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The SCRIT Electron Scattering Facility at the Riken RI Beam Factory

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The SCRIT (Self-Confining Radioactive-Isotope Ion Target) electron scattering facility has been constructed at the RIKEN RI Beam Factory. In the commissioning experiment, the ion-trapping properties of the SCRIT system were studied using stable ions. By using an electron spectrometer, the momentum transfer distribution of the electron elastic scattering of ^{132}Xe was measured at 150, 200, and 300 MeV, and the charge density distribution was deduced. During the measurements, a luminosity of 1.8×10^{27} cm^{-2}s^{-1} was achieved with a 250-mA electron beam and only 10^{8} trapped ions. Production of RIs has begun in an electron-beam-driven RI separator, and developments are underway to increase the production rate of short-lived nuclei. Soon, measurements of electron elastic scattering by short-lived nuclei will be performed.

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1. Introduction

One of the fundamental aspects of nuclear structure is the charge density distribution, which has been investigated intensively using electron scattering [1]. This is a powerful tool for studying nuclear structure because electrons have no internal structure and there are no ambiguous interactions. Although electron scattering has been used for many years with stable nuclei, it has not been applied to short-lived nuclei because of the difficulty of forming a target and realizing the required high luminosity. Despite this, research on the nuclear structure of short-lived nuclei is very active and continues to expand. However, the long-awaited ability to perform electron scattering on short-lived nuclei would improve the understanding of their structure.

The SCRIT (Self-Confined Radioactive-Isotope Ion Target) method [2] is a novel target-forming technique aimed at overcoming the aforementioned difficulties. It uses the ion-trapping phenomenon that is observed in an electron storage ring. As a result of intensive development, the practicality of SCRIT has already been demonstrated [3, 4]. This result led us to construct an electron scattering facility for unstable nuclei at the RIKEN RI Beam Factory. Construction began in 2009, and a commissioning experiment has been performed [5, 6]. Recently, we completed the first electron elastic scattering by ^{132}Xe and deduced its charge density distribution precisely [7]. Radioactive isotope (RI) production began in 2013, and an intense RI beam for experiments with short-lived nuclei is under development. [8].

In this paper, we introduce the SCRIT electron scattering facility and report on its present status and results.

2. SCRIT facility

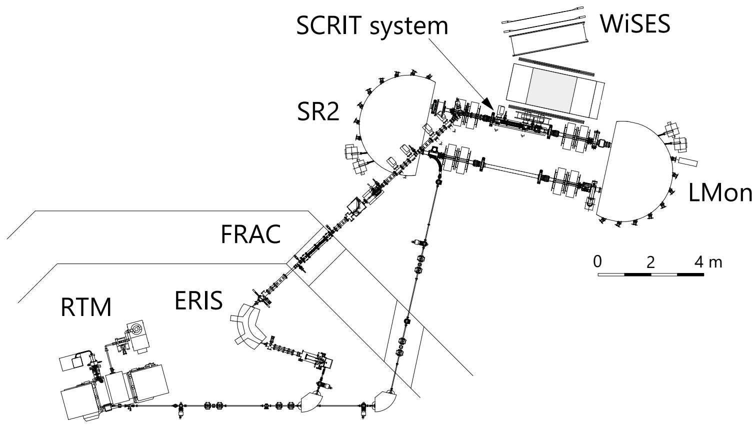

Figure 1: Schematic layout of the SCRIT electron scattering facility.

Figure 1 shows a schematic layout of the SCRIT electron scattering facility [5]. It consists of a racetrack microtron (RTM), an electron storage ring (SR2), an electron-beam-driven RI separator for SCRIT (ERIS) [8], and a fringing-RF-field-activated ion beam compressor (FRAC) [9]. The SCRIT system is located in the straight section of SR2. An electron spectrometer known as a Window-frame Spectrometer for Electron Scattering (WiSES) [10, 11] is installed beside the

SCRIT system, and there is a luminosity monitoring system (LMon) [10] at the downstream exit of the straight section of SR2.

The RTM accelerates the electron beam to 150 MeV prior to being injected into SR2. In ERIS, RIs are produced from a photofission reaction with a uranium carbide target after the injected electron beam has accumulated in SR2. After mass separation, the produced RIs are transported to FRAC. This converts a continuous RI ion beam into a pulsed RI ion beam with the appropriate stacking time. Pulsed RI ions from FRAC are transported through the ion-beam transport line and are injected into the SCRIT system. There, electrons that are scattered by trapped ions are momentum-analyzed by WiSES. The luminosity is monitored continuously by LMon using bremsstrahlung gamma-rays.

2.1 Accelerators

The RTM is a compact microtron used as an injector for both ERIS and SR2. During injection into SR2, the beam power is approximately 0.4 W with a 2-Hz injection repetition rate. In the case of RI production, the pulse width of the electron beam is extended from 1 μs to 5 μs, the peak current is 3 mA, and the repetition rate is increased to 10 Hz. This raises the electron beam power to approximately 10 W.

The SR2 is an electron storage ring that can accelerate an electron beam to 700 MeV. The typical stored current and lifetime are approximately 300 mA and 1 Ah, respectively. The size of the electron beam in the SCRIT system is approximately 2 mm and 0.4 mm in sigma in the horizontal and vertical directions, respectively.

2.2 SCRIT system

The SCRIT system consists of three electrodes for trapping and a switching deflector for ion injection and extraction. The three electrodes form a trap potential in the longitudinal direction; two end electrodes produce the barrier potentials, and the potential applied at the central electrode is set to a few electron volts less than the kinetic energy of the injected ion beam. The ion injection and extraction is controlled by rapidly switching the entrance barrier potential. We use the electric potential produced by the micro-bunched electron beam for the transverse direction.

An ion beam is injected through the switching deflector, merges with an electron beam, and it is guided to the central electrode. Electrons are then scattered automatically in the target region of the SCRIT system. After the measurement, the trapped ions are extracted and transported to a total charge monitor and an E×B velocity filter equipped with channeltrons. There, the total charge and the charge-state distribution of the trapped ions are measured. The luminosity during the measurement is monitored by LMon. The measurements with and without the ion injection are performed simultaneously in order to subtract the effect of residual gasses. More details about the SCRIT system can be found in Refs. [5, 6].

The number of target ions that participated in the electron scattering of ^{132}Xe was evaluated from the obtained luminosity in the case of a 1-s ion trapping time. The luminosity was obtained as 1.4×10^{27} cm^{-2}s^{-1} with a 175-mA electron beam. The electron beam size at the SCRIT system was 3.6 mm^2 in sigma. The number of injected ions was 2.3×10^8 within a 300-μs pulse width. The number of target ions was evaluated as 4.6×10^7 with one pulse injection. The ratio of target ions to injected ions was approximately 20%, which reflects the large size of the ions injected into the SCRIT system. Ion beam transport to the SCRIT system is currently being improved to account for the effect of the potential produced by the electron beam.

2.3 ERIS

The RI beams are produced by ERIS, which is an online isotope separator (ISOL) system that uses photofission of uranium. ERIS consists of a production target, a forced electron beam induced arc discharge (FEBIAD) ion source, and a beam-analyzing transport line. Uranium carbide is used as the production target, which is irradiated with a 150-MeV electron beam. The RIs so produced are ionized in the FEBIAD ion source and are accelerated to 6–20 kV depending on the experimental conditions. The mass selection is performed in the beam-analyzing transport line. Details of ERIS and recent results can be found in Refs. [8, 12].

2.4 FRAC

FRAC is based on RF quadrupoles. It consists of six quadruple electrodes and a set of einzel-lens, injection, extraction, and barrier electrodes. The characteristic feature of FRAC is the use of the RF flinging field between the barrier and the quadruple electrodes; this field has both transverse and longitudinal components. Therefore, some of the continuously injected ions are deaccelerated in the longitudinal direction. By using this effect, FRAC realizes continuous injection followed by trapping without a buffer gas. After accumulation, the number of pulsed ions so extracted is much larger than would be the case using chopping. For example, in the case of a 1-s accumulation time and a 500-μs extracted pulse width, the pulse height extracted using FRAC is about 40 times that using chopping. Details of FRAC can be found in Ref. [9].

2.5 WiSES and LMon

WiSES consists of a window-frame dipole magnet, long plastic scintillators, and drift chambers installed at the entrance and exit of the dipole magnet. A characteristic of WiSES is a large acceptance that is achieved by using a dipole magnet with a wide pole gap (i.e., 1,700 (w) $\times$ 290 (h) $\times$ 1,400 (d) mm^3). This is to cover the wide trap region of the SCRIT system, which is 500 mm along the electron beam line. In the commissioning experiment [10, 11], the acceptance of the long target region was studied, and the momentum resolution was confirmed to be $\Delta P/P \sim 3 \times 10^{-3}$ at 300 MeV.

LMon is a luminosity monitor that uses bremsstrahlung gamma-rays produced by the trapped ions. It consists of a pure-CsI crystal array and two fiber scintillator layers. The pure-CsI crystal array consists of seven crystals assembled in a hexagon mesh. Each crystal is a 200-mm-long regular hexagonal cylinder of side 40 mm. The two fiber scintillator layers are installed in front of the crystal arrays in order to measure the horizontal and vertical position distributions. Each fiber scintillator layer consists of sixteen 2-mm-wide fiber scintillators. The acceptance and transmission efficiency (including the geometrical condition of SR2) are evaluated by GEANT4 simulations. Details and the performance of the detector system can be found in Refs. [10, 11].

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3. Ion-trapping properties and achieved luminosity

The ion-trapping properties of the SCRIT system were studied in previous research [6]. This clarified that the ion-trapping features of the SCRIT system are similar to those of a radio-frequency quadrupole (RFQ) trap because the micro-bunched electron beam makes a periodic potential like an RF potential. This result explains the acceptance by mass-to-charge ratio and the ion-trapping lifetime in the SCRIT system. Furthermore, it was also found that the ion-trapping lifetime depends on the instability of the electron beam. These details were studied using 6-keV ^{132}Xe ion beams.

Figure 2 shows the trapping-time evolution of the luminosity measured by LMon under different electron-beam conditions. The upper and lower panels of Fig. 2 show the time evolutions for different electron-beam energies (E_e) and for different SR2 tuning parameters, respectively. In lower panel of Fig. 2, the decay time of the ion trapping at E_e = 200 MeV is increased by selecting the horizontal (v_x) and vertical (v_y) tuning parameters as v_x = 1.62 and v_y = 1.58. The ion-trapping time evolutions for E_e = 150 and 300 MeV as shown in the upper panel of Fig. 2 were measured using the same tuning parameters as for E_e = 200 MeV. The fact that these are appreciably different from the evolution for E_e = 200 MeV shows that the tuning parameters have a large effect on the ion trapping. From this, we conclude that the ion-trapping time evolution could be controlled by adjusting the tuning parameters.

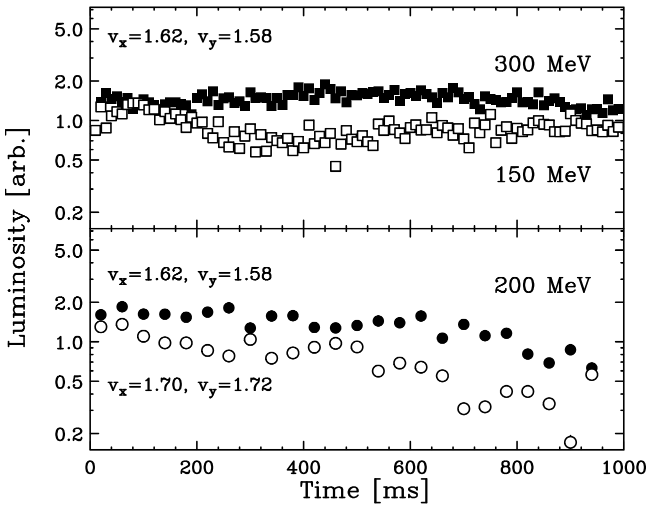

Figure 2: Trapping-time evolution of luminosity using ^{132}Xe ion beams at 6 keV. Luminosity is plotted in arbitrary units. The electron beam current was 210 mA. Upper panel shows the time evolution with horizontal and vertical tuning parameters v_x = 1.62 and v_y = 1.58, respectively, for electron-beam energies of 150 MeV (white squares) and 300 MeV (black squares). Lower panel shows the evolution for 200 MeV with two sets of tuning parameters, v_x = 1.62 and v_y = 1.58 (black circles), and v_x = 1.70 and v_y = 1.72 (white circles).

In addition, for E_e = 150 MeV, the luminosity decreases gradually initially but then increases after 400 ms. This tendency is attributed to the charge state of the trapped ions. Initially, around 100 ms, the charge state of the trapped ions is mainly 1^+ and the luminosity decreases according to the ion-trapping lifetime. After several hundred milliseconds, the charge state of the trapped ions increases to around 10^+ [5], which forces the trapped ions into a smaller volume.

Figure 3 shows the dependence of luminosity on electron-beam current for electron-beam energies of 150, 200, and 300 MeV. Of order 10^8 ions of ^{132}Xe were injected with a 300-μs pulse width. The tuning parameters of the electron beam were optimized according to the electron-beam energy. A luminosity of approximately 1.8×10^{27} cm^{-2}s^{-1} was achieved with a 250-mA electron beam.

Using this high luminosity, electron elastic scattering by ^{132}Xe was performed for 150, 200, and 300 MeV. More details of these measurements can be found in Ref. [7]

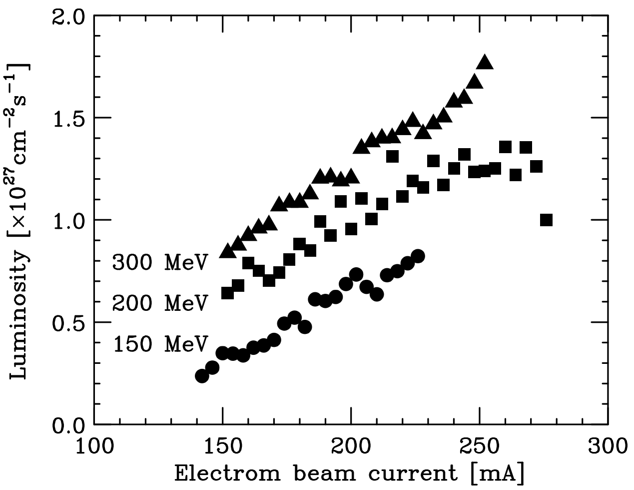

Figure 3: Dependence of luminosity on electron-beam current. Circles, squares, and triangles show the results for electron-beam energies of 150, 200, and 300 MeV, respectively. The measurements were performed using pulsed ^{132}Xe ion beams with a 300-μs pulse width.

4. RI production at ERIS

We prepared our own uranium carbide target disks. Uranium carbide is obtained by the carbothermal reduction of uranium oxide in the presence of carbon. Uranium oxide-coated graphite powder is used to form a thin disk without a binder. Details of the target production can be found in Ref. [13]. The disks so obtained were approximately 0.8-mm thick and 18 mm in diameter. In total, 23 disks were prepared. The total amount of uranium used was about 15 g, and the average mass concentration of uranium in each disk was estimated as 3.4 g/cm^3.

The uranium carbide disks were irradiated with the RTM electron beam with a beam power of around 10 W. Tantalum disks with a thickness of 5 mm and a diameter of 20 mm were inserted in front of the production target to increase the production of gamma-rays. The target temperature was kept at approximately 2,000 °C. The RIs so produced were accelerated to 20 kV and mass-separated by the analyzing magnet. They were identified by using a Ge detector to measure the gamma-rays from the decay of the RIs.

Figure 4 shows the rate of Sn and Xe isotopes at the Ge detector. These rates were estimated from the number of observed gamma-rays based on the efficiency of the Ge detector and the half-life of each isotope. The observed rates for ^{132}Sn and ^{138}Xe were 2.6×10^5 and 3.9×10^6 atoms·s^{-1}, respectively. Comparing the obtained rate with the expected production rate inside the target gives the overall efficiency including the release efficiency from the target, the ionization efficiency, and the transport efficiency. The overall efficiencies for ^{132}Sn and ^{138}Xe were found to be 2.1% and 5.5%, respectively. The luminosity expected for an electron beam of around 250-mA is also indicated in Fig. 4. The efficiency of converting from a continuous beam to a pulsed beam with a 300-μs pulse width was assumed as 10%. The luminosity was estimated to be of order 10^{25} cm^{-2}s^{-1} for the present RI rate of $\sim 10^7$ atoms·s^{-1}, which is insufficient for electron elastic scattering.

Several developments are in progress to increase the RI rate. The RTM electron-beam power will be upgraded to 50 W by increasing the electron gun current and the injection repetition rate. In addition, the overall efficiency will be improved by a factor of four by increasing the ionization efficiency and optimizing the potential structure of the extraction. The dashed lines in Fig. 4 show the RI rates expected with a 50-W electron beam, four times the overall efficiency, and a 30-g uranium target. The RI rate is increased to the order of 10^8 atoms·s^{-1} for Xe isotopes, and the luminosity exceeds 10^{26} cm^{-2}s^{-1}. Under these conditions, electron elastic scattering by short-lived nuclei becomes feasible. However, to perform electron elastic scattering by Sn isotopes as part of future plans, a 1-kW electron beam will be needed, as shown by the dotted lines in Fig. 4. Such a high electron-beam power will necessitate upgrading the entire RTM and modifying ERIS.

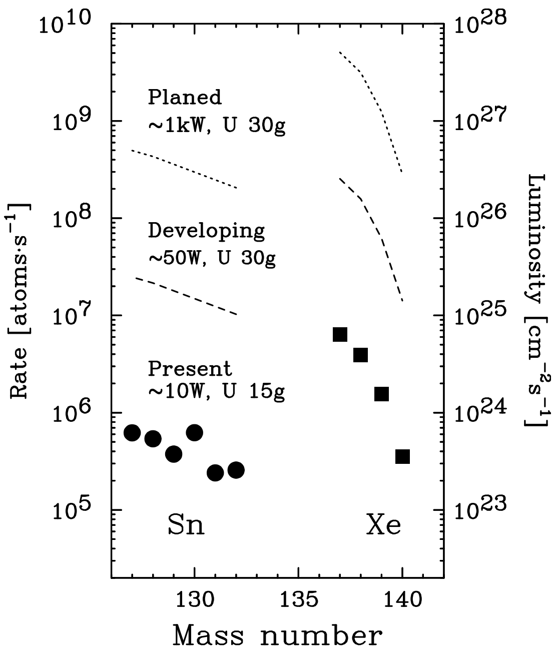

Figure 4: Rates of Sn and Xe isotopes at the ERIS particle identification detector. Circles and squares show the rates of Sn and Xe isotopes, respectively. Currently, the electron beam power is almost 10 W and the total amount of uranium is 15 g. Dashed and dotted lines show the results under various assumptions, the details of which are discussed in the main text.

5. Summary

The SCRIT electron scattering facility has been constructed and the commissioning experiment was performed successfully. The properties of the ion trapping in the SCRIT system were studied intensively and can be adjusted by means of the electron beam parameters. The achieved luminosity is approximately 1.8×10^{27} cm^{-2}s^{-1} with a 250-mA electron beam and the injection of 10^8 ions within a 300-μs pulse width. Electron elastic scattering was performed using stable ^{132}Xe ions, and the charge density distribution was deduced. The production of RIs has already started for experiments with short-lived nuclei, and development is in progress to increase the production rate. Measurements of electron scattering by short-lived nuclei will be performed in the near future.

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