

# Injection of High Energetic Ion Beams to Superfluid Helium as a Host Matrix of Laser Spectroscopic Study of Radioisotope Atoms

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## Abstract

We are developing a laser spectroscopic method for the study of nuclear structure of radioactive isotope utilizing superfluid helium (He II). In the method, He II is used as an efficient stopper for highly energetic ion beams and as an in-situ

laser spectroscopic environment. Recently, we conducted an ion stopping experiment for the energy of approximately 350 AMeV  $^{84}\text{Rb}^{37+}$  at QST-HIMAC. Radioactive  $^{84}\text{Rb}$  ions were produced via projectile fragmentation reaction using accelerated  $^{84}\text{Kr}^{36+}$  and 12-mm thickness Be target. As the first step, we measured the stopping range of the injected ion beam using liquid  $\text{N}_2$  to estimate the stopping range in He II and the spot size of the injected ion beam using a plastic scintillator. Then, laser-induced fluorescence (LIF) detection experiment was performed using He II. We successfully observed the LIF from  $^{84}\text{Rb}$  atoms. We estimated stopping range of  $^{84}\text{Rb}$  ions in superfluid helium from the obtained results. The details of experiment at QST-HIMAC and results are given in this report.

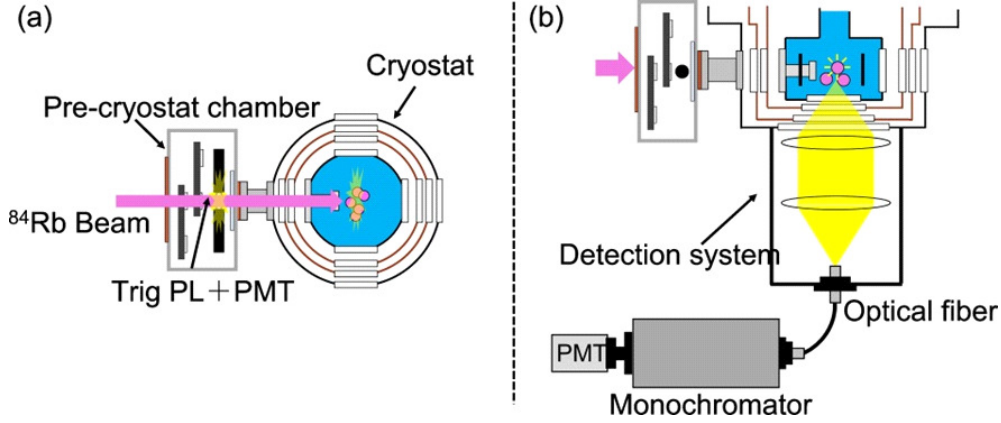
**Keywords:** Ion beam stopping in liquid, Superfluid helium, Nuclear physics experiment, Matrix laser spectroscopy

## 1 Introduction

Nowadays, experiments with cryogenic materials have been developed in many research field such as atomic, molecular, nuclear physics, materials science and so on. Especially, liquid and solid helium provides a unique experimental environment for laser-based research of atoms, ions, and molecules [1]. We are now developing a laser spectroscopic method using atoms in superfluid helium (He II) in order to utilize such a unique environment to the study of radioactive isotopes generated as highly energetic ion beams at accelerator facilities. In our technique, an accelerated ion beam whose kinetic-energy ranges from several tens to several hundreds MeV per nucleon is injected into He II. Owing to the relatively high stopping power of He II, injected ions are stopped in narrow region in the liquid [2]. The injected ions capture electrons from surrounding helium atoms during stopping process. Namely, the ions are neutralized. Moreover, it is known that superfluid helium environment has less influence on nuclear properties, although it has much effect on the electronic transition of implanted atoms [3, 4]. In order to investigate nuclear structure, the production of the atomic spin polarization of the stopped atoms is conducted using optical pumping via a circularly-polarized laser light. We can measure the Zeeman splitting and the hyperfine structure splitting using double resonance method to deduce a nuclear spin and a nuclear electromagnetic moment. We have shown the validity of our method using stable and radioactive isotopes of Rb ( $A = 84 - 87$ ) produced at RIKEN projectile fragment separator (RIPS) in RIKEN Nishina Center for Accelerator Based Science so far. In a series of the previous experiments,  $^{84,86}\text{Rb}$  ions were produced using ion beams of  $^{85,87}\text{Rb}$  which were accelerated approximately up to 66 AMeV. We successfully observed double resonance spectra with the beam intensity of the order of  $10^3$  particles per second [5]. As for the detection of the laser induced fluorescence (LIF) from the stopped atoms, we concluded that the beam intensity of approximately 200 particles per second was enough for the detection using the current setup [6]. As the next step, we are planning to investigate nuclear structure of far from stability line. However, such rare isotopes are often produced using ion beam energy of around 350

AMeV. Recently, we have been launching research and development experiments for applying our technique to such higher energetic ion beams using Heavy Ion Medical Accelerator in Chiba (HIMAC) at QST [7]. We experimentally investigated the stopping region of atoms using  $^{84}\text{Rb}^{37+}$  produced from 350 AMeV  $\text{Kr}^{36+}$  ion beam and Be target. In the experiment, we first used liquid  $\text{N}_2$  as stopping material. Then, LIF detection experiment was performed using He II. We estimated stopping range of  $^{84}\text{Rb}$  ions in superfluid helium from the obtained results. We here show the details of experiment and the results in this report.

## 2 Experiment



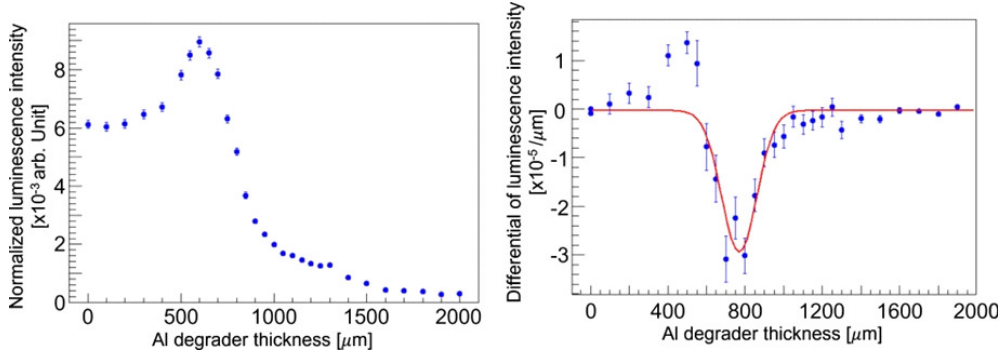
**Fig. 1** The schematic diagram of the setup. (a) top view. (b) side view.

The experimental setup at QST-HIMAC is given in figure 1. The bird view of the SB2 beam line in HIMAC is given in ref [8]. The primary beam of 350 AMeV  $\text{Kr}^{36+}$  beam was impinged on a 12-mm thickness Be target. A radioactive  $^{84}\text{Rb}^{37+}$  beam produced via projectile fragment reaction was selected and delivered to the experimental apparatus. Note that the primary beam was generated as pulsed beam of 200 ms pulse duration. The delivered  $^{84}\text{Rb}^{37+}$  ion beam was injected to the chamber (pre-cryostat chamber) at the upstream of the cryostat. In the pre-cryostat chamber, aluminum energy degraders of different thicknesses were mounted to optimize the beam energy. The ion beam passed through the aluminum degraders and a collimator placed at downstream of the degraders were counted one by one using a plastic scintillator assembled with two photo-multiplier tubes (PMTs). Then, the energy degraded Rb ions were injected into liquid  $\text{N}_2$  from the 10 mm $\phi$  beam port which has 75  $\mu\text{m}$  thickness Kapton foil for vacuum sealing. The ions injected into the cryostat were detected using the plastic scintillator of 250  $\mu\text{m}$  thickness fixed at the center of the cryostat. The luminescence from the plastic scintillator whose intensity is proportional to an energy deposition from the ion beam was detected from the bottom window of the cryostat using the fluorescence detection system. In order to determine stopping

range of the injected ions in the liquid, we measured the luminescence intensity at each degrader thickness by single photon counting.

### 3 Results and Discussion

Figure 2(a) shows the observed luminescence intensity normalized by the beam intensity as a function of the aluminum degrader thickness ( $t$ ). As seen in Fig. 2(a), the curve consists of two components. The main component is the contribution of Rb ions. The second component appearing in thicker aluminum degrader region is due to  $^{82}\text{Kr}$  ions which can not be completely separated ion beam selection process. The peak at around  $t = 600 \mu\text{m}$  is considered as so-called Bragg peak which appears because the energy loss of charged particles in a material is inversely proportional to the square of their velocity. For the stopping range estimation, we calculate the slope of the obtained curve at each aluminum degrader thickness which given in Fig. 2(b). We deduced the thickness of the aluminum degrader to stop Rb ions at the center of the cryostat by fitting to Gaussian function. As a result we obtained aluminum degrader thickness of  $t = 769(27) \mu\text{m}$  as a required thickness for stopping Rb ion. The width of approximately  $214 \mu\text{m}$  at FWHM was the ion stopping range when we considered aluminum as a stopping material.



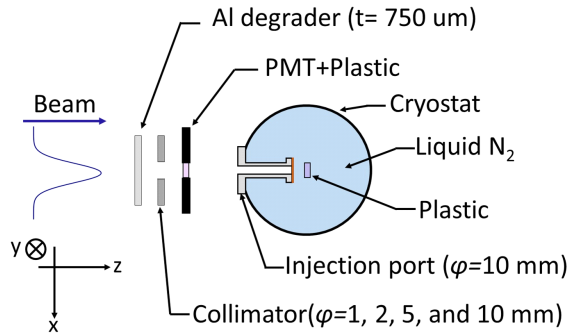
**Fig. 2** (a) The obtained curve in a stopping range measurement shown as a function of aluminum degrader thickness ( $t$ ). (b) Differential of Fig. 2(a). The first peak of the Fig. 2(b) is due to the Bragg peak structure which appears around  $t = 600 \mu\text{m}$ . Two depths at  $t = 800 \mu\text{m}$  and  $t = 1500 \mu\text{m}$  corresponds to the ion stopping of  $^{84}\text{Rb}^{37+}$  and  $^{82}\text{Kr}^{36+}$ , respectively

According to the Bragg-Kleeman rule which is a semi-empirical formula giving a range of ions in a material. the relation between range of same ion species in different material expressed as follows [9],

$$\frac{R_1}{R_2} \approx \frac{\rho_2 \sqrt{A_1}}{\rho_1 \sqrt{A_2}}$$

where  $R_i$ ,  $\rho_i$ , and  $A_i$  are range in material  $i$ , material density of  $i$ , and mass number of material  $i$ , respectively. We estimate the stopping range of  $^{84}\text{Rb}$  ions in superfluid

helium using the values below:  $R_{Al} = 214 \mu\text{m}$ ,  $\rho_{Al} = 2.701 \text{ g/cm}^3$ ,  $A_{Al} = 26.98$ ,  $\rho_{He} = 0.146 \text{ g/cm}^3$ ,  $A_{He} = 4.00$ . We obtained 1.52 mm at FWHM as the estimated stopping range of  $^{84}\text{Rb}$  in superfluid helium. Next, laser induced fluorescence (LIF) detection experiment was performed using He II material and a laser that can excite Rb atomic transition. We successfully observed the LIF from  $^{84}\text{Rb}$  atoms in He II with a beam intensity of approximately 10k particles per second [10]. The stopping range of  $^{84}\text{Rb}$  in He II was evaluated approximately 1.1 mm at FWHM by comparing with the LISE++ calculation. Both results using liquid  $\text{N}_2$  and He II verified that the stopping range of  $^{84}\text{Rb}$  in He II resides within the diameter of conventional excitation lasers.



**Fig. 3** Schematic diagram of the beam transportation. Al degrader, collimator, and plastic scintillator in the left-hand side is stored in the pre-cryostat chamber. The right-hand side blue circle expresses the horizontal cross-sectional view of the cryostat.

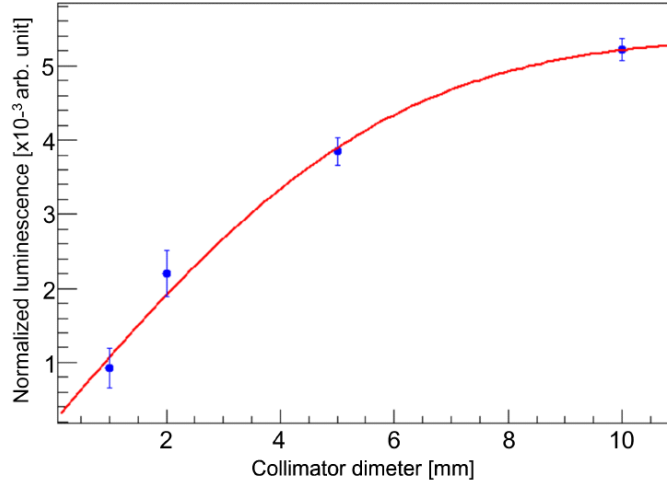
In addition to the stopping range measurement using liquid  $\text{N}_2$ , we measured the ion beam size dependence using different collimator diameter with aluminum degrader thickness of  $750 \mu\text{m}$ . Figure 3 shows the schematic image of the beam transportation. Assuming that the beam profile in the surface perpendicular to the beam propagating axis available to be delivered to the cryostat corresponds to an integrated value of a gaussian function, we investigated the collimator diameter dependence of the beam intensity. Using the relation between Gaussian integration function and an error function as below,

$$\int_{-d/2}^{d/2} \exp\left[-\frac{x^2}{2\sigma^2}\right] = \sqrt{2\pi}\sigma \text{erf}\left[\frac{d}{2\sqrt{2}\sigma}\right]$$

where  $d$  is collimator diameter,  $x$  is distance from the beam center,  $\sigma$  is fitting parameter, we could deduce the transverse width of the  $^{84}\text{Rb}$  in beam to be  $33(5)$  mm in FWHM from the fitting result using error function.

## 4 Conclusion

In conclusion, we are developing a new laser spectroscopic method for investigating nuclear spin and nuclear electromagnetic moment of rare-isotopes. The method utilizes



**Fig. 4** The normalized luminescence intensity displayed as a function of the collimator diameter. Red line shows the resultant fitting curve using error function

superfluid helium (He II) as a efficient stopper for highly energetic ion beam and as a spectroscopic environment for in-situ laser spectroscopy. We have shown the feasibility of our method using an accelerated  $^{84-87}\text{Rb}$  ion beam whose energy was 66 AMeV so far. In order to investigate the stopping range of injected ion with higher kinematic energy, we conducted a ion beam stopping experiment using a 350 AMeV  $^{84}\text{Rb}$  ion beam produced from  $^{84}\text{Kr}$  in QST-HIMAC. In this experiment, we first used liquid  $\text{N}_2$  as a stopping material. The measurement results show that injected  $^{84}\text{Rb}$  ions were successfully stopped in liquid  $\text{N}_2$  using an aluminum degrader whose thickness was 760(27)  $\mu\text{m}$ . We estimated the stopping range of the ions in He II using Bragge-Kleeman rule from the result. We obtained the estimated stopping range in He II of 1.52 mm at FWHM of gaussian distribution. A subsequent experiment using He II as a stopping medium and a single frequency laser as a excitation light source for the stopping Rb at QST-HIMAC is in progress.

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## Declarations

- Funding ‘H. Ueno was supported by JSPS KAKENHI Grants No. 18H05457 and 18H05462’
- Conflict of interest ‘Not applicable’
- Ethics approval ‘Not applicable’
- Availability of data and materials ‘The data that support the findings of this study are available from the first or the corresponding authors upon reasonable request.’

- Authors' contributions 'All the authors contributed to the preparation and conduction of the experiments. KI and AT performed data analysis. YM wrote application for beamtime. KI wrote the main manuscript. All authors approve the manuscript.'

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