Nuclear Data Activities in Nishina Center

Hiroyoshi SAKURAI †

RIKEN Nishina Center for Accelerator-Based Science
2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
†Email: sakurai@ribf.riken.jp

Abstract

The nuclear data activities at the heavy-ion accelerator facility "Radioactive Isotope Beam Factory" operated by RIKEN Nishina Center for Accelerator-Based Science are introduced. The activities extending throughout a whole of nuclear chart are categorized into nuclear physics and nuclear engineering. For each of them, present status is reported and special emphasis would be given to recent highlights selected. Future directions of the nuclear data programs are presented.

1 Introduction

In 2006, RIKEN Nishina Center for Accelerator-Based Science (RNC) was established to organize the world-prestigious heavy ion accelerator facility "Radioactive Isotope Beam Factory (RIBF)" [1]. The RIBF facility was constructed as one of the third generation in-flight facility to aim at three goals: 1) to discover new quantum phenomena under a large isospin asymmetry through investigating nuclear structure in very neutron-rich nuclei, 2) to elucidate the r-process path in explosive processes of the universe, and 3) to develop new applied sciences based on high energy radioactive isotope (RI) beam. Since the RIBF started in operation 2007, multitudes of data on the nuclear structure and reactions have been produced with RIBF as a nuclear data factory.

The RIBF facility delivers a variety of heavy ion beams of hydrogen to uranium at an energy ranging widely from several MeV/u to 345 MeV/u and unique experimental devices and spectrometers are equipped [2]. As shown in Fig. 1, beams accelerated at three cyclotrons (AVF, RRC and SRC) and one liniac (SRILAC) serve experimental programs at gas-filled recoil separators (GARIS-II, III), in-gas-cell laser ion source (KISS), in-flight separators (CRIB, RIPS, BigRIPS). RI beams produced at BigRIPS are delivered to three spectrometers (ZeroDegree, SAMURAI and SHARAQ), and to a storage ring for mass measurement (Rare-RI Ring). The facility has a setup of SCRIT to realize electron-RI scattering, where RIs are produced at an ISOL based on electron induced-fission.

Nuclear data activities at the RIBF facility have extended throughout a whole of the nuclear chart from a light-mass to a super-heavy region and from stable to proton- and neutron-rich nuclei. The data are in general categorized into reaction data and structure data. The reaction data at RIBF stem from RI productions, secondary reactions with RI beams, and electron-RI scattering. Concerning the structure data, nuclear properties of ground and excited states are obtained at RIBF via spectroscopy of mass, decay, missing-mass, invariant-mass and in-beam gamma. The data produced at the RIBF have been compiled and evaluated by the world nuclear database activities guided by IAEA. JCPRG in Hokkaido University and RNC have established an MoU to cooperate together in nuclear data activities of charged-particle induced reactions.

In this article, the nuclear data activities at RIBF are reviewed. The activities are divided into nuclear physics and nuclear engineering, and for each of them, present status and recent highlights are presented. Future directions of the nuclear data activities at RIBF are discussed.

2 Nuclear Physics

In this section, very recent highlights and activities in nuclear physics with RIBF are demonstrated. First, the activities of superheavy element physics are introduced and second, recent achievements in studying

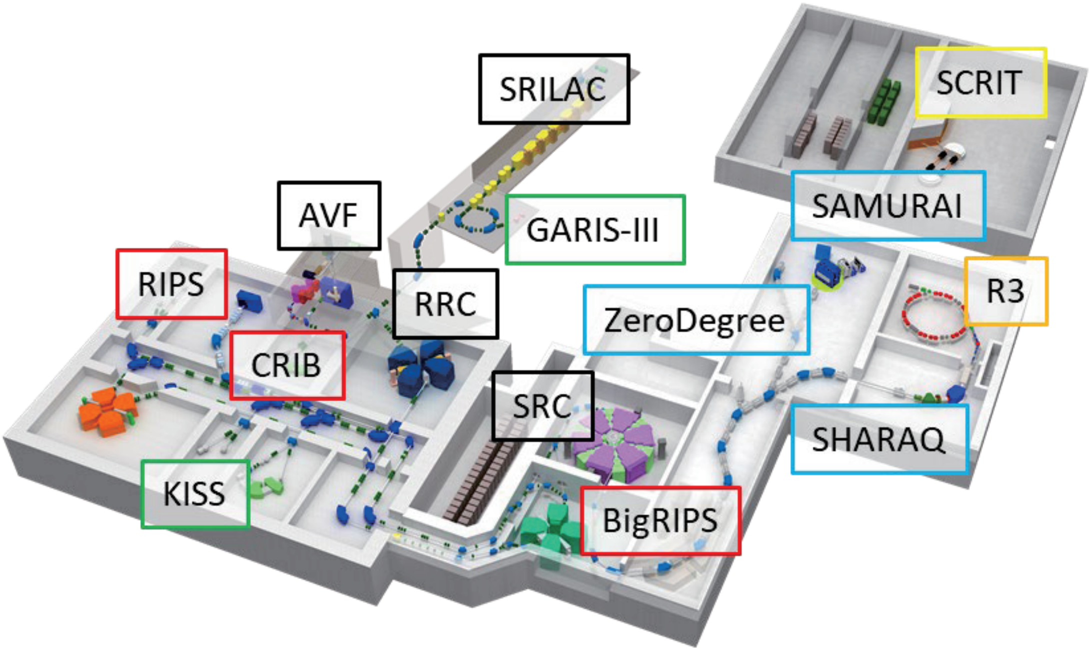

Figure 1: Facility layout of RIBF.

exotic nuclei are shown.

2.1 Superheavy Element

One of the great achievements at RIBF is discovery of Element 113, which was named "Nihonium" by K. Morita and his colleagues in 2016. The superheavy element was produced and identified in three events observed in 2004–2012. The last event in 2012 [3] showed successive alpha-decay down to ^{254}Md, and gave a direct evidence that ^{278}Nh was produced.

The ^{278}Nh isotope was made via the cold fusion reaction with combination of the RILAC linear accelerator and the gas-filled recoil separator GARIS. To conduct further production of superheavy elements, a new separator GARIS-II [4] was designed and constructed to achieve a higher transmission efficiency in the hot fusion reaction, compared with that of GARIS. A KEK-RIKEN collaboration has been formed to measure mass of heavy elements via MR-TOF technique at GARIS-II, and has published results, for example, around Z=100 [5]. The GAIRS-II spectrometer was moved to accept heavy-ion beams from RRC in 2017.

A new setup for production of new elements has been established. First, the intensity and energy upgrade of the RILAC was completed in 2020 with 28GHz ECR ion source [6] and super conducting rf-cavities [7], both newly installed. GARIS-III was newly constructed and installed to be coupled with the upgraded RILAC. GARIS-III was designed to have the same performances as of GARIS-II. A new program to search for Element 119 started at the end of 2020.

2.2 Exotic Nuclei

Exotic nuclei with a large isospin-asymmetry have been produced as intense RI beams at RIBF. High energy heavy-ion beams accelerated at SRC are converted to unstable nuclei at production targets via projectile-fragmentation or fission reactions and the nuclei of interest are collected and separated at BigRIPS, then the RI beams are delivered to several experimental devices.

Since 2007, more than 140 new isotopes have been discovered at BigRIPS. One of recent highlights is discovery of the particle stability of ^{60}Ca and other neighboring nuclei [8]. The neutron-drip line for the fluorine and neon isotopes was determined in 2019 [9], and the drip line has been extended for the first time in 20 years.

Shell evolution has been investigated via in-beam gamma spectroscopy, decay-spectroscopy and mass-spectroscopy. Very selected highlights are discovery of new magicity at N=34 in the neutron-rich Ca isotopes [10], double magicity of ^{78}Ni [11], and exotic structure in ^{40}Mg [12]. Shell evolution and shape deformation was found in ^{75}Cu by employing a new technique of spin-aligned RI beams [13]. Mass spectroscopy of neutron-rich Ca and Ti isotopes confirmed the magicity of N=34 [14], and discovered a deformation region in the neutron-rich Ti isotopes [15]. Neuton-rich nuclei with respect to the double magic nucleus ^{132}Sn have been investigated and all the data obtained so far indicate large shell gaps at Z=50, and at N=82, and no magicity loss has been found. In 2020, the first high-resolution gamma spectroscopy was carried out with germanium tracking detectors under the HiCARI collaboration.

RIBF has published bunch of half-life data for neutron-rich nuclei [16, 17, 18], which are necessary to understand the r-process nucleosynthesis. The abundance calculation with the new data could reproduce reasonably the r-process abundance pattern, especially for $A\sim$120 region and $A\sim$140-160 region. The third data set [18] has striking and large drops of half-lives at N=97 for Ce, Pr, Nd and Sm and N=105 for Eu, Gd, Tb and Dy, and has a direct impact in the r-process abundance calculations affecting almost all mass numbers between A=150 and 170.

The new form of nuclei have been found such as two deformed halo-nuclei, ^{31}Ne [19, 20] and ^{37}Mg [21, 22], and two-neutron halo in ^{29}F [23], all of which are located in the deformation region of $9\leq Z\leq 12$ and $20\leq N\leq 28$. Exotic particle-unbound nuclei have been investigated in a light neutron-rich region. Candidate of 'tetra' neutron state was observed with missing mass spectroscopy [24]. This work has made a great trigger to investigate very exotic few-body systems such as ^{7}H. Invariant mass spectroscopy successfully observed the ground state and 2^+ state in ^{26}O [25], and ^{26}O was found to be well-deformed and a barely unbound system beyond the drip line.

Equation-of-State (EOS) in nuclear matter, especially at a high density and high isospin asymmetry has been highly desired to understand the structure of neutron-stars, and to analyze gravitation wave. When the nuclear matter density is increased, many-body forces such as three nucleon force (3NF) become significant in EOS. At RIBF, polarized deuteron + proton elastic scattering has been studied to obtain $T = 1/2$ channel of 3NF [26]. The other works for EOS have been conducted such as a study of Gamow-Teller resonance in ^{132}Sn [27].

3 Nuclear Engineering

The incident of Fukushima Dai-ichi Unit in 2011 has given a trigger to nuclear physicists in Japan to consider possible contributions to nuclear engineering. In 2014, a reaction study with intense ^{137}Cs and ^{90}Sr beams at RIBF was conducted to seek for a transmutation path way to reduce radioactive waste [28, 29]. This experiment initiated a large project, which was awarded ImPACT grant [30] running in fiscal year of 2014-2018. The project focused accelerator-based transmutation for long-lived fission products (LLFPs) in high-level radioactive waste, and conducted research and development for partitioning, reaction data and theory, reaction database, and accelerator system. In the ImPACT project, RIKEN was in charge of studies for nuclear reactions, and also of accelerator developments.

As shown in Fig. 2, based on intense RI beams available at RIBF, a variety of reaction studies were organized with LLFPs such as ^{107}Pd and ^{90}Zr [31, 32, 33, 34, 35]. So called 'inverse kinematics' technique was employed to obtain spallation reaction data. The advantage of the inverse kinematics technique gives clear particle identification for reaction products, easy control of RI beam energies for study of energy-dependence. In addition, we do not have to prepare RI targets but stable-isotope targets such as protons and deuterons. All these advantages of inverse kinematics lead to nice quality of the data at RIBF.

The reaction study in the ImPACT program was managed under a large domestic collaboration with University of Tokyo, Tokyo Institute of Technology, Kyushu University, Miyazaki University and RIKEN. All the major spectrometers at RIBF, ZeroDegree, SAMURAI and SHARAQ were utilized to identify and analyze reaction products. Zerodegree is suitable for inclusive measurements with relatively heavy fragments. SAMURAI has a wide acceptance in both momentum and scattering angle, hence exclusive measurements were performed to detect reaction products as well as neutrons in projectile frame. At SHARAQ spectrometer, CNS, University of Tokyo and RIKEN worked together to develop an efficient deceleration scheme for RI beams. Study at low energy reactions at $\sim$20 MeV/u [36, 37], and a new devide "OEDO" was installed in the SHARAQ beam line. At the new setup, incomplete fusion reaction data and (d, p) reaction data were obtained with combination of OEDO and SHARAQ, and the data are being prepared for submission.

All these data are very useful to stimulate theoretical works and to improve simulation tools. The reaction data were evaluated by the JAEA nuclear data group and a new data library 'JENDLE/ImPACT-

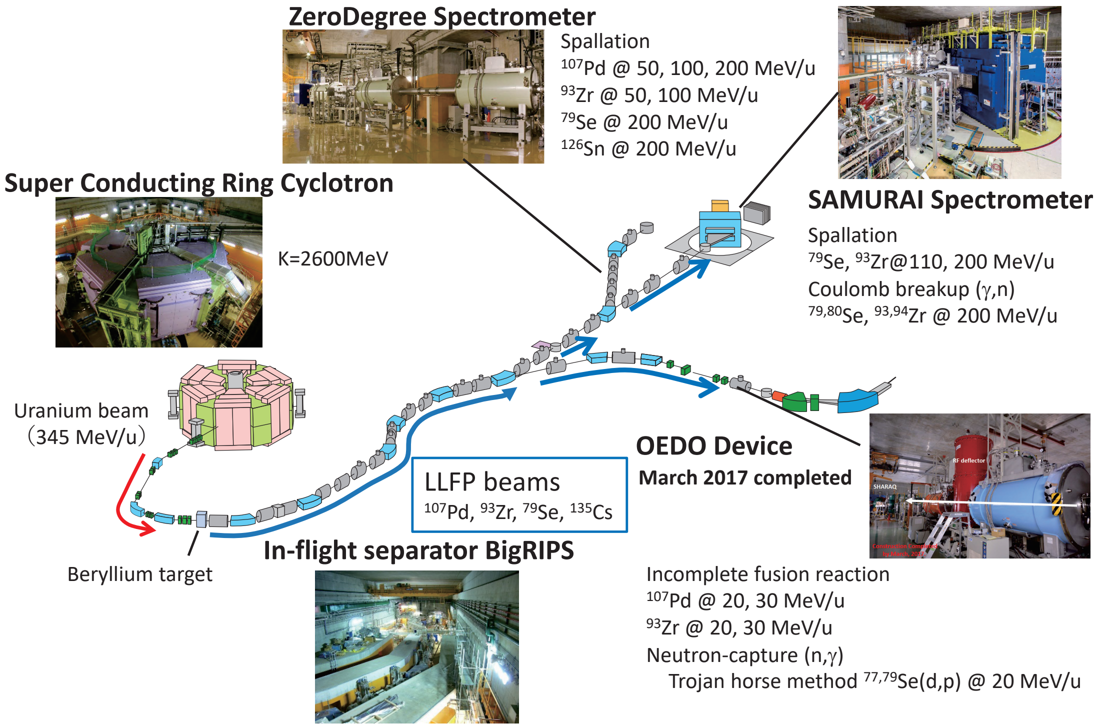

Figure 2: Reaction study for long-lived fission products at RIBF in 2014–2017.

2018' for proton- and neutron-induced reactions up to 200 MeV/u was released [38]. The data library has been a package of the PHITS simulator [39].

The improved simulation tool gave a strategy for LLFP transmutation, and a new transmutation scheme with high-energy neutron produced via deuteron breakup was considered, and a new accelerator scheme delivering 1-ampere deuteron beams has been proposed [40]. In addition, the RIKEN accelerator staff members successfully developed a quarter-wave superconducting RF cavity for efficient acceleration of charged particles [41]. The other transmutation scheme was discussed with 14 MeV neutron produced via muon catalyzed fusion with MERIT [42], that requires negative pion production cross sections with deuteron beams for further designing works.

4 Summary and Outlook

In summary, it would be emphasized that the RIBF facility is the nuclear data factory. Since 2007, RIBF has produced bunch of data of nuclear reaction and structure in both nuclear physics and nuclear engineering, especially for shell evolution, the r-process path, new form of nuclei, EOS and high-level radioactive waste problem.

Unique features of RIBF would be demonstrated to give multitudes of opportunities adapting any demands of nuclear data. RIBF delivers a variety of heavy-ion beams of hydrogen to uranium. Energy of the beams ranges several MeV/u to 345 MeV/u to be employed for any types of reactions. The beams are intense enough to conduct reaction studies and to artificially produce RIs from light and superheavy elements. These powerful beams have been utilized to produce secondary beams of RIs. Several experimental devices serve to separate, identify and analyze reaction products.

In future, the nuclear engineering community would be further encouraged, to promote the LLFP reaction data project, and if necessary, to study fission reaction and precise decay measurement for decay heat and neutron-emission probability necessary in designing nuclear reactors, by utilizing RI beams. The RIBF intensity upgrade is planned by installing new charge stripper rings [43]. More intense heavy-ion beams would create more opportunities for reaction study such as (d, p) reaction with low energy RI beams to study neutron-capture reaction, and for reaction study with minor actinides.

References

[1] Yano, Y., The RIKEN RI Beam Factory Project: A status report, *Nucl. Instrum. Methods Phys. Res., Sect. B* 261 (2007) 1009

[2] Introduction to RI Beam Factory and Users' Information, https://www.nishina.riken.jp/ribf/index.html.

[3] Morita, K., Morimoto, K., Kaji, D., *et al.*, New result in the production and decay of an isotope, ^{278}113, of the 113th element, JPSJ 81 (2012) 103201

[4] Kaji, D., Morimoto, K., Sato, N., *et al.*, Gas-filled recoil ion separator GARIS-II, *Nucl. Instrum. Methods Phys. Res., Sect. B* 317 (2013) 311

[5] Ito, Y., Schury, P., Wada, M., *et al.*, First Direct Mass Measurements of Nuclides around Z=100 with a Multireflection Time-of-Flight Mass Spectrograph PRL 120 (2018) 152501

[6] Nagatomo, T., Higurashi, J., Ohnishi, A., *et al.*, NEW 28-GHz SUPERCONDUCTING ELECTRON CYCLOTRON RESONANCE ION SOURCE FOR SYNTHESIZING SUPER-HEAVY ELEMENTS WITH Z >118 Prof. of 23th Int. Workshop on ECR Ion Sources (ECRIS2018), TUA3, 53 (2018)

[7] Yamada, K., Dantsuka, T., Imao, H., *et al.*, Construction of Superconducting Linac Booster for Heavy-Ion Linac at RIKEN Nishina Center, Prof. 19th Int. Conf. on RF Superconductivity (SRF2019), TUP037, 502 (2019).

[8] Tarasov, O.B., Ahn, D.S., Bazin, D., *et al.*, Discovery of ^{60}Ca and Implications For the Stability of ^{70}Ca, *Phys. Rev. Lett.* 121 (2018) 022501

[9] Ahn, D.S., Fukuda, N., Geissel, H., *et al.*, Location of the Neutron Dripline at Fluorine and Neon, *Phys. Rev. Lett.* 123 (2019) 212501

[10] Steppenbeck, D., Takeuchi, S., Aoi, N., *et al.*, Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca *Nature* 502 (2013) 207

[11] Taniuchi, R., Santamaria, C., Doornenbal, P., *et al.*, ^{78}Ni revealed as a doubly magic stronghold against nuclear deformation *Nature* 569 (2019) 53

[12] Crawford, H.L., Fallon, P., Macchiavelli, O., *et al.*, First Spectroscopy of the Near Drip-line Nucleus ^{40}Mg, *Phys. Rev. Lett.* 122 (2019) 052501

[13] Ichikawa Y., Nishibata, H., Tsunoda, Y., *et al.*, Interplay between nuclear shell evolution and shape deformation revealed by the magnetic moment of ^{75}Cu *Nature Physics* 15 (2019) 321

[14] Michimasa, S., Kobayashi, M., Kiyokawa, Y., *et al.*, Magic Nature of Neutrons in ^{54}Ca: First Mass Measurements of $^{55-57}$Ca, *Phys. Rev. Lett.* 121 (2018) 022506

[15] Michimasa, S., *et al.*, Mapping of a New Deformation Region around ^{62}Ti, *Phys. Rev. Lett.* 125 (2020) 122501

[16] Nishimura, S., Li, Z., Watanabe, H., *et al.*, β-Decay Half-Lives of Very Neutron-Rich Kr to Tc Isotopes on the Boundary of the r-Process Path: An Indication of Fast r-Matter Flow, *Phys. Rev. Lett.* 106 (2011) 052502

[17] Lorusso, G., Nishimura, S., Xu, Z.Y., *et al.*, β-Decay Half-Lives of 110 Neutron-Rich Nuclei across the N=82 Shell Gap: Implications for the Mechanism and Universality of the Astrophysical r Process, *Phys. Rev. Lett.* 114 (2015) 192501

[18] Wu, J., Nishimura, S., Lorusso, G., *et al.*, 94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation, *Phys. Rev. Lett.* 118 (2017) 072701

[19] Nakamura, T., Kobayashi, N., Kondo, Y., *et al.*, Halo Structure of the Island of Inversion Nucleus ^{31}Ne, *Phys. Rev. Lett.* 103 (2009) 262501

[20] Takechi, M., Otsubo, T., Fukuda, M., *et al.*, Interaction cross sections for Ne isotopes towards the island of inversion and halo structures of ^{29}Ne and ^{31}Ne, *Phys. Lett.* B 707 (2012) 357

[21] Kobayashi, N., Nakamura, T., Kondo, Y., *et al.*, Observation of a p-Wave One-Neutron Halo Configuration in ^{37}Mg, *Phys. Rev. Lett.* 112 (2014) 242501

[22] Takechi, M., Suzuki, S., Nishimura, D., *et al.*, Evidence of halo structure in ^{37}Mg observed via reaction cross sections and intruder orbitals beyond the island of inversion, *Phys. Rev.* C 90 (2014) 061305(R)

[23] Bagchi,S., Kanungo, R., Tanaka, Y.K., *et al.*, Two-Neutron Halo is Unveiled in ^{29}F, *Phys. Rev. Lett.* 124 (2020) 222504

[24] Kisamori, K., Shimoura, S., Miya, H., *et al.*, Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction, *Phys. Rev. Lett.* 116 (2016) 052501

[25] Kondo, Y., Nakamura, T., Tanaka, R., *et al.*, Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line, *Phys. Rev. Lett.* 116 (2016) 102503

[26] Sekiguchi, K., Witala, H., Akieda, T., *et al.*, Complete set of deuteron analyzing powers from $\vec{d}p$ elastic scattering at 190 MeV/nucleon *Phys. Rev.* C 96 (2017) 064001

[27] Yasuda, J., Sasano, M., Zegers, R. G. T., *et al.*, Extraction of the Landau-Migdal Parameter from the Gamow-Teller Giant Resonance in ^{132}Sn, *Phys. Rev. Lett.* 121 (2018) 132501

[28] Wang, H., Otsu, H., Sakurai, H., *et al.*, Spallation reaction study for fission products in nuclear waste: Cross section measurements for ^{137}Cs and ^{90}Sr on proton and deuteron *Phys. Lett.* B 754 (2016) 104

[29] Sun, X. H., Wang, H., Otsu, H., *et al.*, Spallation and fragmentation cross sections for 168 MeV/nucleon ^{136}Xe ions on proton, deuteron, and carbon targets *Phys. Rev.* C 101 (2020) 064623

[30] ImPACT: "Reduction and Resource Recycling of High-level Radioactive Waste through Nuclear Transmutation", https://www.jst.go.jp/impact/hp_fjt/en/

[31] Wang, H., Otsu, H., Sakurai, H., *et al.*, Spallation reaction study for the long-lived fission product ^{107}Pd, *Prog. Theor. Exp. Phys.* 2017 (2017) 021D01

[32] Kawase, S., Nakano, K., Watanabe, Y., *et al.*, Study of proton- and deuteron-induced spallation reactions on the long-lived fission product ^{93}Zr at 105 MeV/nucleon in inverse kinematics, *Prog. Theor. Exp. Phys.* 2017 (2017) 093D03

[33] Nakano, K., Watanabe, Y., Kawase, S., *et al.*, Isotope production in proton-, deuteron-, and carbon-induced reactions on ^{93}Nb at 113 MeV/nucleon *Phys. Rev.* C 100 (2019) 044605

[34] Takeuchi, S., Nakamura T., Shikata, M., *et al.*, Coulomb breakup reactions of ^{93,94}Zr in inverse kinematics *Prog. Theor. Exp. Phys.* 2019 (2019) 013D02

[35] Wang, H., Otsu, H., Chiga, N., *et al.*, Enhancement of element production by incomplete fusion reaction with weakly bound deuteron *Comm. Phys.* 2 (2019) 78

[36] Michimasa, S., Imai, N., Dozono, M., *et al.*, New energy-degrading beamline for in-flight RI beams, OEDO, *Nucl. Instrum. Methods Phys. Res., Sect. B* 463 (2020) 143

[37] Sumikama, T., Ahn, D.S., Fukuda, N., *et al.*, Energy-control and novel particle-identification methods combined with range in a multi-sampling ionization chamber for experiments using slowed-down RI beams *Nucl. Instrum. Methods Phys. Res., Sect. A* 986 (2021) 164687

[38] Kunieda, S., Furutachi, N., Minato, F., *et al.*, JENDL/ImPACT-2018: a new nuclear data library for innovative studies on transmutation of long-lived fission products, J. of Nucl. Sci. and Tech. 52, 1073 (2019)

[39] Sato, T., Niita, K., Matsuda, N., *et al.*, Particle and Heavy Ion Transport code System, PHITS, version 2.52, J. of Nucl. Sci. Technol. 50, 913 (2013).

[40] Okuno, H., Sakurai, H., Mori, Y., *et al.*, Proposal of a 1-ampere-class deuteron single-cell linac for nuclear transmutation, Proc. Jpn. Acad. Ser. B 95 430-439 (2019)

[41] Yamada, K., Ozeki, K., Kamigaito, O., *et al.*, First vertical test of superconducting QWR prototype at RIKEN, Prof. of LINAC2016, TUPLR061, 598 (2016).

[42] Mori, Y., Taniuchi, A., Kuriyama, Y., *et al.*., Intense Negative Muon Facility with MERIT ring for Nuclear Transmutation, JPS Conf. Proc.21,011063 (2018).

[43] Imao, H., Charge Stripper Ring for RIKEN RI Beam Factory, J. of Instrum. 15, P12036 (2020)

Acknowledgments

I would like to thank the organizers of SND2020 for the safe organization and attractive program. Because of COVID-19 pandemic, they smartly introduced a "hybrid" meeting, where in-person and on-line participations were effectively arranged and managed.