Unexpected reduction of spin-exchange cross section for fast $^3He^+$ ion incident on Rb atom

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Abstract

The spin-exchange cross section, σ_{se}, was measured for a 6.33 keV/amu $^3He^+$ ion incident on a polarized Rb atom. The result is $\sigma_{se}=0.12^{+0.27}_{-0.26}\times10^{-15}$ cm^2, which is unexpectedly an order of magnitude smaller than the theoretical value $\sigma_{se}=5.9\times10^{-15}$ cm^2 evaluated by the semiclassical impact parameter method assuming formation of molecular orbits.

1 Introduction

A spin-exchange process in atomic collisions is not only of fundamental importance in quantum mechanics but also of practical importance in the various application fields such as 21-cm radio astronomy [1], optical pumping [2], H masers [3], polarized ion sources [4], and so on. The process has been extensively studied in a low energy region less than a few eV for the H-H [1, 5, 6, 7], H-Rb [8, 9], He-Rb [10, 11], Muonium-Cs [12] systems, and so on. On the other hand, the spin-exchange process at higher energies has been limited only to the H-Rb [4, 13], He^+-Na [14] and Ne^+-Na [15] systems.

One of the current topics is the spin-exchange process for the fast $^3He^+$-Rb system (" fast" means a few keV/amu) in view of application to the polarized ion source for nuclear physics research [16, 17, 18]. In this letter we report the first measurement of the spin-exchange cross section, σ_{se}, for this system by using a polarized Rb vapor. We also report a theoretical calculation of σ_{se} by using the semiclassical impact parameter method assuming formation of molecular orbits.

2 Experiment

The spin-exchange cross section is measured by observing an induced polarization of the $^3He^+$ ion after an unpolarized $^3He^+$ ion penetrates through a polarized Rb vapor. Here, the Rb vapor thickness should be at least 1×10^{14} atoms/cm^2 or more to obtain a detectable polarization of the $^3He^+$ ion, since a magnitude of the spin-exchange cross section is expected to be an order of 10^{-15} cm^2 according to theoretical estimation as discussed later. It should be noted that with such a thick vapor the $^3He^+$ ion is polarized not only by the spin-exchange process itself but also by multiple cycles of electron stripping and capture called "electron pumping" [16, 18]. The polarization induced by the latter process is correctly evaluated since the electron stripping and capture cross sections are well established. Though the spin-exchange process between a ^3He atom formed in the electron pumping process and a Rb atom also produces the polarization, this effect is expected to be small as discussed later. A schematic view of an experimental apparatus is shown in Fig. 1. A $^3He^+$ ion was produced by a duoplasmatron ion source and was extracted at 19 kV. The $^3He^+$ ion was momentum analyzed by a sector magnet and led into a Rb oven which was located in the center of a 2T-superconducting solenoidal magnet. A Rb vapor inside the oven was polarized by means of the optical pumping with a high power (4W) laser from a Ti:Sapphire laser excited by a 25W-Ar ion laser. A thickness and polarization of the Rb vapor were measured by the Faraday rotation method [19]. After passing through the region of the solenoidal magnetic field, the polarization is transferred from the $^3He^+$ ion to the ^3He nucleus by the hyperfine interaction. Then, the nuclear polarized $^3He^+$ ion was energy analyzed by an electrostatic deflector and was introduced to a polarimeter, with which the nuclear polarization was measured.

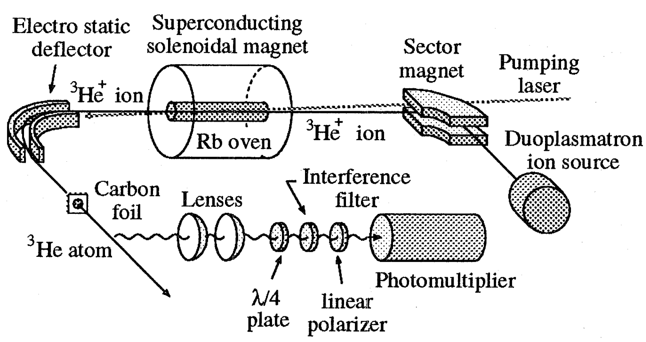

Fig. 1 A schematic view of an experimental apparatus.

The principle of the polarimeter based on the the beam-foil spectroscopy [20]. The nuclear polarized $^3He^+$ ion penetrating a 5 μg/cm^2 carbon foil becomes neutral but in the excited states. The ^3He atom in flight de-excites to the ground or metastable states by emitting photons. During the photon emission a certain amount of the polarization is periodically transferred from the nucleus to the atom by the hyperfine interaction. Consequently, the nuclear polarization can be determined by measuring the circular polarization of the emitted photons. 388.9 nm photons corresponding to the transition between the 3^3P_J and 2^3S_1 (J = 0, 1 or 2) states were used in the present measurement. The photons were analyzed with a polarization optics consisting of a $\lambda/4$ plate, an interference filter and a linear polarizer and finally detected by a photomultiplier [21]. As a result, the polarization of the $^3He^+$ ion was obtained from the measured ^3He nuclear polarization.

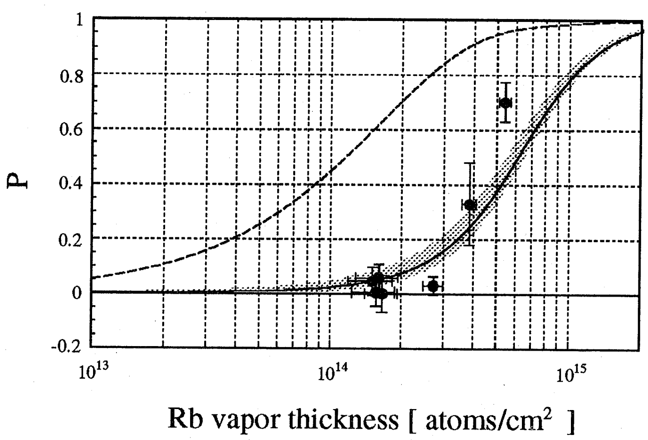

Fig. 2 Observed P (●) as a function of the Rb thickness. A solid curve show the least square fit solving the rate equations. A left edge of a shaded area is a upper error. The right edge of the shaded area is the curve for $\sigma_{se} = 0$ cm^2 A dashed curve is the one for $\sigma_{se} = 5.9 \times 10^{-15}$ cm^2 (theoretical value).

The polarization of the $^3He^+$ ion, P, thus obtained is plotted as a function of the Rb vapor thickness in Fig. 2. Here, the abscissa is a measure of the $^3He^+$ polarization normalized by the Rb polarization.

It is clearly seen that P increases according to an increase of the Rb vapor thickness, which suggest that when the Rb vapor thickness is increased, the number of collision cycles between the ^3He ion/atom and Rb atoms is increased. The polarization of the $^3He^+$ ion increases as the results of the spin-exchange and electron pumping processes [18].

To discuss the above behavior quantitatively, we solved the rate equations according to the prescription of Ref. [16] with some modifications. In this calculation we used the capture and stripping cross sections, which is referred experimental results on He-Rb [22] and He-Cs [23]. The only unknown parameters in these rate equations are σ_{se} for a $^3He^+$ ion and σ_{sea} for a ^3He atom. However, σ_{sea} case does not significantly influence on the value of P due to the following reason: Since the ^3He atom is formed after the polarized electron capture, the atom is highly polarized. As a result, a further growth of the atomic polarization by the spin-exchange becomes less pronounced. In other words, σ_{sea} is not so influential as σ_{se}. This characteristic behavior is shown by solving the rate equations with varying the value for σ_{sea}. The discussion below is done only for σ_{se} assuming σ_{sea} is fixed at 1.0×10^{-15} cm^2 for convenience.

Under the above assumptions, the experimental results were fitted by parameterizing σ_{se} with the χ^2 fit method. The best fitted curve is shown by a solid curve in Fig. 2. The spin-exchange cross section is

$$\sigma_{se} = 0.12^{+0.27}_{-0.26} \times 10^{-15} \quad [\text{ cm}^2], \tag{1}$$

where the errors include a fitting error and errors of the capture and stripping cross sections. The shaded area in Fig. 2 corresponds to the errors in Eq. (1). From this analysis, it is found that the observed P was well reproduced by the model calculation including the process of spin-exchange and electron pumping.

A calculated curve by using theoretical value, which is discussed later, $\sigma_{se} = 5.9\times10^{-15}$ cm^2 is shown by a dashed curve. This shows that the above experimental value of σ_{se} is decisively different from theoretical one over the range of the errors.

3 Theoretical Calculation

Since it is of particular interest to see whether the experimental spin-exchange cross section, σ_{se}, is reproduced by the theory or not, we carried out the model calculation based on the semiclassical impact parameter method assuming formation of molecular orbits, which succeeded in the fast H-Rb system [13, 4].

The σ_{se} is described as [13],

$$\sigma_{se} = 2\pi \int_0^\infty b \sin^2 \frac{\phi_{ts}}{2}\, db, \tag{2}$$

$$\phi_{ts} = \int \frac{V_t - V_s}{\hbar}\, dt = -2 \int_b^\infty \frac{R(V_t - V_s)}{\hbar v \sqrt{R^2 - b^2}}\, dR. \tag{3}$$

Here, V_t and V_s are respectively the potential energies of the ^3He-Rb molecule in the $1^3\Sigma$ and $1^1\Sigma$ (1Σ denotes $^3He^+(1s^1)$ - Rb(5s)) states. b, R and v are respectively an impact parameter, an internuclear separation between a Rb atom and a $^3He^+$ ion, and an incident velocity of a $^3He^+$ ion.

In order to determine the difference between V_t and V_s, i.e. V_{ts}, the molecular electronic states for the $^3He^+$-Rb system were calculated by using the modified valence-bond configuration-interaction method with the Gaussian type pseudopotentials representing the Rb^+ core [24]. The pseudopotential parameters for the Rb^+ core and the Slater type orbitals (STO's) for the Rb atom were taken from Ref. 25. We obtained the orbital exponents of the STO's for the He atom by optimizing its energies. The deviation from the experimental spectroscopic energies at the separated atom limits is better than 0.04 % except for the lowest state, $^3He(1s^2\ 1S)$ - Rb^+ (0.8 %), in the present calculation. The calculated V_{ts} is shown by a solid curve in Fig. 3.

The σ_{se} was calculated as a function of an incident energy of the $^3He^+$ ion by substituting the V_{ts} for the $^3He^+$-Rb system into Eq.(2). This result is shown by a solid curve in Fig. 4. The experimental data at 6.33 keV/amu is also shown by a closed circle. For reference, the results for the H-Rb system are shown in Fig. 4, where the dot-dashed curve is the theoretical results [13] and open circles are the experimental results [4]. The

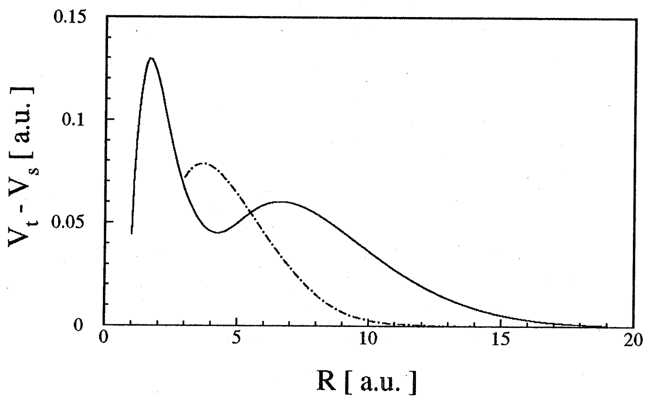

Fig. 3 The difference of potential energy between $1^1\Sigma$ and $1^3\Sigma$ (V_{ts}) as a function of a nuclear separation. The solid curve is our calculation for $^3He^+$-Rb. The dot-dashed curve is Stevens's calculation for H-Rb [24].

calculated results show that σ_{se} for the $^3He^+$-Rb system is obviously a several times larger than that for the H-Rb system in all studied energies. The trend is qualitatively understood in terms of the difference in the shape of V_{ts} between these two systems, i.e. , σ_{se} becomes larger for the former case (a solid curve) than for the latter case (a dot-dashed curve) by Eq. (2), and (3), because V_{ts} for the former case has non-zero values up to a large R as shown in Fig. 3.

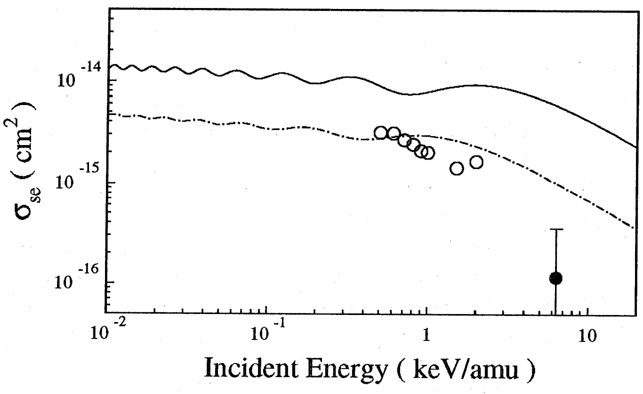

Fig. 4 Calculated σ_{se} as a function of the incident energy for a H atom (a dot-dashed curve) [13] and a $^3He^+$ ion (a solid curve) on a Rb atom and experimentally obtained σ_{se} for H atom (○) [4] and $^3He^+$ ion (●)

4 Discussion and Conclusion

A striking finding is that the experimental σ_{se} for the $^3He^+$-Rb system is an order of magnitude smaller than the theoretical prediction, while those for the H-Rb system are reasonably reproduced by the theory.

The unexpected reduction of σ_{se} for the $^3He^+$-Rb system has not been known so far because no experimental data have been available due to the experimental difficulty. This suggests that the collision mechanism for the $^3He^+$-Rb system are much more complex than that for the H-Rb system. In fact, we assumed only one transition channel for both systems. However, it may be necessary to take effect of the other transition channels into account particularly for the $^3He^+$-Rb system. A more comprehensive calculation along this line now under going.

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