

## 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  $^{40}\text{Mg}$  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.

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 as  $\text{LaBr}_3$  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, 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 LaBr<sub>3</sub> 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.

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 $\pi$ 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  ${}^8\text{C}$  was published in Phys. Rev. C in March 2024.

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**List of Publications & Presentations****Publications****[Original Papers]**

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### [Proceedings]

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## Presentations

### [International Conferences/Workshops]

- H. Sakurai (invited), “Study of neutron-rich nuclei at RIKEN RI Beam Factory,” ANURIB2023, Kolkata (VECC), India & Online, April 26, 2023.
- H. Sakurai (invited), “Overview of achievements and plans at RIBF,” IPSUN, Phu Quoc Island, Vietnam, May 4–8, 2023.
- H. Sakurai (invited), “Nuclear science and technology with RIBF,” VINANST-15, Nha Trang, Vietnam, August 9–11, 2023.
- H. Sakurai (invited), “Overview of the RIBF facility,” Direct Reactions and Spectroscopy with Hydrogen Targets: Past 10 Years at the RIBF and Future Prospects, July 31–August 4, 2023.
- D. Suzuki (invited), “Gamma-ray tracking project at RI Beam Factory,” Frontier nuclear studies with gamma-ray spectrometer arrays (gamma24), Minoh, Osaka, Japan, March 26–28, 2024.
- D. Suzuki (invited), “Studies on explosive burnings around  $^{56}\text{Ni}$  at RI Beam Factory,” Nuclear Astrophysics with Stable Beams (NAPS2024), Tokai, Ibaraki, Japan, February 20–22, 2024.
- D. Suzuki (invited), “RIBF facility upgrade project: Perspective of experiment and instrumentation,” Advancing Physics at Next RIBF (ADRI24), Wako, Japan, January 23–24, 2024.
- D. Suzuki (invited), “Recent progresses and perspectives of RI Beam Factory,” African Nuclear Physics Conference 2023 (ANPC2023) Johannesburg, South Africa, November 29–December 3, 2023.
- D. Suzuki (invited), “New initiatives of in-beam spectroscopy at RI Beam Factory,” Workshop on Science of Intense High Energy Rare Isotope Beams I, 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.
- D. Suzuki (invited), “RIBF facility upgrade project: Perspective of experiment and instrumentation,” RIBF User Group Meeting 2023, Wako, Japan, September 6–7, 2023.
- D. Suzuki (invited), “New initiatives at RIKEN RI Beam Factory: OEDO and MRTOF-MS,” The 2023 Gordon Research Conference on Nuclear Chemistry, New London, USA, June 11–16, 2023.
- S. Nishimura (invited), “Experimental challenges to study on high density matter and neutron star,” Workshop on Highly Baryonic Matter at RHIC-BES and Future Facilities—Beyond the Critical Point towards Neutron Stars—, Tsukuba (University of Tsukuba), Japan, April 30, 2023.
- S. Nishimura (invited), “Role of neutron-rich nuclei in  $r$ -process nucleosynthesis,” Frontiers in Nuclear Astrophysics 2023, Michigan (Michigan State University), USA, May 21–26, 2023.
- S. Nishimura (invited), “Experiments related to neutron-rich nuclei in  $r$ -process nucleosynthesis,” 17th International Symposium on Nuclei in the Cosmos (NIC XVII), Daejeon, Korea, September 17–22, 2023.
- S. Nishimura (invited), “Experiments related to  $r$ -process nucleosynthesis,” Hawaii DNP-JPS Workshop, Hawaii, USA, November 27, 2023.
- S. Nishimura (invited), “Exotic nuclei and  $r$ -process nucleosynthesis,” Origin of Elements and Cosmic Evolution (OECE), Online, China, November 1–3, 2023.
- Y. Wang (invited), “Correlation Function studies at intermediate energies at CSHINE,” Workshop on Particle Correlations and Femtoscopy/Resonance Workshop Conference 2023 (WPCF2023), Catania, Italy, November 6–10, 2023.
- Y. Wang (invited), “Nuclear equation-of-state studies with the compact spectrometer for heavy-ion experiment (CSHINE),” 11th International Symposium on Nuclear Symmetry Energy (Nusym2023), Darmstadt (GSI), Germany, September 18–22, 2023.
- Y. Wang (oral), “Isospin dynamic studies with the compact spectrometer for heavy-ion experiment (CSHINE),” 2023 Annual Meeting of JSPS/NRF/NSFC A3 Foresight Program, “Nuclear Physics in the 21st Century”, Xi’an, China, November 30–December 4, 2023.
- T. T. Yeung (oral), *et al.*, “Beta-delayed neutron measurements of neutron-rich nuclei near  $N = 126$  at RIBF,” 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.
- T. T. Yeung (poster) *et al.*, “Decay spectroscopy and delayed-neutron measurements of neutron-rich nuclei from Os to Po at RIBF,” International Symposium on Quantum Electronics 2024, Tokyo, Japan, February 13–16, 2024.
- P. Doornenbal (invited), “Structural evolution of the neutron-rich calcium isotopes,” ISPUN23, Phu Quoc Island, Vietnam, May 4–8, 2023.
- P. Doornenbal (invited), “Structural evolution of the neutron-rich calcium isotopes,” CGS 17, Grenoble, France, July 17–21, 2023.
- P. Doornenbal (oral), “Status of the SUNFLOWER collaboration,” SUNFLOWER Workshop, York, UK, July 28, 2023.
- P. Doornenbal (invited), “Overview of the SEASTAR project,” Direct Reactions Symposium, York, UK, July 31–August 4, 2023.
- P. Doornenbal (invited), “A new scintillator-based gamma-ray spectrometer for the RIBF,” Direct Reactions Symposium, York, UK, July 31–August 4, 2023.
- T. Isobe (invited), “The SPiRiT TPC for heavy ion collision experiments at RIKEN-RIBF,” TPC 2023, College Station, USA, May 16–18, 2023.
- T. Isobe (invited), “Experimental study of asymmetric nuclear matter EOS from heavy-ion reactions with RIBF-SPiRiT,” Colloque Ganil 2023, Accueil, France, September 25–29, 2023.
- T. Isobe (invited), “Experimental study of asymmetric nuclear matter EOS from heavy-ion reactions,” Equation of State of Dense Nuclear Matter, Waikoloa, USA, November 27, 2023.
- T. Isobe (invited), “Perspectives of heavy ion collision program at RIBF for the study of nuclear EoS,” Advancing physics at next RI Beam Factory (ADRI24), Wako, Japan, January 23–24, 2024.

- T. Isobe (invited), “Experimental study of asymmetric nuclear matter EOS from heavy-ion reactions with RIBF-SPIRIT,” Workshop at the Tomonaga Center for the History of the Universe (TCHoU), Tsukuba, Japan, March 29, 2024.
- N. Watanabe (oral), A. Miyazaki, M. Tsuge, H. Hidaka, and Y. Nakai, “Determination of the activation energy for diffusion of OH radicals on water ice,” 38th Symposium on Chemical Kinetics and Dynamics, Fukuoka, Japan, June 6–9, 2023.
- N. Watanabe (poster), Y. Nakai, W. M. C. Sameera, K. Furuya, H. Hidaka, and A. Ishibashi, “Methanol production via irradiation of low-energy  $\text{CH}_3^+$  ions on an ASW surface,” 2023 Kavli-IAU Astrochemistry Symposium, Astrochemistry VIII—From the First Galaxies to the Formation of Habitable Worlds, Traverse City, USA, July 10–14, 2023.
- N. Watanabe (oral), Y. Nakai, W. M. C. Sameera, K. Furuya, H. Hidaka, and A. Ishibashi, “Methanol production through the impingement of low-energy  $\text{CH}_3^+$  ions onto an ice surface at low temperature,” The 15th International Conference on the Physics and Chemistry of Ice, Sapporo, Japan, September 3–8, 2023.
- N. Watanabe (oral), M. Tsuge, A. Miyazaki, N. -E. Sie, W. M. C. Sameera, Y. Nakai, T. Hama, H. Hidaka, and A. Kouchi, “Visible light induced photodesorption of hydroxyl radicals from amorphous solid water,” The 15th International Conference on the Physics and Chemistry of Ice, Sapporo, Japan, September 3–8, 2023.
- N. Watanabe (oral), Y. Nakai, W. M. C. Sameera, K. Furuya, H. Hidaka, and A. Ishibashi, “Methanol production through irradiation of low-energy  $\text{CH}_3^+$  ions on an ice surface at low temperature,” Workshop on Interstellar Matter 2023, Sapporo, Japan, November 8–10, 2023.
- Y. Nakai (invited), “Reactions through the irradiation of an ice surface with low-energy molecular ions at low temperatures,” Third Laboratory Astrophysics Workshop (ICE2024), Kapaa, Kauai, USA, February 18–22, 2024.
- N. Watanabe (oral), N.-E. Sie, M. Tsuge, Y. Nakai, and W. M. C. Sameera, “Wavelength-dependent photodesorption of OH radicals in a visible range,” Third Laboratory Astrophysics Workshop (ICE2024), Kapaa, Kauai, USA, February 18–22, 2024.
- M. L. Cortés (invited), “First spectroscopy of  $^{62}\text{Ti}$ : Shell evolution towards  $^{60}\text{Ca}$ ” Direct reactions and spectroscopy with hydrogen targets: past 10 years at the RIBF and future prospects, York, UK, July 31–August 4, 2023.
- M. L. Cortés (invited), “In-beam gamma-ray spectroscopy at the RIBF: Recent results and future perspectives” 6th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Hawaii, USA, November 26–December 1, 2023.

#### [Domestic Conferences/Workshops]

- S. Nishimura (招待講演), “Study on the  $r$ -process at RIKEN RIBF,” JPS-KPS symposium, Online, March 21, 2024.
- P. Doornenbal (招待講演), “Towards next-generation in-beam gamma-ray spectroscopy at the RIBF with HYPATIA” ADRIB24 Workshop, Wako, Japan, January 23–24, 2024.
- P. Doornenbal (招待講演), “Towards next-generation in-beam gamma-ray spectroscopy at the RIBF with HYPATIA” RIKEN-IBS Joint Conference, Wako, Japan, January 23–24, 2024.
- V. H. Phong (口頭発表), “Beta-delayed neutron emission probability measurements of the  $r$ -process progenitor nuclei with BRIKEN,” RIBF Users Meeting 2023, Wako (RIKEN), Japan, September 6–7, 2023.
- M. L. Cortés (招待講演), “From SEASTAR to HYPATIA: Probing nuclear structure via direct reactions at the RIBF with an upgraded gamma-ray spectrometer,” Reimei workshop on “Intersection of Nuclear Structure and Direct Reaction,” Tokai (Tokai Culture Center), Japan, February 28–March 1, 2024.
- 櫻井博儀 (招待講演), 「RI ビームファクトリーで展開する不安定核物理と未来」, 原子核談話会創立 70 周年記念シンポジウム「原子核物理学の昨日・今日・明日」, 大岡山 (東京工業大学), 2024 年 3 月 6 日–7 日.
- 櫻井博儀 (招待講演), 「加速器による元素変換と将来」, 日本電機工業会・加速器特別委員会, 2023 年 12 月 11 日.
- 磯部忠昭 (招待講演), 「重イオン衝突による高密度核物質研究 I」, HIMAC における原子核物理学研究の展望, 和光市 (理化学研究所), 2023 年 11 月 17 日.
- 磯部忠昭 (口頭発表), 「非等方的集団運動から探る高密度核物質の状態方程式の研究」, 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 8–9 日.
- 渡部直樹 (口頭発表), 柘植雅士, 北島謙生, 中井陽一, W. M. C. Sameera, 「極低温  $\text{H}_2\text{O}$  氷における負電荷伝導」, 第 17 回分子科学討論会, 豊中市 (大阪大学), 2023 年 9 月 12–15 日.
- 中井陽一 (口頭発表), 「複雑有機分子生成への気相分子イオンと氷星間塵表面の協働: 実験からのアプローチ」, 学術変革領域研究 (A) 次世代アストロケミストリー第 2 回気相実験ワークショップ, 豊島区 (立教大学), 2023 年 11 月 24 日.
- N. Watanabe (ポスター発表), N. -E. Sie, M. Tsuge, Y. Nakai, W. M. C. Sameera, “Photodesorption of hydroxyl radicals from ice surface induced by visible photons,” 原子衝突学会第 48 回年会, 目黒区 (東京工業大学), 2023 年 11 月 25–26 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 II」, 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 18–21 日.

#### [Seminars]

- H. Sakurai, “Physics with exotic nuclei—its achievement and perspective—,” The 3rd Nuclear physics School for Young Scientists (NUSYS2023), August 6–13, 2023.
- D. Suzuki, “Mirror symmetry in atomic nuclei,” Hokkaido (Hokkaido University), Japan, January 17, 2024.

#### Press Release

今井伸明, 堂園昌伯, 大津秀暁, 炭竈聡之, 鈴木大介, Jongwon Hwang 「長寿命核廃棄物の減容および宇宙での元素の起源の解明へ」, 東京大学, 理化学研究所, 京都大学, Institute for Basic Science, 2024 年 2 月 16 日, [https://www.riken.jp/press/2024/20240216\\_1/index.html](https://www.riken.jp/press/2024/20240216_1/index.html).

**Awards**

P. Doornenbal, GSI/FAIR Exotic Nuclei Community Membership Award, 2024.  
磯部忠昭, 日本量子医科学会第3回学術大会優秀発表賞.

**Outreach Activities**

櫻井博儀, 「元素, 原子, 原子核」, 埼玉県立春日部高等学校, 2023 年 10 月.  
櫻井博儀, 2023 年度「はかる!」, 埼玉県立不動岡高等学校.

**Others****[集中講義]**

櫻井博儀, 「不安定核物理のこれまでとこれから」, 大阪大学理学研究科, 2023 年 7 月 3 日–5 日.  
D. Suzuki, “Methods and practices of nuclear spectroscopy with radioactive isotope beams,” 北海道大学理学部, 2024 年 1 月 15 日–17 日.