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Polarization transfer coefficient $K_y^{y'}$ in the ^{2}H$(d,p)^3$H reaction at $\theta=0°$ at very low energies

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The polarization transfer coefficient $K_y^{y'}$ has been measured for the ^{2}H$(d,p)^3$H reaction at a scattering angle of 0° at very low energies (≤90 keV). The polarization of the emitted protons from the reaction was measured with a proton polarimeter using p- ^{28}Si elastic scattering. A value of 0.09 ± 0.10 was obtained for $K_y^{y'}$. This value was compared with the value for $K_y^{y'}$ that we have calculated from the transition amplitudes determined by Lemaître and Schieck for the ^{2}H$(d,p)^3$H reaction [Ann. Physik **2**, 503 (1993)].

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The fusion reactions ^{2}H$(d,p)^3$H and ^{2}H$(d,n)^3$He in the sub-Coulomb energy region have been studied to gain an understanding of the nuclear reaction mechanisms of four-nucleon systems and for applications in fusion energy research. Some researchers have pointed out that the reactions initiated by two parallel-polarized deuterons would be suppressed [1]. The suppression would reduce undesired neutrons created from the simultaneous reaction ^{2}H$(d,n)^3$He in D-^{3}He plasma, thus leading to ‘‘neutron-lean’’ fusion reactors [1,2]. This suggestion has aroused controversy because the values for the ratio of the polarized to the unpolarized cross sections calculated from several models conflict [3–11].

In the 1990s, angular distributions of the unpolarized cross sections and the analyzing powers at very low energies (<100 keV) were measured accurately and systematically by several groups [10,12–14]. Several different analyses were later performed based on these data. However, there is considerable disagreement among these analyses in the predictions for the degree of suppression of the $d+d$ reactions. A simple barrier penetrability model by Lemaître and Schieck predicted that there would be no suppression [9]. Fletcher *et al.* obtained the same result with an R-matrix analysis of the four-nucleon system [10]. Zhang *et al.*, however, derived a different result by a partial wave analysis of the neutron transfer reaction [11]. They suggested that the suppression would not happen at an incident energy of 20 keV but the polarized to unpolarized cross section ratio would quickly decrease with an increase of the incident energy and reach around 20% at $E_d=90$ keV, i.e., the $d+d$ reactions would be suppressed at 90 keV. For the $d+d$ reactions, no direct measurement of the polarized cross section has been performed due to the difficulty in developing a polarized deuteron target for very-low-energy experiments. Thus, it is not clear which analysis is correct. To verify the validity of each analysis, experimental data of observables, which were not included in the analysis, are important. Consequently, in the present work, we measured the polarization transfer coefficient $K_y^{y'}$ in the reaction ^{2}H$(d,p)^3$H at a scattering angle of 0° at very low energies. The preliminaly result was reported at the 14th International Spin Physics Symposium (SPIN2000) [15].

In any reaction of a spin-1 projectile and spin-$\frac{1}{2}$ ejectile, the polarization of the ejectile at a scattering angle of $\theta=0°$ is expressed in simple form using the polarization transfer coefficients with the following particular conditions [16]: if the spin-quantization axis is oriented at an angle of 54.7° with respect to the incident beam direction, the polarization component of the ejectile along the y' axis at $\theta=0°$ can be expressed in terms of the polarization transfer coefficient $K_y^{y'}$ as follows [16]:

$$p_{y'}(0°)=\sqrt{\frac{3}{2}}p_3K_y^{y'}(0°), \tag{1}$$

where p_3 is the vector polarization of the incident beam at the polarized ion source, and the y' axis is perpendicular to the incident beam direction and in a plane given by the spin-quantization axis and the incident beam direction. From Eq. (1), we derived $K_y^{y'}$ for the ^{2}H$(d,p)^3$H reaction at an angle of 0° from measurements of the polarization $p_{y'}$ of the emitted protons and the polarization p_3 of the incident deuterons.

The experiments were performed with a 90-keV polarized deuteron beam from a Lamb-shift polarized ion source at the Tandem Accelerator Center of the University of Tsukuba (UTTAC) [17]. We used a proton polarimeter using p- ^{28}Si elastic scattering to measure the polarization of protons from the ^{2}H$(d,p)^3$H reaction. We should stress two characteristics in the present work that allow polarization measurements at very low energies. First, the polarized ion source at UTTAC utilizes a spin filter for nuclear polarization, so we measured the incident beam polarization with a quenched-ratio method [18] without using any nuclear reactions. We have tested the accuracy of this method with nuclear reactions and estimated it to be correct within 2%. Second, a silicon solid-state detector was used as the analyzing ^{28}Si target of the proton polarimeter, so that the background events could be reduced by requiring coincidence between the analyzing detector and the scattered-proton detector of the polarimeter. As a result, the double-scattering events were well separated from the background and counted with a good signal-to-background ratio.

The measurements were carried out in a scattering chamber of 32-cm diameter. The chamber was joined onto the end of the polarized ion source through a quadrupole magnet

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followed by a Wien filter. The polarimeter and a deuteron target were placed in the chamber. The pressure in the chamber was kept below 4×10^{-4} Pa with a liquid-nitrogen trap.

Deuterated polyethylene $(CD_2)_n$ was used as a deuteron target. The 10-μm $(CD_2)_n$ target was deposited on a 15-μm thick Al foil to limit the rise in target temperature during bombardment, thus reducing the rapid depletion of deuterium caused by beam heating. The targets were prepared by pouring a solution of $(CD_2)_n$ in xylene at 100 °C onto a horizontal sheet of aluminum foil and then evaporating the xylene from the foil at a temperature of 75 °C. The mean penetration range of 90-keV deuterons in $(CD_2)_n$ is 1.34 μm [19]. Hence, the incident deuteron beam was stopped by the $(CD_2)_n$ target. On the other hand, protons emitted from the $^2H(d,p)^3H$ reaction at 0° have a larger energy of 3.44 MeV, so they penetrated the $(CD_2)_n$ target and the aluminum backing and continued towards the proton polarimeter. An incident deuteron, losing its energy in the target, can react with a target deuteron at lower energies than the incident energy of 90 keV. The mean value of the reaction energy estimated from the reaction cross sections [12] and the stopping powers of $(CD_2)_n$ for deuterons is 68 keV [19].

The polarization of the $^2H(d,p)^3H$ protons emitted at 0° was measured by the polarimeter using p-^{28}Si elastic scattering. The polarimeter consisted of two silicon solid-state detectors. The first detector, with an active area of $28\times28\,\mathrm{mm}^2$ and a thickness of 450 μm (HAMAMATSU S5377-03), was placed at a scattering angle of 0° as the silicon target for analyzing the polarization of the protons. The acceptance angle of the detector was ±6.5° around the 0° angle. The p-^{28}Si elastic scattering has a large analyzing power near the 115° laboratory angle below a proton energy of 3 MeV [20]. For the detection of protons scattered by the first detector, the second detector, with an active area of $48\times48\,\mathrm{mm}^2$ and a thickness of 300 μm (HAMAMATSU S4276-02), was placed at the 115° angle with respect to the first detector. Energies ranging from 2 to 3 MeV and laboratory angles of 95° to 135° were used in this polarimeter. The analyzing power A_y of the polarimeter was measured with 3-MeV polarized protons from a tandem accelerator (Pelletron 12UD) at UTTAC. The measured analyzing power was -0.44 ± 0.03. The detection efficiency of the polarimeter was 9.7×10^{-6}. A typical two-dimensional coincidence spectrum between the first and second detectors is given in Fig. 1. The double-scattering events of the 3-MeV protons from the $^2H(d,p)^3H$ reaction lie along a line, with good separation from the background.

The polarization transfer coefficient $K_y^{y'}$ was obtained by measuring separately the double-scattering yields of the incident deuterons in the $m_I=+1$ and -1 magnetic substates from the polarized ion source for the spin-quantization axis oriented at an angle of 54.7° from the beam direction. The spin-quantization axis was controlled by the Wien filter of the polarized ion source. The magnetic substate sequence of the deuteron beam was changed every 5000×10^{-8} C beam charges. The typical beam current was approximately 200 nA and the counting rate of the true events was approximately six events an hour. As a result, the polarization transfer coefficient $K_y^{y'}$ was determined to be 0.09 ± 0.10. The error includes statistical errors for the proton polarization measurement (±0.08) and uncertainties associated with the ion source and the proton polarimeter (±0.04).

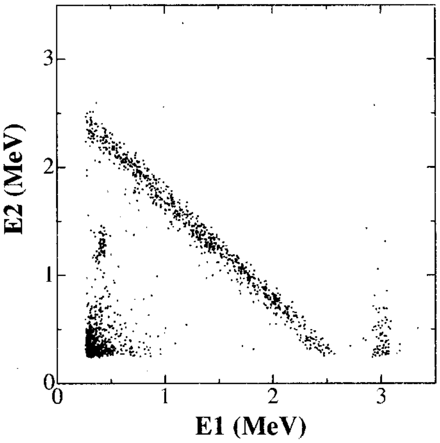

FIG. 1. Two-dimensional coincidence spectrum between the two silicon solid-state detectors of the proton polarimeter. The double-scattering events of protons from the $^2H(d,p)^3H$ reaction lie along a line. $E1$ and $E2$ are the energies deposited in the first and second detectors, respectively.

We compared our experimental estimate of $K_y^{y'}$ with a value calculated using the transition amplitudes determined by Lemaître and Schieck in Ref. [9] for the $^2H(d,p)^3H$ reaction. In the analysis, using a simple barrier penetrability model, they determined all low-energy transition amplitudes for the $^2H(d,p)^3H$ and $^2H(d,n)^3He$ reactions from a fit to the Legendre expansion coefficients of the experimental data for the cross section, analyzing powers and proton polarization induced by unpolarized deuterons for $E_d<500$ keV. The calculated results for incident energies of 10 and 90 keV and the experimental estimate are shown in Fig. 2. The measured value is a mean of $K_y^{y'}$ over deuteron reaction energies lower than an incident energy of 90 keV. The corresponding theo-

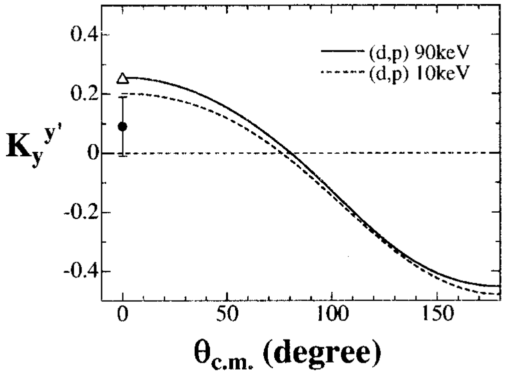

FIG. 2. The measured polarization transfer coefficient $K_y^{y'}$ (solid circle), the values calculated from the transition amplitudes determined by Lemaître and Schieck in Ref. [9] (solid and dashed curves), and the mean value of the calculated value over the incident energies (triangle).

retical mean, evaluated from an energy integration over the calculated $K_y^{y'}$ weighted with the reaction cross section, is 0.25 (shown in Fig. 2 as a triangle). The experimental result differs from the calculation by 1.5 standard deviations.

The polarization transfer coefficient $K_y^{y'}$ for the ^{2}H$(d,p)^3$H reaction at 0° has been previously measured at higher incident energies between 6 and 15 MeV [16,21]. In those experiments, it was found that the measured values for $K_y^{y'}$ were nearly equal to a value of 0.62 derived from a simple stripping model in which the polarization of the outgoing protons are equal to their polarization inside the deuterons. The $K_y^{y'}$ value obtained in the present work is much smaller than the one from the simple stripping model. The fact that $K_y^{y'}$ is constant and consistent with the simple stripping model at higher energies but drastically decreases in the low-energy region has also been observed in the mirror reaction ^{2}H$(d,n)^3$He [22–24].

In summary, we have measured the polarization transfer coefficient $K_y^{y'}$ in the ^{2}H$(d,p)^3$H reaction at a scattering angle of $\theta = 0°$ at very low energies ($E_d \leqslant 90$ keV). In the experiments, the reaction ^{2}H$(d,p)^3$H was induced by 90-keV polarized deuterons from a Lamb-shift-type polarized ion source bombarding the thick deuteron target $(CD_2)_n$. The polarization of the protons was measured with a proton polarimeter in which p- ^{28}Si elastic scattering was used. As a result, a value of 0.09 ± 0.10 for $K_y^{y'}$ was obtained as an integrated value over deuteron energies below 90 keV in the thick target. The experimental result was compared with a result calculated from the transition amplitudes determined by Lemaître and Schieck for the reaction ^{2}H$(d,p)^3$H. The experimental value differs from the calculated value by 1.5 standard deviations. For further discussion about the suppression of the $d+d$ reactions, the values of $K_y^{y'}$ calculated from other models for the $d+d$ reactions should be compared with the present experimental value.

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