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[33] $\left(\frac{d\sigma}{d\Omega}\right)_W (0°) \le \left(\frac{d\sigma}{d\Omega}\right)_{\rm el} (0°)$,

where for *n-d* scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_W (0°) = 30.28 \times \frac{E_{\rm inc} m_n (\sigma_{\rm tot})^2}{(1 + m_n/m_d)^2}.$$

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Proton-Neutron Final-State Interactions in the D(*d, dp*)*n* Reaction*

W. von Witsch, M. Ivanovich, D. Rendic,† J. Sandler, and G. C. Phillips
T. W. Bonner Nuclear Laboratories, Rice University, Houston, Texas 77001
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The reaction D(*d, dp*)*n* has been studied at bombarding energies between 11 and 13 MeV. Two charged particles were detected in coincidence at pairs of angles corresponding to the recoil axes of the reaction D(*d, d*)*d** where *d** is a *p-n* system at zero relative energy. Time-of-flight and ΔE-E information were used for background subtraction and particle identification, respectively. The experimental spectra are dominated by strong peaks at low relative energies in the *p-n* system which are in part attributable to the isospin-forbidden formation of the "singlet deuteron." The shape of the experimental spectra is not predicted very well by either Watson-Migdal or Phillips, Griffy, Biedenharn theories.

INTRODUCTION

Complete three-body experiments have been used quite extensively in recent years as a means of studying nuclear resonances and final-state interactions. Of particular interest, of course, have been reactions which involve not more than three nucleons, since they allow the investigation of the $^1S_0$ nucleon-nucleon interaction with a minimum of interference from other final-state interactions. Several such experiments have been reported,[1-4] and the results obtained by various authors by fitting the data with the theories of Watson-Migdal (WM),[5] Phillips-Griffy-Biedenharn (PGB),[6] or with a modified Born approximation are encouraging although the experimental as well as the theoretical uncertainties are still very large. The next more complicated reactions, then, are those involving four nucleons, such as the D(*d, dp*)*n* reaction, which is the subject of this paper. This reaction has been studied by several authors[2,3] with regard to the quasifree scattering of deuterons from protons. The purpose of the experiment described here, however, was the investigation of the *p-n* final-state interaction in a reaction where the $^1S_0$ ($T = 1$) configuration is isospin forbidden. Although some evidence for the isospin-forbidden production of "singlet deuterons" in the reaction ^{12}C(*d, pn*)^{12}C has recently been reported,[7] no systematic study of this effect is known to us.

A kinematically complete experiment has been performed wherein protons and deuterons were detected in coincidence at angle pairs corresponding to the recoil axes in the D(*d, d*)*d** reaction, where *d** is a *p-n* system at zero relative energy. It was possible to observe final-state-interaction effects for relative energies in the *p-n* system between 0.0 and 2.0 MeV.

EXPERIMENTAL PROCEDURE

A deuteron beam, provided by the Rice University tandem accelerator, of about 50 nA was used to bombard a foil of deuterated polyethylene of about 300-μg/cm^2 average thickness. The elastically scattered deuterons were monitored at 30° in order to allow the extraction of absolute three-body cross sections,[4] using the *d-d* elastic scattering data by Wilson *et al.*[8] A ΔE-E detector telescope and a single E counter were used to identify *p-d* and *d-p* coincidences. The telescope was positioned at an angle of 30° in the laboratory, whereas the single counter was placed on the opposite side of the beam at angles of 44.5, 46.0, and 47.2° for bombarding energies of 11, 12, and 13 MeV, respectively. In this geometry, the *p-d* and *d-p* loci are kinematically well separated, but a considerable reduction of background resulted from the use of particle identification. The solid angles for both detectors were 1.04×10^{-3} sr. The beam was monitored in a Faraday cup in the conventional way.

Time-of-flight information was used to impose fast-coincidence requirements on the data, off

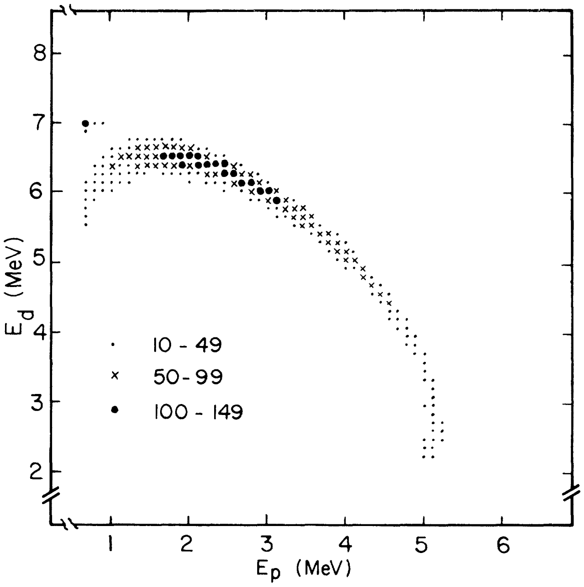

FIG. 1. Two-dimensional plot of the experimental *p-d* coincidence spectrum taken at 12-MeV bombarding energy and at angles of 46 and 30° for protons and deuterons, respectively. Background has been subtracted as described in the text. Less than 10 counts per cell are not shown.

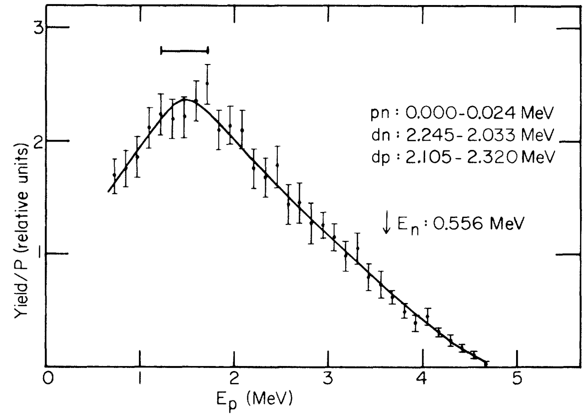

FIG. 3. Projection of the data taken at 11 MeV onto the proton axis. Background has been subtracted and the yield has been divided by the phase-space factor *P* shown in Fig. 2. The error bars represent statistical uncertainties arising from count rate and background subtraction. The curve has been drawn through the experimental points to guide the eye. The horizontal bar above the peak indicates the region in which the relative energy in the *p-n* system is between 0 and 24 keV; this same region corresponds to a relative energy of $2.033 \leq E_R \leq 2.245$ MeV in the *d-n* system, and of $2.105 \leq E_R \leq 2.320$ MeV in the *d-p* system. The vertical arrow points at that part of the spectrum where the energy of the unobserved neutron E_n is at a minimum (0.556 MeV).

line, by applying a narrow window about the true coincidence time peak, and a convenient means for the subtraction of accidental background was thus obtained.

Because of the relatively poor timing characteristics of the ΔE counter, timing signals were derived from the two E counters. For this purpose, the signals from the second output of the Tennelec field-effect-transistor preamplifiers (model No. TC133) were fed into two ORTEC timing single-channel analyzers (model No. 420), the output signals of which were used as start and stop pulses for a time-to-amplitude converter (TAC) (EG & G,

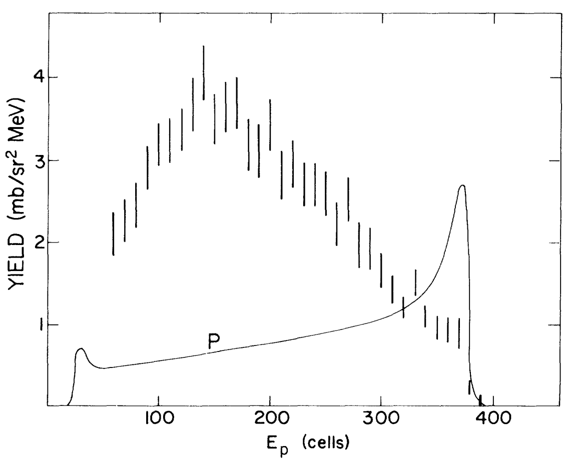

FIG. 2. Projection of the data taken at 11-MeV incident energy onto the proton axis. Background has been subtracted. The error bars represent relative statistical uncertainties; the error in the absolute cross section is ±10%. Also shown is the relative phase-space factor *P* for the transformation from the c.m. to the lab system in arbitrary units.

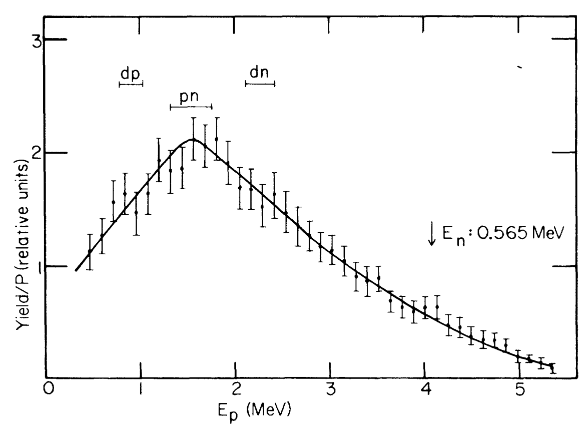

FIG. 4. Same as Fig. 3 but for the data taken at 12 MeV. The horizontal bars labeled *dp*, *pn*, and *dn* mark the sections of the spectrum in which the relative energies between the corresponding particles assume the same values as those indicated in Fig. 3. The position of the peak still coincides with the region of low relative energies in the *p-n* system.

model No. TH200A). A spectrum of the time-of-flight difference of the two detected particles was thus obtained and, together with the ΔE spectrum and the two energy spectra, fed into four 1024-channel analog-to-digital converters of the laboratory's IBM 1800 on-line computer-analyzer system and stored on magnetic tape for subsequent data reduction.

RESULTS AND DISCUSSION

p-d coincidence spectra were obtained at bombarding energies of 11, 12, and 13 MeV, the deuterons being detected at 30° and the protons at the corresponding recoil angles for the D(d, d)d^* reaction. Figure 1 shows a two-dimensional plot of p-d coincidences after background subtraction, with only deuterons allowed in the telescope. Deuterons below about 2.5 MeV and protons below 2.0 MeV were stopped in the ΔE counter and, therefore, did not trigger the TAC. For this reason large parts of the d-p loci (with protons detected at 30°), which come at lower energies than the p-d loci, were cut off and these loci could not be used for analysis. Figure 2 shows the absolute cross sections for the run at 11-MeV bombarding energy, projected onto the proton axis. In Figs. 3–5, projections of the data taken at 11-, 12-, and 13-MeV incident energies are presented; in these and the following figures the yield has been divided by the phase-space factor P which results from the transformation of the over-all c.m. system to the lab system.[4] The data show strong broad peaks at about 1.5-MeV proton energy.

Looking for possible explanations for the occurrence of such peaks, one may first think of the spectator (or quasifree scattering) effect mentioned above. A peak due to a spectator pole would be expected at that proton energy at which the energy of the third undetected particle – in this case the neutron – is at a minimum. In these spectra, however, the minimum neutron energies E_n occur at much higher proton energies than the peaks, as indicated in Figs. 3 – 5 by vertical arrows; furthermore, E_n does not drop below 0.55 MeV in any of the three spectra. The spectator effect can therefore safely be ruled out as an explanation for the observed peaks.

The only known alternative to the spectator-pole effect is a final-state interaction between two of the three final-state particles. Figure 3 suggests that the spectrum taken at 11 MeV peaks somewhere between $E_p = 1.2$ MeV and $E_p = 1.7$ MeV, as indicated by the horizontal bar above the peak. An enhancement of yield in this energy region may be due to a final-state interaction in the p-n system at a relative energy E_R between 0 and 24 keV, in the d-n system at $2.033 \leq E_R \leq 2.245$ MeV, or in the d-p system at $2.105 \leq E_R \leq 2.320$ MeV. In order to distinguish between these three possible final-state interactions, corresponding spectra have been taken at two different energies. In Fig. 4, the

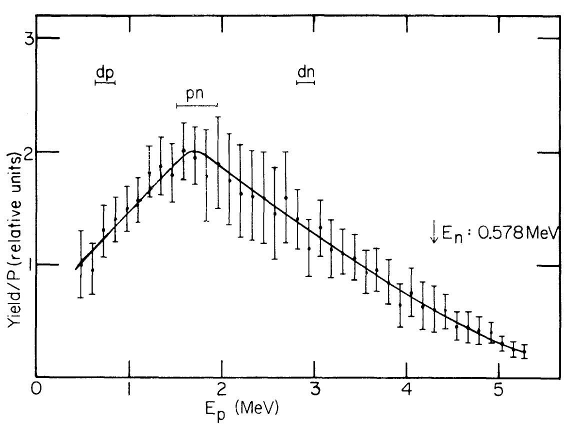

FIG. 5. Same as Fig. 4 but for the data taken at 13 MeV. Here, the distinction between the original three possible final-state interactions of Fig. 3 is even more pronounced than in Fig. 4.

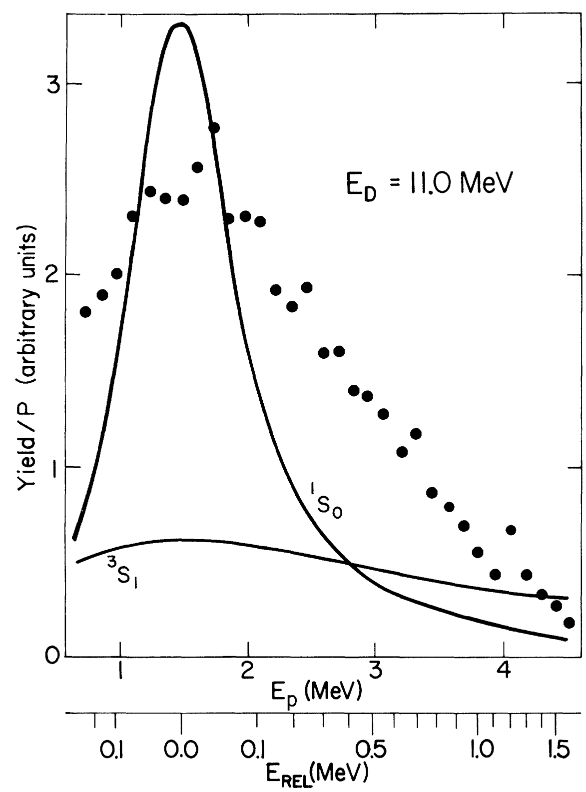

FIG. 6. Comparison between contributions from the $^1S_0$ and $^3S_1$ final-state interactions in the p–n system as calculated with the PGB theory. The curves do not represent fits to the data points nor are they normalized to each other.

data taken at 12 MeV are presented. Here, the horizontal bars labeled *dp*, *pn*, and *dp* represent the same regions of E_R which are indicated in Fig. 3; however, the three possibilities which were degenerate in Fig. 3 now appear at different values of E_p. The position of the peak still coincides with the region of low relative energy in the *p-n* system, so that the two other possibilities can be ruled out. In order to support this result, a further set of data was taken at 13-MeV bombarding energy, the projection of which is shown in Fig. 5. Here, the separation between the three original possibilities of Fig. 3 is even more pronounced. This confirms the conclusion that the peaks in the spectra shown in Figs. 3–5 are due to a final-state interaction in the *p-n* system at very low relative energies.

The question remains whether the singlet or the triplet interaction is responsible for the observed effect. Both will peak at zero relative energy in the c.m. system. However, a dilemma remains: the singlet interaction is isospin forbidden in this reaction, while the triplet interaction gives a peak expected to be much broader than the structure observed in the spectra and can only explain a more or less flat background.

In order to answer this question in a somewhat more quantitative way an attempt was made to fit the data with PGB[6] and WM[5] theories, allowing for contributions from both the singlet and triplet interactions. It is obvious from Fig. 6 that neither the $^3S_1$ interaction nor the $^1S_0$ interaction *alone* can account for peaks like those observed in this experiment, and therefore an attempt was made to fit the data allowing for contributions from both the singlet and triplet interactions. Figures 7–9 show such fits for the data taken at 11, 12, and 13 MeV. In obtaining the calculated curves the values $a_s = 23.72$, $a_t = 5.38$, $r_{0s} = 2.76$, and $r_{0t} = 1.71$ F were used for the singlet and triplet scattering length and effective range, respectively, and a best fit

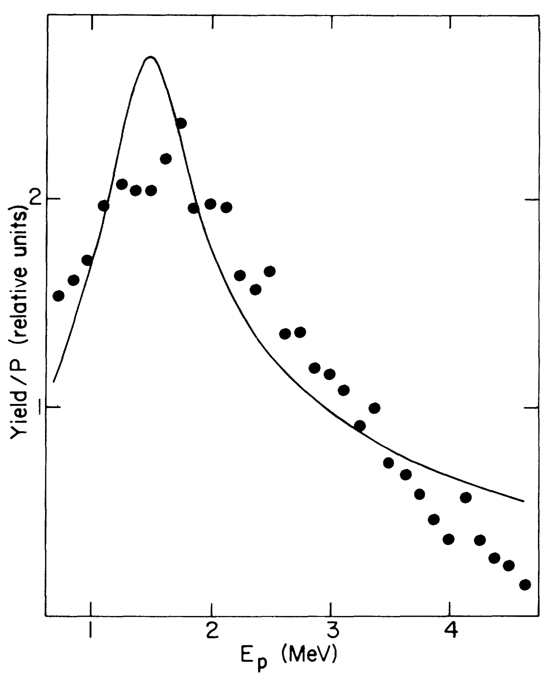

FIG. 7. Theoretical fit to the experimental data taken at 11 MeV, using the PGB theory. The best fit was obtained with the contribution from the $^3S_1$ interaction being about twice as strong as that from the $^1S_0$ interaction.

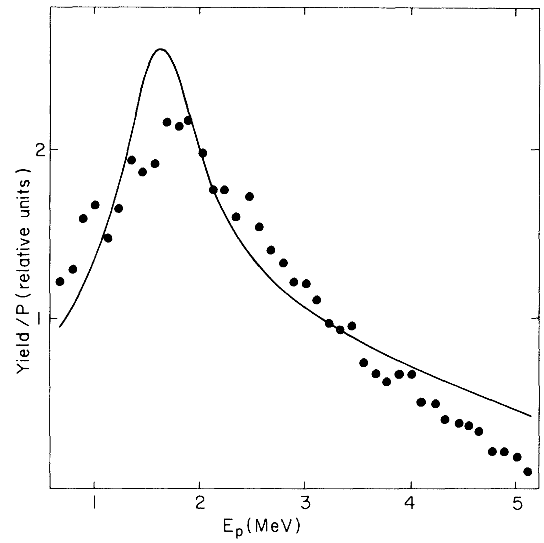

FIG. 8. Same as Fig. 7 but for the data taken at 12-MeV incident energy.

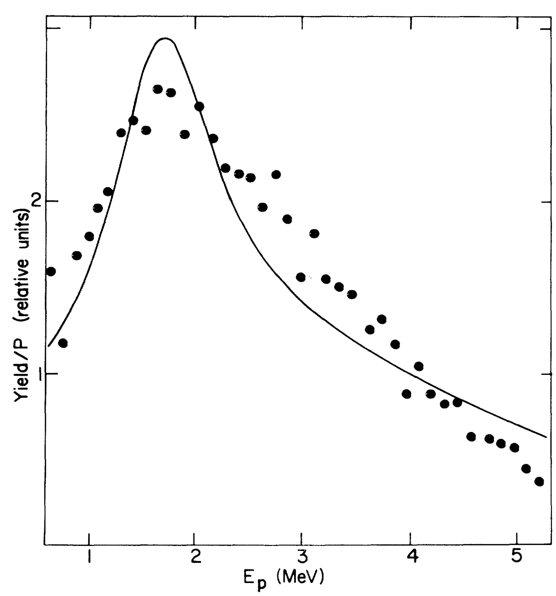

FIG. 9. Same as Fig. 7 but for the data taken at 13-MeV incident energy.

was obtained in each case, with the triplet contribution being about twice as strong as the contribution from the singlet interaction. However, the quality of the fits is poor; the shape of the experimental spectra was not reproduced very well. The relative strength of the two contributions as extracted from these fits must not be taken too seriously, because this parameter varies by a factor of 2 if different parts of the spectrum are included in the fitting procedure. Moreover, simultaneous breakup into three particles may also contribute to the yield and would look very similar to the contribution from the triplet interaction. It is not clear what causes the discrepancies between theory and data in this particular experiment, especially since the same theoretical approach has been used quite sucessfully in similar experiments.[4] However, in view of the isospin-forbidden nature of the singlet contribution to this reaction, a surprisingly large amount of $^1S_0$ admixture is necessary in order to obtain peaks of the kind observed in this experiment, and it seems interesting to continue the investigation of this effect.

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†On leave from Institute "Ruder Boskovic," Zagreb, Yugoslavia.

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