Proposal for Nuclear Physics Experiment at RI Beam Factory  
(RIBF NP-PAC-07, 2010)

Title of Experiment: A construction proposal of an electron scattering facility for structure studies of short-lived nuclei  

[ ] NP experiment [ ] Detector R&D [x] Construction

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Experimental Device:
[ ] GARIS [ ] CRIB [ ] RIPS
[ ] BigRIPS [ ] ZeroDegree [ ] SHARAQ
[x] SCRIT

Beam Time Request Summary
Tuning with beam Days
DATA RUNS Days

Total Days

Primary Beam
Particle: Energy (A MeV) Intensity

Sheet for an experiment with RI beam
[ ] CRIB
[ ] RIPS
[ ] BigRIPS
[ ] ZeroDegree
[ ] SHARAQ

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<th>RI Beams</th>
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Your proposal should be sent to User Support Office, (UserSupportOffice@rihf.riken.jp)
Estimated date ready to run the experiment: depends on budget condition

Dates which should be excluded, if any: 

Summary of Experiments

This is a construction proposal for the electron scattering facility currently under construction at RIBF. This facility will, for the first time, enable us to perform electron scattering experiments for short-lived nuclei. Electron accelerators, consisting of an injector and a storage ring, have started its operation since the end of last year. We will determine the charge density distributions of short-lived nuclei by the measurement of elastic cross section. The “Day-one” experiment is for Sn isotopes including $^{132}\text{Sn}$.

In this constructing proposal, we propose to construct 1) an ISOL system based on photo- (and electro-) fission reaction of $^{238}\text{U}$ target and 2) the electron detection system, both of which are needed to realize electron scattering experiments for short-lived nuclei.

List of Collaborators

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A construction proposal of an electron scattering facility for structure studies of short-lived nuclei

1. Introduction

a. Electron scattering

Electron scattering provides the most reliable structure information of atomic nuclei by virtue of the fact that the electron is a point-like particle, and probes nuclei through the fairly weak and well-understood electromagnetic interaction. Since the electron scattering process off a nucleus is perfectly described by QED [1], extraction of the internal structure information from experimental data is straightforward and precise. Thus, electron scattering has consistently played a key role in the structure studies of atomic nuclei.

It has been, however, limited only to stable nuclei, that one can prepare targets for electron scattering experiments. Correctly speaking, there are several examples for unstable nuclei whose lifetime are very long, see [2], but no experiment for highly unstable (short-lived) nuclei, locating far from the stability line, has been ever conducted.

The final goal of this proposal is the measurements of the charge distribution of short-lived nuclei by elastic electron scattering. Even after the Nobel-prize experiments by R. Hofstadter and his colleagues about a half century before, elastic electron scattering is still one and only way to determine the charge density distribution.

b. A novel technique to realize electron scattering off short-lived nuclei

To realize electron scattering for short-lived nuclei, we have proposed a novel internal-target forming technique, named SCRIT (Self-Confining RadioIsotope Target) [3], which is based on the ‘ion trapping’ phenomena notoriously known at electron storage rings. SCRIT aims at forming a target of short-lived nuclei of interests on electron beam in an electron ring. Since the target ions are confined on electron beam, electron scattering takes place automatically and rather high luminosity is expected using small number of ions.

To demonstrate feasibility of this new idea, a prototype was constructed and installed at the electron ring (KSR) of Kyoto University. After years of R&D efforts, this technique has been finally demonstrated to be a way to our physics goal [4, 5]. Details of the R&D studies will be described below.

c. Electron scattering facility at RIBF

Based on the success of the SCRIT feasibility studies, we started to plan an electron scattering facility at RIBF. This project had been, fortunately, boosted up with two fortunate events;

1) donation of a 700-MeV electron ring from SHI (Sumitomo Heavy Industries), who terminated its use as a synchrotron-radiation light source facility,
2) FY2008 supplementary budget from the government that enabled us to install the ring at RIBF.

The electron accelerator and related infrastructures have been already installed, and the commissioning of the electron accelerator is now underway to recover its performance.
Short-lived nuclei will be produced by electro- (and photo-) fission reaction of uranium, \(^{238}\text{U}\). Due to the long beam lifetime of the electron ring; typically a few hours, a 150-MeV injector microtron can be used mostly for isotope production. A new ISOL system is under designing.

Scattered electrons will be detected by a magnetic spectrometer to identify elastic scattering. The spectrometer will cover a wide scattering angular range, 30 - 60 deg. at once, and have an acceptance for a long target region, 30 - 40 cm.

d. Purpose of this construction proposal

We submit this construction proposal in order to ask the PAC review of our project whose construction is currently underway, and to get further support to complete the proposed electron scattering program at RIBF. In addition, we appreciate very much if we get comments from the PAC to make our facility useful and fruitful.

Specifically, we propose constructions of the ISOL system and the spectrometer, which are now missing in the budgetary aspect. We would like to have a support from Nishina Center for the ISOL construction including basic infrastructure such as a hot laboratory. The total costs estimated is about 2 M$.

As for the spectrometer we are making efforts to request a construction budget, 2M$, of Grants-in-Aid for Scientific Research from JSPS (Japan Society for the Promotion of Science). Our application got through screening, and is in the final stage of review. We will be notified of the results in the end of the coming May.

2. Physics Case

Since no electron scattering has been ever conducted for short-lived nuclei, any experiment will provide brand-new data for their internal structure. To start with, elastic cross section will be measured. This makes sense because elastic cross section is largest among scattering processes at low momentum transfer region and one determines the charge density distribution, one of the basic ground-state properties of a nucleus.

a. Elastic scattering and charge density distribution

The differential cross section from a spin-less nucleus under PWIA (Plane Wave Impulse Approximation) is given as

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

where \(\sigma_{\text{Mott}}\) is the Mott cross section, and \(F_c(q)\) the charge form factor. \(q\) is the momentum transfer defined by incident and scattered electron momentum vectors as

\[
\vec{q} = \vec{e} - \vec{e}'.
\]

The Mott cross section is the elastic cross section from a point particle of charge \(Z\),

\[
\sigma_{\text{Mott}} = \frac{(Z\alpha)^2 \cos^2 \left(\frac{q}{2}\right)}{4e^2 \sin^4 \left(\frac{q}{2}\right)},
\]
where $e$ is an electron energy, $\theta$ scattering angle and $\alpha$ the fine-structure constant. The form factor is a Fourier component of the charge density distribution, $q_c(r)$, for a momentum transfer $q$,

$$F_c(q) = \int \rho_c(r)e^{-i\hat{q} \cdot \hat{r}}d\hat{r}.$$ 

One can, thus, determine $q_c(r)$ of a target nucleus from the elastic cross section measured over the momentum transfer $q$. For the most of stable nuclei, a complete data set of their form factors measured up to high momentum transfer region, equivalently precise charge density distribution, are available [2].

For short-lived nuclei, one may not be able to assume that the elastic cross section will be measured up to high momentum transfer region, since not-high luminosities expected for rarely-produced short-lived nuclei will limit an accessible momentum transfer range. Note that the elastic cross section decreases as $1/q^4$.

The measurement in a limited momentum transfer range will reveal only gross features of the charge distribution, such as only the radius and surface diffuseness. Despite this limitation, however, those radial properties along the isotopic chains would be certainly very important, and be essential as inputs for any nuclear structure models applicable for short-lived nuclei.

Figure 1 shows the results of a toy-model calculation for the charge form factor of Sn. A two-parameter Fermi distribution, a typical profile of stable nuclei, is assumed in the calculation,

$$\rho(r) = \frac{\rho_0}{1 + e^{\exp\left(\frac{r-r_0}{a}\right)}}.$$ 

The results modifying the parameters for the diffraction radius, $r_0$, and the surface diffuseness, $a$, for ±5 % and ±10 % are plotted together. The dip position and the height of the diffraction maxima are independently sensitive to the change in size and diffuseness. The form factor measurement covering the first maximum will, thus, allow us to determine the (diffraction) radius and the surface diffuseness.

In reality, the PWIA framework is known to be not adequate for medium and heavy nuclei, such as Sn isotopes, due to serious distortion of the incoming and outgoing electron waves in the Coulomb fields of the nucleus. The distortion effects can be precisely treated by the partial wave analysis. Figure 2 shows the results of distorted wave calculations using DREPHA [6], and the
similar sensitivities to changes of radius and surface diffuseness are found even with the serious distortion.

![Momentum transfer (MeV/c) vs. $d\sigma/d\Omega$ (cm$^2$/sr) for Sn isotope calculated by a distorted-wave calculation, DREPHA [6].](image)

The parameters for the size, $r_0$, and diffuseness, $a$, in the Fermi distribution are changed for $\pm 5\%$ and $\pm 10\%$, respectively.

b. Day-One experiment: the charge density distribution of $^{132}\text{Sn}$

The targets for the Day-One electron scattering experiment are unstable Sn isotopes including $^{132}\text{Sn}$. The $^{132}\text{Sn}$ nucleus is a doubly magic nucleus whose life time is 40 seconds.

The Sn has the largest number of stable isotopes among elements, i.e. $^{112}\text{Sn} - ^{124}\text{Sn}$. Consequently, their charge density distributions precisely determined by elastic electron scattering are available [7]. Figure 3 shows the mass (equivalently neutron) number dependence of the parameters of the charge-density distribution of the stable Sn isotopes. Clear neutron-number dependence of the RMS (root-mean-squared radius) and surface diffuseness were observed.

We will be able to extend the plot up to the mass number 132 in the Day-One experiments. Electron scattering for $^{132}\text{Sn}$ (including also $^{126}\text{Sn} - ^{130}\text{Sn}$) will show how the charge distributions change with further additional neutrons.

Fig. 3. The mass number dependence, equivalently neutron number dependence, of the RMS radius and the surface diffuseness of stable Sn isotopes determined by elastic electron scattering [7].

Precise measurement of the neutron-number dependence of the charge density distribution over a wide range of neutron numbers will shed a light on the isospin dependent term in the potential which may create a deeper potential for the protons with increasing neutron number. In addition, one may learn how the proton and neutron distribution can decouple each other.
Figure 4 shows the results of a simulation using the DWBA code under experimental conditions currently planned; luminosity of $1 \times 10^{27}$ /cm$^2$/s and 5-day measurement. According to the results of the simulations, it is expected to determine the size and the diffuseness with an accuracy better than a few %. The luminosity of $1 \times 10^{27}$ /cm$^2$/s is the required luminosity for elastic electron scattering for Sn isotopes.

![Graph showing expected counting rate of elastic scattering for Sn](image)

**c. Other physics opportunities**

**Elastic scattering**

**Other elements**: it is straightforward to extend elastic scattering experiments to other short-lived elements if they are available from the ISOL system. A series of experiments for many elements along isotopic chain will be essential input for any sophisticated nuclear structure models.

**Peculiar structure**: Recently, CAEN theorists predict a “bubble” structure in the charge density distribution of $^{46}\text{Ar}$ [8], which can be identify only by elastic electron scattering.

**Beyond elastic scattering**

When higher luminosities, $\sim 10^{28-29}$ /cm$^2$/s, are realized, the measurements of inelastic scattering including giant resonance excitation become possible. From inelastic scattering experiments, one can determine the transition density of a transition to a specific level, and study on dynamical behavior of collective motion at nuclei where the numbers of proton and neutron are not balanced. Under this luminosity, the coincidence experiments, (e,e$'$p) type, in the quasi-elastic kinematics will be also possible. One determines the single particle properties of the bound protons, and their spectroscopic factors [9].

In an extreme case with much higher luminosity than $\sim 10^{30}$ /cm$^2$/s, one may probe the single neutron properties through magnetic electron scattering, in principle. So far, the most precise information on the neutron orbit for stable nuclei was obtained by magnetic elastic scattering [10].
3. Electron scattering facility based on the SCRIT technique

a. SCRIT and its R&D studies

SCRIT (Self-Confining RI Target) is a novel target-forming technique utilizing “ion trapping” phenomena known at electron storage rings [3]. While the phenomena is problematic for the stability of the stored electron beam, it will provide a new way to form a target of short-lived nuclei on the electron beam. Since the target ions are trapped on electron beam, electron scattering takes place automatically and rather high luminosity is expected using a small number of ions.

“Ion trapping” confines transversely ions of interests. The longitudinal confinement of the ions will be realized by a longitudinal mirror potential produced by electrodes placed along the electron beam. In this way, a three-dimensionally localized target of short-lived nuclei is produced on the circulating electron beam in an storage ring.

A control of applied voltage for electrodes to form the mirror potential enable us to manipulate the trapped ions of interests, namely controlling injection, trapping for electron scattering measurement and ion ejection from the trapped region. This cycle, whose repetition needs to be controlled depending on the lifetime of the target nuclei, is essential to keep target “purity” for short-lived nuclei.

In order to study whether the required luminosity, $1 \times 10^{27}$ /cm$^2$/s, is achievable with this new technique, we installed a SCRIT prototype at an electron storage ring, KSR [11], of Kyoto University. The electron energy is 120 MeV, and a typical stored beam current is 70-80 mA with the beam lifetime of about 100 second. For this study, a stable nucleus, $^{133}$Cs, was employed.

The prototype installed at the 2-m straight line of KSR, shown in Fig. 5, consists of an external Cs ion source, electrodes for forming the mirror potential, an analyzer for monitoring the Cs ions extracted from the trap, and electron detector, all of which are in vacuum except the electron detectors consisting of a drift chamber and calorimeters.

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At an averaged electron beam current of 75 mA, we repeated the ion injection-trap-ejection cycle with the trapping time of 50 ms to simulate short-lived nuclei, and tried to measure elastically scattered electrons from the trapped Cs ions. Clear signals of elastically scattered electrons from ions at the trapped region were observed, and their angular distributions clearly shows that they are from the trapped Cs ions, not from the trapped residual gas such as hydrogen, C, O etc., as shown in Fig. 6 [5]. This is the first demonstration of elastic electron scattering with the SCRIT scheme.

Detailed analysis shows that the luminosity of $1 \times 10^{26}$ /cm$^2$/s was achieved at the averaged electron beam current of 75 mA with $10^6$ trapped ions. The luminosity achieved in the R&D study at KSR was found to be one order lower than that of required. However, since much improved luminosities can be expected with larger stored electron-beam current and improved ion-injection technique, we conclude that the SCRIT technique will provide the requested luminosity for elastic scattering measurements.

**b. Electron scattering facility at RIBF**

Figure 7 shows a layout of the electron scattering facility at RIBF. It consists of an electron accelerator, an ISOL system and an electron detection system. The electron accelerator consists of a 150-MeV injector microtron and 700-MeV electron storage ring donated from SHI in 2008. With the support of the FY2008 supplementally budget from the government, they were already installed at the B1F floor of the RIBF building.

The basic configuration of the electron ring is the same as that of the SR light source facility, HiSOR [12]. Immediately after install completion, its commissioning has started since last December. Commissioning activities are underway without any serious troubles. Currently, pulsed 150-MeV electron beam with the peak current of 0.5 mA and the pulse width of 1 μs is continuously injected with the repetition rate of 2 Hz to fill the ring. After filling the ring, the electron energy is ramped up to 700 MeV, which takes about a minute. The peak current, pulse width and reputation rate of the beam injection to the ring will be switched to higher values when the commissioning stage is over.

We are continuing the highest energy operation to provide highest power of synchrotron radiation for vacuum improvement, which is crucial for higher beam current and longer beam lifetime. According to our experience from the commissioning, a few hundred mA stored current with a beam lifetime of a few hours will be realized without difficulties.

Much improved electron-beam conditions of the present facility compared with KSR, such as stored current, stability and beam lifetime etc., will bring much higher luminosity with the same number of trapped ions. The detailed study of achievable luminosity at this new facility will start this summer using stable Cs ions.
c. ISOL

Production of short-lived nuclei, specifically Sn isotopes including $^{132}\text{Sn}$ for the Day-One experiment, will be carried out using 150-MeV electron beam bombarding on an uranium carbide target, $^{238}\text{UC}_x$. Photo-fission (and electro-fission) of uranium is known to be a very efficient way to produce Sn isotopes, especially those around $^{132}\text{Sn}$ [13].

Photo-fission of uranium is mainly induced by an excitation of the giant dipole resonance of uranium at $E_\gamma \sim 15$ MeV. Since an incident energetic electron beam is immediately converted to lots of low energy $\gamma$, e$^-$ and e$^+$ through electromagnetic-shower process in the target, the incident electron energy is not so crucial. 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 becomes larger than 100 MeV.

Since a long beam lifetime (a few hours) of the storage ring will allow us to use the injector microtron mostly for isotope production, we decided to build an ISOL system using the photo-fission process of uranium. Although it is anticipated to connect this electron scattering facility to the PALIS facility [14], for example, at BigRIPS in future, the proposed ISOL system makes a stand-alone operation of the electron scattering facility possible. We believe this is very important and efficient to perform rather long-term measurements, typically one week, for many short-lived nuclei.

The ISOL system, shown in Fig. 8, is being designed based on construction- and operation-experience of JAEA-ISOL [15] with the proton beam of 36 MeV and 3$\mu$A, whose beam power is similar to our beam power of 100 W. The main player is Dr. S. Ichikawa, who has much experience for construction and operation of the JAEA-ISOL. The detailed design of the whole
system including local shielding, an ion source, a remote handling system of the ion source, used-UCx target handling system etc. are intensively underway.

The average yield of $^{132}$Sn in the photo-fission process is known to be around 1 % [13]. Therefore, the production rate of $^{132}$Sn is expected to be about $10^8$ s$^{-1}$ at 100-W electron beam power. An efficient extraction with a good separation of the target isotopes, their pulsing for the SCRIT injection after accumulation are both important R&D issues.

![Diagram of ISOL system](https://via.placeholder.com/150)

Fig. 8. The ISOL system. A 150-MeV electron beam from the injector microtron bombards a UCx target. Produced isotopes are extracted from the ion source, and mass-separated. Further purification of element separation and forming pulsed ion beam after accumulation for the SCRIT injection are also performed.

Improvement of the beam power from 100 W to 1 kW is foreseen in future by increasing reputation rate up to 150 Hz with wider pulse width of 10μs, which requires replacement of the krystron and its modulator. The shielding walls of the RIBF building accepts this improvement.

**d. Electron spectrometers**

In order to identify elastic scattering, an electron detection system must have an energy (or equivalently momentum) resolution to resolve at least 1 MeV excitation energy. Consideration of momentum transfer region we must cover and the geometrical configuration, the electron energy will be in the range of 150 - 300 MeV as shown in Fig.4. The momentum resolution of the electron detection system, thus, must be better than $3 \times 10^{-3}$.

Due to the fact that the SCRIT provides spatially extended target, 30-40 cm, any focusing-type magnetic spectrometer, whose resolution can reach $1\times 10^{-4}$, can not be employed. In addition, the small solid angle of such spectrometers, typically around 10 mrad, is obviously insufficient to deal with the small yield from expected low luminosities.

Non magnetic spectrometer, employing calorimeters for example, may provide larger acceptance, but their resolution, typically larger than a few % at 150-300 MeV, is insufficient for the elastic scattering measurements.

We will, thus, employ a non-focusing magnetic spectrometer with tracking detectors placed at both the entrance and exit of the magnet to measure the trajectories of the scattered electrons.
The magnet is an H-type dipole type with a gap of 20 cm. At the normal field of 1 T, electrons with momentum 300 MeV/c will be deflected over 36 deg. and the length of the trajectory in the field is 860 mm. Having a precise field map and the position resolution of 150 μm of the drift chamber, the target resolution will be realized.

Fig. 9. Electron detectors and luminosity monitors. A magnetic spectrometer and calorimeters sandwich the SCRIT region. A bremsstrahlung luminosity monitor is placed at the downstream of the target region. The place for the luminosity monitor utilizing ultra-forward scattered electrons is not yet determined.

The spectrometer must cover a wide scattering angle. A wide coverage of the scattering angle is important to determine precise angular dependence of the elastic cross section. We plan to cover the scattering angle from 30 - 60 deg. at once. The solid angle will be an order of 100 msr.

In addition, we will place the calorimeters and the drift chamber, that were used for the SCRIT R&D studies, inside the ring as shown in Fig. 9. This detection system is easy to increase the solid angle by additional calorimeters in future, and also to cover a wider angular range. The energy resolution of the calorimeter for 300 MeV is about 3 %, which is obviously insufficient for elastic measurement. However, since we can estimate inelastic contribution in the momentum spectrum measured by the magnetic spectrometer, it will be possible to extract the elastic contribution in the energy spectrum measured by the calorimeter.

**e. Luminosity monitors**

We will employ two types of detectors to determine the luminosity during the measurement. They are based on the reaction processes between electron and the trapped ions; bremsstrahlung and elastic scattering at very forward angle.

The luminosity monitor using bremsstrahlung is placed at the downstream of the SCRIT region, as shown in Fig. 9. It consists of a set of collimators, a plastic veto detector, and a set of calorimeter. The collimators define the angular range for integration of the bremsstrahlung process, the plastic removes the charge particles, and the calorimeter measures the energy spectrum of the bremsstrahlung. This system enables us to determine the absolute luminosity.

The other is to utilize elastically scattered electrons at very forward angle, such as a few degrees, by the trapped ions. Since the cross section is huge, such as a few hundred barn or even more, the monitor will allow us to determine the luminosity immediately, when once calibrated. The monitor may be a very simple system, consisting of a pair of plastic scintillators. It will be
placed very close to the electron beam line at the down stream of the SCRIT region, and we measure only the number of electrons scattered from the trapped ions. In our R&D studies at KSR, its practical performances has been firmly confirmed [16].

4. Collaboration

The domestic collaborators are from RIKEN, Rikkyo Univ., Tohoku Univ. and Nagaoka Univ. of Technology. In addition, we have collaborated with Peking University group for years.

Recently, Toshimi Suda moved out from RIKEN to Tohoku University to establish a research group at Sendai, which is expected to enlarge the SCRIT collaboration.

We have regularly exchanged information with ELIse group of FAIR/GSI, who plans to construct an electron-ion collider for the same purpose of our electron scattering facility. Their collaboration is anticipated when our facility starts to operate.

5. Summary

The proposed electron scattering facility will open a completely new research field in nuclear physics. Feasibility of the key device, SCRIT, has been confirmed, and the electron scattering facility with the SCRIT system is now under commissioned at RI Beam Factory. Much improved electron-beam conditions of the present facility compared with KSR, such as stored current, stability, lifetime etc., will bring much higher luminosity with the same number of trapped ions. This is equivalent to smaller number of ions required to realize the luminosity of $10^{27}$ /cm$^2$/s necessary for elastic scattering experiments.

We are proposing to construct the ISOL system and electron detection system to start never-yet-performed electron scattering for rarely-produced short-lived nuclei. Supports and comments for this electron scattering facility including ISOL and detector system is much appreciated.

The success of this facility may change a way of the structure studies of short-lived nuclei. At laboratories where low-energy beam of unstable nuclei are available, such as ISOL facilities, one can easily carry out electron scattering that is the best way for the structure studies.

References


