Polarization and polarization transfer in the ^{3}H$(d, n)^4$He reaction at 7 MeV†

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The six polarization transfer coefficients $K_z^{x'}$, $K_z^{z'}$, $K_x^{z'}$, $K_x^{x'}$, $K_y^{y'}$, and $K_{yy}^{y'}$ for the reaction ^{3}H$(d, n)^4$He have been measured at a laboratory deuteron energy of 7.0 MeV. The laboratory angular range 0° to 105° was covered. Special attention is given to the zero degree longitudinal polarization transfer case, where it is shown that a beam of neutrons with accurately known polarization may be produced.

[NUCLEAR REACTIONS ^{3}H(d,n), $E=7.0$ MeV, measured analyzing powers A_y, A_{xx}, A_{yy}, A_{zz}; polarization function $P^{y'}$; and polarization transfer coefficients $K_z^{x'}$, $K_z^{z'}$, $K_x^{z'}$, $K_x^{x'}$, $K_y^{y'}$, and $K_{yy}^{y'}$ at $\theta_{lab}=0°$ to $\theta_{lab}=105°$. Enriched target.]

I. INTRODUCTION

The present work is a continuation of our efforts to measure spin-transfer coefficients in the various light nuclear systems. The reaction ^{3}H-$(d, n)^4$He is particularly interesting for such a study because of its potential utility as a source of polarized 20–40 MeV neutrons for other experiments. A deuteron energy of 7 MeV was selected for the present measurements, for two reasons: (1) the availability of cross section[1] and some earlier spin-transfer data[2] near this energy and (2) our desire to provide data of maximum usefulness to the phenomenological analysis of the five nucleon system. The higher energy data cannot be unambiguously assimilated until the lower energy fits are well established.[3] An energy lower than 7 MeV would be perhaps desirable from this point of view, but the performance of the accelerator beam transport system seriously deteriorates at energies lower than this; thus, 7 MeV is a compromise between these two conditions.

The ^{3}H$(\vec{d}, \vec{n})^4$He polarization transfer reaction has been previously studied at 0° as a function of energy.[4] Also, Broste[2] has measured the outgoing neutron polarization, at 7 and 11 MeV deuteron energies, for an $m_I=1$ deuteron beam 75% polarized along the normal to the reaction plane. A number of angles between 30° (left) and 75° (right) were studied in that work. However, no attempt was made to separate the various polarization parameters, so these results are not in the most convenient form for theoretical analysis. The present results do, however, support these early measurements.

II. PARAMETRIZATION

It is convenient to use two frames of reference for the description of the particle polarizations in a polarization transfer experiment. The incident deuteron polarization is referred to the "projectile helicity frame." This frame has its z axis along the projectile momentum and its y axis along the normal to the reaction plane, i.e., along $\vec{k}_{in}\times\vec{k}_{out}$. The outgoing neutron polarization is referred to the "outgoing particle laboratory helicity frame"; this system has its z' axis along the outgoing lab neutron direction and its y' axis again along $\vec{k}_{in}\times\vec{k}_{out}$. The x and x' axes are in each case chosen as required to form an orthonormal right-handed system.

The present experiment was restricted to measurements in which the deuteron polarization symmetry axis was along either the x, y, or z axis. For the polarization symmetry axis along the y direction, the differential cross section $I(\theta)$ may be written[5,6]

$$I(\theta)=I_0(\theta)[1+\tfrac{3}{2}p_Z A_y(\theta)+\tfrac{1}{2}p_{ZZ}A_{yy}(\theta)], \tag{1}$$

where I_0 is the differential cross section for an unpolarized beam; p_Z and p_{ZZ} are the deuteron vector and tensor polarization, respectively, with respect to the polarization symmetry axis; $A_y(\theta)$ is the vector analyzing power; and $A_{yy}(\theta)$ is one of the several second-rank tensor analyzing powers. The outgoing neutron polarization components, $p_{x'}$, $p_{y'}$, and $p_{z'}$, may be written for this case

$$\begin{aligned} &p_{x'}=0,\\ &p_{y'}I(\theta)=I_0(\theta)[P^{y'}(\theta)+\tfrac{3}{2}p_Z K_y^{y'}(\theta)+\tfrac{1}{2}p_{ZZ}K_{yy}^{y'}(\theta)],\\ &p_{z'}=0, \end{aligned} \tag{2}$$

where $P^{y'}(\theta)$ is the polarization function, and $K_y^{y'}(\theta)$ and $K_{yy}^{y'}(\theta)$ are polarization transfer coefficients. For the deuteron polarization symmetry axis along the z direction, the corresponding relations are

$$\begin{aligned} &I(\theta)=I_0(\theta)[1+\tfrac{1}{2}p_{ZZ}A_{zz}(\theta)],\\ &p_{x'}I(\theta)=I_0(\theta)[\tfrac{3}{2}p_Z K_z^{x'}(\theta)],\\ &p_{y'}I(\theta)=I_0(\theta)[\tfrac{1}{2}p_{ZZ}K_{zz}^{y'}(\theta)],\\ &p_{z'}I(\theta)=I_0(\theta)[\tfrac{3}{2}p_Z K_z^{z'}(\theta)]. \end{aligned} \tag{3}$$

TABLE I. Calculated and "effective" n-^{4}He analyzing power at 115°.

θ_{lab} (deg)	E_n (MeV)	$A_y^{(2)}$ (115°) Calculated	Corrected
0	24.22	0.862	0.814
10	24.09	0.868	0.820
20	23.70	0.867	0.819
30	23.07	0.855	0.809
45	21.77	0.789	0.749
60	20.18	0.956	0.899
75	18.47	0.909	0.849
90	16.80	0.938	0.873
105	15.28	0.956	0.888

Expressions for the case in which the deuteron polarization symmetry axis is along the x direction may be obtained from Eq. (3) by replacing A_{zz}, $K_z^{x'}$, $K_{zz}^{y'}$, and $K_z^{z'}$ by A_{xx}, $K_x^{x'}$, $K_{xx}^{y'}$, and $K_x^{z'}$, respectively. $K_{zz}^{y'}$ and $K_{xx}^{y'}$ were not studied in the present experiment.

III. EXPERIMENTAL DETAILS

The measurement techniques employed were exactly as described by Salzman *et al.*[7] and the reader is referred to that paper for details. Briefly, the polarization of the neutrons was detected by scattering in a liquid-helium polarimeter system. A transverse or a longitudinal magnetic field was used to precess the neutron spin in a way that permitted sensing of the z' and y' polarization components, respectively. (The system detects the x' component of the neutron polarization in the absence of a precession field.) Three counting periods, using an $m_I = 1$, 0, and -1 polarized deuteron beam in sequence, were used for the measurements involving z' and x' outgoing spin components. Six counting periods are required for measurement of the y' spin transfer coefficients. The measurements are completely dependent on the accuracy with which the integrated charge is measured. However, many parameters are simultaneously determined. For example, in the y-axis case, A_y, A_{yy}, $P^{y'}$, $K_y^{y'}$, and $K_{yy}^{y'}$ are simultaneously determined.

The tritium target was contained in a cell 3 cm long at a pressure of 6 atm. Beam currents in the range 100–200 nA with a polarization of about 75% of the ideal values were used. The entire data set presented here was acquired in a 6-day running period.

The n-^{4}He analyzing power $A_y^{(2)}(115°)$ was calculated from the phase shifts of Lisowski[8] for the energy range below 19 MeV and from the phase shifts of Hoop and Barschall[9] for higher energies. Finite geometry and multiple scattering corrections were calculated with the code MOCCASINS.[10] Both the calculated and corrected values of $A_y^{(2)}$ are given in Table I.

The data at 45°, corresponding to a neutron energy of 21.77 MeV, are strongly affected by the nearby resonance in n-^{4}He scattering. In that case, the results are not reliable and the quoted errors for $p^{y'}$ and each of the polarization transfer coefficients should be increased by ~15% of the tabulated value. Conceivably the adjacent angles at 30° and 60° could also be affected by a few percent.

Occasional background runs with an unpolarized beam and with the target cell evacuated were taken. The background counting rate was in all cases less than 1% of the foreground counting rate. A suitable correction for this minor effect was applied to the data.

IV. RESULTS

The data obtained are presented in Tables II and III. Except for the observable $K_z^{x'}$, the mirror reaction data of Hardekopf *et al.*[11] appear to agree well with the present data.

The errors quoted in the final results are a quadratic combination of errors arising from background, multiple scattering, and counting statistics. The error in the multiple scattering correction was taken to be $\frac{1}{3}$ of its value, or about 0.008, and the error in the background correction was taken to be $\frac{1}{2}$ of its value. Thus, in the present

TABLE II. Polarization function and analyzing tensors for the ^{3}H$(d,n)^4$He reaction at 7 MeV.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	$P^{y'}(\theta)$	$A_y(\theta)$	$A_{xx}(\theta)$	$A_{yy}(\theta)$	$A_{zz}(\theta)$	$A_{xx}+A_{yy}+A_{zz}$
0	0	···	···	···	0.728 ± 0.022	−1.330 ± 0.023	0.126 ± 0.050
10	11.82	0.152 ± 0.019	−0.098 ± 0.019	0.583 ± 0.026	0.772 ± 0.022	−1.291 ± 0.025	0.064 ± 0.041
20	23.59	0.335 ± 0.019	−0.243 ± 0.019	0.278 ± 0.023	0.794 ± 0.021	−1.041 ± 0.032	0.031 ± 0.045
30	35.25	0.531 ± 0.017	−0.486 ± 0.020	0.042 ± 0.028	0.685 ± 0.027	−0.620 ± 0.039	0.107 ± 0.055
45	52.42	0.301 ± 0.027	−0.616 ± 0.019	0.227 ± 0.046	−0.010 ± 0.040	−0.307 ± 0.053	−0.090 ± 0.081
60	69.10	−0.048 ± 0.023	−0.425 ± 0.018	0.506 ± 0.041	−0.644 ± 0.041	0.014 ± 0.039	−0.124 ± 0.070
75	85.15	−0.325 ± 0.020	−0.214 ± 0.016	0.558 ± 0.040	−0.986 ± 0.037	0.263 ± 0.038	−0.165 ± 0.077
90	100.50	−0.408 ± 0.022	0.131 ± 0.019	0.745 ± 0.033	−0.789 ± 0.042	−0.106 ± 0.048	−0.150 ± 0.072
105	115.13	−0.518 ± 0.022	0.571 ± 0.021	−0.090 ± 0.047	0.137 ± 0.040	−0.070 ± 0.047	−0.023 ± 0.078

TABLE III. Polarization transfer coefficients for the $^3H(d,n)^4He$ reaction at 7 MeV.

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	$K_x^{x'}(\theta)$	$K_x^{z'}(\theta)$	$K_z^{x'}(\theta)$	$K_z^{z'}(\theta)$	$K_y^{y'}(\theta)$	$K_{yy}^{y'}(\theta)$
0	0	···	···	···	0.159± 0.017	0.426± 0.022	···
10	11.82	0.285± 0.037	0.009± 0.037	−0.079± 0.018	0.083± 0.018	0.319± 0.024	0.116± 0.032
20	23.59	0.156± 0.026	0.184± 0.027	−0.062± 0.025	0.038± 0.026	0.146± 0.025	0.360± 0.031
30	35.25	0.007± 0.026	0.350± 0.043	0.208± 0.033	−0.119± 0.037	−0.257± 0.027	0.726± 0.037
45	52.42	0.020± 0.053	0.437± 0.051	0.212± 0.071	−0.049± 0.041	−0.429± 0.028	0.733± 0.049
60	69.10	0.233± 0.049	0.605± 0.045	0.054± 0.038	−0.007± 0.037	−0.093± 0.022	0.521± 0.049
75	85.15	−0.022± 0.042	0.612± 0.054	0.078± 0.041	−0.278± 0.035	0.121± 0.018	0.393± 0.046
90	100.50	−0.565± 0.044	0.269± 0.043	0.180± 0.040	−0.276± 0.044	−0.078± 0.021	0.014± 0.050
105	115.13	−0.235± 0.040	0.079± 0.043	0.464± 0.036	0.200± 0.040	−0.412± 0.025	−0.204+ 0.044

case, counting statistics are usually the dominant source of error.

A consistency check on the data is available from the relation

$$A_{xx}+A_{yy}+A_{zz}=0 \qquad (4)$$

which follows from the overcompleteness of the Cartesian spin-1 basis set. The measured values of this sum are included in Table II. Only two out of nine of these measurements lie within ±1 standard deviation of zero, instead of the six one would expect on the basis of a normal distribution. It would therefore appear that the errors on these quantities are underestimated by about a factor of 2. This is believed to be because of inaccurate run-to-run charge normalization. The effect of this uncertainty on the measured polarization transfer coefficients is difficult to evaluate in a precise way. Our best estimate is that the quoted errors should be combined quadratically with a current integration-induced uncertainty of ±0.03. The errors induced in the spin-transfer coefficients and the analyzing powers would be expected to be similar. A better evaluation of this can perhaps be obtained in the course of fitting the data with phenomenological parameters.

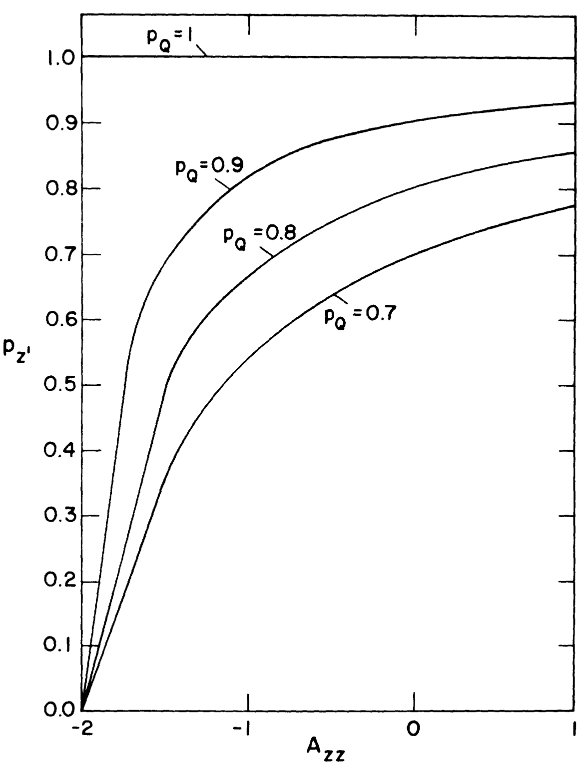

FIG. 1. The 0° neutron polarization, $p_{z'}(0°)$ as a function of A_{zz}, for beam polarization values, p_Q, of 0.7, 0.8, 0.9, and 1.0.

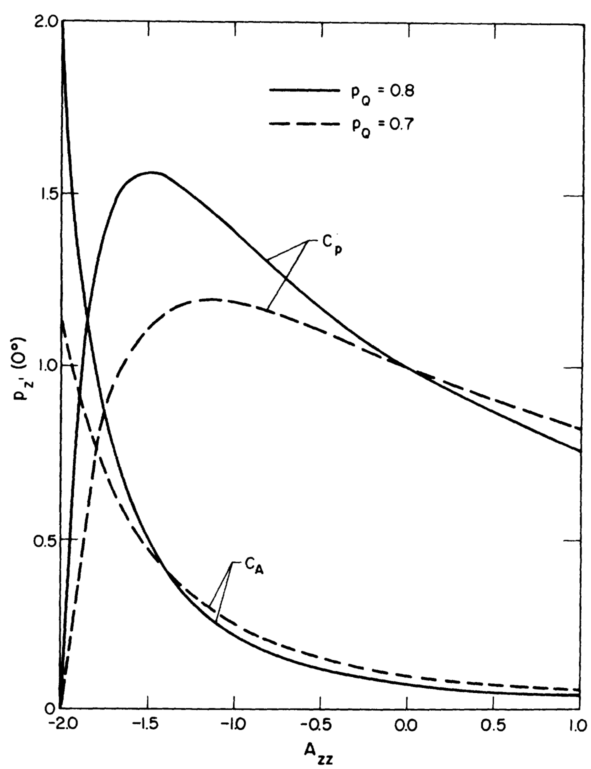

FIG. 2. The coefficients C_p and C_A as a function of A_{zz} for beam polarization values 0.7 and 0.8.

V. ABSOLUTE NEUTRON POLARIZATION

The ^{3}H$(d,n)^4$He reaction has the spin structure $1+\frac{1}{2}\rightarrow\frac{1}{2}+0$. From this, one can show that the neutron polarization at 0° emission angle is known if (1) the deuteron vector and tensor polarization is known and (2) if the analyzing power $A_{zz}(0°)$ is known,[6,12] as follows.

For any (d,n) reaction, for a deuteron beam with its polarization along its momentum vector, we have

$$p_{z'}(0°)=\frac{\frac{3}{2}p_Z K_z^{z'}(0°)}{1+\frac{1}{2}p_{ZZ}A_{zz}(0°)} . \tag{5}$$

For the spin structure of the ^{3}H$(d,n)^4$He reaction, it can also be shown,[6,12] that

$$\tfrac{3}{2}K_z^{z'}(0°)=1+\tfrac{1}{2}A_{zz}(0°) \tag{6}$$

so that

$$p_{z'}(0°)=\frac{[1+\frac{1}{2}A_{zz}(0°)]p_Z}{1+\frac{1}{2}p_{ZZ}A_{zz}(0°)} . \tag{7}$$

For a deuteron beam polarized in the $m_I=1$ state, the vector and tensor polarization are equal, and will be denoted by p_Q. Thus, for a beam polarized in this way, a knowledge of p_Q and A_{zz} is sufficient to determine $p_{z'}(0°)$. The manner in which $p_{z'}(0°)$ varies with p_Q and $A_{zz}(0°)$ is shown in Fig. 1.

It is of interest to calculate the error within which $p_{z'}$ is known for given uncertainties in p_Q and A_{zz}. This is given by

$$\Delta p_{z'}(0°)=[C_A^2(\Delta A_{zz})^2+C_p^2(\Delta p_Q)^2]^{1/2} ,$$
$$C_A=\frac{\frac{1}{2}p_Q(1-p_Q)}{(1+\frac{1}{2}p_Q A_{zz})^2} , \tag{8}$$
$$C_p=\frac{1+\frac{1}{2}A_{zz}}{(1+\frac{1}{2}p_Q A_{zz})^2} .$$

The quantities C_A and C_p are plotted versus A_{zz} in Fig. 2.

These results may be applied to the present data, where $A_{zz}(0°)=-1.330\pm0.023$. This yields, for $p_Q=0.75$, $C_A=0.373$, and $C_p=1.33$. The uncertainty which applies to p_Q typically at LASL is 1.5%. Thus, the neutron polarization and uncertainty, based on $p_Q=0.75$ and the present data, would be $p_{z'}(0°)=0.501\pm0.022$. It is clear that the dominant source of error is the uncertainty in the beam polarization.

At 15 MeV deuteron energy,[13] the value of A_{zz} has fallen to −0.9, and the error situation is somewhat more favorable. For very high energies, a simple stripping concept suggests that $A_{zz}(0°)$ should approach zero, so that C_p would become 1 and C_A would be very small, and the error propagation situation would become still more favorable. With care, there is no reason why p_Q cannot be known to $\sim\frac{1}{2}$% accuracy, so this technique could permit the production of neutrons with a comparably well known polarization. A 90° spin precession would, of course, have to be provided to obtain transversely polarized neutrons.

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[13]Based on the 0° relation $A_{zz}=-2A_{yy}$ and the data of Ref. 4.