Electron Scattering for Exotic Nuclei

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Abstract.

Electron scattering is known to be one of the key experimental tools to study detailed internal structures of atomic nuclei, though its application to production-hard short-lived nuclei was not possible to date. Due to advances in accelerator technologies with efficient production scheme of unstable nuclei, the world’s first electron-scattering facility for exotic nuclei has started its operation. Long-awaited structure studies of exotic nuclei by electron scattering will be soon realized.

1. Introduction

It is well known that electron scattering is the best probes for the structure studies of atomic nuclei. Indeed, it has been playing an essential role in revealing their internal structures and in establishing modern pictures of the nuclear structure. Following the pioneering works by R. Hofstadter and his colleagues [1, 2, 3, 4], electron scattering has been consistently a unique and irreplaceable probe for nuclear structure studies.

Their reasons are:

- electron is a point-like particle,
- the interaction is precisely described by quantum electrodynamics (QED),
- the momentum transfer is variable for a fixed energy transfer.

There are many excellent review papers [5, 6, 7], and textbooks [8, 9], on electron scattering for nuclear physics, to which we refer the readers.

So far, the nuclei ever targeted for electron scattering experiments have been primarily limited to stable ones as shown in Fig. 1. To be exact, some unstable nuclei have been studied in details by electron scattering. They are such as 3H, 14C and 41Ca whose lifetime are rather long and, of course whose structure studies were important. It should be noted here that electron scattering has never been applied for short-lived exotic nuclei whose production is hard and half-lives are short.

In order to realize electron scattering for exotic nuclei far from the stability line, a key parameter is naturally the collision luminosity between electron and exotic nuclei, since one must cope with the small number of target nuclei that can be prepared, due to their small production probability and short half-lives.

The luminosity \( \mathcal{L} \) is defined as
Figure 1. Nuclei ever studied by elastic electron scattering [11] are shown by red squares. Magic numbers known for stable nuclei are shown by back (red) lines for neutrons (protons).

\[
\frac{dN}{dt} = \mathcal{L} \times \sigma, \tag{1}
\]

where \(dN/dt\) is the event rate of electron scattering per unit time and \(\sigma\) is the scattering cross section to be measured.

To begin with, it may be useful to show the luminosities realized for "traditional" electron-scattering experiments with a fixed target. Assuming that electron beam with the intensity of \(N_e\) [s\(^{-1}\)] irradiate a fixed target whose thickness is \(N_t\) [cm\(^{-2}\)], the luminosity, \(\mathcal{L}\) [cm\(^{-2}\)s\(^{-1}\)], reads,

\[
\mathcal{L} [\text{cm}^{-2}\text{s}^{-1}] = N_e [\text{s}^{-1}] \times N_t [\text{cm}^{-2}]. \tag{2}
\]

For a fixed-target electron scattering experiment, \(N_t\) is given by

\[
N_t = \frac{t \rho N_A}{A}, \tag{3}
\]

where \(t\) is the target thickness, \(\rho\) is the density, \(N_A\) is the Avogadro constant, and \(A\) is the mass number, respectively.

In early day's experiments such as those of Hofstadter [1], the electron beam current and the target thickness were typically \(10^9\) s\(^{-1}\) and an order of \(10^{19}\) cm\(^{-2}\), resulting in a luminosity, \(\mathcal{L}\), of an order of \(10^{28}\) cm\(^{-2}\)s\(^{-1}\). Today, at modern electron-scattering facilities such as JLAB, an
extremely high luminosity is realized, which enables one to measure quite small cross sections such as those involves the weak interaction. On example is parity-violating electron-scattering experiments, where the intensity of the high-energy electron beam of an order of $10^5 \mu A$, $N_e \sim 10^{15} \text{s}^{-1}$ with a quite thick target of $\sim 10^{21} \text{cm}^{-2}$ yields the luminosity of an order of $10^{36} \text{cm}^{-2} \text{s}^{-1}$ [10].

In this report, I will discuss never-yet-performed electron scattering for exotic nuclei and show the world’s first electron-scattering facility for exotic nuclei constructed in RIKEN RI Beam Factory in operation.

2. Electron scattering for exotic nuclei
Due to the fact that very low luminosities for electron scattering experiments with exotic nuclei are anticipated, it is reasonable to discuss elastic electron scattering as the first generation experiments, like the pioneering works for stable nuclei by R. Hofstadter and his colleagues about a half century ago. This is because the elastic cross section is the largest among all electron-scattering processes at least up to medium momentum transfer.

The PWIA elastic cross section for a spin-less nucleus is expressed as,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{\text{Mott}}}{d\Omega} |F_c(q)|^2,$$

where $d\sigma_{\text{Mott}}/d\Omega$ and $|F_c(q)|$ are the Mott cross section and the charge form factor, respectively. The Mott cross section describes electron-scattering cross section off a point particle with the charge $Z$ under ultra-relativistic limit, namely $m_e \rightarrow 0$,

$$\frac{d\sigma_{\text{Mott}}}{d\Omega} = \frac{Z^2\alpha^2 \cos^2(\theta/2)}{4E_e^2 \sin^4(\theta/2)}. \quad (5)$$

Here, $\alpha$ is the fine-structure constant, $\theta$ is the electron scattering angle.

The form factor is the Fourier component of the charge density distribution, $\rho_c(r)$, at the momentum transfer $q$.

$$F_c(q) = \frac{1}{(2\pi)^3/2} \int \rho_c(\vec{r}) e^{-\vec{q} \cdot \vec{r}} d^3r,$$

The main physics goal of electron scattering off short-lived nuclei is to determine the charge density distributions [12] by measuring elastic-scattering cross section. For exotic nuclei, however, one must accept the fact that the anticipated low luminosities limit the accessible momentum transfer range due to the $q^{-4}$-dependence of the cross section. Thus, the measurements will be in the limited $q$ range, resulting that only gross features of the radial properties of the charge distribution will be revealed. Even under such limitation, the findings will certainly be essential inputs for nuclear-structure models applicable to exotic nuclei, and surely go beyond the root-mean-squared radii by the isotope-shift measurements, which are integrated quantities of the charge density.

3. Electron scattering facility
A novel experimental technique based on the trapped-ion scheme, named SCRIT (Self-Confining Radioactive isotope Ion Target), was proposed in 2004 by Wakasugi et al. as a new way for realizing electron scattering off exotic nuclei [13].

The SCRIT technique uses an ion-trapping phenomenon notoriously known at electron storage rings such as synchrotron radiation facilities. Ion trapping is a phenomenon that residual-gas ions ionized by the electron beam are immediately trapped by the electron beam itself. The trapped ions staying in the electron beam kick out the circulating electrons, that is nothing but
electron scattering off the trapped ions. Since the ion trapping reduces the beam lifetime and the facility performances, much effort has been paid so far to remove the effect.

The SCRIT concept uses this ion-trapping in a positive way to keep the exotic-nucleus ions staying on the high-energy electron beam. One of the advantages over the collider scheme is that electron scattering off exotic-nucleus target takes place automatically once the ions are trapped on the electron beam. A series of proof-of-principle experiments conducted to study the feasibility of the SCRIT scheme have demonstrated that it fulfills the luminosity requirements for elastic electron scattering with a small number of target ions, such as $10^7 - 8$ [14, 15], and their success have pushed forward the construction of the world’s first electron scattering facility dedicated to short-lived nuclei based on this method. Construction of the facility started in the year 2009 at the RIKEN RI Beam Factory in Japan, and the final commissioning experiment using stable $^{132}\text{Xe}$ has been successfully completed in 2017.

Figure 2. The SCRIT electron scattering facility in RIKEN RI Beam Factory.

Figure 2 shows the layout of the SCRIT electron-scattering facility. The details of the facility are described elsewhere [16]. The facility consists of electron accelerators, an ISOL (Isotope Separator On-Line) system, and detectors. The electron accelerators include a 150-
MeV racetrack microtron (RMT) and a 700-MeV electron storage ring equipped with a SCRIT system (SR2). RTM acts both as an injector to SR2 and a driver for the ISOL system.

The SCRIT system, which is the heart of the facility, consists of a set of ion-deflectors, three electrodes and an ion analyzer. A set of ion-deflectors controls the injection (ejection) of ions into (out of) the trap region. Once the ions are merged with the circulating electron beam, they are automatically guided toward the electrodes with the transverse confinement by ion trapping. The three racetrack-shaped electrodes form a mirror potential along the electron beam to trap the ions in the longitudinal direction. The potential of the central electrode is adjusted so that the kinetic energies of the trapped ions are of the order of eV.

The ISOL system, named ERIS (Electron-beam-driven RI separator for SCRIT), is a generator of neutron-rich exotic nuclei via the photo-fission of uranium [17]. The long lifetime of the stored beam of SR2 enables us to operate RTM as a driver for ERIS after the beam injection to SR2. Produced exotic nuclei are extracted from ERIS as positive ions, followed by mass separation. They are, then, cooled and bunched by FRAC [18] followed by transferring the ions to the SCRIT device as a pulsed ion beam. Today, fission fragments, such as $^{132}$Sn and $^{138}$Xe isotopes, are produced and identified using house-made uranium targets at a beam power of about 10 W[17].

The detectors comprise a magnetic-spectrometer system, WiSES (Window-frame Spectrometer for Electron Scattering), for measuring scattered electrons from exotic nuclei, and a calorimeter system for measuring the collision luminosity. WiSES consists of a large window-frame dipole magnet, a pair of drift chambers sandwiching the magnet for trajectory measurements, and a plastic-scintillator trigger system. The 20 cm gap of the dipole magnet is filled with He gas to minimize the multiple-scattering effect. WiSES detects scattered electrons covering a wide scattering angular range, $30^\circ \leq \theta \leq 60^\circ$, from a spatially extended target formed by the SCRIT system ($L = 50$cm). The designed momentum resolution is $\Delta p/p = 10^{-3}$ for $E_e = 300$ MeV. The azimuthal angular coverage ranges from $\pm 5^\circ$ to $\pm 10^\circ$ depending on the scattering angle $\theta$.

The collision luminosity between the electron beams and the trapped target is continuously monitored during the electron-scattering measurements. One detects the bremsstrahlung photons produced by the collision at the SCRIT region. The luminosity monitor consists of a calorimeter with seven large CsI crystals for energy measurements, as well as plastic-fiber scintillators to measure the spatial distributions by detecting pair-produced electrons and positrons of bremsstrahlung photons. The luminosity monitor is placed $\sim 7$ m downstream from the SCRIT system.

The SCRIT facility is only an electron-scattering facility dedicated for short-lived exotic nuclei in operation as of today. There are several future plans of electron scattering facilities for exotic nuclei, such as the ELISe project of GSI/FAIR, an electron-ion collider of the DUBUNA DERICA project and an ETIC (electron-trapped ion collider) project of Saclay.

4. The first physics results from the SCRIT facility
In order to demonstrate performance of the new facility, we have performed an elastic scattering measurement using the stable $^{132}$Xe as a target nucleus. It is worth pointing out here that no stable Xe isotopes had ever been studied by electron scattering [11]. The measurement was carried out by fully mimicking that for exotic nuclei.

The difference was to use natural Xe gas instead of beam irradiation to the uranium target to produce exotic nuclei. The natural Xe gas was supplied to ERIS followed by ionization at ERIS. The mass-separated $^{132}$Xe ions were cooled and bunched at FRAC, then delivered to the SCRIT device. The number of the injected $^{132}$Xe ions was $\sim 2 \times 10^8$/pulse, and the number of $^{132}$Xe contributing to electron collisions was estimated to be on the order of $10^7$.

The ion-trapping cycles were repeated at a frequency of 2 Hz under a stored beam current
of 180 - 250 mA, and the $^{132}$Xe ions were injected every two cycles under control at ERIS. The trapping time was set to 240 ms for each cycle to simulate a short-lived isotope. Comparative measurements with and without the $^{132}$Xe ions enabled us to subtract the residual gas contribution.

![Momentum Spectra](image)

**Figure 3.** a) The momentum spectra of $^{132}$Xe($e, e'\) $E_e = 151, 201$ and $301$ MeV. b) the elastic cross section (times Luminosity) of $^{132}$Xe($e, e'\) as a function of the momentum transfer.

Figure 3 shows the momentum spectra of the scattered electrons for $E_e = 151, 201,$ and $301$ MeV. The elastic-scattering events were clearly identified in the momentum spectrum of the scattered electrons detected by WiSES. The solid and shaded histograms show the observed momentum distributions by WiSES with and without the trapped $^{132}$Xe ions. A clear peak
observed in the histograms corresponds to the elastic-scattering events from $^{132}$Xe ions. The tails toward the lower energies seen in each momentum spectrum are due to the radiative process of the elastic process. The radiative-tail contributions are corrected for in order to determine the yields of elastic events [20].

After subtracting the ion-off contributions, the elastic events are sorted by the scattering angle, and corrected for the WISES acceptance to extract the cross section. Assuming the two-parameter Fermi distribution for the $^{132}$Xe nucleus, we fit the experimental data to determine the parameters. The results show $r_0 = 5.42^{+2.09}_{-1.44}$ fm and $\alpha = 2.71^{+10.05}_{-14.05}$ fm, respectively. The obtained rms radius determined by our measurement is $4.79^{+0.17}_{-0.17}$ fm, which shows a perfect agreement with that determined by the muonic X-ray measurement, 4.787 fm[21].

5. New physics opportunity with low-luminosity electron scattering

Recently, H. Kurasawa and T. Suzuki has point out a new physics case of electron scattering for atomic nuclei [22]. They discuss the n-th order moments of the nuclear charge density distribution determined by elastic electron scattering.

The nth-moment of the charge density distribution, $\rho_c(r)$, is defined as,

$$< r^n_c > = \int r^n \rho_c(r) \, \text{d}^3r. \quad (7)$$

The second moment is known as the root-mean-charge-radius, and many of them are today available including exotic nuclei [23]. In their recent paper [22], they discussed, for the first time to our knowledge, the 4-th order moment of the charge density distribution in details in the fully relativistic framework, and pointed out that the neutron density in a nucleus is accessible through the 4th-order moment of the charge density distribution determined by elastic electron scattering.

The 4th-order moment in the fully relativistic representation is described as,

$$< r^4_c > = < r^4_{(\text{point})} > + \frac{10}{3} < r^2_{(\text{point})} > < r^2_p > + \frac{10}{3} < r^2_{n(\text{point})} > < r^2_n > \frac{N}{Z} \text{ (rel. corr.)}, \quad (8)$$

where $< r^2_p >$ and $< r^2_n >$ are the charge radius of proton and neutron, $Z, N$ are the number of proton and neutron in a nucleus, and "rel. corr." denotes the relativist correction, respectively. Combining the 2nd-order moment from which one determines the point proton radius, $< r^2_{p(\text{point})} >$, one may determine both the point proton radius and point neutron radius, $< r^2_{n(\text{point})} >$, simultaneously by elastic electron scattering.

Information for the neutron distributions in nuclei has been so far obtained mostly by hadronic probes. It is an ill problem that the extraction of the structure information from the experimental data are seriously model dependent due to their reaction mechanism. The new way that Kurasawa and Suzuki suggest, however, is free from such problem since the electromagnetic interaction is fully understood.

The experimental determination of the 4th order moment of the charge density distributions may be two folds. The first one is to determine the charge density distribution, $\rho_c(r)$, and obtain according to eq.(7). The charge density distribution is determined as the inverse Fourier transformation of the charge form factor measured by elastic electron scattering covering a wide range of the momentum transfer, eq.(6). The other way is to use the Taylor expansion of the form factor at the low momentum transfer region. It is known that the charge form factor, $F_c(q)$, has a form at low $q$ if the charge distribution has the spherical symmetry,

$$F_c(q) \sim 1 - \frac{< r^2 >_c}{6} q^2 + \frac{< r^4 >_c}{120} q^4 + ... \quad (9)$$
Since the elastic cross section has $1/q^4$ dependence, the cross section at low $q$ is huge, which may make it possible to determine the 4-th moment from low-luminosity electron scattering experiments for exotic nuclei.

As seen in eq. (7), the higher order moments have larger sensitivities at the surface of the charge distributions. One can, thus, expect larger neutron contribution in $< r^4 >$ for the neutron-rich exotic nuclei, which are targets at the SCRIT facility. Detailed studies for the SCRIT facility have just started.

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