileios TZOGANIS (University of Liverpool)

Visiting Scientists
Akira GOTO (Yamagata University)
Toshiyuki HATTORI (Tokyo Institute of Technology)

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 stripers 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 stripers 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 stripers for high power beams (foil, low-Z gas)
   (Hasebe, H., Imao, H. Okuno, H.)
   We are developing the charge stripers 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.

Team Leader
Hiroki OKUNO (Deputy Group Director)

Members
Jun-ichi OHNISHI (Senior Technical Scientist)
Hiroshi IMAO (Research Scientist)

Nishina center Technical Scientist
Hiroo HASEBE

Special Postdoctoral Researcher
Hironori KUBOKI ( - Mar. 31, 2014)

Visiting Scientists
Noriyosu HAYASHIZAKI (Tokyo Institute of Technology) - Mar. 31, 2013
Mitsuhiko FUKUDA (RCNP, Osaka Univ.) - Mar. 31, 2013
Andreas ADELMANN (PSI, Switzerland)

Research Consultants
Yoshiaki CHIBA - Mar. 31, 2013
Isao YAMANE - Mar. 31, 2013
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 heavy-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 ions

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 beam
(T. Nakagawa, J. Ohnishi, M. Kidera, Y. Higurashi, K. Ozeki and T. Nagatomo)

The RIBF is required to supply uranium 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.

Team Leader
Takahide NAKAGAWA

Member
Takeshi NAGATOMO (Technical Scientist)

Nishina Center Research Scientists
Masanori KIDERA
Yoshihide HIGURASHI

Contract Researcher
Kazutaka OZeki

Postdoctoral Researcher
Tatsuya URABE (- Mar. 31, 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.

Team Leader
Eiji IKEZAWA

Member
Yutaka WATANABE (Senior Technical Scientist)

Research Consultants
Toshiya CHIBA (Mar. 31, 2014)
Masatake HEMMI (Mar. 31, 2014)
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 for the rebuncher system

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 rebuncher cavity
   Development of the intermediate-energy polarized deuteron beams.

Team Leader
Naruhiko SAKAMOTO

Nishina Center Research Scientist
Kenji SUDA

Foreign Postdoctoral Researcher
Liang LU (-July 31, 2013)

Research Consultant
Yoshiaki CHIBA (-Mar.31, 2014)
1. Abstract
The cascaded cyclotrons used in RIKEN RI Beam Factory (RIBF) requires not only severe matching of the beam 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 studies 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.

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 $^{238}\text{U}^{64+}$ 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.

Team Leader
Nobuhisa FUKUNISHI (Deputy Group Director)

Members
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 KOBAYASHI-KOMIYAMA
Akiito UCHIYAMA

Postdoctoral Researcher
Takuya MAEYAMA

Temporary Employee
Makoto NAGASE (Mar. 31, 2014)

Visiting Scientists
Hiromichi RYUTO (Photonics and Electronics Science and Engineering Center, Kyoto University)
Jun-ichi ODAGIRI (Accelerator Laboratory, High Energy Accelerator Research Organization (KEK))
Shin-ichiro HAYASHI (Faculty of Health Science, Hiroshima International University) (Mar. 31, 2014)
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.).

**Team Leader**

Hiroki OKUNO (Deputy Group Director)

**Member**

Masato NAKAMURA (Senior Technical Scientist)

**Nishina Center Technical Scientist**

Takeshi MAIE

**Technical Staff-I**

Tomoyuki DANTSUKA

**Temporary Employee**

Kumio IKEGAMI ( - Mar. 31, 2014)

**Part time Worker**

Shizuhiko TSURUMA
RIBF Research Division
Accelerator Group
Infrastructure Management Team

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.

Team Leader
Masayuki KASE (Deputy Group Director)

Members
Shu WATANABE (Senior Technical Scientist)
Hiromi YAMASAWA (Manager)

Research Consultant
Shin-ichi WATANABE (- Mar. 31, 2014)

Temporary Employee
Tadashi FUJINAWA (-Mar. 31, 2014)

Visiting Scientist
Hideshi MUTO (Tokyo Univ. of Sci. Suwa)
1. Abstract
This group develops core experimental installations at the RI Beam factory. Experimental installations currently under construction include designs containing common elements enabling multiple use (SLOWRI), as well as others that are highly program specific (SCRIT and Rare-RI Ring). All are designed to maximize the research potential of the world's most intense RI beams, made possible by the exclusive equipment available at the RI Beam Factory. Beam manipulation techniques, such as a beam accumulation and a beam cooling etc., 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. Future Plan for each project is described in subsections. SCRIT is now partially under construction and the system has been already tested using stable isotopes. ISOL system for SCRIT experiment (ERIS) is now under development. Rare RI Ring construction has been started in 2012 and we succeeded in the first beam circulation using alpha particle in this year. There are many things we have to do to make it ready for starting mass measurement, but it is now ready for operation. SLOWRI is now under construction.

Group Director
Masanori WAKASUGI

Senior Visiting Scientist
Akira OZAWA

Student Trainees
Saki MATSUO
Yohei SUMI
Mamoru TOGASAKI

Assistants
Yoshiko SAKATA
Noriko KIYAMA
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 spectograph. In the R&D works at the present ring cyclotron facility, an extraction efficiency of 33% for a 100A MeV $^9$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, $^9$Li. A high mass resolving power of 170,000 has been obtained for an isobaric doublet of 40K and 40Ca 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 (1) Construction of stopped and low-energy RI-beam facility (SLOWRI) and (2) Laser spectroscopy of trapped radioactive Beryllium isotopes. demonstrate 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, $^9$Li. A high mass resolving power of 170,000 has been obtained for an isobaric doublet of 40K and 40Ca 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 (1) Construction of stopped and low-energy RI-beam facility, SLOWRI. (2) Laser spectroscopy of trapped radioactive Beryllium isotopes.

2. Major Research Subjects

(1) Construction of stopped and low-energy RI-beam facility, SLOWRI.
(2) Laser spectroscopy of trapped radioactive Beryllium isotopes.
(3) Development of a multi-reflection time-of-flight mass spectograph for precision mass measurements of short-lived nuclei.
(4) Development of parasitic slow RI-beam production method using resonance laser ionization.
(5) Development of ion-surfing gas cell.

3. Summary of Research Activity

(1) Construction of stopped and low-energy RI-beam facility (SLOWRI)

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 RF Carpet 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 (EQQ1 to EQQ11) and 7 beam profile monitors (BPM). SD1 and SD2, located right after the gas catchers will be used for isolate 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 EQQs. The EQQs 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 EQQs 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, TAKAMINE, Aiko, 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 $^{11}\text{Be}$, 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 $2s\,^2\text{S}_{1/2} - 2p\,^2\text{P}_{3/2}$ transition of $^7\text{Be}^+$, $^9\text{Be}^+$, $^{10}\text{Be}^+$ and $^{10}\text{Be}^+$ ions and the nuclear charge radii of these isotopes were determined. The hyperfine structures of $^7\text{Be}^+$ and $^9\text{Be}^+$ ions using the laser-microwave double resonance spectroscopy were also performed and the magnetic hyperfine constants of $^7\text{Be}^+$ and $^9\text{Be}^+$ ions were determined with accuracies of better than 10^{-7}.

(3) Development of a multi-reflection TOF mass spectrograph 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 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 isotopes are in progress. These beryllium isotopes through laser-laser double resonance spectroscopy. 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 $2s\,^2\text{S}_{1/2} - 2p\,^2\text{P}_{3/2}$ transition of $^7\text{Be}^+$, $^9\text{Be}^+$, $^{10}\text{Be}^+$ and $^{10}\text{Be}^+$ ions and the nuclear charge radii of these isotopes were determined. The hyperfine structures of $^7\text{Be}^+$ and $^9\text{Be}^+$ ions using the laser-microwave double resonance spectroscopy were also performed and the magnetic hyperfine constants of $^7\text{Be}^+$ and $^9\text{Be}^+$ ions were determined with accuracies of better than 10^{-7}.

(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 isotope 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 $\text{Ar}^+$ 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^{-4} 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 experiment. 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.
Team Leader
Michiharu WADA

Member
Hideyuki YAMAZAWA (concurrent)

Nishina Center Research Scientists
Tetsu SONODA
Kensuke KUSAKA (concurrent)

Nishina Center Technical Scientist
Takeshi MAIE (concurrent)

Contract Researcher
Peter SCHURY

Research Associate
Yuta ITO (- Mar. 31, 2014)

Research Consultant
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Visiting Scientists
Hideki IIMURA (Japan Atomic Energy Agency)
Kunihiro OKADA (Sophia University)
Hans SCHUESSLER (Texas A&M University)
Aiko TAKAMINE (Aoyama Gakuin University) - Mar. 31, 2014
Hideki TOMITA (Graduate School of Engineering, Nagoya University)
Klaus WENDT - Mar. 31, 2014
Hermann WOLLNIK (University of Giessen) - Mar. 31, 2014

Part-time Workers
Shigeaki ARAI
Ichirou KATAYAMA
Tadashi FUJINAWA (- Mar. 31, 2014)

Student Trainees
Takuma NOTO
Takaaki TAKATSUKA - Mar. 31, 2014
Fumiya ARAI
Yoshitaka ADACHI - Mar. 31, 2014
Takahide TAKAMATSU - Mar. 31, 2014
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 (rare-RI) 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)” is now under construction at RIKEN RI Beam Factory. Our target performance in the mass determination is to achieve an 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, rare-RIs with a large momentum spread, $\Delta p/p = 0.5\%$, 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 the construction has been started in 2012. Construction of the infrastructures and fabrication of major parts of hardware relating to R3 have already been roughly completed. We are now setting up and testing all equipment including the power supplies, the control system, the vacuum system, and so on, toward the first commissioning planned in 2014.

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, $\mu$, 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. They are reused magnets used in TARN-II, which was constructed at INS Tokyo University more than 20 years ago. 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, $^{78}\text{Ni}$ 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 $\Delta p = 0\%$ particle, the circumference is 60.35 m and the betatron tunes are $\Delta x = 1.21$ and $\Delta y = 0.84$ in horizontal and vertical directions, respectively. The momentum acceptance is $\Delta p/p = 0.5\%$ and the transverse acceptances are 20$m/mm$rad and 10$m/mm$rad 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 has to be completed within the flight time of the rare-RI from an originating point 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. Output current of our kicker power supply rises at 250 ns and the center of the flat top of the magnetic field is at smaller than 500 ns from the trigger input.

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 172 MHz, which corresponds to the harmonic number of 56, and a measured quality factor is over 7000 and shunt impedance is 400 k$\Omega$. We can detect single ion circulation of $^{79}\text{Ni}^{29+}$ 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 $\mu$g/cm$^2$. The rare-RI with the energy of 200 MeV/u survives only for first 1000 turns because of an energy loss at the foil.

Major components of R3 have already been fabricated and the ring components were precisely arraigned. We are now setting up and testing every device individually, and we advance all preparations toward the commissioning scheduled in 2014.
VI. RNC ACTIVITIES

Team Leader
Masanori WAKASUGI (Group Director)

Members
Tamaki WATANABE (concurrent)
Yutaka WATANABE (concurrent)
Naohito INABE (concurrent)
Yoshiyuki YANAGISAWA (concurrent)
Hideyuki YAMAZAWA (concurrent)

Nishina Center Research Scientist
Yoshitaka YAMAGUCHI

Nishina Center Technical Scientists
Takeshi MAIE (concurrent)
Misaki KOMIYAMA (concurrent)

Junior Research Associate
Yasushi ABE (University of Tsukuba)

Visiting Scientists
Daisuke NAGAE (Inst. Phys., Univ.of Tsukuba)
Tetsuro KOMATSUBARA (University of Tsukuba) - Mar. 31, 2014

Research Consultant
Akira NODA ( - Mar. 31, 2014)

Student Trainees
Ayano ENOMOTO
Shunsuke OKADA - Mar. 31, 2014
Yuta SAITO - Mar. 31, 2014
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 ion source is now under improvement. The detector system consisting of a high-resolution magnetic spectrometer, drift chambers, trigger scintillators, and luminosity monitors is now under construction. We are going to perform the first experiment of electron scattering from unstable nuclei within a fiscal year 2014.

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).

(Wakasugi, Ohnishi, Kurita, Suda, Tamae, Hori, Hara, Ichikawa)

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 $10^{27}$ $(/\text{cm}^2\text{s})$ was obtained in case of the number of injected ions of $10^8$. 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 issues 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 $^{126-128}$Sn and $^{138-141}$Xe isotopes were extracted. Since the yield of extracted RIs is still below our expectation and there is some problem in durability of the ion source, the target ion source is now under improvement. A cooler buncher system 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. We are now developing the cooler buncher based on a RFQ linear trap. This was constructed in 2013 and is now under testing offline. This will be installed within this year.

In last year, we constructed a new detector for scattered electrons. This 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 $10^4$, 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. This detector system is now under setting up offline and they are expected to be available soon.

Team Leader
Masanori WAKASUGI (Group Director)

Member
Tetsuya OHNISHI (Senior Technical Scientist)

Senior Visiting Scientist
Toshitada HORI (Hiroshima University)

Visiting Scientists
Toshimi SUDA (Research Center of Electron Photon Science, Tohoku Univ.)
Shuo WANG (Research Center of Electron Photon Science, Tohoku Univ.) - Jun. 30, 2013
Research Consultants
Takeshi EMOTO (-Mar. 31, 2014)
Shin-ichi ICHIKAWA (-Mar. 31, 2014)
Masahiro HARA (-Mar. 31, 2014)
Tadaaki TAMAE (-Mar. 31, 2014)

Student Trainees
Takaya MIYAMOTO  - Mar. 31, 2014
Yuto SHIMAKURA  - Mar. 31, 2014
Yuji HARAGUCHI
Shunpei YONEYAMA
Teruaki TSURU
**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 five teams, we are in charge of the design, construction, operation and improvement of the core research instruments at RIBF, such as BigRIPS separator, ZeroDegree spectrometer, GARIS spectrometer and SAMURAI spectrometer, and the related infrastructure and equipment. 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) Design, construction, operation, and improvement of the core research instruments at RIBF and their related infrastructure and equipment for continuous enhancement of activities and competitiveness of experimental research

   (2) R&D studies on technical issues of the core research instruments and related equipment at RIBF

   (3) Experimental research on exotic nuclei using the core research instruments at RIBF

**Group Director**  
Toshiyuki KUBO

**Senior Visiting Scientist**  
Toshio KOBAYASHI (Tohoku University)

**Junior Research Associate**  
Daichi MURAI

**Student Trainee**  
Katrina KOEHLER

**Research Supporting Staff (part time Worker)**  
Meiko UESAKA

**Assistant**  
Emiko ISOGAI
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.

Team Leader
   Koichi YOSHIDA

Members
   Naohito INABE (Senior Technical Scientist)
   Masao OHTAKE (Senior Technical Scientist)
   Yoshiyuki YANAGISAWA (Senior Research Scientist)
   Kanenobu TANAKA (concurrent)

Nishina Center Research Scientists
   Kensuke KUSAKA
   Naoki FUKUDA
   Hiroyuki TAKEDA

Contract Researcher
   Daisuke KAMEDA

Postdoctoral Researchers
   Deuk Soon AHN
   Hiroshi SUZUKI

Part-time Worker
   Hidekazu KUMAGAI (- Mar. 31, 2014)

Senior Visiting Scientist
   Jerry NOLEN (ANL)

Visiting Scientists
   Bradley SHERRILL (NSCL, Michigan State Univ., USA)
Daniel BAZIN (NSCL, Michigan State Univ., USA)
Oleg TARASOV (NSCL, Michigan State Univ., USA)
David MORRISSEY (NSCL, Michigan State Univ., USA)
Mauricio PORTILLO (NSCL, Michigan State Univ., USA)
Hans GEISSEL (GSI, Germany)
Martin WINKLER (GSI, Germany)
Michael FAMIANO (Western Michigan Univ., USA)
Yutaka MIZOI (Osaka Electro-Commnication Univ.)
Naohito IWASA (Tohoku Univ.)
Sadao MOMOTA (Kochi University of Technology)
Kazuo IEKI (concurrent) (Rikkyo Univ.) - Mar. 31, 2013

**Student Trainee**

Yohei OHKODA (Tohoku Univ.) - Mar. 31, 2014
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. 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"

Team Leader
Hiromi SATO

Member
Ken-ichiro YONEDA (concurrent: Deputy Team Leader)

Research Associate
Yohei SHIMIZU

Visiting Scientists (JST)
Bertis Charles RASCO (Louisiana State University, USA)
Julien Didier GIBELIN (JSPS: LPC-Caen, France) - Aug. 8, 2013

Visiting Technician
Nobuyuki CHIGA (Tohoku University) - Mar. 31, 2014
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 28 CPU cores and totally 200 TB RAID of highly-reliable Fibre-channel HDD. We have replaced the data analyses servers and RAID file systems for the experimental data in the spring of 2012. 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.

(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/Unix cluster system. This server was replaced in the summer of 2011 since it passed more than five years from the installation. 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 WWW 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).

(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. These new circuits are successfully working.

(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). 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.
VI. RNC ACTIVITIES

Team Leader
Takashi ICHIHARA (concurrent)

Member
Yasushi WATANABE (concurrent)

Nishina Center Research Scientist
Hidetada BABA

Student Trainee
Ryousuke TANUMA - Mar. 31, 2014
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
1. Abstract
This group promotes various applications of ion beams from RI Beam Factory. Radiation Biology Team studies various biological effects of fast heavy ions and develops new technology to breed plants and microbialis 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.

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

Group Director
Tomoko ABE

Assistant
Yoshiko SAKATA
Noriko KIYAMA
1. Abstract
Radiation biology 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. This 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 (ESB) 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 known 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 mutation 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 2013 it consisted of 164 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, ‘Nebarikko 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, 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 lines in the more delicious commercial rice varieties, ‘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.
VI. RNC ACTIVITIES

Team Leader
Tomoko ABE (Group Director)

Members
Katsunori ICHINOSE (Senior Technical Scientist)
Masako IZUMI (Senior Research Scientist)
Tokihiro IKE (Senior Research Scientist)
Kazuhide TSUNEIZUMI (Senior Research Scientist)
Teruyo TSUKADA (Senior Research Scientist)
Ryouhei MORITA (Technical Scientist)

Postdoctoral Researcher
Kotaro ISHII

Technical Staff I
Yoriko HAYASHI (-Mar. 31, 2014)
Sachiko KOGURE (-Mar. 31, 2014)

Technical Staff II
Sumie OHBU

Visiting Scientists
Mari AMINO (Tokai University Hospital) -Mar. 31, 2013
Chang-Hy U BAE (Sunchon Natl. Univ., Korea) -Mar. 31, 2013
Hiroyuki DAIMON (Osaka Pref. Univ.) -Mar. 31, 2013
Ali FERJANI (Tokyo Gakugei Univ.)
Makoto FUJWARA (Grad. Sch., Col. Arts Sci., Univ. of Tokyo)
Eitaro FUKATSU (Forest tree breeding Cet.)
Toshinari GODO (Botanic Gardens Toyama)
Atsushi HIGASHITANI (Grad. Sch. Life Sci., Tohoku Univ.) -Mar. 31, 2013
Akiko HOKURA (Tokyo Denki Univ.)
Hiroyuki ICHIDA (Meiji Univ.)
Yuji ITO (Natl. Agric. Res. Cen., Hokkaido Region)
Akihiro IWASE (Grad. Sch. Engin., Osaka Pref. Univ.)
Hiroshi KAGAMI (Shizuoka Citrus Exp. Station) -Mar. 31, 2013
Tetsuya KAKO (Suntory Flowers, Ltd.) -Mar. 31, 2013
Tsutomu KUBOYAMA (Ibaraki Univ.) -Mar. 31, 2013
Norihiko MISHIMA (Fukuda Denshi Co., Ltd.) -Mar. 31, 2013
Yutaka MIYAZAWA (Grad. Sch. Life Sci., Tohoku Univ.)
Kazumitsu MIYOSHI (Fac. Bioresour. Sci., Akita Pref. Univ.)
Kozi MURAI (Fukui Pref. Univ.)
Francesco MUSUMECI (Catania Univ.) -Mar. 31, 2013
Koichi NISHIKAWA (FLORSAIKAI CIA. LTD.) -Mar. 31, 2013
Norihiro OHTSUBO (Natl. Inst. Floricult. Sci.)
Masaya SAKAI (Fukuda Denshi Co., Ltd.) -Mar. 31, 2013
Kouichi SAKAMOTO (YUKIGUNI AGRURI Co., Ltd.) -Mar. 31, 2013
Katsuomo SASAKI (National Agriculture and Food Research Organization)
Mikio SHIMADA (Kyoto Univ.) -Mar. 31, 2013
In-Ja SONG (Jeju National University)
Fumio SUGAWARA (Tokyo Univ. of Sci.) -Mar. 31, 2013
Ryoji SUGIYAMA (Ajinomoto Co., INC.) -Mar. 31, 2013
Kenichi SUZUKI (Suntory Flowers, Ltd.) -Mar. 31, 2013
Kunio SUZUKI (Technoflora, Co., Ltd.)
Hinako TAKEHISA (Natl. Inst. Agric. Sci.)
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Sachie TANAKA (Tokai Univ.)  - Mar. 31, 2013
Ken TOKUHARA (Dogashima Orchid Cen.)  - Mar. 31, 2013
Masanori TOMITA (CRIEPI)
Tomoo KOIDE (RIKEN VITAMIN Co., Ltd.)
Hisashi TSUJIMITO (Fac. Agri., Tottori Univ.)
Kozo TSUKADA (Nippon Veterinary and Life-sci. Univ.)  - Mar. 31, 2013
Makoto UBUKATA (Hokkaido Univ.)
Masao WATANABE (Fac. Agri., Tohoku Univ.)
Yasuko YOSHIIHARA (Japan Atomic Energy Agency)  - Mar. 31, 2013
Koichiro YOSHIOKA (Tokai University Hospital)  - Mar. 31, 2013

Visting Technicians
Tomoo KOIDE (Riken Vitamin Co., Ltd.)
Takaji YOSHIDA (Takii Seed Co., Ltd.)

Research Fellows
Hideki ASAUMI (Ehime Agricultural Experiment Station)  - Mar. 31, 2013
Fumiko HIDAKA (Kagoshima Pref. Inst. for Agric. Dev.)  - Mar. 31, 2013
Takeya ICHIKI  - Mar. 31, 2014
Hiroaki KISAKA (Ajinomoto, Co., INC.)  - Mar. 31, 2013
Tadanori MINO (Wadomari Cho Agr. Exp. Station)  - Mar. 31, 2013
Miyuki NISHI (Saga Agricultural Experiment Station)  - Mar. 31, 2014
Tadahito OOTUBO (Wadomari Cho Agr. Exp. Station)  - Mar. 31, 2013
Yosihide SAKITA (Wadomari Cho Agr. Exp. Station)  - Mar. 31, 2013
Tsukasa SHIRAO (Kagoshima Biotechnology Inst.)  - Mar. 31, 2013
Kei-ichiro UENO (Kagoshima Biotechnology Inst.)  - Mar. 31, 2013

Consultant
Hiroyuki SAIITO  - Mar. 31, 2013

Part-time Workers
Yuki SHIRAKAWA
Hideo TOKAIRIN
Taeko WAKANA
Satoko YASUDA
Mieko YAMADA
Anju MATSUNAGA  - Apr. 5, 2013
Honami OOHASHI  (Aug. 22, 2013-Sep. 6, 2013)

Students
Junior Research Associate

Student Trainees
Kentaro FUJITA
Hiroki KAWAMOTO  - Mar. 31, 2014
Kana MIYOSHI
Takato TAKAHASHI  - Mar. 31, 2014
Fumitaka TAMEZAWA
Megumi UTSUGI
Fumitaka YAMAGISHI
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, chemistry, biology, medicine, and pharmaceutical and environmental sciences. We use the RIs mainly for nuclear and radiochemical studies such as development of RI production technologies and chemistry of superheavy elements. The purified RIs such as \( ^{65}\text{Zn} \) and \( ^{109}\text{Cd} \) 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 analysis 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 radioisotracers at RIBF and conducted their application studies in collaboration with many researchers in various fields. With 14-MeV proton, 24-MeV deuterion, and 50-MeV alpha beams from the AVF cyclotron, we presently produce about 30 long-lived radioisotracers from \( ^7\text{Be} \) to \( ^{209}\text{Bi} \). Among them, \( ^{65}\text{Zn}, ^{109}\text{Cd}, \) and \( ^{88}\text{Y} \) 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 \( ^{48}\text{Ti}, ^{107}\text{Ag}, ^{107}\text{Pd}, \) and \( ^{197}\text{Au} \) irradiated with a 135-MeV \( ^{14}\text{N} \) beam from the RIKEN Ring Cyclotron. These multitracers are also supplied to universities and institutes as collaborative researches.

In 2013, we installed a new RI production system having an effective shield on the beam line of AVF to increase production yields of RIs by intense beam irradiations. We produced \( ^{65}\text{Zn}, ^{109}\text{Cd}, \) and \( ^{88}\text{Y} \) for our scientific researches on a regular schedule and supplied the surpluses through Japan Radioisotope Association to the general public. In 2013, we have accepted 14 orders of \( ^{65}\text{Zn} \) with a total activity of 72.7 MBq, 5 orders of \( ^{109}\text{Cd} \) with 14.15 MBq, and 1 order of \( ^{88}\text{Y} \) with 30 kBq. We also developed production technologies for new radioisotopes such as \( ^{28}\text{Mg}, ^{70}\text{Se}, ^{85}\text{Sr}, ^{99}\text{Mo}, \) and \( ^{124}\text{I} \) which were strongly demanded but lack supply sources in Japan. We also investigated the excitation functions for the \( ^{48}\text{Ti}(d,x), ^{107}\text{Ag}(d,x), ^{107}\text{Pd}(d,x), ^{197}\text{Au}(\alpha,x), ^{99}\text{Mo}(d,x), \) and \( ^{124}\text{I}(d,x) \) reactions to effectively produce useful RIs.

(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 SHEs such as \( ^{264}\text{Rf}, ^{262}\text{Db}, \) and \( ^{264}\text{Sg} \) are produced, 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 radioactivity 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 2013, the isotope of \( ^{262}\text{Db} \) was produced in the reaction of \( ^{nat}\text{Zn}(d,x), ^{nat}\text{Zr}(d,x), ^{nat}\text{Hf}(d,x), ^{nat}\text{Pt}(d,x) \) reactions to effectively produce useful RIs.

(3) Applications of RIKEN RI technologies for the Fukushima accident in 2011

At the AVF cyclotron, an automated hydroxide precipitation apparatus was developed in collaboration with Osaka Univ. Using the apparatus, the hydroxide complexation of \( ^{264}\text{Rf} \) was investigated with its homologues \( ^{85}\text{Zr} \) and \( ^{109}\text{Hf} \). A batch-type solid-liquid extraction apparatus for a repetitive extraction experiment of SHEs was also developed in the HCI-TIAO system with Osaka Univ. using \( ^{85}\text{Zr} \) and \( ^{109}\text{Hf} \). In 2013, a reversed-phase TTA extraction of \( ^{264}\text{Rf} \) and its homologues \( ^{85}\text{Zr} \) and \( ^{109}\text{Hf} \) was conducted in HF/HNO\(_3\) solutions using Automated Rapid Chemistry Apparatus (ARCA) developed at GSI-Mainz Univ.-JAEA. In collaboration with Niigata Univ. and JAEA, a reversed-phase TBP extraction experiment of \( ^{90}\text{Nb} \) and \( ^{170}\text{Ta} \) were conducted using ARCA for the future \( ^{262}\text{Db} \) chemistry.
Since the Fukushima Dai-ichi power plant accident in 2011, we have contributed radioactivity measurements of various samples such as soils and foods, and developed a low-cost radiation detector for foods.

(4) 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}–10^{-15} level) and is expected to be especially effective for measurements of low-electron-affinity elements such as 26Al, 41Ca, and 53Mn. In 2013, 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. Furthermore, we analyzed sulfur and lead isotope ratios for cinnabar samples from ancient tombs in Japan to elucidate the origin of cinnabar.

(5) Development of chemical materials for ECR ion sources of RIBF

In 2013, we investigated a production method of 238U(C_8H_8)_2 for the ECR ion source of RIBF. We also prepared metallic 238U and 238UO_2 on a regular schedule.

Team Leader
Hiromitsu HABA

Member
Kazuya TAKAHASHI (Senior Research Scientist)

Postdoctoral Researcher
Minghui HUANG ( - Mar. 31, 2014)

Technical Staff I
Jumpei KANAYA ( - Mar. 31, 2014)

Research Consultant
Seiichi SHIBATA ( - Mar. 31, 2014)

Junior Research Associate
Masashi MURAKAMI (Niigata Univ.)

Part-time Worker
Michiko KITAGAWA

Visiting Scientists
Mayeen Uddin KHANDEKAR (Univ. Malaya)
Hitotoshi KIKUNAGA (Tohoku Univ.)
Kazuhiko OOE (Niigata Univ.)
Hiroshi SHIMIZU (Rissho University)
Miho TAKAHASHI (Tokyo Univ. Marine Sci. and Tech.)
Masayoshi TODA (Tokyo Univ. Marine Sci. and Tech.)
Takahiro YAMADA (Japan Radiation Association)
Akihiko YOKOYAMA (Kanazawa Univ.)

Visiting Technicians
Yuichiro WAKITANI (Japan Radiation Association)
Shinya YANOU (Japan Radiation Association)

Student Trainees
Ryuii AONO (Niigata Univ.) - Mar. 31, 2014
Yosihiko FUKUDA (Kanazawa Univ.) - Mar. 31, 2014
Naoya GOTO (Niigata Univ.) - Mar. 31, 2014
Kazunori HAYASHI (Kanazawa Univ.) - Mar. 31, 2014
Junichi HIRATA (Tokyo Univ. Marine Sci. and Tech.)
Hajime KITAYAMA (Kanazawa Univ.) - Mar. 31, 2014
Yuuta KITAYAMA (Kanazawa Univ.) - Mar. 31, 2014
Takumi KOYAMA (Niigata Univ.) - Mar. 31, 2014
Eita MAEDA (Kanazawa Univ.) - Mar. 31, 2014
Kouhei NAKAMURA (Osaka Univ.) - Mar. 31, 2014
Daisuke SATO (Niigata Univ.) - Mar. 31, 2014
Yudai SHIGEKAWA (Osaka Univ.) - Mar. 31, 2014
Yuuki SHIGEYOSHI (Kanazawa Univ.) - Mar. 31, 2014
Takumi TANIGUCHI (Kanazawa Univ.) - Mar. 31, 2014
Keigo TOYOMURA (Osaka Univ.) - Mar. 31, 2014
Shohei TSUTO (Niigata Univ.) - Mar. 31, 2014
Shingo UENO (Kanazawa Univ.) - Mar. 31, 2014
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 missions. 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.

**Group Director**
Hideyuki SAKAI

**Deputy Group Director**
Hideki UENO (concurrent: User Support)

**Members**
Mieko KOGURE (Technical Assistant) (-Mar. 31, 2014)
Aiko NAKAO (Senior Research Scientist) (Feb. 1, 2013-Apr. 30, 2013)

**Special Temporary Employee**
Tadashi KAMBARA

**Senior Visiting Scientists**
Ikuo HAMAMOTO (The Lund University)
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**Assistants**
Yoshiko SAKATA (- Oct. 31, 2013)
Noriko KIYAMA
Tomoko IWANAMI
Katsura IWAI
Emiko ISOGAI (- Mar. 31, 2013)
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.

Team Leader
Ken-ichiro YONEDA

Deputy Team Leader
Yasushi WATANABE (concurrent)

Technical Staff I
Narumasa MIYAUCHI

Visiting Scientists
Yoshiteru SATO (Seoul National University) - Aug. 31, 2013
Masayuki YAMAGAMI (University of Aizu) - Aug. 31, 2013
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 2013, we delivered five shipments of Cd-109 with a total activity of 14.15 MBq and 14 shipments of Zn-65 with a total activity of 72.7 MBq. In addition, we delivered the first shipment of Y-88 with an activity of 0.03 MBq. The final recipients of the RIs were eight universities, two research institutes and one private company.

(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 industrial PAC met for the first time in January 2010, and reviewed and approved two proposals as trial uses. The beam times of both proposals were executed successfully in 2010 at the RIKEN Ring Cyclotron and RILAC. The second meeting held in June 2010 reviewed four proposals and approved three of them as trial uses. Beam times of two of the proposals were successfully executed in 2010 and 2011 at the RIKEN Ring Cyclotron. The third meeting held in July 2012 reviewed one proposal and approved it.

(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. This new method was developed by a close collaboration with Sumitomo Heavy Industry, which led to an application of a patent. 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. In the past, those RIs were produced at the RIPS separator using beams from the RRC, which are constantly used for the academic research. The RI beam production by the AVF cyclotron alone increases flexibility in the beam-time scheduling and more importantly leads to reduce the production cost for industrial users.

As we can provide RI beams of different nuclides and control the implantation depth, we have developed a novel method of wear diagnostics in collaboration with Sumitomo Heavy Industry (SHI) Examination & Inspection Ltd., SHI Technology Research Center and CNS and jointly applied for a patent. Implantation of different RI for both machine parts contacting each other, one can distinguish the wear-loss rate of both interacting parts simultaneously. Implantation of one or a few RIs with controlling its depth profile, it can be applicable for processing a wear-loss gauge on a machine part. 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.

Team Leader
Atsushi YOSHIDA

Members
Hirosige TAKEICHI (Senior Research Scientist)
Aiko NAKAO (Jan. 31, 2013)

Visiting Scientists
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 meet the requirement due to the installations of SLOWRI and R3 detectors. Four neutron monitors were additionally placed around the rooms, and connected with the interlock system to stop the ion beam when radiation level rose. The local shields in the experiment vaults were partly modified.

A new experiment room for measurement of short-half-life radionuclide was made in the pump room of the linac building, and an exhaust system with a high-efficiency particulate air (HEPA) filter was installed there. Contamination test apparatuses were installed.

For the above modifications we applied for the government license 5 times, and underwent the government inspections 4 times.

We developed ionization chambers which were fairly resistant to radiation, and installed them in the SRC vault. The real-time dose rate values are shown at the entrance of the vault.
Part-time Workers
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Shin FUJITA
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Satomi IIZUKA
Hiroshi KATO
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Tsutomu YAMAKI (- Mar. 31, 2013)
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 is proposed, 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) SHARAQ project
(7) 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 a 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 experiments using the low-energy RI beam separator CRIB. In September, 2013, beta-delayed alpha decay of 16N, which is relevant for the astrophysical 12C(a,g) reaction rate, was measured at CRIB using an active target system (GEM-MSTPC). Many decay events were detected from 16N beam particles stopped in the active target. 15O and 10Be beams were produced for the first time at CRIB, and both beams will be used for resonant scattering experiments.

Based on recent collaboration on nuclear astrophysics at CRIB, two memoranda of understanding on the collaborated research have been made between CNS and IBS (Korea), and CNS, INFN-LNS (Italy) and CNS-SKKU (Korea).

(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 going to start as another approach on exotic nuclei.

In 2013, the following progress has been made.

Experimental programs under the EURICA collaboration were performed for studying evolution of deformation in neutron-rich Z~60 nuclei, which are being analyzed now. High-spin states in A~40 nuclei were measured at Tandem ALTO facility at IPN Orsay by using fusion reaction, where a new candidate of superdeformed states were found in 38S.

Gamow-Teller transitions of 6He 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 (3He,3Li*(1+)) on 12C and 4He are being analyzed now. Experiment on the tetra-neutron system via the 4He(4He,4Be)4n reaction is being analyzed, where several tens of events were identified to be candidates of the 4n system just above the threshold.

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.

Experimental setup of studying tetra neutron system using the double-charge exchange reaction 4He(4He,4Be)4n at 200 A MeV was prepared for the measurement in April 2012.
(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; dark photon searches in low mass Dalitz decays, \( J/\psi \) production in ultra-peripheral Au+Au collisions, and electron measurement from semi-leptonic decay of heavy flavor mesons which uses the Si VTX detector subsystem.

As for ALICE, the group has involved in the data analyses, which include production of multi-particle correlation in Pb+Pb collisions, nuclear modification of energetic neutral pions in Pb+Pb collisions, and measurement of low-mass lepton pairs in Pb+Pb and p+Pb collisions. The group started to involve in the ALICE-TPC upgrade using a Gas Electron Multiplier (GEM) in 2012. Systematic studies of gain stability, ion back flow, and energy resolutions with various field configurations are underway at CNS and at CERN. Performance evaluation of the COBRA-GEM for the ALICE-TPC upgrade is underway.

R&D of GEM and related techniques has been continuing. Development of resistive GEM with resistive anodes and GEM with glass insulator have been progressing in collaboration with the Tamagawa group of RIKEN.

(5) Nuclear Theory

The nuclear theory group has been promoting the RIKEN-CNS Collaboration project on large-scale nuclear structure calculations since 2001 and maintain its PC cluster. Based on this experience and its achievements, we participated in activities of HPCI Strategic Programs for Innovative Research (SPIRE) Field 5 “The origin of matter and universe” since 2011. The SPIRE project aims at an integral understanding of the origin and structure of matter and the universe utilizing the K computer.

In the SPIRE project, we are in charge of the elucidation of nuclear properties using ultra-large-scale simulations of quantum many-body systems and its applications. In order to perform large-scale shell-model calculations, we developed an efficient computer program of the Monte Carlo Shell Model (MCSM) method for massive parallel computation, and performed benchmark calculations at K computer. We have studied both the medium-heavy and light nuclei with large model space on K computer in 2013. In medium-heavy nuclei, we successfully described the shape coexistence for \(^{68}\text{Ni}\). In light nuclei, systematic calculations have been performed with increasing the number of the major shells. The \( \alpha \) cluster structure in Be isotopes has been also studied.

(6) SHARAQ project

A main subject of the SHARAQ program is charge-exchange reactions induced by heavy-ion beams, with which a variety of selectivities in transferred quantum numbers, \( \Delta S, \Delta T, \Delta T_z, \Delta L \) etc, are available.

This year SHARAQ group made preparations for the coming two experiments. One was for the development of parity-transfer probe \( (^{16}\text{O}, \ ^{16}\text{F}(\text{g.s.})) \) reaction. A MWDC was installed at the exit of the first dipole magnet of SHARAQ to track the proton produced from the instant decay of \(^{16}\text{F}(\text{g.s.}) \rightarrow ^{15}\text{F} + \text{p} \). The other was for the mass measurement around \( A \approx 50 \) isotopes including \(^{54}\text{Ca}\) by the Bp-TOF method. For this purpose, a set of CVD diamond detectors was developed and we attained a time resolution of 27–ps. Also a detector system for tagging the isomers at the final focal plane of the SHARAQ was developed.

As a project of near future, a letter of intent was submitted to NP-PAC aiming at studying spin-isospin response of isomers by \( (p,n) \) reaction.

(7) Active Target Development

In a project of active target development launched as an intergroup collaboration in 2009, two types of active target have been developed. Technical development such as a capability of gating operation of GEM has been done for one active target and the alpha emission following the beta decay of \(^{15}\text{N}\) was measured with the same active target. The development for the high intensity beam injection is being performed for the other active target. The test experiment with a high intensity \(^{122}\text{Xe}\) beam was performed.
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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 research 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 $^{31}\text{Ne}$. It suggests that $^{31}\text{Ne}$ nucleus has a neutron halo. It is consistent with the soft E1 excitation measurement. We also found an enhancement at $^{37}\text{Mg}$. 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.

(3) 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 Skyme-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.

Director
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Scientific Staff
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Sho KANESAWA
**VI. RNC ACTIVITIES**

**Partner Institution**
Radioactive Nuclear Beam Group, IPNS (Institute for Particle and Nuclear Studies)
KEK (High Energy Accelerator Research Organization)

**1. Abstract**

The on-line tests of the KISS (KEK Isotope Separation System) were performed by using $^{56}$Fe and $^{124}$Xe beam from RIKEN Ring Cyclotron. The performance (overall extraction efficiency and selectivity) with increasing those beam intensities was investigated. Especially in the test using the $^{124}$Xe beam, the target ($^{198}$Pt)-recoils were successfully extracted as singly charged ions. Although the overall efficiency achieved so far was smaller by about one order of magnitude than expected, measurements of lifetime of beta-decaying Pt-like recoils are to be performed, while further developing the performance by using $^{124}$Xe beam. Some other activities related to the research subjects itemized below are also included.

**2. Major Research Subjects**

1. Radioactive isotope beam production and manipulation for nuclear experiments.
2. Explosive nucleosynthesis (rp- and r-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. Therefore, it is desirable that the gas cell would keep high performance of extraction efficiency and selectivity (ratio of the number of ions extracted with laser operation to that without laser operation) throughout these processes. The absolute extraction efficiency and selectivity of the gas cell was investigated in the on-line test experiments where stable beams of $^{56}$Fe and $^{124}$Xe were directly injected for providing the gas cell with controlled number of atoms ($^{56}$Fe case) and energetic target (a thin foil of $^{198}$Pt irradiated by $^{124}$Xe)-like recoils, respectively. Also investigated were the so-called plasma effects which are thought to degrade the performance due to the plasma formed in the cell by the primary beam injection.

Injecting into the cell the $^{56}$Fe beam of 90 MeV/nucleon from the RRC after being properly energy-degraded to 1.5 MeV/nucleon for complete stop around the center of the cell, we extracted laser-ionized $^{56}$Fe atoms. Here, we have used a modified gas-cell, which was originally designed to reduce the plasma effect, but more deeply bent for better shadowing the beam irradiation region (plasma formation region) than previously used. The extraction efficiency for $^{56}$Fe was measured to be about 0.25% and almost constant with increasing primary beam intensity (increasing number of injected iron atoms). The selectivity of about 50% was achieved, though showing a moderate deterioration by beam intensity of up to 4 pnA. Although the gas cell was well baked (outgassed) for the test, additional contamination was observed due to the beam irradiation, by which the laser-ionized $^{56}$Fe atoms were fragmented into $^{56}$Fe (A=56), $^{56}$Fe (H2O) (A=74) and $^{56}$Fe Ar2 (A=136) at the same intensity. Once the contamination could be removed, the extraction efficiency for $^{56}$Fe would be restored accordingly.

After successfully demonstrating the performance of the KISS with iron, a series of online tests are planned to check the universality of the performance (if the performance demonstrated is element-independent). In a first test along the line, we used the $^{198}$Pt atoms introduced into the gas cell as recoils out of the $^{198}$Pt target by elastic scattering of $^{124}$Xe of 10.75 MeV/nucleon from the RRC. The transformation of those laser-ionized $^{198}$Pt atoms to sidebands was different from what was observed for $^{56}$Fe; the laser-ionized-$^{198}$Pt-related ions were mostly observed as ions of $^{198}$Pt, $^{198}$Pt (H2O), and $^{198}$Pt Ar2 in the intensity ratio of 1:4:10. The extraction efficiency for $^{198}$Pt in the form of $^{198}$Pt Ar2 was estimated to be about 0.15% from the cross section of elastic scattering between $^{198}$Pt and $^{124}$Xe. Even with the present efficiency of 0.15%, the beta-decay half-lives of more than 20 unknown nuclei around $N=126$ and $Z<82$ would be measured. While addressing the current development issues, we are going to measure the lifetime of beta-decaying Pt-like recoils in the year of 2014.

For the beta-decay lifetime measurements of the nuclei, mostly having Q$_\beta$ values as small as 2 MeV, two double-layered plastic scintillators holding the implantation spot on a tape transport station in-between will be used. Two 0.5-mm and 1.0-mm thick scintillators with a size of 20-cm wide and 14-cm height were fabricated and tested. Almost full solid angle can be covered with the size (geometrical acceptance of 80%). When we measured the detection efficiency of the thinner scintillator wrapped with the aluminized Mylar, we found a rather large position dependency of the detection efficiency. While using instead a reflection sheet which is often used for the liquid crystal display, the position dependence as well as the detection efficiency was improved. Due to the thinness of the tested, multi-reflection of the scintillation lights in the scintillator seemed to make the efficiency worse. Using the $^{90}$Sr/$^{90}$Y source, the coincidence efficiency of the two layers was observed to be 60% which is consistent with the GEANT simulation. The remaining 20% were almost stopped in the first layer, indicating the absolute efficiency of close to 100%. The tape transport station equipped with the plastic scintillators will be installed in the beginning of the 2014.

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 \(^{136}\)Xe on \(^{198}\)Pt for producing heavy neutron-rich isotopes around the mass number of 200 with the neutron magic number of 126, the analysis of the data taken at GANIL in March 2012 is under progress. Using the elastic scattering data for \(^{136}\)Xe, special efforts are currently being paid for extracting the absolute cross sections of projectile-like MNT channels, as well as of target-like fragments (TLFs) identified by their de-excitation gamma-rays. Some of the results, especially the cross sections of TLFs, would be directly compared to those estimated from the ongoing test experiments of the KISS as mentioned above.

The systematics of the single particle structure of even-odd nuclei along isotopic and/or isotonic chains give insights into the evolution of the relevant nuclear shell structure. We have investigated the first three bound states of \(^{31}\)Mg by measuring their isobaric analog resonances through the proton resonance elastic scattering off \(^{30}\)Mg in order to pin down the underlying mechanism of the island of inversion. The experiment was performed by using the post-accelerator REX-ISOLDE at CERN. A thick polyethylene target of 5.6 mg/cm\(^2\) was impinged on by the \(^{30}\)Mg ion beam accelerated up to 2.92 MeV/nucleon. The excitation function of the protons scattered around 0 degree in the laboratory frame was measured. The angular momenta \(l\) and spectroscopic factors \(S\) of the first three bound states in \(^{31}\)Mg were deduced. The \(l\) values are consistent with those previously assigned by the beta decay. Comparing the \(S\) with the spectroscopic factors for the N=19 nuclei \(^{37}\)Ar and \(^{35}\)S measured by the \((d, p)\) reaction shows that the \(S\) for the positive parity states in \(^{31}\)Mg were largely quenched. This means that the overlap between the wave function of the positive parity state and that of the neutron coupled to the ground state of \(^{30}\)Mg is small, demonstrating that the border of the island of inversion is placed between \(^{30}\)Mg and \(^{31}\)Mg.

We have developed a nanoscale diffusion measurement method using alpha-emitting radioactive \(^{6}\)Li tracer. In the method, while implanting a pulsed \(^{6}\)Li beam of 8 keV, the alpha particles emitted at a small angle \((\theta = 10 \pm 1^\circ)\) relative to a sample surface were detected as a function of time. The method has been successfully applied to measure the lithium diffusion coefficients for an amorphous Li\(_4\)SiO\(_4\) - Li\(_3\)VO\(_4\) (LVSO) of several hundreds nm in thickness, well demonstrating that the present method has a sensitivity to the diffusion coefficients down to a value of \(10^{-12}\) cm\(^2\)/s, more sensitive by about two orders magnitude than previously achieved. It should be noted that in the previous method sensitive to microscale diffusion the angles subtended by the \(\alpha\)-particle detectors were within 63 \(\pm 1^\circ\) and the incident energy of \(^{6}\)Li was about 4 MeV. The present method is therefore supposed to be sensitive to nanoscale Li diffusion as compared to the previous method where tracer atoms were deeply implanted (several micrometers).

**Group Leader**

Hiroari MIYATAKE

**Members**

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Yutaka WATANABE

Hironobu ISHIYAMA

Sunchan JEONG

Michihiro OYAIZU

Yung-Hee KIM (PhD. Student, Seoul National University)

Momo MUKAI (D. Student, Tsukuba University)

Sota KIMURA (D. Student, Tsukuba University)
# RNC Activities (April 2013 - March 2014)

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<th>2013</th>
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<td>Apr. 1</td>
<td>Start of Nuclear Spectroscopy Laboratory, taking over Polarized RI Beam Team, Start of Research Group for Superheavy Element</td>
<td></td>
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<tr>
<td>Apr. 20</td>
<td>Wako Open campus</td>
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<tr>
<td>May 7</td>
<td>RBRC Managing and Steering Committee held in Wako Campus</td>
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<tr>
<td>May 28</td>
<td>New-Comers Seminar</td>
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<tr>
<td>May 30</td>
<td>Effect of MOU between College of Science, Yonsei Univ. (Korea) and RNC</td>
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<tr>
<td>Jun. 5</td>
<td>Effect of MOU between RNC and Department of Physics, Kyungpook National University (Korea)</td>
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<tr>
<td>Jun. 26 - 27</td>
<td>RIBF Users Meeting 2013</td>
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<td>Jun. 28 - 29</td>
<td>RNC NP-PAC</td>
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<tr>
<td>Jul. 2-3</td>
<td>RNC ML-PAC</td>
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<td>Jul. 11</td>
<td>Scientific Policy Committee (FY2013)</td>
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<td>Aug. 6 - 16</td>
<td>Nishina School</td>
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<tr>
<td>Aug. 19 - 23</td>
<td>Participation in Science Agora 2013 held in Odaiba</td>
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<tr>
<td>Aug. 28</td>
<td>Effect of MOU between Department of Physics, Korea Univ. and RNC</td>
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<tr>
<td>Sep. 12</td>
<td>Effect of MOU For the use of MINOS device at RIKEN between CEA-DSM and RNC</td>
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<td>Oct. 2</td>
<td>President of Vietnam National University of Hanoi-Hanoi University of Science visits RNC</td>
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<td>Oct. 16</td>
<td>Effect of MOU between Institute of Basic Science, Rare Isotope Science Project, Korea and RNC for research collaboration in the area of rare ion accelerator and related fields</td>
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<tr>
<td>Oct. 23</td>
<td>Effect of Agreement for International Joint Graduate School Program between RIKEN and Department of Physics, Yonsei University (Korea)</td>
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<td>Oct. 31</td>
<td>RBRC Scientific Review Committee</td>
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<td>Nov. 9 - 10</td>
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<tr>
<td>Dec. 13 - 14</td>
<td>RNC NP-PAC</td>
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<tr>
<td>Dec. 27</td>
<td>Effect of Addendum No.26 to the Memorandum of Understanding for the RD51 Collaboration, Participation of the Nishina Center for Accelerator-Based Science, RIKEN</td>
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<tr>
<td>2014</td>
<td>Jan. 30</td>
<td>Effect of Extension of MoU between RNC and Michigan State University</td>
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<td>Feb. 4</td>
<td>Effect of Memorandum of Understanding for Research Collaboration between RNC and the “Horia Hulubei” National Institute of Physics and Nuclear Engineering Bucharest-Magurele, Romania</td>
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<tr>
<td>Feb. 20</td>
<td>Associate Chief Scientist Interim Review Program (Dr. Emiko HIYAMA)</td>
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<tr>
<td>Feb. 26</td>
<td>Effect of Statement of Work for MOU between RNC and MSU</td>
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### CNS

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<td>Aug. 28 - Sep. 03</td>
<td>The 12th CNS international Summer School (CNSS13) <a href="http://indico.cns.s.u-tokyo.ac.jp/conferenceDisplay.py?confId=81">Link</a></td>
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### Awards (April 2013 - March 2014)

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<th>Award</th>
<th>Organization</th>
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<td>Hiroshi Imao</td>
<td>Accelerator R&amp;D Team</td>
<td>ACFAP-IPAC13 Accelerator Prize</td>
<td>The Asian Committee for Future Accelerators</td>
<td>May 16</td>
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<tr>
<td>Emiko Hiyama</td>
<td>Strangeness Nuclear Physics Laboratory</td>
<td>The 33rd annual Saruhashi Award</td>
<td>The Association for the Bright Future of Women Scientists</td>
<td>May 25</td>
</tr>
<tr>
<td>Kimiko Sekiguchi</td>
<td>Visiting Scientist Spin Isospin Laboratory</td>
<td>15th Morita Fellowship Award</td>
<td>Japanese Association of University Women</td>
<td>May 25</td>
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<tr>
<td>Hiroshi Imao, Hiroki Okuno &amp; Hironori Kuboki</td>
<td>Accelerator R&amp;D Team / Accelerator Group / Special Postdoctoral Researcher, Accelerator Group</td>
<td>PASJ Award for Technical Contributions</td>
<td>Particle Accelerator Society of Japan</td>
<td>Aug. 4</td>
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<tr>
<td>Tomoko Abe &amp; 7 others</td>
<td>Accelerator Applications Research Group</td>
<td>Excellent Presentation Award: 123rd Meeting of The Japanese Society of Breeding</td>
<td>Japanese Society of Breeding</td>
<td>Aug. 4</td>
</tr>
<tr>
<td>Tomoko Abe</td>
<td>Accelerator Applications Research Group</td>
<td>The BSJ Special Prize for Botanical Research</td>
<td>The Botanical Society of Japan</td>
<td>Sep. 14</td>
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<tr>
<td>Tomoko Abe &amp; 3 others</td>
<td>Accelerator Applications Research Group</td>
<td>Excellent Presentation Award: 124th Meeting of The Japanese Society of Breeding</td>
<td>Japanese Society of Breeding</td>
<td>Nov. 19</td>
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<td>Nobuyuki Chiga</td>
<td>Visiting Technician Research Instruments Group</td>
<td>FY2013 Technical Division Award: Graduate School of Science</td>
<td>Technical Division Graduate School of Science Tohoku University</td>
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<td>Yasushi Watanabe, et al.</td>
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<td>Unveil the last 1/100 seconds of mass falling into a black hole – the first discovery of high-energy X-rays</td>
<td>Shin'ya Yamada, et al. (High-Energy Astrophysics Lab.)</td>
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<td></td>
<td>from a gas just falling into a black hole</td>
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<td>Jul. 17</td>
<td>Development of high precision mass spectrometry for short-lived nuclei, MRTOF</td>
<td>Michiharu Wada, et al. (SLOWRI Team)</td>
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<tr>
<td></td>
<td>--- sub ppm precision with a few millisecond flight times</td>
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<td>Sep. 14</td>
<td>From quarks to the structure of neutron stars – intimate relation between the quark mass and the</td>
<td>Takumi Doi, et al. (Quantum Hadron Physics Lab.)</td>
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<td></td>
<td>neutron-star mass is revealed</td>
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<td>Oct. 9</td>
<td>Discovery of exotic isomers with a magic number</td>
<td>Hiroshi Watanabe, Shunji Nishimura &amp; Hiroyoshi Sakurai (Radioactive Isotope Physics Lab.)</td>
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<td>Oct. 10</td>
<td>Evidence for a new nuclear ‘magic number’ of 34 – a key to access a dream region of ‘island-of-stability’</td>
<td>David Steppenbeck &amp; Satoshi Takeuchi (Radioactive Isotope Physics Lab.)</td>
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<td>Oct. 11</td>
<td>Harvest of salt-tolerance rice in saline paddy field</td>
<td>Tomoko Abe (Radiation Biology Team)</td>
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<td>Nov. 20</td>
<td>‘Magic numbers’ disappear and expand area of nuclear deformation</td>
<td>Pieter Doornenbal &amp; Hiroyoshi Sakurai (Radioactive Isotope Physics Lab.)</td>
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<td>Feb. 20</td>
<td>Asymmetric explosion of core-collapse supernovae – the first mapping of radioactive 44Ti nuclei in Cassiopeia A</td>
<td>Takao Kitaguchi (High-Energy Astrophysics Lab.)</td>
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VII. LIST OF PUBLICATIONS
& PRESENTATIONS
RIKEN Nishina Center for Accelerator-Based Science

Publications

[Book · Proceedings]

(Others)


Oral Presentations

(International Conference etc.)


(Domestic Conference)


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Quantum Hadron Physics Laboratory

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Kamikado K. and Kanazawa T. : "Chiral dynamics in a magnetic field from the functional renormalization group ",JHEP03.009 (2014)*.


Naidon P: "Universality of the three-body parameter in atomic Efimov physics", 2013 joint meeting of the APS Division of Atomic, Molecular, & Optical Physics and the CAP Division of Atomic, Molecular & Optical Physics (DAMOP 2013) Quebec city, Canada, June (2013). 
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Satow D.: “Ultrasoft Fermion Mode at Finite Temperature and Density”, Frontiers of Hadronic Physics: Brain


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上田和彦, 国広陽二, 大西明, 森田健司: “Effects of baryon number density fluctuation on QCD critical point”, 日本物理学会秋季大会高知大学, 高知県, 9月 (2013).
Theoretical Nuclear Physics Laboratory

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[Journal]

(Original Papers) *Subject to Peer Review


[Book · Proceedings]

(Original Papers) *Subject to Peer Review


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Washiyama K.: “Fusion and quasi-fission in heavy systems with the microscopic time-dependent energy density functional theory”, VI International Conference FUSION14, (Inter University Accelerator Centre), New Delhi, India, Feb. (2014).
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Strangeness Nuclear Physics Laboratory

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“Deformations of $^4$s$^1$pf$^1$s shell hypernuclei”, International Workshop on Strange Nuclear Physics, Xiamen, China, Dec. (2013).

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“Block BiCGSTAB for lattice QCD on the K computer”, The 4th AICS International Symposium, Kobe, Dec.(2013).

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Accelerator R&D Team

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Ion Source Team

Publications

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RILAC Team

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[Book · Proceedings]
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Oral Presentations

(Impernational Conference etc.)


Cyclotron Team

Publications

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Oral Presentations

(International Conference etc.)

Beam Dynamics & Diagnostics Team

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Cryogenic Technology Team

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Infrastructure Management Team

Publications

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SLOWRI Team

Publications

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Rare RI-ring Team

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Rare RI-ring Team

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(Ori{ginal Papers)}


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SCRIT Team

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BigRIPS Team

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SAMURAI Team

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Computing and network Team

Oral Presentations

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Detector Team

Publications

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Oral Presentations

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Radiation Biology Team

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Niigata University

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(Domestic Conference)


Radioactive nuclear beam group
IPNS (Institute for Particle and Nuclear Studies)
KEK (High Energy Accelerator Research Organization)

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[Journal]
(Original Papers)  *Subject to Peer Review


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(International Conference etc.)
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