Nuclear Science Research Division
Nuclear Dynamics Research Group

1. Abstract

The Nuclear Dynamics Research Group (previous Spin Isospin Laboratory) pursues various aspects of nuclear reacitons and dynamical phenomena in nuclear systems. At present, the laboratory is focusing on nucleon and cluster knockout reactions, charge exchange reactions and nuclear fissions, but will extend the research scope to other reactions such as transfer and fusion reactions at low energies.

The group studies dynamics in weakly-bound and unbound states, in particular around and beyond the neutron dripline, too. In parallel, dynamical aspects of nuclear matter are investigated using knockout reactions, charge exchange reactions, and nuclear fissions.

We are also developing methodologies and devices necessary for the reaction/dynamics studies: the TOGAXSI telescope array specialized for inverse-kinematics knockout reactions, neutron detectors, the spin-polarized proton target, and storage rings.

2. Major Research Subjects

(1) Studies of knockout reactions and their applications to production and spectroscopy of exotic nuclei
(2) Study of spin-isospin responses using charge exchange reactions
(3) Development of storage rings and their applications to study of *r*-process nucleosynthesis
(4) Development of techniques and devices for reaction studies with RI-beams

3. Summary of Research Activity

(1) Studies of knockout reactions and their applications to production and spectroscopy of exotic nuclei

Knockout reactions are among the best reactions used to nuclear studies at RIBF energies. We are advancing experimental programs using the knockout reactions.

(1-1) Multi-neutron correlations near the neutron dripline

Forms of existences of neutron-rich matter occurring in nuclei near the neutron dripline is the main subject of the program with large-acceptance SAMURAI spectrometer. By combining advanced devices such as MINOS (Saclay) and NeuLAND (GSI) from Europe, we have revealed new aspects of multi-neutron corelations in nuclei: Dineutron correlation in ^{11}Li, ^{14}Be, ^{17}B [Y. Kubota *et al*., PRL 125 and A. Corsi *et al*., PLB 840], halo structure in ^{17}B [Z. H. Yang *et al*., PRL 126], and tetraneutron [M. Duer *et al*., Nature 606]. We have also take data on ^{7}H populated with the ^{8}He$(p, 2p)$ reaction.

(1-2) Nuclear cluster formation

Nuclear physicists know that the formation of clusters is essentially important at both edges of the nuclear chart: clusters pronouncedly develop in light nuclei such as ^{12}C, and (pre-)formation of α clusters is essential in understanding decays of nuclei heavier than lead. What about in the other areas of the nuclear chart? We have to say that we have quite limited knowledge about it.

We tried to answer this question by probing α clusters in tin isotopes using the $^{112\text{–}124}$Sn$(p, p\alpha)$ knockout experiment in a close collaboration with the TU Darmstadt group. The excess-neutron (*N*-*Z*) dependence of the $(p, p\alpha)$ cross section shows a monotonic decrease with *N*-*Z*, which is in good agreement with a relativistic mean-field predictions done by S. Typel [J. Tanaka, Z. H. Yang *et al*., Science 371].

Triggered by the new knowledge obtained in this and other experiments, we have started a new research project named "ONOKORO" project where we comprehensively investigate clustering in medium-to-heavy mass nuclei using (p, pX) cluster knockout reactions under normal and inverse kinematics. The project will probe d, t, ^{3}He, α clustering both in stable and unstable nuclei in the mass region of A = 36–220. The TOGAXSI detector array is constructed to detect scattered protons and knocked-out clusters in a wide kinematical conditions.

(1-3) 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 and fragment distributions in neutron-deficient and neutron-rich regions beyond Pb.

(1-4) Other knockout reaction related activities

We have also applied (p, pN) reactions to gamma-ray spectroscopy (SEASTAR project in collaboration with the RI Beam Physics Group) and reaction meachnism studies [N. Paul *et al*., PRL 122 and A. Frotscher *et al*., PRL 125].

(2) Study of spin-isospin responses using charge exchange reactions

The study of spin-isospin responses in nuclei forms one of the essential cores of nuclear physics. A variety of collective states, for example isovector giant dipole resonances, isobaric analogue states, Gamow-Teller resonances, have been extensively studied by use of electromagnetic and hadronic reactions from stable targets.

The research opportunities can be largely enhanced with light of availabilities of radioactive isotope (RI) beams and of physics of unstable nuclei. There are three possible directions to proceed. The first direction is studies of spin-isospin responses of unstable nuclei via inverse-kinematics charge exchange reactions. A neutron-detector array WINDS has been constructed, under a collaboration of CNS, Tokyo and RIKEN, for inverse kinematics (p, n) experiments at the RIBF. We have already applied WINDS to the (p, n)

experiments for ^{11}Li, ^{132}Sn and plan to extend this kind of study to other exotic nuclei.

(3) Development of storage rings and their applications to study of *r*-process nucleosynthesis

Storage rings will become mandatory experimental tools in future research programs with RI-beams. We have constructed the Rare RI Ring, in close collaboration with the Instrumentation Development Group, which is the first storage ring constructed at the cyclotron-based facility such as RIBF.

We have successfully published the first result from the Rare RI Ring in 2022: The mass of ^{123}Pd around the *r*-process second peak was measured together with ^{126}In, ^{125}Cd [H. F. Li, S. Naimi *et al*., PRL 128]. The measurement was the first demonstration of the storage-ring application in a cryclotron facility and two novel methods, the individual injection of the preidentified rare nuclei and the isochronous mass spectroscopy in a cyclotron-type storage ring. Through detailed comparisons with *r*-process network calculations, it is concluded that the new ^{123}Pd mass increases the neutron capture cross section on ^{123}Pd by a factor of 2.2 and the β-delayed neutron emission probability of ^{123}Rh by 14%, and, at the same time, decreases the neutron capture cross section on ^{122}Pd by a factor of 2.6. This results in pileup of material at $A = 122$ and reproduces the trend of the solar *r*-process abundances.

In parallel to the mass measurements using the Rare RI Ring, we are about to develop a storage ring specialized to nuclear reaction study, named RUNBA.

(4) Development of techniques and devices for reaction studies with RI-beams

(4-1) TOGAXSI: a detector array specialized to inverse-kinematics cluster knockout reaction studies

As described in (1-3) and (1-4), use of cluster knockout reactions will form a core of the research program in the Nuclear Dynamics Group. We started construction of a new detector array optimized for inverse-kinematics cluster knockout reactions, named TOGAXSI, with the KAKENHI support [KAKENHI Specially Promoted Research FY2021–2025]. The TOGAXSI consists of silicon strip detectors for tracking and GAGG:Ce scintillators for total energy measurements of scattered protons and knocked-out clusters. The demonstrator array will be completed in 2023 and the full array in 2024.

(4-2) Application of spin-polarization technique to RI-beam experiments and other fields

A technique to produce nuclear polarization by means of electron polarization in photo-excited triplet states of aromatic molecules can open new applications. The technique is called "Triplet-DNP." A distinguished feature of Triplet-DNP is that it works under a low magnetic field of 0.1–0.7 T and temperature higher than 100 K, which exhibits a striking contrast to standard dynamic nuclear polarization (DNP) techniques working in extreme conditions of several Tesla and sub-Kelvin.

We have constructed a polarized proton target system for use in 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. Experiments with the target system allow us to explore the spin effects in exotic nuclei. 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. Now the polarized target is being applied to spin-correlation measurement of the proton-deuteron elastic scattering.

We plan to apply the same technique to other field such as sensitivity enhancement in NMR spectroscopy of biomolecules and MRI. In close collaboration with the organic chemistry group in Kyushu University lead by Prof. Yanai, we are developing several new molecules and techniques to open Triplet-DNP applications to NMR and MRI.

Members

Director
Tomohiro UESAKA

Senior Research Scientists
Masaki SASANO
Ken-ichiro YONEDA

Research Scientists
Yuki KUBOTA
Kenichiro TATEISHI

Technical Scientist
Yoshitaka YAMAGUCHI

Contract Researcher
Susumu SHIMOURA

Special Postdoctoral Researcher
Yoshiki CHAZONO

Postdoctoral Researcher
Junki TANAKA

Junior Research Associate
Ryohsuke YOSHIDA

International Program Associate
Yutian LI (IMP, CAS)

Research Consultant
Yasuyuki SUZUKI (Niigata Univ.)

Senior Visiting Scientist
Hiroyuki SAGAWA (Univ. of Aizu)

Visiting Scientists
Satoshi ADACHI (Tohoku Univ.)
Hidetoshi AKIMUNE (Konan Univ.)
Didier BEAUMEL (IJCLab Paris-Saclay Univ.)
Konstanze BORETZKY (GSI)
Anna CORSI (CEA Saclay)
Masanori DOZONO (Kyoto Univ.)
Zoltan ELEKES (ATOMKI)
Zsolt FULOP (ATOMKI)
Igor GASPARIC (Rudjer Boskovic Inst.)
Valdir GUIMARAES (Inst.o de Fisica da Univ. de Sao Paulo)
Zoltan HALASZ (ATOMKI)
Kaori KAKI (Shizuoka Univ.)
Takahiro KAWABATA (Osaka Univ.)
Yuma KIKUCHI (NIT, Tokuyama College)
Yosuke KONDO (Tokyo Tech)
Attila KRASZNAHORKAY (ATOMKI)
Dorottya S. KUNNE (ATOMKI)
Istvan KUTI (ATOMKI)
Valerie LAPOUX (Inst.ion CEA-Saclay)
Pengjie LI (IMP, CAS)
Yury LITVINOV (GSI)
Yohei MATSUDA (Konan Univ.)
Kenjiro MIKI (Tohoku Univ.)
Tetsuaki MORIGUCHI (Tsukuba Univ.)
Sarah NAIMI (IJCLab (Laboratoire de physique des 2 infinis - Irène Joliot-Curie))
Takashi NAKAMURA (Tokyo Tech)
Alexandre OBERTELLI (TU Darmstadt)
Shoya OGAWA (Kyushu Univ.)
Valerii PANIN (GSI)
Aldric REVEL (CEA Saclay)
Yoshiteru SATO (Tokyo Tech)
Kimiko SEKIGUCHI (Tokyo Tech)
Baohua SUN (Beihang Univ.)
Yelei SUN (TU Darmstadt)
Junki TANAKA (Osaka Univ.)
Takashi WAKUI (QST)
Atomu WATANABE (Tokyo Tech)
Takayuki YAMAGUCHI (Saitama Univ.)
Zaihong YANG (Peking Univ.)
Yuhu ZHANG (IMP, CAS)

Visiting Technicians
Denis CALVET (CEA)
Alain DELBART (CEA Saclay)
Clement HILAIRE (CEA)
Shoji SUZUKI (KEK)

Visiting Researcher
Thomas F. POHL (JSPS)

Student Trainees
Kazuki ARADONO (Kyushu Univ.)
Marcell BEGALA (Univ. of Debrecen)
Shiyo EN'YO (Kyoto Univ.)
Samu A. ETELAENIEMI (Osaka Univ.)
Yuto HIJIKATA (Kyoto Univ.)
Kento HIRASAWA (Kyushu Univ.)
Yuya HONDA (Osaka Univ.)
Teruki IKEDA (Tokyo Tech)
Soichiro ISHIGURO (Tokyo Tech)
Kakeru ISOBE (Tokyo Tech)
Marcell JUHASZ (Univ. of Debrecen)
Takafumi KAJIHARA (Kyushu Univ.)
Yukari KOIZUMI (Saitama Univ.)
Sandor KOVACS (Univ. of Debrecen)
Hyeji LEE (Tokyo Tech)
Yifan LIN (Osaka Univ.)
Yasuto MAKIMURA (Tokyo Tech)
Ryusei MATSUI (Kyushu Univ.)
Takaya MATSUI (Tokyo Tech)
Tomoki MATSUI (Tokyo Tech)
Yohei NAGAO (Kyushu Univ.)
Ryo NAGATAKE (Kyushu Univ.)
Satoru NISHIZAWA (Saitama Univ.)
Shintaro OKAMOTO (Kyoto Univ.)
Kengo OKUBO (Saitama Univ.)
Yuma OSAWA (Tokyo Tech)
Futa SAITO (Konan Univ.)
Yuko SAITO (Tohoku Univ.)
Soki SAKAJO (Osaka Univ.)
Kensuke SAKAMOTO (Kyushu Univ.)
Kosuke SAKANASHI (Osaka Univ.)
Kenta SASAKI (Saitama Univ.)
Hiromitsu SHIMIZU (Kyushu Univ.)
Hiroki SUGAHARA (Tokyo Tech)
Kotaro SUZUKI (Tokyo Tech)
Daichi TAKAHASHI (Tokyo Tech)
Rio TAKAHASHI (Tokyo Tech)
Kyouhei TAKENAKA (Kyushu Univ.)
Kazuki TAKIURA (Saitama Univ.)
Yusuke TANAKA (Kyushu Univ.)

Ryotaro TSUJI (Kyoto Univ.)
Satoshi UMEMOTO (Konan Univ.)
Ren URAYAMA (Tohoku Univ.)
Kensei USHIJIMA (Kyushu Univ.)
Nobuhiro YAMASAKI (Konan Univ.)
Shumpei YAMAZAKI (Tohoku Univ.)
Ryohsuke YOSHIDA (Kyoto Unv.)
Hanbin ZHANG (Tsukuba Univ.)

Research Part-time Workers

Takaya MATSUI
Yuko SAITO

List of Publications & Presentations

Publications

[Original Papers]

B. D. Linh, A. Corsi, A. Gillibert, A. Obertelli, P. Doornenbal, C. Barbieri, T. Dugue, M. Gómez-Ramos, J. D. Holt, B. S. Hu, T. Miyagi, A. M. Moro, P. Navrátil, K. Ogata, S. Péru, N. T. T. Puch, N. Shimizu, V. Somà, Y. Utsuno, N. L. Achouri, H. Baba, F. Browne, D. Calvet, F. Château. S. Chen, N. Chiga, M. L. Cortés, A. Delbart, J.-M. Gheller, A. Giganon, C. Hilaire, T. Isobe, T. Kobayashi, Y. Kubota, V. Lapoux, H. N. Liu, T. Motobayashi, I. Murray, H. Otsu,V. Panin, N. Paul, W. Rodriguez, H. Sakurai, M. Sasano, D. Steppenbeck, L. Stuhl, Y. L. Sun, Y. Togano, T. Uesaka, K. Wimmer, K. Yoneda, O. Aktas, T. Aumann, L. X. Chung, F. Flavigny, S. Franchoo, I. Gašparic, R. B. Gerst, J. Gibelin, K. I. Hahn, N. T. Khai, D. Kim, T. Koiwai, Y. Kondo, P. Koseoglou, J. Lee, C. Leh, T. Lokotko, M. MacCormick, K. Moschner, T. Nakamura, S. Y. Park, D. Rossi, E. Sahin, D. Sohler, P.-A. Söderström, S. Takeuchi, H. Törnqvist, V. Vaquero, V. Wagner, S. T. Wang, V. Werner, X. Xu, Y. Yamada, D. Yan, Z. Yang, M. Yasuda, and L. Zanetti, "Onset of collectivity for argon isotopes close to $N = 32$," Phys. Rev. C **109**, 034312 (2024).

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I. Kuti, H. Miki, K. Miki, T. Motobayashi, H. Otsu, A. Saastamoinen, M. Sasano, H. Sato, T. Shimada, Y. Shimizu, L. G. Sobotka, I. Stefanescu, L. Stuhl, H. Suzuki, H. Takeda, Y. Togano, T. Tomai, L. Trache, D. Tudor, T. Uesak, Y. Utsuki, H. Wang, A. Yasuda, K. Yoneda, and Y. Yoshitome, "Shape coexistence in ^{66}Se," Phys. Lett. B **844**, 138072 (2023).

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[Review Articles]

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Presentations

[International Conferences/Workshops]

H. Sagawa (invited), "QCD-based Charge Symmetry Breaking (CSB) interaction," New Frontiers in Nuclear Physics and Astrophysics-2, Antalya (Akdeniz University), Turkey, September 5–10, 2023.

H. Sagawa (invited), "Beyond mean field study of Giant resonances (Gamow-Teller), beta-decay and QCD-based charge symmetry breaking interaction," COMEX7 (Collective motion in Exotic Nuclei 7), Catania, Italy, June11–16, 2023.

H. Sagawa (invited), "Magnetic Dipole (M1) transitions in Sn isotopes and tensor interactions," Workshop in OMEG Institute, Soongsil University, Korea, August 20–26, 2023.

H. Sagawa (invited), "Beyond mean field study of Giant resonances (Gamow-Teller), beta-decay and ground state densities with tensor interactions," ISPUN 23 (International Symposium of Physics in Unstable Nuclei 2023), Phu Quoc Island, Vietnam, May 4–8, 2023.

H. Sagawa (invited), "QCD-based Charge Symmetry Breaking (CSB) interaction and ONS anomaly," Soongsil Univsersity workshop on Nuclear Physics, Korea, October 17, 2023.

T. Uesaka (invited), "Knockout reaction studies of clustering in nuclei," International Symposium on Physics of Unstable Nuclei 2023, Phu Quoc Island, Vietnam, May 4–8, 2023.

T. Uesaka (invited), "Methodologies for direct reaction studies with RI-beams ~ Present and future~," Direct Reactions and Spectroscopy with Hydrogen Targets: Past 10 Years at the RIBF and Future Prospects, York, England, July 31–August 3, 2023.

Y. Kubota (invited), "Dineutron correlation in neutron drip-line nuclei," in Workshop on Nuclear Cluster Physics (WNCP2023), Osaka, Japan, November 27–29, 2023.

Y. Kubota (invited), "Dineutron correlation in neutron drip-line nuclei—Experimental study using quasi-free knockout reaction at intermediate energy (~250 A MeV)," in WPCF 2023—XVI Workshop on Particle Correlations and Femtoscopy & IV Resonance Workshop 2023, Catania, Italy, November 6–10, 2023.

S. Shimoura (invited), "Tetra-neutron system populated by exothermic double-charge exchange reaction," Direct Reactions and Spectroscopy with Hydrogen Targets: Past 10 Years at the RIBF and Future Prospects, York, UK, July 31–August 4, 2023.

S. Shimoura (invited), "Tetra-neutron system populated by reactions with RI-beams," New Frontiers in Nuclear Physics and Astrophysics-2, Antalya (Akdeniz University), Turkey, September 5-10, 2023.

S. Shimoura (invited), "Experiments on 4*n* using SHARAQ spectrometer," 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, Hawaii, USA, November 26–December 1, 2023.

Y. Kubota (invited), "Dineutron correlation in neutron drip-line nuclei," in Direct Reactions and Spectroscopy with Hydrogen Targets: Past 10 Years at the RIBF and Future Prospects, York, UK, July 31–August 4, 2023.

H. Chazono (invited), "Theoretical model of the (p, pd) reaction for understanding deuterons inside nuclei," Direct Reactions and Spectroscopy with Hydrogen Targets: Past 10 Years at the RIBF and Future Prospects, York, UK, July 31–August 4, 2023.

R. Tsuji, "Study of cluster formation in heavy nuclei and nuclear matter with cluster knockout reaction," Quasi-Free Scattering with Radioactive-Ion Beams (QFS-RB 2023), Porto Galini Seaside Resort & Spa, Greece, October 1–6, 2023.

Y. Kubota (invited), "Generalized nuclear clustering in light and medium heavy nuclei," in Advancing physics at next RIBF (ADRIB24), Wako, Saitama, Japan, January 23–24, 2024.

M. Sasano, "The spin-isospin responses of ^{11}Li investigated by the charge exchange (p, n) reaction in inverse kinematics," 2023 IReNA Workshop on Weak Interactions in Nuclear Astrophysics, Michigan (Michigan State University), USA, July 10–12, 2023.

M. Sasano, "Gamow-Teller Giant Resonance in ^{11}Li neutron drip line nucleus," The 7th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX7), Dipartimento di Fisica e Astronomia, Catania, Italy, June 11–16, 2023.

G. Hudson-Chang, "Enhancing mass measurement accuracy using a novel position sensitive Schottky cavity doublet," International Conference of Physics Students 2023, Manila and Baguio City, Philippines, September 7–13, 2023.

Y. Chazono (invited), "Study on deuteron-like correlation via (p, pd) reactions," The Workshop on Frontier Nuclear Studies with Gamma-ray Spectrometer Arrays (Gamma24), Minoh (Osaka University), March 26–28, 2024.

Y. Chazono, "Reaction model for a correct understanding of the (p, pd) reaction," The 16th Varenna Conference on Nuclear Reaction Mechanisms (NRM2023), Villa Monastero, Varenna, Italy, June 11–16, 2023.

K. Tateishi, "Triplet dynamic nuclear polarization of bio-relevant molecules by new polarizing agents," International Hyperpolarization Conference (HYP23), University of Leipzig, Germany, September 24–28, 2023.

R. Yoshida, "The cross-section measurement of ^{16}N at intermediate energies for ESPRI*," A3F-CNS Summer School, Wako (RIKEN), Japan, August-4-10, 2023

[Domestic Conferences/Workshops]

佐川弘幸 (招待講演), “RPA and SSRPA for spin-isospin excitations,” RIKEN Workshop on “Giant Monopole Resonances and related topics,” 和光市（理化学研究所), 2023 年 5 月 18 日.

茶園亮樹 (招待講演), “Reaction model for correlated two-nucleon pairs knockout,” Reimei Workshop, “Intersection of nuclear structure and direct reaction,” 東海村（東海文化センター), 2023 年 2 月 28 日–3 月 1 日.

T. Pohl, “Reaction mechanisms in one-nucleon removal direct reactions at intermediate energies,” Reimei Workshop, “Intersection of nuclear structure and direct reaction,” 東海村（東海文化センター), 2023 年 2 月 28 日–3 月 1 日.

久保田悠樹 (招待講演), “Knockout measurements using solenoid spectrometer,” in ドラえもんスペクトロメータ移設のためのインフォーマルワークショップ, 和光市（理化学研究所), 2024 年 2 月 9 日.

吉田凌祐, 堂園昌伯, 銭廣十三, 土方佑斗, 荻尾真吾, 辻崚太郎, 八尋寛太, 矢野隆之, 坂口治隆, 大田晋輔, 田中純貴, 松田洋平, 齋藤風太, 梅本学嗣, 西村太樹, 網谷芽衣, 中村佑生, 福嶋知隼, 寺嶋知, 今井伸明, 矢向謙太郎, 道正新一郎, Thomas William Chillery, 小嶋玲子, 花井周太郎, 上坂友洋, 高田栄一, 「陽子弾性散乱実験のための ^{16}N アイソマー生成断面積測定」, 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 18 日–21 日.

立石健一郎, 「常温・低磁場における核スピン超偏極法の開発〜化学分析から原子核物理まで〜」, 日本量子医科学会第 3 回学術大会, 和光市（理化学研究所), 2023 年 12 月 8 日–9 日.

立石健一郎, 「トリプレット DNP を用いた原子核実験用偏極標的の開発」, 第二回 DNP 研究会, 豊中市（大阪大学豊中キャンパス), 2024 年 3 月 21–22 日.

下浦享, 「核内相関のプローブとしての核反応」, 「現代核物理の広がりと展望」, 福岡市（九州大学), 2023 年 7 月 19–21 日.

[Seminars]

M. Sasano, “Gamow-Teller giant resonances in unstable nuclei,” Dynamics of Spin Degrees of Freedom in Atomic Nuclei, Suita (RCNP), Osaka, December 11–13, 2023.

茶園亮樹 (招待講演), 「ノックアウト反応で見る新奇なクラスター」, 九州大学理論核物理研究会, 「現代核物理の拡がりと展望」, 福岡市 (九州大学), 2023 年 7 月 19 日–7 月 21 日.

Y. Kubota (invited), “Probing nuclear clustering using knockout reactions,” in 3rd RIKEN-IBS Joint Conference on Nuclear Physics, Wako, Japan, January 25–26, 2024.

Y. Kubota (invited), “Generalized nuclear clustering in light and medium heavy nuclei,” in Advancing Physics at Next RIBF (ADRIB24), Wako, Japan, January 23–24, 2024.

Awards

久保田悠樹, 2023 年度理研桜舞賞（研究奨励賞), 2024.

立石健一郎, 日本量子医科学会第 3 回学術大会優秀発表賞物理学部門, 2023.

茶園亮樹, RIBF Users Group Thesis Awards, 2023.