Resonant and direct components in the ^{3}He$(d,p)^4$He reaction at low energies

B. Braizinha,[1,*] C. R. Brune,[2] A. M. Eiró,[1] B. M. Fisher,[3] H. J. Karwowski,[3] D. S. Leonard,[3] E. J. Ludwig,[3] F. D. Santos,[1] and I. J. Thompson[4]

[1]*Departamento de Física and Centro de Física Nuclear da Universidade Lisboa, 1649-003 Lisboa, Portugal*

[2]*Ohio University, Athens, Ohio 45701, USA*

[3]*Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3255, USA and Triangle Universities Nuclear Laboratory, Durham, North Carolina 22708-0308, USA*

[4]*Department of Physics, Surrey University, Guildford GU2 7XH, United Kingdom*

(Received 8 October 2003; published 25 February 2004)

New experimental results for the cross section and A_{yy} tensor analyzing power observables of the ^{3}He$(d,p)^4$He reaction at a scattering angle of $\theta=0°$ are presented for $E_d=0.52, 0.89$, and 1.49 MeV, and all linearly independent scattering amplitudes at this angle are calculated. A hybrid R-matrix+potential model is used to fit these results and other ^{3}He$(d,p)^4$He reaction data for $E_d<1$ MeV. This analysis indicates significant direct process contributions to the reaction mechanism.

DOI: 10.1103/PhysRevC.69.024608 PACS number(s): 24.10.−i, 24.30.−v, 24.70.+s, 25.55.−e

I. INTRODUCTION

Nuclear reactions of interest in astrophysics often proceed both by resonant and direct reaction mechanisms. To decouple these processes one should obtain as much information on reaction observables as possible. Polarization observables are particularly important in this context.

The ^{3}He$(d,p)^4$He reaction is dominated at deuteron energies below 1 MeV by a broad $J^\pi=\frac{3}{2}^+$ S-wave resonance in ^{5}Li at $E_d=0.430$ MeV. However, recent measurements [1] have shown significant deviation from the expected S-wave resonant behavior. These discrepancies may be due to $L>0$ contributions to the reaction mechanism arising from direct transfer processes or tails of distant resonances. Additional experimental information as well as appropriate models are required to identify these processes and obtain information on the relative importance of direct and resonant mechanism.

In this work new experimental results for the cross section and A_{yy} tensor analyzing power observables of the ^{3}He$(d,p)^4$He reaction at a scattering angle of $\theta=0°$ are obtained. These results, together with recent measurements of the polarization-transfer observable $K_y^{y'}(0°)$ at the same energies [2], allow the calculation of all the linearly independent elements of the scattering matrix at $\theta=0°$. Moreover the new tensor observable measured, being very sensitive to the reaction process, provides an excellent tool to test a theoretical study of the mechanism of the reaction.

In previous analyses, direct processes have been found to exist in transfer reactions at sub-Coulomb energies [3,4], as for example in (p,α) reactions where the outgoing particles have energies significantly above the Coulomb barrier. Other studies of the same reaction [5,6] at energies near low-energy resonances suggested the need for including direct processes. This work describes a similar high Q value reaction, constituting the first attempt for a systematic modeling of low-energy nuclear reactions by including both resonant processes, and direct mechanisms from a potential model.

We start by describing the experimental setup and procedures in Sec. II. The data analysis and the calculation of the observables are also explained in Sec. II. In the third section the linearly independent scattering matrix amplitudes are calculated. Finally, we analyze these data together with the data of Geist *et al.* [1], with a hybrid R-matrix + potential model.

II. EXPERIMENT

The experiment was performed in the 61-cm-diameter scattering chamber at the Triangle Universities Nuclear Laboratory (TUNL) using the FN Tandem accelerator.

A. A_{yy} measurement

The A_{yy} analyzing power at $\theta=0°$ was measured with a polarized deuteron beam incident on a ^{3}He gas cell target. The setup is shown schematically in Fig. 1.

The gas target was 2.54 cm diameter cell with a 6.3 μm Havar-foil cylindrical window. This cell was filled with ^{3}He gas and the pressure (1 atm for runs at $E_d=0.52$ MeV and 2 atm for runs at $E_d=0.89$ and 1.49 MeV) monitored to be constant during the experiment.

The polarized deuteron beam was obtained from the atomic beam polarized ion source [7] at TUNL via a three polarization state method with fast state switching [8]. During the measurements the beam current on target ranged from 100 nA to 200 nA, depending on the energy.

Three silicon detectors were positioned inside the chamber, a central detector (labeled C) at $\theta=0°$ and the others at 10° left (L), and right (R), from the 0° detector. Consecutive runs at the deuteron energies of interest were intercalated with runs at $E_d=4$ MeV to determine the tensor beam polarization p_{zz}.

The beam current was integrated from the gas cell and a tantalum foil in front of the 0° detector. Calculations with SRIM [9] were performed to obtain the beam energies corresponding to the mean reaction energies at the center of the

*Electronic address: B.Braizinha@surrey.ac.uk

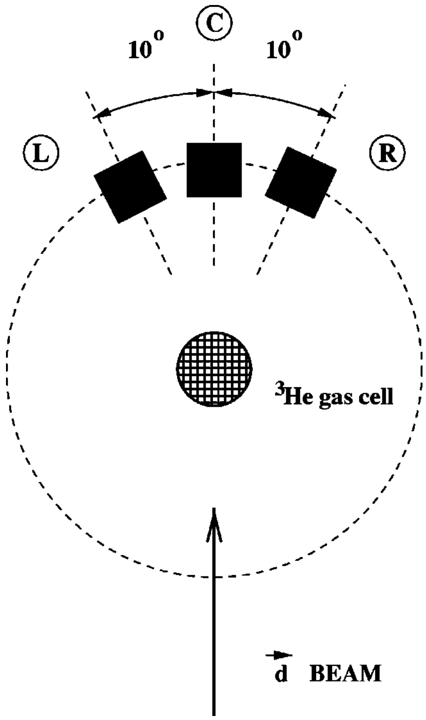

FIG. 1. Experimental setup used in the A_{yy} measurement.

gas cell. This procedure was also used for the self-supported targets described later in Sec. II B.

For the determination of the analyzing power, $A_{yy}(0°)$, the normalized yield Y^i for a detector in the ith polarization state is determined by normalizing the number of reaction counts collected in that detector and state to the charge collected. These yields also include a correction for dead time in the data acquisition system. A value of $i=0$ is used to represent the unpolarized state. The analyzing power is calculated using [1]

$$A_{yy}(0°) = \frac{2(Y_C^i/Y_C^0 - 1)}{p_{zz}^i}, \tag{1}$$

where the subscript C denotes the central detector, and p_{zz}^i is the beam polarization in the ith polarized state.

The beam polarization was calculated from the 4 MeV runs using

$$p_{zz}^i = \frac{Y_L^i/Y_L^0 + Y_R^i/Y_R^0 - 2}{A_{yy}(10°)}, \tag{2}$$

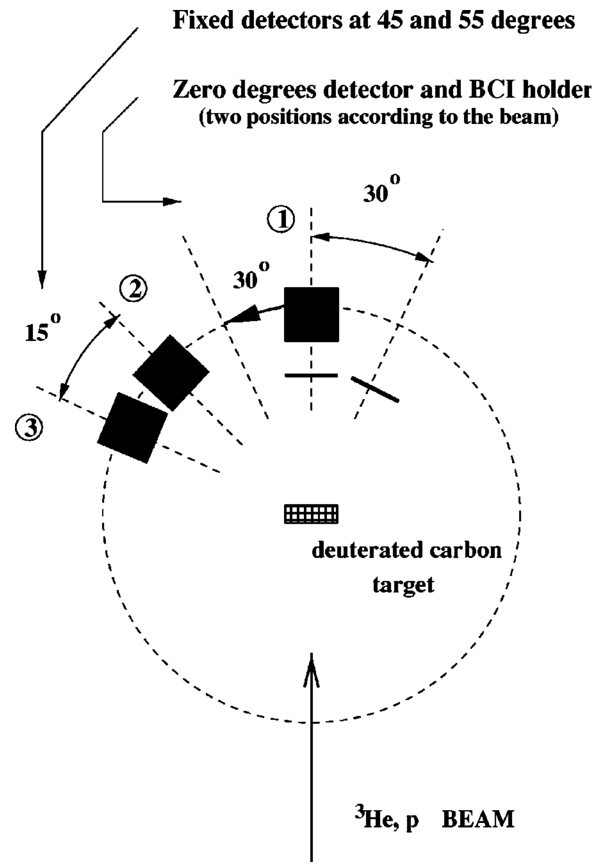

FIG. 2. Experimental setup used in the cross section measurement.

where L and R denote the left and right detectors, respectively, and $A_{yy}(10°)=0.818\pm0.004$ is the value obtained from Bittcher *et al.* [10]. During the experiment, the on target beam polarizations were determined to be stable for both polarization states. The average of the magnitudes of the two polarizations was 75%.

The final values, given in Table I, are the averages of both spin states.

B. Cross section measurement

The cross section at $\theta=0°$ was measured in inverse kinematics with a ^{3}He beam incident on a deuterated carbon target. The setup is shown schematically in Fig. 2.

The self-supported deuterated carbon targets were produced using the plasma-assisted chemical vapor deposition

TABLE I. Values of measured A_{yy}, cross-section, and $K_y^{y'}$ at 0° and of calculated scattering amplitudes (errors quoted include statistical errors only).

E_d (MeV)	$A_{yy}(0°)$	$\sigma(0°)$(mb/sr)	$K_y^{y'}(0°)$[a]	$\|M1\|^2$ (mb/sr)	$\|M2\|^2$ (mb/sr)	ϕ (deg)
0.52	0.47 ± 0.02	54.9 ± 0.7[b]	-0.68 ± 0.03	35.5 ± 0.7	9.7 ± 0.4	180.0 ± 10.1
0.89	0.35 ± 0.02	31.9 ± 0.4	-0.67 ± 0.05	18.1 ± 0.4	6.9 ± 0.2	162.9 ± 9.7
1.49	0.32 ± 0.03	18.8 ± 0.4	0.62 ± 0.05	10.3 ± 0.3	4.3 ± 0.2	151.7 ± 11.3

[a]$K_y^{y'}$ values from Ref. [2].
[b]Value obtained by polynomial interpolation.

technique with deuterated methane gas. These targets have been shown [8] to be stable and to have a slow decrease of deuterium thickness.

To normalize the results to the *p-d* elastic cross section, the ^{3}He runs were intercalated with proton runs for the same value of the magnetic field in the analyzing magnet (at $E_p = \frac{3}{4}E_d$). The proton beam was obtained from the direct extraction negative ion source. Typical beam currents on target were 40 nA for the proton beam and 70 nA for the ^{3}He beam.

Three detectors were positioned inside the chamber, two fixed detectors (monitors) at 45° and 55° (detectors 2 and 3, respectively), and a central detector (detector 1), positioned at $\theta=0^{\circ}$ for the ^{3}He beam and sliding to 30° when running with the proton beam. In this way, one avoids radiation damage of the detector during the proton runs and is able to avoid solid angle corrections.

During the ^{3}He runs beam current integration was performed from the target and a tantalum foil in front of detector 1. During the proton runs the current was measured from the target and a Havar foil that slid rigidly with the central detector and was located at 0°.

The differential cross section at 0° for the $^3\mathrm{He}(d,p)\alpha$ reaction, $\sigma(0°)$, is determined using

$$\sigma(0°) = \frac{\Delta\Omega_m}{\Delta\Omega_1}\frac{Q}{Q'}\frac{N_1^{\alpha}}{N_m^{p}}\sigma_{el}(\theta_m), \tag{3}$$

where Q' and Q are the collected charges obtained during ^{3}He runs and proton runs, respectively, and N^{α} and N^{p} are the dead-time-corrected integrals of the counts in the α peak and proton elastic peak, respectively. The subscripts denote the detectors, as shown in Fig. 2, and *m* refers to the detector used for *p-d* elastic scattering. The elastic *p-d* cross section, $\sigma_{el}(\theta_m)$, is obtained from Kievsky [11]. These calculations, which have been shown to have excellent agreement with experimental data in this energy range [15,16], use correlated hyperspherical harmonics to calculate the continuum wave functions [12] corresponding to a realistic Hamiltonian consisting of the Argonne V18 two-nucleon [13] and Urbana IX three-nucleon interactions [14]. A Kohn variational principle is used to determine the scattering matrix elements. Equation (3) is applied to consecutive ^{3}He and proton runs, assuming that the target thickness does not change during these runs.

For $E_d=1.49$ MeV, one can use detector 1 for *p-d* elastic yields; thus $m=1$, $\theta_m=30°$, and the ratio of solid angles in Eq. (3) vanishes. However, for the lower energy the scattered particles are absorbed by the foil in front of detector 1. The ratio of solid angles $\Delta\Omega_m/\Delta\Omega_1$ is then obtained from the proton runs at $E_p=1.68$ MeV using

$$\frac{\Delta\Omega_m}{\Delta\Omega_1} = \frac{N_m^{p}}{N_1^{p}}\frac{\sigma_{el}(30°)}{\sigma_{el}(\theta_m)}. \tag{4}$$

The angles in Eqs. (3) and (4) are laboratory angles.

The final values, given in Table I, are the average of the values obtained from normalizing to different detectors.

C. Uncertainties

To estimate the systematic errors introduced in the analyzing power measurement by the uncertainties in the reaction energies and gas leaking effects in the target, SRIM [9] calculations were performed. The systematic errors in the A_{yy} values associated with the uncertainties in the reaction energies are 2.2%, 2.1%, and 0.9% for $E_d=0.52, 0.89$, and 1.49 MeV, respectively. Furthermore, it was found that 5% uncertainty in the gas pressure during a run corresponds to a 0.5% systematic error in the values of A_{yy} obtained in this experiment. Also, the systematic error in the value of $A_{yy}(10°)$ obtained from Bittcher *et al.* [10] corresponds to a 0.5% systematic error in the values of A_{yy}. The systematic error associated with the angular acceptance introduced by the collimators was found to be negligible (less than 0.1%).

Detector position, energy loss in the target, and beam motion effects were found to be the main sources of systematic uncertainties involved in the determination of the cross section. The errors in the detector angles were determined, through the peak positions, to be accurate within 0.25°. Based on angular dependence data [1,10,11], the systematic errors associated with the positions of the detectors were found to be 0.9% and 1.1% for $E_d=0.89$ and 1.49 MeV, respectively. Based on a previous experiment [8], the upper limit to the systematic errors in the cross section values introduced by the uncertainties in the reaction energies is 2%. Horizontal 3 mm beam motion effects were found to introduce a 2.9% systematic uncertainty in the cross section value at $E_d=0.89$ MeV. The systematic error in the cross section values associated with the angular acceptance introduced by the collimators was found to be negligible.

III. SCATTERING AMPLITUDES

The observables measured in a reaction can always be calculated from the scattering matrix. In some cases, when the number of independent polarization observables is sufficient, experimental data can be used to obtain information about the *T* matrix amplitudes. Due to the spin structure of the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction $\frac{1}{2}+1\rightarrow\frac{1}{2}+0$, the scattering matrix *T* has 6×2 complex elements. Conservation of parity reduces the number of different amplitudes to six. For 0° scattering angle, no preferential transverse direction is defined, so *T* must be invariant under rotations along the *Z* axis (Madison frame). The scattering matrix is thus completely determined by two amplitudes [17]. These correspond to three real numbers since one relative phase factor can be chosen arbitrarily: $M1=|M1|$ and $M2=|M2|e^{i\phi}$. Consequently, these amplitudes can be calculated from the three linearly independent observables $K_y^{y'}, A_{yy}$, and the cross section using

$$|M1|^2 = \frac{\sigma(0°)}{3}[1+2A_{yy}(0°)], \tag{5}$$

$$|M2|^2 = \frac{\sigma(0°)}{3}[1-A_{yy}(0°)], \tag{6}$$

$$\phi = \arccos\left[\frac{\sigma(0°)K_y^{y'}(0°)}{2|M1||M2|}\right]. \quad (7)$$

The experimental results obtained in this work, together with recent measurements [2] for the $K_y^{y'}(0°)$ observable, defined as

$$K_y^{y'}(0°) = \frac{2}{3}\frac{p_Z^{(p)}}{p_Z^{(d)}}, \quad (8)$$

where $p_Z^{(d)}$ and $p_Z^{(p)}$ are the vector polarization of the deuteron beam and outgoing proton, respectively, allow the determination of all the scattering matrix elements at $\theta=0°$. The results are given in Table I.

From the $K_y^{y'}(0°)$ measurements Fletcher *et al.* [2] concluded that the reaction mechanism is dominated by the $\frac{3}{2}^+$ S-wave resonance in ^{5}Li at $E_d=0.430$ MeV with no sizable nonresonant contributions at deuteron energies below 1 MeV. In fact, the results are consistent with the predictions of a pure S-wave resonant behavior of $K_y^{y'}(0°)=-\frac{2}{3}$. The same model predicts $iT_{11}=0$ and $A_{yy}=-(1/\sqrt{2})T_{20}-\sqrt{3}T_{22}=0.5$. Although the measured result for $A_{yy}(0°)$ at $E_d=0.52$ MeV is consistent with that prediction, at higher energies, $E_d=0.89$ and 1.49 MeV, the discrepancy is of the order of 30%, suggesting that the reaction mechanism is not purely resonant. This conclusion is also supported by iT_{11} vector analyzing power measurements of Geist *et al.* [1], who obtained positive iT_{11} inconsistent with zero for $E_d<1$ MeV. These results reveal the importance of negative parity contributions in the entrance channel.

In order to calculate the remaining scattering amplitudes necessary to describe the ^{3}He$(d,p)^4$He reaction observables at all angles, and to determine the relative importance of direct and resonant mechanisms, it is necessary to develop a model that extracts this information from the available experimental data.

IV. MODEL DESCRIPTION

Due to the dominant effect of the $\frac{3}{2}^+$ S-wave resonance at $E_d=0.430$ MeV on the ^{3}He$(d,p)^4$He reaction observables for $E_d<1$ MeV, our theoretical model should be tested in this energy range. Geist *et al.* [1] obtained precise measurements of vector and tensor analyzing powers, and of total and differential cross sections at several energies in this range. In our analysis we will use these measurements, the ^{3}He-d elastic cross section data [19], and the new measurements presented in this work.

The dominant mechanism of the reaction is clearly resonant and well described by an R-matrix procedure. However, positive vector analyzing power data are a clear signature of other competing processes, namely, those related to odd partial waves. The simplest R-matrix fit, where only a $\frac{3}{2}^+$ S-wave resonance is considered, predicts values for tensor analyzing powers and $K_y^{y'}$ in good agreement with much of the measured data. However, in such a simplified model iT_{11} is zero, as shown in Fig. 3, in clear disagreement with measurements of Geist *et al.* [1]. We therefore expand the

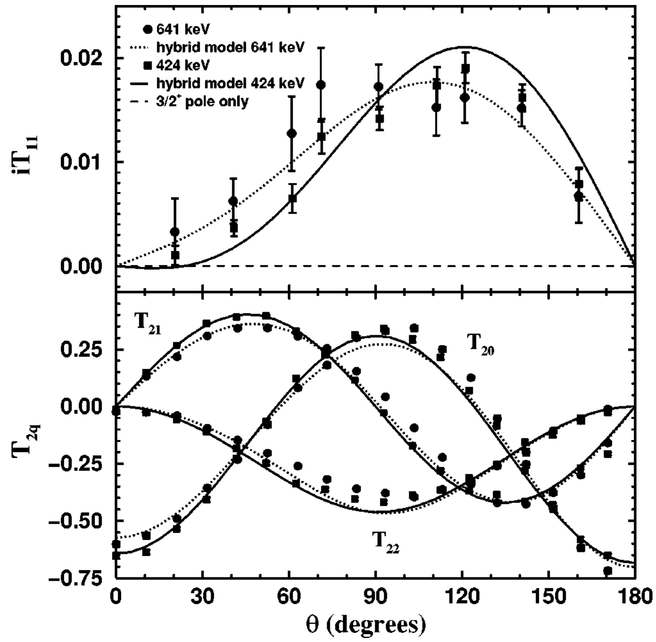

FIG. 3. Hybrid model angular distributions for iT_{11} and T_{2q} measurements of Geist *et al.* [1] at two deuteron energies, 0.424 and 0.641 MeV.

R-matrix model to include the next excited state, the $\frac{3}{2}^-$ state at $E_d=2.62$ MeV [18], as an R-matrix pole. The T_{2q} and $K_y^{y'}$ are still well described, but the predictions for iT_{11}, although nonzero, do not reproduce the data. This behavior indicates the strong sensitivity of this observable to other contributions to the reaction mechanism. To account for these other mechanisms, we develop a model that takes into consideration the direct component of the reaction through a potential description [20]. The scattering wave functions generated by the potential are expanded in an R-matrix basis [21] and can therefore be added to the resonant contribution to calculate the scattering amplitudes. In this model, the $\frac{3}{2}^+$ and $\frac{3}{2}^-$ resonant states are introduced through R-matrix poles, and the other negative parity contributions to the reaction mechanism are obtained through a fitted potential. To improve the quality of the fits we also include $\frac{1}{2}^+$ and $\frac{3}{2}^+$ background poles at $E_d=3$ MeV.

With this hybrid R-matrix+potential model we are able to describe successfully [20] the vector and tensor analyzing powers, and the total and differential cross section data for the ^{3}He$(d,p)^4$He reaction measured by Geist *et al.* [1]. The results obtained at $E_d=0.424$ and 0.641 MeV for the angular distributions of iT_{11} and T_{2q} observables are shown in Fig. 3. Other data at lower energies exhibit similar agreement.

The predictions of this model for the energy dependence of $A_{yy}(0°)$, $\sigma(0°)$, and $K_y^{y'}(0°)$, shown in Fig. 4, are also in good agreement with the experimental data. The hybrid model results for $K_y^{y'}(0°)$ are −0.69 and −0.68 for 0.52 and 0.89 MeV, respectively, in excellent agreement with the measurements of Ref. [2]. It is known [22] that if the reaction proceeds by a direct mechanism and only the S state of the deuteron is considered, $K_y^{y'}(0°)=+\frac{2}{3}$. The inclusion of the deuteron D state lowers this result, but it will still be posi-

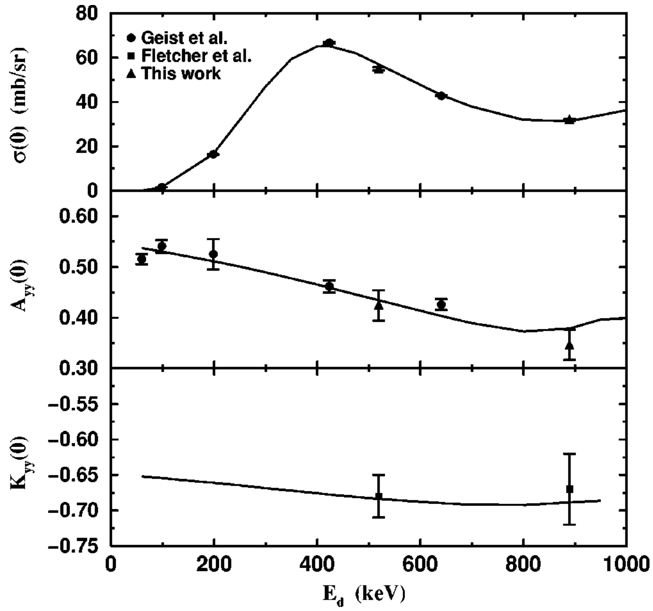

FIG. 4. Hybrid model results for the energy dependence of $A_{yy}(0°)$, $\sigma(0°)$, and $K_y^{y'}(0°)$.

tive. This feature is clearly seen in the data shown in Ref. [2] in the energy region where the direct process dominates. The results obtained for the spin transfer coefficient with this model are therefore particularly interesting because they allow us to conclude that values of $K_y^{y'}(0°)$ close to $-\frac{2}{3}$ can still be consistent with a mixed mechanism of the reaction. Furthermore, the strong sensitivity of this observable to the direct mechanism sets a limit on the amount of mixing.

This analysis indicates that direct process contributions to the reaction mechanism should not be neglected as they compete with the resonant mechanism through p and f waves in the entrance channel [20], accounting for up to 15% of the total cross section in the energy range below 1 MeV.

V. CONCLUSIONS

Measurements of $A_{yy}(0°)$ and $\sigma(0°)$ of the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction were taken at $E_d=0.52, 0.89$, and 1.49 MeV, complementing the existing $K_y^{y'}(0°)$ data at those energies. These measurements allow, for the first time, the determination of all linearly independent scattering matrix elements at 0°.

These and previous results at $E_d<1$ MeV were described using a hybrid model that accounts for both resonant and direct mechanisms by combining R-matrix poles and a potential description. We conclude that a consistent description of the different polarization observables, vector and tensor analyzing powers, and spin transfer coefficients can be achieved by assuming that the reaction proceeds by a mixed mechanism where the dominant resonant component competes with a non-negligible direct component.

ACKNOWLEDGMENTS

The Portuguese government support through the FCT Grant No. SFRH/BD/1124/2000; UK support from the EPSRC, Grant No. GR/M/82141; and US-DOE support from Grant Nos. DE-FG02-97ER41033 and DE-FG02-97ER41041 is acknowledged.

[1] W. H. Geist, C. R. Brune, H. J. Karwowski, E. J. Ludwig, K. D. Veal, and G. M. Hale, Phys. Rev. C **60**, 054003 (1999).
[2] K. A. Fletcher, C. R. Brune, B. M. Fisher, R. P. Fitzgerald, H. J. Karwowski, D. S. Leonard, E. J. Ludwig, R. C. Runkle, M. H. Wood, W. H. Geist, K. D. Veal, and G. M. Hale, Phys. Rev. C **66**, 057601 (2002).
[3] G. Raiman, B. Bach, K. Grun, H. Herndl, H. Oberhummer, S. Engstler, C. Rolfs, H. Abele, R. Neu, and G. Staudt, Phys. Lett. B **249**, 191 (1990).
[4] Y. Yamashita, Nucl. Phys. **A582**, 270 (1995).
[5] A. Redder, H. W. Becker, H. Lorenz-Wirzba, C. Rolfs, P. Schmalbrock, and H. P. Trautvetter, Z. Phys. A **281**, 211 (1977).
[6] H. Lorenz-Wirzba, P. Schmalbrock, H. P. Trautvetter, M. Wiescher, C. Rolfs, and W. S. Rodney, Nucl. Phys. **A313**, 346 (1979).
[7] T. B. Clegg *et al.*, Nucl. Instrum. Methods Phys. Res. A **357**, 200 (1995).
[8] W. H. Geist, Ph.D thesis, University of North Carolina at Chapel Hill, 1998, available from University Microfilms International, 300 N. Zeeb Rd., Ann Arbor, Michigan 48106, order no. 9902466.
[9] J. F. Ziegler and J. P. Biersack, SRIM-2000.39 computer program, URL http://www.research.ibm.com/ionbeams/
[10] M. Bittcher, W. Grüebler, V. König, P. A. Schmelzbach, B. Vuaridel, and J. Ulbricht, Few-Body Syst. **9**, 165 (1990).
[11] A. Kievsky (private communication).
[12] M. Viviani, S. Rosati, and A. Kievsky, Phys. Rev. Lett. **81**, 1580 (1998).
[13] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[14] B. S. Pudliner, V. R. Pandharipande, J. Carlson, and R. B. Wiringa, Phys. Rev. Lett. **74**, 4396 (1995).
[15] M. H. Wood, C. R. Brune, B. M. Fisher, H. J. Karwowski, D. S. Leonard, E. J. Ludwig, A. Kievsky, S. Rosati, and M. Viviani, Phys. Rev. C **65**, 034002 (2002).
[16] C. R. Brune, W. H. Geist, H. J. Karwowski, E. J. Ludwig, K. D. Veal, and M. H. Wood, Phys. Rev. C **63**, 044013 (2001).
[17] G. Ohlsen, Rep. Prog. Phys. **35**, 717 (1972).
[18] D. R. Tilley, C. M. Cheves, J. L. Godwin, G. M. Hale, H. M. Hofmann, J. H. Kelley, C. G. Sheu, and H. R. Weller, Nucl. Phys. **A708**, 3 (2002).
[19] B. Jenny, W. Grüebler, V. König, P. A. Schmelzbach, R. Risler, H. R. Bürgi, and D. O. Boerma, Nucl. Phys. **A324**, 99 (1979).
[20] B. Braizinha *et al.* (unpublished).
[21] I. J. Thompson, in *Scattering*, edited by R. Pike and P. Sabatier (Academic, New York, 2001).
[22] F. D. Santos, Nucl. Phys. **A236**, 90 (1974).