Direct-reaction and isospin symmetries in $\vec{d}+d$ reactions

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We have measured angular distributions of the analyzing powers A_y, A_{xx}, A_{yy}, and A_{xz} for the $^2H(\vec{d},p)^3H$ reaction at deuteron lab energies E_d of 13.39 and 17.00 MeV. These distributions do not show the symmetry or antisymmetry about 90° (c.m.) expected on the basis of a simple direct-neutron-transfer reaction mechanism. In a companion experiment, we have measured the same four analyzing powers for both the $^2H(\vec{d},p)^3H$ reaction and its charge-symmetric partner $^2H(\vec{d},n)^3He$ at E_d = 15.50 and 17.00 MeV in a restricted angular range. These latter data were obtained by simultaneously detecting the tritons and helions. Only small differences were observed in the respective analyzing powers for the two reactions, which suggests a weakening of the mechanism responsible for the larger differences found by others at lower energies.

[NUCLEAR REACTIONS $^2H(\vec{d},p)$, $E=13.39$, 17.00 MeV; measured $A_y(\theta)$, $A_{xx}(\theta)$, $A_{yy}(\theta)$, $A_{xz}(\theta)$. $^2H(\vec{d},p)$, $(\vec{d},n)$ simultaneously, $E=15.50$, 17.00 MeV; measured $A_y(\theta)$, $A_{xx}(\theta)$, $A_{yy}(\theta)$, $A_{xz}(\theta)$.]

I. INTRODUCTION

The two-body $\vec{d}+d$ reactions present interesting possibilities for the study of symmetry properties in few-nucleon systems. One such aspect is concerned with reaction mechanisms, as has been discussed by Conzett,[1] and subsequently by Haglund *et al.*[2] (the latter in reference to the $\vec{t}+{}^3He \to d+\alpha$ reaction). Conzett[1] has described how the assumption of a simple, direct, neutron-transfer mechanism for the $^2H(\vec{d},p)^3H$ reaction leads to the following symmetry relations for the (spherical) analyzing powers $T_{kq}(\theta)$:

$$T_{kq}(\theta)=(-1)^q T_{kq}(\pi-\theta)\,. \tag{1}$$

In the present work we deal with the Cartesian analyzing powers

$$A_y=\frac{2}{\sqrt{3}}iT_{11}\,,\quad A_{xx}=-\frac{1}{\sqrt{2}}T_{20}+\sqrt{3}T_{22}\,,$$
$$A_{yy}=-\frac{1}{\sqrt{2}}T_{20}-\sqrt{3}T_{22}\,,\quad A_{xz}=-\sqrt{3}T_{21}\,, \tag{2}$$

and Eq. (1) can be stated as follows: A_y and A_{xz} should be antisymmetric about 90° (c.m.), and A_{xx} and A_{yy} should be symmetric about 90° (c.m.). This reaction has been studied by Grüebler *et al.*[3] in the deuteron lab energy range $E_d=3.0-11.5$ MeV, and, although T_{20} does approach symmetry about 90° in the lower part of that range, in general Eq. (1) is not even roughly satisfied by that data. On the other hand, measurements of A_y have been reported[1,4,5] up to $E_d=30$ MeV and show a strong tendency toward antisymmetry about 90° as E_d is increased. To further study the applicability of Eq. (1), especially to the tensor analyzing powers, we have measured angular distributions of the Cartesian analyzing powers at $E_d=13.39$ and 17.00 MeV.

Another aspect of $\vec{d}+d$ reactions which has attracted attention is the study of isospin symmetry by comparing the charge-symmetric reactions $^2H(\vec{d},p)^3H$ and $^2H(\vec{d},n)^3He$. A recent such comparison by König *et al.*[6] for $E_d=2.5-11.5$ MeV has shown large and complex differences between the respective analyzing powers over the entire energy range studied. Earlier work by Hardekopf *et al.*[7] had shown that the polarizations of the p and n reaction products produced by unpolarized deuterons in the incident channel could be brought into agreement if they were compared at equal energies in the exit channel rather than at equal bombarding energies. However, when König *et al.*[6] performed this energy shift for their data, they found that, although the differences for T_{20} and T_{22} decreased, the differences for iT_{11} and T_{21} increased. Thus the simple feature found by Hardekopf *et al.*[7] for the p and n polarizations in this energy range does not exist for the deuteron analyzing powers. Because of the intriguing results of Ref. 6, we felt it worthwhile to explore these mirror reactions at higher energies. We therefore measured the four analyzing powers of Eq. (2) for the $^2H(\vec{d},p)^3H$ and $^2H(\vec{d},n)^3He$ reactions at $E_d=15.50$ and 17.00 MeV by simultaneously detecting the tritons and helions.

II. EXPERIMENT

A. Apparatus

The experiment was performed at the Los Alamos Van de Graaff facility[8] and made use of the FN tandem Van de Graaff accelerator and the Lamb-shift polarized ion source.[9,10] Polarized hydrogen isotopes can be accelerated at this facility to a maximum energy of about 17 MeV. The scattering chamber used was a 61-cm cube[11,12] called the "supercube." Among the many features of this chamber are its four independently moveable turntables for mounting detectors in each of four azimuthal quadrants and its capability of being rotated about the beam direction. Here we exploited this rotatability; however, we used only two of the turntables. An SDS-930 or MODCOMP IV/25 computer was used to perform on-line data processing, to control some of the supercube and ion-source functions, and to record the capacitance-manometer readout of the gas-target pressure.

The deuterium gas target used for obtaining most of the data was a 9.7-cm-diam cell having a beam entrance snout about 6 cm long. A 2.5-μm-thick Havar[13] foil covered the 2.5-mm-diam, beam-entrance aperture on the snout, and a 7-μm-thick Kapton[14] foil covered the 300° cell opening through which the beam and detected particles emerged. This gas target was operated at room temperature and at a pressure of about 290 Torr. For the 13.39-MeV data only, the gas target was a cylindrical, 2.54-cm-diam cell encircled by a 6.25-μm-thick Havar foil and was operated at a pressure of about 1250 Torr.

Silicon surface-barrier detectors were positioned behind standard gas-target collimator assemblies, which had an angular acceptance of 1° full width at half maximum (FWHM) in the reaction plane and which were mounted symmetrically on the "left" and "right" turntables of the supercube. For most of the data a 2- or 3-detector stack was used, one on each of the two turntables, and the detected particles were mass identified. For the 13.39-MeV data only, an additional single detector was mounted on each turntable at an angle 45° larger than that of the detector stack and was used to perform singles-mode detection of protons at backward angles.

B. Measurement techniques

A polarized deuteron beam of up to 80 nA was delivered to the supercube. The spin-quantization axis was always positioned in the horizontal plane, and the angle β between this axis and the beam direction was set to an accuracy[15] of about ±0.5°. The beam was aligned and its position monitored by means of two sets of four-way slits, one at the entrance to the supercube and the other in the Faraday cup assembly.

Our measurement technique was similar to the "three spin state method" discussed in Ref.16—the only difference being that the use of two turntables instead of four required us to rotate the supercube through 90° to obtain data at the necessary four azimuthal angles. Thus, data for each of three spin states m_I were obtained in each of the following three configurations:

(1) $\beta=90°$, detectors in the horizontal plane. Here we determined A_{xx}.

(2) $\beta=90°$, detectors in the vertical plane. Here we determined A_y and A_{yy}.

(3) $\beta=45°$, detectors in the horizontal plane. Here we determined A_{xz}. [A_{yy} can also be extracted, but less accurately than in configuration (2).]

The relative beam polarizations p_Z and p_{ZZ} (neglecting the unpolarized background) in the spin states used are given by[10,15]

$$m_I=1: p_Z=1, \quad p_{ZZ}=1,$$

$$\text{“}m_I=0\text{”}: p_Z=0.012, \quad p_{ZZ}=-1.966,$$

and

$$\text{“}m_I=-1\text{”}: p_Z=-0.984, \quad p_{ZZ}=0.952.$$

Those states labeled with quotation marks contain small admixtures of states with other m_I values. The absolute beam polarizations are obtained by multiplying p_Z and p_{ZZ} by p_Q, the fraction of the total beam that is actually polarized. This fraction was determined by the quench-ratio technique[17,18] and typically had values near 0.78. This method results in the beam polarizations being known to about ±1.5%.

III. RESULTS

The measured analyzing powers for the $^2H(\vec{d},p)^3H$ reaction at 13.39 and 17.00 MeV are presented in Fig. 1. The relative errors range from ±0.007 to ±0.037 with an average of ±0.014. The vector analyzing powers A_y usually have smaller errors than do the tensor analyzing powers.

The measured analyzing powers for the comparison of the mirror reactions $^2H(\vec{d},p)^3H$ and $^2H(\vec{d},n)^3He$ at 15.50 and 17.00 MeV are shown in Figs. 2 and 3. These data are more accurate than those of Fig. 1 because we accumulated more counts at each angle. The relative errors range from ±0.006 to ±0.012 with an average of ±0.009. Furthermore, because the results for the two reactions were obtained simultaneously, many systematic discrepancies from changing experimental

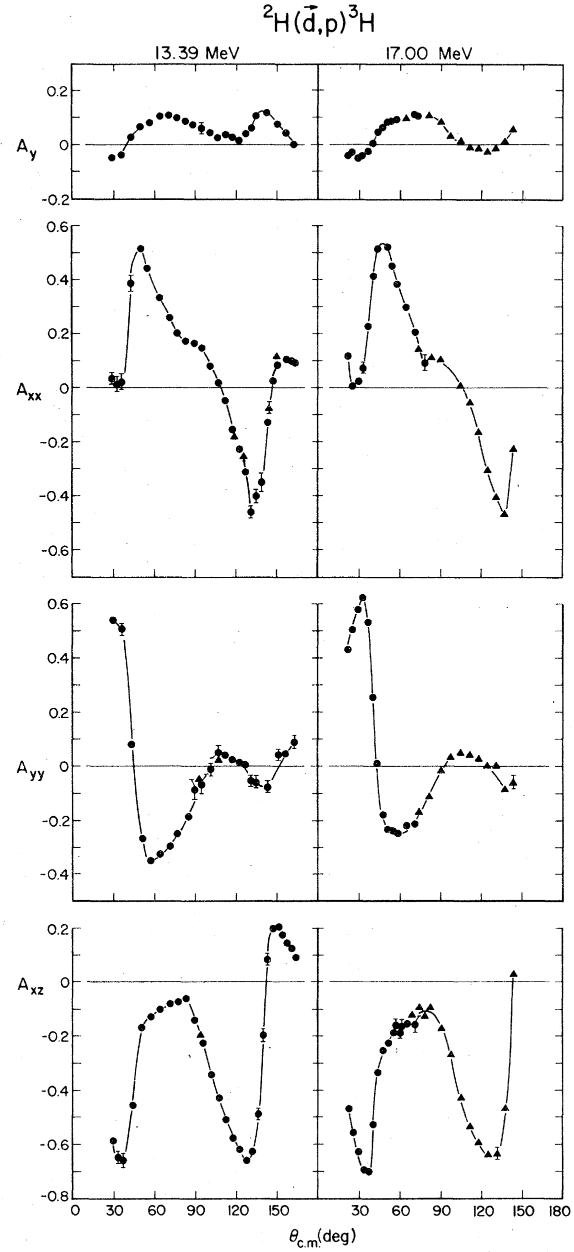

FIG. 1. Analyzing powers for $^2H(\vec{d},p)^3H$ at 13.39 and 17.00 MeV deuteron bombarding energies. The circles show data obtained by detecting protons, and the triangles show data obtained by detecting tritons. A few triangles which would overlap circles have not been plotted. The relative errors are indicated whenever they exceed the size of the plotting symbols. The smooth curves are to guide the eye.

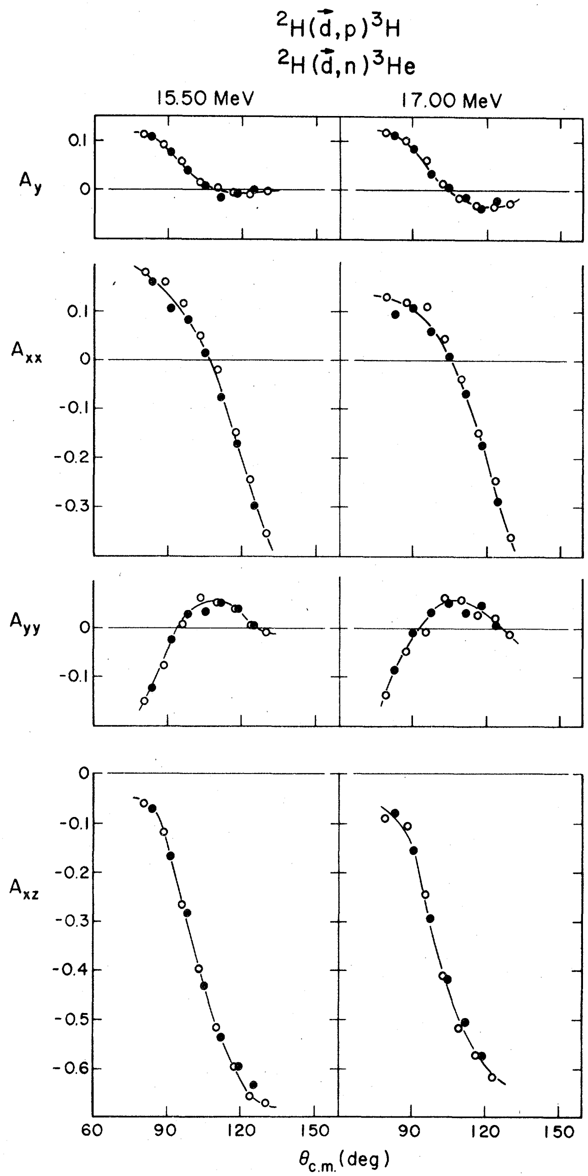

FIG. 2. Analyzing powers for $^2H(\vec{d},p)^3H$ (solid circles) and $^2H(\vec{d},n)^3He$ (open circles) at 15.50 and 17.00 MeV. The statistical errors are usually smaller than the size of the plotting symbol. The smooth curves are to guide the eye.

conditions are eliminated. In addition to the relative errors, there is a scale error in all the data of ±1.5% of the analyzing power. The lab angles are accurate to ±0.04°. The uncertainty in the energy loss of the deuteron beam as it penetrates to the center of the gas target, and other small contributions,[19] yield an overall error in the beam energy of ±25 keV for the 13.39-MeV data and ±15 keV for the rest. An estimate, in the Gaussian approximation,[20] of the beam energy spread (FWHM) resulting from straggling in the target gas and cell entrance foil gives 50 keV for the 13.39-MeV data and 35 keV for the other data. Data tables for all the data shown in Figs. 1 and 2

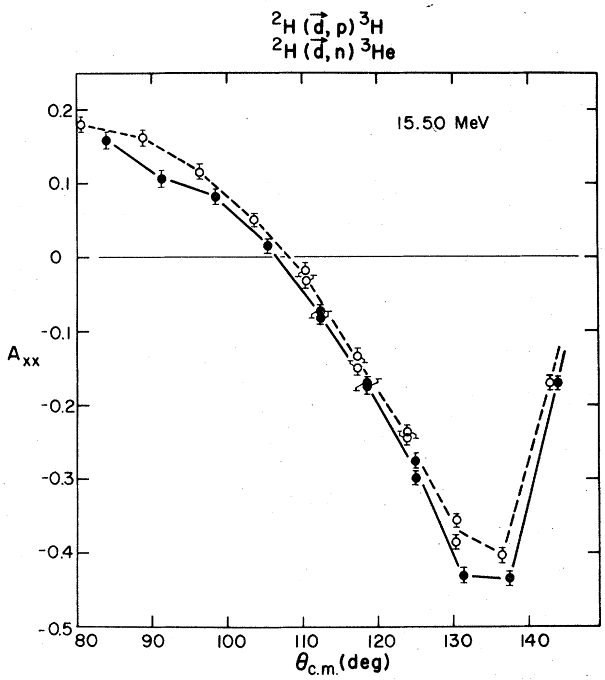

FIG. 3. Tensor analyzing power A_{xx} at 15.50 MeV for the charge-symmetric reactions $^2H(\vec{d},p)^3H$ (solid circles) and $^2H(\vec{d},n)^3He$ (open circles). For ease in comparison, the data points for these two reactions are connected by solid and broken line segments, respectively.

and some of the data shown in Fig. 3 are available in a Los Alamos report.[21]

The relative errors are composed of the errors from counting statistics added in quadrature to an additional error of 0.005, as discussed, for example, in Ref. 19.

IV. DISCUSSION

A. Simple direct-reaction symmetries

Our data shown in Fig. 1 do not obey the symmetry properties implied by Eqs. (1) and (2). In fact, A_{xx} and A_{xz} show a significant component of a symmetry opposite to that given by those equations. There is some hint that A_y is tending to become more antisymmetric about 90° as the energy is raised, and such a trend is consistent with the data of others.[4,5] We conclude that at these energies the simple reaction model of Ref. 1 is not valid. It also appears that deviations from that model might be manifested more sensitively in the tensor analyzing powers than in A_y.

The causes of such deviations could be numerous and complex. For example, states[22] in ^{4}He could be exerting their influence. Also, according to Hackenbroich,[23] significant "spin-flip" components in the interaction could cause deviations from the simple symmetry properties expressed by Eq. (1). Thus, even a "direct" mechanism, but with spin flip (i.e., not "simple"), could violate Eq. (1).

B. Isospin Symmetry

In Fig. 2 we display our initial comparisons of the charge-symmetric reactions $^2H(\vec{d},p)^3H$ and $^2H(\vec{d},n)^3He$ at the same bombarding energies.

A cursory look at these data shows little if any difference between the two reactions in this angular range. However, the work of König *et al.*[6] does indicate that A_{xx} and A_{yy} would be the most likely analyzing powers to exhibit differences in our angular range, and indeed a more detailed inspection of our data reveals a small but definite difference in the A_{xx} values for the two reactions at 15.50 MeV, this difference being about one half that observed by König *et al.*[6] at 11.5 MeV in this same angular region. This motivated us to obtain additional data for A_{xx}. A somewhat different detector arrangement was used for these second measurements, allowing us to detect triton reaction products at more forward angles than before in order to study A_{xx} across its minimum near 135° (c.m.). Both these second measurements and the A_{xx} data of Fig. 2 are shown in Fig. 3. The differences between the two reaction channels are clearly evident, although, as mentioned above, these differences are only about one half as large as observed[6] at 11.5 MeV. Therefore, it appears that the mechanism causing the differences found[6] below 12 MeV is weakening near 15 MeV.

V. CONCLUSION

We have studied several symmetry properties connected with the two-body $\vec{d}+d$ reactions. The simple, direct-reaction symmetry discussed in Ref. 1 does not appear in the $^2H(\vec{d},p)^3H$ analyzing-power angular distributions at our energies. From the work of others,[4,5] however, it is known that the vector analyzing power begins to show the predicted antisymmetry about 90° as the bombarding energy is raised toward 30 MeV, and it therefore would be of some interest to study as well the angular distributions of the tensor analyzing powers at these higher energies. Such a study might throw light on the level structure of ^{4}He or on possible spin-flip reaction mechanisms.

We have also found that, in the angular range studied, some of the differences which had been observed[6] at lower energies in the respective analyzing powers for the $\vec{d}+d$ reactions to the charge-symmetric two-body final states are still present, but to a lesser degree, at our higher energies.

It is difficult to put forth any very convincing simple argument that these differences, especially their energy dependence over the range 2.5–17 MeV, are entirely due to the Coulomb interaction. Certainly, theoretical work on this problem is needed. Perhaps efforts along the line of the multichannel calculation of Heiss *et al.*[24] for the mass-4 system would aid in clarifying the mechanisms for a possible breaking of charge symmetry.

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