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ANALYZING POWERS FOR $\vec{d}$+d REACTIONS FROM 13.39 TO 17.00 MeV

by

Ronald E. Brown, F. D. Correll, R. F. Haglund, Jr.,
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ABSTRACT

We have measured and tabulated 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 of 13.39 and 17.00 MeV, and have observed that these distributions are not of the shapes expected for a simple direct-neutron-transfer reaction mechanism. We have also measured and tabulated 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 deuteron lab energies of 15.50 and 17.00 MeV in the c.m. angular range 80 - 130°. These latter data were obtained by simultaneous detection of the tritons and ^3He particles. No appreciable differences in the respective analyzing powers for the two reactions were observed, which is in contrast to published work of others at lower energies.

I. INTRODUCTION

The main purpose of this report is to present the experimental details and to tabulate the data for a series of measurements of vector and tensor analyzing powers for $\vec{d}$+d reactions. Only brief mention of the motivation and interpretation of the results is given; an expanded discussion is in preparation for publication.

We 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 lab deuteron energies E_d of 13.39 and 17.00 MeV. This experiment was motivated by the work of Conzett,[1] who pointed out that if that reaction were to occur through a simple direct-neutron-transfer mechanism, then the analyzing powers 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.). We have also made direct comparisons of the same four analyzing powers for that reaction with those of the charge-symmetric reaction $^2H(\vec{d},n)^3He$ by simultaneous detection of the tritons and helions. This experiment was carried out at E_d = 15.50 and 17.00 MeV in the c.m. angular range 80 - 130° and was motivated by the work of König et al.,[2] who observed significant differences in the respective analyzing powers between the two reactions in the energy range E_d = 2.5-11.5 MeV.

II. EXPERIMENT

A. General Apparatus and Procedure

The experiment was performed at the Los Alamos Scientific Laboratory Van de Graaff facility,[3] and

made use of the FN tandem Van de Graaff accelerator and the Lamb-shift polarized ion source.[4,5] The scattering chamber used was a 61-cm cube,[6,7] called the "supercube." Among the many features of this chamber are its four independently rotatable turntables for mounting detectors in each of four azimuthal quadrants and its capability of being rotated about the beam direction. We exploited this rotatability, but we used only two of the turntables. The type of deuterium-gas target and the detector arrangement varied throughout different phases of the work and are described below.

A polarized deuteron beam of up to 80 nA in the supercube was used during the experiment. 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[8] of about $\pm 0.5°$. The beam was aligned and its position monitored by means of two sets of four-way slits, one set at the entrance to the supercube and the other in the Faraday cup assembly.

Our measurement technique was very similar to the three spin state method" discussed in Ref. 9—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, to determine A_{xx}.
(2) $\beta = 90°$, detectors in the vertical plane, to determine A_y and A_{yy}.
(3) $\beta = 45°$, detectors in the horizontal plane, to determine A_{xz}. [A_{yy} can also be extracted, but less accurately than in configuration (2).]

This data-taking technique is illustrated in Fig. 1.

The relative polarizations p_z and p_{zz} (neglecting the unpolarized background) in the spin states used are given by[5,8]

$m_I = 1$: $p_z = 1$, $p_{zz} = 1$,
"$m_I = 0$": $p_z = 0.012$, $p_{zz} = -1.966$, and
"$m_I = -1$": $p_z = -0.984$, $p_{zz} = 0.952$.

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[10,11] and typically had values near 0.78. This method results in the beam polarizations being known to about $\pm 1.5\%$.

On-line data processing, control of some of the supercube and ion-source functions, and capacitance-manometer monitoring of the gas-target pressure were carried out with the SDS-930 computer.

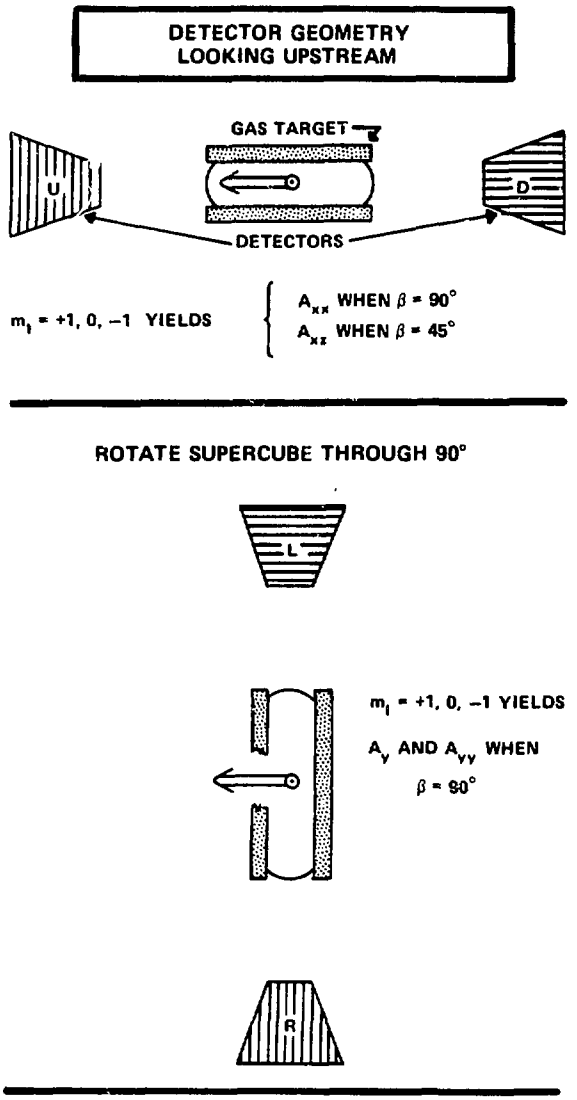

Fig. 1.
Schematic illustration of our use of the "three spin state method" (Ref. 9) for measuring analyzing powers with a polarized deuteron beam.

B. $^2H(\vec{d},p)^3H$ at 13.39 MeV

The deuterium target gas was contained in a cylindrical, 2.54-cm-diam cell encircled by a 6.25-μm-thick Havar* foil affixed with epoxy to the top and bottom of the cell and to the two thin posts supporting the top. It was operated at room temperature at a pressure of about 1250 torr.

Particle-detection assemblies consisting of silicon surface-barrier detectors behind standard gas-target collimator arrangements were mounted symmetrically on the "left" and "right" turntables of the supercube. Each of the turntables supported both a ΔE-E telescope (150- and 1500-μm-thick detectors) at angle θ and a single detector (1000 μm thick) at angle $\theta + 45°$. The telescope was used to mass identify protons (and tritons at some angles), and the other detector was used to record proton events in singles mode, which was quite feasible at back angles. The data obtained cover a lab-angle range of 20-150° in steps of 2.5 or 5.0°. The angular acceptance of the detector was 1° full width at half maximum (FWHM). These data are presented in Table I and Fig. 2.

C. $^2H(\vec{d},p)^3H$ at 17.00 MeV

For this part of the experiment the gas target was a 9.7-cm-diam cell having a beam-entrance snout about 6 cm long. A 2.5-μm-thick Havar foil covered the 2.5-mm-diam, beam-entrance aperture on the snout, and a 7-μm-thick Kapton** 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.

A detector telescope consisting of a stack of 3 silicon surface-barrier detectors was mounted on both the "left" and "right" turntables. As before, the detector collimator system subtended an angle of 1° (FWHM) in the reaction plane. The thicknesses of the detectors in a stack were 100, 1000, and 1500 μm from front to back. We used the 100- and 1000-μm detectors to perform ΔE-E mass identification of the tritons, and simultaneously used the 1000- and 1500-μm detectors to identify the protons. The electronic circuitry was approximately as shown in Fig. 3 of Ref. 12.

By making measurements in the lab-angle range of about 15-50° we covered the c.m.-angle range of 22-143°. These data are presented in Table II and Fig. 2.

D. Comparisons of $^2H(\vec{d},p)^3H$ with $^2H(\vec{d},n)^3He$

The gas target and detector arrangement were as described in Sec. II.C; however, the detector thicknesses were 17, 85, and 1500 μm. We used the 17- and 85-μm detectors to identify the helions, and simultaneously used the 85- and 1500-μm detectors to identify the tritons. We made measurements in the lab-angle range 20-37.5°, thereby covering a c.m.-angle range of about 80-130° for the reaction products p and n. These data are presented in Tables III and IV and Fig. 3.

III. RESULTS

The measured analyzing powers are listed in Tables I-IV and are illustrated in Figs. 2 and 3. The relative errors are given in the tables and are a quadratic combination of the error due to counting statistics and an additional relative error of 0.005. The existence of such an additional relative error has been mentioned elsewhere.[8,12-14] It arises from a variety of effects, including fluctuations in the beam-current measurements necessary to determine the quantity p_Q by the quench-ratio technique, fluctuations in beam position, and uncertainties in background subtraction and beam-current integration. The value of 0.005 is based on experience over the years with repeatability of data for this type of experiment. We also estimate a systematic uncertainty of about 1.5% in the determination of the absolute beam polarization. Thus, in addition to the analyzing-power relative errors listed in the tables, there is a scale error of 0.015 times the analyzing power. The lab angles for all the data 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

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*Havar is the trade name for a cobalt "superalloy" manufactured by Hamilton Technology, Inc., Lancaster, PA 17604.

**Kapton is a polyimide film made by E. I. duPont de Nemours and Company, Wilmington, DE 19898.

TABLE I

ANALYZING POWERS FOR $^2H(\vec{d},p)^3H$ AT LAB ENERGY 13.39 MeV

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	A_y	A_{xx}	A_{yy}	A_{zz}
20.0	29.08	−0.049(12)[a]	0.038(21)[a]	0.542(16)[a]	−0.582(19)[a]
22.5	32.66	---	0.012(23)	---	−0.645(23)
25.0	36.24	−0.037(17)	0.024(28)	0.506(23)	−0.657(27)
30.0	43.33	0.029(11)	0.388(29)	0.081(18)	−0.456(19)
35.0	50.33	0.066(10)	0.518(14)	−0.263(18)	−0.167(17)
40.0	57.22	0.084(07)	0.444(12)	−0.346(10)	−0.123(16)
45.0	64.00	0.103(07)	0.337(11)	−0.321(10)	−0.100(10)
50.0	70.64	0.108(07)	0.263(09)	−0.292(10)	−0.078(09)
55.0	77.14	0.099(07)	0.202(10)	−0.249(11)	−0.071(10)
60.0	83.47	0.088(07)	0.176(11)	−0.182(11)	−0.059(11)
65.0	89.62	0.074(20)	0.167(11)	−0.084(36)	−0.139(12)
35.0[b]	93.45	0.075(07)	0.144(10)	−0.044(10)	−0.193(10)
70.0	95.58	0.060(21)	0.150(18)	−0.064(37)	−0.223(13)
75.0	101.34	0.013(10)	0.081(11)	−0.010(22)	−0.341(13)
80.0	106.88	0.025(13)	0.020(11)	0.054(22)	−0.426(13)
30.0[b]	106.93	0.029(07)	0.023(13)	0.026(09)	−0.431(11)
85.0	112.21	0.035(09)	−0.048(12)	0.045(13)	−0.509(13)
90.0	117.31	0.028(09)	−0.153(18)	0.027(15)	−0.575(20)
25.0[b]	119.73	0.023(09)	−0.182(14)	0.026(13)	−0.605(12)
95.0	122.19	0.015(10)	−0.223(17)	0.017(16)	−0.619(15)
22.5[b]	125.98	---	−0.304(14)	---	−0.649(12)
100.0	126.85	0.040(11)	−0.312(19)	0.009(18)	−0.660(17)
105.0	131.29	0.060(12)	−0.459(22)	−0.051(21)	−0.624(20)
20.0[b]	132.14	0.066(09)	−0.413(15)	−0.055(14)	−0.627(13)
110.0	135.51	0.105(13)	−0.401(24)	−0.055(23)	−0.486(22)
17.5[b]	138.24	---	−0.347(26)	---	---
115.0	139.54	---	−0.349(33)	---	−0.195(24)
120.0	143.38	0.117(12)	−0.126(18)	−0.074(21)	0.084(21)
15.0[b]	144.28	---	−0.073(22)	---	---
125.0	147.03	---	0.025(15)	---	0.200(18)
12.5[b]	150.29	---	0.119(23)	---	---
130.0	150.54	0.074(11)	0.084(12)	0.045(21)	0.206(14)
135.0	153.90	---	---	---	0.176(12)
140.0	157.12	0.042(08)	0.103(09)	0.049(13)	0.146(10)
145.0	160.23	---	0.100(08)	---	0.128(09)
150.0	163.24	0.003(14)	0.091(16)	0.092(24)	0.092(16)

[a]The numbers in parentheses give the relative standard deviation and refer to the two least significant digits in the analyzing power. For example, the first entry in column 3 is to be read −0.049 ± 0.012. In addition to the relative error there is a scale error in all the data of 1.5% of the analyzing power.

[b]The recoil triton was detected at the specified lab angle. The associated c.m. angle refers to the proton.

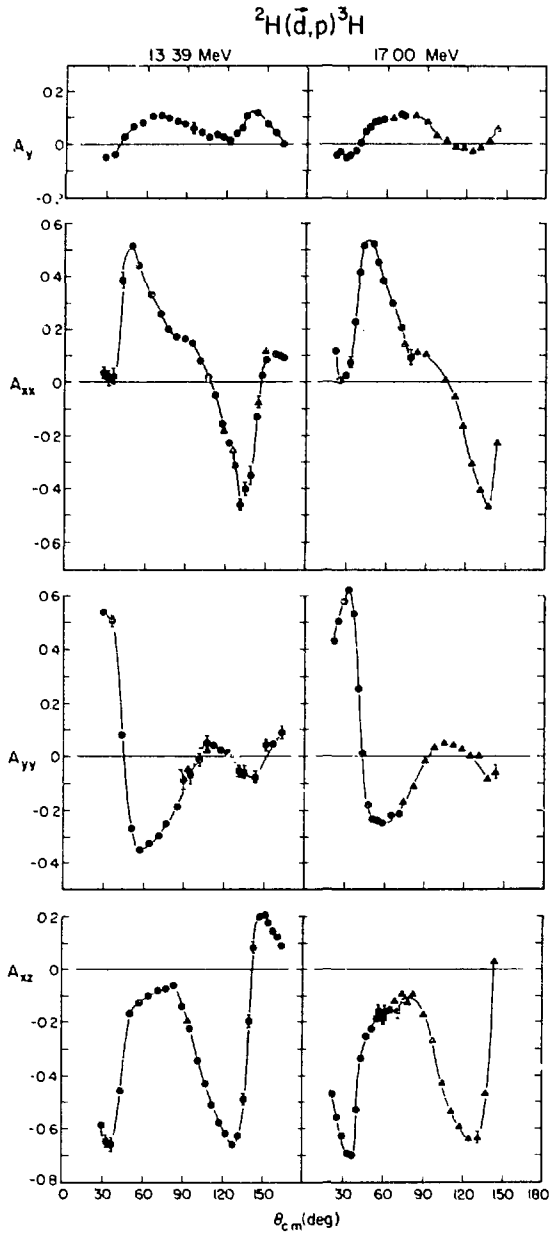

Fig. 2.
Analyzing powers for $^2H(\vec{d},p)^3H$ at 13.39 and 17.00 deuteron bombarding energies. The circles show data obtained by detecting protons, and the triangles show data obtained by detecting tritons. A few triangles that would overlap circles have not been plotted. The relative errors are indicated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

and other small contributions[12] yield an overall error in the beam energy of ±25 keV for the 13.39-MeV data and ±15 keV for the rest. A simple estimate of the beam energy spread (FWHM) as a result of 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. No data adjustments have been made for beam energy resolution or uncertainty, for angular resolution or uncertainty, or for multiple scattering.

IV. DISCUSSION

As was mentioned in Sec. I, a simple direct-neutron-transfer process for the $^2H(\vec{d},p)^3H$ reaction is expected[1] to be manifested in the following symmetries: A_{xx} and A_{yy} should be symmetric about 90° (c.m.), and A_y and A_{xz} should be antisymmetric about 90° (c.m.). It is known that the vector analyzing power A_y shows marked deviations from antisymmetry at low energies,[15] with an increasing trend toward antisymmetry as E_d is raised toward 30 MeV.[1,16,17] There is a hint of such a trend for A_y in our data depicted in Fig. 2. It is seen, however, that the tensor analyzing powers show no trend toward such direct-reaction shapes; in fact A_{xx} and A_{xz} show a significant component of a symmetry opposite to that expected. It appears, therefore, that if the reaction mechanism in this energy region involves important contributions from states in ^4He, the influence of such states is stronger on the tensor analyzing powers than on the vector analyzing power.

In Fig. 3 we display our comparisons of the charge-symmetric reactions $^2H(\vec{d},p)^3H$ and $^2H(\vec{d},n)^3He$. Very little difference between the two is observed at these energies. This is in contrast to the work of Ref. 2 in the lower energy range of 2.5-11.5 MeV. It appears, therefore, that whatever the mechanism for breaking isospin symmetry may be at the lower energies, its effect has largely disappeared above 15 MeV.

TABLE II

ANALYZING POWERS FOR $^2H(\vec{d},p)^3H$ AT LAB ENERGY 17.00 MeV

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)	A_y	A_{xx}	A_{yy}	A_{xz}
15.0	22.16	−0.040(07)[a]	0.116(11)[a]	0.434(09)[a]	−0.466(14)[a]
17.5	25.83	−0.030(08)	0.004(12)	0.508(10)	−0.553(11)
20.0	29.48	−0.050(09)	0.025(13)	0.582(11)	−0.629(13)
22.5	33.12	−0.043(11)	0.075(21)	0.623(13)	−0.693(18)
[illegible]	36.74	−0.025(12)	0.229(17)	0.532(16)	−0.700(15)
27.5	40.35	0.005(12)	0.417(15)	0.254(18)	−0.525(18)
30.0	43.93	0.042(11)	0.517(16)	0.011(18)	−0.331(19)
32.5	47.49	0.063(10)	---	−0.175(18)	−0.254(17)
35.0	51.02	0.083(10)	0.520(14)	−0.230(17)	−0.226(16)
37.5	54.53	0.086(10)	0.451(15)	−0.234(17)	−0.188(16)
38.8	56.34	---	---	---	−0.159(21)
40.0	58.01	0.092(10)	0.382(15)	−0.244(17)	−0.162(20)
41.25	59.74	---	---	---	−0.186(22)
42.5	61.46	---	---	---	−0.161(22)
45.0	64.87	0.097(10)	0.300(16)	−0.213(17)	−0.151(16)
41.25[b]	68.73	---	---	---	−0.121(16)
50.0	71.60	0.111(11)	0.206(19)	−0.212(20)	−0.156(29)
40.0[b]	73.87	0.109(07)	0.145(10)	−0.165(11)	−0.090(13)
38.8[b]	78.00	---	---	---	−0.124(20)
55.0	78.17	---	0.095(27)	---	---
37.5[b]	82.47	0.110(08)	0.111(11)	−0.105(12)	−0.094(17)
35.0[b]	90.28	0.083(10)	0.104(11)	−0.019(16)	−0.172(17)
32.5[b]	97.60	0.031(08)	---	0.033(11)	−0.266(10)
30.0[b]	104.61	0.012(07)	0.008(10)	0.050(10)	−0.428(13)
27.5[b]	111.38	−0.012(07)	−0.054(10)	0.043(10)	−0.531(09)
25.0[b]	117.99	−0.019(07)	−0.166(13)	0.026(10)	−0.595(09)
22.5[b]	124.46	−0.030(07)	−0.307(12)	0.002(10)	−0.636(11)
20.0[b]	130.84	−0.015(07)	−0.405(16)	0.001(11)	−0.634(21)
17.5[b]	137.13	0.010(13)	−0.467(16)	−0.084(19)	−0.467(19)
15.0[b]	143.36	0.054(16)	−0.227(19)	−0.056(25)	0.029(19)

[a]See footnote a of Table I.

[b]See footnote b of Table I.

TABLE III

ANALYZING POWERS FOR $^2H(\vec{d},p)^3H$ AT LAB ENERGIES 15.50 AND 17.00 MeV

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)[a]	A_y	A_{xx}	A_{yy}	A_{xz}
			15.50 MeV		
37.5	83.95	0.107(08)[b]	0.159(11)[b]	−0.125(12)[b]	−0.069(11)[b]
35.0	91.49	0.074(08)	0.106(11)	−0.026(11)	−0.168(11)
32.5	98.63	0.039(08)	0.082(10)	0.025(11)	−0.283(10)
30.0	105.49	0.011(07)	0.015(10)	0.031(10)	−0.433(10)
27.5	112.14	−0.017(07)	−0.074(09)	0.051(09)	−0.535(09)
25.0	118.65	−0.007(07)	−0.171(09)	0.037(10)	−0.596(09)
22.5	125.03	−0.003(08)	−0.298(09)	0.004(10)	−0.636(09)
			17.00 MeV		
37.5	82.47	0.112(08)	0.094(12)	−0.084(12)	−0.077(12)
35.0	90.28	0.086(09)	0.107(12)	−0.006(12)	−0.152(12)
32.5	97.60	0.032(08)	0.061(11)	0.033(11)	−0.293(11)
30.0	104.61	0.009(07)	0.008(10)	0.056(10)	−0.416(10)
27.5	111.38	−0.015(07)	−0.066(10)	0.036(09)	−0.503(09)
25.0	117.99	−0.033(07)	−0.169(09)	0.048(09)	−0.569(11)
22.5	124.46	−0.022(09)	−0.284(12)	0.009(11)	−0.592(12)

[a]Tritons were detected; however, the c.m. angle refers to the proton.

[b]See footnote a of Table I.

TABLE IV

ANALYZING POWERS FOR $^2H(\vec{d},n)^3He$ AT LAB ENERGIES 15.50 AND 17.00 MeV

θ_{lab} (deg)	$\theta_{c.m.}$ (deg)[a]	A_y	A_{xx}	A_{yy}	A_{xz}
			15.50 MeV		
37.5	80.63	0.108(08)[b]	0.181(10)[b]	−0.153(11)[b]	−0.060(10)[b]
35.0	88.79	0.092(08)	0.162(11)	−0.078(11)	−0.121(11)
32.5	96.36	0.058(08)	0.115(10)	0.005(11)	−0.264(10)
30.0	103.55	0.016(07)	0.050(09)	0.059(10)	−0.402(09)
27.5	110.48	0.005(07)	−0.018(09)	0.049(09)	−0.517(09)
25.0	117.21	−0.006(07)	−0.151(09)	0.040(10)	−0.595(09)
22.5	123.79	−0.011(07)	−0.244(09)	0.005(10)	−0.656(09)
20.0	130.26	−0.006(08)	−0.356(09)	−0.007(12)	−0.670(10)
			17.00 MeV		
37.5	79.17	0.118(08)	0.132(11)	−0.135(11)	−0.085(11)
35.0	87.63	0.102(08)	0.122(11)	−0.046(12)	−0.103(11)
32.5	95.40	0.061(08)	0.113(11)	−0.003(11)	−0.241(11)
30.0	102.74	0.015(07)	0.047(10)	0.063(10)	−0.410(10)
27.5	109.78	−0.014(07)	−0.034(09)	0.060(09)	−0.516(09)
25.0	116.61	−0.029(06)	−0.146(09)	0.032(09)	−0.569(09)
22.5	123.28	−0.035(06)	−0.244(09)	0.022(09)	−0.616(09)
20.0	129.82	−0.026(07)	−0.358(09)	−0.007(10)	---

[a] ^3He particles were detected; however, the c.m. angle refers to the neutron.

[b] See footnote a of Table I.

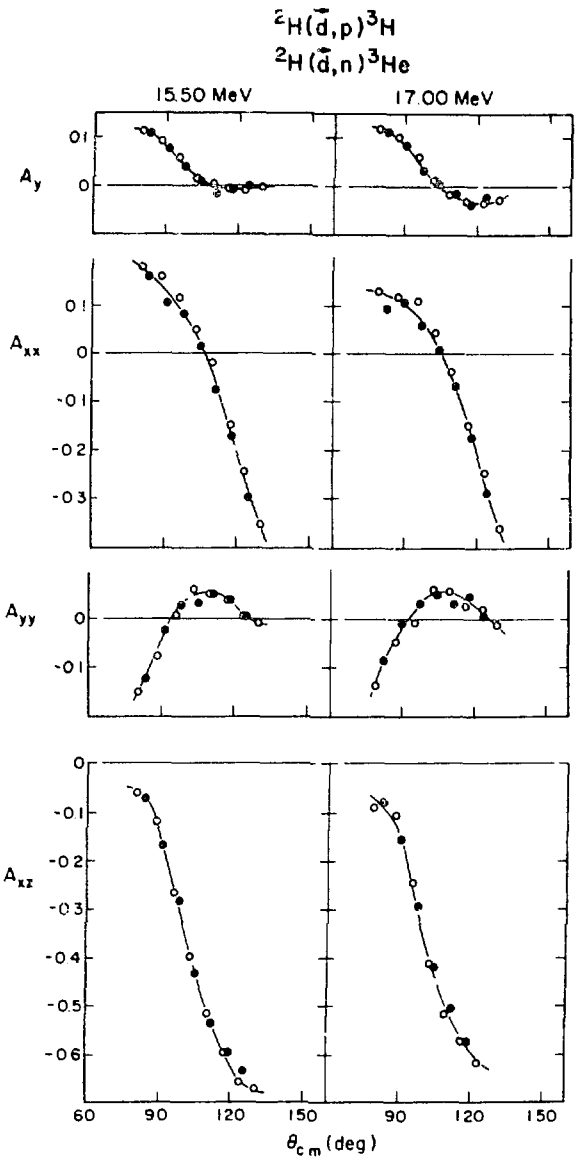

Fig. 3.
Analyzing powers for $^2H(\vec{d},p)^3H$ (solid circles) and $^2H(\vec{d},n)^3He$ (open circles) at 15.50 and 17.00 MeV. The statistical errors are usually smaller than the size of the plotting symbol. The smooth curves are to guide the eye.

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