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$K_y^{y'}(0°)$ for ^{3}He$(d,p)^4$He near the $J^\pi=\frac{3}{2}^+$ resonance

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The polarization transfer coefficient $K_y^{y'}(0°)$ has been measured for the ^{3}He$(d,p)^4$He reaction at energies of 520, 890, and 1490 keV. The measured values are $\approx -2/3$, consistent with expectations based on the presence of a broad $J^\pi=\frac{3}{2}^+$ resonance at $E_d=430$ keV. A comparison with data taken at somewhat higher energies reveals a large change in this observable as the reaction becomes dominated by direct neutron transfer.

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Detailed information on the relative role of processes such as resonance capture and direct nucleon transfer is useful in describing low-energy reaction cross sections of interest in nuclear physics and nuclear astrophysics. For some of these reactions, it is difficult to experimentally determine this information directly, and the description of the reaction process often must rely on theoretical models.

Nuclear polarization measurements complement cross section measurements because polarization observables provide additional constraints on the scattering matrix elements. For some special cases, such as the low-energy ^{3}He$(d,p)^4$He reaction, polarization measurements can actually be used to determine the relative importance of competing reaction mechanisms.

At deuteron energies below 1 MeV, the ^{3}He$(d,p)^4$He reaction is dominated by a broad, $\frac{3}{2}^+$ S-wave resonance in ^{5}Li at $E_d=430$ keV. The assumption that the reaction proceeds via this single resonance yields well-defined predictions for the observables [1]. However, measurements of cross sections [2–5] and analyzing powers [6–10] at low energies cannot be explained by this assumption alone. This is especially true for the polarization observables. For example, in the recent measurements of Geist *et al.* [6], the tensor analyzing power data deviate from the S-wave resonance predictions by as much as 20% at some angles and the vector analyzing powers are nonzero. These discrepancies presumably result from the presence of additional $L\leq 2$ reaction channels that compete with the dominant resonance and may arise from direct transfer mechanisms or from the tails of distant resonances. Additional experiments are required to identify the non-S-wave processes.

In this paper we present the results of the first measurements of the polarization transfer observable $K_y^{y'}(0°)$ at energies near the resonance. For this reaction under the experimental conditions described below, the observable $K_y^{y'}(0°)$ is related to the vector polarization of the deuteron beam $p_Z^{(d)}$ and the polarization of the outgoing protons $p_Z^{(p)}$ via

$$K_y^{y'}(0°)=\frac{2}{3}\frac{p_Z^{(p)}}{p_Z^{(d)}}. \quad (1)$$

The $K_y^{y'}(0°)$ observable was chosen because it was expected to be somewhat sensitive to the relative importance of these two reaction mechanisms. This can be shown using a simplistic S-wave scattering model with deuterons in the S state for two extreme cases: pure S-wave resonance and direct neutron transfer. In each case, the deuteron beam is assumed to be polarized along the axis normal to the reaction plane, with $m_j=+1$. If the reaction is assumed to proceed entirely through the S-wave $\frac{3}{2}^+$ resonance, then the deuterons can only interact with the ^{3}He target nucleus with $m_j=+1/2$. In this case, the proton and α particle would be ejected in a relative D state, with the m_j of the proton equal to $-1/2$. For this $\frac{3}{2}^+$ resonance case, the incident deuterons are spin-up and the emitted protons are spin-down, resulting in a polarization transfer coefficient of $-2/3$ [11]. Conversely, if the reaction mechanism proceeds through the direct transfer of a neutron as in the simple stripping model [12], then the $m_j=+1$ deuteron must react with a ^{3}He target nucleus with $m_j=-1/2$ in order to form a spin-0 α particle. The remaining proton would have $m_j=+1/2$, and the polarization transfer coefficient would be positive. This model ignores the possible contributions from higher order partial waves; in particular, the deuteron D state also affects

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$K_y^{y'}(0°)$ [12]. However, this heuristic model does suggest the utility of the polarization transfer measurement for reaction model studies.

The present measurements complement earlier measurements [13] of $K_y^{y'}(0°)$ made from 4 to 14 MeV. A similar study was made of the $^3\mathrm{H}(d,n)^4\mathrm{He}$ reaction in which $K_y^{y'}(0°)$ was measured at energies from 3.9 to 15 MeV [14]. Here the influence of the $\frac{3}{2}^+$ S-wave resonance was evident at the lower energies. At higher reaction energies in both polarization transfer-reaction studies, direct transfer competes with the $\frac{3}{2}^+$ S-wave resonance mechanism.

The low-energy $K_y^{y'}(0°)$ data were obtained using polarized deuteron beams from the atomic beam polarized ion source [15] at Triangle Universities Nuclear Laboratory, via a three polarization state method with fast state switching [16]. The deuterons were accelerated through the tandem Van de Graaff accelerator. The beam energy was determined via an analyzing magnet system with an energy-calibrated NMR magnetometer. The deuteron beam polarization was measured in the same scattering chamber as the $^3\mathrm{He}(d,p)^4\mathrm{He}$ measurements, as described below. Typically the deuteron vector polarizations $p_Z^{(d)}$ were -0.60 for one of the polarized states and $+0.42$ for the other polarized state. A 2.54-cm-diameter cylindrical gas cell with 6-μm Havar foil walls was mounted at the center of the chamber and filled with $^3\mathrm{He}$ to a pressure of 2.0 atm. In addition, the target cell could be raised out of the beam path as needed. Because the deuteron beams were stopped in the exit foil of the gas cell, the cell was electrically isolated from the chamber, and the incident charge was integrated to determine the total beam intensity. The polarization of the outgoing protons was determined using a $^4\mathrm{He}(p,p)^4\mathrm{He}$ proton polarimeter [17]. This proton polarimeter was mounted on a plate that could be rotated to position it directly behind the gas cell (at $0°$) or completely out of the beam path.

For the lowest-energy measurement, the deuteron beam was accelerated to an energy of 1.58 MeV. After passing through the scattering chamber entrance slits, the deuterons passed through a 20-μg/cm^2 carbon foil oriented at 45°. On either side of the carbon foil, at the 90° position, 300-μm surface barrier detectors were mounted so that the $^{12}\mathrm{C}(d,p)^{13}\mathrm{C}$ reaction could be used to determine the deuteron beam polarization. At this beam energy, the effective analyzing power for the $^{12}\mathrm{C}(d,p)^{13}\mathrm{C}$ polarimeter was measured to be $+0.429\pm0.005$, based on a cross calibration using a deuteron polarimeter [18] mounted behind the scattering chamber. This value for the effective analyzing power agrees with that for a similar device [19] at this energy. At this beam energy, the deuteron and proton polarizations were measured simultaneously.

After passing through the deuteron polarimeter, the beam entered the $^3\mathrm{He}$ target gas cell at the center of the chamber. The computer code SRIM-2000.39 [20] was used to estimate the energy losses of the deuterons through the carbon foil, the Havar gas cell wall, and throughout the interior of the gas cell. The Havar foil was modeled using elemental concentrations given in Ref. [22]. For this lowest-energy data the pressure in the $^3\mathrm{He}$ target cell was 1 atm. The reaction energy was determined by weighting the energy at each step within the gas cell by the $^3\mathrm{He}(d,p)^4\mathrm{He}$ cross section. For deuterons entering the scattering chamber at 1.58 MeV, the reaction energy in the gas cell was found to be 520 ± 40 keV, where the uncertainty represents the spread in energy calculated by SRIM-2000.39.

Protons produced at $0°$ by the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction passed through the Havar gas cell window, and entered the proton polarimeter through a 300-μm silicon Δ-E detector and a 50.8-μm stainless steel entrance foil. Using SRIM-2000.39, the proton energy was determined to be 13.8 MeV, giving an effective analyzing power at this energy of -0.623 ± 0.014 for the proton polarimeter.

A second set of data was taken with a deuteron beam energy of 1.90 MeV. The cross-section weighted reaction energy was determined to be 890 ± 40 keV for this case, where the pressure in the $^3\mathrm{He}$ gas cell was 2 atm. At 1.90 MeV, the effective analyzing power for the $^{12}\mathrm{C}(d,p)^{13}\mathrm{C}$ deuteron beam polarimeter was found to be rather small (-0.135 ± 0.003), so to measure the deuteron beam polarization for these runs, a 25-μm Havar foil was rotated in front of the deuteron polarimeter to degrade the beam energy to about 1.62 MeV, where the effective analyzing power was measured to be $+0.461\pm0.005$. This value was consistent with that for a similar polarimeter calibrated at a beam energy of 1.62 MeV with no foil in place [21], indicating that there was no depolarization within the Havar foil. Although the deuteron and proton polarizations were not measured simultaneously in this case, the deuteron polarization runs were interspersed with proton polarization measurements to compensate for any long-term variations in beam polarization. The energy of the protons entering the proton polarimeter was 14.6 MeV, corresponding to an analyzing power of -0.609 ± 0.014.

The beam energy for the third set of measurements was 2.30 MeV, corresponding to a reaction energy of 1490 ±30 keV within the 2-atm $^3\mathrm{He}$ gas cell. As in the second set of measurements, the effective analyzing power of the $^{12}\mathrm{C}(d,p)^{13}\mathrm{C}$ polarimeter was too low (-0.088 ± 0.003) for a good measurement of the deuteron beam polarization. At this energy, the deuteron beam polarization was found by raising the target cell, rotating the proton polarimeter out of the beam path, and sending the deuteron beam to a calibrated $^2\mathrm{H}(d,p)^3\mathrm{H}$-based polarimeter [19,23] mounted behind the scattering chamber. As before, the deuteron and proton polarization measurements were interspersed. For these runs, an additional Havar foil was mounted behind the gas cell to stop the α particles emerging from the $^3\mathrm{He}$-d reaction, leading to a proton energy within the proton polarimeter of 14.6 MeV as before.

The resulting values for the polarization transfer coefficient $K_y^{y'}(0°)$ are shown in Table I. At all three energies, the measurements are consistent with the single-resonance model prediction of $-2/3$. In Fig. 1 these new results are plotted with the earlier results of Hardekopf *et al.* [13] to illustrate the transition from the region dominated by the $\frac{3}{2}^+$ resonance to higher energies, where direct neutron transfer

TABLE I. Results of the $K_y^{y'}(0°)$ measurements. The uncertainties quoted for the measurements are statistical errors.

E_d (keV)	$K_y^{y'}(0°)$
520 ± 40	-0.68 ± 0.03
890 ± 40	-0.67 ± 0.05
1490 ± 30	-0.62 ± 0.05

and higher order partial waves become more important. Between 2 and 10 MeV, $K_y^{y'}(0°)$ values indicate a mixture of resonance and direct contributions that might be individually evaluated by appropriate calculations if additional polarization observables are included in the analysis. Such calculations are now underway for this reaction [24]. A prediction for this observable based on a multichannel R-matrix parametrization of the $A=5$ system performed at Los Alamos National Laboratory is also shown in Fig. 1. The R-matrix parameters for this calculation are determined based on available $A=5$ data [25] using methods similar to those described in Ref. [26]. The maximum energy for this analysis is 8 MeV. The R-matrix predictions show good agreement with the new data, and account well for the transition from the resonance-dominated low-energy region to the higher energies, where other effects come into play.

In summary, we have measured the polarization transfer coefficient $K_y^{y'}(0°)$ for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction at energies of 520, 890, and 1490 keV. The data are consistent with predictions based on the presence of the broad $\frac{3}{2}^+$ S-wave resonance at $E_d=430$ keV, having values close to $-2/3$, which are opposite in sign from the expectations of a simple stripping model. This illustrates that this observable can be quite useful for identifying resonant and nonresonant contributions in few-body reactions. In this particular case, the results indicate that there are no sizable nonresonant contributions to $K_y^{y'}(0°)$ at energies up to 1 MeV. In addition, our $K_y^{y'}(0°)$ data will further constrain reaction models by allowing for the determination of relevant matrix elements at 0°. This will hopefully provide quantitative information about additional reaction channels near the dominant $\frac{3}{2}^+$ resonance as indicated in previous measurements.

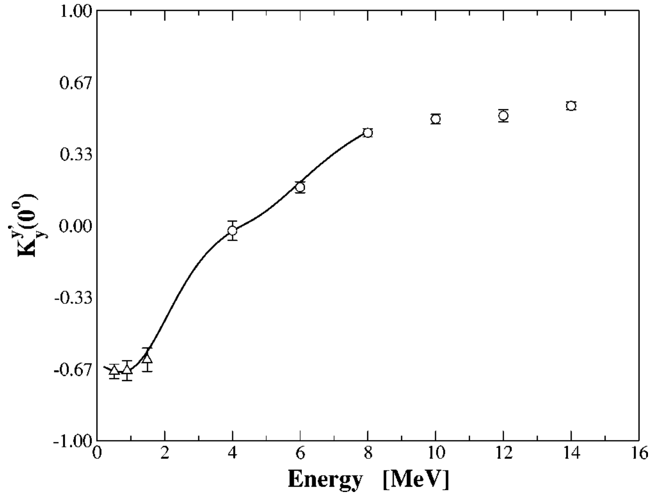

FIG. 1. The polarization transfer observable $K_y^{y'}(0°)$ for the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction as a function of deuteron energy. The triangular data points represent the new measurements described here. Circular data points represent the measurements of Ref. [13]. The solid line shows the predictions from an R-matrix analysis of the $A=5$ system as described in Refs. [25,26].

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