

Nuclear Science and Transmutation Research Division Radioactive Isotope Physics Laboratory

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” has been proposed at PAC 2018. MINIBALL and several Ge tracking detectors from Japan, Europe, the USA and Korea are being 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. A part of the HiCARI programs was successfully conducted in 2020. The other HiCARI programs will be performed in 2021.

Concerning a next generation detector, a discussion forum has been established to write up a white paper on tracking germanium detectors and high-efficient crystal detectors such LaBr₃ and GAGG.

(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, 54 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 and three physics proposals have been approved. The commissioning run was conducted in autumn 2016. The major physics runs were conducted in 2017–2020.

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 data analysis is in progress to produce the first physics results. The first physics paper has been published in 2020.

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 α -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 in 2018.

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List of Publications & Presentations

Publications

[Original Papers]

- B. Moon, A. Jungclaus, H. Naïdja, A. Gargano, R. Lozeva, C. -B. Moon, A. Odahara, G. S. Simpson, S. Nishimura, F. Browne, P. Doornenbal, G. Gey, J. Keatings, G. Lorusso, Z. Patel, S. Rice, M. Si, L. Sinclair, P. -A. Söderström, T. Sumikama, J. Taprogge, H. Watanabe, J. Wu, Z. Y. Xu, A. Yagi, D. S. Ahn, H. Baba, F. L. Bello Garrote, S. Bönig, R. Daido, J. M. Daugas, F. Didierjean, F. Drouet, Y. Fang, N. Fukuda, R. Gernhäuser, B. Hong, E. Ideguchi, S. Ilieva, N. Inabe, T. Ishigaki, T. Isobe, H. S. Jung, D. Kameda, I. Kojouharov, T. Komatsubara, T. Kröll, T. Kubo, N. Kurz, Y. K. Kwon, C. S. Lee, P. Lee, Z. Li, A. Montaner-Pizá, S. Morimoto, K. Moschner, D. Mücher, D. Murai, M. Niikura, H. Nishibata, I. Nishizuka, R. Orlandi, H. Sakurai, H. Schaffner, Y. Shimizu, K. Steiger, H. Suzuki, H. Takeda, K. Tshoo, Z. Vajta, A. Wendt, R. Yokoyama, and K. Yoshinaga, “Nuclear structure of Te isotopes beyond neutron magic number $N = 82$,” *Phys. Rev. C* **103**, 034320 (2021).
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[Review Articles]

- H. Yamaguchi, D. Kahl, and S. Kubono, “CRIB: The low energy in-flight RI beam separator,” *Nuclear Physics News (NUPECC)* **30**, 21 (2020).

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Presentations**[International Conferences/Workshops]**

- H. Sakurai (invited), “Highlights and future directions of RIBF,” Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics, Kanazawa, Japan, March 1–5, 2021.
- H. Sakurai (invited), “Physics of exotic nuclei in a 10-year perspective,” Workshop on Frontiers of Nuclear Structure and Nuclear Astrophysics and Toward PKU-UT Joint Research Center on Nuclear Physics, Fragrant Hill Hotel and Online, Beijing, October 14–16, 2020.
- P. Doornenbal (invited), “High-resolution in-beam gamma-ray spectroscopy at the RIBF with HiCARI,” NUSTAR Annual Meeting 2021, Online, February 22–26, 2021.
- D. Suzuki (invited), “Two neutron transfer resonances via alpha scattering,” International mini-workshop on physics in resonant reaction induced by low-energy RI beam, Japan, February 22, 2021.
- D. Suzuki (invited), “Spectroscopy of light exotic nuclei beyond the proton drip line,” Yamada Conference LXXII: The 8th Asia-Pacific Conference on Few-Body Problems in Physics, Kanazawa, Japan, March 1–5, 2021.
- K. Asahi (invited), “Electric dipole moment of diamagnetic atom ^{129}Xe as a probe for new physics,” Fundamental Sciences and Quantum Technologies using Atomic Systems (FSQT2020) (on-line), Physical Research Laboratory, Navrangpura, Ahmedabad, India, September 28–October 1, 2020.
- S. Kubono (invited), “Challenge to explosive hydrogen burning in nuclear physics—study of rp-process and vp-process,” NAOJ Workshop on Stellar Alchemy to Galactic Archeology, October 26–29, 2020.

[Domestic Conferences/Workshops]

- 櫻井博儀 (招待講演), 「不安定核ビームが開拓するエキゾチック原子核の物理」, シンポジウム「大強度不安定核ビームが拓く新領域」, 日本物理学会第76回年次大会, オンライン開催, 2021年3月12–15日.
- S. Nishimura (invited), “Frontier of experimental activities relevant to r-process nucleosynthesis at RIBF,” KEK Workshop: Beta decay, r process and related weak interaction processes, February 19, 2021.
- S. Nishimura (invited), 「不安定核から探るランタノイド元素合成の謎」, NAOJ Workshop: Stellar Alchemy to Galactic Archeology, October 26–29, 2020.
- 槇口雄仁, 堀内渉, 小濱洋央 (口頭発表), 「原子核密度分布に対する反陽子-原子核散乱の有用性」, 日本物理学会2020年秋季大会, オンライン開催, 2020年9月14–17日.
- F. Browne (oral), “Single-particle energies and strengths around ^{55}Sc ,” FY2020 SPDR Presentation Session, Wako, Japan, January 18, 2021.

[Seminars]

- H. Sakurai, “Overview of research activities and plans at RIBF,” The C2R2 (CENS, CENuM, RUA, RULIC) Seminar, on-line, CENS, IBS, Korea, October 22, 2020.
- K. Asahi, “Electric dipole moment of diamagnetic atom ^{129}Xe as a probe for new physics,” ISOLDE Physics Group Seminar, on-line & CERN, Geneva, Switzerland, November 19, 2020.
- T. Isobe, 「理研不安定核ビームで探る中性子星の状態方程式」, Physics Seminar, Nara Women’s University, Nara, Japan, July 21, 2020.

Awards**Press Releases**

「フッ素-29が「2中性子ハロー原子核」であることを発見—魔法数20の消失と中性子ハロー構造の出現—」, 2020年8月21日.