Kinematically incomplete three-nucleon breakup reaction $^1H(\vec{d},p)pn$ at 16 MeV

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We have measured the analyzing powers A_y, A_{xx}, A_{yy}, and A_{xz} for the kinematically incomplete three-nucleon breakup reaction $^1H(\vec{d},p)pn$ at a deuteron bombarding energy of 16.0 MeV. Similar data for the elastic channel were obtained at the same time. Data were acquired at laboratory angles from 15.0° to 42.5°. The detected proton continua extended over a range in excitation energy E^* for the residual pn system, and this range varied from $E^* = 0$–2.6 MeV at 15.0° to $E^* = 0$–0.2 MeV at 42.5°. The experimental energy resolution was about 150 keV (lab). The breakup tensor analyzing powers attain magnitudes as large as about 0.2 at the lowest excitation energies. Faddeev calculations have been performed for a variety of final-state configurations having $E^* = 0$ and 200 keV and indicate that a full kinematically incomplete calculation would probably show no major disagreement with the data.

[NUCLEAR REACTIONS $^1H(\vec{d},p)pn$, $E=16$ MeV; measured $A_y(\theta,E_p)$, $A_{xx}(\theta,E_p)$, $A_{yy}(\theta,E_p)$, $A_{xz}(\theta,E_p)$. Faddeev calculations for $E_p=0$ and 200 keV.]

I. INTRODUCTION

Studies of the three-nucleon system are of interest because they provide a means of studying certain aspects of the nucleon-nucleon (NN) interaction, such as its off-energy-shell properties or the nature of possible three-body forces, that cannot be studied in reactions involving just two nucleons. They have the advantage over many-particle reactions that the observables can be compared with the results of exact three-body calculations, which use as input the nuclear force between individual pairs of nucleons. Consequently, the experimental three-nucleon data can be used to test the quality of the assumed NN interaction and perhaps to discover whether or not more complicated forces, including three-body forces, are needed to explain the observed phenomena. Polarization observables, such as analyzing powers, are of particular interest in this context because they are expected to contain more information about the dynamics of the breakup reaction than do the more commonly measured spin-averaged breakup cross sections.

We have, therefore, been engaged in a series of three-nucleon-breakup experiments in which we bombard protons with 16-MeV polarized deuterons. In the course of this work, we have developed a formalism[1] for describing analyzing powers in reactions with three particles in the final state, have performed kinematically incomplete[2] and kinematically complete[3,4] breakup experiments, and have made a number of three-body calculations[3-5] for comparison with our data, using the Faddeev code of Doleschall. In the present paper we report on our kinematically incomplete experiment.

II. EXPERIMENT

The experiment was performed at the Los Alamos Scientific Laboratory Van de Graaff facility,[6] and made use of the FN tandem Van de Graaff accelerator and the Lamb-shift polarized ion source.[7,8] The scattering chamber used was a 61-cm cube,[9,10] 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 used only two of the turntables, but did rotate the supercube as part of the data-taking procedure.

A 9.7-cm-diam gas target cell was used for the measurements. This target cell has a beam-entrance snout about 6 cm long. A 2.5-μm-thick Havar[11] foil covered the 2.5-mm-diam beam-entrance aperture on the snout, and a 7-μm-thick Kapton[12] foil covered the 300° cell opening through which the beam and detected particles emerged. The target was operated at a pressure near 300 Torr and at room temperature. Temperature and pressure were monitored, and the target gas was flushed occasionally.

A polarized deuteron beam of 8 to 120 nA was used during the experiment. At the most forward angles, the beam current had to be limited to keep the counting losses at an acceptable level, generally below 10%. These losses, coming mainly from deadtime in the analog-to-digital converters, were measured and used to correct the data.

In reactions involving three-body final states, parity conservation[13] does not require any of the analyzing powers to vanish for the general kinematically *complete* situation; however in a kinematically *incomplete* experiment, in which only one of the three particles in the final state is detected, parity conservation requires that the analyzing powers A_x, A_z, A_{xy}, and A_{yz} vanish,[1] just as they do for two-body final states. Therefore, we employed the data taking procedure we have used many times in the past for two-body reactions. That procedure is a modified version of the "three spin state method"[14] and is thoroughly described in Refs. 15 and 16. Briefly it consists in orienting the supercube and the spin quantization axis appropriate to the analyzing power (or combination of analyzing powers) to be measured and then accumulating data as the spin state of the deuteron beam is stepped through its three (nearly pure) projections of $m_I = +1$, 0, and -1. The fraction of the total beam that is actually polarized was determined by the quench-ratio technique[17,18] and typically had values near 0.82. This method results in the beam polarization being known to about ±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 LASL Van de Graaff MODCOMP IV/25 computer system.

Each of the two detector assemblies, mounted symmetrically on either side of the incident beam, consisted of an 86.5-μm ΔE and a 1500-μm E silicon surface barrier detector mounted behind a standard gas-target collimator arrangement which had an angular acceptance of $\frac{1}{2}$° full width at half maximum (FWHM). The detectors were cooled with thermoelectric devices. A multiple-input analog-to-digital converter was used for the four detectors, and protons were identified by setting appropriate windows on two-dimensional E vs ΔE computer displays of the digitized signals. A proton pulse-height spectrum is shown in Fig. 1.

The experimental energy resolution, inferred from the width of the proton group arising from the elastic scattering $^1H(\vec{d},p)^2H$, was found to be about 130 keV for one detector assembly and 150 keV for the other. In terms of the excitation energy E^* of the residual pn system, the energy resolution is in the range 70–90 keV.

An energy calibration was carried out for each detector assembly by measuring the position of the elastic proton group in the spectrum as the detector angles were varied over a range large enough to yield proton energies appropriate for analysis of the continuum data. This procedure

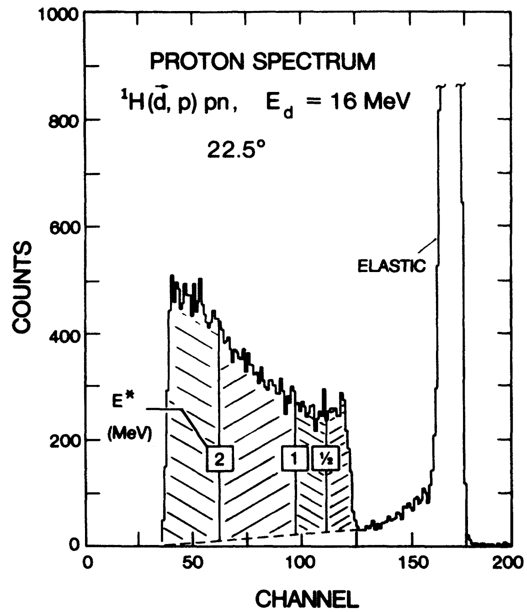

FIG. 1. Proton spectrum from $^1H(\vec{d},p)pn$ at 22.5° (lab), at a deuteron bombarding energy of 16 MeV, and for the deuteron spin state $m_I = 0$. Excitation energies $E^* = 0.5$, 1.0, and 2.0 MeV are indicated.

yields a relationship between the proton pulse height and the calculated proton energy at the center of the target. In this way, the calibration directly determines the energy of interest, automatically taking into account the energy loss of the reaction protons as they traverse the gas target and exit foil.

III. DATA REDUCTION

The elastic data were reduced in the usual way.[14-16] For the breakup data a computer code was used to calculate and set channels that divided the proton continuum into equal steps in E^*. The data were processed initially using both a 100-keV step and a 200-keV step in E^*. A comparison of the results for the 100-keV step size with those for the 200-keV step size is shown in Fig. 2, in which A_{xz} at 27.5° (lab) is plotted vs E^*. One readily sees that it is sufficient to use a 200-keV step size to represent the E^* dependence, and that was the step size chosen for the final reduction of the breakup data to analyzing powers.

The measurement of analyzing powers in a continuum is subject to an error from "binning" that is not present when well resolved discrete groups are measured. This results from drifts in the energy calibration and/or resolution functions of the two detectors, and, to some extent from "quantization errors" associated with selection of a discrete number of channels for summing. For our analysis using 200-keV steps, the summing interval was typically 9 or 10 channels. Thus, a rounding difference of one channel between the spectra recorded in the two detector stacks could result in a yield difference of 10% or so in the corresponding summing bins. However, this does not seriously affect the analyzing powers since our method extracts an observed quantity from each detector stack separately, and only then are the two results combined. If the electronics and accelerator were perfectly stable, the binning problem would affect only the energy resolution of the measured quantities. However, drifts during a three-spin counting sequence could introduce genuine errors. These effects can best be estimated from the consistency of the data, which appears to be better than ± 0.02 for each of the analyzing-power observables. There is also a scale error of $\pm 1.5\%$ from the determination of the absolute beam polarization.

The uncertainty in the energy loss of the deuteron beam as it penetrates to the center of the gas target, and other small contributions, yield an overall error in the beam energy of ±15 keV. A simple estimate of the beam energy spread as a result of straggling in the target gas and cell entrance foil gives 35 keV (FWHM). No corrections for energy resolution, angular resolution, or multiple scattering have been made to the data, and such corrections should be quite small.

IV. EXPERIMENTAL RESULTS

As was mentioned, Fig. 2 shows the variation of A_{xz} with E^* at 27.5° (lab). At other angles, A_{xz} shows a similar variation with E^*. At $E^* = 100$ keV, A_{xz} has values in the range of about −0.1 to −0.2, and for $E^* > 1.5$ MeV A_{xz} tends to reach a plateau at a value of about +0.1. At 25° (lab) A_{xx} also shows a rather rapid variation versus E^*, dropping from 0.06 to −0.01 as E^* increases; however, this effect is not nearly so striking as that exhibited by A_{xz}. In addition, the variation of A_{xx} with E^* changes as a function of laboratory angle much more than it does for A_{xz}. A_{yy} tends to drop from about 0.1 to about 0.02 as E^* increases, and the values for A_y are usually consistent with zero.

In Fig. 3 we compare angular distributions of the experimental elastic analyzing powers (represented by curves) with those of the breakup reaction (points) for the E^* interval 0–200 keV. For the breakup data there is a kinematic spread in the c.m. angle for a finite E^* step, which spread (not shown) varies from about 1° to 4° over the angular range of Fig. 3. For A_{xx} and A_{xz}, large differences between the elastic and inelastic values are observed. Such differences are not particularly surprising, because elastic scattering leads to a pure triplet pn final state, whereas the breakup reaction near threshold should have a significant

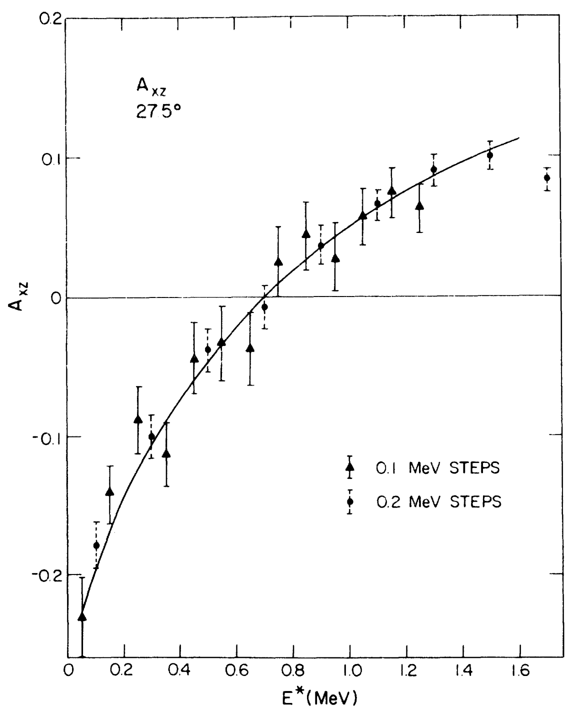

FIG. 2. Measured analyzing power A_{xz} at 27.5° (lab) vs excitation energy E^* for 100- and 200-keV intervals in E^*. The curve is to guide the eye.

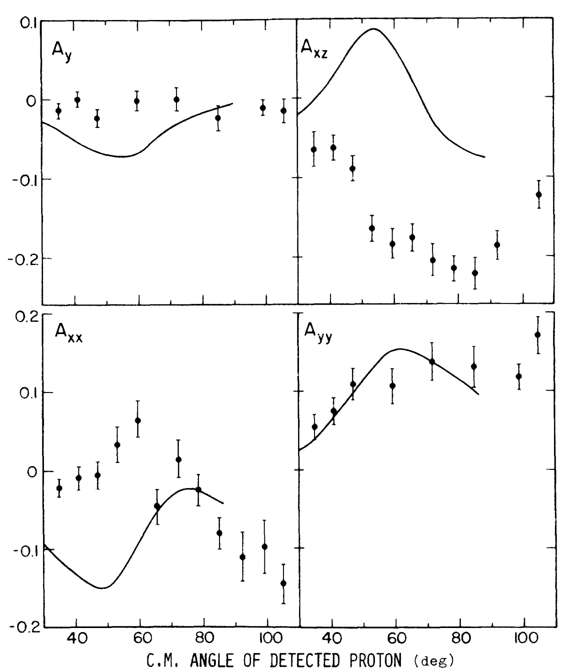

FIG. 3. Measured analyzing-power angular distributions for the elastic scattering $^1H(\vec{d},p)^2H$ (represented by smooth curves) and for the breakup reaction $^1H(\vec{d},p)pn$ with $E^* = 0$–200 keV (points).

contribution from the singlet pn state. However, previous $\vec{p}+d$ results[19] at 22.7 MeV and $\vec{d}+d$ results[20] at 21 MeV showed that the breakup vector analyzing powers summed over the E^* interval 0–1 MeV were smaller in magnitude than, but similar in angular shape to, the corresponding elastic quantities. This seemed to imply triplet contributions that were unexpectedly more important than indicated by differential cross-section results.[21] From the present experiment, however, one sees that $E^*=0-1$ MeV is far too large an interval to allow clear information about the effect of the singlet state to be extracted. Such a conclusion was also suggested by Faddeev calculations.[22] Except for a recent measurement[23] of the proton observable A_y at 21 MeV and 75° (lab), the present data are the first analyzing powers reported with energy resolution better than about 0.5 MeV.

Earlier data obtained at LASL on this process were presented at the Few Nucleon Conference in Graz.[24] The present data are of higher quality and, in particular, have better energy resolution. The values of A_{xz} at low E^* approximately double when the summing interval is reduced from 500 keV (Graz) to 200 keV (present analysis). Data obtained with still finer intrinsic resolution in E^* than the 70–90 keV employed in this experiment might reveal additional information, but from the comparison of the results in Fig. 2 using 100- and 200-keV intervals it appears unlikely.

The numerical data and additional figures from this experiment are given in a Los Alamos report.[25] There we give not only the analyzing powers A_y, A_{xx}, A_{yy}, and A_{xz}, but also the differential cross sections for both the elastic and breakup channels at $E_d=16$ MeV. In addition, data are presented for A_{xz} at several angles with $E_d=12$, 13, 14, and 15 MeV.

V. FADDEEV CALCULATIONS

We have performed some Faddeev calculations of $\vec{d}+p$ breakup observables at $E_d=16$ MeV to compare with the present data. The Doleschall code[26,27] was used on a CDC 7600 computer at Los Alamos. This code solves the AGS form[28] of the Faddeev equations using as input a separable NN interaction that has been adjusted to reproduce the NN phase parameters.[29,30] We have neglected the Coulomb force in these calculations.

A general separable two-particle interaction in momentum space can be written as the following sum of products of form factors

$$\langle p(LS)J|V|p'(L'S')J\rangle=\sum_{nn'}^{M} g_{n(LS)J}(p)\lambda_{nn'}g_{n'(L'S')J}(p')\,, \quad (1)$$

where $\lambda_{nn'}$ are the elements of a symmetric matrix, and the sum runs from 1 to M. We choose a form factor similar to that of Ref. 27:

$$g_{n(LS)J}(p)=p^L\sum_{i=0}^{N}\gamma_{nLi}p^{2i}\Big/\prod_{i=0}^{N+L}(1+\beta_{nLi}p^2)\,, \quad (2)$$

with $\beta_{nLi}\geq 0$. The NN relative momentum p is of the Lovelace form[26] and is expressed in $\mathrm{MeV}^{1/2}$. One-term ($M=1$) interactions were used for the following NN states: ${}^1S_0(nn)$, ${}^1S_0(np)$, ${}^1P_1$, ${}^3P_{2,1,0}$, ${}^1D_2$, and ${}^3D_{3,2}$. Of these, the S-state interactions fit the phase shifts of Ref. 29, and the P- and D-state interactions fit the np phase shifts of Ref. 30. The fits are quite good up to an NN laboratory energy of about 50–100 MeV for the S and ${}^3P_0$ interactions and about 300–400 MeV for the D and other P interactions. The constants of the interactions [Eqs. (1) and (2)] are given in Tables I and II. In addition, a four-term ($M=4$) ${}^3S_1$-${}^3D_1$ tensor interaction, which is denoted by $4T4B$ and whose constants are given in Tables III and IV, was used. This interaction, which yields a 4% D-state probability for the deuteron, is considerably better than several other ${}^3S_1$-${}^3D_1$ interactions that have been used previously. The force $4T4B$ fits well the ${}^3S_1$ and ${}^3D_1$ phases up to 300–400 MeV, and also yields a reasonable fit to the mixing parameter ϵ_1 of Ref. 29. In Fig. 4 we show a comparison of ϵ_1 with the empirical values of Ref. 29 for $4T4B$ and two other interactions. The $YY4$ interaction is of Yamaguchi[31] form (one term) and is the interaction of Ref. 32 that has a 4% deuteron

TABLE I. Constants in Eqs. (1) and (2) for the P-state NN interaction. For all entries we have $n=n'=1$, $N=2$, and $L=1$. A number in parenthesis is the power of 10 by which the immediately preceding number is to be multiplied. The units for β_{nLi} are MeV^{-1}, for γ_{nLi} are $\mathrm{MeV}^{-i-L/2}$, and for $\lambda_{nn'}$ are $\mathrm{MeV}^{-1/2}$.

State	i	β_{nLi}	γ_{nLi}	$\lambda_{nn'}$
${}^1P_1$	0	5.000(−2)	1.0	1.382(−2)
	1	5.000(−2)	4.379(−3)	
	2	3.793(−3)	1.209(−3)	
	3	2.946(−3)		
${}^3P_0$	0	3.778(−2)	1.0	−5.897(−3)
	1	3.488(−2)	5.963(−2)	
	2	3.488(−2)	3.800(−3)	
	3	3.034(−2)		
${}^3P_1$	0	5.000(−2)	1.0	8.820(−3)
	1	5.000(−2)	3.640(−2)	
	2	2.445(−3)	8.634(−4)	
	3	2.445(−3)		
${}^3P_2$	0	1.356(−2)	1.0	−6.227(−4)
	1	6.205(−3)	1.289(−2)	
	2	2.838(−3)	7.248(−5)	
	3	2.838(−3)		

TABLE II. Constants in Eqs. (1) and (2) for the NN interaction in the states $^1S_0$, $^1D_2$, $^3D_2$, and $^3D_3$. For all entries we have $n=n'=1$. For $^1S_0$ we have $N=0$ and $L=0$, for $^1D_2$ and $^3D_2$ we have $N=2$ and $L=2$, and for $^3D_3$ we have $N=1$ and $L=2$. A number in parenthesis is the power of 10 by which the immediately preceding number is to be multiplied. The units for β_{nLi} are MeV^{-1}, for γ_{nLi} are $\mathrm{MeV}^{-i-L/2}$, and for $\lambda_{nn'}$ are $\mathrm{MeV}^{-1/2}$. The S-state interactions yield the singlet scattering lengths $a_{nn} = -16.97$ fm and $a_{np} = -23.67$ fm and the singlet effective ranges $r_{nn} = 2.84$ fm and $r_{np} = 2.51$ fm.

State	i	β_{nLi}	γ_{nLi}	$\lambda_{nn'}$
$^1S_0(nn)$	0	1.890(−2)	1.0	−1.585(−1)
$^1S_0(np)$	0	1.542(−2)	1.0	−1.481(−1)
$^1D_2$	0	2.229(−2)	1.0	−5.876(−5)
	1	1.362(−2)	−5.526(−3)	
	2	1.362(−2)	4.071(−4)	
	3	1.362(−2)		
	4	0		
$^3D_2$	0	3.187(−2)	1.0	−2.662(−4)
	1	1.813(−2)	2.996(−3)	
	2	1.813(−2)	6.776(−4)	
	3	1.813(−2)		
	4	0		
$^3D_3$	0	2.546(−2)	1.0	−5.824(−6)
	1	3.220(−3)	1.091(−2)	
	2	3.220(−3)		
	3	3.220(−3)		

TABLE III. Constants in Eq. (2) for the $^3S_1$-$^3D_1$ tensor NN interaction. For all entries we have $M=4$ and $N=1$. A number in parenthesis is the power of 10 by which the immediately preceding number is to be multiplied. The units for β_{nLi} are MeV^{-1} and for γ_{nLi} are $\mathrm{MeV}^{-i-L/2}$. This tensor interaction, including the constants in Table IV, yields a deuteron binding energy of 2.225 MeV, a deuteron quadrupole moment of 0.286 fm^2, a deuteron D-state probability of 0.04, a deuteron asymptotic D- to S-state ratio of 0.026, an NN triplet scattering length of 5.39 fm, and an NN triplet effective range of 1.76 fm.

L	n	i	β_{nLi}	γ_{nLi}
0	1	0	2.048(−2)	1.0
		1	1.941(−2)	2.738(−2)
0	2	0	5.000(−2)	1.0
		1	5.000(−2)	8.445(−4)
0	3	0	8.675(−3)	−1.0
		1	2.081(−3)	1.569 032(−2)
0	4	0	5.000(−2)	−1.0
		1	5.000(−2)	6.072 741(−2)
2	1	0	1.037(−2)	−1.188 63(−2)
		1	1.037(−2)	−4.186 789(−4)
		2	1.037(−2)	
		3	1.012(−2)	
2	2	0	5.000(−2)	3.392 733(−2)
		1	3.110(−3)	2.861 958(−4)
		2	3.110(−3)	
		3	3.110(−3)	
2	3	0	1.538(−2)	−7.358(−2)
		1	1.538(−2)	9.828 159(−4)
		2	1.538(−2)	
		3	7.211(−3)	
2	4	0	2.244(−2)	1.270(−1)
		1	8.978(−3)	−1.584 534(−3)
		2	8.978(−3)	
		3	8.978(−3)	

D-state probability. The $2T4$ interaction is a two-term force also yielding a 4% D-state probability and was used, for example, in Ref. 33. It is seen that the $4T4B$ interaction gives the best reproduction by far of the empirical variation of ϵ_1 with energy.

With the NN force specified by Eqs. (1) and (2) and Tables I–IV, we then solve the Faddeev equations for values of the total angular momentum in the incident $d+p$ channel of $\frac{1}{2}^-, \frac{1}{2}^+, \ldots, \frac{7}{2}^+, \frac{9}{2}^-$. For the remaining values of $\frac{9}{2}^+, \ldots, \frac{17}{2}^-$ accurate approximations are used: for the breakup calculation the solution is taken to be equal to the inhomogeneous term, and for the elastic calculation[26] a one step iteration is used. The results of the elastic calculation are not shown here, but do agree well with our data.

When calculating breakup observables, the three-particle configuration must be completely specified, as in a kinematically complete experiment. No automatic provision exists in the code for calculating the results of a kinematically incomplete experiment, which requires integrating over all allowed configurations of the undetected particles. Of course, it is possible to simulate such an experiment in a coarse way by repeating the calculations for a number of different allowed

TABLE IV. The matrix elements $\lambda_{nn'}$ of Eq. (1) for the $^3S_1$-$^3D_1$ tensor NN interaction. The units for $\lambda_{nn'}$ are $\mathrm{MeV}^{-1/2}$. See also the heading for Table III.

n \ n'	1	2	3	4
1	−1.715 321(−1)	0	0	0
2	0	1.776(−1)	−3.885(−2)	−4.202(−3)
3	0	−3.885(−2)	2.417(−1)	−7.474(−2)
4	0	−4.202(−3)	−7.474(−2)	−2.029(−2)

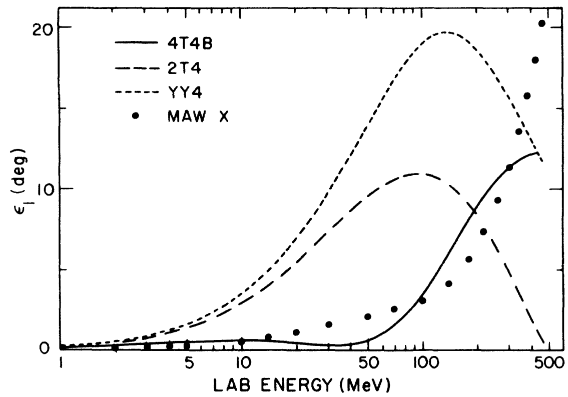

FIG. 4. The ${}^3S_1-{}^3D_1$ mixing parameter ϵ_1 for the NN system as given by three interactions: $4T4B$ (the four-term interaction used in the present calculations), $2T4$ (a two-term interaction), and $YY4$ (a Yamaguchi interaction), and by the MAW X (Ref. 29) NN phase-shift analysis.

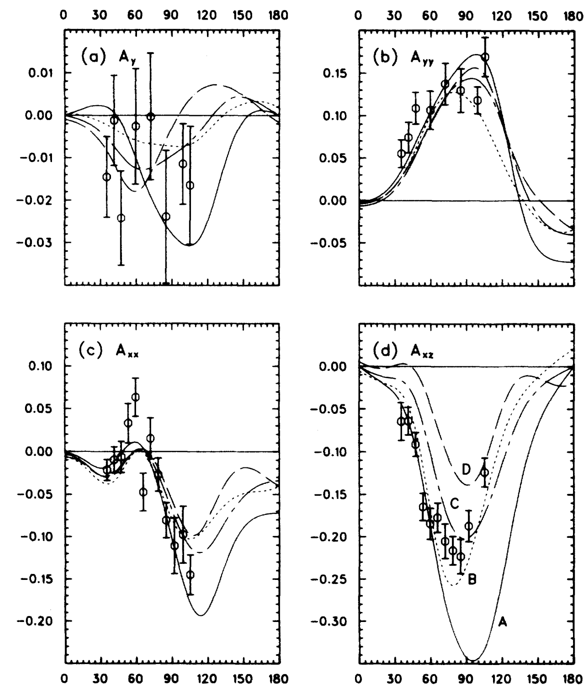

FIG. 5. Analyzing-power angular distributions. The points are experimental data for $E^* = 0$–200 keV. The curves show some results of the present Faddeev calculations. The solid curves [A in panel (d)] are for the unique configuration having excitation energy $E^* = 0$. The other curves [B, C, and D in panel (d)] are for selected configurations having $E^* = 200$ keV. See the text for details.

configurations. This is the procedure we use here to obtain theoretical predictions to compare with our kinematically incomplete data. We focus our attention on the excitation region $0 \leq E^* \leq 200$ keV, and our analyzing-power measurements summed over that interval, which are shown in Fig. 3, are repeated in Fig. 5. Our first calculation was for the final-state-interaction condition $E^* = 0$. The condition $E^* = 0$ uniquely specifies the three-particle configuration for each detected proton angle. The results of that calculation are shown in Fig. 5 as solid curves A [although the labeling A, B, C, and D is indicated only in panel (d) of Fig. 5, any reference to such a label will always be meant to include the corresponding curves in the other panels]. Except for A_{xz}, the $E^* = 0$ calculation does reasonably well in reproducing the trend of the data. We then calculated the analyzing powers for several configurations for which $E^* = 200$ keV. The results for four of these configurations are shown by the remaining three curves in each panel of Fig. 5. For each of these configurations the relative momentum of the undetected pn pair is perpendicular to the c.m. momentum of the detected proton. Curves B and D correspond to configurations in which the two undetected particles lie in the plane determined by the beam direction and the direction of the detected proton (the xz plane[1,14]). The difference between the curves B and D arises from interchanging the positions of the two undetected particles. Curve C results when the two unobserved particles lie in the plane determined by the direction perpendicular to the reaction plane (y axis[1,14]) and the direction of the detected proton in the c.m. system. This single curve actually represents calculations for two configurations related to each other by interchanging the positions of the two undetected particles. We also studied two configurations in which the relative momentum of the unobserved pn pair was parallel to the c.m. momentum of the detected proton. The results for these configurations are not shown in Fig. 5, but lie within or near the range spanned by curves B, C, and D.

The difference in Fig. 5 between curve A and the set B, C, D gives an indication of the calculated E^* dependence of the different analyzing powers at low values of E^*. It is clear that A_{xz} is calculated to have the strongest dependence, with A_{xx} having the next strongest dependence. This is in general agreement with conclusions drawn from our data (Sec. IV and Ref. 25). The configuration dependence of the analyzing powers is indicated by comparison among the curves B, C, and D. Again, it is A_{xz} that shows the strongest dependence.

A proper calculation for comparison with measurements summed over the range $0 \leq E^* \leq 200$ keV would involve averaging the calculations for the configurations studied here plus an infinity of others. Such an approach is not practical with the present code, but our results suggest that the appropriately averaged quantities would agree reasonably well with the experimental data. It appears that Faddeev calculations employing our reasonably complete NN interaction are able to give a satisfactory description of the analyzing powers for small E^* in the kinematically incomplete $^1\mathrm{H}(\vec{d},p)pn$ reaction.

VI. CONCLUSIONS

All the analyzing powers allowed by parity conservation have been measured for the kinematically incomplete reaction $^1\mathrm{H}(\vec{d},p)pn$ at a deuteron bombarding energy of 16 MeV. The data were obtained as a function of angle and of excitation energy E^* in the residual pn system. The instrumental resolution in E^* was 70–90 keV. The complete set of data is available in a Los Alamos report[25]; however, in the present paper we have stressed the study of the region of low excitation energy E^* (commonly called the d^* or final-state-interaction region), where the singlet-state pn interaction might manifest itself. In contrast to previous indications in the literature, we have found striking differences between the elastic and breakup analyzing powers, especially for A_{xz} and to a lesser extent for A_{xx}. This difference from past results is attributable to the relatively good energy resolution of the present experiment and to the fact that A_{xx} and, especially, A_{xz} show strong variations with E^*. Because of this variation we conclude that, at the energy of the present experiment, A_{xz} is the analyzing power most sensitive to pn singlet-state contributions.

We have used the Doleschall code to perform Faddeev calculations of the breakup analyzing powers for configurations where the final-state pn pairs have low relative energies. This allowed us to make a brief study of the E^* and configuration dependence of the analyzing powers and to make a semiquantitative comparison with the data. We initially performed a breakup calculation for $E^* = 0$ and were able to reproduce the experimental data reasonably well, except for A_{xz} where the calculated values were a factor of 2 larger at some angles than those actually measured. We then made calculations for six different configurations of the final-state nucleons, each with $E^* = 200$ keV, and observed a strong dependence of A_{xz} on E^* and on the choice of configuration. Although precise quantitative conclusions are difficult, it appears that the discrepancy between the energy-averaged experimental results and the zero-energy calculation can be accounted for by this type of strong energy and configuration dependence. With regard to the other analyzing powers, we observed a weaker configuration dependence, although the calculations at $E^* = 200$ keV do seem to provide a better representation of our data. Thus, we conclude from this study that averaging kinematically incomplete breakup data over an energy interval even as small as 200 keV can be significant if comparisons are made to calculations at a single energy. Additionally, we find that the analyzing power A_{xz} has the greatest sensitivity to changes in E^* and to the precise configuration of the final-state nucleons. Finally, we conclude that the NN interaction used in the present Faddeev calculations reproduces our kinematically incomplete data satisfactorily.

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