

Nuclear Science Research Division Radioactive Isotope Physics Group

1. Abstract

This Laboratory works as one of core research groups conducting programs at the world-premiere heavy-ion accelerator facility of RIKEN “RI Beam Factory (RIBF).” The 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 radioactive isotope (RI) beams at RIBF, to discover new phenomena and properties in exotic nuclei. The Laboratory is focusing three major subjects; shell evolution of very neutron-rich nuclei, the *r*-process path and equation-of-state in asymmetric nuclear matter. The Laboratory has initiated international collaborations for in-beam gamma spectroscopy, decay spectroscopy and heavy-ion induced reactions, and has formed a discussion forum for next generation gamma-ray detectors.

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. In 2019, results of the first spectroscopy of ^{40}Mg was published in PRL, to demonstrate the exotic structure which is very different from in other neutron-rich Mg isotopes.

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 $Z \sim 20$ to 40. The program was submitted to the PAC 2013 as a new category of proposal, “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 three campaigns were organized in 2014, 2015 and 2017 to study very neutron-rich isotopes, and were very productive to access very neutron-rich nuclei such as Ar-52, Ca-56, Ni-78, Kr-100, Zr-110. In 2019, the result of the first spectroscopy of Ni-78 was published in Nature.

A new project of high resolution gamma spectroscopy with fast beams “HiCARI” was proposed at PAC 2018. MINIBALL and several Ge tracking detectors from Japan, Europe, the USA and Korea were combined to form an array of germanium detectors. The new setup aims to accelerate researches of the nuclear structure by observing gamma-lines in even-odd nuclei and measuring lifetimes of excited states. The two workshops were organized in 2019, and the machine time of 43.5 days in total was approved at PAC 2019. The experiments with the MINOS setup were canceled due to the travel difficulties of COVID-19 for French engineers. The 31.5 days experiments were successfully conducted in 2020 and 2021. The first HiCARI paper was published in PLB, 2024.

Concerning a next generation detector, a new gamma-ray detector array “HYPATIA” based on GAGG and CeBr₃ was proposed as a construction proposal at the RIBF-PAC 2023. The proposal was approved with S-rank. The HYPATIA array is being constructed under an international collaboration.

(2) Decay spectroscopy

Beta- and isomer-spectroscopy is an efficient method for studying nuclear structure, especially for non-yrast levels. We had accumulated experimental techniques at the RIPS facility to investigate nuclear structure in light mass region via beta-gamma and beta-*p* coincidence. Concerning the medium and heavy mass region available at RIBF, we have developed two position-sensitive active-stoppers, strip-silicon detectors and a cylindrical active stopper called CAITEN, to achieve a low-background measurement by taking correlation between heavy ion stop position and beta-ray emission position. A site of decay-spectroscopy at the new facility of RIBF is the final focal plane of ZDS, where high precision of TOF in particle identification is obtained due to a long flight path from BigRIPS to ZDS.

At the end of 2009, the first decay spectroscopy was organized with a minimum setup of four clover gamma detectors and silicon

strip detectors, to study neutron-rich nuclei with $A \sim 110$. The first campaign was found successful and efficient to publish four letter articles in 2011, two PRL's and two PLB's. One of the PRL papers is associated to the r -process path where half-lives for 18 neutron-rich nuclei were determined for the first time. The other PRL paper reported a finding of deformed magic number 64 in the Zr isotopes.

The success of the first decay-spectroscopy campaign stimulated to form a new large-scale collaboration "EURICA," where a twelve Euroball cluster array is coupled with the silicon-strip detectors to enhance gamma efficiency by a factor of 10. A construction proposal of "EURICA" was approved in the PAC 2011, and the commissioning was successfully organized in spring 2012. Since then, physics runs had been conducted for programs approved to survey nuclei of interest as many as possible, such as Ni-78, Pd-128, Sn-100. The EURICA collaboration finished its physics programs in summer 2016. So far, more than 50 papers including 14 PRL's and 13 PLB's were published. One of the highlights is discovery of a seniority isomer in Pd-128, of which cascade gamma decay gives the energy of first excited state and robustness of $N = 82$ magic number, and the other is a half-life measurement for 110 neutron-rich nuclei across the $N = 82$ shell gap, which shows implications for the mechanism and universality of the r -process path.

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 was coupled with the AIDA silicon strip system. A construction proposal was approved at the PAC 2013. The commissioning run was conducted in autumn 2016. The major physics runs were conducted in 2017–2021. One of the recent highlights is "Beta-Delayed One and Two Neutron Probabilities Southeast of Sn-132 and the Odd-Even Systematics in r -Process Nuclide Abundances," published in PRL, 2022.

A new project "IDATEN" has been launched in 2021 to measure lifetime of excited states with a large size LaBr₃ array, which is formed by combination of FATIMA and Khala arrays. The construction proposal was submitted to PAC, 2021, and proposals with IDATEN were evaluated at PAC, 2022. The project has been conducted under UK, Korea, China, and Japan.

Based on the great success of EURICA, a new decay-spectroscopy setup "C2URIE" based on germanium detectors was proposed as a construction proposal at the RIBF-PAC, and was approved with S-rank. Experiment programs are under discussions, and the proposals will be submitted to the RIBF-PAC in 2025.

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 "S π RIT," Construction proposal was submitted at the PAC 2012, and physics proposals were approved at the PAC 2012 and 2013. The physics runs were successfully conducted in spring 2016. The first three papers were published in 2020 and 2021. One of them, which was published in PRL, has been ranked as the TOP 1% paper by WoS.

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.

In 2018, a new project based on missing mass spectroscopy was launched to investigate an exotic cluster state in a very proton-rich nucleus. The experiment was organized at GANIL with combination of RIKEN liquid hydrogen target CRYPTA and the MUST2 detector array. A result on ^8C was published in Phys. Rev. C in March 2024.

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List of Publications & Presentations

Publications

[Original Papers]

- M. Singh, R. Yokoyama, R. Grzywacz, A. Keeler, T. T. King, J. Agramunt, N. T. Brewer, S. Go, J. Liu, S. Nishimura, P. Parkhurst, V. H. Phong, M. M. Rajabali, B. C. Rasco, K. P. Rykaczewski, D. W. Stracener, A. Tolosa-Delgado, K. Vaigneur, and M. Wolińska-Ciocka, “YSO implantation detector for beta-delayed neutron spectroscopy,” *Nucl. Instrum. Methods Phys. Res. A* **1073**, 170239 (2025).
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[Review Articles]

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[Proceedings]

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Presentations

[International Conferences/Workshops]

- H. Sakurai (invited), “Study of exotic nuclei at RIKEN,” International Symposium on Nuclear Science, Sofia, Bulgaria, September 9–13, 2024.
- H. Sakurai (invited), “Overview of TOPTIER Project -Japan,” Korea-Japan Symposium on TOPTIER Platform in Extreme Rare Isotope Science, Seoul, Korea, December 16–17, 2024.
- S. Nishimura (invited), “Role of neutron-rich nuclei in *r*-process nucleosynthesis,” Chendu, China, September 7–13, 2024.
- D. Suzuki (invited), “Study on molybdenum puzzle at the RI Beam Factory,” 2024 Annual Meeting of A3 Foresight Program “Nuclear Physics in the 21st Century,” Daejeon, Korea, July 17, 2024.
- D. Suzuki (invited), “Gamma-ray tracking project GT-5 at RI Beam Factory,” Joint SUNFLOWER and SHARAQ/OEDO Workshop, RIKEN Nishina Center, Wako, September 6, 2024.
- D. Suzuki (invited), “Advances of nuclear science at RI Beam Factory,” International Conference on Nuclear Physics and Applications (ICNPA-2024), University of Delhi, Delhi, India, October 21–25, 2024.
- D. Suzuki (invited), “Transfer reaction studies from exotic structure to nucleosynthesis,” 3rd CAS-RIKEN symposium, RIKEN Nishina Center, Wako, November 7–8, 2024.
- D. Suzuki (invited), “Recent progress of nuclear astrophysics at RI Beam Factory,” Nucleosynthesis and Evolution of Neutron Stars (XRB2025), YITP, Kyoto University, Kyoto, January 28, 2025.
- T. Isobe (invited), “Experimental study of asymmetric nuclear matter EOS from heavy-ion reactions with RIBF-SPiRIT,” Evolution of Matter in the Universe, Wako, Japan, June 5–7, 2024.
- T. Isobe (invited), “Systematic measurement of charged pion production in HIC with RI beams at RIKEN-RIBF,” XIIth International Symposium on Nuclear Symmetry Energy (NuSym24), Caen, France, September 9–14, 2024.
- T. Isobe (invited), “Heavy ion collision experiments by using RI beam at RIBF for the study of high dense neutron rich nuclear matter,” 3rd RIKEN RNC—CAS IMP Joint Symposium, Wako, Japan, November 7–8, 2024.
- T. Isobe (invited), “From nucleus to neutron star: experimental study of nuclear matter by using heavy ion collisions,” Korea-Japan Symposium on TOPTIER Platform in Extreme Rare Isotope Science, Seoul, Korea, December 15–17, 2024.
- T. Isobe (invited), “Heavy ion collision experiment by using RI beam at RIBF for the study of density dependent symmetry energy,” RCNP-CENuM-OMEG Symposium on Nuclear Structure, Reaction, and Astrophysics (NuSRAP2024), Osaka, Japan, December 18–20, 2024.
- T. Isobe (invited), “High density, Neutron Star EoS,” The 2nd Workshop on Highly Baryonic Matter at RHIC-BES and Future Facilities—beyond the Critical Point towards Neutron Stars—(WHBM2025), Tsukuba, Japan, March 8–9, 2025.
- P. Doornenbal (invited), “The HYPATIA project,” HYPATIA Workshop, London, UK, March 20–21, 2025.
- P. Doornenbal (oral), “The HYPATIA project,” DREB, Wiesbaden, June 24–28, 2024.
- P. Doornenbal (invited), “Shell structure of neutron-rich calcium isotopes,” Shell Model Symposium, Argonne, July 19–21, 2024.
- P. Doornenbal (invited), “Experimental nuclear physics,” 5th Andean School, Bogota, December 9–13, 2024.
- M. L. Cortes (invited), “Status of GAGG development,” HYPATIA Workshop-Science Opportunities Institute of Physics, London, UK.

March 21–22, 2025.

- M. L. Cortes (invited), “The HYPATIA project: Development of a new gamma-ray spectrometer at the RIBF,” Fourth Andean School on Nuclear Physics: Radioactive Nuclei and Nuclear Astrophysics Bogotá, Colombia. December 9–13, 2024.
- M. L. Cortes (invited), “The HYPATIA project: Development of a new gamma-ray spectrometer at the RIBF,” SUNFLOWER Workshop 2024 RIKEN Nishina Center, September 5–7, 2024.
- M. L. Cortes (oral), “Intermediate-energy Coulomb excitation of $N = 52$ isotones towards 100Sn ,” International Conference on Direct Reactions with Exotic Beams (DREB2024) Wiesbaden, Germany, June 24–28, 2024.
- V. H. Phong (oral), “Measurements of beta-delayed neutron emission probabilities around the medium-mass mid- to the doubly-closed shell region,” Nuclear Structure 2024 Conference, Argonne National Laboratory, USA, July 21–26, 2024.
- V. H. Phong (invited), “Digital DAQ system at RIBF for beta-decay studies,” Workshop on Active Stoppers for Decay Experiments, Valencia, Spain, March 24–26, 2025.
- V. H. Phong (oral), “Decay spectroscopy of neutron-rich Sn isotopes,” Workshop on Decay Spectroscopy at the Radioactive Isotope Beam Factory (RIBF) at RIKEN, Valencia, Spain, March 27–28, 2025.
- T. T. Yeung (oral), “New isomers in ^{213}Tl and ^{215}Tl revealing shell evolution beyond $N = 126$ shell closure,” The V International Conference on Nuclear Structure and Dynamics, Valencia, Spain, May 27–31, 2024.
- T. T. Yeung (poster), “Half-life and β -delayed neutron measurements of neutron-rich nuclei near $N = 126$ at RIBF,” Nuclear Physics in Astrophysics XI, Dresden, Germany, September 15–20, 2024.
- T. T. Yeung (invited), “Waveform analysis with WAS3ABi for measurements of ion implantation and charged-particle decays,” Workshop on Active Stoppers for Decay Experiments, Valencia, Spain, March 24–26, 2025.
- N. Watanabe (oral), S. Ni-En, M. Tsuge, and Y. Nakai, “The photodesorption efficiency of OH radical on ice from ultraviolet to visible range,” CPLT2024 Chemistry and Physics at Low Temperatures, Niseko, Japan, July 6–11, 2024.
- N. Watanabe (poster), Y. Nakai, W. M. C. Sameera, K. Furuya, H. Hidaka, and A. Ishibashi, “Reactions via irradiation of an ice surface with low-energy ions at low temperature conditions,” CPLT2024 Chemistry and Physics at Low Temperatures, Niseko, Japan, July 6–11, 2024.
- N. Watanabe (poster), Y. Nakai, W. M. C. Sameera, K. Furuya, H. Hidaka, and A. Ishibashi, “Reactions of low-energy ions with an ice surface at low temperature conditions,” Symposium on Next Generation Astrochemistry, Chuo-ku, Tokyo, Japan.

[Domestic Conferences/Workshops]

- 西村俊二 (招待講演), 「変形原子核衝突を利用した集団運動」, 東海村, 2025 年 3 月 6–7 日.
- 渡部直樹 (口頭発表), 中井陽一, 日高宏, 「低エネルギーイオンと氷表面との反応実験 III」, 日本物理学会第 79 回年次大会, 札幌市 (北海道大学), 2024 年 9 月 16–19 日.
- 磯部忠昭 (招待講演), 「RI ビーム衝突を用いた原子核 EOS の実験的研究」, 第 2 回 J-PARC と重イオン衝突実験の交差点, 東海村 (日本原子力研究機構), 2025 年 3 月 6–7 日.
- P. Doornenbal (口頭発表), “Status of SUNFLOWER Collaboration,” SHARAQ/OEDO and SUNFLOWER Workshop, Wako, September 5–7, 2024.
- M. L. Cortes (招待講演), “The HYPATIA project at RIBF,” Advancing physics at next RIBF (ADRI25) RIKEN Wako Campus, January 22–23, 2025.
- V. H. Phong (口頭発表), “Experimental beta-decay half-lives and beta-delayed neutron emission probabilities in medium-mass nuclei ($A \sim 110$),” RIBF ULIC Mini-workshop on Structure of Neutron-rich Matter Revealed by Beta Decay, RIKEN, Japan, July 29–30, 2024.
- V. H. Phong (招待講演), “Toward the r -process path: Challenges in β -decay spectroscopy,” Workshop on Advancing physics at next RIBF (ADRI25), RIKEN, Japan, January 29–30, 2025.
- T. T. Yeung (口頭発表), “Beta-decay and conversion-electron spectroscopy of neutron-rich isotopes beyond $N = 126$ at RIKEN,” RIBF ULIC Mini-workshop on Structure of Neutron-rich Matter Revealed by Beta Decay, Wako, Saitama, July 29–30, 2024.

[Seminars]

- D. Suzuki, “Single-particle and collective motions in atomic nuclei,” Nuclear physics School for Young Scientists (NUSYS-2024), Beijing Normal University, Zhuhai, China, July 27–August 2, 2024.
- T. Isobe, “Measurement of charged pion ratio in RI collisions Measurement of charged pion ratio in RI collisions for the constraint of density dependent nuclear symmetry energy at RIKEN-RIBF” Tsinghua University, Serial Seminars on Nuclear Physics, Beijing, China, August 29, 2024.
- M. L. Cortes (invited), “Intermediate-energy Coulomb excitation of $N = 52$ isotones towards 100Sn ,” Nuclear Physics Seminar University of Manchester, UK. March 19, 2025.
- S. Kubono, Experimental Challenge to Explosive Nucleosynthesis in X-Ray Bursts and Supernovae, Fudan University, September 13, 2024.

Outreach Activities

- 櫻井博儀, 「原子核物理学での日中共同研究—理研を舞台にした今昔—」, 日中科学技術交流協会, 文京区 (東京大学), 2024 年 6 月 18 日.
- 櫻井博儀, 「宇宙での元素合成」, 埼玉県立春日部高等学校, 2024 年 11 月 12 日.
- 鈴木大介, 「原子核物理新 100 年の挑戦—多様性の起源と未来—」, 2024 年度理化学研究所和光地区一般公開, 理化学研究所和光キャンパス仁科 RIBF 棟大会議室, 2024 年 10 月 5 日.

木村真明, 鈴木大介, 「祝！ 量子力学 100 年 夢の原子核工場 RI ビームファクトリーの挑戦」, 理研 DAY：研究者と話そう！, オンライン, 2025 年 2 月 28 日.

中井陽一, 「非専門家が学んだ放射線物理学-阻止能とその周辺を中心に」, 第 32 回原子衝突セミナー, 船橋市（東邦大学）, 2025 年 3 月 27-28 日.

Others

[国内雑誌]

鈴木大介, 上坂友洋, 原子核の温故知新「1934 年のグッゲンハイマー II」, 原子核研究 第 69 巻 1 号.