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 spectrosocpy 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 31.5days 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 $LaBr_3$ 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, 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. 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 $LaBr_3$ 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 "SπRIT," 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.

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List of Publications & Presentations

Publications

[Original Papers]

M. Enciu, H. N. Liu, A. Obertelli, P. Doornenbal, F. Nowacki, K. Ogata, A. Poves, K. Yoshida, N. L. Achouri, H. Baba, F. Browne, D. Calvet, F. Chateau, S. Chen, N. Chiga, A. Corsi, M. L. Cortes, A. Delbart, J. -M. Gheller, A. Giganon, A. G illibert, C. Hilaire, T. Isobe, T. Kobayashi, Y. Kubota, V. Lapoux, 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. Gasparic, R. -B. Gerst, J. Gibelin, K. I. Hahn, D. Kim, Y. Kondo, P. Koseoglou, J. Lee, C. Lehr, P. J. Li, B. D. Linh, T. Lokotko, M. MacCormick, K. Moschner, T. Nakamura, S. Y. Park, D. Rossi, E. Sahin, P. -A. Soderstrom, D. Sohler, S. Takeuchi, H. Toernqvist, V. Vaquero, V. Wagner, S. Wang, V. Werner, X. Xu, H. Yamada, D. Yan, Z. Yang, M. Yasuda, and L. Zanetti, "Extended $p_{3/2}$ neutron orbital and the $N = 32$ shell closure in ^{52}Ca," Phys. Rev. Lett. **129**, 262501 (2022).

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Presentations

[International Conferences/Workshops]

H. Sakurai (invited), "Neutron-rich nuclei, a treasure-chest of discovery and application," The 28th International Nuclear Physics Conference (INPC 2022), Cape Town, South Africa, September 11–16, 2022.

H. Sakurai (invited) "Recent progress and plans at RIBF," Pioneer symposium in Korean Physical Society, Hybrid, April 21, 2022.

H. Sakurai (invited) "Recent progress and plans at RIBF," CPS-APS-IOP-JPS-DPG Joint Session on Large-Scale Facilities for Science in Chinese Physical Society, Hybrid, November 18–22, 2022.

S. Nishimura (invited), "Dense matter from nuclear reactions in astro- and heavy-ion physics," Intersection of Nuclear Structure and High-Energy Nuclear Collisions, Washington University (INT), Seattle, USA, January 23–27, 2023.

S. Nishimura (invited), "Exotic nuclei: Toward the dripline," Nuclear Physics in Astrophysics -X, CERN, Geneva, Switzerland, September 4–9, 2022.

S. Nishimura (invited), "Experiments Relevant to *r*-Process Nucleosynthesis," The 15th Asian Pacific Physics Conference (APPC15), August 21–26, 2022.

S. Nishimura (invited), "Experiments related to *r*-process nucleosynthesis," Mean-field and Cluster Dynamics in Nuclear Systems 2022 (MCD2022), May 9–June 17, 2022.

P. Doornenbal (invited), "First Spectroscopy of ^{56,58}Ca," Reimei Workshop, Darmstadt, Germany, October 10–12, 2022.

D. Suzuki (invited), "Spectroscopy of ^{8}C: mirror symmetry beyond the proton drip line," Halo Week 2022, Bergen, Norway, July 20–15, 2022.

M. L. Cortés (invited), "In-beam gamma-ray spectroscopy towards ^{100}Sn: Recent results and future perspectives" Reimei workshop on "Unveiling nuclear shells and correlations in exotic nuclei through knockout reactions," TU Darmstadt, Germany, October 9–11, 2022.

Y. Nakai (poster), W. M. C. Sameera, K. Furuya, H. Hidaka, A. Ishibashi, and N. Watanabe, "Methanol production through irradiation of low-energy CH_3^+ ions on a water ice surface," Symposium on Next Generation Astrochemistry, Tokyo, Japan, November 29–December 2, 2022.

V. H. Phong (invited), "Experimental studies of the β-decay properties among other important nuclear data inputs for the *r*-process nucleosynthesis at the RIKEN RIBF," International Symposium on Origin of Matter and Evolution of Galaxies OMEG16 2022, Hanoi, Vietnam, October 24–28, 2022.

V. H. Phong (oral), "Beta-delayed one and two neutron emission probabilities south-east of ^{132}Sn : Impact on the odd-even abundance pattern of the second *r*-process peak," UKAKUREN-RCNP Conference on AstroNuclear Physics ANP2022, Osaka, Japan, July 20–21, 2022.

V. H. Phong (oral), "Beta-Delayed Neutron-Emission Probabilities of 20 neutron-rich Ag, Cd, In and Sn isotopes: Impacts on the second *r*-process peak formation," Astrophysics with Radioactive Isotopes 2022, Budapest, Hungary, June 12–17, 2022.

V. H. Phong (oral), "20 β-delayed neutron emission probabilities across the $Z = 50$ and $N = 82$ shell closure: Implication on the formation of the second *r*-process peak," International Nuclear Physics Conference (INPC) 2022, Cape Town, South Africa, September 11–16, 2022.

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F. Minato (poster), S. Tanaka, and N. Nishimura, "Fission fragment yields of neutron-rich nuclei evaluated by the Langevin model calculation," 2022 Symposium on Nuclear Data, Osaka, Japan, November 17–18, 2022.

[Domestic Conferences/Workshops]

西村俊二（招待講演), 「中性子捕獲反応と元素合成: 鍵を握る原子核データの収集と研究戦略」, 中性子捕獲反応で迫る宇宙の元素合成, 東京大学本郷キャンパス, 2023 年 2 月 9–10 日.

鈴木大介（一般講演), 「非束縛核 ^{8}C におけるミラー対称性の研究」, 2022 年日本物理学会秋季大会, 岡山県岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

鈴木大介（招待講演), 「RI ビームファクトリーにおける超新星爆発下の核反応研究」, 中性子捕獲反応で迫る宇宙の元素合成, 東京都文京区 (東京大学), 2023 年 2 月 9–10 日.

鈴木大介（招待講演), 「RI ビームを用いた高速陽子捕獲反応の研究」, 星の進化と爆発天体における核反応の物理, 埼玉県和光市 (理化学研究所), 2023 年 2 月 20–21 日.

中井陽一 (口頭発表), 「低エネルギーイオンと低温氷表面との反応」, 文科省科研費 学術変革領域（A）次世代アストロケミストリー 気相実験ワークショップ, 宮崎県宮崎市 (KITEN ビルコンベンションホール), 2022 年 9 月 7 日.

中井陽一 (口頭発表), 日高宏, 渡部直樹, 「低エネルギーイオンと氷表面との反応実験」, 日本物理学会 2022 年秋季大会, 東京都目黒区 (東京工業大学), 2022 年 9 月 12–15 日.

中井陽一 (口頭発表), 「低エネルギーイオンと極低温氷表面との分子生成反応」, 学術変革領域次世代アストロケミストリー 第 3 回 領域全体集会, 東京都文京区 (東京大学), 2022 年 3 月 7–9 日.

中井陽一 (口頭発表), 渡部直樹, 柘植雅士, 副島浩一, 「極低温氷表面に存在する OH ラジカルの可視域光による光脱離」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

P. Doornenbal (invited), "Past achievements and future perspectives for in-beam gamma-ray spectroscopy at the isospin frontier at the RIBF," Physics of RI: Recent progress and perspectives workshop, Wako, Japan, May 30–June 1, 2022.

M. L. Cortés (invited), "In-beam gamma-ray spectroscopy towards ^{100}Sn: Recent results and future perspectives" RIBF Users Meeting 2022, RIBF, RIKEN, Japan, September 20–22, 2022.

有友嘉浩 (口頭発表), 田中翔也, 西村信哉, 西村紘志, 「r プロセス計算へ向けた動力学模型による核分裂研究」, 日本物理学会 2022 年秋季大会, 岡山県岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

湊太志 (ポスター), 田中翔也, 西村信哉, 「r プロセス計算へ向けた中性子過剰核領域における核分裂収率の理論評価」, 2022 (令和 4) 年度 国立天文台 CfCA ユーザーズミーティング, 東京都三鷹市 (国立天文台), 2023 年 1 月 26–27 日.

有友嘉浩 (口頭発表), 田中翔也, 西村信哉, 湊太志, 西村紘志, 「r プロセス計算へ向けた核分裂の評価」, [RIBF-ULIC-miniWS038] 理論と実験で拓く中性子過剰核の核分裂, 東京都和光市 (理化学研究所), 2023 年 2 月 16–17 日.

有友嘉浩 (口頭発表), 田中翔也, 西村信哉, 西村紘志, 湊太志, 「動力学模型による中性子過剰核の核分裂収率計算」, 日本原子力学会 2023 年春の年会, 東京都目黒区 (東京大学), 2023 年 3 月 13–15 日.

湊太志 (口頭発表), 田中翔也, 西村信哉, 「ランジュバン計算と統計模型を用いた核分裂収率および即発中性子の評価」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

[Seminars]

D. Suzuki (invited), "Radioactive isotope physics," INTPART School 2023, Okinawa, Japan, February 20–March 3, 2023.

P. Doornenbal, "Latest Results and Future Potential for In-Beam γ-Ray Spectroscopy at the RIBF," SFB Seminar, Darmstadt, Germany, May 19, 2022.

田中翔也, 「動力学模型による核分裂の理論計算」, 第 57 回「基礎科学セミナー」, 千葉県習志野市 (千葉工業大学), 2023 年 2 月 25 日.

Press Releases

極低温氷表面での OH ラジカルの動きやすさを初めて測定—宇宙の氷微粒子上で分子進化が活性化する温度が明らかに—, 北海道大学, 理化学研究所, 2022 年 11 月 24 日, https://www.riken.jp/press/2022/20221124_1/index.html .

加速器実験による r 過程の同位体比の再現に成功—宇宙初期と太陽系のバリウムは中性子星合体が起源か？ — 2022 年 10 月 19 日, https://www.riken.jp/press/2022/20221019_1/index.html .

Awards

P. Doornenbal, Friedrich Wilhelm Bessel Research Award, 2022.

水野るり惠, 放射線化学討論会, 優秀発表賞 (学生), 2022 年 9 月.

Outreach Activities

櫻井博儀,「理研で進展する元素変換科学—宇宙での元素進化—」, 埼玉県立春日部高等学校, 2023 年 2 月.

櫻井博儀, 2022 年度「はかる! 」, 埼玉県立不動岡高等学校.