Present status of the RIKEN Radioactive Ion Beam Factory, RIBF

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Abstract. The present operation status of the RIKEN Radioactive Ion Beam Factory (RIBF) and recent research highlights are reported. One of the major devices of the RIBF, an electron scattering facility for short-lived nuclei, is described in detail. This facility will open a completely new research field of structure studies of short-lived nuclei.

1. RIKEN Radioactive Ion Beam Factory
The RIKEN RIBF [1] is a next-generation radioactive-beam facility that provides intense exotic beams for various basic sciences. The RIBF consists of an heavy-ion linac injector followed by four cyclotrons to boost the primary beam energy up to 350 AMeV. The intensity goal of primary beams ranging from protons to uranium is 1 pμA (particle micro-Ampere).

BigRIPS [2] is a large acceptance fragment separator consisting of two stages. They are the production stage where the primary beam is converted to radioactive ion (RI) beams by the in-flight fission of a uranium beam as well as projectile fragmentation of other primary beams, and the tagging stage to tag the produced secondary beam on an event-by-event basis for experiments using these RI downstream.

After completion of the facility construction in 2006, continuous efforts have been made for improving the facility performances; primary beam species, beam intensity, and its stability etc... So far, uranium beams with an intensity of 10⁹/sec and the world’s most intense ⁴⁰Ca beam with the intensity of 200 pnA have been provided for nuclear physics experiments.

1. Major experimental devices
There are several large-scale experimental devices to enhance the research capability of this facility.

The major devices in operation today are the ZeroDegree spectrometer [2] and a high-resolution spectrometer SHARAQ [3]. The ZeroDegree is a large-acceptance beam-line spectrometer for particle identification of the reaction products at the secondary target that is bombarded by the tagged secondary beam. SHARAQ, in connection with a long beam transport line for dispersion matching purpose, provides a unique opportunity to carry out high resolution studies using secondary beams; such as missing mass spectroscopy with secondary beams as a “probe”.

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Devices under construction are SAMURAI (Superconducting Analyzer for MUlti particles from RAIDo Isotope beams) [4] and an electron scattering facility for short-lived nuclei based on a novel SCRIT concept.

SAMURAI is a versatile large acceptance spectrometer having a large gap that allows the detection of neutrons emitted forward in coincidence with other charged particles for spectroscopic studies of unbound states excited by nuclear reactions. It will be completed in FY2011. As for the electron scattering facility, it will be described in details in the next section of this report.

Additional unique devices currently under budget requests are SLOWRI [5] and the Rare Isotope ring [6]. SLOWRI aims to provide slow radioactive beams after stopping a fast radioactive beam by a gas catcher. The Rare Isotope ring measures the mass of rare isotopes with a mass precision of $10^{-6}$.

1. Recent results from RIBF experiments
As of today, an intense, stable, $^{48}$Ca primary beam, $\sim$ 200 pnA, has been regularly provided for several BigRIPS experiments, and a uranium beam of 0.3 pnA has been used for new isotope search measurements. Updated information of the primary beam intensity is always available at the RIBF web site: http://www.nishina.riken.jp/UserGuide/accelerator/tecinfo.html

Campaign-type experiments using the intense $^{48}$Ca beam have been conducted in 2008. Three independent experiments were successfully performed. The key of the success resulted from obtaining secondary beam intensities of very neutron-rich isotopes, which were unexpectedly high compared with those based on our experience with lower energy RIPS experiments. As an example, the $^{31}$Ne beam intensity was 400 times more intense, a result which is attributed to the larger production cross section at higher beam energy in addition to a thicker production target and a larger acceptance of the separator.

The experiments performed were the measurements of the reaction cross-section [7], including Coulomb breakup [8] and inelastic scattering by detecting de-excitation gamma rays [9]. These measurements that $^{31}$Ne is a halo nucleus, the heaviest halo nucleus discovered so far.

The intensity of U, typically $\sim$0.3 pnA, is still far from the goal intensity of 1 pμA. Nevertheless, many new isotopes were discovered in one-shot experiments thanks to the large acceptance of the separator [10,11]. A higher intensity U beam is expected in the next few years resulting from charge-stripper developments, and medium-heavy exotic nuclei will soon be available as targets for studies of nuclear structure and reactions.

2. Electron scattering facility based on SCRIT scheme at the RIBF
An electron scattering facility dedicated to the structure studies of short-lived nuclei is being under construction at the RI Beam Factory. Although electron scattering is well known to be a very powerful tool for structure study of atomic nuclei, it has never been never used for short-lived nuclei.

2. 1. Electron scattering
Electron scattering provides the most reliable structure information of atomic nuclei by virtue of the fact that the electron is a point particle, and probes a target nucleus through the fairly weak and well-understood electromagnetic interaction. Since this scattering process is perfectly described by QED, one can unambiguously extract structure information of the target nucleus from experimental data.
Thus, as is well known, electron scattering has consistently played a key role in nuclear structure studies. It has been, however, strictly limited to stable nuclei except for a few exceptions, and no experiments for highly unstable (short-lived) nuclei has been ever conducted.

Once electron scattering becomes feasible for short-lived nuclei, one may start with the measurements of elastic scattering, since its cross section is the largest in low momentum transfer region and the charge density distribution, one of the fundamental ground state properties of nuclei, is determined. According to the results of simulations for elastic scattering off $^{132}\text{Sn}$ which is our first target for electron scattering, a luminosity of $10^{27}$/cm$^2$/s is required to determine the size and surface diffuseness with an accuracy better than a few %.

2. A novel technique for electron scattering experiments

We have proposed a novel experimental technique [12] to open up this new research field, namely the structure study of exotic nuclei by electron scattering. It is named as SCRIT (Self Confining RI Target), which uses “ion trapping” notoriously known at electron ring facilities. Since ion trapping reduces the performance of electron rings by inducing beam instability and shorter beam lifetime, much effort has been paid so far to remove these effects. Our idea is to grab exotic nuclei of interest on the electron beam using this ion trapping technique.

Ions (exotic nuclei) of interest will be externally injected and trapped by a circulating electron beam. Once they are trapped on the electron beam, they can not escape. Therefore, a rather high collision luminosity is expected with a small number of trapped ions. Since the ions are trapped on the electron beam, electron scattering off the target nucleus takes place automatically.

To confine the trapped ions longitudinally also, electrodes are placed in the electron beam direction to form a mirror potential. Controlling the mirror potential, one can inject the target ions from the external ion source, trap them for a certain duration depending on the lifetime of the target nuclei, and extract them from the trap region for the next injection to keep the purity of the target.

2. 3. Feasibility studies

In order to study the achievable luminosity by this novel SCRIT approach, a prototype was constructed and installed at an existing electron ring, KSR, of Kyoto University. Stable Cs ions are used instead of exotic nuclei for this study. Figure 1 shows the SCRIT prototype installed on the 2-m straight line of KSR.

![Figure 1. The SCRIT prototype installed at KSR for feasibility studies.](image-url)
Cs ions extracted from an ion source are transported and merged with the electron beam at the deflector. They are transversely trapped by the electron beam, and are longitudinally confined by a mirror potential created by electrodes. By adjusting the mirror potential shape the ion-trapping length was set to 260 mm. The scattered electrons emerging to the air through a thin Be window are detected by an electron detection system consisting of a drift chamber for scattering angle measurement and calorimeters for energy measurements.

Using 120 MeV electron beams whose stored current is 70 mA with a beam lifetime of 100 s, we measured the scattered electron spectrum with the ion injection-trap-release cycle by controlling the ion source and the mirror potential. In order to mimic short-lived nuclei, the trapping time was set to be 50 msec. Clear signals of elastically scattered electrons from ions trapped in the trapping region are observed, and their angular distribution clearly shows that they are from the trapped Cs ions as shown in figure 2 [13,14]. Detailed analysis shows that the luminosity of $1 \times 10^{26}$/$cm^2$s is achieved with $10^6$ trapped ions. Since much improved luminosities are expected with larger stored electron-beam current and improved ion-injection technique, we conclude that a luminosity of $1 \times 10^{26}$/$cm^2$s is achievable, and the SCRIT technique is a way to realize never-yet-performed electron scattering of rarely-produced short-lived nuclei.

2.4 Electron scattering facility at RIKNE RI Beam Factory

Based on the success of the feasibility studies described above, we started to plan the construction of an electron scattering facility at the RIBF. This has been, fortunately, boosted up by three fortunate recent events:

- Donation of a 700-MeV electron storage ring system from SHI (Sumitomo Heavy Industries), who terminated its use as a light source facility
- FY2008 supplementary budget from the government that enabled us to install the ring at the RIBF
- Grant-in-Aid for Scientific Research (S) has been approved in FY2010 for construction of the electron detection system

![Figure 2. Angular distribution of electron elastic scattering. Solid circles show the elastic events, and the solid line the results of a distorted wave calculation by DREPHA for $^{133}$Cs.](image-url)
Figure 3 shows a layout of the electron scattering facility at the RIBF. The facility consists of an electron accelerator, an ISOL system and an electron detection system. The donated electron ring system has already been installed and is now in operation.

2. 4. 1. Electron storage ring system
The system consists of a 150-MeV injector microtron, the beam transport line and 700-MeV electron storage ring. The basic configuration is the same as that of the SR light source facility of Hiroshima University, HiSOR. Commissioning is underway at the highest electron energy 700 MeV and, as of today, the stored beam current is higher than 400 mA with a beam lifetime of nearly 2 hours. The much improved electron-beam conditions of the new facility compared with those of KSR, such as stored current, stability and beam lifetime etc., will result in a much higher luminosity for the same number of trapped ions.

2. 4. 2. ISOL
Production of short-lived nuclei, specifically Sn isotopes including $^{132}$Sn as the first targets, will be carried out using 150 MeV electron beam bombarding on an uranium carbide target, $^{238}$UC$_x$. Photo-fission (and electro-fission) of uranium is known to be a very efficient way to produce neutron rich Sn isotopes, especially $^{132}$Sn [15]. Photo-fission of uranium is mainly induced by an excitation of the giant dipole resonance of uranium. Numerical simulations show that the number of photo-fission per unit beam power for the optimized target geometry becomes nearly constant, an order of $10^8$ fission/s/watt, when the incident electron energy is larger than 100 MeV.

Since a long beam lifetime (a few hours) of the storage ring will allow us to operate the injector microtron mostly for isotope production, we decided to build an ISOL system using the photo-fission process of uranium. At the electron beam power of 1 kW, the production rate of $^{132}$Sn will be $10^9$/s based on the $^{132}$Sn yield ratio in photo-fission process being 1% [15]. Detailed design of the ISOL system including an element-separator, mass separator and ion pulsing for the SCRIT injection after accumulation is underway.

2. 4. 3. Electron spectrometer
In order to identify elastic scattering, an electron spectrometer must have an energy resolution at least better than 1 MeV to resolve elastic and inelastic scatterings. The electron beam energy will need to be 300 MeV from considerations of the momentum transfer range required for the measurement of the charge density distribution, and the geometrical limitation of where the spectrometer can be placed. Thus, the momentum resolution must be better than 3 x 10^-3.

Due to the fact that the SCRIT provides a spatially extended target, 30-40 cm, any focusing-type high-resolution magnetic spectrometer can not be employed. In addition, the solid angle of such high-resolution spectrometer, typically a few 10 msr, is obviously insufficient to deal with the small yield from low luminosity experiments.

A non-focusing magnetic spectrometer with tracking detectors as shown in figure 3 will be employed. This spectrometer covers a wide scattering angular range of 30-60 deg., and has a solid angle of the order of 100 msr.

2. 4. 4. Time schedule
In the next three years, the construction for the ISOL system and the electron detection system will be carried out. The first collisions of electrons and the trapped Sn nuclei are planned for 2014.

3. Summary
The RIKEN RIBF has started its full-scale operation with the world’s most intense 40Ca beams of 350 AMeV since 2008. In addition to efforts to improve the facility performance including targeting a primary-beam intensity goal of 1 pμA, the physics program using the full potential of major experimental devices will be continuously conducted. An electron scattering facility for short-lived nuclei, which is quite unique, is under construction based on a new experimental technique, named SCRIT. The first collision between electrons and short-lived nuclei will take place in 2014.

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