# Polarization transfer in $(\vec{d},\vec{n})$ reactions on light nuclei at $\theta=0°$

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(Received 29 June 1981)

Transverse vector polarization transfer coefficients $K_y^{y'}$ have been measured at a reaction angle of 0° for the processes $^{12}C(d,n)^{13}N$, $^{14}N(d,n)^{15}O$, $^{16}O(d,n)^{17}F$, and $^{28}Si(d,n)^{29}P$. The deuteron beam energy ranged from about 5 to 15 MeV for most cases. For the $^{12}C(d,n)^{13}N$ reaction an excitation function of the differential cross section at 0° also was obtained from 6 to 14 MeV for the ground state and first excited state transitions. The polarization transfer coefficients were all positive and typically just slightly lower than the value of $\frac{2}{3}$. This indicates that the contribution from spin transfer $s=\frac{3}{2}$ is small at 0°. Theoretical predictions of $K_y^{y'}(0°)$ using the distorted-wave Born approximation agree with the data to within about 10%.

[NUCLEAR REACTIONS $^{12}C,^{14}N,^{16}O,^{28}Si$ $(\vec{d},\vec{n})$, $E=5-15$ MeV; measured polarization transfer $K_y^{y'}(0°)$. $^{12}C(d,n)$, $E=6-14$ MeV; measured $\sigma(0°)$. Comparison of $K_y^{y'}(0°)$ to DWBA.]

## I. INTRODUCTION

A few years ago polarized ion sources reached sufficient intensities to permit exploratory measurements of "triple-scattering" polarization parameters involving neutrons in the exit channel. The type of experiment considered in the present paper is one which measures the observable which connects the transverse polarization of the outgoing neutron beam to the transverse polarization of an incident deuteron beam in $(d,n)$ reactions. The measured parameters are called polarization transfer coefficients, and the symbol $K_y^{y'}$ is employed for the transverse polarization transfer. Prior to the present work measurements of this parameter for $(d,n)$ reactions had been limited to targets of the hydrogen isotopes.[1-3] In fact, most of the $(d,n)$ data were limited to very low $Z$ targets also, namely hydrogen or helium isotopes.[1-3] For heavier targets, no systematic data existed at the time the present experiment[4,5] was conducted. The results reported here helped stimulate theoretical calculations for polarization transfer coefficients in deuteron stripping reactions and tend to verify the predictions.

The triple-scattering nature of polarization transfer experiments makes them very difficult to carry out to high accuracy. Furthermore, because the counting rates are low, the statistical accuracy of the data will be relatively poor if one is to accomplish a systematic study with a few targets at many energies and angles. Our approach was to limit our study to the reaction angle of 0° and to measure in intervals of about 1.5 MeV over a range of 8 MeV for four targets. At the time of the preliminary presentation of our data,[4,5] we intended to continue our survey, so we withheld a full publication of the results. However, it is clear that we will not obtain more data of this type in the near future. Therefore, we are reporting here the full details of this unique set of experiments.

The reactions investigated were $^{12}C(\vec{d},\vec{n}_0)^{13}N$, $^{12}C(\vec{d},\vec{n}_1)^{13}N$, $^{14}N(\vec{d},\vec{n})^{15}O$, $^{16}O(\vec{d},\vec{n}_1)^{17}F$, and $^{28}Si(\vec{d},\vec{n})^{29}P$. The second and the last two are $l_p=0$ transfer reactions which have differential cross sections which peak at the reaction angle of 0°. The first one is an $l_p=1$ transfer which was chosen to permit an observation of the polarization transfer for a reaction which did not have its main stripping peak at 0° and to observe the effects of compound nuclear resonances on the polarization transfer coefficient, since for that reaction at $\theta=0°$ considerable resonance structure is apparent in the cross section. We also report values for the neutron yield from 6 to 14 MeV for the $n_0$ and $n_1$ neutron groups for the reaction $^{12}C(d,n)^{13}N$. The latter data were taken to observe the compound nuclear contribution to those channels in regions where no other data existed and to determine the size of such effects for targets with a thickness comparable to that used in the $K_y^{y'}$ measurements.

The formalism for polarization transfer at 0° for $(d,n)$ reactions is applied to the $K_y^{y'}(0°)$ data from the present work as well as from earlier work on the targets $^2H$ and $^3H$. The effects of $s=\frac{1}{2}$ and $s=\frac{3}{2}$ spin transfers are interpreted in view of the results. Lastly, calculations in the distorted-wave Born approximation (DWBA) are compared to the data for the $^{28}Si\ (d,n)$ reaction between 6 and 16 MeV.

## II. EXPERIMENTAL METHOD

The polarization transfer experiments were performed in the Van de Graaff laboratory of the Triangle Universities Nuclear Laboratory (TUNL) using the polarized ion source facility[6] to provide a purely vector polarized deuteron beam with $p_y=0.47$ and $p_{yy}=0.0$. The use of such a beam avoids an auxiliary measurement of the tensor analyzing power $A_{yy}(0°)$ which otherwise enters into the calculation of $K_y^{y'}(0°)$ through the general formula[1]

$$p_{y'}(0°)=\frac{\frac{3}{2}K_y^{y'}(0°)p_y}{1+\frac{1}{2}A_{yy}(0°)p_{yy}} . \qquad (1)$$

Here $p_y$ and $p_{yy}$ are the vector and tensor beam polarizations, respectively, and $p_{y'}(0°)$ is the observed neutron polarization produced at an angle of 0° in the $(\vec{d},\vec{n})$ reaction. The usual conventions for the $y$ axis and $y'$ axis are that both axes are to be taken along the normal to the reaction plane. However, at the reaction angle of 0° the reaction plane is undefined. Therefore, we took both the $y$ axis and the $y'$ axis to be along the direction of the vector polarization of the incident beam.

From Eq. (1) it can be seen that for our situation with $p_{yy}=0$ we have the simple relation

$$p_{y'}(0°)=\tfrac{3}{2}K_y^{y'}(0°)p_y . \qquad (2)$$

Thus $\frac{3}{2}K_y^{y'}(0°)$ is equal to the ratio of the transverse component of the neutron polarization along the $y'$ axis to the transverse deuteron vector polarization along a parallel $y$ axis. So when $K_y^{y'}(0°)$ takes on the value of $\frac{2}{3}$, the magnitude of the polarization of the neutron beam is identical to the magnitude of the deuteron (vector) polarization. In one sense this value of $\frac{2}{3}$ indicates no change in polarization, i.e., no "depolarization" in the reaction. This situation can be compared to the elastic scattering of spin-$\frac{1}{2}$ particles from spin-0 targets, for which the familiar[1,7] depolarization parameter $D\equiv K_y^{y'}$ is equal to 1.0.

A schematic diagram of the experimental equipment is shown in Fig. 1. This apparatus is similar to that described earlier[8] and will therefore only be discussed briefly here. The polarization of the 0° neutrons was determined by scattering from $^4He$ contained in a high-pressure gas scintillation cell located approximately 100 cm from the target. A pair of NE102 plastic-scintillator side detectors was symmetrically placed at 120° (lab) at a center-to-center distance of about 19 cm and was used to detect the neutrons which scattered from $^4He$.

For the $^{12}C$ and $^{28}Si$ measurements solid targets attached to 0.3 mm thick tantalum beam stops were used. A 7.6 cm long gas cell with a 2.6 μm molybdenum entrance foil and 0.3 mm tantalum beam stop was used for the other experiments. Thick targets were chosen in order to provide a

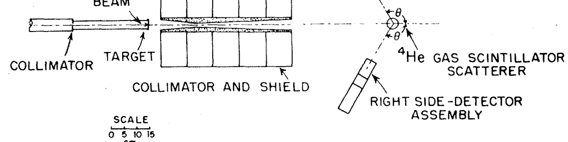


FIG. 1. Experimental arrangement for $K_y^{y'}(0°)$ measurements.

reasonable counting rate and to perform some energy averaging of the polarization transfer coefficients. Except for some of the $^{12}C(d,n)^{13}N$ measurements, where the energy loss was about 500 keV, the average energy loss in the targets was about 200 keV.

Data were accumulated in an alternating series of neutron spin-up and neutron spin-down sets, each taken for equal charge integration intervals. This procedure was followed in order to minimize false asymmetries. The neutron spin direction was changed from up to down by inverting the deuteron quantization axis at the polarized ion source, a method which minimizes beam movement on target during spin reversal. The incident deuteron polarization was measured at a beam stop upstream of the target after each pair of an "up-down" set by means of the quench ratio method.[9] The validity of the quench ratio technique for purely vector polarized deuteron beams was checked in a separate experiment. In that work we compared beam polarization values determined by deuteron elastic scattering[10] from $^4He$ at 12.0 MeV with those obtained from the quench ratio method. The quench ratio beam polarization agreed with that determined from $^4He(d,d)^4He$ to better than $\pm 0.010$.

The neutron polarization data in the $K_y^{y'}(0°)$ experiments were taken in two-parameter mode with each event consisting of the pulse height for a helium recoil in the gas scintillator and a time-of-flight signal for coincidence between pulses from the helium scintillator and one of the side detectors. The helium-recoil events were sorted into true and accidental categories according to gates set in the time-of-flight spectra using an on-line computer code. The computer also automatically monitored and controlled the direction of the deuteron spin at the polarized ion source and measured the beam polarization, i.e., the quench ratio. Typically, the beam polarization measurement was made about every 20 min and the spin inverted every 10 min. As most of the measurements required about 90 min for completion, these intervals seemed sufficiently short to eliminate problems associated with slow drifts in the beam polarization or in the detector electronics.

The helium-recoil spectra generated in this coincidence mode consisted of Gaussian-shaped peaks associated with the discrete neutron groups and an underlying, smoothly-varying background which was highly polarized. The background is illustrated in Fig. 2 which shows a representative spectrum

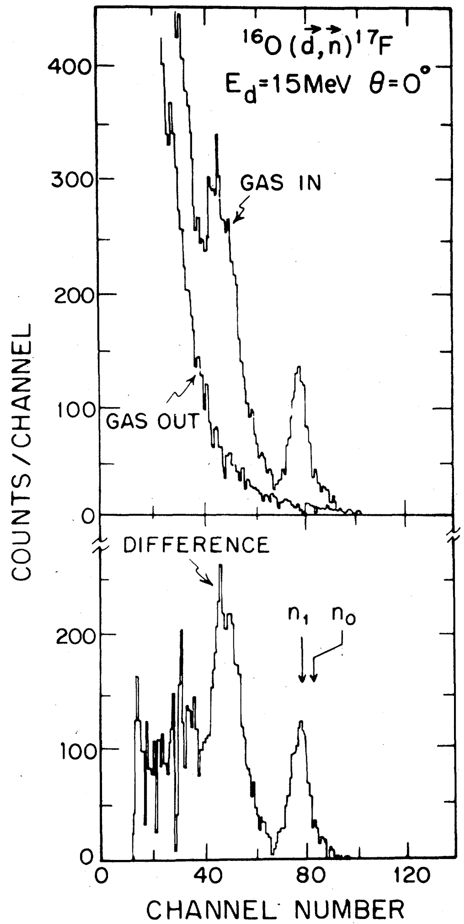


FIG. 2. Coincidence-gated $^4He$ recoil spectrum for $^{16}O(d,n)^{17}F$ obtained at $\theta=0°$ and $E_d=15$ MeV. The upper half shows the spectrum obtained with and without the $^{16}O$ gas in the cell. The lower half shows the spectrum after subtraction of the target-out background.

from the $^{16}O(\vec{d},\vec{n})^{17}F$ study. In this case the coincidence peak results from the unresolved $n_0+n_1$ neutron groups, which are separated by only 0.5 MeV. Background counts from the target assembly alone were observed to produce an approximately exponential tail extending throughout the entire region of interest of the gated recoil spectrum, as can be seen in Fig. 2. These background counts were observed to have large values for the neutron asymmetry $\epsilon$ defined as

$$\epsilon=\frac{r-1}{r+1},$$

where $r$ is the ratio of left to right detector counts, defined by the relation

$$r=\left[\left[\frac{N_L}{N_R}\right]_{\text{spin up}}\times\left[\frac{N_R}{N_L}\right]_{\text{spin down}}\right]^{1/2} .$$

Here $N_L$ and $N_R$ are the numbers of counts in the region of the peak for the left and right detectors, respectively.

The spectra for which "target-out" runs were obtained were analyzed with an off-line computer and carefully compared to the "target-in" spectra. This analysis included a computer program for subtracting a smooth, polarized background and for fitting Gaussian functions to the peaks of interest. It was found that the polarization of the background neutrons in the energy region of interest was identical (within statistics) to that of the main group of interest. From the systematic corrections obtained for the polarization of the main group, these analyses convinced us that the effect of the background from the target-out neutrons could be well estimated at nearby energies. Because of this feature and also because the contribution of the background to the peak of interest was at most about 20%, to avoid using the excessive accelerator time necessary to obtain target-out data for each energy and target, the target-out background measurements were only performed occasionally. [Our previous measurements[11] of neutrons produced in the breakup of deuterons on tantalum also showed very large values of $K_y^{y'}(0°)$. We therefore believe that the target-assembly related background was largely due to deuteron breakup in the tantalum beam stop.]

The lower half of Fig. 2 illustrates the difference of the upper two spectra. After subtraction of the gas-out from the gas-in spectra, a small, unpolarized tail still remains in the valley on the left side of the peak of interest. This remaining background probably arose both from room-scattered neutrons and gamma-ray interactions which led to valid coincidences. The analysis code for fitting the spectral shapes permitted us to estimate a correction for this tail.

Values of the neutron polarization $p_{y'} \pm \Delta p_{y'}$ were obtained by dividing the background corrected asymmetry $\epsilon \pm \Delta\epsilon$ by the polarimeter analyzing power. The $n+{}^4$He phase shifts of Lisowski[12] were used to calculate the geometry and multiple-scattering averaged analyzing power $A_y(120°)$ as a function of neutron energy. Results for $K_y^{y'}(0°)$ were finally obtained using Eq. (2). The errors assigned to the $K_y^{y'}(0°)$ data are largely statistical in origin, although the uncertainty does include the effects of the background subtraction and peak fitting procedures. The latter uncertainties were generally small compared to the statistical components.

In order to observe the relative amount of resonance contribution to the flux at forward angles in the ${}^{12}$C$(d,n){}^{13}$N reactions, yield measurements were made for a reaction angle of 0°. For this study, the unpolarized pulsed-beam facility of TUNL was employed. The target mounting and neutron collimator arrangement was very similar to that shown in Fig. 1. In place of the polarimeter, a 3.8 cm diameter by 2.5 cm thick cylindrical NE213 scintillator mounted on an RCA 8575 phototube was inserted on the collimator axis at a distance of 205 cm from the carbon target. A 0.91 mg/cm$^2$ thick carbon foil was used as the target; this foil is about 80 keV thick for 8.0 MeV deuterons.

Depending on the neutron energy, different biases for the pulses from the NE213 scintillator were used. For neutron energies below or above 4 MeV, biases corresponding to recoil proton energies of 1.3 MeV or 3.2 MeV, respectively, were used. A leading edge and crossover timing electronics arrangement served to provide pulse shape discrimination (PSD) against $\gamma$ rays, and both PSD and time-of-flight (TOF) information were stored on magnetic tape in 2-parameter mode by our computer. The time resolution was about 2 ns FWHM; as such, the $n_0$ and $n_1$ neutron groups were not completely resolved for the highest deuteron energies. An off-line data reduction program using a Gaussian least-squares fitting procedure was employed to unfold the TOF spectra. Background from time-uncorrelated sources and from the ${}^{12}$C$(d,n){}^{12}$C, $p$ reaction was subtracted and the corrected yield $Y$ from each computer-folded discrete neutron group was determined. The differential cross section was then calculated using the expression

$$\sigma(0°)=\frac{1}{\eta(E_n)}\frac{Y}{N_0 n\Omega} , \tag{3}$$

where $N_0$ is the number of bombarding deuterons (obtained from target current integration), $n$ is the number of ${}^{12}$C atoms/cm$^2$, and $\Omega$ is the detector solid angle. The efficiency $\eta(E_n)$ was determined by normalizing the results of a Monte Carlo calculation for our detector efficiency[13] to measured efficiency values obtained from neutron yields and available cross section data[14] for the ${}^2$H$(d,n){}^3$He reaction. This procedure allowed us to provide a good functional representation of our scintillator efficiency at energies between the measured points. The error in the efficiency which results from such a procedure is difficult to determine accurately, but we believe that the absolute efficiency is correct to within $\pm 15\%$. This estimate includes conservative estimates of the errors in the Monte Carlo calculation as well as in our experimental efficiency determination.

## III. RESULTS

### A. $^{12}C(d,n)^{13}N$ reactions

In the energy range from threshold to 12 MeV, the $^{12}C(d,n)^{13}N$ reaction and the mirror reaction $^{12}C(d,p)^{13}C$ exhibit considerable structure in the forward angle cross-section excitation functions. This structure must be due to compound nucleus effects or multistep processes in the interaction, so it is not surprising that DWBA calculations have never been able to describe suitably the angular dependences of the differential cross section, polarization, and analyzing power. On the other hand, the $^{12}C(d,n)^{13}N$ reaction has the interesting feature that although the magnitudes of the differential cross sections change appreciably with energy in the region of peaks in the excitation function, the angular dependences are not grossly altered from that of the characteristic $l_p=0$ and $l_p=1$ stripping shapes of the $^{12}C(d,n_0)$ and $^{12}C(d,n_1)$ reactions, respectively. We take this as an indication that a direct reaction mechanism predominates in this reaction.

Originally, a measurement of $K_y^{y'}(0°)$ was conducted for $^{12}C(\vec{d},\vec{n}_0)^{13}N$ because it was felt that such a measurement would aid in understanding the relative strengths of the reaction processes in the $d+{}^{12}C$ system. Because the $^{12}C(d,n_1)^{13}N^*$ reaction is an $l_p=0$ transfer which has a large yield at 0°, it was convenient to determine $K_y^{y'}(0°)$ values for this reaction also. Targets for the studies were either 1.4, 2.7, or 6.4 mg/cm$^2$ in thickness and the energy loss was kept between 120 and 420 keV.

The results are shown in Figs. 3–6. The cross sections are seen to vary by a factor of more than 1.3 in some regions. For the $^{12}C(d,n_0)$ case, about $\frac{2}{3}$ of the $K_y^{y'}(0°)$ values lie between 0.48 and 0.58, i.e., they lie between 70% and 90% of the value $\frac{2}{3}$. For the $^{12}C(d,n_1)$ case, the structure in the yield curve is less pronounced, and the values of $K_y^{y'}(0°)$ all lie between 83% and 100% of $\frac{2}{3}$. As shown in Fig. 5, the values of $K_y^{y'}$ near 6.6 and 7.0 MeV were measured with two different target thicknesses to verify the narrow structure. The set of measurements confirmed the observation that $K_y^{y'}$ does indeed dip to about 0.5 and rise to about 0.7 between 6.5 and 7.1 MeV.

The $^{12}C(d,n_1)$ data presented in Fig. 6 were verified by Tenhaken and Quin.[15] However, their target thickness was 5 mg/cm$^2$, which makes it impossible to compare exactly their $^{12}C(d,n_0)$ data to ours at low energies where the narrow structure exists in the $K_y^{y'}(0°)$ parameter. Qualitatively, there is good agreement except for their 7.2 MeV datum which falls two standard deviations below our point.

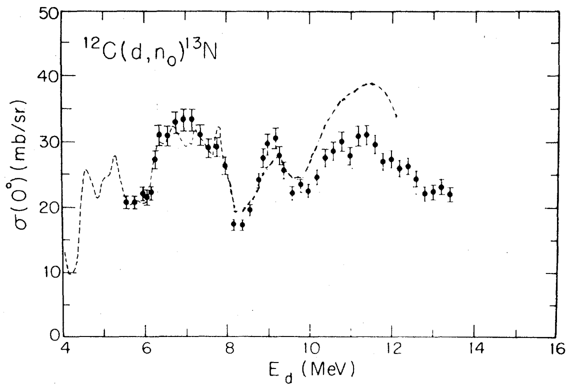


FIG. 3. Zero-degree differential cross section data for $^{12}C(d,n_0)^{13}N$. The data are compared to the results of Davis and Din (Ref. 18) which are represented by the dashed curve.

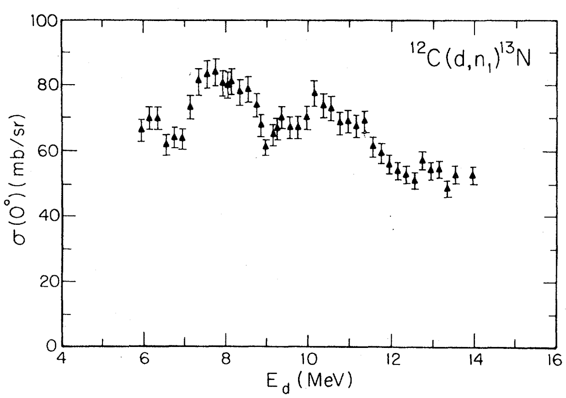


FIG. 4. Zero-degree differential cross section data for $^{12}C(d,n_1)^{13}N$.

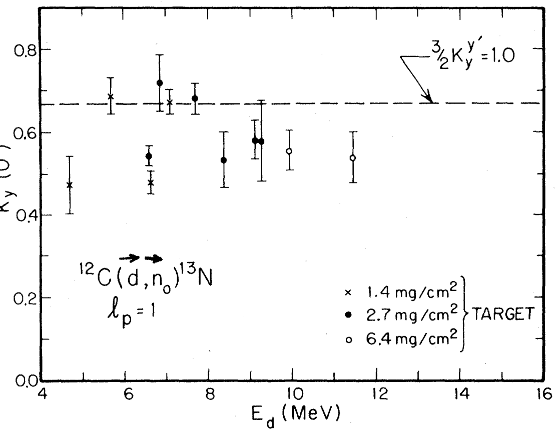


FIG. 5. Measured values of the vector polarization transfer coefficient $K_y^{y'}$ (0°) for the ground state transition in $^{12}C(\vec{d},\vec{n})^{13}N$.

### B. The $^{14}N(d,n)^{15}O$, $^{16}O(d,n)^{17}F$, and $^{28}Si(d,n)^{29}P$ reactions

For each of the reactions $^{14}N(d,n)^{15}O$, $^{16}O(d,n)^{17}F$, and $^{28}Si(d,n)^{29}P$ the dominant contribution to the observed neutron groups was an $l_p=0$ stripping process. The first two reactions, however, do contain some contribution from other stripping processes and will be discussed below.

In the case of $^{14}N(d,n)^{15}O$, the neutron groups leading to the ground state and first three excited states of $^{15}O$ contribute little to the zero degree yield, primarily because they are $l_p=1$ or 2 transfer reactions.[16] A spectrum obtained with 7.7 MeV deuterons is shown in Fig. 7. The dominant peak results largely from the $n_4$ neutron group, i.e., the group which leaves $^{15}O$ in the fourth excited state at 6.79 MeV. This group is produced in an $l_p=0$ reaction.[16] The shoulder on the low energy side of the peak is at the proper energy for the next $l_p=0$ reaction, which leaves $^{15}O$ in the seventh excited state at 7.55 MeV. The $n_5$ and $n_6$ neutron groups could also have been detected, but they are produced in $l_p=2$ transfer reactions and should contribute significantly less to the yield at 0° than the $l_p=0$ groups.

A similar condition was involved in the $^{16}O(d,n)^{17}F$ study, where our polarimeter was unable to resolve the $l_p=0$ first excited state neutron group from the $l_p=2$ ground state neutron group which is 500 keV away in energy. As in the case of $^{14}N(d,n)^{15}O$, it was not possible to completely unfold the spectrum. However, in each of the above cases, because of the relatively low intensity resulting from the competing neutron groups[17] and because of our choices of summing windows in the gated recoil spectra, the polarization transfer coefficients result almost entirely from $l_p=0$ neutron groups.

The results are shown in Fig. 8. All of these reactions exhibit $K_y^{y'}$ (0°) values which have a

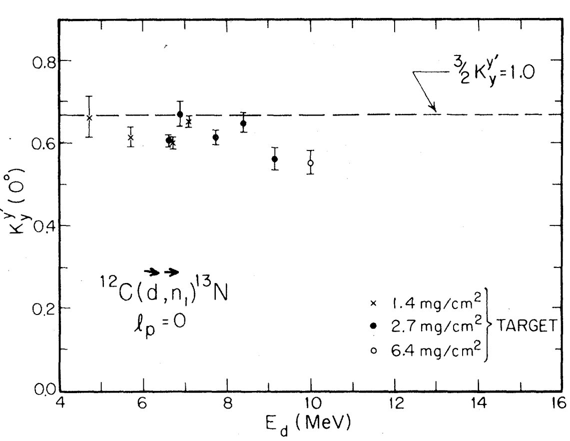


FIG. 6. Measured values of the vector polarization transfer coefficient $K_y^{y'}$ (0°) for the first excited state transition in $^{12}C(\vec{d},\vec{n})^{13}N$.

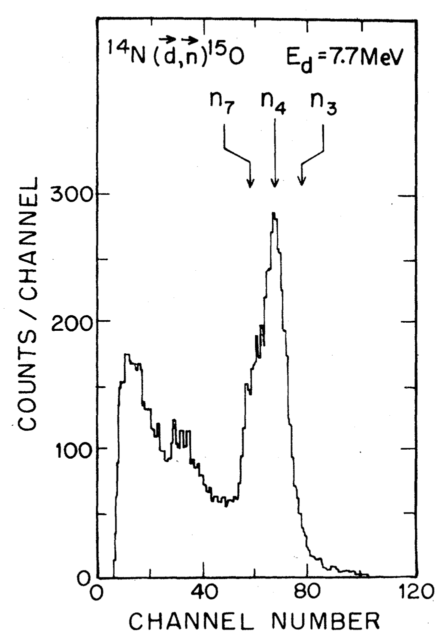


FIG. 7. Coincidence-gated $^4He$ recoil spectrum for $^{14}N$ $(d,n)^{15}O$ obtained at $\theta=0°$ and $E_d=7.7$ MeV. The arrows indicate the location of $l_p=1$ or $l_p=0$ transitions in the region of the peak as discussed in the text.

structureless energy dependence and are near $\frac{2}{3}$. Other than those results discussed in Ref. 15 (and our preliminary reports),[4,5,19] the only previously reported data[20] in this mass region are for $^{28}Si(\vec{d},\vec{p})^{29}Si$ at 12.1 MeV. In that case $K_y^{y'}(0°)$ was also seen to be large (0.67±0.07).

## IV. DISCUSSION

### A. Introduction

Theoretical investigations of polarization transfer effects in $(\vec{d},\vec{n})$ reactions have generally taken one of two approaches: a simple spectator model or a distorted-wave Born approximation (DWBA). In the former, the neutron is considered to be just a spectator to the reaction. Neglecting *D*-state effects in the model, one obtains a value of $K_y^{y'}(0°)=\frac{2}{3}$, which means that the emitted neutron beam has a (transverse) polarization equal to the vector polarization of the incident deuteron beam. An estimate of the effect of the deuteron *D* state was made by Broste *et al.*,[21] who discussed the spin polarization of the "neutron in the deuteron" in a static approximation, i.e., no dynamics of the nuclear reaction were considered. Their calculation showed that if there were no reaction-dependent polarization effects, the spectator neutron would emerge with a polarization of 1.0-$(\frac{3}{2})P_D$, where $P_D$ is the *D*-state probability. Therefore, in this spectator model the presence of the *D* state with a 6% probability decreases the polarization transfer coefficient from $\frac{2}{3}$ to about $\frac{3}{5}$. We will comment briefly on this naive model at the end of Sec. IV.

The main interest in the present paper is to approach calculations of polarization transfer coefficients in deuteron stripping reactions in a more exact formalism. We do this through the use of the polarization tensor formalism,[22] in which case the polarization observables can be separated into terms that have definite spin transfer. The $K_y^{y'}(0°)$ values obtained in the present experiment are analyzed using this method and are compared with a few resulting DWBA calculations.

### B. Polarization tensor formalism and the DWBA

The study of polarization transfer effects is conveniently made using the polarization tensors $M_{kq}^{ss'}$ defined in Eq. (7) of Ref. 22. These tensors are model-independent quantities which have definite

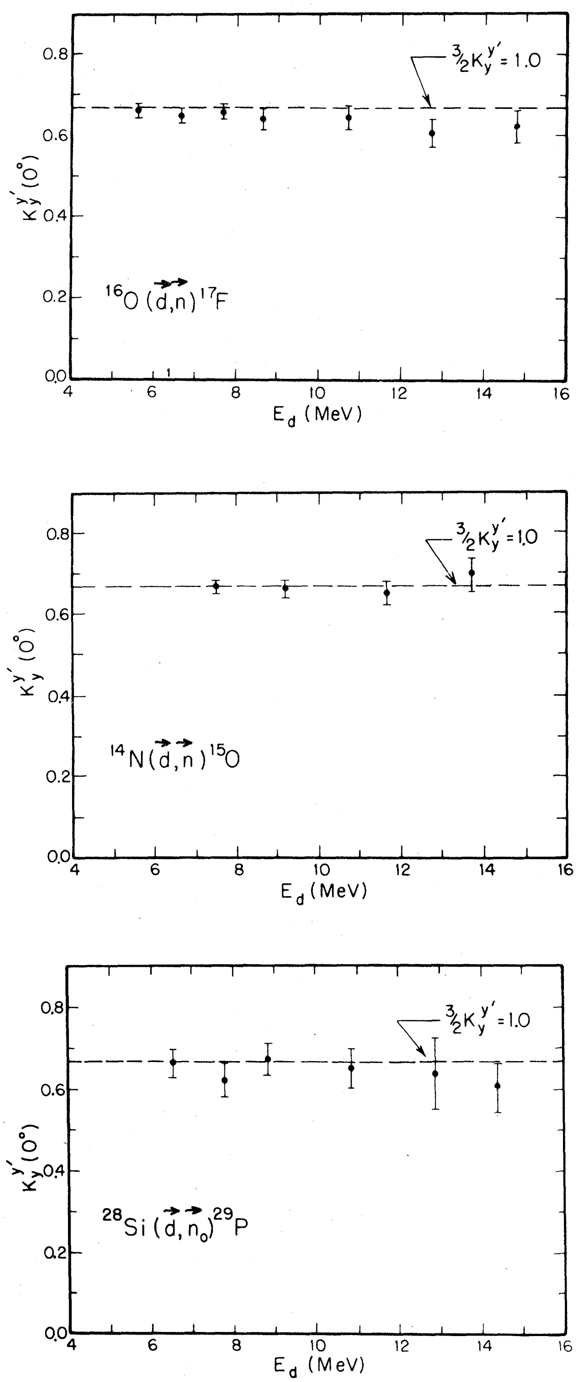


FIG. 8. Zero-degree vector polarization transfer data for the $^{14}N(\vec{d},\vec{n})^{15}O$, $^{16}O(\vec{d},\vec{n})^{17}F$, and $^{28}Si(\vec{d},\vec{n})^{29}P$ reactions.

spin transfer[23] quantum numbers $s$ and $s'$; in deuteron stripping reactions the spin transfer is either $\frac{1}{2}$ or $\frac{3}{2}$. In the DWBA, assuming no spin-dependent distortions, there is a one-to-one correspondence between the $s=\frac{1}{2}$ and $s=\frac{3}{2}$ values and the contributions from the deuteron $S$ state and $D$ state to the transition matrix. Furthermore, it follows that if both spin-dependent distortions and deuteron $D$-state effects are neglected, then the only allowed value of spin transfer is $s=\frac{1}{2}$. In other words, the $s=\frac{3}{2}$ transfer can only arise from spin-dependent forces which might act in the reaction entrance and exit channels or between the nucleons in the deuteron.

It is important to note another basic connection. The tensors of the form ${M_{kq}}^{1/2\,3/2}$ should have large $D$-state effects because these terms result mainly from the interference between the $S$-state amplitude and the smaller $D$-state amplitude. Generally, the tensors of the form ${M_{kq}}^{3/2\,3/2}$ should be smaller than the ${M_{kq}}^{1/2\,3/2}$ since they involve the square of the $D$-state amplitude.

The reaction cross section $\sigma(\theta)$ for an unpolarized incident beam, being a scalar quantity, is necessarily a linear combination of the scalars ${M_{00}}^{1/2\,1/2}$ and ${M_{00}}^{3/2\,3/2}$ corresponding to pure spin transfers $\frac{1}{2}$ and $\frac{3}{2}$. In fact, $\sigma(\theta)$ is given by the relation[22]

$$\sigma(\theta)\propto {M_{00}}^{1/2\,1/2}+\sqrt{2}{M_{00}}^{3/2\,3/2} \qquad (4)$$

apart from kinematical and statistical factors. The observable[22]

$$\begin{aligned} I&=\tfrac{1}{2}(K_x^x+K_y^y+K_z^z)\\ &=({M_{00}}^{1/2\,1/2}-{M_{00}}^{3/2\,3/2}/\sqrt{2})\\ &\quad\times({M_{00}}^{1/2\,1/2}+\sqrt{2}{M_{00}}^{3/2\,3/2})^{-1} \end{aligned} \qquad (5)$$

is also a function of ${M_{00}}^{1/2\,1/2}$, ${M_{00}}^{3/2\,3/2}$, and of no other polarization tensor components. This relationship means that the quantity $I$ measures the relative importance of the $s=\frac{1}{2}$ and $s=\frac{3}{2}$ transfers in the cross section, and hence, $I$ plays an important role in the analysis of the mechanism of deuteron stripping reactions. Equation (4) shows that the ratio of the $s=\frac{3}{2}$ to the $s=\frac{1}{2}$ cross section can be conveniently expressed as

$$R=\sqrt{2}{M_{00}}^{3/2\,3/2}/{M_{00}}^{1/2\,1/2}\ . \qquad (6)$$

By substitution of Eq. (6) into Eq. (5) we obtain

$$I=\frac{1-R/2}{1+R}\ . \qquad (7)$$

This equation shows that $I$ varies between the extreme values of $-\frac{1}{2}$ and 1, corresponding to pure $s=\frac{3}{2}$ ($R=\infty$) and pure $s=\frac{1}{2}$ ($R=0$), respectively. To determine $I$, it is necessary to measure the three vector polarization transfer coefficients, except at $\theta=0°$ and 180°, where only two are required since $K_x^x=K_y^y$. It should be noticed that the polarization transfer coefficients $K_i^i$ in Eq. (5) are referred to the same coordinate systems for the description of the polarization of both the incoming and outgoing beams. Usually,[1] separate helicity frames are chosen for both the incoming and outgoing beams in the reaction. At $\theta=0°$ the two frames (unprimed and primed coordinate axes) coincide, and, therefore, $K_x^x(0°)=K_x^{x'}(0°)$, $K_y^y(0°)=K_y^{y'}(0°)$, and $K_z^z(0°)=K_z^{z'}(0°)$. For $\theta\neq 0°$ the $K_i^{i'}$ have to be rotated in order to obtain the $K_i^i$.

Approximate relations beween the various polarization observables can be obtained by assuming that some of the $M_{kq}^{ss'}$ vanish. In low energy $(d,p)$ and $(d,n)$ reactions the deuteron $D$-state effects are much smaller than the deuteron $S$-state effects; hence, we may assume that ${M_{20}}^{3/2\,3/2}={M_{22}}^{3/2\,3/2}=0$. This approximation implies that

$$K_i^i=\tfrac{2}{3}(I+\tfrac{1}{2}A_{ii})\ ,\quad i=x,y,z\ , \qquad (8)$$

where $I$ is given in Eq. (5). This result is central to the discussion of our $K_y^y(0°)$ results in terms of this formalism. [We point out that the expression in Eq. (8) is a corrected version of the one given in Eq. (83) in Ref. 22. It should be noted that in this reference some of the numerical coefficients in Eqs. (59) and (60) are incorrect due to an error in a table used to evaluate the $9j$ symbols of Eq. (17) and (19). An erratum is being prepared by the author.]

The relations (8) can be simplified a step further by putting ${M_{00}}^{3/2\,3/2}=0$ in Eq. (5); this leads to $I=1$. However, this step is generally a less reliable approximation than that leading to Eq. (8), because it neglects all $s=\frac{3}{2}$ contributions to the cross section. In this limit, however, $I=1$ and then Eq. (8) becomes

$$K_i^i=\tfrac{2}{3}(1+\tfrac{1}{2}A_{ii})\ ,\quad i=x,y,z\ . \qquad (9)$$

Using the exact relations[1] $A_{zz}(0°)=-2A_{yy}(0°)=-2A_{xx}(0°)$, we obtain from Eq. (9)

$$K_x^{x'}(0°)=K_y^{y'}(0°)=\tfrac{2}{3}[1-\tfrac{1}{4}A_{zz}(0°)]\ , \qquad (10a)$$

$$K_z^{z'}(0°)=\tfrac{2}{3}[1+\tfrac{1}{2}A_{zz}(0°)]\ . \qquad (10b)$$

Actually, it has been previously shown[1] that the relation (10b) is exact in the particular case of reactions with the spin structure $\frac{1}{2}(1, \frac{1}{2})0$. Finally, we note that in the extreme case of pure spin transfer $\frac{1}{2}$, only $M_{00}{}^{1/2\,1/2}$ is nonzero and Eq. (59) of Ref. 22 immediately gives the simple result

$$K_i^i = \frac{2}{3}\ , \quad i = x,y,z\ . \tag{11}$$

This result can also be obtained from Eq. (10) above by substitution of $A_{zz}(0°)=0$, as required by $A_{zz}=\sqrt{2}T_{20}$ (from Ref. 1) and $T_{2q}=0$ [from Eq. (59) of Ref. 22 for pure spin transfer $\frac{1}{2}$].

### C. Application to the $^2$H$(d,n)$ and $^3$H$(d,n)$ reactions

Before turning to the data reported in the present paper, we will apply these relations to two cases involving light nuclei for which fairly complete data sets have been obtained and note the implications for the relative contribution of $s=\frac{1}{2}$ and $s=\frac{3}{2}$ transfers. In fact, the $^2$H$(d,n)^3$He and $^3$H$(d,n)^4$He reactions are the only presently available cases where the data sets are sufficiently complete for checking the above spin transfer model. We note that $I(0°)=0.505\pm0.031$ in the $^3$H$(d,n)^4$He reaction at 7 MeV,[24] and $I(0°)=0.853\pm0.028$ in the $^2$H$(d,n)^3$He reaction at 10 MeV.[25] Using these measured values of $I(0°)$ and Eq. (7), we obtain for the ratio $R(0°)$ of the $s=\frac{3}{2}$ to the $s=\frac{1}{2}$ cross section the values 0.1 in the $^2$H$(d,n)^3$He reaction and 0.5 in the $^3$H$(d,n)^4$He reaction, which indicates that at forward angles the spin transfer $\frac{3}{2}$ is considerably stronger in the latter reaction.

In the $^2$H$(d,n)^3$He reaction the experimental values of Salzman *et al.*[25] for $A_{yy}(0°)$, $K_y^{y'}(0°)$, and $K_z^{z'}(0°)$ at 10 MeV are quite well described by Eq. (8) for $K_y^{y'}(0°)$. That is,

$$K_y^{y'}(0°)=\frac{2}{3}[I(0°)+\frac{1}{2}A_{yy}(0°)]\ . \tag{12}$$

Furthermore, if it is assumed that $I(0°)$ is constant with energy and equal to the measured value[26] at 10 MeV, we can use Eq. (12) to compare with the existing $K_y^{y'}(0°)$ data[26] from 4–15 MeV. Using $I(0°)=0.853$ as above and taking the measured value $A_{zz}(0°)=-2A_{yy}(0°)=-0.461$ of Lisowski *et al.*,[26] which describes the data for deuteron energies between 3 and 15 MeV, we obtain from Eq. (12)

$$K_y^{y'}(0°)=0.646\pm0.019\ .$$

This result is in good agreement with the $K_y^{y'}(0°)$ measurements of the same Ref. 26.

The successful application of the model in these two reactions indicates that the measurement of $I(\theta)$ in other reactions should provide useful information on the reaction mechanism of deuteron stripping reactions, since $I(\theta)$ distinguishes in the cross section the effects of interactions that depend on spin from those that do not depend on spin.

### D. Present data and *D*-state effects

Switching now to the data reported in the present paper, the fact that $K_y^{y'}(0°)$ is experimentally observed to be close to the value $\frac{2}{3}$ is a clear indication that the spin transfer is predominantly $\frac{1}{2}$ at forward angles in all the reactions. This result can be understood in the context of the DWBA by noting that at forward angles the spin-dependent distortion is generally small at our energies.[27] Furthermore, deuteron *D*-state effects are known to be relatively small for low momentum transfer, especially in $l_p=0$ transitions. As shown by Eqs. (7) and (8), the importance of *D*-state effects on $K_y^{y'}$ depends crucially on the relative magnitudes of the $s=\frac{1}{2}$ and $s=\frac{3}{2}$ cross sections. Since $M_{00}{}^{1/2\,1/2}$ tends to have more pronounced oscillations as a function of scattering angle than $M_{00}{}^{3/2\,3/2}$, observable *D*-state effects on $K_y^{y'}$ will be more likely in the minima of the $s=\frac{1}{2}$ cross section.[20] As a result, because of the forward stripping peak for $l_p=0$ reactions, it is expected that *D*-state effects on $K_y^{y'}(0°)$ are relatively small.

It is known from extensive DWBA calculations[27,28] that in low energy deuteron stripping reactions the magnitude of deuteron *D*-state effects on the reaction transition matrix is determined by the parameter $D_2$, which is approximately given by

$$D_2 \simeq \rho_D/\alpha^2\ . \tag{13}$$

Here $\rho_D$ is the ratio of the asymptotic *D*-state component to the *S*-state component of the deuteron wave function and $\alpha$ is the deuteron wave number. Hence, the magnitude of deuteron *D*-state effects on the cross section and polarization observables is also, of course, essentially determined by $D_2$.

Although the plane-wave Born approximation (PWBA) is an oversimplified model which is unreliable for detailed quantitative data analysis, it nevertheless provides a simple expression for $K_y^{y'}(0°)$ which is useful for discussing *D*-state effects in a qualitative way. In the plane-wave limit we obtain

$$K_y^{y'}(0°)=\tfrac{2}{3}[1+(1/\sqrt{2})\Delta-\Delta^2]/(1+\Delta^2)\ , \quad (14)$$

where $\Delta$ is the ratio in momentum space of the radial part of the $D$ state to the $S$ state in the deuteron.[29] For low momentum transfer, one obtains

$$\Delta=D_2(\tfrac{1}{2}\vec{k}_d-\vec{k}_n)^2\ , \quad (15)$$

where $\vec{k}_d$ and $\vec{k}_n$ are the asymptotic momenta. Equation (14) clearly shows that the $D$ state may either decrease or increase $K_y^{y'}(0°)$ from the value $\frac{2}{3}$, depending on the value of $\Delta$. The term linear in $\Delta$ in the numerator of Eq. (14) arises from the interference between the deuteron $S$- and $D$-state amplitudes and, therefore, is the result of a *coherent* $D$-state effect. The $\Delta^2$ term results from an *incoherent* $D$-state effect, since $\Delta^2$ is proportional to the square of the $D$-state amplitude. Since at low energies $\Delta<1$, the coherent $D$-state effects, therefore, tend to be larger than the incoherent effects in spite of the $1/\sqrt{2}$ factor in Eq. (14). In fact, for $0<\Delta<\sqrt{2}/4$, $K_y^{y'}(0°)$ exceeds the value $\frac{2}{3}$. Using the Yamaguchi wave function to calculate $\Delta$ in the way described in the Ref. 29, we obtained values of $K_y^{y'}(0°)$ slightly greater than $\frac{2}{3}$ for all the reactions studied here.

More realistic calculations for the $^{28}$Si$(\vec{d},\vec{n}_0)^{29}$P and $^{16}$O$(\vec{d},\vec{n}_1)^{17}$F reactions using the DWBA formalism in the computer code DWCODE[30] gave $K_y^{y'}(0°)$ values which are all very close to $\frac{2}{3}$. Figure 9 shows the results of DWBA calculations for the $^{28}$Si$(\vec{d},\vec{n}_0)^{29}$P reaction using deuteron optical potentials obtained from the adiabatic model of Johnson and Soper[31] and neutron optical potentials of Becchetti and Greenlees.[32] We find in this reaction that for deuteron energies between 6 and 16 MeV the effect of the $D$ state is to increase $K_y^{y'}(0°)$ by about 2% to 3%. In the $^{16}$O$(\vec{d},\vec{n}_1)^{17}$F reaction at 12.3 MeV the inclusion of $D$-state effects decreases $K_y^{y'}(0°)$ by 1%. Such apparent insensitivity of the calculation to $D$-state effects indicates that the more difficult studies at angles other than $\theta=0°$ will be necessary if one desires to probe the details of such effects in $(d,n)$ polarization transfer.

It should be noted that the spectator model of polarization transfer in deuteron stripping reactions is based on a misleading oversimplification of the reaction mechanism. The model provides a relation between the $D$-state probability $P_D$ and $K_y^{y'}(0°)$, which is erroneous in that, at low energy,

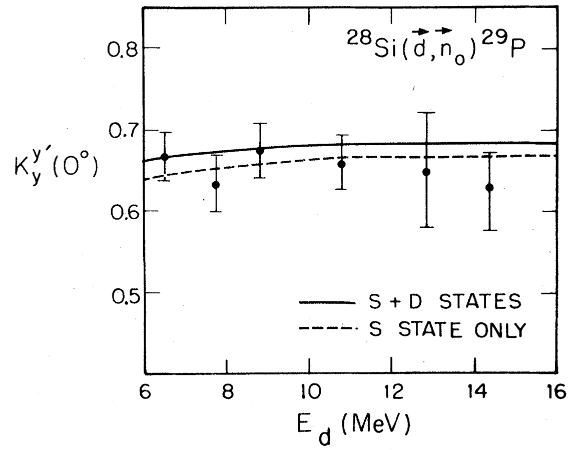


FIG. 9. Comparison of DWBA calculations for $K_y^{y'}(0°)$ in the $^{28}$Si$(\vec{d},\vec{n}_0)^{29}$P reaction. The solid curve includes the effects of the deuteron $S$ and $D$ states while the dashed curve is obtained neglecting the $D$ state.

the deuteron $D$-state effects on $K_y^{y'}$ are actually determined by $D_2$, not by $P_D$. Also, in the spectator model the $D$ state can only decrease $K_y^{y'}(0°)$ from the value $\frac{2}{3}$, which is inconsistent with both the simple PWBA result of Eq. (14) and with the more exact results of DWBA calculations.

## V. SUMMARY

The present paper reports a set of studies of $K_y^{y'}(0°)$ for $(d,n)$ reactions on several light nuclei. The experiments are difficult, but a method for obtaining this observable in a reasonable length of time has been developed.

The overall consistency of the values is indicated in Fig. 10, which presents all of our $l_p=0$ data along with a curve which represents a least-squares fit to our earlier $^2$H$(\vec{d},\vec{n})^3$He data.[26] In general, the data follow the results of the $^2$H$(\vec{d},\vec{n})^3$He reaction quite closely.

It is evident from Fig. 10 that over a wide range of exit neutron energies, compound nucleus excitation energies, and target masses, there is little variation in $K_y^{y'}(0°)$. This behavior suggests that the polarization transfers at $\theta=0°$ reported here are largely a result of direct reaction mechanism effects. Since the analysis of the present measurements using the spin transfer formalism shows that the dominant spin transfer at 0° is $s=\frac{1}{2}$, in the context of the DWBA this confirms that spin-dependent distortion and deuteron $D$-state effects

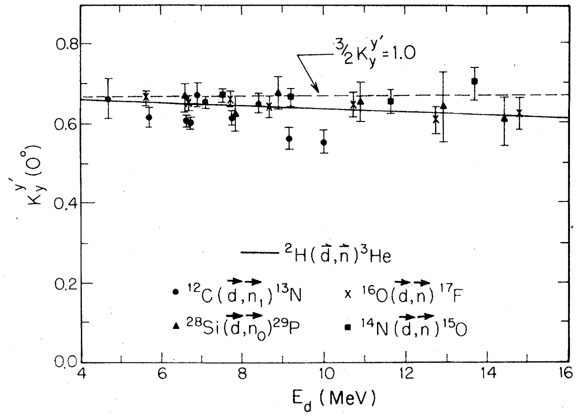


FIG. 10. Zero-degree vector polarization transfer data for $l_p=0$ transitions in several $(\vec{d},\vec{n})$ reactions. The solid line was obtained using the $K_y^{y'}(0°,E_d)$ parametrization for the $^2H(\vec{d},\vec{n})^3He$ reaction from Ref. 26.

are small in the forward direction. We note with interest that while the DWBA predictions give $K_y^{y'}(0°)\simeq\frac{2}{3}$, the data, particularly at the higher deuteron energies, tend to favor values of $K_y^{y'}(0°)$ which are smaller than $\frac{2}{3}$. This apparent discrepancy is probably due to an inadequate treatment of the $s=\frac{3}{2}$ contributions to the reaction transition matrix in the DWBA. In particular, it may be related to inadequate representations for the energy dependence of the optical model potential parameters, especially those for the spin-orbit terms.

We also call attention to the observed drop in the value of $K_y^{y'}(0°)$ near some of the resonances in the $^{12}C(d,n)_0)^{13}N$ reaction, which is an $l_p=1$ transfer. The nature of the resonances in this energy range is not understood at the present; if better data of all types could be obtained in this region for this reaction, one might be able to make some unique tests with improved $K_y^{y'}(0°)$ data. On the other hand, it is difficult to increase the quality as well as the quantity of data reported here, and it probably will be a few years before one would be willing to attempt a higher resolution and higher accuracy experiment of this type.

In closing, we make the observation that measurements of all three vector polarization transfer coefficients $K_x^{x'}$, $K_y^{y'}$, and $K_z^{z'}$ would be particularly useful, since these then directly determine the observable $I$. The determination of $I$, and especially of its angular distribution, is of special interest because it makes possible the specific study of the effect of spin-dependent interactions in the reaction.

This project was supported in part by the U. S. Department of Energy.

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