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Electron scattering for exotic nuclei

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Abstract. A brand-new electron scattering facility, the SCRIT Electron Scattering Facility, will soon start its operation at RIKEN RI Beam Factory, Japan. This is the world's first electron scattering facility dedicated to the structure studies of short-lived nuclei. The goal of this facility is to determine the charge density distributions of short-lived exotic nuclei by elastic electron scattering. The first collision between electrons and exotic nuclei will be observed in the year 2014.

Keywords. SCRIT; electron scattering; exotic nucleus; charge density distribution.

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1. Introduction

Electron scattering is one of the most powerful tools for studying the structure of atomic nuclei. Indeed, it has consistently played a key role in our understanding of the nuclear structures. A well-known classic example is the charge density distributions of stable nuclei precisely determined by elastic scattering [1]. Ever since the Nobel-prize winning experiments by Hofstadter and his colleagues about half a century ago [2], elastic scattering has remained the one and only way to determine the charge density distributions. It is one of the fundamental ground-state properties of atomic nuclei, and has been an essential testing ground of nuclear structure theories.

So far, electron scattering experiments have been limited to stable nuclei, with some exceptions such as ^{3}H having a rather long lifetime. No experiment has been attempted for highly unstable nuclei, some of which have peculiar structures such as halo, skin, magicity loss and some have new magic numbers. Due to the obvious advantages of electron scattering for structure studies [3], application of electron scattering for structure studies of exotic nuclei has been long-awaited.

Electron scattering of highly unstable nuclei is not easy because it is difficult to produce them and their lifetimes are short. One way to overcome this difficulty is to employ a collider between an electron beam and a beam of exotic nucleus, and this was supposed to be the only way. The invention of an alternative way which is discussed in this paper, however, changed this situation completely.

About a decade ago, we proposed a novel target production technique for the electron scattering experiments of short-lived nuclei [4]. The technique, named SCRIT (Self-Confining RI Target), uses ion trapping phenomena to keep the target exotic nucleus on the electron beam. The ion trapping is generally a problematic phenomenon at electron storage rings. Ionized residual gases by the circulating electron beams are trapped by the electron beam itself. Electrons scatter off the trapped ions introducing shorter beam life. When the ion trapping is more, beam instability is also invoked. Our idea is to trap the short-lived target nucleus on a high-energy electron beam by using this ion trapping effectively. A proof-of-principle experiment of the SCRIT scheme has proved that this scheme provides the luminosity required for the elastic electron scattering experiments [5,6].

Based on the success, we have started the construction of the world's first electron scattering facility, the SCRIT Electron Scattering Facility, dedicated to the structure studies of short-lived nuclei.

The facility has been partly commissioned, and will start its operation soon. It is planned that the first observation of the scattered electrons off the unstable nuclei will be during the year 2014. In this paper, we present the details of the facility including the current status and operation schedule as well as the physics programmes of this facility.

2. The SCRIT Electron Scattering Facility

2.1 *Facility overview*

Figure 1 shows the floor plan of the SCRIT electron scattering facility. It consists of an electron accelerator, an ISOL system for the production of neutron-rich isotope and an

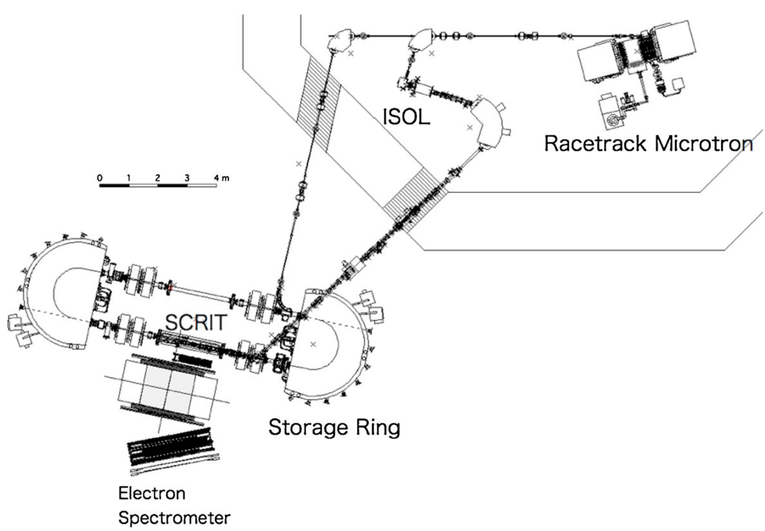

Figure 1. The SCRIT Electron Scattering Facility.

electron spectrometer. The electron accelerator consists of a 150 MeV injector racetrack microtron and a 700 MeV electron storage ring equipped with the SCRIT system. The stored electron beam energy is variable from 150 to 700 MeV. The stored beam current as of today is 300 mA with a beam lifetime of over 200 min.

2.2 *The SCRIT system*

Figure 2 shows the SCRIT system installed in the straight section of the storage ring. The system consists of a set of deflectors for ion injection and ejection, three electrodes and a trapped-ion analyser. Two sets of beam scrapers and two sets of button-type beam position monitors (BMPs) are installed along the electron (and ion) beam line. The electrodes at both ends form a mirror potential to keep the ions longitudinally inside the SCRIT device, and the central electrode of 500 mm length is to trap the ions with the kinetic energy of an order of a few eV.

The pulsed ion beam from an external ion source is transported through the deflector and merged with the stored electron beam. The ions are introduced into the mirror potential by controlling the voltage of the entrance electrode, and they are trapped in the electron beam. After a specified trapping time for electron scattering experiment, they are ejected from the potential to refresh the (short-lived) target ions. The trapped-ion analyser is used to measure the charge state of the ejected ions. By controlling the voltage applied to the electrodes for the mirror potential, one can easily control ion injection and ejection, thereby, the ion-trapping period becomes essential for targeting short-lived nuclei.

2.3 *ISOL (ERIS)*

An ISOL system, ERIS (Electron-beam-driven RI separator for SCRIT) [7] to produce neutron-rich nuclei via the photofission process of uranium is under construction. The

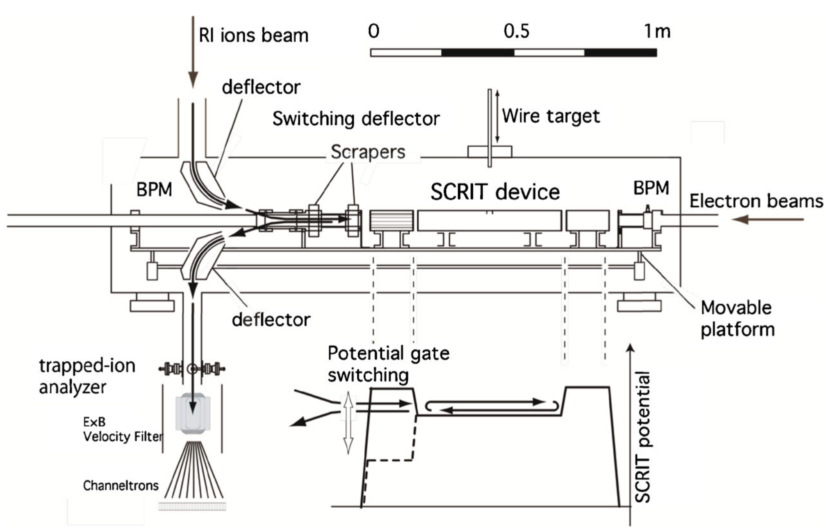

Figure 2. The SCRIT device.

long beam lifetime of the stored electron beam, typically two hours, facilitate the use of the microtron as a driver for the ISOL. The ISOL system makes it possible to operate the facility completely independent of the other facilities of the RI Beam Factory.

The production of short-lived nuclei is carried out by bombarding a uranium carbide target, $^{238}UC_x$, with the 150 MeV electron beam. Photofission (and electrofission) of uranium is known to be an efficient way to produce medium-heavy neutron-rich nuclei, such as Sn isotopes, including ^{132}Sn [8].

Photofission of uranium is mainly induced by the excitation of the giant dipole resonance of ^{238}U at $E_\gamma \sim 15$ MeV. The GEANT simulations show that the rate of photofission per unit beam power for the optimized target geometry does not depend strongly on the incident electron energy: $\sim 10^8$ fission/W.

After the beam power upgrade to 1 kW, fission rate of $\sim 10^{11}$/s is expected to result in the production rate of ^{132}Sn to about 10^9/s.

The commissioning of the UC_x targets has already begun and fission products, the ^{132}Sn isotope, were successfully extracted from ERIS after mass separation, transported and identified.

2.4 *Electron spectrometer*

An electron spectrometer has been constructed and its commissioning will soon begin. It consists of a dipole magnet and a set of drift chambers at both the entrance and the exit of the magnet to measure the trajectories of the scattered electrons, as shown in figure 3.

In order to measure the elastic scattering cross-section, the spectrometer must have the momentum resolution better than $\Delta p/p \sim 1 \times 10^{-3}$. This resolution is needed to identify the elastic scattering events from those of inelastic scattering. In addition, the spectrometer should cover a wide range of scattering angle (30–60°) enabling one to measure an accurate angular distribution, and have enough acceptance of scattered electrons from the spatially extended target, $\sim$500 mm, along the electron beam. This angular coverage corresponds to the momentum transfer range from 80 to 300 MeV/c for 150 and 300 MeV electron beam energies.

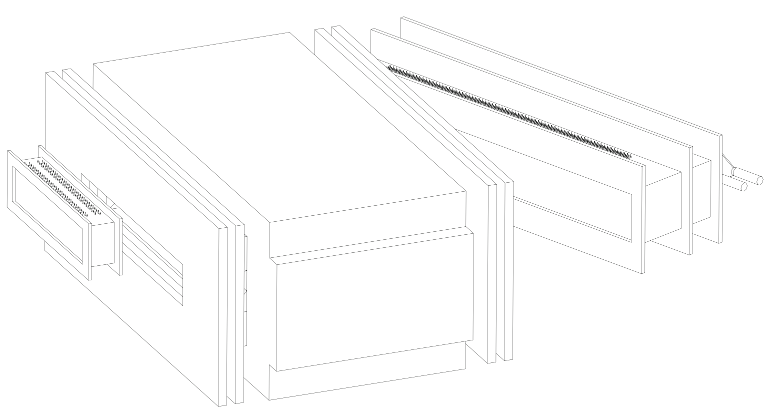

Figure 3. Electron spectrometer.

In order to fulfill these requirements, a window-frame shaped dipole magnet with a gap of 170 (width) $\times$ 29 (height) $\times$140 cm (length) is employed. Such a magnet is known to provide uniform magnetic field distribution over the whole gap region. Two field-clamps were installed on each side to minimize the field leakage at the position of the circulating electron beam.

The magnetic field distribution in the wide region including the gap region has been measured using a three-dimensional hole probe at 4 and 8 kG excitations corresponding to the electron beam energy of 150 and 300 MeV, respectively. The absolute value of the magnetic field has been continuously monitored by an NMR system during the measurements. Good uniformity of the distribution is confirmed, and the residual field at the electron beam position is found to be about 5 G which is considered to be acceptable.

The OPERA-3D calculations [9] is found to reproduce the measured field distribution reasonably well with an accuracy of 10^{-3}. Further improvements in calculation is underway so that the calculated field distribution can be used for ray tracing.

3. Performance studies of the facility

A series of performance studies of the whole facility has been conducted immediately after commissioning the accelerator [10]. The primary objective was to study the luminosities achievable at the new facility. The electron beam energy was fixed as 150 MeV.

As the ERIS device was under construction, stable Xe ions were used instead of unstable nucleus. The electron magnetic spectrometer was not yet available, and so an electron detection system consisting of pure CsI calorimeters and a drift chamber was used whose energy resolution was not suitable for resolving elastic scattering events unambiguously.

Natural Xe gas ionized at ERIS was pulsed, accelerated to 6.05 kV, mass separated and transported to the SCRIT system. The pulse width was set as 300 μs. The size of the ion beam at the merging position with the electron beam was tuned to be about 1 mm in radius. Optimization of the spatial overlap between the electron beam and the injected Xe ions was done by measuring the scattered electrons at an extremely forward angle, where the elastic cross-section was huge [11].

Ion-trapping cycles were repeated at a frequency of 20 Hz at a storage beam current of about 200 mA. In order to mimic the target with short-lived nuclei, the trapping time was set at 45 ms. The Xe ions were injected every two cycles by controlling the grid of the ion source for repetitive measurements of the scattered electrons with and without the trapped Xe ions.

In order to measure the collision luminosity of the electron beam and the trapped Xe ions, the scattered electrons were detected by the electron detection system. As the elastic cross-section for Xe is rather well predicted from the charge distribution systematics, the luminosity is determined by measuring elastically scattered electrons. Here, it is interesting to note that elastic electron scattering data are not available for even stable Xe isotopes, probably due to the difficulties in preparing isotopically-separated Xe target. It is now easy to perform such measurements for even stable nucleus at the SCRIT Facility.

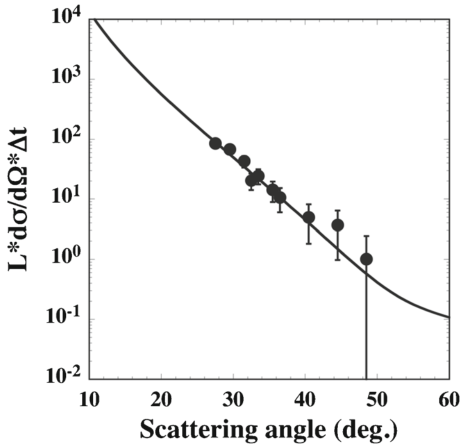

Figure 4. Xe angular distribution. The line denotes the result of DWBA calculation.

It should be noted here that a contribution from inelastic scattering is safely neglected under this kinematics, where the momentum transfer is as low as 80–120 MeV/c.

Figure 4 shows the angular distribution of the elastic scattering events after correcting for the detector acceptance. Detailed analysis including a DWBA calculation using DREPHA code [12] estimated the absolute luminosity achieved to be $4\times 10^{26}/\text{cm}^2/\text{s}$. The number of injected Cs ions was $2 \times 10^9/\text{s}$ on average, and about 17% of them were found to contribute to the collision luminosity [11]. This is close to the luminosity required of elastic scattering of short-lived nuclei. We, thus, conclude that elastic electron scattering experiments for short-lived nuclei are feasible at the SCRIT Electron Scattering Facility.

4. Physics programme and future perspectives

As mentioned, the construction of the facility is almost complete and the facility has been partly commissioned. The facility has already demonstrated that the luminosity required for elastic scattering is achievable. Currently, the commissioning of the ISOL system is underway.

The SCRIT Electron Scattering Facility will soon be ready for operation, and it is expected that the first scattered electrons from short-lived nucleus trapped in the SCRIT system will be observed in 2014.

The goal of the facility is to determine the charge density distributions of many short-lived isotopes. The first target nucleus of the electron scattering experiment is the Sn isotopes including the doubly magic nucleus ^{132}Sn whose lifetime is 40 s. A series of electron scattering for unstable Sn isotopes will reveal a systematic change of charge distributions of Sn for 20 neutron differences, i.e., ^{112}Sn–^{132}Sn. We shall, then, extend the elastic scattering experiments to other short-lived isotopes once the elements are available from the ISOL system.

A peculiar 'bubble' structure in the charge density distribution is suggested in ^{46}Ar [13], which is due to an inversion of the 1/2 state with the states usually located above in the neutron-rich Ar isotopes. Elastic electron scattering is the only way to quantify this structure if it exists.

As the luminosity improves, studies beyond elastic scattering for charge density distribution measurements will gain attention. For instance, the measurements of inelastic scattering will be feasible with the luminosity of $\sim 10^{28}/\text{cm}^2/\text{s}$. One determines the transition densities of a specific excitation level, from which one obtains information on the wave function of the excited states as demonstrated for stable nuclei.

Recently, a new research possibility at the electron scattering facility was identified; possible determination of the total photoabsorption cross-section of short-lived nuclei [14]. The total photoabsorption is the most basic response of an atomic nucleus to external fields, and the cross-section of many stable nuclei have been measured [15].

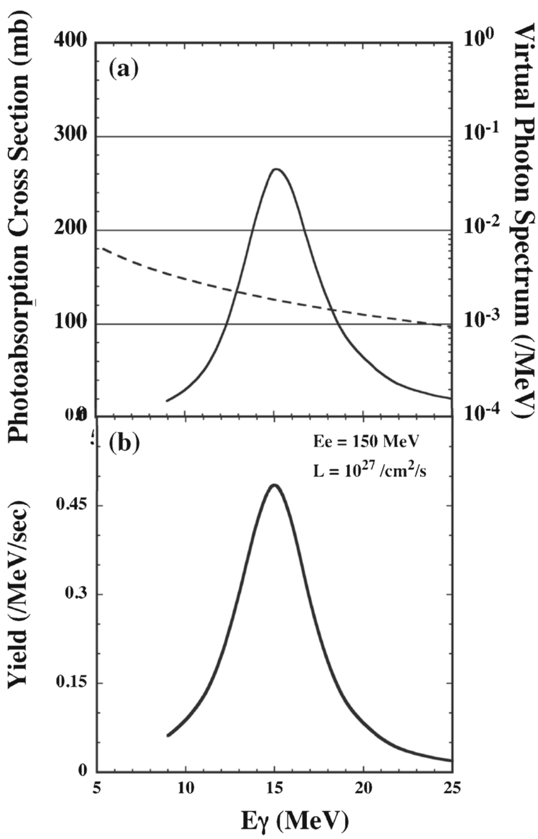

Figure 5. (**a**) The expected photoabsorption rate at the GDR region of Sn isotope (solid line) and the calculated virtual photon flux (dashed line). Note that the total photoabsorption cross-section for stable ^{124}Sn is used. (**b**) Expected event rate at a luminosity of $10^{27}/\text{cm}^2/\text{s}$.

It is known that there are several (E1) sum rules connecting the integrated total photoabsorption cross-section to the ground-state properties, such as the number of nucleons, mean radius and polarizability. In addition to the sum rules, the effects of ground-state deformation are known to appear as the photonenergy dependence of the giant dipole resonance [16].

So far, the total photoabsorption cross-sections of exotic nuclei have been studied with Coulomb excitation. Exotic nuclei are obtained by fast secondary beams impinging on a high-Z target, such as Pb. Detecting all possible final states in the inverse-kinematics, the total photoabsorption cross-sections were determined in the limited excitation energy range, typically up to 20 MeV.

It is realized that the SCRIT facility can be used to determine the total photoabsorption cross-section of exotic nucleus. As electron beam is used to excite the target nucleus, one is completely free from any problem related to the reaction mechanism, which has always been difficult in the Coulomb excitation in heavy-ion collisions. It is well known that the inelastic electron scattering cross-section at the ultraforward angle is equivalent to those of excitation by real photons [17]. The inelastic cross-section at the forward angle is measured to determine the photonuclear response of exotic nuclei in the photon energy range from a few MeV to 40 MeV, which includes the GDR completely. The luminosity achieved for elastic electron scattering, $\sim 10^{27}/\mathrm{cm}^2/\mathrm{s}$, is high enough for the measurement as the virtual photon flux at the forward angle scattering is huge. The calculated virtual photon flux, photoabsorption and the expected counting rate as a function of photon energy are shown in figure 5.

Inelastically scattered electrons at the forward angle will be momentum-analysed and detected by the bent magnet of the storage ring. Knowing the absolute luminosity, one can determine the total photoabsorption cross-section. A feasibility study for detecting lower-energy electrons inside the dipole magnet was carried out with success.

5. Conclusions

The SCRIT Electron Scattering Facility will open a completely new research field in nuclear physics: the structure studies of short-lived nuclei by electron scattering. The primary goal of this facility is to determine their charge density distributions for the first time by elastic electron scattering. The minimum required luminosity, $\sim 10^{27}/\mathrm{cm}^2/\mathrm{s}$, has been demonstrated to be feasible at this facility. The target for the world's first electron scattering experiment is set to the Sn isotopes including the doubly magic nucleus ^{132}Sn. The first observation of scattered electrons from exotic nucleus will be done in the year 2014. An additional research possibility of this facility, the measurement of the total photoabsorption cross-section, has been identified, and its feasibility study has begun.

Acknowledgement

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