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Development of a helium cryostat for laser spectroscopy of atoms with unstable nuclei in superfluid helium

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ABSTRACT

We are developing a new nuclear laser spectroscopic technique for the study of nuclear structure that can be applied to short-lived low-yield atoms with unstable nuclei. The method utilizes superfluid helium (He II) as a trapping medium for high-energy ion beams. A liquid helium cryostat with optical windows is a key apparatus for this type of experiment. We describe the design and the performance of the cryostat which is developed for the present project.

1. Introduction

We have been developing a novel technique in nuclear laser spectroscopy using superfluid helium (He II) for the study of structure of unstable nuclei. We name the method OROCHI, which stands for the Optical Radioisotope Observation in Condensed Helium as Ion-catcher. In the OROCHI, He II works as a trapping medium to stop accelerated ion beams and as a host matrix for laser spectroscopy of trapped atoms. We are planning to measure Zeeman splittings and hyperfine structure splittings to determine nuclear spins and moments using laser-radio frequency/microwave (RF/MW) double resonance spectroscopy of stopped atoms in He II. The most prominent characteristic of He II as host matrix for laser spectroscopy is the large spectral shift between emission and absorption of the embedded atoms [1]. Thanks to this characteristic, we can perform highly sensitive detection of the signal form introduced atoms by making use of this characteristic. So far, Zeeman splittings and hyperfine structure splittings measurements using double resonance method have been performed for stable isotopes of Cs and Rb [2,3]. We also have successfully demonstrated that precision spectroscopy of atoms in He II is applicable to alkali and alkali-like atoms using the combination of optical pumping and double resonance method [4]. A high degree of spin polarization is achieved for stable species of Rb (~50%), Cs (~90%), Ag (~80%), and Au (~80%) atoms [5]. It is also shown that the nuclear spins and moments can be deduced from the Zeeman splitting and hyperfine splitting measurements using stable isotopes of these elements. In order to apply the OROCHI method to atoms with unstable nuclei generated in accelerator facilities, we need to construct a liquid helium cryostat with optical windows specially designed for the experiments to be installed in the beam line.

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Compared with the cryostat being used for the stable atoms in the laser laboratory, the design and the operation of the cryostat for beam line experiments are different in many aspects. For instance, all the liquid helium operation processes need to be remote controlled, the location of the optical detection window is restricted to the bottom of the cryostat to avoid interference with the beam-line, and so forth. It is inevitable to establish the operation procedure of such a cryostat for the success of the experiment because the cryostat is a key apparatus to realize superfluid helium condition (<2 K) that is necessary for both stable beam injection and highly sensitive laser spectroscopy. In this paper, we describe the details of the cryostat such as the design, performance, and operating method.

2. Design and characteristic

2.1. Basic structure of a helium cryostat

The schematic layout of the helium cryostat with optical windows is shown in Fig. 1. Basically, the cryostat consists of four baths. The role of each part is described below. (1) The outer vacuum chamber which is to prevent thermal radiation from the outside. The pressure of the outer vacuum chamber is continuously monitored by a cold cathode pirani gauge. (2) Liquid nitrogen bath (77 K bath) which is filled with liquid nitrogen and suppresses evaporation of liquid helium. (3) Liquid helium bath (4.2 K bath) which is filled with liquid helium which is supplied to the superfluid helium bath. The 4.2 K bath has a diaphragm pressure gauge and a liquid helium level sensor. These instruments enable us to monitor the pressure variation and the amount of liquid helium remaining. (4) Superfluid helium bath (1.5 K bath) which is the most important part of our cryostat as an observation region. The 1.5 K bath has a thermometer, a diaphragm pressure gauge and a liquid helium level sensor. We can monitor the temperature, pressure and liquid helium level inside of the 1.5 K bath. To stabilize the 1.5 K bath, a needle valve and a butterfly valve, which are used to control the flow rate of liquid helium and pumping speed, respectively, are indispensable. They are controlled by LabVIEW with a GPIB interface.

2.2. Superfluid helium bath

As mentioned above, the most important part of the cryostat is the superfluid helium bath (1.5 K bath). In this section, we will describe it more in detail. The 1.5 K bath plays two important roles.

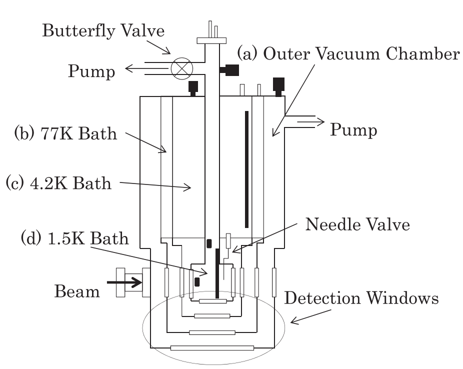

Fig. 1. Schematic layout of the helium cryostat. The helium cryostat has four baths. Each part has a different role. The outer vacuum chamber is pumped continually using a rotary pump and a turbo molecule pump. We can connect the 1.5 K bath to a rotary pump and a mechanical booster pump. After introducing liquid helium in the 1.5 K bath, we pump out the 1.5 K bath to decrease the temperature of liquid helium using vaporization heat.

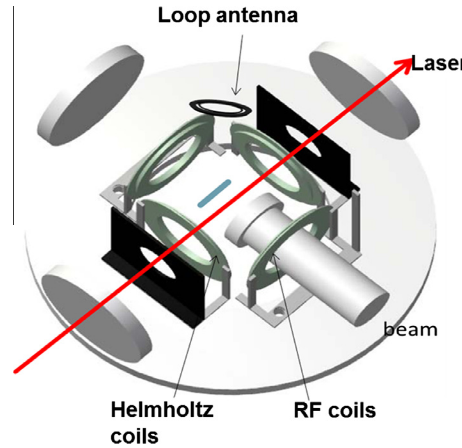

Fig. 2. Schematic diagram of the 1.5 K bath.

One is to maintain the superfluid helium condition steadily. The other is to realize the environment suitable for laser spectroscopy. Fig. 2 shows the schematic diagram of the 1.5 K bath. In the 1.5 K bath, a pair of Helmholtz coils which are important to produce atomic spin polarizations and double resonance method are placed in the parallel direction along the laser path. A pair of RF coils for measuring Zeeman splittings is placed in the perpendicular direction to the laser path. A MW loop antenna that is necessary to measure hyperfine structure splittings is installed upward of the laser path. These instruments are carefully located at the position where they do not disturb the laser path. If these instruments interfere with the laser path, intense scattered light would be induced, which disturbs the observation of laser-induced fluorescence (LIF) emitted from atoms in the observation region. Special care should be taken to use quartz windows at the bottom of the 1.5 K bath to detect LIF efficiently.

3. Cooling procedure

The cooling procedure is as follows:

(i) Pump out the 1.5 K and 4.2 K baths (24 h).
(ii) Pre-cool the 1.5 K, 4.2 K and 77 K baths using liquid nitrogen (24 h).
(iii) Remove liquid nitrogen from the 1.5 K and 4.2 K baths (3 h).
(iv) Pump out the 1.5 K and 4.2 K baths again (2 h).
(v) Fill the 1.5 K and 4.2 K baths with helium gas (two times) (2 h).
(vi) Transfer liquid helium to the 4.2 K bath (1 h).
(vii) Transfer liquid helium from the 4.2 K bath to the 1.5 K bath slowly (1 h).
(viii) Pump out the 1.5 K bath slowly (1 h).
(ix) Finally, liquid helium in the 1.5 K bath becomes superfluid (He II).

After we achieve the He II condition of the 1.5 K bath, we stabilize the height of the liquid surface and the pressure inside the 1.5 K bath using the GPIB controlled instruments such as stepping motors to move the butterfly valve and the needle valve.

4. Results

In September 2012, we performed a beam-line experiment using the cryostat. Fig. 3 shows variations of parameters during the experiment. As a consequence of our development, we evaluated the continuous operation time with a single helium transfer as 19 h and we could stabilize the liquid helium level of the 1.5 K