Photon detection from stopped $^{87}$Rb atoms injected into superfluid helium for a new nuclear laser spectroscopy of rare radioisotopes

T Furukawa$^1$, T Wakui$^2$, A Sasaki$^2$, S Izumi$^2$, Y Ichikawa$^3$, A Yoshimi$^3$, K Tajiri$^4$, Y Ishii$^1$, N Yoshida$^1$, Y Matsuura$^5$, Y Kato$^5$, Y Yamaguchi$^5$, K Imamura$^6$, M Makuta$^6$, A Hatakeyama$^3$, M Wada$^3$, T Sonoda$^3$, Y Ito$^7$, T Nanao$^1$, T Kobayashi$^8$, S Nishimura$^3$, M Nishimura$^9$, Y Kondo$^1$, N Aoi$^3$, K Yoneda$^3$, S Kubono$^9$, Y Ohshiro$^9$, H Ueno$^3$, T Shimoda$^4$, T Shinozuka$^2$, K Asahi$^1$ and Y Matsuo$^{3,4}$

$^1$ Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
$^2$ Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi, 980-8578, Japan
$^3$ RIKEN Nishina Center, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan
$^4$ Department of Physics, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
$^5$ Department of Physics, Meiji University, 1-1-1 Higashi-Mita, Tama-ku, Kawasaki-shi, Kanagawa 214-8571, Japan
$^6$ Department of Applied Physics, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei-shi, Tokyo 184-8588, Japan
$^7$ Department of Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan
$^8$ RIKEN Advanced Science Institute, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan
$^9$ Center for Nuclear Study, University of Tokyo, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

E-mail: takeshi@yap.nucl.ap.titech.ac.jp

Abstract. We have been developing a new nuclear laser spectroscopic method “OROCHI” for determining spins and moments of exotic RIs. This is a method based on the combination of superfluid helium as a stopper of radioactive isotope (RI) beam and in-situ laser spectroscopy of RI atoms. This unique method will enable us to measure nuclear spins and electromagnetic moments of extremely low yield RI (less than 1 particle per second). To confirm the feasibility of this method for rare radioisotopes, we carried out the first on-line experiment with a $^{87}$Rb beam, aiming at evaluating the minimum beam intensity required for the measurement. The LIF (Laser Induced Fluorescence) photons from the $^{87}$Rb atoms stopped in He II are successfully observed in the on-line experiment. The obtained LIF intensity is nearly consistent with the intensity calculated from the photo-absorption cross section of atoms in He II.
1. Introduction
Nuclear spins and electromagnetic moments are often key observables for studying nuclear structures because they are directly correlated with the quantum states and configurations of valence nucleons [1]. So far, the studies of nuclear spins and moments have revealed precisely the nuclear structures from the stable to the unstable. Further attempts have been made to apply such studies to short-lived unstable nuclei far from the $\beta$-stability line [2]. To investigate the exotic structures of short-lived exotic nuclei, intensive studies have been attempted in the field of nuclear physics in decades. However, they have not always been successful mainly due to the low-yield of such the short-lived exotic nuclei produced by the nuclear reaction.

To measure the spins and moments of low yield exotic radioisotopes (RI) which are difficult to measure with existing methods, we have been developing a new nuclear laser spectroscopy method using superfluid helium (He II). We call this method as “OROCHI (Optical Radioisotope atom Observation in Condensed Helium as Ion-catcher).” In the OROCHI, He II liquid is adopted as a stopping material of RI beams and also as host material of in-situ laser spectroscopy for the introduced RI atoms. With characteristic features of the atoms immersed in He II [3], such as the blue-shifted and broadened absorption spectra due to the pressure of surrounding helium liquid, it will become feasible to measure the nuclear spins and moments of the extremely low yield RIs.

By using the OROCHI method, we demonstrated that we could deduce successfully the nuclear spins and moments with stable Rb, Cs, Ag and Au isotopes which were introduced into He II by laser sputtering technique [4]. Recently, we carried out the first on-line experiment with a $^{87}$Rb beam to observe the atoms from an accelerated ion beam injected and stopped in He II. In this on-line experiment, we aim at evaluating the minimum beam intensity required for the observation. In this paper, we briefly report the result of the recent on-line experiment using the OROCHI setup.

2. Experiment
The experiment was performed at RIPS (RIKEN Projectile fragment Separator) in RIKEN RI Beam Factory. Figure 1 shows the schematics of our experimental setup. The $^{87}$Rb beam (energy: 66 AMeV, diameter: 3 mm) was injected into He II. The typical beam intensity of $^{87}$Rb beam was approximately $10^5$ particles per second. The introduced Rb ions were counted one by one with a plastic scintillator (BC408, thickness: 100 $\mu$m) placed in front of the cryostat. Aluminum foils of thickness ranging from 0 $\mu$m to 800 $\mu$m (“Energy degraders” in Fig. 1) reduced the injected beam energy to adjust the range of $^{87}$Rb in He II to the center of cryostat (7 mm down from the injection window). The vacuum of both beamline and cryostat was sealed by thin Kapton foils (75 $\mu$m thickness), respectively. The injection window was made of a thin havar foil (21 $\mu$m thickness). The stopped $^{87}$Rb atoms were subjected to irradiation of the cw pumping laser light (cw Ti:Sapphire laser, 899-01, Coherent Co.Ltd., power: 200 mW, diameter: 5 mm). The wavelength of the pumping laser light was tuned to the D1 absorption line of Rb atoms in He II (780 nm). The LIF photons from laser-excited $^{87}$Rb atoms were collected, wavelength-separated, and then detected with the photo-detection system [5]. Figure 1-b) shows the schematic diagram of the fluorescence detection system. It consist of three Fresnel lenses, a pair of slits (parallel and perpendicular to the laser light), wavelength filters, and a Peltier cooled photomultiplier tube (PMT, Hamamatsu Co.Ltd., R633-10P + C9143). The light emitted from atoms was collected and focused on the slits by the first Fresnel lens (Lens 1). Light which has passed through the slits was collimated with the second lens (Lens 2) so that the light enters at normal incidence to the wavelength filters for perfect separation of wavelength. The light was then focused on the photoelectric surface of the PMT by the third lens (Lens 3).
3. Observed LIF intensity in the on-line experiment

In the on-line experiment we measure the LIF intensity with the injection of the $^{87}$Rb beam on and off. Figure 2 shows the typical time evolution of the detected photon intensity with the $^{87}$Rb beam on and off. The observed intensity is increased with injecting $^{87}$Rb beam and decreased with stopping the beam injection. The decrease of LIF intensity with the stop of Rb beam injection indicates that the atoms introduced into He II flow out from the observed region of He II. The resident time of introduced $^{87}$Rb atoms are approximately 0.5 sec, which is as long as that of laser sputtered atoms in the off-line experiments. Such long resident time suggests that this injection method with accelerated ion beam achieved equivalent performance to that with laser sputtering method, and hence it is feasible to introduce this method to study atomic properties of all the elements in He II.

From the difference in counting rates, we concluded that the observed LIF intensity is approximately $0.8 \times 10^5$ photons/sec, with the injected $^{87}$Rb of $1.7 \times 10^5$ ions/sec. The obtained LIF intensity is nearly consistent with the intensity calculated from the photo-absorption cross section of atoms in He II with 780 nm wavelength photons [6].

4. Conclusion

In summary, we have been developing the new laser spectroscopy method "OROCHI" for determining nuclear spins and moments of exotic RI far from the $\beta$-stability. In the OROCHI, we use superfluid helium (He II) as an effective stopper of RI beam and a host matrix of laser spectroscopy. The blue-shifted and broadened absorption spectra of atoms in He II enable us to measure the extremely low yield RI whose yield is less than 1 particle per second. So far, we have demonstrated successfully the determination of nuclear spins and moments of stable Rb, Cs, Ag and Au isotopes from their atomic hyperfine and Zeeman splittings.

Here, we have reported the first on-line experiment with a $^{87}$Rb beam to observe the atoms from an accelerated ion beam stopped in He II. In this on-line experiment, we aim at evaluating the minimum beam intensity required for the observation. In the on-line experiment we measure
Figure 2. Time evolution of LIF intensity with turning on and off the beam injection. The LIF intensity is increased as the $^{87}\text{Rb}$ beam is injected.

the LIF intensity in turning on and off the injection of the $^{87}\text{Rb}$ beam. The decrease of LIF intensity with the stop of Rb beam injection indicates that the atoms introduced in He II flow out from the observation region of He II. The resident time of introduced $^{87}\text{Rb}$ atoms are approximately 0.5 sec, which is as long as that of laser sputtered atoms in off-line experiments. The observed LIF intensity is approximately $0.8 \times 10^5$ photons/sec with the injected $^{87}\text{Rb}$ of $1.7 \times 10^5$ ions/sec. The observed Intensity is nearly consistent with the intensity calculated from the photo-absorption cross section of atoms in He II with 780 nm wavelength photons. In the near future, we will measure the hyperfine structure of unstable $^{84,86}\text{Rb}$ isotopes in He II with the OROCHI method to demonstrate the determination of the spins and moments of radioisotopes, and will apply it to measure the nuclear spins and moments of rare isotopes.

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