A Spin Polarizer for Low Energy Radioactive Nuclear Beams


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Abstract. A versatile spin polarizer for radioactive nuclear beams is proposed for spectroscopic studies of exotic nuclei far from stability. The polarizer takes advantage of the polarized electron transfer process, as in the optically pumped polarized proton ion sources. This method is applicable for low energy beams with a wide variety of nuclear species. The feasibility of the polarizer has been experimentally investigated by using stable nuclear beams at the test stand of RCNP. The beams with 2+ charge were injected into the polarizer and the nuclear polarization of the 1+ charge ions was selectively measured. The polarization measurement was based on the method of beam-foil spectroscopy. The nuclear polarization was observed for 10 keV/amu $^3$He, 3.4 keV/amu $^{14}$N and $^{15}$N beams to be $(3.89 \pm 0.76)\%$, $(3.04 \pm 0.11)\%$ and $(1.32 \pm 0.40)\%$, respectively with $P$(Rb) = 70 - 80 %. The transmission efficiency of the $^{14}$N beam, (2+ ion $\rightarrow$ 1+ ion) was found to be $\sim$ 60%. The performance is very promising for practical applications.

INTRODUCTION

The nuclear spin orientation allows the measurements of the magnetic and quadrupole moments of the ground state of the $\beta$-decaying nuclei. The magnetic moment is sensitive to the configuration of the valence nucleons and the quadrupole moment is primarily sensitive to the spatial distribution of protons. They therefore provide insight into the nuclear structure of the loosely bound nuclei. Aiming at such spectroscopic studies of exotic nuclei far from stability, we proposed a versatile method to produce spin-polarized radioactive nuclear beams (RNB) of a wide variety of nuclear species [1]. The principle of the polarizer is the same as that in the optically pumped polarized proton ion-sources [2–4]. The procedure is as follows:

(i) The spin polarization of the outermost electron of Rb atom is produced by the laser optical pumping.

(ii) The radioactive nuclear beam passes through the Rb vapor and the nucleus picks up the polarized electron into its atomic state.

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CP570, SPIN 2000, 14th International Spin Physics Symposium, edited by K. Hatanaka et al. © 2001 American Institute of Physics 0-7354-0008-5/01/$18.00

811
The hyperfine interaction between the nucleus and the electron induces the nuclear polarization.

It should be noted that this method works, in principle, for any non-zero spin nuclear species. The cross section of the electron transfer process is expected to be highest at the beam energy of a few keV/amu. This method is, therefore, best suited to the ISOL based RNB's. The feasibility of the polarizer however is subject to the unknown problems inherent in the nature of RNB's; (a) the depolarization effect after the electron transfer process, and (b) the transmission efficiency of RNB. The latter problem depends on the electron pickup and stripping cross sections. As for the former problem, the electron is transferred mostly to the atomic excited states because of the lower ionization potential of Rb than that of the beam ion and the depolarization may occur during the transition to the lower atomic states. In the proton ion-sources this problem is overcome by applying high magnetic field (~ 2 T) so as to decouple the spin-orbit interaction in the hydrogen atom. This method is, however, not applicable for RNB, because such decoupling field is not always feasible, furthermore, the emittance blowup in high field must be serious [5] for RNB whose intensity is limited. However, it is expected that without high field some part of polarization remains in the atomic states [6]. It is worth noting that the polarization even on the order a few % enables the nuclear spectroscopic studies. The polarizer of this type is possibly a versatile tool. In order to investigate the feasibility of the polarizer, we have constructed a test stand of the polarizer at RCNP, Osaka University, and some successful results have been obtained with stable nuclear beams of $^{14}$N. In the following the experimental method and the results are described.

**EXPERIMENTAL SETUP**

The test stand essentially consists of four parts; an ion-source to supply the beam, a Rb cell which contains high density Rb vapor, a polarimeter to measure the nuclear polarization, and a laser system for the optical pumping. The layout of the test stand is shown in Fig. 1. The beam of stable nucleus at a few keV/amu is supplied from a 2.45 GHz ECR ion-source. After the mass/charge state analysis, the beam goes through the Rb cell where Rb vapor is contained. The outermost electron in the Rb atom is spin polarized by the laser optical pumping. Thus the beam ion picks up the polarized electron in the collisions with the Rb atoms. In order to select ions that have picked up the electron, the beam goes to the electrostatic deflector and the beam direction is bent by 90°. The beam ions finally reach the polarimeter where the polarization of stable nucleus is measured through the atomic transition in the beam-foil interaction. The detail of the polarimeter is described in Ref. [7]. A low magnetic field (~ 10 Gauss) to preserve the nuclear polarization is applied in the whole region downstream of the Rb cell.

The Rb cell consists of two coaxial cylinders and the liquidized Rb is contained in the outer cylinder which serves as the reservoir for the Rb vapor at a saturated...
FIGURE 1. Layout of the test stand.

vapor pressure and the Rb vapor diffuses into the inner cylinder through thin slits. The Rb density is controlled by the Rb temperature. The Rb vapor is evacuated through the apertures at both ends of the inner cylinder. The beam goes through the inner cylinder. In the whole region of the cell a magnetic field is applied in the axial direction by a solenoid coil in order to cause Zeeman splitting for the optical pumping. The maximum field strength is 5 kG at the center of the cell. A pumping laser beam (tuned for the D1 transition in Rb; 795 nm, 2.4 W) to polarize the Rb atom is supplied from the right hand side in Fig. 1 through the vacuum window on the analyzer magnet. The polarization axis is parallel to the laser beam direction. Another laser beam (780 nm, 18 mW) to monitor both the Rb polarization and the Rb thickness is shot from the left hand side in Fig. 1. These measurements are based on the Faraday rotation effect.

RESULTS

Figure 2. shows the Rb polarization as a function of the Rb thickness. The magnetic field strength at the Rb cell was 2 kG. It should be noted that very high polarization has been achieved at the density around $10^{13} - 10^{14}$ atoms/cm$^2$, which is related to the roughly estimated cross section on the order of $10^{-14}$ cm$^2$ for the electron pickup reaction. The decrease of polarization at higher Rb density is due to the relaxation at the cell wall and due to the “radiation trapping”. If the electron pickup cross section is small, we need higher density of Rb and consequently higher laser power. The cross section was measured in the transmission experiment: Figure 3. shows the intensity of the $^{14}$N ions after the Rb cell, resulting from the 4 keV/amu $^{14}$N$^{++}$ beam, as a function of the Rb thickness. The intensity was measured as an electric current on a Faraday cup placed downstream of the electrostatic deflector. The intensities are normalized to the incident beam intensity. The intensity of the $^{14}$N$^+$ ion (N$^+$) increases with increasing Rb thickness and that of the $^{14}$N$^{++}$
FIGURE 2. Polarization of Rb as a function of Rb thickness.

FIGURE 3. Transmission efficiency of N ions as a function of Rb thickness.

FIGURE 4. Nuclear polarization of (a) $^3$He, (b) $^{14}$N and (c) $^{15}$N. The upper (lower) part shows the nuclear polarization with the pumping laser helicity +1 (-1).
(N++) decreases. This observation is due to the single electron pickup process. The intensity of the neutralized beam (N0), which is due to the subsequent electron pickup processes or double electron pickup process, was deduced by subtracting the N+ and N++ from the incident beam intensity. This process is significant at the Rb density higher than 10^{14} \text{atoms/cm}^2. Because of this process the ^{14}\text{N}^+ intensity is limited: The highest transmission efficiency for the ^{14}\text{N}^+ ion is approximately 60\% at the Rb density of 7 \times 10^{13} \text{atoms/cm}^2. This efficiency is reasonably high for the practical application of the polarizer. It should be noted that the Rb polarization is sufficiently high at this density region: The laser we used is intense enough. From the data in Fig. 3. the cross section of the single electron pickup process was estimated to be 1.5 \times 10^{-14} \text{cm}^2. The nuclear polarization of 10 \text{keV/amu} \text{^3He}^+, 3.4 \text{keV/amu} \text{^{14}N}^+ and 3.4 \text{keV/amu} \text{^{15}N}^+ ions was measured by the method of beam-foil spectroscopy: The circular polarization of the fluorescence P_{atom} was observed for the atomic transitions 2s ^3S \rightarrow 3p ^3P (388 \text{nm in He}^+) and 2s^22p3s ^3P \rightarrow 2s^22p3p ^3D (568 \text{nm in N}^+), and the nuclear polarization P_{nucleus} was evaluated as P_{nucleus} = P_{atom}/A, where A is the analyzing power which depends on the nuclear spin and atomic spins of the initial and final states. The Rb thickness was set at 7 \times 10^{13} \text{atoms/cm}^2 and the Rb polarization was 70 - 80\%, which is somewhat smaller than that shown in Fig. 2, due to bad laser condition. The results are shown in Fig. 4. The upper (lower) part shows the results with the pumping laser helicity +1 (−1). The sign of the nuclear polarization is opposite for the opposite laser helicity, ensuring that we are not observing spurious polarization. Combining these results the nuclear polarization was determined to be (3.89 \pm 0.76)\%, (3.04 \pm 0.11)\% and (1.32 \pm 0.40)\%, for \text{^3He}, \text{^{14}N} and \text{^{15}N}, respectively. The smaller polarization for \text{^{15}N} (I = 1/2) than for \text{^{14}N} (I = 1) suggests that the atomic polarization we observed does not properly reflect the nuclear polarization. This may be because of the cascade atomic transitions leading to the initial state of the fluorescence. The nuclear polarization must be larger than that inferred from the beam-foil spectroscopy results.

The performance of the polarizer is very promising for practical applications with radioactive nuclear beams. The conditions to increase the polarization are under investigation, and the direct measurement of the nuclear polarization based on the \beta-NMR method is planned.

REFERENCES