POLARIZED ^{3}He ION SOURCE BASED ON ELECTRON PUMPING

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A novel concept, "electron pumping" for producing a highly polarized beam has been demonstrated experimentally for energetic ^{3}He$^+$ ions passing through a polarized thick Rb vapor target in a strong magnetic field.

1 Introduction

The electron pumping was proposed in 1995 by Tanaka et al.[1] as a novel method to produce a highly polarized ^{3}He beam. Though somewhat similar pumping principles were proposed by Anderson et al. [2] and Wakuta et al.[3], they have not been demonstrated experimentally. The electron pumping technique applied to polarized ^{3}He$^+$ ions involves multiple capture and stripping of electrons between energetic ^{3}He$^+$ ions and polarized alkali atoms in a magnetic field, B_{LS}, strong enough to decouple not only the hyperfine but also the spin orbit interactions in excited levels. Fig. 1-(a) illustrates an intuitive explanation of the method. Suppose that an unpolarized ^{3}He$^+$ ion beam with an energy of a few keV/A is incident from the left on a polarized alkali vapor target. Major processes at this energy are electron capture for ^{3}He$^+$ ions and electron stripping for ^{3}He atoms, while an electron stripping for a ^{3}He$^+$ ion to form a ^{3}He^{2+} ion is negligibly small. As a result, only successive processes of electron capture for ^{3}He$^+$ ions and stripping for ^{3}He atoms are significant. An incident ^{3}He$^+$ ion, first, captures a polarized electron from an alkali atom and forms an excited state ^{3}He atom. The excited ^{3}He atom deexcites either to the ground or a metastable state by radiative decay. To avoid the depolarization of the captured electron during radiative decay, a 2-T decoupling field B_{LS} is applied to the collision region. During further passage of the ^{3}He atom through the polarized alkali vapor, an electron stripping process takes place and the ^{3}He atom is converted into a ^{3}He$^+$ ion again. Since either of the two electrons of the ^{3}He atom can be stripped with approximately the same probability, the

$^3He^+$ ion is polarized by this process. If the alkali vapor thickness is large enough to allow repeated capture and stripping cycles, the polarization of the $^3He^+$ ion will increase further and finally reaches a maximum value determined by the polarization of the alkali vapor.

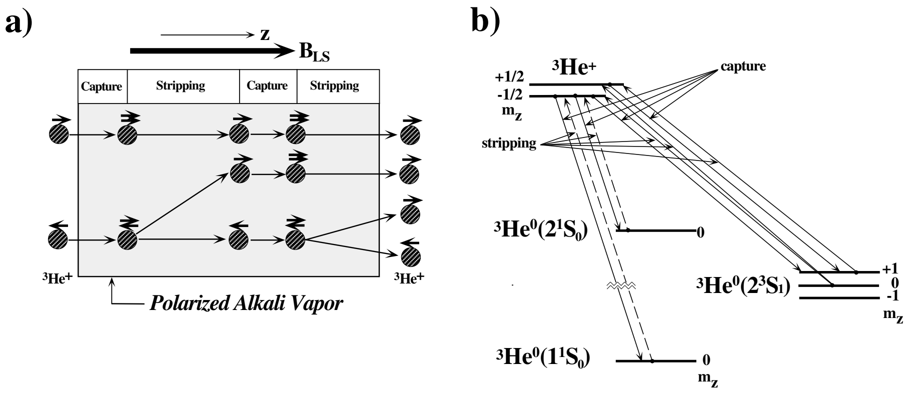

Figure 1: Principle of electron pumping. (a) An unpolarized $^3He^+$ ion incident on a polarized Rb atom captures a polarized electron followed by stripping of one of the two electrons in the ^3He atom. By repeating this cycle a number of times, the degree of $^3He^+$ polarization increases. Arrow lengthes qualitatively give mean free paths for a $^3He^+$ ion and ^3He atom. (b) Schematic explanation of electron pumping in analogy with optical pumping.

The multiple-collision processes can be discussed alternatively. An energy level diagram for a $^3He^+$ ion and a ^3He atom is shown in Fig. 1-(b), where the levels of the ^3He atom with S=0 (singlet levels, S) and with S=1 (triplet levels, T) are separately indicated. An incident $^3He^+$ ion, firstly, captures a polarized electron from an alkali atom and forms a ^3He atom in an excited state. The excited ^3He atom then deexcites to the ground or a metastable state of the ^3He atom by radiative decay. The radiative decay keeps the spin multiplet unchanged. Fig. 1-(b) shows the energy levels of the $^3He^+$ ion, including the 2 metastable levels and the ground level of the ^3He atom. For simplicity other levels of the ^3He atom are not shown. In the capture process, a $^3He^+$ ion with an $m_z = +\frac{1}{2}$ magnetic substate captures a polarized electron to form only a ^3He (T) atom with $m_z = +1$, while a $^3He^+$ ion with $m_z = -\frac{1}{2}$ captures a polarized electron and forms either a ^3He (T) or ^3He (S) state with $m_z = 0$. When an electron stripping process takes place, a $^3He^+$ ion is formed again. An electron stripping process for the ^3He (T) atom with $m_z = +1$ forms only a $^3He^+$ ion with $m_z = +\frac{1}{2}$, while an electron stripping for the ^3He (T or S) atom with m_z =0 forms a ^{3}He$^+$ ion with m_z =either $+\frac{1}{2}$ or -$\frac{1}{2}$ with the equal probability. Most ^{3}He singlet atoms are in the ground level and the electron stripping process from this level is negligibly small at our incident energy. After a number of repetitions of these capture and stripping processes, the ^{3}He$^+$ ions with m_z =$+\frac{1}{2}$ predominate so that the electron of the ^{3}He$^+$ ion is polarized. The above scenario is almost identical to the principle of the optical pumping if one replaces a polarized electron with a circularly polarized photon. Thus, the aim of the present work is to experimentally prove validity of the electron pumping by measuring P_T as a function of the polarized Rb vapor thickness. The Rb vapor is polarized by optical pumping.

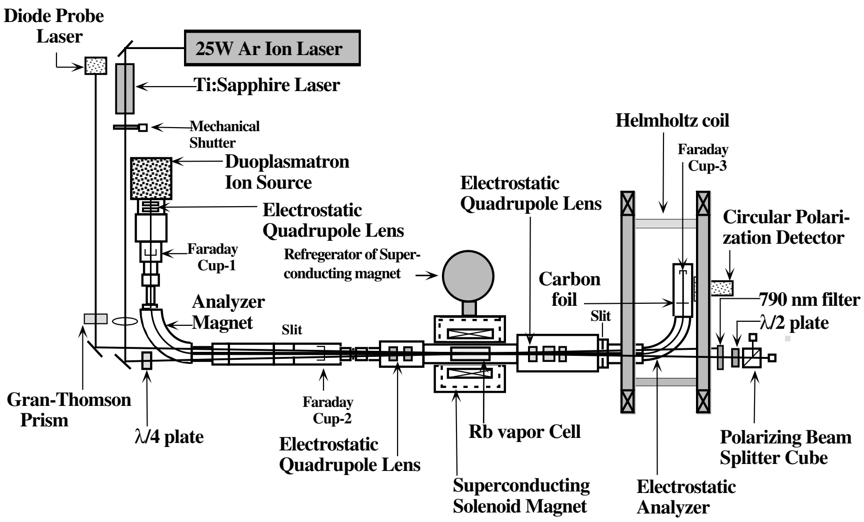

Figure 2: Experimental setup. A ^{3}He$^+$ ion beam produced by a duoplasmatron is incident on a Rb vapor cell located along the center axis of a 2-T superconducting magnet. The emerging ^{3}He$^+$ is transported to a polarimeter after passing through a 90° electrostatic analyzer. To maintain the polarization a guiding field is applied to the region of the polarimeter and the electrostatic analyzer. The principle of the polarimeter is based on a beam foil spectroscopy as described in the text.

2 Experimental Procedure

Fig. 2 shows the apparatus which has been constructed at the RCNP, Osaka University. A 19-keV ^{3}He$^+$ ion beam is extracted from a duoplasmatron ion source and is incident on a 32-cm long Rb vapor cell. Though the maximum ^{3}He$^+$ beam current could exceed 100 μA, the current is usually reduced to less than 20 μA in order to avoid a damage to a thin carbon foil, which is used for the polarization measurement as discussed below. The Rb vapor cell is located in a 2-T axial magnetic field supplied by a 6-T superconducting solenoidal coil. In order to change the Rb vapor thickness from 1×10^{14} to 6×10^{14} atoms/cm^2, the Rb cell temperature is varied from 100 to 120 °C with a precision better than 0.1 °C. The Rb vapor is polarized using the D_1 transition of the Rb atom (795 nm) with a 4-W Ti:Sapphire laser pumped by a 25-W Ar ion laser. The linewidth of the pumping laser is $\sim$20 GHz. It is sufficient to fully cover the Doppler-broadened linewidth and inhomogeneity of the solenoidal magnetic field. To monitor the thickness and polarization of the Rb vapor, we use Faraday rotation. For this purpose, linearly polarized 790-nm light provided by a semiconductor probe laser is incident on the Rb vapor cell through a Gran-Thomson prism which defines the direction of the linear polarization. The probe laser light penetrating the Rb cell is transported to a polarizing beam splitter cube through a $\lambda/2$ plate to measure the Faraday rotation angle. We measure the Faraday rotation angle with a precision of 3×10^{-2} degrees. P_{Rb} decreases from 0.6 to 0.2 when the Rb thickness is increased from 2×10^{14} to 10×10^{14} atoms/cm^2. This result is qualitatively consistent with the result of TRIUMF[4].

The ^{3}He$^+$ ions emerging from the Rb vapor cell become partially nuclear polarized by the hyperfine interaction when they reach a region where the external magnetic field is null. The ^{3}He nuclear polarization, P_N is half of the electron polarization, P_e, of the ^{3}He$^+$ ion influenced in the strong magnetic field, i.e.,

$$P_N = \frac{1}{2} \times P_e. \tag{1}$$

The nuclear polarized ^{3}He$^+$ ions, then, are separated from the fast ^{3}He atoms by a 90° electrostatic analyzer and enter a polarimeter which measures the ^{3}He nuclear polarization by means of a beam foil spectroscopy[5]. To preserve the direction of the ^{3}He polarization, a weak magnetic field (B$\sim$10 G) from a Helmholtz coil is applied to the region of the electrostatic analyzer and the polarimeter. When a nuclear polarized ^{3}He$^+$ ion is incident on a thin carbon foil ($\sim$5 μg/cm^2), most of the emerging particles are neutralized and are in the excited state. Through the hyperfine interaction, the ^{3}He nuclear polarization is partially converted into an electronic polarization in the excited state of the ^{3}He atom downstream from the foil, which induces a circular polarization for the emitted photons from the excited ^{3}He atoms. By measuring the circular polarization of the emitted photons, the electronic polarization of the ^{3}He$^+$ ions as well as the ^{3}He nuclear polarization can be obtained. We observe a circular polarization of the 389-nm photons corresponding to the transitions between the 3^3P_J(J=0,1,2) and 2^3S_1 states in the ^{3}He I atom. These transitions predominated among the observed transitions. The 389-nm photons have been successfully used for our previous measurements[6,7]. A computer controlled measurement of the thickness and polarization of the Rb vapor, the circular polarization, the temperature of the Rb vapor cell, and the beam current detected by a Faraday cup is done with a combination of a UNIX and VME system.

3 Results and Discussion

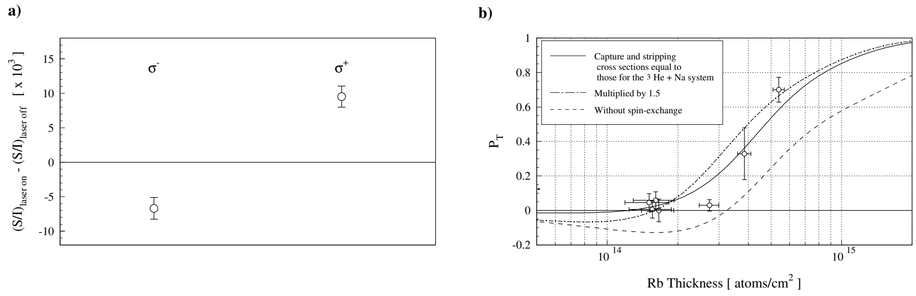

Figure 3: a) Observed Stokes parameters corrected by the baseline shift due to the system asymmetry. σ^+ (σ^-) indicates the right (left) circular polarization for the pumping laser, respectively. b) Experimental and theoretical values of the polarization transfer coefficient, P_T plotted as a function of the Rb vapor thickness. P_T is defined as a $P_{^3He}/P_{Rb}$, where $P_{^3He}$ is an electron polarization of the $^3He^+$ ion after emerging from the polarized Rb vapor.

Fig. 3-(a) shows the observed Stokes parameter, S/I taken at the Rb vapor thickness of 5.3×10^{14} atoms/cm^2. Here, S/I is defined as

$$S/I = A \times P_N, \tag{2}$$

where A and is an analyzing power for the photons[6]. σ^+ (σ^-) in Fig. 3-(a) indicates right (left) circular polarization for the pumping laser, respectively. To correct the instrumental asymmetry, S/I taken without the pumping laser is subtracted from S/I with the pumping laser. The experimental result clearly demonstrates that the polarimeter works successfully because S/I changes its sign when circular polarization of the pumping lasers is changed. Fig. 3-(b) shows the observed polarization transfer coefficient, P_T taken at different Rb vapor thicknesses. P_T is defined by P_e/P_{Rb}, where P_e and P_{Rb} are the electron polarization of the $^3He^+$ ions, and the Rb polarization, respectively. P_T is extracted from the observed value of S/I, the calculated values of A, and P_{Rb} using eq. (1), and (2). The error bars indicated are mainly due to uncertainty in the measurement of the Faraday rotation angle and counting statistics. The observed P_T's in Fig. 3-(b) clearly demonstrate an increase with an increase of the Rb vapor thickness. The experimental results are compared with the theoretical calculations for the electron pumping. For this purpose, the rate equations prescribed in ref. [1] are solved with a few sets of the collision cross sections. The solid, dashed, and dot-dashed curves are, respectively, the calculated results for the capture and stripping cross sections deduced for the sodium + ^{3}He system in ref. [6], the result with the spin-exchange cross section not involved, and the result with the cross sections multiplied by 1.5 relative to the first case. The calculated results in Fig. 3-(b) demonstrates that the increase of P_T, as the Rb vapor thickness increases, is not extremely sensitive to the absolute values of the cross sections, and that the effect of the electron pumping is enhanced by spin exchange. More precise experimental data are needed for further detailed comparison with the theory of the electron pumping. One concludes that the basic principle is verified in the present measurement.

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