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Laser spectroscopy of atoms in superfluid helium for the measurement of nuclear spins and electromagnetic moments of radioactive atoms

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Abstract A new laser spectroscopic method named "OROCHI (Optical RI-atom Observation in Condensed Helium as Ion catcher)" has been developed for deriving the nuclear spins and electromagnetic moments of low-yield exotic nuclei. In this method, we observe atomic Zeeman and hyperfine structures using laser-radio-frequency/microwave double-resonance spectroscopy. In our previous works, double-resonance spectroscopy was performed successfully with laser-sputtered stable atoms including non-alkali Au atoms as well as alkali

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Rb and Cs atoms. Following these works, measurements with $^{84-87}$Rb energetic ion beams were carried out in the RIKEN projectile fragment separator (RIPS). In this paper, we report the present status of OROCHI and discuss its feasibility, especially for low-yield nuclei such as unstable Au isotopes.

Keywords Laser spectroscopy in superfluid helium · Double-resonance spectroscopy · Optical pumping · Nuclear spin · Electromagnetic moments · Hyperfine interaction

1 Introduction

Nuclear spins and electromagnetic moments are key observables for investigating nuclear structures as they are sensitive to the configurations of valence nucleons. Laser spectroscopy is an effective tool for understanding nuclear structure through the determination of those observables [1]. However, the application of these methods to far-unstable rare isotopes, for which anomalous nuclear properties have so far been reported, is still limited mainly due to various technical difficulties arising from the low production yield of rare isotopes. Hence, we have developed a new laser spectroscopic method named OROCHI (Optical Radioisotope atom Observation in Condensed Helium as Ion catcher) for low-yield RI atoms. In this method, atomic Zeeman and hyperfine structure splittings are measured using a laser-radio frequency (RF)/microwave (MW) double-resonance method. The significant feature of the OROCHI method is the utilization of superfluid helium (He II) as both an effective trapping material and a host matrix for laser spectroscopy taking advantage of characteristic properties of atoms in He II [2]. We have started performing measurements of not only stable alkali Rb and Cs atoms but also non-alkali Au atoms. Furthermore, we have successfully applied this technique to $^{84-87}$Rb energetic ion beams. Here, we report on the present status of OROCHI for measurements with laser-sputtered atoms and with energetic ion beams. Then, we discuss the feasibility of OROCHI for the measurement of nuclei far from stability, which will be performed under changing conditions, such as high ion injection energy at low yield.

2 OROCHI–new laser spectroscopic method for studying RIs

In the OROCHI method, energetic ion beams are injected into He II. These ion beams are decelerated and finally stopped as neutralized atoms via the capture of free electrons. He II can be utilized to stop almost all the atoms in the observation region (2×5 mm^2) owing to its high stopping power. The injected atoms reside in the observation region for a sufficiently long period owing to the slow diffusion of atoms in He II (typically a few mm/s). Moreover, no macroscopic bubbles appear because He II evaporates only from the surface [3].

The trapped atoms are irradiated with a pumping laser and emit laser-induced fluorescence (LIF) photons. The absorption lines of atoms in He II are blue shifted and considerably broadened compared with those in vacuum. This is caused by the interaction with the surrounding helium atoms. These characteristic properties enable us to perform the measurement with high signal-to-noise ratio by reducing the background photon count. By taking advantage of the difference between the wavelengths of absorption and emission lines, a wavelength separation device such as an interference filter or a monochromator can be utilized to efficiently reduce the detection of stray laser light, which is the main source of

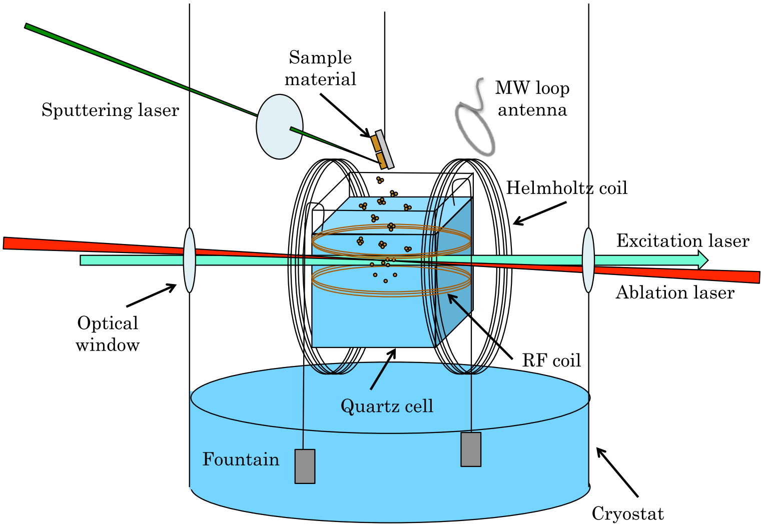

Fig. 1 Schematic diagram of the measurements with laser-sputtered atoms. In a cryostat, An open-topped cubic quartz cell (7 × 7 × 7 cm^3) filled with He II at a temperature of approximately 1.6 K was placed in a cryostat. The sample material was placed 1 cm above the He II surface. Around the quartz cell, Helmholtz coils, RF coils and an MW loop antenna were installed to perform double-resonance spectroscopy. The applied external magnetic field was typically 1 G. The emitted LIF photons were observed using a monochromator and a PMT

the background count. We then obtain the atomic Zeeman and hyperfine splittings in He II by the laser-RF/MW double-resonance method, efficiently [4].

3 Double-resonance spectroscopy using laser-sputtered atoms in He II

We have measured the Zeeman and hyperfine splittings of Rb, Cs and Au. Figure 1 shows the experimental setup. An open-topped cubic quartz cell (7 × 7 × 7 cm^3) in a cryostat was fully filled with He II by use of the superfluid fountain effect. The temperature of He II was typically maintained at 1.6 K. The sample material was placed 1 cm above the He II surface and ablated by a second- or third-harmonic pulse of a Nd:YAG (yttrium aluminum garnet) laser (wavelength: 355 or 532 nm, pulse duration: 8 ns). Most of the sputtered particles, which entered He II, were formed as clusters. To dissociate the clusters, we irradiated them with a femtosecond Ti:sapphire laser (wavelength: 800 nm, repetition rate: 500 Hz) [5]. Helmholtz coils, RF coils and an MW loop antenna were installed around the quartz cell to perform optical pumping and laser-RF/MW double-resonance spectroscopy. The applied external magnetic field was typically 1 G. LIF photons emitted from laser-excited atoms were focused with three lenses and the wavelength was separated by a monochromator and detected by a photomultiplier tube (PMT).

The LIF intensity was decreased when atoms were polarized by the irradiation of a circularly polarized pumping laser light. Then, the atomic spin polarizations were determined from the ratio of LIF intensities observed by irradiating with linearly and circularly polarized lasers. In our measurements, large atomic spin polarizations were confirmed using alkali Cs atoms ($\simeq$ 90 %) and Rb atoms ($\simeq$ 50 %) in He II, respectively. Recently, the spin

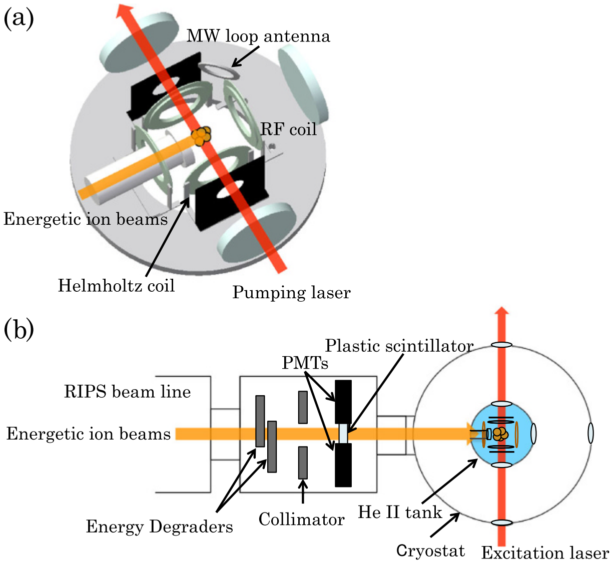

Fig. 2 Setup of expiredent at the RIPS ion beam line. **a** Inside of the cryostat filled with He II at a temperature of approximately 1.5 K. Helmholtz coils, RF coils and an MW loop antenna were installed to perform RF/MW double-resonance spectroscopy. **b** System used to optimize beam-stop position. Two aluminum degraders were installed upstream of the cryostat to adjust the beam energy. A plastic scintillator upstream of the cryostat detected the intensity of injected ions

polarization of Au atoms has also been successfully achieved using a pulsed laser light, here the degree of atomic spin polarization was larger than 80 %.

Using the large atomic spin polarization, we also succeeded in measuring Zeeman and hyperfine resonances for stable Rb, Cs and Au atoms. Further analysis of the experimental data is in progress.

4 Experiment using energetic ion beams

We have also performed measurements using $^{84-87}$Rb energetic ion beams with energies of 60–66 MeV/u at the RIKEN projectile fragment separator (RIPS) at the RIKEN Radioactive Isotope Beam Factory (RIBF) [6, 7]. Figure 2a shows the inside of the cryostat for the ion beam experiment (fulfilled with He II at a temperature of approximately 1.5 K). The energetic ion beams from the RIPS beam line were injected into the cryostat (horizontal arrow in Fig. 2b) and the stopped RI atoms were subjected to a pumping laser (vertical arrow in Fig. 2b, cw Ti: sapphire laser, wavelength: 780 nm, laser power: ∼120 mW, beam diameter: typically 2 mm). Beneath the cryostat, a photodetection system for observing LIF photons, which included three lenses, an interference filter and a Peltier-cooled PMT were installed. We performed a laser RF/MW double-resonance spectroscopy measurement with the RI atoms stopped in He II. One of the crucial points in this measurement was the optimization of the beam-stop position. Only the photon signals from the observation region (the center of the region shown in Fig. 2a) were focused and detected. To the optimize the beam stop position, two Al degraders and a plastic scintillator were installed upstream of the cryostat, as shown in Fig. 2b. We adjusted the thickness of the Al degraders from

Table 1 Nuclear spins derived in previous works

	Nuclear spin		
Isotopes	Our result	Literature value	Ref.
^{84}Rb	1.9(1)	2	[8]
^{84m}Rb	6.2(2)	6	[8, 9]
^{85}Rb	2.5(1)	5/2	[8]
^{86}Rb	1.9(2)	2	[8]
^{87}Rb	1.53(6)	3/2	[8]

Details of experimental results and the discussion is in reference [2]

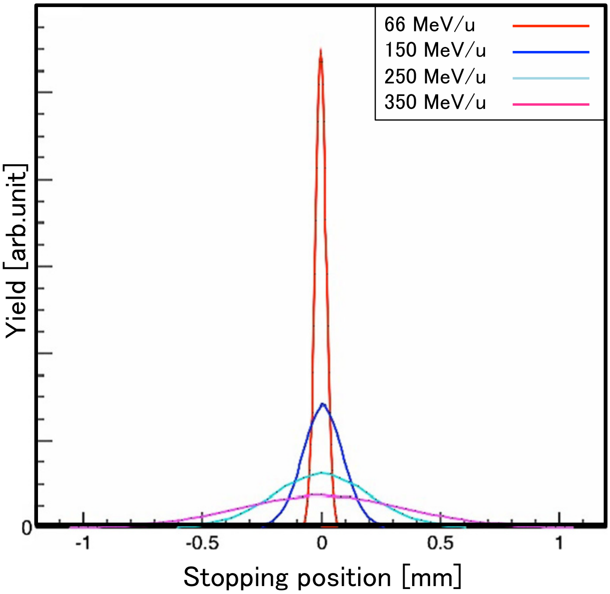

Fig. 3 LISE++ calculation result for the spread of the stopping range for beam energies of 66, 150, 250 and 350 MeV/u [11]. The previous measurements at the RIPS beam line were performed with a beam energy of 66 MeV/u [6]. Note that we did not take into account the energy distribution upstream of the cryostat

0 to 800 μm with a 12.5 μm step to vary the beam energy. The plastic scintillator was used to count the number of injected ions. The beam-stop position was estimated by counting the LIF photons from atoms while changing the degrader thickness.

Zeeman resonance frequencies were determined for $^{84-87}$Rb. The intensity in the measurements were on the order of 10^4 pps, and the FWHM of the stop range was approximately 1 mm. The deduced nuclear spins were consistent with the literature values as shown in Table 1 [2, 8, 9].

For the future application of OROCHI, to nuclei far from stability, we plan to perform measurements at BigRIPS at RIBF, where the energy of ions becomes as high as 345 MeV/u [10]. In this case, the stopping range should be considered and optimized carefully. Figure 3 shows the result of a LISE++ calculation [11] estimating the stopping distribution for ^{87}Rb primary beams of 66, 150, 250 and 350 MeV/u. The FWHMs are 0.05 mm for the 66 MeV/u beam, 0.12 mm for a 150 MeV/u beam, 0.48 mm for a 250 MeV/u beam and 0.82 mm for a

350 MeV/u beam. All the FWHMs are within 1 mm. We conclude that the area can be fully covered by the pumping laser.

5 Conclusion

A new laser spectroscopic method named OROCHI (Optical RI-atom Observation in Condensed Helium as Ion catcher) has been developed for the investigation of nuclear spins and electromagnetic moments of low-yield exotic nuclei. In this method, we utilize He II as both an effective trapping material and a host matrix for laser spectroscopy by taking advantage of the characteristic properties of atoms in He II. Nuclear spins and electromagnetic moments can be derived from the atomic Zeeman and hyperfine structures observed by the laser-RF/MW double-resonance method. In our previous works, we have successfully performed measurements on laser-sputtered non-alkali Au atoms as well as alkali Rb and Cs atoms. We have also succeeded in observing atoms from injected energetic $^{84-87}$Rb beams produced by RIPS with a beam intensity on the order of 10^4 pps.

We have performed LISE++ calculations pertinent to future applications with higher-energy beams. It was found that in the case of measurements with 350 MeV/u beams, the straggling of stopping position in He II is within 1 mm. The pumping laser can fully cover the area in which atoms are stopped. Note that we did not take into account the energy distribution upstream of the cryostat. It will be necessary to perform further calculations for the future application of OROCHI to exotic lower-yield nuclei such as unstable Au isotopes.

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