RI Beam Factory Project at RIKEN

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The RI Beam Factory at RIKEN is introduced in connection with the present research activities with RI beams.

1 Introduction

Radioactive isotope (RI) beams providing a high isospin degree of freedom have given a great opportunity to investigate nuclei far from stability and to reveal out new phenomena in extreme conditions of isospin asymmetry [1]. To enforce the advantage of RI beams, the RI Beam Factory (RIBF) project at RIKEN aims to expand the range of radioactive nuclei, and to open up a new era for nuclear physics [2].

The RIBF project was proposed to further promote research fields by utilizing RI beams which are now being provided at the RIKEN accelerator research facility (RARF). We first introduce the present research-activities with RI beams at RIKEN, where many experimental programs undergoing are shown as examples for the future programs. Then, the accelerator complex and experimental devices at this project will be described.

2 Research activities at RARF

High-energy ($\sim$100 A MeV) and high-intensity ($<$500 pnA) primary beams of light-atomic mass (A<60), obtained from a ring cyclotron (RRC) at RARF, are converted into RI beams via the projectile fragmentation reaction. The RI beam intensity obtained there is the world-highest level, which has been made possible by the combination of the powerful primary beams and the RIKEN projectile fragment separator (RIPS) [3].

RIPS has large momentum and angular acceptances as well as a sizable maximum magnetic rigidity, hence has a high collecting power of projectile fragments. These features were adopted in taking into account energy dependences of RI beam intensity as well as kinematical broadening of projectile fragments. Another feature to be pointed out is that at the upstream of production target a beam swinger system is equipped to produce polarized RI beams. Such a high capability of RI beam production has stimulated nuclear experimentalists to discover new phenomena and new properties, especially for very neutron-rich nuclei.

Resent experimental results have been reported in variety of studies. The global characteristics of nuclei have been investigated toward the drip-line. Information on particle stability and instability has been obtained in the experiments searching for new neutron-rich isotopes [4]. One of the recent highlights is the experimental evidence for particle stability of ^{31}F and instability of ^{28}O. The decay properties ($T_{1/2}$ and P_n) of neutron drip-line nuclei in the B, C and N isotopes have been measured [5]. Formation of a halo structure has been deduced from the total cross section measurements at intermediate energies, where tail parts of nuclear matter distributions become sensitive to the cross sections [6]. By using the polarized RI beams, nuclear moments (μ- and Q-moments) for many isotopes have been obtained via the β-NMR method [7].

High yield rates of RI beams have allowed to research the nuclear structure in details. Especially, the magicity loss at neutron rich nuclei at N=8 and 20 has been intensively studied. The light neutron-rich isotopes around N=8 (e.g. ^{11}Be, ^{11}Li) have called attentions with respect to the formation of neutron-halo system and the problem of single-particle level ($1p_{1/2}$ and $2s_{1/2}$) inversion. The neutron-rich isotopes at $N\sim20$ (e.g. ^{32}Mg) have manifested the large deformation in spite of the magic number of 20.

β-spectroscopy in double- or triple coincidences of β-rays and delayed-neutron or γ-rays [8] has been possible due to the high intensity of RI beams available at RIPS. Several direct reactions in inverse kinematics have been widely used to deduce spectroscopic informations for the nuclear structure and to study dynamical response of exotic nuclear matters; elastic and inelastic scattering for very neutron-rich nuclei [9], electromagnetic dissociation for halo nuclei [10], the charge exchange reaction for isobaric analog states of halo nuclei [11], Coulomb excitation for nuclei in the deformation region [12], quasi-free nucleon-nucleon scattering for single-hole information [13].

Applications of RI beams for nuclear astrophysics are ones of the major activities at RIPS. The electromagnetic dissociation reaction has been applied for astrophysical cross section determination in an indirect method [14], where the cross sections at a few 100 keV are deduced by using the intermediate energy beams. Direct cross section measurements with RI beams at astrophysical energies have been performed [15], too.

Isospin-dependences in reactions have been investigated. Fusion cross sections at the sub-Coulomb barrier energy ($\sim5A$ MeV) have been measured with low energy Be-isotope beams in a variety of isospin [16]. The fusion reaction was once applied to observe correlations of two valence neutrons in a halo nucleus of ^{11}Li [17].

It should be noted that most of the above reaction experiments have been based on newly developed spectroscopy methods; the missing mass method with exit channel determinations [9], the invariant mass spectroscopy [10, 11, 14], in-beam γ-spectroscopy with high energy beams [12], and in-beam α-spectroscopy with a multi-target system [16].

3 RIBF project

According to the performances of primary beams at the present RARF, the efficient productions for RI beams are now in the relatively light nuclear region, $Z<20$. In the region with higher Z, interesting subjects in extremely high-isospin asymmetry conditions are waiting for nuclear physicists investigating; the nuclear structure at the magic numbers as well as the collectivity [18], the dynamical aspects of nuclear matters in terms of the neutron skin formation [19], and the nuclear astrophysics, especially for the r-process path [20]. The RIBF project aims to proceed to such new domains of the nuclear chart.

To realize the wide dynamic-range of available RI beams over the nuclear chart needs more powerful primary beam than at the present facility, of which energies may be more than $100A$ MeV upto Uranium, and of which intensities be as high as possible. To achieve such high performances in heavy ion beams, two new ring cyclotrons, IRC and SRC, are to be built as post accelerators of the existing ring cyclotron RRC, as shown in Fig. 1 [2]. The cascade operation of these cyclotrons boosts energies of heavy ion beams up to 400 A MeV for light heavy ions like Oxygen, 300 A MeV for Kr ions, 200 A MeV for Xe ions and 150 A MeV for U ions. The expected beam intensity is as high as 1 pμA.

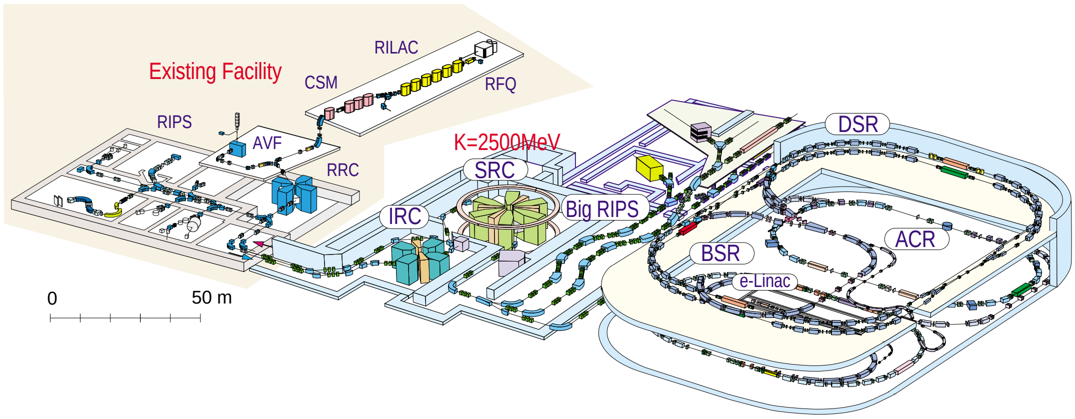

Figure 1: Bird's eye view of RI Beam Factory layout.

The heavy-ion beams accelerated at SRC are to be used for RI beam productions via not only the projectile fragmentation reaction but also the fission reaction of Uranium beams. Fragments of interest are collected and separated at fragment separators, called "Big-RIPS". We will have two types of Big-RIPS's; one is dedicated to the experiments by using stoppers or fixed targets, as described in the previous section, another is for the MUSES facility. The MUSES facility consists of four rings as shown in Fig. 1. Detail descriptions are not shown here, but found in Ref. [21].

The first Big-RIPS system aims for the high isospin frontier. The choice of the fission reaction with ^{238}U is essential for RI productions around ^{78}Ni (a double magic nucleus with N=50) and $^{\sim 104}$Zr (a largely deformed nucleus) region, since the production cross sections of such neutron-rich fission fragments are a few orders of magnitude higher than in the case of the projectile fragmentation [22]. The momentum and angular acceptances of Big-RIPS must be determined according to the kinematical broadening of fission fragments.

We here emphasize two experimental points with RI beams. One of them is that a purity of a RI of interest in RI beams is not 100%. Thus, in general, particle identification to determine Z and A of RI beams particle-by-particle is essential to deduce reliable results. At RIPS, the mass region of intense RI beams is A<60, thus the particle identification does not require nice resolutions in the Z and A determination. However, in the RIBF project, experimentalists will treat more heavier isotopes. In this sense, to achieve nice resolutions for particle identification is essential and the first priority in designing the experimental facility.

Another point is energies of RI beams especially for reaction experiments. The research based on nuclear reactions needs appropriate energies of beams according to the reaction type. For instance, transfer reactions are efficient at a few 10 A MeV, and quasi-free nucleon-nucleon scattering demands ~200 A MeV RI beams which allow us to assume one step reaction inside a nucleus and to deduce reliable spectroscopic information. Thus, the dynamic range of beam energy is one of important aspects of RI beams.

Taking into account such requirements for experimental programs at RIBF, we are now proposing a cascade configuration of two fragment separator. The first separator could be dedicated to the RI production and separation only. The second one which also has a momentum dispersive focal plane provides a several functions for the requirements. High-resolution particle identification can be realized on the basis of accurate determination of fragment momenta. More efficient decrease of RI beam energies may be possible with an achromatic energy-degrader to be placed at the focal plane, compared with in the case of a flat-shaped degrader.

Experimental devices will come to the end of the cascade separator system. Relatively large devices proposed so far are, for instance, a large dipole magnetic spectrometer with a high acceptance for particles decayed from particle-unbound excited states, a forward spectrometer with a high resolution for particle identification of ejectiles, some γ-ray detectors based on Ge- and CsI-crystals for particle bound excited states. Such devices are being designed for high energy and/or heavy RI beams.

4 Summary

The RIBF project aims to open a new era of nuclear physics in the next century. The construction of the part including SRC and Big-RIPS will start soon, and the RI beams at RIBF will be ready a few years later.

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