Polarization Transfer in the $^2H(d,p)^3H$ Reaction at $\theta = 0°$*

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Measurements of the polarization transfer coefficients $K_y^{y'}$ and $K_{yz}^{x'}$ for the $^2H(d,p)^3H$ reaction at an angle of 0° and for six incident deuteron energies from 6 to 15 MeV are reported. The experimental method used is independent of the knowledge of the analyzing tensor A_{zz} and of current integration. Our measurements of $K_y^{y'}$ agree well with the results of Simmons *et al.* for the mirror reaction $^2H(d,n)^3He$, supporting their conclusion that the outgoing-nucleon polarization is nearly constant over this energy range but less than that which is calculated for the nucleons in the incident deuterons.

[NUCLEAR REACTIONS $^2H(d,p)$, E = 6–15 MeV, $\theta = 0°$; measured polarization transfer.]

I. INTRODUCTION

There has been active interest recently in the comparison of polarization effects for the $^2H(d,p)$-^3H and $^2H(d,n)^3He$ mirror reactions. Earlier disagreement in the outgoing-neutron and -proton polarization values when compared at the same deuteron bombarding energy[1] was shown to disappear when these data were instead compared at the same energy in the outgoing-proton and -neutron channel.[2] Recent measurements of the vector and tensor analyzing powers of these two reactions have shown that small differences exist in T_{20} and T_{22}[3,4] and in iT_{11}[5] when the data are compared at the same deuteron bombarding energy. It has been suggested that because many of the differences are observed to be large at low energies and smaller at higher energies, they reflect the added 0.76-MeV Coulomb energy in the $p+^3H$ system and not a violation of the charge symmetry of the nuclear forces involved.[2,4]

As a further experimental test of the similarity of these two reactions, we report here our recent measurement of the polarization transfer coefficients $K_y^{y'}$ and $K_{yz}^{x'}$ for the $^2H(d,p)^3H$ reaction for incident deuteron energies between 6 and 15 MeV. Measurements have previously been made in this laboratory of $K_y^{y'}$ for the $^2H(d,n)^3He$ reaction,[6] and our values for $^2H(d,p)^3H$ agree very well with these results. This finding is consistent with a description of these as predominantly direct reactions with no orbital angular momentum transfer. Then the outgoing nucleon is a spectator retaining the same spin orientation as in the incident deuteron. The experimentally measured values of nucleon polarization at 0° are interpreted in Ref. 6 to be slightly less than those calculated for either nucleon in the incident deuteron when the deuteron D state is considered. They conclude that some other spin-dependent interaction which is not yet understood contributes to the small nucleon depolarization.

The experimental methods are introduced below in Sec. II with a discussion of the formalism describing possible ways of measuring polarization transfer coefficients. Arguments are made about the most satisfactory experimental techniques. The method chosen required a careful check of the orientation of the spin-alignment axis of the polarized beam at the scattering chamber. Also required was an efficient polarimeter to detect the reaction protons at zero degrees. Its design and calibration are briefly described. Finally, additional experimental details of the $^2H(d,p)^3H$ measurements at zero degress are described. Then in Sec. III the experimental results are given and compared with the work of others.

II. EXPERIMENTAL TECHNIQUES

A. Formalism Describing Polarization Transfer Measurements

We discuss here two ways of making polarization transfer measurements at 0° and point out the advantages of the method used in this experiment. The equations apply to any reaction of the type $1+A \to \frac{1}{2}+B$ where 1 and $\frac{1}{2}$ are the spins of the incoming and outgoing particles and A and B may have arbitrary spins. We choose a right-handed coordinate system such that the positive y axis is along the direction $\vec{k}_{in}\times\vec{k}_{out}$ where $\vec{k}_{in}$ and $\vec{k}_{out}$ are the incident- and scattered-particle momentum directions.[7] If the z axis is taken along $\vec{k}_{in}$, then according to Gammel, Keaton, and Ohlsen[8] the general parity-conserving expressions for the outgoing-proton or -neutron polarization components, $p_{x'}(\theta)$ and $p_{y'}(\theta)$, may be written as follows:

$$I(\theta)=I_0(\theta)[1+\tfrac{3}{2}p_y\underline{A_y}(\theta)+\tfrac{2}{3}p_{xz}\underline{A_{xz}}(\theta)+\tfrac{1}{3}p_{xx}A_{xx}(\theta)+\tfrac{1}{3}p_{yy}A_{yy}(\theta)+\tfrac{1}{3}p_{zz}A_{zz}(\theta)], \quad (1)$$

$$p_{x'}(\theta)I(\theta)=I_0(\theta)[\tfrac{3}{2}p_xK_x^{x'}(\theta)+\tfrac{3}{2}p_z\underline{K_z^{x'}}(\theta)+\tfrac{2}{3}p_{xy}\underline{K_{xy}^{x'}}(\theta)+\tfrac{2}{3}p_{yz}K_{yz}^{x'}(\theta)], \quad (2)$$

$$p_{y'}(\theta)I(\theta)=I_0(\theta)[\underline{P^{y'}}(\theta)+\tfrac{3}{2}p_yK_y^{y'}(\theta)+\tfrac{2}{3}p_{xz}K_{xz}^{y'}(\theta)+\tfrac{1}{3}p_{xx}\underline{K_{xx}^{y'}}(\theta)+\tfrac{1}{3}p_{yy}\underline{K_{yy}^{y'}}(\theta)+\tfrac{1}{3}p_{zz}\underline{K_{zz}^{y'}}(\theta)], \quad (3)$$

where $I(\theta)$ and $I_0(\theta)$ are the polarized and unpolarized nucleon differential cross sections; the p_i and p_{ij} are the Cartesian components of the vector and tensor polarization, respectively, of the incident beam at the target. The $A_i(\theta)$ and $A_{ij}(\theta)$ are the vector and tensor analyzing powers, and the $K_i^{j'}(\theta)$ and $K_{ij}^{k'}(\theta)$ are the vector- and tensor-polarization transfer coefficients of the reaction. The subscripts and superscripts, i, j, k, may assume any of the values x, y, and z, and primed quantities refer to the outgoing channel. The quantity $P^{y'}(\theta)$ is the vector polarization of the outgoing particles if an unpolarized beam is incident. The underlined quantities are antisymmetric functions of θ and thus vanish when $\theta=0°$.

The equations describing the first method, that used by Simmons *et al.*[6] may be derived from Eqs. (1) and (3) by requiring first that the spin quantization axis of the incident beam be along the y axis, and recalling the normalization condition $p_{xx}+p_{yy}+p_{zz}=0$ and similar conditions for the A_{ij} and $K_{ij}^{k'}$. If one specifies finally, then, that $\theta=0°$, the outgoing-particle polarization may be written

$$p_{y'}(0)=\frac{\tfrac{3}{2}p_yK_y^{y'}(0)}{[1+\tfrac{1}{2}p_{yy}A_{yy}(0)]}\ . \quad (4)$$

This equation of Simmons *et al.*[6] shows that a measurement of the outgoing-particle polarization $p_{y'}(0)$ does not lead to a value of $K_y^{y'}(0)$ without knowledge of $A_{yy}(0)$. Since measuring $A_{yy}(0)$ requires intensity ratios with the incident beam having successively two different values of tensor polarization, accurate current integration is required. This is a possible problem when the reaction protons are to be detected at $\theta=0°$.

These difficulties can be avoided so that $K_y^{y'}(0)$ can be determined independently of $A_{yy}(0)$ and current integration. A second method of measurement is suggested if in Eqs. (1)–(3) one first requires that $\theta=0°$ so the underlined terms vanish. Since the x and y axes can be defined arbitrarily for $\theta=0°$, $A_{xx}=A_{yy}=-\tfrac{1}{2}A_{zz}$; $K_x^{x'}=K_y^{y'}$; and $K_{xz}^{y'}=-K_{yz}^{x'}$. Then using the equations which relate the Cartesian components of the vector and tensor polarization, p_3 and p_{33}, of the beam at the polarized ion source,[8] one finds,

$$I(0)=I_0(0)[1+\tfrac{1}{4}(3\cos^2\beta-1)p_{33}A_{zz}(0)], \quad (5)$$

$$p_{x'}(0)I(0)=I_0(0)[-\tfrac{3}{2}p_3\sin\beta\sin\phi K_x^{x'}(0)+\sin\beta\cos\beta\cos\phi\, p_{33}K_{yz}^{x'}(0)], \quad (6)$$

$$p_{y'}(0)I(0)=I_0(0)[\tfrac{3}{2}\sin\beta\cos\phi\, p_3K_y^{y'}(0)-\sin\beta\cos\beta\sin\phi\, p_{33}K_{xz}^{y'}(0)]. \quad (7)$$

In these expressions β is the angle shown in Fig. 1 between the incident beam direction and the spin quantization axis at the target. The angle ϕ lies in the x-y plane and is measured from the y axis to the projection of the spin quantization axis in this plane. If the spin quantization axis at the target is the y-z plane (i.e., $\phi=0°$) at an angle $\beta=54.7°$ with respect to the beam axis, then these equations reduce to:

$$I(0)=I_0(0),$$

$$p_{x'}(0)=\tfrac{1}{3}\sqrt{2}\,p_{33}K_{yz}^{x'}(0), \quad (8)$$

$$p_{y'}(0)=(\tfrac{3}{2})^{1/2}p_3K_y^{y'}(0). \quad (9)$$

Immediately then one sees that a measurement of $p_{y'}(0)$, the outgoing-proton polarization component along the y' axis gives a measure of $K_y^{y'}(0)$. A simultaneous measurement of $p_{x'}(0)$ gives the tensor-polarization transfer coefficient $K_{yz}^{x'}(0)$.

In our experiment the deuteron beam, with its spin quantization axis in the horizontal plane at $\beta=54.7°$ as shown in Fig. 1, was incident on a deuterium gas cell. Since the reaction protons exited at $\theta=0°$, the direction $\vec{k}_{in}\times\vec{k}_{out}$ was undefined. We have then taken the y and y' axes to be in the horizontal plane so that $\phi=0°$. The protons entered a ^4He-gas-filled polarimeter where they were scattered into four identical detectors

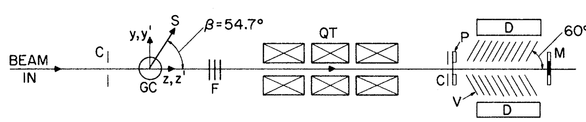

FIG. 1. Shown schematically is a view in the horizontal plane of the experimental arrangement for the polarization transfer measurements. The notation is as follows: (C) beam collimators; (GC) deuterium gas cell; (S) spin quantization axis direction for the incident polarized deuteron beam; (F) thin tantalum foils to stop the incident beam; (QT) quadrupole-triplet lens to focus the reaction protons; (P) polarimeter passing detector; (D) polarimeter side detectors; (V) polarimeter vanes to define the scattering angle; and (M) polarimeter monitor detector.

at $\theta_{lab}=60°$, two of which are shown schematically in Fig. 1. These detectors were placed down, up, left, and right in the polarimeter. Thus the down-up detector pair yielded an experimental asymmetry ϵ_{DU} from the equation

$$\epsilon_{DU}=A_p p_{y'}(0)=\frac{r_{DU}-1}{r_{DU}+1} \tag{10}$$

and similarly for the right-left detector pair, since the x' axis is down

$$\epsilon_{RL}=A_p p_{x'}(0)=\frac{r_{RL}-1}{r_{RL}+1}\,. \tag{11}$$

The A_p is the analyzing power of the polarimeter and the $r_{DU}(r_{RL})$ is a ratio of counts in the down (right) detector to the counts in the up (left) detector.

B. Check of the Spin-Axis Alignment

Before we could make the polarization transfer measurements it was necessary to perform a separate experiment to ascertain that the deuteron spin quantization axis had the desired direction of $\beta=54.7°$ when the beam reached the target. One may rewrite Eq. (1) so the dependence on the components p_i and p_{ij} of the beam polarization at the target is replaced by a dependence on p_3 and p_{33}, the beam polarization components at the ion source, and the angles β and ϕ which define the spin-axis direction at the target.[8] The resulting equation gives four separate expressions for the intensity $I(\theta)$ in detectors placed in the scattering chamber down, left, up, and right. The sum of these four expressions is found to be

$$\begin{aligned} T(\theta) &= I_{down}(\theta)+I_{left}(\theta)+I_{up}(\theta)+I_{right}(\theta) \\ &= 4I_0(\theta)[1+\tfrac{1}{4}(3\cos^2\beta-1)p_{33}A_{zz}]\,. \end{aligned} \tag{12}$$

One sees that at $\beta=54.7°$, $T(\theta)=4I_0(\theta)$. This is independent of the incident-beam polarization, p_{33}, and analyzing power, A_{zz}.

The angle β between the spin axis and the beam axis was varied by choosing appropriate values for the crossed electric and magnetic fields in the "spin precessor" at the polarized source.[9] The magnetic field precessed the spin axis in the horizontal plane to an angle such that after the inflection, analyzing, and switching magnets, it had the desired orientation at the scattering chamber. This polarized deuterium beam, after acceleration to 12 MeV, was incident on ^{4}He gas at a pressure of approximately 1 atm. Detectors placed down, left, up, and right in the chamber detected the scattered particles at $\theta_{lab}=37.5°$, an angle where the tensor analyzing power A_{zz} of ^{4}He$(d,d)^4$He is large.[10]

Successive measurements were made for the same total integrated beam current with the "spin filter" in the polarized source[11] selecting first deuterons in the $m_I=1$ state and then deuterons in the $m_I=0$ state. The beam polarizations associated with these two states were typically $p_{33}=0.80$ and $p_{33}=-1.60$, respectively. The quantity

$$\frac{2[T(\theta)-T'(\theta)]}{p_{33}T'(\theta)-p'_{33}T(\theta)}=\tfrac{1}{2}(3\cos^2\beta-1)A_{zz} \tag{13}$$

was calculated, where $T(\theta)$ is given by Eq. (12) and the unprimed and primed quantities on the left side of *this* expression correspond to measurements with the deuterons in the $m_I=1$ and $m_I=0$ states, respectively. The left side of Eq. (13) is plotted in Fig. 2 versus the voltage applied to the plates which provide the electric field in the "spin precessor." As can be seen from Fig. 2, a precessor voltage of -1200 ± 10 V corresponds to a ratio of zero. This implies that $\beta=54.7\pm0.25°$.

The angle of spin precession between the ion source and the chamber is independent of the beam energy emerging from the accelerator if the beam follows the same trajectory at all energies. Pos-

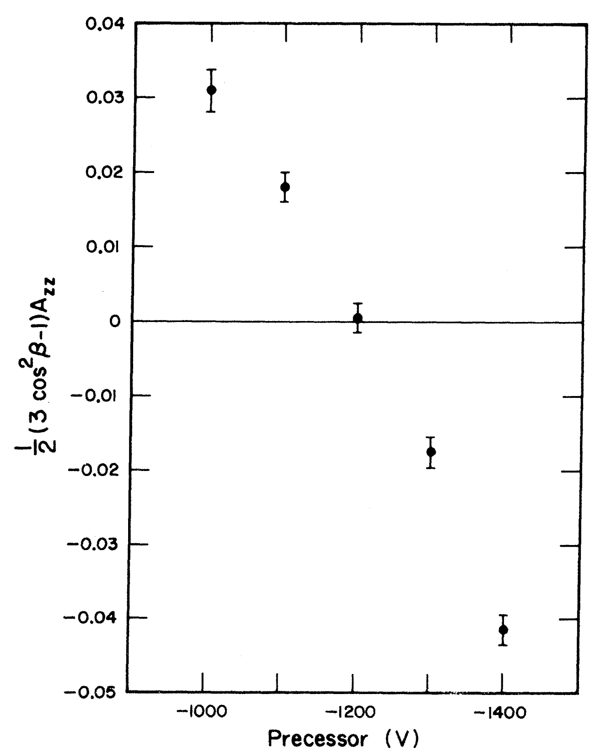

FIG. 2. Results are shown for the experiment described in Sec. II B to determine that the deuteron-spin quantization axis had the desired direction of $\beta=54.7°$. These experimental results show that $\beta=54.7\pm0.25°$ for a spin-precessor voltage setting of -1200 ± 10 V.

sible differences which could affect the spin direction involve different vertical positions at which the low-energy beam enters the inflection magnet and different combinations of magnetic and electrostatic deflection for the low-energy beam before it enters the accelerator. With reasonable beam position and steering, spin direction changes of less than ±1° seem likely.[12] As experimental verification of the reproducibility of the $\beta = 54.7°$ settings, the experiment described here has been repeated 5 times in the last three years. The settings used in this experiment have always produced $\beta = 54.7 \pm 0.5°$.

C. Calibration of the Polarimeter

The polarimeter shown schematically in Fig. 3 was calibrated for the experiment. It was a helium-filled gas chamber which operated at 20 atm. The protons whose polarization was to be measured entered the high-pressure region through 12.7-μm Havar[13] foil placed between 0.63-cm-diam tantalum collimators. They then passed through a silicon transmission detector, and through the helium gas before being stopped in a thick silicon detector at the rear. In the left, right, up, and down directions around the central region were copper vanes which allowed protons scattered at $\theta_{lab} = 60 \pm 7.5°$ half width at half maximum to impinge upon rectangular silicon detectors, each with a surface area of 1×5 cm^2.

A fast-coincidence requirement between each of these side detectors and the transmission detector reduced backgrounds under the peaks of interest to approximately 1%. The most likely source of background was protons from (d,p) reactions in the Havar of the deuterium gas cell. This contribution was found to be smaller than 1% at 10 MeV by taking data with the deuterium gas pumped out of the cell. Accidental coincidences, also less than 1%, were stored and later subtracted from the true coincidence spectra. The monitor detector in the rear of the polarimeter was collimated with a 0.3-cm-diam aperture. The over-all efficiency of the polarimeter, defined as the ratio of the number of particles scattered into a pair of side detectors to the number entering the polarimeter, was approximately 8×10^{-5}.

Calibration of the polarimeter was accomplished by placing it in the direct polarized proton beam from the accelerator. For these measurements the beam was defocused until the count rate in the transmission detector was approximately 8×10^4 per second. With the incident beam polarization, $p_{x'}(0)$ or $p_{y'}(0)$, known from the quench-ratio method,[14] Eqs. (10) and (11) show that measuring ϵ_{DU} and ϵ_{RL} yields a value for A_p, the polarimeter analyzing power. Both the right-left and down-up detector pairs had the same analyzing power within experimental error. A plot of the measured polarimeter analyzing power versus energy of the incident protons is shown in Fig. 4. More detailed information about the polarimeter can be found in the work of Hardekopf, Armstrong, and Keaton.[15]

D. Polarization Transfer Measurements

With the above preliminary experiments complete, the $^2H(d,p)^3H$ polarization transfer measurements were made with the apparatus shown in Fig. 1. The primary target for the polarized deuteron beam from the accelerator was a 2.54-cm-diam deuterium-filled gas cell covered with

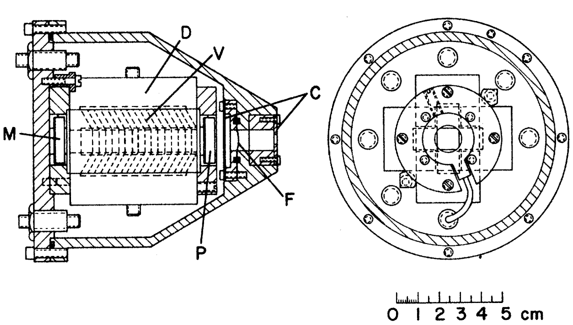

FIG. 3. Two views are shown of the polarimeter used in the present experiment. On the right is a front view as seen by the incoming-reaction proton beam; on the left is a side view. Parts of the polarimeter are labeled as follows; (C) beam collimators; (F(Havar entrance foil; (P) passing detector; (D) one of the four side detectors; (V) vanes to define the scattering angle; and (M) monitor detector.

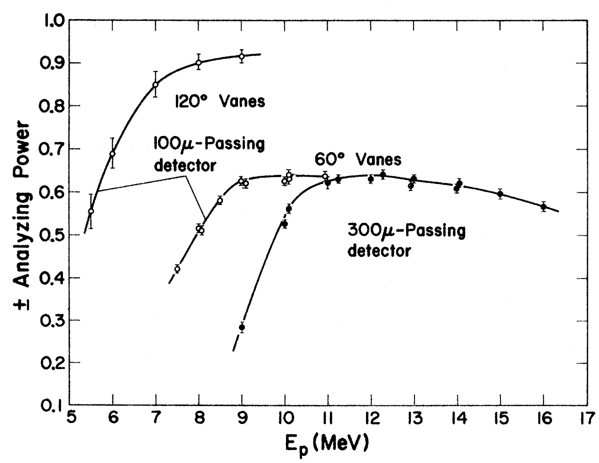

FIG. 4. A plot is shown of the measured polarimeter analyzing power versus energy of incident protons. The hand-drawn curves shown were used for the experimental analyzing power.

12.7-μm-thick Havar[13] foil. The deuterium pressure was adjusted so the beam energy loss in the gas was 500 keV. This required cooling the gas cell to 77°K with liquid nitrogen for beam energies above 8 MeV. Immediately following the cell, placed in rotating holders, were eight tantalum foils with thicknesses ranging between 12.5 and 300 mg/cm^2. With these, the proper thickness of tantalum could be placed into the beam at each energy so the direct deuteron beam passing through the gas cell was barely stopped. The ^{2}H$(d, p)^3$H reaction protons at 0°, however, passed through.

The emerging protons entered a magnetic quadrupole triplet lens which focused them on the polarimeter described above. The magnetic lens has been described previously.[16] It subtends a solid angle at the primary gas cell of 3.1×10^{-3} sr, accepts protons which enter within an angle of ±3.0° in the vertical plane and ±1.1° in the horizontal plane. It causes an average depolarization of protons which pass through it of approximately 0.7% for vertical polarization and 0.1% for horizontal polarization. The current through the lens coil was adjusted by maximizing the count rate of the particles in the monitor detector at the rear of the polarimeter.

Polarized beam currents on the primary target ranged between about 25 and 100 nA. The average time for a measurement of $K_y^{y'}$ and $K_{yz}^{x'}$ at each energy was approximately two hours. The beam polarizations, determined several times during each run by the quench-ratio method,[14] rarely showed a variation of more than 0.01. At each energy two successive runs were taken with the incident deuterons in the $m_I=+1$ state ($p_3=p_{33} \simeq 0.80$) and the spin direction first parallel and then antiparallel to the $\beta=54.7°$, $\phi=0°$ direction shown in Fig. 1. This allowed a calculation of $K_y^{y'}$ at each energy according to Eqs. (9) and (10). To eliminate false instrumental asymmetries from unequal detector efficiencies, the quantity $r_{\rm DU}$ in Eq. (10) was calculated as the geometric mean ratio

$$r_{\rm DU}=[N_{\rm D}/N_{\rm U})\uparrow(N_{\rm U}/N_{\rm D})\downarrow]^{1/2},$$

where $N_{\rm D}$ ($N_{\rm U}$) is the number of counts in the down (up) detector. The arrows (↑) and (↓) indicate that the spin direction is parallel or antiparallel, respectively, to the $\beta=54.7°$, $\phi=0°$ direction at the target.

A third run was taken at each energy with the incident deuterons in the $m_I=0$ state ($p_3\simeq 0.0$; $p_{33}\simeq -1.60$). A value of $K_{yz}^{x'}$ was calculated for each of the three runs according to Eqs. (8) and (11). The weighted average of these three values is our quoted result. This method of calculation of $K_{yz}^{x'}$ eliminates to first-order instrumental asymmetries arising from unequal detector efficiencies. It is expected that the three values obtained prior to averaging might not always agree within their individual errors because of experimental instrumental asymmetries. This in fact was the case for most of these data.

Finally, as an internal consistency check, at 12 MeV the deuteron spin axis was processed to $\beta=90°$, $\phi=0$ (along the y axis) to make a measurement of $K_y^{y'}$ using the method described by Eq. (4). The same sequence of three runs was carried out. A measurement of $A_{yy}(0)$ was made using the ratio of counts in the polarimeter monitor detector for the incident deuterons in the $m_I=1$ state to counts when the beam was in the $m_I=0$ state. The result was $A_{yy}(0)=0.213\pm0.010$. This value is consistent with earlier results for ^{2}H$(d,p)^3$H at 10 MeV[4] and ^{2}H$(d,n)^3$He at 12 MeV.[6] Using this and the experimental value for $p_{y'}(0)$ from Eq. (10) we obtained a value for $K_y^{y'}(0)$ from Eq. (4) which agreed with our previous measurement within the experimental error. The value reported in Table I for $K_y^{y'}(0)$ at 12 MeV is the weighted average of these two results.

III. EXPERIMENTAL RESULTS

Our values for $K_y^{y'}(0)$ for the ^{2}H$(d,p)^3$H reaction are given in Table I and are plotted in Fig. 5. The rms errors given result from the statistical uncertainty and the polarimeter calibration uncertainty. Errors from the uncertainty in the incident-beam polarization and the uncertainty in the spin quantization axis direction at the primary target were negligible. The results have been

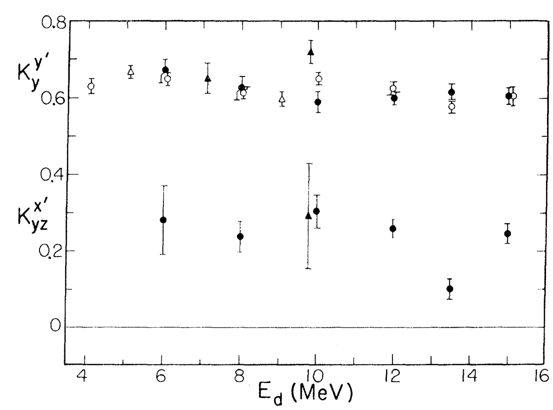

FIG. 5. Our results for the polarization transfer coefficients $K_y^{y'}$ and $K_{yz}^{x'}$ at $\theta=0°$ for the ^{2}H$(d,p)^3$H reaction are shown plotted versus incident deuteron bombarding energy: ●. For comparison the results of other authors are shown: ○: ^{2}H$(d,n)^3$He, Ref. 6; △: ^{2}H$(d,n)^3$He, Ref. 18; and ▲: ^{2}H$(d,p)^3$H, Ref. 17.

TABLE I. Summary of the measurements of proton-polarization transfer coefficients in the reaction ^{2}H-$(d,p)^3$H at 0°.

$E_d \pm \frac{1}{2}(\Delta E)$ (MeV)	$K_y^{y'}$	$K_{yz}^{x'}$
6.00 ± 0.25	0.673 ± 0.036	0.277 ± 0.091
8.00 ± 0.25	0.626 ± 0.030	0.238 ± 0.038
10.00 ± 0.25	0.589 ± 0.029	0.306 ± 0.042
12.00 ± 0.25	0.615 ± 0.016	0.260 ± 0.022
13.50 ± 0.25	0.615 ± 0.021	0.098 ± 0.024
15.00 ± 0.25	0.602 ± 0.020	0.246 ± 0.023

corrected for the small depolarization of the reaction protons in the quadrupole-triplet lens between the primary target and the polarimeter. Also plotted in Fig. 5 for comparison are the measured values of $K_y^{y'}(0)$ for the ^{2}H$(d, n)^3$He reaction from Simmons *et al.*[6] The agreement is very good at all energies. Our measurements, taken withthe A_{yy} results from Ref. 4, then confirm for ^{2}H$(d, p)^3$H the result for ^{2}H$(d, n)^3$He. The polarizations fall below the value which one would expect if the outgoing nucleons maintained the polarization of 0.91 calculated for the nucleons in the incident deuterons.[6]

While this experiment was in progress, we learned of other measurements of $K_y^{y'}$ and $K_{yz}^{x'}$ which had been made at Wisconsin.[17] These results are shown also in Fig. 5 for comparison. Also recent measurements of $K_y^{y'}$ in ^{2}H$(d, n)^3$He by Lisowski[18] are shown. When all these data are plotted in this way, one still sees little evidence for disagreement between the $K_y^{y'}$ values for these two mirror reactions. Except for the two points at incident deuteron energies near 10 MeV, all the measurements lie nearly on a smooth curve.

Our results for $K_{yz}^{x'}$ are also given in Table I and plotted in Fig. 5. The rms errors given result from the same experimental uncertainties as for the $K_y^{y'}$ data. Again the results have been corrected for proton depolarization in the quadrupole triplet. Our results show that $K_{yz}^{x'}$ is also approximately independent of energy between E_d = 6 and 15 MeV except for the data point at E_d = 13.5 MeV. The rms errors shown do not reflect any additional uncertainty which might result from incomplete canceling of instrumental asymmetries.

IV. ACKNOWLEDGMENTS

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