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Control of stopping position of radioactive ion beam in superfluid helium for laser spectroscopy experiments

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ABSTRACT

In order to investigate the structure of exotic nuclei with extremely low yields by measuring nuclear spins and moments, a new laser spectroscopy technique – "OROCHI" (Optical Radioisotopes Observation in Condensed Helium as Ion-catcher) has been proposed in recent years. The feasibility of this technique has been demonstrated by means of a considerable amount of offline and online studies of various atoms in superfluid helium. For in-situ laser spectroscopy of atoms in He II, trapping atoms in the observation region of laser is a key step. Therefore, a method which enables us to trap accelerated atoms at a precise position in He II is highly needed for performing experiment. In this work, a technique making use of a degrader, two plastic scintillators and a photon detection system is established for checking the stopping position of beam based on the LISE++ calculation. The method has been tested and verified by on-line experiments with the ^{84,85,87}Rb beam. Details of the experimental setup, working procedure and testing results of this method are presented.

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1. Introduction

Importance of the ground and isomeric state properties of nuclei such as nuclear spins, moments and mean-square charge radii is due to their direct relation with nuclear structure. These properties can be derived from the precise measurement of atomic Zeeman and hyperfine structures, as well as isotope shifts by model-independent nuclear laser spectroscopy method [1,2] or beta-NMR method using polarized radioisotopes (RI) [3]. However, for unstable nuclei near the drip-line, measurement of these properties becomes difficult due to the low yield, high contamination and small polarization of beams of such short-lived nuclei.

Taking advantage of the characteristic optical properties of atoms in He II [4] and atomic laser physics methods such as optical detection, optical pumping and double resonance, the unique laser spectroscopy technique "OROCHI" (Optical Radioisotope atom Observation in Condensed Helium as Ion-catcher) has been developed and improved through years of research and development [5–9]. Based on the offline experiments on stable atoms, OROCHI method is supposed to be feasible to systematically measure nuclear spins, magnetic moments, and also hyperfine anomaly of RI and isomers of a wide variety of atomic species with extremely low yield. This method uses He II as an ideal stopper of energetic RI beam taking advantage of its high trapping efficiency. He II is also an intriguing matrix for laser spectroscopy of trapped atoms that exhibits largely shifted and broadened photo-absorption

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spectra and gives a long spin polarization relaxation time (>2 s for Cs atom in He II) [5,9].

For OROCHI experiment, trapping RI beam at an accurate position in He II is crucial. To adjust the stopping position range, a method has been developed and tested for two experiments using ^{87}Rb and ^{84,85}Rb beams. In this paper, we describe the setup, working procedure, experimental results and the evaluation for this method. In addition, the recent upgrade of the system based on the LISE++ program calculation is also presented.

2. Experimental setup

Two OROCHI experiments have been performed at RIKEN Projectile fragment Separator (RIPS [10]) for ^{87}Rb in 2010 [8] and ^{84,85}Rb in 2012, respectively. The first step in these experiments is to precisely stop the atoms just on the line through which the pumping laser beam passes, because the maximum volume of the observation region for the photon detection system is only limited to $5 \times 2 \times 2$ mm^3. To achieve the accurate stopping of beam in He II, a combination (shown in Fig. 1(a)) of Al degrader, plastic scintillators in both pre-cryostat chamber and cryostat, and a photon detection system is used. The energy degrader used for adjusting the energy of RI beams is made of aluminum foils, as shown in Fig. 1(b). The foils are mounted on two separate rotary mounting wheels, and the thickness of each foil differs from its neighbor by 12.5 μm. By rotating the two wheels and matching different combination of foils, the total thickness of two foils in the beam path can be adjusted from 0 to 800 μm. The adjustment is remotely controlled by a LabVIEW program. A difference in stopping position caused by 12.5 μm step is less than 0.2 mm, which sufficiently meets current system requirement for precision. One plastic scintillator (BC 408, thickness: 100 μm) (Tr-PL,) assembled with two photomultiplier tubes (PMTs) placed in a pre-cryostat chamber (in air) is used to count the Rb ions introduced into the chamber. Another scintillator (BC 408, thickness: 500 μm) (He-PL) located at the center of the cryostat (in vacuum) is used to check the stopping position of atoms by photon counting using the photon detection system placed under the cryostat. It can be removed from the laser observation region by connecting it to a removable pipe from the top of cryostat. For determining the stopping position of the beam, the procedure consists in decreasing the incident beam energy step by step using the degrader so that the beam is stopped near the surface of He-PL. The good overlap with laser beam is then confirmed by detection of laser induced fluorescence (LIF) from the stopped atoms optically pumped by the laser beam (cw Ti:Sapphire laser, 899-01, Coherent Co. Ltd.). Both the photon from He-PL (N_H)and LIF are counted using the detection system. This detection system is composed of three large Fresnel lenses, a pair of orthometric slits remotely controlled by LabVIEW program, band-pass and edge-pass interference filters at both He-PL photon and LIF wavelength, and a cooled PMT [11]. The only air space in the whole experiment setup is inside the pre-cryostat chamber which is isolated from the high vacuumed RIPS beam line and cryostat by 75 μm Kapton foils.

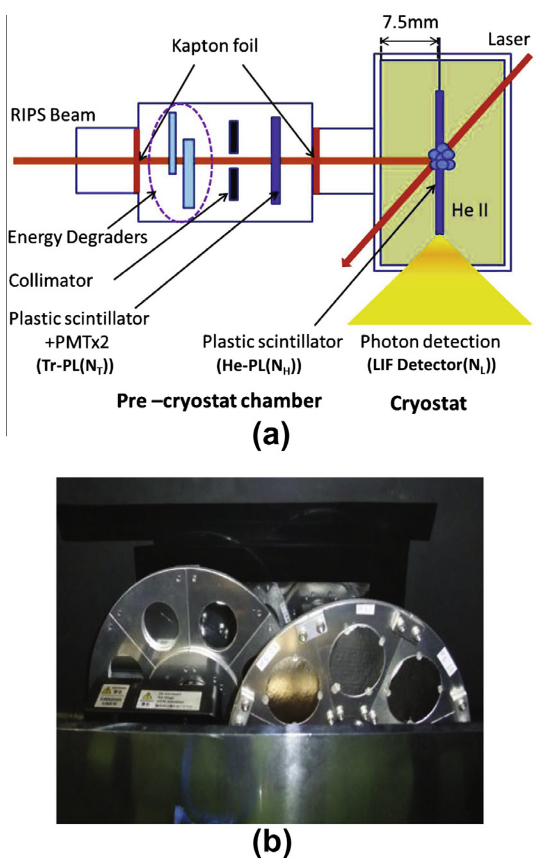

Fig. 1. (a) Schematic drawing of the latest system for checking stopping position of beam in He II. Al degrader, plastic scintillators in both pre-cryostat chamber and cryostat and a photon detection system are used to adjust and determine the stopping position of beam in He II. The photon counts from the Tr-PL, He-PL and laser induced fluorescence (LIF) are marked by N_T, N_H and N_L, respectively, in the following text. (b) The photo of the degrader. The two mounting wheels for multi-thickness aluminum foils can be seen in the front.

3. LISE++ calculation and system upgrade

Calculations using LISE++ program are needed prior to the experiment in order to estimate the stopping position of the beam. In the first on-line experiment in 2010, LISE++ program with ATIMA code [12,13] which is often used for the calculation of the beam production was employed. The Ziegler [14] code was also used for LISE++ calculations and Fig. 1(a) shows a comparison of results obtained from the two codes for the stopping in He II for several Rb isotopes. Systematic difference of > 10% are observed. Calculations of degrader thickness for a stopping position at 7.5 mm from the entrance window in He II are shown in Table 1. Larger differences of ∼ 15% are found. Fig. 2(b) shows the variation of the ratio of the plastic signals N_H/N_T when the degrader thickness is increased. Above about 62.5 μm, the signal in N_H becomes minimum, so the optimal degrader thickness should be around this value. This optimal value is determined experimentally by requiring the LIF count rate to be maximum (good overlap between implanted ion zone and laser beam). The experimental results are compared with calculations from both ATIMA and Ziegler code in Table 1. We found Ziegler code is more reliable in calculating the energy loss of Rb beam. However, we note that for secondary beam ^{84}Rb, the straggling (FWHM) of stopping position from calculation result using both ATIMA and Ziegler code is about 0.5 mm corresponding to a approximately 30 μm straggle of degrader thickness. For primary

Table 1
LISE++ calculation results for ^{84,85,87}Rb using both ATIMA and Ziegler program codes and experimental results (the beam energy is 66 Mev/u for primary ^{85,87}Rb and ∼ 62 MeV/u for secondary beam ^{84}Rb)). The optimal degrader thickness for a stopping position at exactly 7.5 mm is calculated from the linear fitting results of Fig. 2(b). The experiment setups for ^{87}Rb and ^{84,85}Rb are different, the details of which can be found in Fig. 3.

	ATIMA (μm)	Ziegler (μm)	Experimental result (μm)
^{87}Rb	119.15	76.40	87.5
^{85}Rb	351.9	307.50	337.5
^{84}Rb	119.60	70.05	50.0

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