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RIKEN radioactive isotope beam factory project – Present status and perspectives

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Abstract. Programs for studying nuclear reactions and structure of exotic nuclei available at the RIKEN radioactive isotope beam factory project are introduced and discussed by demonstrating recent highlights. Special emphasis is given to the present status and future plans of new devices.

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1. Introduction

The RIKEN radioactive isotope beam factory (RIBF) is a world-class RIB facility, that has become operational since 2007, and aiming for three goals: (a) to establish new framework of nuclear physics, (b) to elucidate the origin of elements and (c) to explore new applications with fast RIBs. 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 figure 1, the accelerator complex consists of the old facility and a newly constructed one [1]. 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 2500 MeV (superconducting, SRC), respectively, boost energies of the RRC beams up to 440 A MeV for light ions and 350 A 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 and extracted from SRC.

The new in-flight separator BigRIPS [2] 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 nuclei and provides high yield rates of exotic nuclei. In 2007, the first commissioning with a 350 A MeV ^{238}U beam successfully discovered two new isotopes, ^{125,126}Pd, even with a low intensity

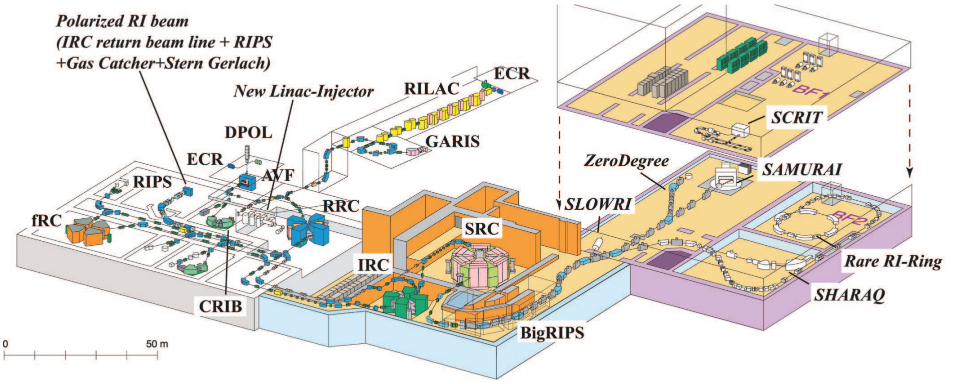

Figure 1. A schematic view of the existing facility (left-hand side) and the RIBF under construction (right-hand side). The italic-labelled installations are the major ones planned in the phase-II program of the RIBF project.

of 0.03 pnA [3]. This result has demonstrated high performances of RIBF in RIB production and identification.

To maximize the potentials of intense RI beams available at RIBF, several new devices are proposed [4,5]. The new devices are categorized into two phases, phase-I and phase-II. The phase-I programs at BigRIPS and a multifunction beam transport line (ZeroDegree) have already been started in 2008. Other experimental devices, as shown in figure 1, are in the phase-II. All of these devices together give unique opportunities at RIBF in terms of energy ranging from several 10 keV to a few 100 A MeV.

In this report, the devices and the associated physics programs are introduced and discussed.

2. BigRIPS and ZeroDegree

Combination of BigRIPS and the ZeroDegree provides opportunities for several types of experiments [6].

The ZeroDegree is appropriate for inclusive- and semiexclusive experiments, where ejectiles scattered at forward angles via reactions are identified by ΔE-TOF-Bρ-E measurements. The users world-wide are using the BigRIPS/ZeroDegree Facility from 2007. Technical information is available in a website for RIBF users [7].

Experimental programs in the phase-I, 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.

2.1 *Rare-isotope physics programs and recent highlights*

The rare-isotope physics programs consist of (1) production and identification of new isotopes toward the drip of lines, (2) measurements of ground-state properties and low-lying excited states by transmission method and β-spectroscopy and (3) reaction studies for single-particle level, collectivity and matter distribution by in-beam γ and missing mass methods. These programs are dedicated for a global survey to search for anomalous regions newly accessed at RIBF. Experimental sites at BigRIPS and the ZeroDegree are shown in ref. [6].

In November 2008, the second attempt to search for new isotopes in the $Z{\sim}28$–53 region was performed by utilizing the U beam with an intensity of 0.3 pnA and a few tens of new isotopes were produced and identified [8]. At the same time, the ZeroDegree commissioning was performed and the detectors and optical conditions were examined.

In December 2008, the first spectroscopic experiments for exotic nuclei in the island-of-inversion region were performed in a 'DayOne' campaign by utilizing intense RIBs produced with a 345 A MeV ^{48}Ca beam. The maximum ^{48}Ca beam intensity was as high as 170 pnA. Typical intensities of the exotic nuclei were, for example, 10 and 5 counts/s for ^{31}Ne and ^{32}Ne, respectively, for a primary beam intensity of 100 pnA. Compared with the yield rate of ^{31}Ne in the first identification experiment at RIPS [9], 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: (a) in-beam γ-spectroscopy by Scheit *et al* [10] to determine the energy of the first excited state in ^{32}Ne, (b) inclusive Coulomb-breakup measurement by Nakamura *et al* [11] to search for possible halo-nuclei in the island-of-inversion region and (c) in a light mass region and total interaction cross-section measurement by Takechi and Otsubo *et al* [12] to investigate exotic forms of nuclear matter in the neutron-rich Ne isotopes.

One of the highlights in these experiments is that the degree of deformation for the neutron-rich Ne isotopes is increased as a function of neutron numbers [10]. Possible roles of weakly bound neutrons in collectivity enhancement would be very interesting for future works at RIBF. Further studies of the exotic structure would be made possible via the intense ^{48}Ca beam.

2.2 *Light-ion programs and recent highlights*

Specific programs with deuteron beams are polarized deuteron and proton elastic scattering for three-body interactions [13] and production of deeply-bound pionic atoms by (d,^{3}He) reaction [14].

The 3NF study by deuteron and proton elastic scattering with a 250 A MeV polarized deuteron beam was performed in April 2009 [15]. 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 dueteron analysing 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 datasets 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 [16]. Further analysis would give future upgrade plans to improve the optical conditions including the SRC and BT line.

3. Phase-II devices

In this section new devices for phase-II [4] at RIBF are introduced. Those currently planned include common devices enabling multiple-use as well as others that are highly program-specific. All are designed to maximize the research potential of the world's most intense RI beams, made possible by the exclusive equipment available at RIBF. All the devices proposed are introduced here.

3.1 *SHARAQ*

The high-resolution RI-beam spectrometer (SHARAQ) with a momentum resolution of 15,000 has been constructed [4,17]. 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 the 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 scheduled for October 2009.

3.2 *SAMURAI*

The large-acceptance multiparticle spectrometer (SAMURAI) [4,18] has been funded to exclusively measure products arising from reactions as well as particle decay, mainly by 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 the 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 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 the budget limitation, the SAMURAI consists of a minimum set-up for (p,2p)-type missing mass spectroscopy and invariant mass spectroscopy. To set up additional detectors and to cover other scientific programmes, external investments are encouraged.

3.3 *SCRIT*

The new system for electron scattering experiments on unstable nuclei using the self-confining radioactive ion target (SCRIT) [4,19] 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, 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 [20]. The luminosity achieved at KSR was $10^{26}/\text{cm}^2/\text{s}$ with a number of trapped ions of 4×10^7.

The SCRIT system under construction consists of an e-storage ring and a 150 MeV microtron injector. The injector is also used as a driver for U-based photofission, ISOL [21]. Based on this system, the first data for exotic nuclei such as ^{132}Sn will be given in 2011. Medium-range upgrade plans have already been discussed to improve the electron driver beam intensity and stored current, and to install an additional electron spectrometer with a high resolution.

3.4 *SLOWRI*

The slow RI-beam facility (SLOWRI) [22] aims to provide universal slow or trapped RI with 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 β-delayed charge-particle emissions for a wide variety of RIs, heretofore unavailable in the 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 [23]. A multireflection TOF system for mass measurement [24] is being developed.

3.5 *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 [4,25]. In this scheme, we measure the time-of-flight of a particle in the ring along with its injection velocity just prior to its 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.

3.6 *IRC-to-RIPS BT line*

The IRC-to-RIPS BT line [4,26] is proposed to couple RIPS [27] with IRC, and to have multiuse capability which is realized by IRC-beam sharing between RIPS and BigRIPS users. At RIPS, specific programs at an intermediate energy are (1) electromagnetic 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 [26]. The intermediate energy at IRC is appropriate for the production of polarized RI beams as well as beam implantation into a sample material at a finite depth. Thus, β-decay and β-γ spectroscopy, material science are promoted via spin-related research techniques such as β-NMR, γ-PAD/PAC [4].

RIB intensities of light isotopes at the present RIPS coupled with RRC are world-class. For example, a recent experiment performed at RIPS was dedicated for the exotic structure of ^{8}He via the missing mass spectroscopy [28]. VECC group in India has proposed an experiment on hot-GDR via a BaF_2 array [29]. Recently an RF separator has been installed [30], which is useful to purify proton-rich RIBs.

4. Summary and outlook

The programs for studying nuclear structure and reactions at the experimental devices at RIBF have been introduced by demonstrating recent highlights. One of research highlights at RIBF is to obtain brand-new results in the island of inversion region by utilizing the intense ^{48}Ca beam. 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 going to be used for programs approved at the BigRIPS/ZeroDegree. At the end of 2009, the Xe beam commissioning and DayTwo campaign with the ^{48}Ca and U beams are scheduled. Due to the installation of superconducting ECR ion source at RILAC, the intensity of U beam in the campaign is expected to be increased. In 2010, a new linac, RILAC-II, coupled with the SC-ECRIS will be completed to deliver more intense heavy-ion beams. In addition to the primary beam upgrades, the experimental devices going to be completed in future are giving more and more physics opportunities at RIBF.

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