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Angular Distribution and Excitation Function of the Singlet Deuteron in the $d(p,\tilde{d})p$ Reaction*

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The $d(p,pn)p$ reaction has been studied to determine the $d(p,\tilde{d})p$ angular distribution and excitation function for the proton bombarding energy range 7 to 17 MeV. Protons and neutrons were detected in coincidence at the same angle to enhance the detection of $d(p,\tilde{d})p$ events. The spectra were fitted using the density-of-states function of Phillips, Griffy, and Biedenharn for the singlet deuteron, and a flat background arising from reactions other than $d(p,\tilde{d})p$. Angular distributions were taken at 7, 8, 10, 12, 13.5, 15, and 17 MeV. There was forward peaking at all energies, contrary to calculations on the doublet state in n-d scattering by Aaron, Amado, and Yam. The excitation function shows little structure between 7 and 17 MeV.

INTRODUCTION

We have investigated the $d(p,\tilde{d})p$ reaction, where $\tilde{d}$ is defined as a virtual deuteron in which proton and neutron are in an unbound singlet state. Angular distributions were measured at 7, 8, 10, 12, 13.5, 15, and 17 MeV. An excitation function was measured with $\frac{1}{3}$–$\frac{1}{2}$-MeV steps at a lab angle of 25°. This was done by coincidence detection of protons and neutrons at the same angle.

The measurement of cross sections for specific three-body reactions like $d(p,\tilde{d})p$ as a function of angle and bombarding energy may lead to a better understanding of the three-body problem in general. For example, at a recent conference on the three-body problem,[1] several authors discussed searching for excited states of ^{3}He in the excitation functions for the $d(p,\tilde{d})p$ reaction,[2] and pointed out that interpretation of the existing data was difficult because angular distributions for this reaction were not available.

It has become an accepted approach to treat certain cases of three-body breakup as a sequential process.[3-5] For reactions where only three elementary particles are involved this process involves two outcoming particles, which have low relative energy, staying together as a virtual particle (singlet deuteron, diproton, etc.) and breaking up after they are out of the range of interaction with the third particle. In this sequential breakup reaction we call the first part the production reaction, and the second part the breakup reaction. The final-state interaction determines a density of states[3] as a function of breakup energy (see Fig. 7) and a delay time for the decay of the virtual particle. As Niiler points out,[2] this results in a most probable lifetime for the singlet deuteron which is long enough for it to travel far enough away from the third particle to satisfy the assumptions of the sequential breakup model.

Earlier studies of $p+d\rightarrow p+p+n$ have usually involved detecting the two outgoing protons in coincidence.[6] In some of these experiments the emphasis was on investigating the simultaneous breakup model,[5] determining the parameters of the final-state interaction,[7-9] or the shape of the density-of-states function.[2] Others measured the ratios of virtual-particle production, such as singlet versus triplet virtual deuteron.[7,8] In one case,[8,10] angular distributions of singlet and triplet virtual deuterons were measured. This was done with 52-MeV deuterons on protons.

A. Experiment

Figure 1 is a schematic drawing of the experimental scattering area. The neutron detector is drawn larger than scale, in order to show clearly the effect of kinematics on the proton coincidence spectrum. The angle subtended by the neutron detector as seen from the target was 10°. The neutron detector was a $3\frac{1}{2}\times\frac{3}{4}$-in. Pilot B scintillator, mounted on a 5-in. C70133B RCA photomultiplier. The neutron energy was measured by a standard time-of-flight method with a time resolution of 1 nsec. Protons were detected with a surface-barrier detector. The coincidence data were stored in a two-dimensional 64×64 channel array. A detailed description of the electronics involved has been reported previously.[11]

The target was a CD_2 foil of 0.5 or 2 mg/cm^2, depending on the energies of the detected protons. The beam current from the University of Pittsburgh three-stage Van de Graaff accelerator was varied from 10 to 300 nA in order to keep the proton and neutron count rates at 10–30 kHz. The individual runs varied from $\frac{1}{2}$ to 3 h. For normalization, a monitor counted the protons elastically scattered from deuterium at $\theta_{lab}=30°$.

The center arrow in Fig. 1 represents the velocity vector of a singlet deuteron ($\bar{d}$) coming from the target, as in the sequential breakup model. Possible resultant velocity vectors for the proton and neutron, following the $\bar{d}$ breakup, are also shown. From this picture it is clear that singlet deuterons, breaking up in an arbitrary direction, have a larger detection probability when the breakup energy, E_{BU}, is small. This is represented in the peak in the phase-space factor $\rho(E_{BU})$, which is discussed in Appendix B.

B. Data Analysis

In this experiment, the two-dimensional coincidence events were identified by the proton energy E_p, and the flight time difference T_n between the proton and neutron. T_n is a monotonic function of the neutron energy E_n. Because of the much larger neutron flight path it is close to the inverse square root of E_n. It follows from conservation of momentum and energy[5,7,8] that the coincidence events of the reaction under consideration fall along a locus in the T_n-E_p plane. Along this locus the relative energy of the detected proton and neutron varies. With our choice of equal proton and neutron angle the resulting locus in the T_n-E_p plane corresponds to $d(p, p_1n)p_2$ events with low relative p_1-n energy. We shall discuss the yield along this curve as a function of E_{p_1}, and call it a spectrum.

Figure 2 shows three examples of measured spectra. They can be analyzed in terms of a peak due to the singlet deuteron, plus a flat background due to all other reactions. We shall justify this with the help of Fig. 3. Figure 3(a) shows a diagram of the reaction: p_0 is the bombarding proton, p_1 and n are the detected proton and neutron, p_2 is the undetected proton. According to the sequential breakup model any pair of these outgoing particles may form a virtual particle. The density-of-states function ($\mathfrak{D}'$) for these virtual particles is different when they are in a singlet or a triplet state. Figure 3(c) shows the breakup energies for the three possible pairs of outgoing particles, and Fig. 3(b) shows the spectra for all the possible processes. All of the spectra except the simultaneous breakup have been calculated assuming the sequential breakup model, with the virtual particles in s states. Figures 3(b) and 3(c) are calculated for one particular bombarding energy and scattering angle. Within the constraints of this experiment, the qualitative features of the picture do not change for other values of these variables. The region of proton energy that we used for analysis lay within the E_p interval for which the relative p_1-n energy was ≤ 1 MeV, as indicated by the dotted lines in Figs. 3(b) and 3(c). Because of the large breakup energies for the p_1p_2 and p_2n channels within this interval, the applicability of a sequential model to these channels is questionable. Another factor that would change the shape of these curves is a structured angular distribution for the production reaction, since different breakup energies correspond to different angles of emission for the virtual particle. We shall call all reactions, except the p_1n singlet [see Fig. 3(b)], background reactions.

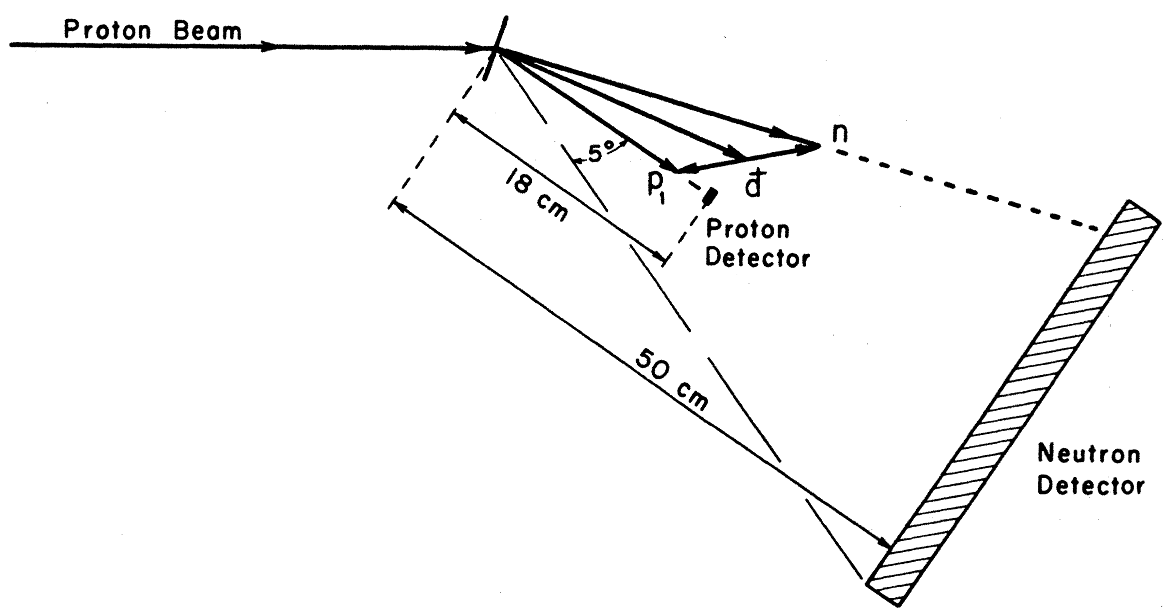

FIG. 1. Schematic representation of the experimental setup. The arrows show the velocities of the different particles in the lab system before and after breakup of the singlet deuteron, $\bar{d}$. The size of the neutron detector has been exaggerated.

Two additional effects may contribute to the background. One is the proximity of a pole in the quasi-free scattering process.[1,7,8,12] In our experiment, events of this type would appear on the tails of the peaks seen in the spectra. However no enhancement was seen in these regions and we therefore assume that this effect does not cause a larger distortion of the spectrum than any of the other background processes. The second possible contribution arises from the breakup in the silicon detector (BUS effect) of elastically recoiling deuterons. The proton coming from this breakup is detected, and the neutron may be detected in coincidence with it. The locus along which these events fall in the T_n-E_p plane is, in our case, unresolved from the $d(p,pn)p$ locus. The deuteron breakup angular distribution has been measured previously[13] and was found to be forward peaked. The BUS effect was measured in a separate experiment. The resulting spectra were flat in the region of interest and the number of BUS events per deuteron correspond to less than 1% of the $d(p,pn)p$ events in our experiment. We conclude that among all imaginable background effects there is none which varies more strongly than the ones shown in Fig. 3(b).

We see that the singlet p_1n peak is by far the most pronounced of all spectra. A discussion of the contribution of the density of states $\mathfrak{D}'$ and the phase-space factor to this peak and the details of the calculations are given in the appendices.

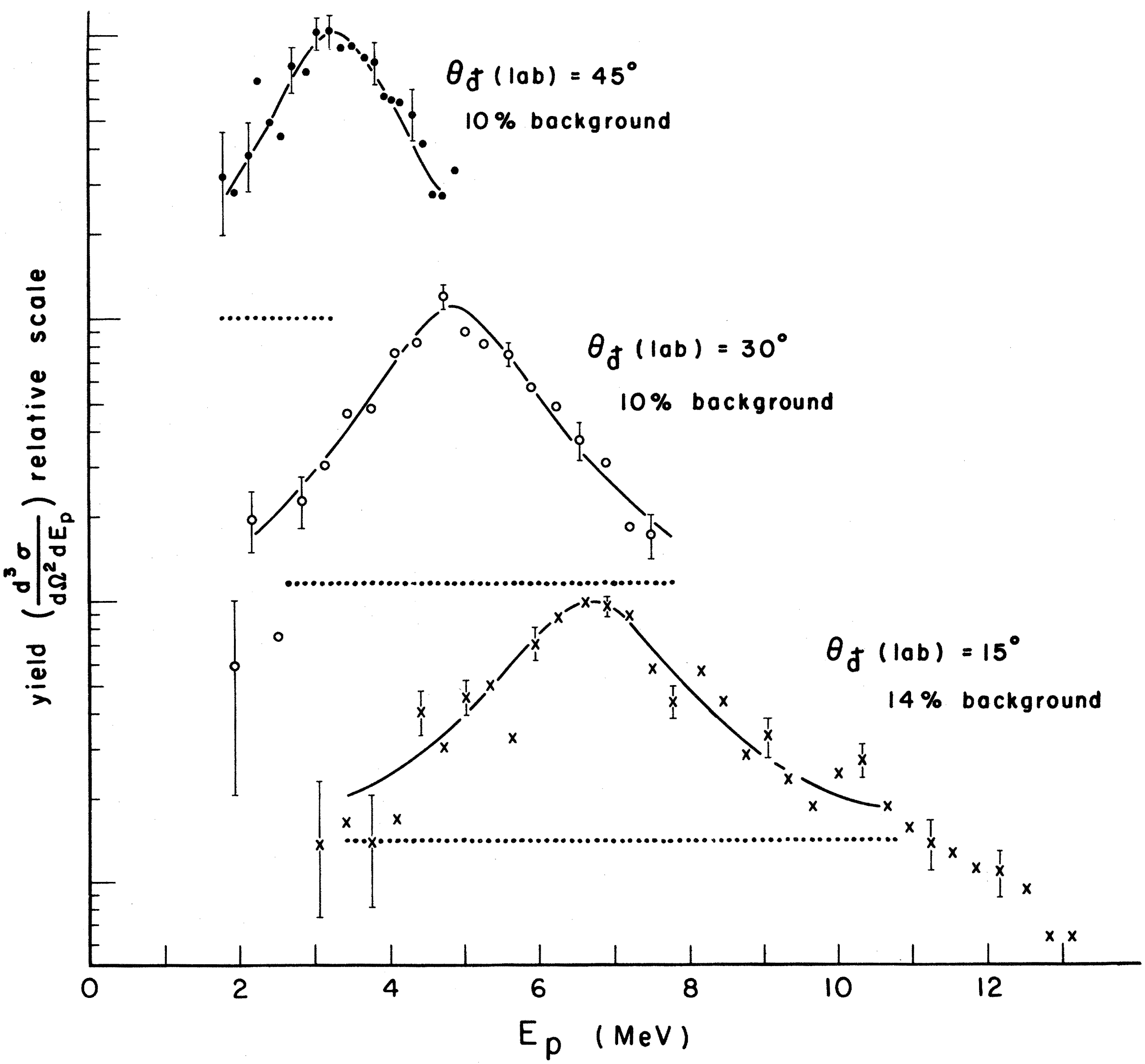

FIG. 2. Spectra at 17-MeV bombarding energy. Continuous curve: calculated fit, including background. Dotted line: corresponding background.

If we assume that all background reactions add up to a flat spectrum, and add this incoherently[7,8] to the p_1n singlet peak, we can define a parameter R_f as the ratio of this background to the total at the position of the peak. R_f can be determined from the data. Considering Fig. 3(b), the assumption of a flat background may not be correct. But we can make an estimate of the maximum error such an assumption can introduce by giving the background the pure shape of the p_1n triplet curve. An analogously defined parameter for this case, R_t, can again be determined from the data. We did this for several spectra of different angle and bombarding energy, and found for R_f and R_t typically 0.1 and 0.17. These small values justify the incoherent addition. Since a more detailed analysis was not possible we analyzed all cases assuming a flat background and assigned the result an error of $\frac{1}{2}R_f$.

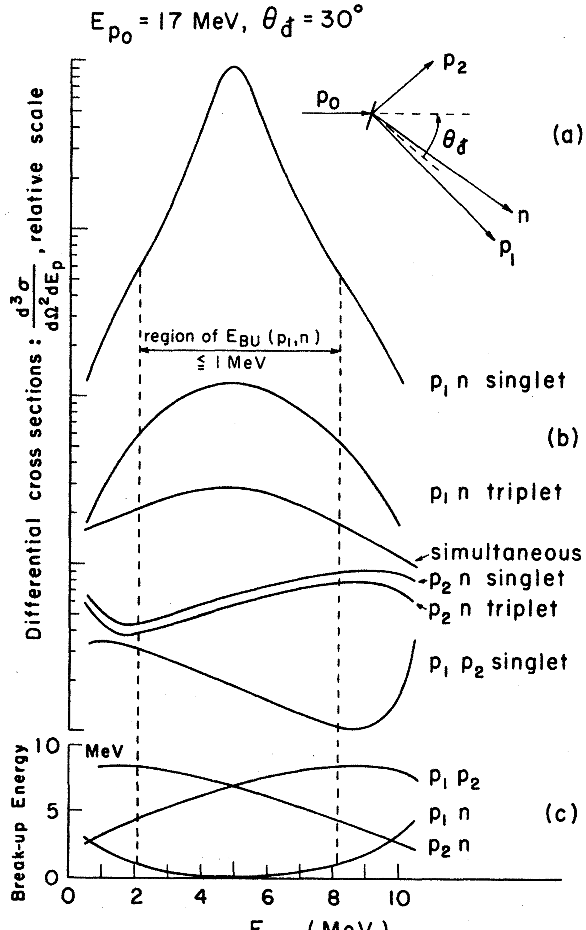

FIG. 3. (a) Schematic diagram of the $d(p, pn)p$ reaction. p_1 and n are the detected proton and neutron, p_2 is the undetected proton. (b) spectra for different sequential breakup processes and simultaneous breakup, as a function of the energy of p_1. (c) breakup energy for the three different pairs of outgoing particles, if they were to come off as a virtual particle.

C. Results

Angular Distributions

Figure 4 shows the measured angular distributions. The cross-section scales are explained in Appendix A. Points for the same energy and angle were taken on different running periods, and show good reproducibility. The error bars are mainly a result of statistics and the background subtraction described in Sec. B. Normalization was obtained by comparing the $\vec{d}$ yield with the yield of elastic p-d scattering in the monitor, and using the elastic p-d cross sections from the literature.[1] The relative cross sections at different energies have an over-all uncertainty of about 15%. A large part of this uncertainty arises from inconsistencies in the measured $d(p,p)d$ cross sections and the interpolation between them.

One common feature of these angular distributions is the forward peak. One might expect[14] that the angular distribution would be similar to the one for the doublet state in n-d scattering as calculated by Aaron, Amado, and Yam.[15] But as shown in Fig. 5 this curve drops over a factor of 10 where we find the peak. For comparison we also show the angular distribution measured by Brückmann *et al.*[10] at a higher energy.

Excitation Function

As mentioned above, much interest was paid to excitation functions for this reaction. Our result is shown in Fig. 6 in both normalizations. The error bars have only been drawn for the data normalized for all E_{BU}. Regarding the indicated errors, there is no resonance of more than 20% for the $d(p, \vec{d})p$ reaction between 7 and 17 MeV. The slight bump at 10 MeV may be due to the "threshold effect" (a combination of increasing phase space and decreasing matrix element) as also noticed and discussed by Niiler.[2,16] Our excitation function does not justify a curve as sharply peaked as that presented by Niiler. His data are in good agreement with ours.

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APPENDIX A: CALCULATION OF THE SINGLET DEUTERON PEAK

The spectrum due to the singlet deuteron, has the following form:

$$S(E_p)=\frac{d\sigma}{d\Omega}\times \mathfrak{D}'(E_{\mathrm{BU}}(E_p))\times\rho(E_p)\times d\Omega_p\times d\Omega_n\,. \quad \text{(A1)}$$

In this equation, $d\sigma/d\Omega$ is the differential cross section for singlet deuteron production, ρ is the phase-space factor, defined below, and $\mathfrak{D}'$ is the normalized density-of-states function (see Appendix B). The product $\mathfrak{D}'\times\rho$ has some dependence on the relative angle between the proton and neutron. Therefore we integrated it over the neutron detector solid angle. The proton solid angle is very small. It finally turned out that in the integration the differences on opposite sides of the center of the neutron detector practically cancelled out.

For the normalization several conventions exist. One[11] is to integrate over all the breakup energies that are kinematically possible

$$\mathfrak{D}'(E_{\mathrm{BU}})=\mathfrak{D}(E_{\mathrm{BU}})\Big/\int_0^{E_0-B}\mathfrak{D}(x)k(x)dx\,, \quad \text{(A2)}$$

where $\mathfrak{D}(E_{\mathrm{BU}})$ is the unnormalized density-of-states

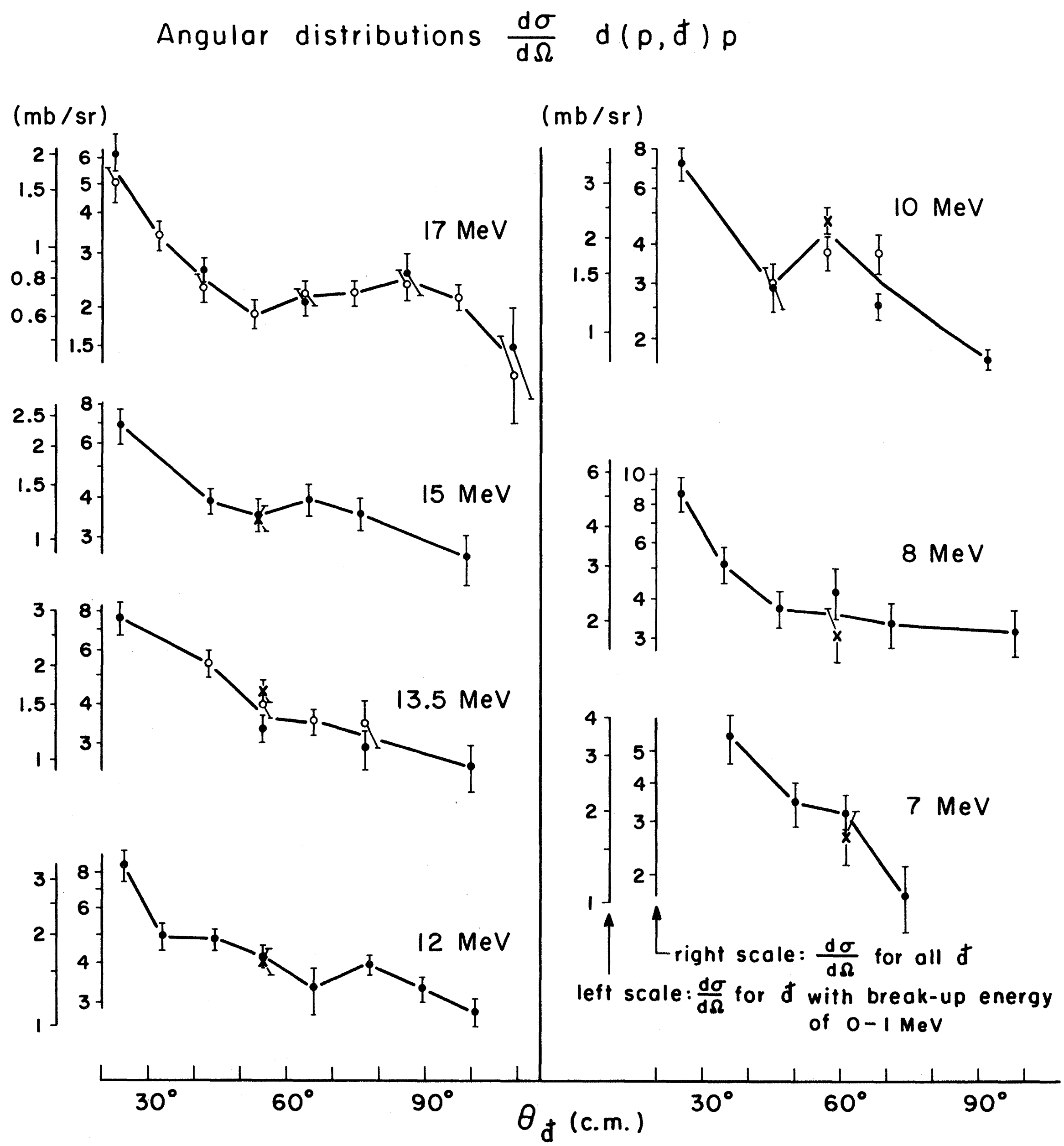

FIG. 4. Measured angular distributions of $\tilde{d}$ in $d(p,\tilde{d})p$. Right scale: $d\sigma/d\Omega$ for all E_{BU}. Left scale: $d\sigma/d\Omega$ for $E_{\mathrm{BU}}=0\text{–}1$ MeV (see Appendix A). Over-all normalization error for each energy is 15%.

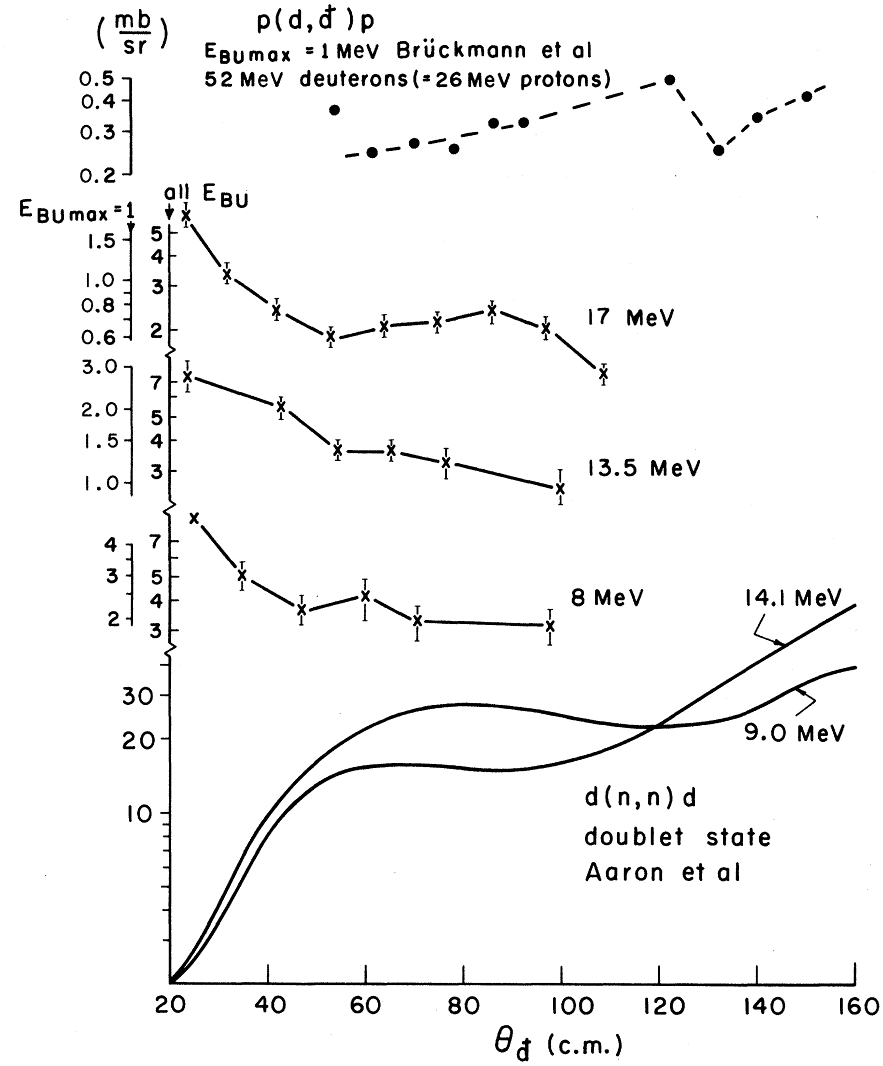

FIG. 5. Comparison of measured angular distributions (x) with other work. Same scales as in Fig. 4.

function (see Appendix B) and $k(E_{BU})$ is a phase-space factor: $k(E_{BU}) = (E_0 - B - E_{BU})^{1/2}$, which is included in $\rho(E_{BU})$ of (A1). The integrand in (A2) is the relative probability for production of a singlet deuteron at any scattering angle, with breakup energy x. E_0 is the bombarding energy in the c.m. system, and B is the deuteron binding energy.

Following another convention[17] it is assumed that the sequential breakup model can only be trusted for breakup energies not higher than a certain limit E_L, and normalization is done by integrating only from 0 to E_L in (A2). The choice of E_L seems to be rather arbitrary. Niiler[8] has an argument for it to be 0.7 MeV. In order to make comparison with other work, we present our results in both ways, choosing $E_L = 1$ MeV.

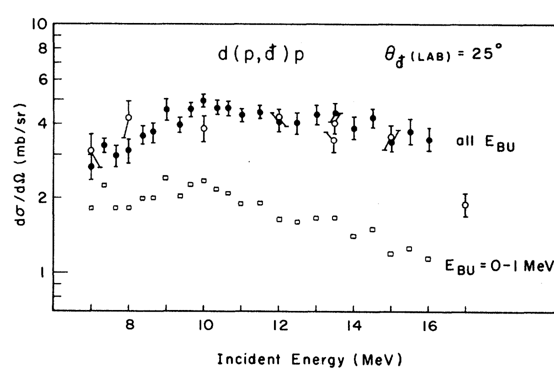

FIG. 6. Excitation function of d^* in $d(p, d^*)p$ (c.m. system units) at θ_{d^*}(lab) = 25°. The error bars represent errors due to measurement and analysis; uncertainties (≈15%) in the cross sections for elastic p–d scattering at 30°, used for normalization, have not been included. For E_{BU} = 0–1 MeV only the data of one running period are shown. They have the same error bars as the corresponding points for all E_{BU}.

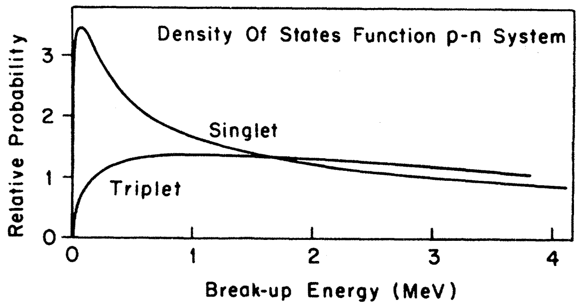

FIG. 7. The relative density of states function, $\mathfrak{D}(E_{BU})$, for p-n system in singlet and triplet state, versus break-up energy.

APPENDIX B: DENSITY-OF-STATES FUNCTION AND PHASE-SPACE FACTOR

The density-of-states function is given by

$$\mathfrak{D}(E_{BU}) = \frac{1}{k^2}\left[ka_1 - \left(\frac{1}{ka} + \frac{1}{2}kr_0\right)\sin^2\delta - \frac{1}{2}\sin 2(ka_1 - \delta)\right].$$

δ is the p-n scattering phase shift, for low energies given by $\cot\delta = -1/ka + \frac{1}{2}kr_0$. The nucleon wave number k is given by $k = (2\mu E_{BU}/\hbar^2)^{1/2}$ (μ = reduced mass of p-n system). r_0 is the effective range of the neutron-proton interaction and a is the p-n scattering length. a_1 is the renormalization radius. We used the following values:

	Singlet (in fm)	Triplet (in fm)
a_1	2.5	2.5
a	−23.806	5.37
r_0	2.49	1.65

Figure 7 shows $\mathfrak{D}(E_{BU})$ for a singlet and triplet deuteron. *The phase-space factor* in formula (A1) has the form

$$\rho = \frac{2m_p + m_n}{m_n}\,\frac{k}{P_{p_2}(2m_p E_{BU})^{1/2}} \times \frac{P_{p_1} P_n{}^2}{\left|P_{p_1}\dfrac{m_n + m_p}{m_n} - P_0\cos\theta_n + P_p\cos\theta_{p_1 n}\right|},$$

where P = momentum, m = mass, θ_n = neutron scattering angle, $\theta_{p_1 n}$ = angle between p_1 and n, all in the lab system. k is the c.m. system relative p_2-d wave number in the production reaction.

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