Study of Prominent Two-Body Processes in the D(p, 2p)n Reaction at 30.3 MeV

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The D(p, 2p)n reaction has been studied at $E_p = 30.3$ MeV at kinematic conditions where either final-state interactions or quasifree scattering predominate, and at kinematic conditions where the kinematic domains of these two processes are near each other. Data were obtained at 25°–91°, 30°–80°, 37.5°–68°, 25°–25°, 30°–30°, 42.5°–42.5°, 24°–60°, 30°–56°, 35°–43°, 37°–47°, 63°–30°, 55°–40°, and 49.5°–49.5°. The results are compared with predictions of the Amado model and, in general, there is good agreement between the model and the data.

I. INTRODUCTION

The D(p, 2p)n reaction has been extensively studied over a wide energy range. Prominent features of correlation spectra obtained in such studies are pronounced enhancements associated with kinematic conditions of low N-N relative energies [final-state interactions (FSI)] and of quasifree scattering (QFS). Various models have been used to fit the data corresponding to FSI and QFS peaks. For example, the Watson-Migdal theory[1] has usually been used to fit FSI peaks. In most cases the QFS data have been compared with the simple impulse approximation (SIA) of Kuckes, Wilson, and Cooper[2] and with modifications of the SIA which have included a sharp[3] or a smooth[4] radial cutoff in the wave function of the deuteron, final-state interaction effects,[5] and attenuation effects.[6] A general conclusion[7] is that none of these models are capable of predicting all aspects of the data. It has been difficult to obtain a definite understanding of the relative merits and failures of some of these models partly because of lack of complete and extensive data.

Recently it has become apparent that models[8–11] based on a rigorous treatment of the three-body problem using the Faddeev equations are very successful in predicting the prominent features of the N+d breakup data. The Amado model[12] produces very good fits to D(p, 2p)n,[13, 14] D(p, pn)p,[15, 16] D(n, 2n)p,[17, 18] and D(n, np)p [19] data, as well as to elastic scattering[9] and reaction-cross-section data.[9, 20]

Recently Kloet and Tjon have used Padé techniques[21] to sum the Faddeev multiple-scattering series and to calculate elastic and inelastic nucleon-deuteron scattering cross sections.[22] Local S-wave N-N interactions were used with two sets of potentials, one with a soft core for both spin singlet and triplet S waves and the other with a soft core only for the spin singlet S wave. These authors pointed out that the latter potential predicts a higher total reaction cross section, suggesting that breakup processes are sensitive to short-range correlations in the two-particle system. One could indeed perform a systematic search to find domains most sensitve to specific features of the N-N interaction. It should be mentioned that the two potentials used by Kloet and Tjon are not phase equivalent and that one of them gives a better fit to the N-N data.

This work was initiated to obtain additional data on the D(p, 2p)n reaction and thus complement information obtained previously by this[23] and other research groups.[24] The aim of this work was threefold: to perform correlation measurements at kinematic conditions where FSI predominates and thus obtain the angular distribution of the D(p, p')d^* reaction; to perform measurements at kinematic conditions where QFS predominates and thus study the angular dependence of QFS; to obtain data at kinematic conditions where FSI or QFS are near enough to the domain of the other for the effect of interference to be observed. Here we report data obtained at 25°–91°, 30°–80°, and 37.5°–68°, where FSI predominates, at 25°–25°, 30°–30°, 42.5°–42.5°, 24°–60°, 30°–56°, 35°–43°, and 37°–47°, where QFS predominates, and at 63°–30°, 55°–40°, and 49.5°–49.5°, where the kinematic domains of FSI and QFS are near each other. The results are compared with predictions of the Amado model, the modified simple impulse approximation (MSIA) using a sharp radial cutoff, and the Watson-Migdal theory.

II. EXPERIMENTAL PROCEDURE

The experiment was performed using the University of California, Los Angeles sector-focused cyclotron. The energy-analyzed proton beam entered a scattering chamber 48-cm i.d. and was focused, typically, to a spot of 1.5×5 mm in area at its center. The target was a CD_2 foil, 5 mg/cm^2 thick, placed at the center of the scattering chamber. It could be rotated about a vertical axis to minimize energy losses of low-energy protons. Measurements for some pairs of angles were repeated using a D_2 gas target. Two ΔE-E solid-state counter telescopes were used to detect the outgoing protons in the scattering plane. They were placed on movable arms inside the chamber. Each counter telescope consisted, typically, of a 300–500-μm ΔE surface-barrier silicon detector and an E detector of a total Si(Li) thickness of 5–6 mm. The angular resolution was typically $\Delta\theta_3 = \Delta\phi_3 = 0.5°$, $\Delta\theta_4 = \Delta\phi_4 = 1°$. Here $\theta_3\phi_3$, $\theta_4\phi_4$ are defined as polar and azimuthal angles of the two detected particles on opposite sides of the incident beam direction.

Pulses from the detectors were processed through conventional electronics. A block diagram is shown in Fig. 1. Crossover timing was performed with the output of the two ΔE detectors. The output of the time-to-amplitude converter was a spectrum containing the "reals" peak and four

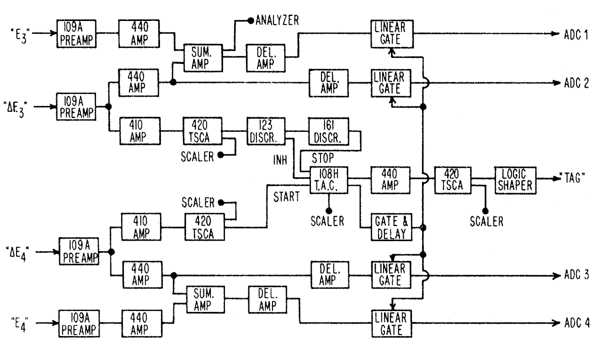

FIG. 1. Block diagram of the electronics.

"accidentals" peaks corresponding to adjacent beam bursts ~30 nsec apart. The timing resolution varied from run to run but, at all times, it was sufficient to resolve the peaks cleanly. A single-channel analyzer window was set around the "reals" peak and its output was used to tag these events for identification. The position of this window was monitored and adjusted during the runs. The ΔE and E linear signals of each telescope were summed, both of the ΔE and $\Delta E + E$ signals were processed by analog-to-digital converters and an on-line XDS computer. Each signal was digitized to 1024-channel accuracy and stored on magnetic tape event by event. The data were continuously displayed in a 64×64-channel array.

The energy calibration of the two-dimensional analyzer was obtained by detecting coincident p-p elastic scattering events using a CH_2 target and by examining accidental lines of protons and deuterons from elastic scattering events in the CD_2 target.

The absolute cross sections were obtained by detecting protons from p-d elastic scattering in the CD_2 target. This was accomplished by taking "singles" spectra with one detector placed at 63° to the incident beam for a fixed amount of integrated beam. These "monitor" spectra were taken in between data runs, thus a time profile of the deuterium content of the CD_2 target was obtained. A 64×64-channel array of true coincident events was obtained by subtracting $\frac{1}{4}$ of the "accidentals" array from the "reals" array subsequently to particle identification which eliminated deuteron accidental lines. Events on the three-body contour were projected along the E_3 axis. Conversion of these correlation spectra to cross sections required knowledge of the p-d elastic scattering cross section, which was obtained by interpolation of existing data.[25]

III. RESULTS AND DISCUSSION

Projected correlation spectra are shown in Figs. 2, 3, and 5. The error bars are due only to statistics. The uncertainty in the absolute value of the differential cross sections is estimated to be 10%. The dashed curves are the predictions of the Amado model calculated from the code of Ref. 14. This code calculates the correlation cross section using an S-wave separable N-N interaction, assuming nonrelativistic kinematics and neglecting nucleon-deuteron partial waves higher than 7. The dashed-dotted curves are the predictions of the MSIA calculation using a sharp cutoff radius of 7.4 fm. This value was determined by requiring a fit to the data obtained at 42.5°–42.5°. It also matches into the energy dependence of R for the D(p, 2p)n

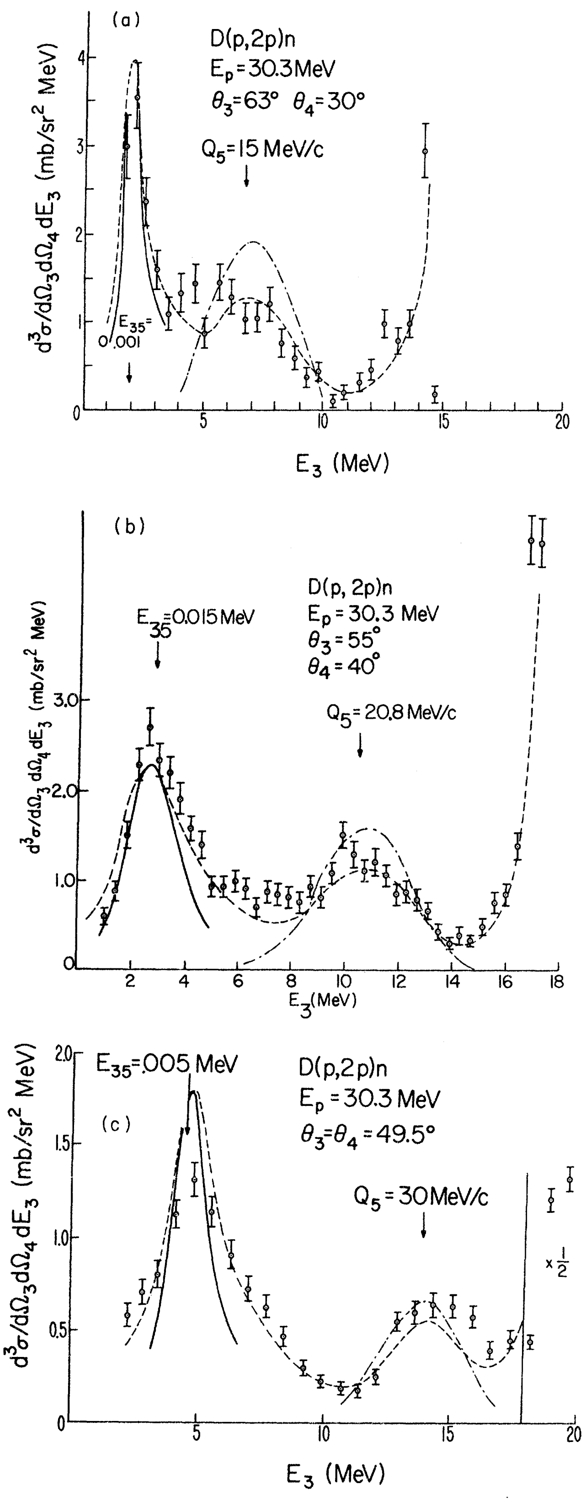

FIG. 2. Energy spectra of the D(p, 2p)n reaction at E_p = 30.3 MeV for kinematic conditions where both FSI and QFS enhancements are present. The dashed lines are the Amado-model predictions, the dashed-dotted lines are the MSIA predictions with R = 7.4 fm, and the solid lines are the Watson-Migdal predictions.

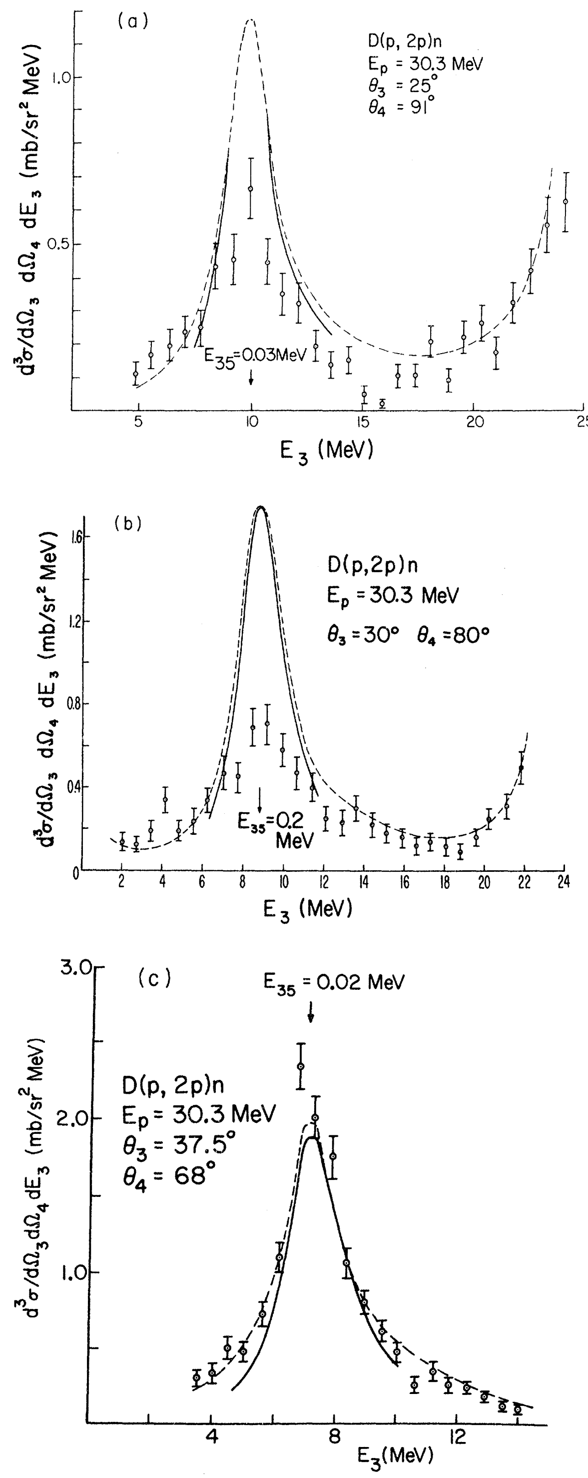

FIG. 3. Energy spectra of the D(p, 2p)n reaction at E_p = 30.3 MeV for kinematic conditions where FSI is the only prominent process. The dashed lines are the Amado-model predictions and the solid lines are the Watson-Migdal predictions.

reaction reported previously.[23] The same cutoff radius was used for all pairs of angles. The solid curves are the predictions of the Watson-Migdal model, where only the $^1S_0$ n-p FSI was included. The results of the Watson-Migdal calculation were normalized to the peak cross section of the Amado model. The normalization factor was different for the various pairs of angles.

Finite-energy and angular-resolution effects were not taken into account in the above three calculations. These effects are expected to be most important for the usually sharp FSI peaks and much less so for the QFS peaks. The effect of a change of 1° in angular setting was specifically investigated for the Amado model at 30°–80°, 30°–81° and 25°–91°, 26°–91°. The change in value of the FSI peak cross section was 20–30%, while the QFS peaks for 24°–60°, 25°–59° differed only about 5%. This corroborates that FSI enhancements are very sensitive on the angular and energy resolution, while QFS enhancements are much less.

Figures 2(a)–2(c) show examples where both QFS and FSI enhancements are present. The arrows indicate the position of the minimum relative energy E_{35} for particles 3 and 5 and the minimum momentum Q_5 for the undetected "spectator" neutron. The Amado model gives an excellent fit to the data at 55°–40° and 63°–30°, and a very satisfactory fit to the data at 49.5°–49.5°. An important feature of these three figures is that the Amado model fits the magnitude as well as the shape of both FSI and QFS peaks quite well, while the Watson-Migdal peak is narrower than the Amado-model prediction.

It is obvious that for the n-p FSI one has to include interactions in both the $^1S_0$ and $^3S_1$ states. This is done correctly in a rigorous treatment based on the Faddeev approach. In our use of the Watson-Migdal model the $^3S_1$ amplitude has been

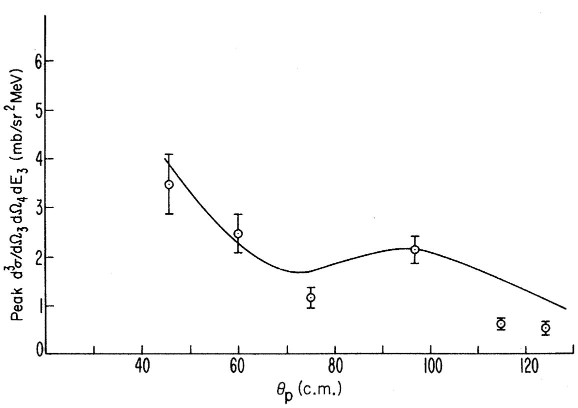

FIG. 4. Angular distribution of the D(p,p')d^* reaction at E_p = 30.3 MeV. The solid line is the Amado-model prediction.

neglected. However, when we added the $^3S_1$ n-p FSI to the $^1S_0$ FSI with statistical weights $\frac{3}{4}$ and $\frac{1}{4}$, respectively, it was also not possible to obtain a good fit to all of the present data. Thus, one concludes that the conventional comparison procedure should not be used to extract N-N scattering parameters when one of the reactions involved contains a n-p pair in the final state.

Figures 3(a)–3(c) show data taken at pairs of angles where one is far from QFS kinematic conditions, and the only prominent peaks are those associated with FSI. Here the Amado model fits are less satisfactory. In particular, at 30°–80° and 25°–91° the theory predicts a FSI peak that is considerably higher and narrower than the data. The fit at 37.5°–68° is adequate.

Although the data of the FSI type are sensitive to uncertainties in angle and energy, as we discussed, and thus to angular and energy resolutions, we feel that the discrepancy observed at angles 30°–80° and 25°–91° is much more than can be related to the possible experimental error. Similar discrepancies between the Amado model and the angular distribution of the D(p,p')d^* data have also been reported earlier.[26]

Figure 4 shows the angular dependence of the D(p,p')d^* reaction as deduced from the present experiment. These data complement previous work on d^* angular distributions.[27] The average peak cross sections of the FSI enhancements of data taken at 63°–30°, 55°–40°, 49.5°–49.5°, 37.5°–68°, and 25°–91° are plotted vs the c.m. angle of the inelastically scattered proton θ_p(c.m.). The solid curve is the corresponding prediction of the Amado model. Both the theory and the data include the contribution of both singlet n-p FSI and triplet n-p FSI processes. Figure 4 shows that the Amado model gives a qualitative fit to the data but discrepancies are definitely present.

Figures 5(a)–5(g) show correlation spectra for pairs of angles where QFS is the predominant process and one is reasonably far from FSI kinematic conditions. These data, together with those shown in Fig. 2, represent the results of our study of the angular dependence of QFS. As a check of consistency between the present experiment and previously obtained data, it should be noted that our present data taken at $\theta_3 = \theta_4 = 42.5°$ agree within the error bars with data taken previously.[23] The dashed lines are the MSIA predictions for R = 7.4 fm. Again, the Amado model fits the entire spectra quite well in most cases, e.g., at 42.5°–42.5°, 30°–30°, 37°–47°, and 30°–56°. Adequate fits are obtained at 25°–25° and 35°–43°, but the quality of the data at these angles does not allow a very accurate test. The only serious discrepancy is seen at 24°–60°.

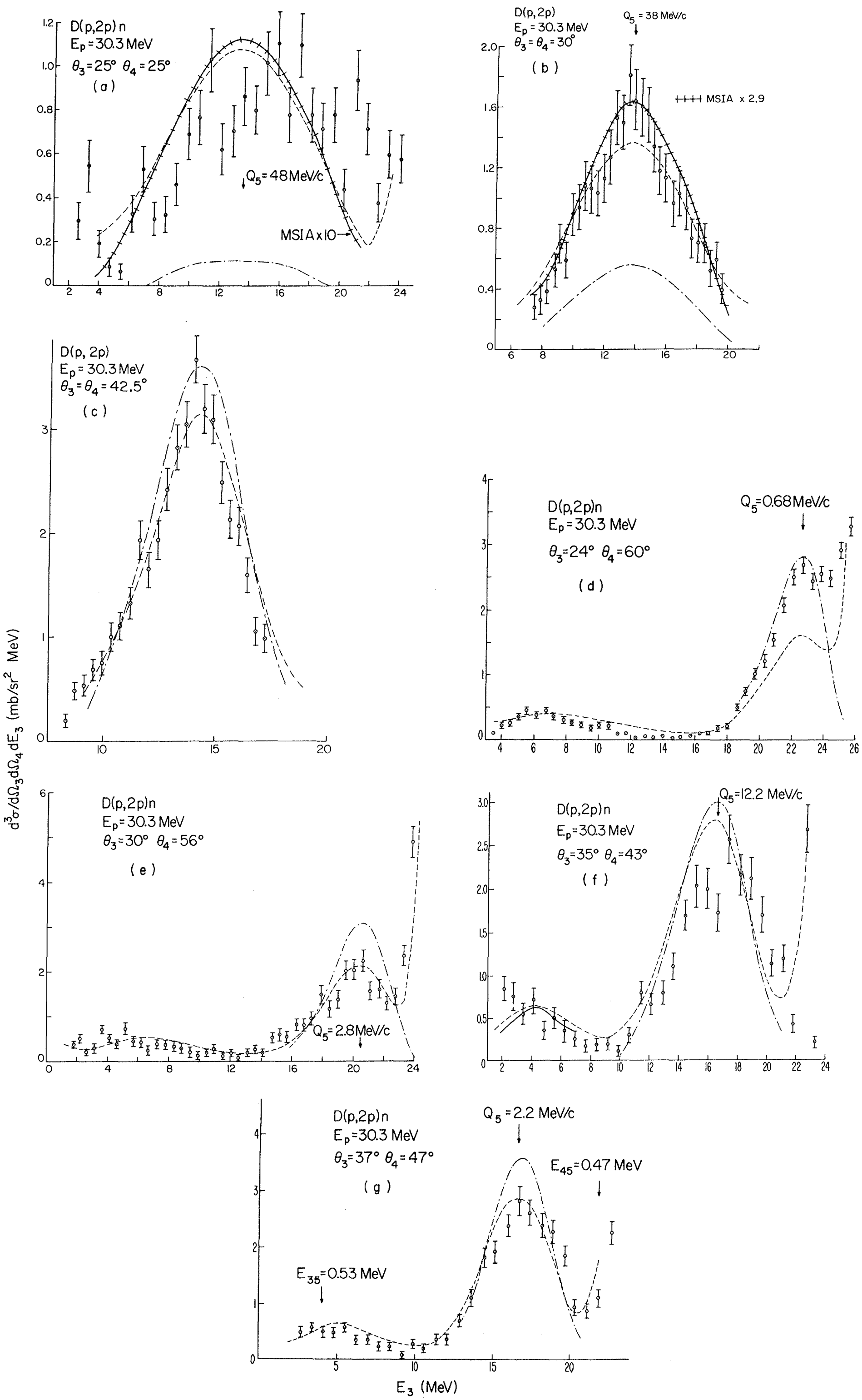

FIG. 5. (a)–(g) Energy spectra of the D($p,2p$)n reaction at E_p = 30.3 MeV for kinematic conditions where QFS is the only prominent process. The dashed lines are the Amado-model predictions and the dashed-dotted lines are the MSIA predictions with R = 7.4 fm.

The MSIA calculation using a sharp cutoff with $R = 7.4$ fm does not give a satisfactory fit to all the QFS data. Apparently the MSIA fit becomes worse as one moves away from QFS conditions and to a large extent irrespective of whether one comes close to the FSI region or not. A better fit to individual spectra could be obtained by adjusting the cutoff radius. However, there is no physical justification for such a procedure and thus the fact that one cannot fit all the QFS data with a single cutoff radius is a serious indication that the MSIA model is not an adequate general description of QFS processes. This inadequacy of the MSIA becomes obvious in such studies of angular dependences.

Calculations are usually performed employing a very simple deuteron wave function of the Hulthén type. We also used various modified Hulthén-type wave functions[28] as well as the deuteron wave function proposed by Gourdin *et al.*[29] and we conclude that in the SIA or the MSIA the differences between this deuteron wave function and the Hulthén wave functions are of the order of a few percent. A similar conclusion has been reached by Haftel,[30] who used the Humberstone and Wallace deuteron wave function.[31]

IV. CONCLUSIONS

An extensive set of data for the D(p, $2p$)n reaction at 30.3 MeV has been presented, covering kinematic regions where FSI or QFS predominate and regions where the two processes interfere. In almost all cases the Amado model has produced a remarkably good fit to the data, matching absolute cross sections as well as shapes of spectra. Such success over a wide range of kinematic conditions is not enjoyed by any of the simpler models known presently. Some discrepancies between the Amado model and the data have been observed in FSI and QFS regions. It is possible that such discrepancies may be removed by using an improved N-N interaction as an input to the Amado model. For example, the use of an S-wave separable potential[32] that fits N-N data better than the potential used in the code of Ref. 14 seems to provide an improved fit to symmetric-angle data for the D(p, $2p$)n reaction at 45 MeV.

The present study points out once again that only models based on a rigorous theory using the Faddeev equations can provide a good over-all description of the $p+d$ breakup process. Simpler models including truncations of the multiple scattering series do not give good results.[31] Fortunately, computer codes for the Amado-model calculation are now available in a form convenient for analysis and at low computer cost; thus, one hopes, their expanded use in future studies will lead to a more complete understanding of the $N+d$ breakup process.

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