Quantum Jump in Nuclear Physics with RIBF – recent results and future plans –

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Programs for studying the nuclear structure and reactions with exotic nuclei available at the RIKEN Radioactive Isotope Beam Factory (RIBF) are introduced and discussed. Special emphasis is given to the world-best performances of RIBF which have caused quantum jumps in the history of nuclear physics, and also given to recent research-highlights. Future plans at RIBF are presented to promote collaborations.

1. Introduction

The Radioactive Isotope Beam Factory is a top world-class RIB facility, which was constructed to establish a new framework of nuclear physics, to elucidate the origin of elements, and to explore new applications with fast RIBs. To achieve these goals, the RIBF facility consists of a high-power accelerator complex, a large-acceptance in-flight separator and unique devices to cover various experimental programs.

As illustrated in Fig. 1, the accelerator complex consists of the old facility and a newly constructed one [2]. The old facility has a K540-MeV ring cyclotron (RRC) and two injectors, a variable-frequency heavy-ion linac (RILAC) and a K70-MeV AVF cyclotron. A new high-power heavy-ion booster system consisting of three ring cyclotrons with K=570 MeV (fixed frequency, fRC), 980 MeV (intermediate stage, IRC), and 2600 MeV (superconducting, SRC), respectively, boost energies of the RRC beams up to 440A MeV for light ions and 350A MeV for very heavy ions. The goal of the primary beam intensity is set to be 1 pμA. At the end of 2006, the first primary beam was successfully accelerated at and extracted from SRC. The new in-flight separator BigRIPS [3] is to convert the SRC primary beams into RIBs. Combination of the high-power accelerator complex and the in-flight separator makes it possible to explore the limit of of nuclei and provides high yield rates of exotic nuclei.

The RIBF facility has started delivering RI beams since 2007. In 2007, the first commissioning with a 350A MeV ^{238}U beam successfully produced and identified two new isotopes, ^{125,126}Pd, even with a low intensity of 0.03 pnA [4]. In November 2008, the second attempt to search for new isotopes was performed by utilizing the U beam with a 10 times higher intensity of 0.3 pnA and more than 40 of new isotopes were produced and identified [5]. These results have demonstrated high performances of RIBF in RIB production and identification.

To maximize the potentials of intense RI beams available at RIBF, several new devices in the new facility are proposed [6, 7]. A few devices have already started to provide physics outputs. A multi-function beam line spectrometer (ZeroDegree) and a high resolution spectrometer (SHARAQ) were launched in 2008 and 2009, respectively. Other experimental devices, as shown in Fig. 1, are under construction or to be funded. All of these devices give unique opportunities at RIBF in terms of energy ranging from several 10 keV to a few 100A MeV as well as of a wide coverage of scientific programs.

In this report, the experimental devices and their associated physics programs are intro-

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duced and discussed.

2. On-going nuclear physics programs at BigRIPS, ZeroDegree and SHARAQ

At present, experimental devices available at the new facility are BigRIPS, ZeroDegree and SHARAQ spectrometers. In this section, nuclear physics programs and their recent highlights for each device are introduced and discussed.

A. BigRIPS and ZeroDegree

Combination of BigRIPS and the ZeroDegree spectrometer provides opportunities for several types of experiments [8].

The ZeroDegree is appropriate for inclusive- and semi-exclusive experiments, where ejectiles scattered at forward angles via reactions are identified by ΔE-TOF-Bρ-E measurements. The BigRIPS/ZeroDegree facility has been open for the world-wide users since 2007. Technical information is available in a web-site for RIBF users [9].

Experimental programs at BigRIPS/ZDS, which have been proposed so far, are divided into two categories. The first one is to utilize fast RI beams for rare-isotope physics, and the second is a specific program with (polarized) deuteron beams. In this section, the rare-isotope programs and the program with the light-ion beams at BigRIPS/ZeroDegree are introduced.

1. Rare-Isotope Physics Programs

The rare-isotope physics programs at BigRIPS/ZeroDegree are (1) production and identification of new isotopes toward the driplines, (2) measurements for ground-state properties and low lying excited states via transmission method and beta-spectroscopy, and (3) reaction studies for single-particle-level, collectivity and matter distribution via inbeam gamma and missing mass methods. These programs are dedicated for global survey to search for anomalous regions newly accessed at RIBF. Experimental sites at BigRIPS and the ZeroDegree are shown in Ref. [8].

In December 2008, the first spectroscopic experiments for exotic nuclei in the island-of-inversion region were performed in a "Day-One" campaign by utilizing intense RIBs produced with a 345A MeV ^{48}Ca beam. The maximum ^{48}Ca beam intensity was as high as 170 pnA. Typical beam intensities for the exotic nuclei were, for example, 10 and 5 counts/sec for ^{31}Ne and ^{32}Ne, respectively, for an intensity of 100 pnA. Compared with the yield rate of ^{31}Ne in the first identification experiment at RIPS [10], that at BigRIPS is 10^5 times higher. This great gain for RIB intensities has demonstrated that the new facility of RIBF is indeed the next generation facility.

In the DayOne campaign, three experimental programs were performed, in-beam gamma spectroscopy by H. Scheit et al. [11, 12] to determine the energy of low-lying excited states in ^{32}Ne and other nuclei, inclusive Coulomb-breakup measurement by T. Nakamura et al. [13] to search for possible halo-nuclei in the island-of-inversion region and in a light mass region, and total interaction cross section measurement by Takechi and Otsubo et al. [14] to investigate exotic forms of nuclear matter in the neutron-rich Ne isotopes.

One of the highlights in these experiments suggests that the degree of deformation for the neutron-rich Ne isotopes increases as a function of neutron number [11]. Possible roles of weakly bound neutrons and pairing in collectivity would be very interesting subjects for future works at RIBF. In addition, discovery of the halo nucleus ^{31}Ne in the deformed region [13, 14] gives a trigger to consider a possible mechanism of deformed halo states, which has been already discussed in theoretical works [15].

Further studies for the exotic structure would be made possible via the intense ^{48}Ca beam. In 2010, the above programs accessed neutron-rich Mg and Si isotopes up to N=28. The preliminary results were presented in the ARIS 2011 conference [16].

The first decay spectroscopy on fission fragments produced via the in-flight fission of ^{238}U beam was performed in December, 2009. The maximum primary beam intensity was as high

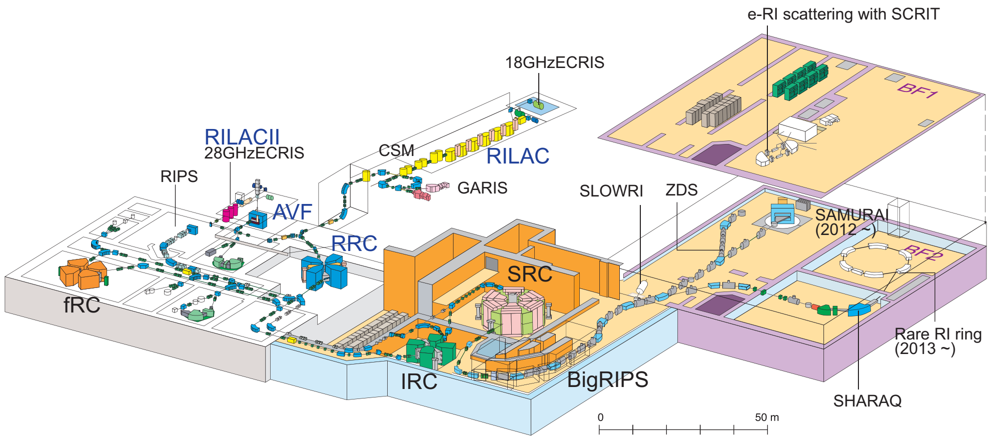

FIG. 1: A schematic view of the existing facility (left-hand side) and the RIBF under construction (right-hand side).

as 0.8 pnA, and the intensity on average was 0.2-0.3 pnA. In this experiment proposed by Sumikama and Nishimura et al. [17, 18], half-life measurement, beta-gamma spectroscopy, and isomer spectroscopy were accomplished at the same time with a setup equipped by four germanium clover detectors and two $LaBr_3$ detectors for gamma-rays, as well as nine stacks for double sided silicon strip detectors to detect beta-rays and heavy-ions. The data is now under analysis. One of recent results published is a half-life measurement associated with the r-process path, and 18 new data for neutron-rich nuclei with $A\sim110$ have been reported [17]. The other results obtained are (1) possible oblate-prolate shape isomer in ^{109}Nb [18], (2) discovery of deformed magic number N=64 in the Zr isotopes [19], and (3) development of axial asymmetry in ^{110}Mo [20]. All of four letter-papers were based on data accumulated for 2.5 days. This high productivity of RIBF has been demonstrated via the decay spectroscopy programs.

2. Light-Ion Programs

Specific programs with deuteron beams are polarized-deuteron and proton elastic scattering for three-body interactions [21] and production of deeply-bound pionic atoms via (d,^{3}He) reaction [22].

The 3NF study via deuteron and proton elastic scattering with a 250A MeV polarized deuteron beam was performed in April, 2009 [23]. In this experiment, the AVF-RRC-SRC acceleration scheme was applied to accelerate the polarized deuteron beams. A single turn extraction of the beam was successfully achieved, and the polarization amplitudes were as high as 80%. A polarimeter has been newly constructed to obtain a complete set of deuteron analyzing power in the scattering. The polarimeter was installed at the beam transport line between the exit of SRC and the production target at BigRIPS. Other data-sets at different and higher energies will be obtained in future.

In the (d,^{3}He) program, the entire BigRIPS will be utilized as a high resolution spectrometer employing the missing mass technique. The missing mass spectrometer mode was examined in May, 2009 [24]. Further analysis would give future upgrade plans to improve optical conditions including the SRC and BT line.

B. SHARAQ

The high-resolution RI-beam spectrometer (SHARAQ) with a momentum resolution of 15

000 has been constructed [6, 25]. With the advent of this spectrometer, a new type of missing mass spectroscopy, whereby an RI beam is used as a probe to investigate stable nuclei via standard kinematics, is applied to investigate phenomena such as the double Gamow-Teller states, which have been hardly accessible with reactions induced by stable beams. The SHARAQ project has been under leadership of CNS, Univ. of Tokyo.

A commissioning experiment was performed in March and May, 2009, and the dispersion matching mode was examined and confirmed. The first physics experiment for (t,^{3}He) reaction was performed in October, 2009 to observe isovector spin-monopole resonances [26]

3. New devices/equipments to be constructed

In this section the other devices which are under construction or to be funded are introduced.

A. SAMURAI

The large-acceptance multi-particle spectrometer (SAMURAI) [6, 27] has been funded to exclusively measure products arising from reactions as well as particle-decay, mainly through observing particle-unbound states via the invariant mass method. The main part of the spectrometer system is a large-gap (80 cm) superconducting magnet with a bending power of 7 Tm. This magnet is used for momentum analysis of heavy projectile fragments and projectile-rapidity protons with large angular and momentum acceptances. The large gap also enables measurements of projectile-rapidity neutrons with a large angular acceptance in coincidence with heavy projectile fragments. The open geometry of SAMURAI also provides other unique opportunities to study for three-body interactions in break-up channels and dynamical properties of isospin-asymmetry nuclear matter.

Construction of SAMURAI will be finished in 2011. Due to a budget limitation, the budget covers a minimum setup for (p,2p)-type missing mass spectroscopy and invariant mass spectroscopy. Additional detectors based on external investments are encouraged to strengthen the setup and to cover other scientific programs.

B. SCRIT

The new system for electron scattering experiments on unstable nuclei using the SCRIT (Self-Confining Radioactive Ion Target) [6, 28] has been funded. The SCRIT is the trapped-ion cloud formed at a localized position in the electron storage ring. Ions are three-dimensionally confined in the transverse potential well produced by the projectile electron beam itself in combination with an applied longitudinal mirror potential. RI ions are injected into the potential well from outside. This design feature, therefore, requires a slow RI ion source, like that of an ISOL. A test experiment with stable Cs ions at KSR-ring in Kyoto University has successfully demonstrated the feasibility of the SCRIT scheme [29]. The luminosity achieved at KSR was 10^{26}/cm^{2}/sec with a number of trapped ions of 4×10^{7}.

The SCRIT system under construction consists of an e-storage ring and an 150 MeV microtron injector. The injector is also used as a driver for U-based photo-fission ISOL [30]. Based on this system, the first data for exotic nuclei such as ^{132}Sn will be taken in 2012. Medium-range upgrade plans have been already discussed to improve the electron driver beam intensity and stored current, and to install additional electron-spectrometer with a high resolution.

C. SLOWRI

The slow RI-beam facility (SLOWRI) [31] aims to provide universal slow or trapped RI with a high purity, which is achieved by combining BigRIPS and a gas-catcher system. This will allow unique opportunities to perform precision atomic spectroscopy, mass spectroscopy and beta-delayed charge-particle emissions for a wide variety of RIs, heretofore unavailable in existing facilities worldwide.

Recently, on-line laser spectroscopy has been performed for the Be ions at a prototype of the rf ion-guide system developed at

RIPS [32]. A multi-reflection TOF system for mass measurement [33] is being developed.

D. Rare-RI Ring

The new precision mass measurement system (Rare RI-ring) consisting of individual injection/extraction kickers and a precisely tuned isochronous ring is proposed for energetic rare RI beams [6, 34]. In this scheme, we measure the time-of-flight of a particle in the ring along with its injection velocity just prior to entrance in the ring. The goal accuracy of mass measurements is 10^{-6} for a momentum acceptance of 10^{-2}. Detailed design for this system is in progress.

E. IRC-to-RIPS BT Line

The IRC-to-RIPS BT line [6, 35] is proposed to couple RIPS [36] with IRC, and to have multi-use capability which is realized by IRC-beam sharing between RIPS and BigRIPS users. At RIPS, specific programs at an intermediate energy are (1) electro-magnetic moment measurements based on polarized RIBs as well as applications for material science, (2) nuclear structure for very light nuclei such as ^{8}He and ^{11}Li, and (3) reaction studies with the intermediate energy or low energy RIBs. The IRC-to-RIPS BT line further enhances such activities [35]. The intermediate energy at IRC is appropriate for production of polarized RI beams as well as beam implantation into a sample material at a finite depth. Thus, beta-decay and beta-gamma spectroscopy, material science are promoted via spin-related research techniques such as beta-NMR, gamma-PAD/PAC [6].

RIB intensities of light isotopes at the present RIPS coupled with RRC are in the top world-class. For example, a recent experiment performed at RIPS was dedicated for exotic structure of ^{8}He via the missing mass spectroscopy [37]. Recently an rf separator has been installed [38], which is useful to purify proton-rich RIBs.

4. Summary and Outlook

The RIBF programs ignited by Prof. Akito Arima have been introduced. Special emphasis has been given to recent highlights in the programs for studying nuclear structure and reactions at several experimental devices. One of research highlights at RIBF is to obtain brand-new results in the island of inversion region and $A\sim110$ region by utilizing the intense ^{48}Ca beam and ^{238}U beam, respectively. The great gain of RIB intensities in that region has demonstrated that the new facility of RIBF is indeed the next generation facility. Other promising primary beams, such as Ge, Kr, Xe and U, are to be used for programs approved at the BigRIPS/ZeroDegree. At the end of 2009, the first decay experiment with the U beam was performed. In this year, a new linac RILAC-II coupled with a 28 GHz SC-ECRIS has been completed to deliver more intense heavy-ion beams. In addition to the primary beam upgrades, two of new experimental devices, the SAMURAI spectrometer [27] and the SCRIT system [28, 29], will be completed in FY2011, and are giving more and more physics opportunities at RIBF.

References

[1] <http://www.rarf.riken.go.jp/Eng/>

[2] Y. Yano, Nucl. Instrum. Methods B **261**, 1009 (2007).

[3] T. Kubo, Nucl. Instrum. Meth. B **204**, 97 (2003).

[4] T. Onishi et al., J. Phys. Soc. Japan **77**, 083201 (2008).

[5] T. Onishi et al., J. Phys. Soc. Japan **79**, 073201 (2010).

[6] Technical information on the devices are found in <http://rarfaxp.riken.go.jp/RIBF-TAC05>

[7] H. Sakurai, Eur. Phys. J. ST **150**, 249 (2007).

[8] H. Sakurai, Nucl. Instrum. Methods B **266**, 4080 (2008).

[9] <http://www.nishina.riken.jp/ Users-Guide/ BigRIPS>

[10] H. Sakurai et al., Phys. Rev. C **54**, R2802-R2805 (1996).

[11] P. Doornenbal, H. Scheit, N. Aoi et al., Phys. Rev. Lett. **103**, 032501 (2009).

[12] P. Doornenbal, H. Scheit, N. Aoi et al., Phys. Rev.C **81**, 041305R (2010).

[13] T. Nakamura et al., Phys. Rev. Lett. **103**, 262501 (2009).
[14] M. Takechi et al., Nucl. Phys. A **834**, 412c (2010); M. Takechi et al., Phys. Lett. B, in press.
[15] M. Misu et al., Nucl. Phys. A **614**, 44 (1997); I. Hamamoto, Phys. Rev. C **69**, 041306R (2004).
[16] <http://iks32.fys.kuleuven.be/aris2011>
[17] S. Nishimura et al., Phys. Rev. Lett. **106**, 052502 (2011).
[18] H. Watanabe et al., Phys. Lett. B **696**, 186–190 (2011).
[19] T. Sumikama et al., Phys. Rev. Lett. **106**, 202501 (2011).
[20] H. Watanabe et al., Phys. Lett. B **704**, 270–275 (2011).
[21] K. Sekiguchi et al., Phys. Rev. Lett. **95**, 162301 (2005).
[22] K. Suzuki et al., Phys. Rev. Lett. **92**, 072302 (2004).
[23] K. Sekiguchi et al., Phys. Rev. C **83**, 061001 (2011).
[24] K. Itagaki, private communication.
[25] T. Uesaka et al., Nucl. Instrum. Methods B **266**, 4218 (2008).
[26] K. Miki, H. Sakai et al., in preparation.
[27] K. Yoneda, Contribution to the 8th International Conference on Radioactive Nuclear Beams, Grand Rapids, USA, May, 2009.
[28] M. Wakasugi et al., Nucl. Instrum. Methods A **532**, 216 (2004).
[29] M. Wakasugi et al., Phys. Rev. Lett. **100**, 164801 (2008); T. Suda et al., Phys. Rev. Lett. **102**, 102501 (2009).
[30] M. Wakasugi, private communications.
[31] M. Wada et al., Nucl. Instrum. Methods A **532**, 40 (2004).
[32] K. Okada et al., Phys. Rev. Lett. **101**, 212502 (2008).
[33] Y. Ishida et al., Nucl. Instrum. Methods B **241**, 983 (2005).
[34] Y. Yamaguchi et al., Nucl. Instrum. Methods B **266**, 4575 (2008).
[35] H. Ueno, Eur. Phys. J. ST **162**, 221 (2008).
[36] T. Kubo et al., Nucl. Instrum. Meth. B **70**, 309 (1992).
[37] J.L. Lou et al., Phys. Rev. C **83**, 034612 (2011); Z.X. Cao et al., Phys. Lett. B in press.
[38] K. Yamada et al., Nucl. Phys. A **746**, 156c (2004).