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Polarization Transfer in the ^{3}He$(d,p)^4$He Reaction*

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Measurements have been made of seven polarization transfer coefficients for the ^{3}He$(d,p)^4$He reaction. The experiment used a polarized-deuteron beam from the Los Alamos Scientific Laboratory Lamb-shift polarized-ion source, a liquid-nitrogen cooled ^{3}He gas target, a magnetic quadrupole triplet for focusing the reaction protons, and a helium-filled polarimeter for simultaneously measuring the proton polarization along both transverse axes. Measurements were made of the polarization transfer coefficients $K_y^{y\prime}$ and $K_{yz}^{x\prime}$ at $\theta = 0°$ for 4- to 14-MeV deuterons. A comparison of the $K_y^{y\prime}$ results with the values reported for the ^{3}H$(d,n)^4$He reaction over the same energy range shows good agreement, as would be expected for the two charge-symmetric reactions. In addition, we have measured the proton polarization $P^{y\prime}$; the vector transfer coefficients $K_y^{y\prime}$, $K_x^{x\prime}$ and $K_z^{x\prime}$; and the tensor transfer coefficients $K_{xx}^{y\prime}$, $K_{yy}^{y\prime}$, $K_{zz}^{y\prime}$, and $K_{xz}^{y\prime}$ at 8.0 MeV for laboratory angles of 15, 30, 45, and 60°. Calculated values for these observables from an R-matrix parametrization of the five-nucleon system are in good agreement with the data.

[NUCLEAR REACTIONS ^{3}He(d,p): $E = 4$–14 MeV, $\theta = 0°$; $E = 8$ MeV, $\theta = 15, 30, 45, 60°$; measured polarization transfer coefficients.]

I. INTRODUCTION

Considerable effort is being extended both experimentally and theoretically toward an understanding of few-nucleon systems. Much of the experimental effort has been directed toward improving the quantity and precision of differential cross-section and polarization data to provide more reliable input data for phenomenological analyses. With the improvement of polarized-ion sources and polarized targets there is now an opportunity for experimentalists to obtain more extensive data on higher-order spin-dependent observables, namely polarization transfer and spin correlation coefficients. The importance of these new data to the analysis of few-nucleon systems and their contribution to our understanding of nuclear forces remains to be seen. It can be argued, however, that determination of the scattering amplitudes for a reaction requires the knowledge of more than the readily determined cross-section, polarization, and analyzing-power observables.

In fact, Simonius[1] has shown that a complete set of measurements for a reaction must include experiments that together correlate the spins of all reacting particles. In the ^{3}He$(d,p)^4$He reaction, this can be satisfied by polarization transfer ^{3}He$(\vec{d},\vec{p})^4$He and spin correlation $^3\vec{\text{He}}(\vec{d},p)^4$He measurements. The more difficult experiment linking the ^{3}He and proton spins is not required, nor is the experiment linking all three spins. Of course, all of the observables are not independent, so the question of which polarization transfer or spin correlation measurements are needed for completeness still arises.

For the ^{3}He$(d,p)^4$He reaction, the 36 possible parity-conserving observables (correlating no more than two spins at a time) are catagorized in Table I. Since the M matrix for the reaction contains only 6 complex elements, in principle only 11 measurements are necessary to determine all of the scattering amplitudes up to an over-all phase. Practically speaking, however, experimental data are not exact, and redundancy may not only be desirable but necessary for a unique determination of the scattering amplitudes. Our approach, therefore, is to measure those observables that are experimentally feasible. We report here measurements of two polarization transfer coefficients at zero degrees for several incident deuteron energies in the ^{3}He$(\vec{d},\vec{p})^4$He reaction. In addition, we report the measurement of seven polarization transfer coefficients (six independent) for four angles at 8 MeV.

II. FORMALISM FOR POLARIZATION TRANSFER MEASUREMENTS

A. Basic Equations and Coordinate Systems

Gammel, Keaton, and Ohlsen[2] have derived the basic equations relating the observables for a reaction with the spin structure $\vec{1} + A \rightarrow \vec{1}/2 + B$, where A and B may have arbitrary spins. We adopt the Cartesian coordinate representation and nomenclature of that report, except that we will denote the polarization transfer coefficients by K's and analyzing powers by A's. This is consistent with the Madison convention,[3] with the notation used by Ohlsen in his recent review of polarization transfer and spin correlation experiments,[4] and is a straightforward generalization of the spin formalism as discussed by Wolfenstein.[5] In this representation, the cross section and outgoing polarization components are given by:

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

$$p_{x'}(\theta) I(\theta) = I_0(\theta)[\tfrac{3}{2} p_x K_x^{x'}(\theta) + \tfrac{3}{2} p_z \underline{K}_z^{x'}(\theta) + \tfrac{2}{3} p_{xy} \underline{K}_{xy}^{x'}(\theta) + \tfrac{2}{3} p_{yz} K_{yz}^{x'}(\theta)], \tag{2}$$

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

$$p_{z'}(\theta) I(\theta) = I_0(\theta)[\tfrac{3}{2} p_z K_z^{z'}(\theta) + \tfrac{3}{2} p_x \underline{K}_x^{z'}(\theta) + \tfrac{2}{3} p_{xy} K_{xy}^{z'}(\theta) + \tfrac{2}{3} p_{yz} \underline{K}_{yz}^{z'}(\theta)]. \tag{4}$$

The reaction coordinate system used in these equations is in accordance with the Madison convention,[3] that is, a right-handed system in which the positive z axis is along the beam momentum $\vec{k}_{in}$ and the y axis is along $\vec{k}_{in} \times \vec{k}_{out}$. The small p's on the left are the outgoing spin-$\frac{1}{2}$ polarizations along the x', y', and z' axes, where the primes on a subscript or superscript refer to the outgoing particle coordinate system. For this system, we choose the laboratory helicity frame,[4] a right-handed system with the z' axis along the proton's laboratory momentum $\vec{k}_{out}$ and the y' axis in the same direction as the y axis. With this choice, a polarimeter directly measures the quantities $p_{x'}$ and $p_{y'}$ contained in Eqs. (2) and (3).

The p_i and p_{ij} on the right of the equations are the the Cartesian components of the vector and tensor polarization, respectively, of the incident beam at the target. $I(\theta)$ and $I_0(\theta)$ are the polarized and unpolarized differential cross sections, and the $A(\theta)$ are the Cartesian representation of the analyzing powers for the reaction. The capital $P^{y'}(\theta)$ on the right of Eq. (3) is the polarization function, that is, the y' component of the outgoing proton polarization when the incident beam is unpolarized. The $K(\theta)$ are polarization transfer coefficients relating the beam vector or tensor components, denoted by subscripts, to the outgoing spin-$\frac{1}{2}$ polarization components, denoted by superscripts. In all, 13 polarization transfer coefficients are allowed by parity conservation for this spin structure. Only 12 of these are independent, however, because of the relation

$$K_{xx}^{y'}(\theta) + K_{yy}^{y'}(\theta) + K_{zz}^{y'}(\theta) = 0 \tag{5}$$

which is a result of the overcompleteness of the operators used in the Cartesian representation. The underlined quantities in Eqs. (1)–(4) are antisymmetric functions of (θ) and thus vanish for $\theta = 0°$.

These equations simplify considerably when a specific beam quantization axis orientation at the target is chosen. Because of the axial symmetry of the deuteron beam from a polarized-ion source, only four quantities are needed to describe its polarization. Let p_3 and p_{33} be the vector and tensor polarizations of the beam with respect to its quantization axis. For example, for a pure nuclear magnetic substate $m_I = 1$ deuteron beam $p_3 = p_{33} = 1$ while for an $m_I = 0$ deuteron beam $p_3 = 0$ and $p_{33} = -2$. Let β and ϕ describe the orientation of the beam quantization $\vec{s}$ at the target. β is the angle $\vec{s}$ makes with the z axis and ϕ is the angle between the y axis and the projection of $\vec{s}$ on the xy plane. The beam polarization components are given by:

$$\begin{aligned}
p_x &= -p_3 \sin\beta \sin\phi ,\\
p_y &= p_3 \sin\beta \cos\phi ,\\
p_z &= p_3 \cos\beta ,\\
p_{xx} &= \tfrac{1}{2} p_{33}(3 \sin^2\beta \sin^2\phi - 1) ,\\
p_{yy} &= \tfrac{1}{2} p_{33}(3 \sin^2\beta \cos^2\phi - 1) ,\\
p_{zz} &= \tfrac{1}{2} p_{33}(3 \cos^2\beta - 1) ,\\
p_{xy} &= -\tfrac{3}{2} p_{33} \sin^2\beta \sin\phi \cos\phi ,\\
p_{xz} &= -\tfrac{3}{2} p_{33} \sin\beta \cos\beta \sin\phi ,\\
p_{yz} &= \tfrac{3}{2} p_{33} \sin\beta \cos\beta \cos\phi .
\end{aligned} \tag{6}$$

TABLE I. Experimental observables for the $^3He(d,p)^4He$ reaction.

Category	Reaction shorthand	Symbol	Number of observables
Differential cross section	$^3He(d,p)^4He$	$I_0(\theta)$	1
Analyzing powers	$^3He(\vec{d},p)^4He$	$A(\theta)$	4
Analyzing power	$^3\vec{He}(d,p)^4He$	$A^T(\theta)$	1
Polarization	$^3He(d,\vec{p})^4He$	$P(\theta)$	1
Polarization transfer coefficients	$^3He(\vec{d},\vec{p})^4He$	$K(\theta)$	12
Polarization transfer coefficients	$^3\vec{He}(d,\vec{p})^4He$	$k(\theta)$	5
Spin correlation coefficients	$^3\vec{He}(\vec{d},p)^4He$	$C(\theta)$	12
		Total	36

For example, for a beam with its quantization axis in the y direction, $\beta = 90°$ and $\phi = 0°$ so $p_y = p_3$, $p_{yy} = p_{33}$, $p_{xx} = p_{zz} = -\frac{1}{2}p_{33}$, and all other beam components are zero.

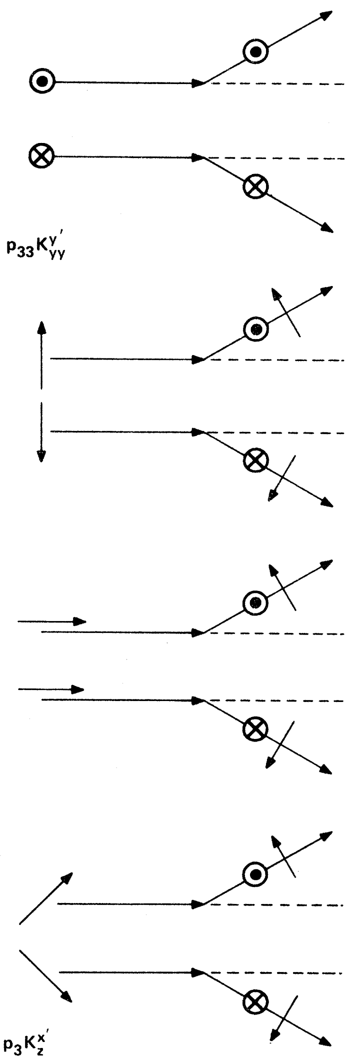
B. Angular Distribution

The incident spin orientations which were used in this experiment for reaction angles other than 0° are depicted in Fig. 1. The symbols represent the incident deuteron vector polarization direction and the measured proton polarizations along the x' and y' axes. The y and y' axes are perpendicular to the plane of the diagrams. The equations on the left in this figure result from Eqs. (2) and (3) when the particular beam quantization axes shown on the right are chosen. In these equations the argument θ is suppressed for the observables. Since the z' component of proton polarization cannot be measured with a conventional polarimeter, the equations for $p_{z'}$ are not shown.

In order to cancel instrumental asymmetries associated with the analyzing detectors, it is convenient to be able to reverse the outgoing polarization direction between two runs. A simple geometric average [see Eq. (9)] can then be used to determine the polarization independent of detector efficiency and current integration. The diagrams in Fig. 1 show, for each incident spin orientation, a scattering both to the left and to the right of the beam axis in order to illustrate what we call a "proper rotation." For example, for a beam polarized in the y direction as described by the first two equations of Fig. 1, reversing the incident spin direction would change the sign of p_3 and thus the sign of one term only in the second equation. Clearly then, the proton polarization $p_{y'}$ measured by the polarimeter would not have just a simple sign change. In this case, one must change to the opposite side of the beam axis *and* change the incident spin direction in order for the outgoing polarization to have the same magnitude. This may be viewed simply as a rotation of the experiment about the z axis, and rotational invariance requires the resulting polarizations to be identical in the new coordinate system. Note that in each case shown in the figures, the x' and y' polarization components change direction in the laboratory, so that if the orientation of the polarimeter is held fixed in the laboratory, instrumental asymmetries associated with the analyzing detectors may be effectively canceled. For the third case shown, where the incident spin is along the beam direction, the deuteron spin direction is not flipped when going from the left to the right side of the beam. Also in the fourth case, with the spin at 45° in the xz plane, a proper rotation requires changing the spin orientation 90° as shown.

The type of proper rotation used in this experiment is not the only way one can obtain the transfer coefficients relatively free of instrumental ef-

$$\vec{1} + A \to \vec{\tfrac{1}{2}} + B$$



$$p_{x'} = 0$$

$$p_{y'}\frac{I}{I_0} = p^{y'} + \frac{3}{2}p_3K_y^{y'} + \frac{1}{2}p_{33}K_{yy}^{y'}$$

$$p_{x'}\frac{I}{I_0} = \frac{3}{2}p_3K_x^{x'}$$

$$p_{y'}\frac{I}{I_0} = p^{y'} + \frac{1}{2}p_{33}K_{xx}^{y'}$$

$$p_{x'}\frac{I}{I_0} = \frac{3}{2}p_3K_z^{x'}$$

$$p_{y'}\frac{I}{I_0} = p^{y'} + \frac{1}{2}p_{33}K_{zz}^{y'}$$

$$p_{x'}\frac{I}{I_0} = \sqrt{\frac{9}{8}}\,p_3K_x^{x'} + \sqrt{\frac{9}{8}}\,p_3K_z^{x'}$$

$$p_{y'}\frac{I}{I_0} = p^{y'} + \frac{1}{2}p_{33}K_{xz}^{y'} - \frac{1}{4}p_{33}K_{yy}^{y'}$$

FIG. 1. Four schematic diagrams showing the experimental procedure used to measure the polarization transfer coefficients for reaction angles other than 0°. Each diagram is a top view and shows a scattering both to the left and to the right of the beam axis, illustrating the proper rotation described in the text. The small arrows represent the incident deuteron vector polarization (quantization axis orientation) and the measured components of the outgoing proton polarization. The equations to the left and below each diagram relate these polarizations to the polarization transfer coefficients.

fects. Alternatively, one could rotate the polarimeter between runs, or the apparatus could be left fixed and only the incident beam m_I state changed. The latter method[7] has the advantage of not introducing possible errors from changing the analyzing detector positions with respect to the slope of the differential cross section.[8] However, the transfer coefficients can in general be obtained only by solving series of equations by iterative techniques, and the outgoing polarizations $p_{x'}$ and $p_{y'}$ are not directly measured. We chose the proper rotation technique because it was experimentally convenient, the transfer coefficient and error calculations were direct, and corrections to the outgoing polarizations due to depolarizations due to depolarization in the magnetic quadrupole triplet (discussed later) were easily made. Calculations showed that false asymmetries arising from nonuniform illumination of the polarimeter due to a changing cross section were less than 0.001 for our geometry.

7 of the 13 polarization transfer coefficients of Eqs. (1)–(4) are contained in the equations of Fig. 1. The six remaining were not measured, either because they involved the z' component of proton polarization or because they required a deuteron spin orientation at the target which is difficult to achieve.

C. Zero Degree Measurements

For measurements at $\theta=0°$, we consider only the nonvanishing transfer coefficients, that is, the ones not underlined in Eqs. (2) and (3). In addition, because the x and y axes are arbitrary for $\theta=0°$ (because $\vec{k}_{in}\times\vec{k}_{out}$ is undefined) we have the relations

$$K_x^{x'}(0)=K_y^{y'}(0)\,,$$
$$K_{xz}^{y'}(0)=-K_{yz}^{x'}(0)\,, \qquad (7)$$
$$A_{xx}(0)=A_{yy}(0)=-\tfrac{1}{2}A_{zz}(0)\,.$$

Using Eqs. (2), (3), (6), and (7), one can easily show that for a spin orientation of $\beta=54.7$, $\phi=0°$ the equations for $\theta=0°$ reduce to

$$I=I_0\,,$$
$$p_{x'}=\frac{\sqrt{2}}{3}\,p_{33}K_{yz}^{x'}\,, \qquad (8)$$
$$p_{y'}=\sqrt{\tfrac{3}{2}}\,p_3K_y^{y'}\,.$$

Thus, the two nonzero polarization transfer coefficients that are available with our polarimeter can be measured simultaneously and independently of the I/I_0 ratio. This method is described in more detail in Ref. 9.

III. EXPERIMENTAL METHOD

A. Experimental Setup

Figure 2 shows the over-all experimental setup. A 2.5-cm-diam gas cell filled with from 2 to 5 atm of ^{3}He at liquid nitrogen temperature was in the center of the primary scattering chamber. For the angular distribution, the deuteron energy loss in the ^{3}He was 0.7 MeV, and the incident deuteron energy was adjusted to give an energy of 8.0 MeV in the center of the cell. For the $\theta=0°$ excitation function, the pressure in the primary target was adjusted at each energy to give an energy loss of 0.5 MeV.

The reaction protons were focused into a polarimeter placed in the center of the secondary chamber 2.3 m away. The magnetic quadrupole triplet shown has a solid-angle acceptance of 3.1×10^{-3} sr. For the measurements at zero degrees, the deuteron beam was stopped by tantalum foils placed just behind the primary target. The whole apparatus is mounted on a gun mount such that it can be rotated about a vertical axis through the center of the primary target.

B. Proton Polarimeter

When the incident deuteron beam in the ^{3}He(d,p) reaction is polarized, the outgoing protons may have polarization components along all three coordinate axes as described in Eqs. (2)–(4). The helium polarimeter, shown in Fig. 3, was designed to measure the x' and y' components of the proton polarization simultaneously. This polarimeter has been described previously in Refs. 9 and 10, but a brief description is inlcuded here for completeness and to point out the operating conditions used in this experiment.

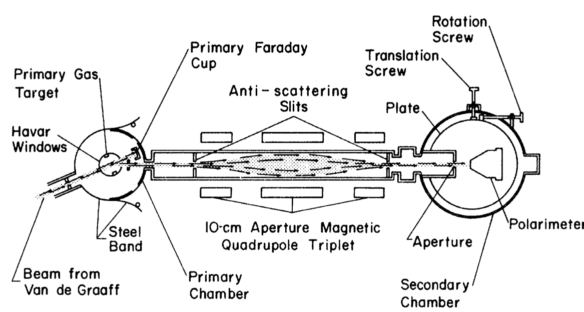


FIG. 2. Diagram showing the over-all experimental arrangement for the polarization transfer measurements. The magnetic quadrupole triplet and primary and secondary chambers rotate right or left of the beam about an axis through the center of the primary target. The steel band on the primary chamber maintains the vacuum seal, and the Faraday cup is rotated to intercept the primary beam.

On the left side is a side view and on the right is a front view of the polarimeter. The protons enter through two 0.63-cm-diam tantalum collimators labeled C, between which is a foil F held by double O rings. For this experiment we used a 50-μm stainless-steel foil to contain the helium in the polarimeter at 40 atm. The protons passed through a 300-μm silicon transmission detector P and were scattered by the high-pressure helium into four rectangular side detectors S with surface areas of 1×5 cm^2. The vanes V defined a mean analyzing angle of 60°. The monitor detector M at the rear gave an energy calibration for the protons traversing the polarimeter. The quadrupole triplet was adjusted to focus the scattered protons through a 0.32-cm collimator into the center of this detector by observing the counting rate on a ratemeter. A fast coincidence between pulses in the passing detector and the side detectors restricted events in these spectra to particles entering the front of the polarimeter and scattering from the helium gas.

The analyzing power was calibrated by defocusing a polarized proton beam from the accelerator and allowing it to impinge directly on the polarimeter. Figure 4 shows the calibration data as a function of proton energy in the monitor detector. These energies correspond to incident proton energies from 7.5 to 16 MeV. For all of the ^{3}He-$(d,p)^4$He measurements reported here, the high-energy protons from the reaction (Q value = 17.6 MeV) were degraded in energy by tantalum foils so that the monitor energy was 8.5 to 9.5 MeV (incident energy about 14 MeV). In this region the polarimeter analyzing power is flat at −0.63 and the efficiency is about 10^{-4} for each pair of side detectors. In addition, protons from reactions in the walls of the gas cell and elastically scattered deuterons were either stopped in the foils or degraded so much in energy that they did not present a problem. The quadrupole lens also provided a partial energy selection for charged particles, and its use allowed the physical separation necessary to keep the neutron background at the polarimeter at a low level. Thus the background from particles other than $^3He(d, p)^4He$ protons and accidental background caused by high count rate in the passing detector were completely negligible.

C. Incident Deuteron Beam Characteristics

As indicated in Fig. 1, polarization transfer experiments require accurate control of the incident spin direction at the target. The calibration of the polarized-source spin precessor[11] was checked prior to the experiment by scattering the polarized-deuteron beam from ^{4}He in a "cube" scattering chamber immediately behind the secondary chamber shown in Fig. 2. By measuring A_{zz} and using the null technique described in Ref. 9, accurate calibration points were established for $\beta = 54.7$ and $\beta = 125.3°$. A similar technique measuring A_y established a calibration point for $\beta = 0°$. A linear fit to these points gave the spin quantization axis at the target to an accuracy of ±0.5°. Conditions that can affect this calibration are discussed in Ref. 9 and in more detail in Ref. 11, but for this experiment, the spin direction is believed to be known within the accuracy stated.

For the data at reaction angles other than 0°, 16

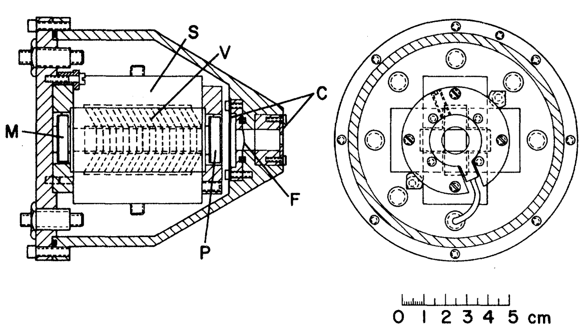


FIG. 3. A side view (left) and a front view (right) of the proton polarimeter used. Parts are labeled as follows: C, tantalum collimators; F, 50-μm stainless-steel foil; P, 300-μm passing detector; V, vanes defining the analyzing angle of 60°; S, one of four side detectors; M, 1000-μm monitor detector. The entire volume of the polarimeter was filled with ^{4}He gas to a pressure of 40 atm. The electronics required a coincidence between events in P and any of the other five detectors.

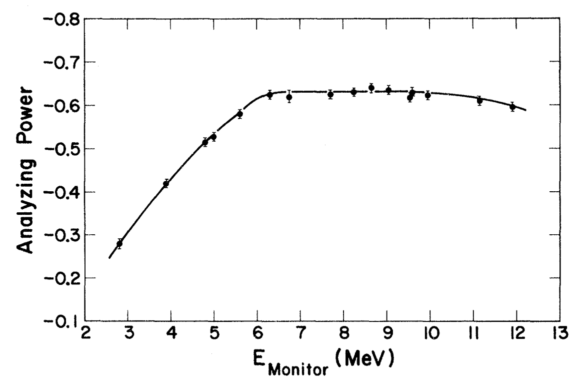


FIG. 4. Polarimeter analyzing power versus proton energy in the monitor detector M. The calibration points shown were obtained at a polarimeter pressure of 20 atm, but checks at 40 atm gave the same results for the flat portion of the curve between 7 and 11 MeV. Monitor energies in the present experiment were from 8.5 to 9.5 MeV, corresponding to an incident proton energy of about 14 MeV.

runs were taken at each angle with different combinations of incident spin direction, deuteron beam nuclear magnetic substate ($m_I = 1, 0, -1$), and polarimeter to the left or right of the beam axis. The $m_I = -1$ state is similar to the $m_I = +1$ state except that the direction of the vector polarization p_3 with respect to the quantization axis is reversed. The equivalent beam was therefore obtained by selecting $m_I = +1$ in the polarized-source spin filter and reversing the magnetic fields in the spin filter and ionization regions.[11] For simplicity of notation, however, this will be referred to as an $m_I = -1$ beam.

The beam polarizations were obtained by an atomic beam method known as the quench ratio.[12] Basically, this consists of measuring p_Q, the percent of the beam that is in the selected magnetic substate, by applying sufficient fields in the polarized-source spin filter to "quench" this substate. For the operating conditions of the polarized source,[11] the beam vector and tensor polarizations are given by

$$m_I = \pm 1 \begin{cases} p_3 = \pm p_Q \\ p_{33} = p_Q , \end{cases}$$

$$m_I = 0 \quad \begin{cases} p_3 = 0.012 p_Q \\ p_{33} = -1.966 p_Q . \end{cases}$$

Refinements to this procedure and the accuracy obtainable in the beam polarization measurements are discussed in detail in Ref. 12.

Typical values for $m_I = 1$ beams were $p_3 = p_{33} \simeq 0.76$ and for $m_I = 0$ beams $p_3 \simeq 0$, $p_{33} \simeq -1.5$. The beam polarization was measured several times during each run and the results (usually varying less than 0.01) were averaged. Beam currents on target ranged from a low of 50 nA at the lowest energy to a high of 160 nA at 12 MeV. For the 8-MeV angular distribution, the average beam current was about 130 nA. Including the time required to change spin direction and rotate the target assembly, about 1 day was required to obtain the necessary data at each angle.

D. Experimental Procedure for Angular Distribution

For incident spin directions along the x, y, and z axes, the experimantal procedure was the same. Pairs of runs (see Fig. 1) were taken for $m_I = \pm 1$ with the polarimeter on the left and right of the beam axis such that the outgoing polarization directions were reversed in the laboratory. The polarimeter was not rotated, so the roles of the analyzing detectors were reversed and polarimeter instrumental asymmetries could be canceled in the usual way for spin-$\frac{1}{2}$ polarization. That is, the geometric mean ratios r_{13} and r_{24} were formed for the two runs having reversed proton polarization, e.g.

$$r_{24} = \left[\left(\frac{N_2}{N_4} \right) \uparrow \left(\frac{N_4}{N_2} \right) \downarrow \right]^{1/2} . \tag{9}$$

In this equation, the subscripts 2 and 4 stand for the (physically) left and right polarimeter detectors, N represents the number of counts in the peak, and the arrows designate the two runs taken with a proper flip. The proton polarization along the y' axis is then given by

$$p_{y'} = \frac{1}{A_p} \left[\frac{r_{24} - 1}{r_{24} + 1} \right], \tag{10}$$

where A_p is the analyzing power of the polarimeter A similar expression for $p_{x'}$ can be written using polarimeter detectors 1 and 3 (down and up in the laboratory).

The runs were repeated using an $m_I = 0$ deuteron beam and the outgoing polarizations determined in the same manner. For these runs, all $p_{x'}$ values should be near zero because they depend only on the beam vector polarization. Within statistics the data gave this result, providing a check on the method. The transfer coefficients depending on the beam tensor polarization were determined to a greater precision with the $m_I = 0$ runs, since the magnitude of p_{33} nearly doubled. The quoted results for these coefficients are statistically averaged values for both types of beams; the individual results usually agreed within the statistical error. With the beam polarization at 45° in the xz plane only $m_I = 0$ runs were taken in order to determine $K_{xz}^{y'}$; the transfer coefficients obtainable from the $m_I = \pm 1$ beam had already been determined.

All polarizations were corrected for a small depolarization in the magnetic quadrupole triplet.[8] The angular acceptance of the triplet is ±3.0° in the vertical plane causing a depolarization in $p_{y'}$ of 0.7% and ±1.1° in the horizontal plane causing a depolarization in $p_{x'}$ of 0.1%. Depolarization of the protons in the slowing down foils has been calculated to be negligible at the 1% level.[8]

The equations in Fig. 1 show that the polarization function $P^{y'}$ always appears in the expression for $p_{y'}$. This function was therefore determined accurately with an unpolarized beam since the error in its measurement must be included in the error analysis for five of the seven transfer coefficients measured. With the polarizing fields in the ion source turned off, data were obtained both left and right of the beam axis and $P^{y'} = p_{y'}$ calculated from Eq. (10).

The I/I_0 ratios were obtained from the analyzing powers of Grüebler *et al.*[13] using values calculated from their Legendre polynomial fit to the experimental data. By using the fitted values, we re-

TABLE II. Experimental results for $^3He(\vec{d},\vec{p})^4He$ excitation function at $\theta = 0.0°$.

E_d (±0.25 MeV)	$K_y^{y'} = K_x^{x'}$	$K_{yz}^{x'} = -K_{xz}^{y'}$
4.0	−0.023 ± 0.045	−0.709 ± 0.064
6.0	0.179 ± 0.025	−0.361 ± 0.038
8.0	0.432 ± 0.019	−0.016 ± 0.028
10.0	0.496 ± 0.022	0.168 ± 0.034
12.0	0.512 ± 0.029	0.264 ± 0.035
14.0	0.557 ± 0.018	0.330 ± 0.030

duced error propagation in these ratios. Although only at most two Cartesian analyzing powers are used for I/I_0 calculation for each incident spin direction [Eqs. (1) and (6)], these were determined from as many as three of the spherical tensor analyzing powers reported in Ref. 13. The other alternative for obtaining the I/I_0 ratios was direct measurement of the singles counts in our polarimeter monitor detector. Qualitative agreement with the calculated values was obtained using this method, but because of variations in the secondary beam focusing by the quadrupole triplet, it was felt that the calculated values were more reliable.

The above measured and calculated quantities were then used in the equations of Fig. 1 to obtain the polarization transfer coefficients. For the measurements with the incident beam alignment axis in the y direction, the equations show that $K_y^{y'}$ and $K_{yy}^{y'}$ are contained in the same expression for $p_{y'}$. For this case, therefore, $K_{yy}^{y'}$ was calculated first from the $m_I = 0$ runs assuming $p_3 = 0$, and this value was then used for the $m_I = \pm 1$ runs to determine $K_y^{y'}$. A simple iteration of the calculations accounted for the small value for p_3 during the $m_I = 0$ runs.

E. Experimental Procedure for $\theta = 0°$

For these measurements the beam quantization axis was oriented at 54.7° from $\vec{k}_{in}$ and runs were taken for $m_I = \pm 1$ and 0. The polarizations $p_{x'}$ and $p_{y'}$ were then used in Eq. (8) to directly calculate $K_y^{y'}$ and $K_{yz}^{x'}$.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The values for $K_y^{y'}$ and $K_{yz}^{x'}$ at $\theta = 0°$ are listed in Table II, and the results for the polarization function $P^{y'}$ and the seven polarization transfer coefficients measured at 8.0 MeV are listed in Table III. All measurements have been corrected for the small depolarization of the reaction protons in the quadrupole triplet lens.

A. Errors

The final errors quoted are quadratically combined errors from the counting statistics, a relative error of ±0.010 assigned to the polarimeter analyzing power, and where applicable the experimentally determined errors for $P^{y'}$ and any other polarization transfer coefficient used in a calculation (e.g., the error for $K_{yy}^{y'}$ was included in the error calculation for $K_y^{y'}$ and $K_{xz}^{y'}$). The small relative error for the polarimeter analyzing power is based on the fact that nearly the same proton energy in the polarimeter was achieved for all of the measurements, and several calibration points were taken for this energy.

The relative error in beam polarization was neglected since fluctuations during a run were generally much less than 0.01. As discussed in Sec. II B, errors arising from nonuniform illumination of the polarimeter were calculated to be negligible for our geometry. Because of the precision with which the spin quantization axis of the beam was determined (see Ref. 9 for an example), the error resulting from its uncertainty is also considered negligible. Calculation of the error from a possible misalignment would be quite difficult because of the many transfer coefficients, some of which were not determined, that would enter such a calculation. The errors in the I/I_0 ratios were neglected because of the relative precision of the analyzing power data of Ref. 13 and the smoothing of these data afforded by the Legendre polynomial fit.

In addition to the sources of error already con-

TABLE III. Experimental results for $^3He(\vec{d},\vec{p})^4He$ at 8.0 MeV.

θ_{lab} (deg) / $\theta_{c.m.}$ (deg)	0.0 / 0.0	15.0 / 17.9	30.0 / 35.5	45.0 / 52.8	60.0 / 69.6
$P^{y'}$		0.227 ± 0.012	0.588 ± 0.014	0.377 ± 0.018	−0.005 ± 0.018
$K_y^{y'}$	0.432 ± 0.018	0.304 ± 0.032	−0.545 ± 0.039	−0.468 ± 0.045	−0.039 ± 0.045
$K_x^{x'}$	0.432 ± 0.018	0.246 ± 0.031	−0.157 ± 0.047	0.081 ± 0.060	0.282 ± 0.063
$K_z^{x'}$		−0.136 ± 0.016	0.385 ± 0.042	0.431 ± 0.043	−0.056 ± 0.050
$K_{xx}^{y'}$		0.354 ± 0.035	−0.070 ± 0.074	−0.159 ± 0.068	0.268 ± 0.067
$K_{yy}^{y'}$		0.210 ± 0.026	0.817 ± 0.047	0.772 ± 0.088	0.445 ± 0.076
$K_{zz}^{y'}$		−0.555 ± 0.043	−0.724 ± 0.074	−0.737 ± 0.077	−0.522 ± 0.070
$K_{xz}^{y'}$	0.016 ± 0.028	−0.311 ± 0.080	−0.909 ± 0.122	−0.062 ± 0.096	−0.171 ± 0.082

TABLE IV. Consistency checks for polarization transfer data.

$E_d = 8.0$ MeV		$\theta = 0°$		
$\theta_{\rm lab}$	$K_{xx}^{y'} + K_{yy}^{y'} + K_{zz}^{y'}$	E_d (MeV)	$(\frac{3}{2}K_y^{y'})^2 + (K_{yz}^{x'})^2$	$1 - \frac{1}{2}A_{zz} - \frac{1}{2}A_{zz}^2$
15	0.007 ± 0.062	4.0	0.504 ± 0.091	0.480 ± 0.036
30	0.023 ± 0.112	6.0	0.202 ± 0.034	0.276 ± 0.040
45	-0.124 ± 0.134	8.0	0.419 ± 0.037	0.452 ± 0.037
60	0.192 ± 0.124	10.0	0.583 ± 0.051	0.661 ± 0.033
		12.0	0.659 ± 0.069	0.836 ± 0.029
		14.0	0.807 ± 0.050	0.933 ± 0.026

sidered, an uncertainty could arise from an absolute error in the polarimeter analyzing power or errors in the determination of the beam polarization. Such a scale error could result from errors in the quench ratio p_Q which has been demonstrated accurate to better than 1% for protons[12,14] and is accurate to 2% for deuterons. Considering the way in which these uncertainties enter into the calculations, we assign a normalization error of 2% to the data.

B. Consistency Checks

Comparison of our values for $P^{y'}$ with results of Brown and Haeberli[15] shows good agreement except for the highest point at 35.5° c.m. where their point is several standard deviations higher than the present measurement. A single value of $K_y^{y'}$ (0°) at 10 MeV has been reported by Keaton *et al.*,[16] and is within 1 standard deviation of the present measurement.

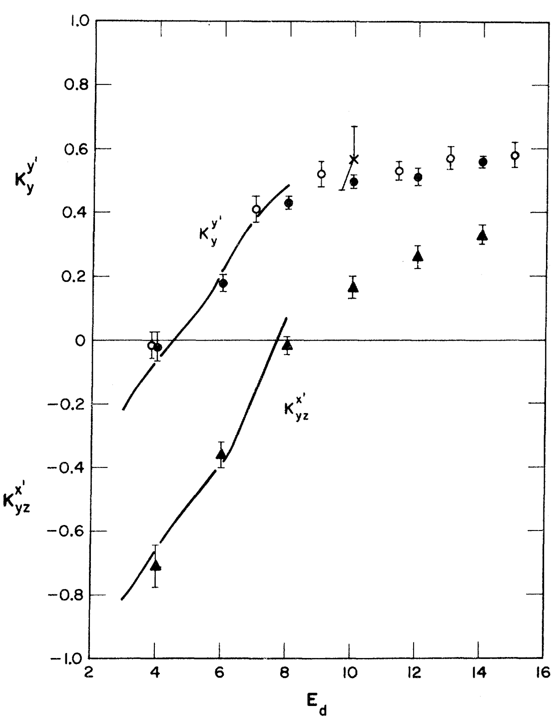


FIG. 5. Polarization transfer coefficients for $\theta = 0°$ as a function of deuteron energy for the ^{3}He$(d,p)^4$He and ^{3}H$(d,n)^4$He reactions. For ^{3}He$(d,p)^4$He, the closed circles and triangles are $K_y^{y'}$ and $K_{yz}^{x'}$ results from the present work and the ⨯ is from Ref. 16. The open circles are $K_y^{y'}$ results for ^{3}H$(d,n)^4$He from Ref. 20. The lines through the data are from an R-matrix parametrization of the five-nucleon system as described in the text.

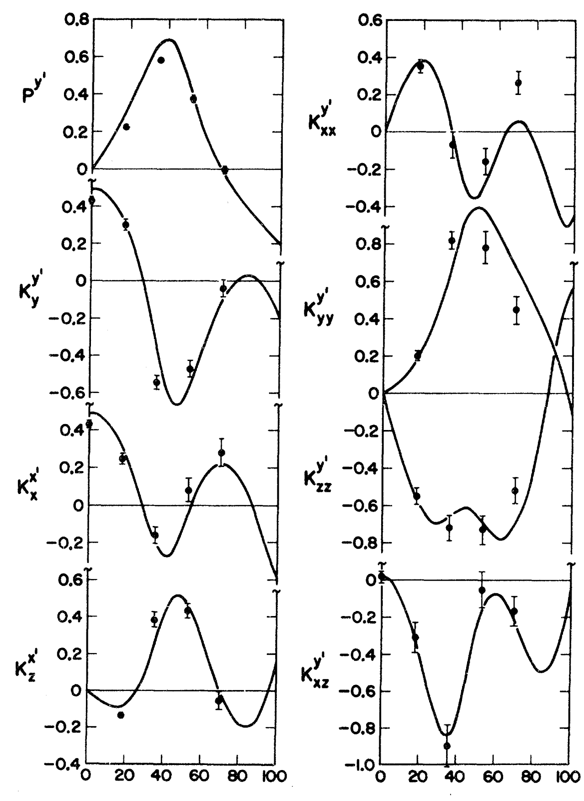


FIG. 6. Partial angular distributions of the polarization function $P^{y'}$ and the polarization transfer coefficients K for ^{3}He$(d,p)^4$He at a deuteron energy of 8.0 MeV. The lines through the data are from an R-matrix parametrization of the five-nucleon system as described in the text.

For the polarization transfer data, several other checks can be made for internal consistency and for consistency with other types of data. On the left in Table IV are the calculated values and errors for $K_{xx}^{y'}+K_{yy}^{y'}+K_{zz}^{y'}$. According to Eq. (5) this sum should be zero, and the results for three of the four angles are within 1 standard devaition of this value.

The second check uses one of the quadratic relations deduced by Ohlsen, Keaton, and Gammel.[17] The first quadratic relation of Table I in Ref. 17 reduces for $\theta = 0°$ to

$$(\tfrac{3}{2}K_x^{x'})^2 + (K_{yz}^{x'})^2 = (1 - A_{yy})(1 - A_{zz}) . \qquad (11)$$

Using the 0° relation for the analyzing powers [Eq. (7)], the right side of Eq. (11) becomes $1 - \frac{1}{2}A_{zz} - \frac{1}{2}A_{zz}{}^2$. The two columns in Table IV thus compare the present polarization transfer data with analyzing power data of Grüebler *et al.*[18] (interpolated, from 4.0 to 10.0 MeV) and Lisowski *et al.*[19] (12.0 and 14.0 MeV) through this quadratic relation. The errors listed were calculated from the quoted errors of Table II and Refs. 18 and 19. The consistency of these two types of data is good at the lower energies, but an unexplained systematic deviation occurs above 10 MeV.

C. Zero Degree Results

Figure 5 shows the two polarization transfer coefficients measured at zero degrees as a function of energy. The coefficient $K_y^{y'}$ is analogous to the Wolfenstein D parameter[5] in nucleon scattering. Our data are compared to the $K_y^{y'}$ data obtained at Los Alamos by Broste *et al.*[20] for the mirror reaction ^{3}H(d, n)^{4}He, shown as open circles. If the outgoing nucleons from these reactions retained the same polarization as the incident deuterons, $K_y^{y'}$ would be $\frac{2}{3}$. The data approach this value at the higher energies, but the effect of the $\frac{3}{2}^+$ resonance in ^{5}Li at low energies is clearly seen.[20] Over all, the agreement between these data for the two mirror reactions is excellent, and there is no indication of a charge effect. Also plotted in Fig. 5 are the $K_{yz}^{x'}$ data obtained in the present experiment.

D. Angular Distribution Results

Figure 6 shows the ^{3}He(d, p) data obtained at 8 MeV for laboratory angles of 15, 30, 45, and 60°. The lines through the data on both Figs. 5 and 6 are calculated values from the R-matrix parameters of Dodder and Hale of Los Alamos.[21] Their analysis of the five-nucleon system included at this time all previously published data up to 8 MeV, but did not include the data shown. The excellent agreement between the predicted values and our data gives increased confidence in their parametrization, and in addition it appears that there is some sensitivity of their parameters to this type of data. Dodder and Hale are adding this data to the search and extending their analysis of the five-nucleon system to higher energies.

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