^{2}H(p,2p)n Cross Sections for Constant *NN* Relative Energies*

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Measurements and various s-wave model calculations of $p+d$ breakup cross sections were made along constant-relative-energy loci as suggested by Jain, Rogers, and Saylor. The measurements utilized special gas scattering apparatus to accurately measure cross sections in the vicinity of destructive interference minima. The data agreed with the most realistic of the models used except at the position of the interference minimum where a discrepancy of a factor of 3 was found.

This article reports a theoretical and experimental investigation of destructive interference effects in $p+d$ breakup at a laboratory energy of 39.5 MeV. Interference effects are of special interest because the breakup cross section in the region of destructive interference minima is especially sensitive to the nucleon-nucleon (*NN*) potential. In particular, exact three-body calculations yield cross-section predictions which may vary by a factor of 2 or 3 for different *NN* potential models which are the input to such calculations, even though these different potential models predict only small differences for most other three-body observables.[1,2] We are not currently in a position to provide unambiguous information about the unknown features of the *NN* interaction from these measurements because three-body calculations using realistic *NN* potentials are not yet available. However, using the available s-wave potential model calculations it is demonstrated here that it is possible to distinguish one *NN* potential model from another.

We have utilized a procedure proposed by Jain, Rogers, and Saylor[3] for systematically investigating such interference effects. In this scheme the variation of the breakup cross section for fixed values of the final-state *NN* relative energies and a fixed value of the momentum of one of the emerging protons is studied. This procedure defines a one-dimensional kinematic locus along which the cross section may be measured and calculated. Such loci are characterized by the fixed angle and energy of one of the emerging protons. The desirable feature of these "constant-relative-energy loci" is that by choosing the relative energies and fixed momentum in a particular way one may guarantee that the model cross section is dominated by the crucial M_{d2} amplitude[4] along most of the locus.

By searching the entire four-dimensional phase-space volume, Kloet and Tjon[1] recently showed that the greatest differences between calculations with different potential models occurred in the regions of cross-section minima where M_{d2} is the only nonzero amplitude. The occurrence of such minima is due to a delicate cancelation of the Born, or single-scattering, part of the M_{d2} breakup amplitude with the multiple-scattering parts.[5] The value of the cross section in such regions depends in a subtle way on the dynamics of the three-body scattering as expressed in the Faddeev equations. The behavior is in marked contrast to the frequently studied quasifree scattering region in which the behavior of the cross section is directly traceable to properties of the isolated (on-shell) *NN* interaction. The potential value of the final-state interaction region for investigating off-shell effects has been

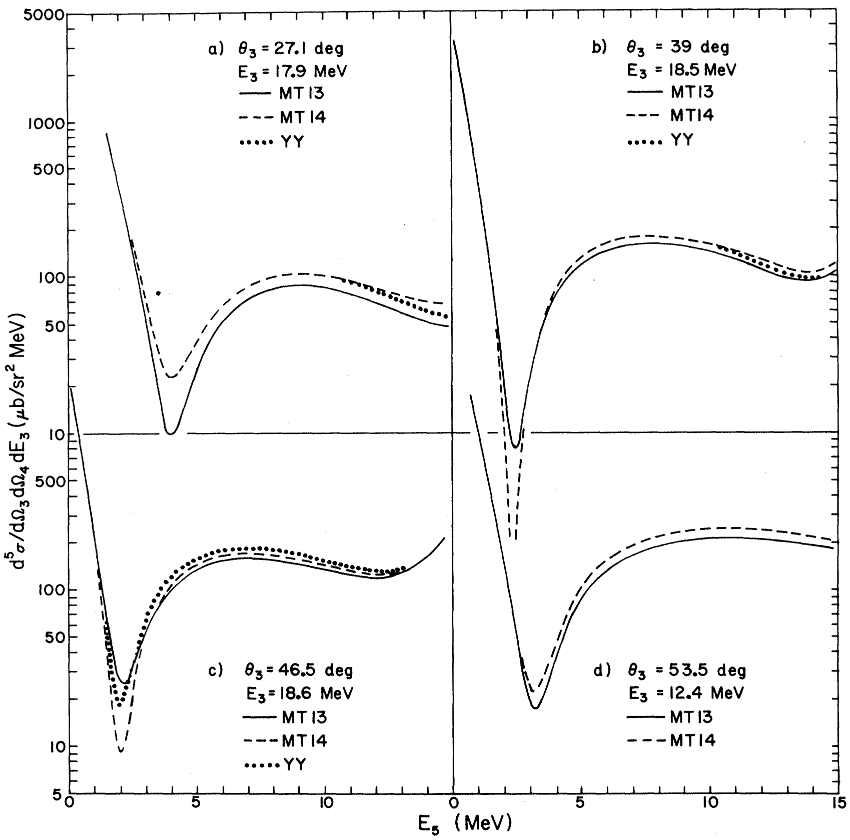

FIG. 1. s-wave model calculations along constant-relative-energy loci. θ_3 and E_3 define the fixed nucleon momentum. Details of the three models are explained in the text.

discussed recently by Haftel and Petersen.[6]

Before performing measurements, four constant-relative-energy loci were surveyed using three different s-wave potential model calculations. The survey was confined to a particular class of constant-relative-energy loci, namely those loci which allow symmetric coplanar scattering ($\theta_3 = \theta_4$, $\varphi_3 - \varphi_4 = 180$ deg)[7] at one point on the locus. As shown in Ref. 3, this is a sufficient condition for ensuring that the magnitude of M_{d2} is much larger than the other amplitudes over most of the locus.

Figure 1 shows the results of the three s-wave potential model calculations along loci at various angles (θ_3) for the direction of the fixed nucleon momentum. The curves labeled MT13 and MT14 are calculations[1] using the local Malfliet-Tjon potentials[2] with and without, respectively, a repulsive core in the $^3S_1$ NN state. The curves labeled YY are a calculation by Jain and Doolen[8] utilizing a separable potential model with Yamaguchi form factors. We chose to measure the cross section along the constant-relative-energy locus at $\theta_3 = 27.1$ deg. The model cross section along this locus [Fig. 1(a)] shows a large dependence on the NN potential in the region of the minimum. Furthermore, the cross section varies fairly slowly as a function of the neutron energy (E_5) so that the measured cross section should be less affected by kinematic broadening than would be the case for the loci with a sharper mimimum.

Measurements were performed at the University of Manitoba's Cyclotron Laboratory using a 39.5-MeV proton beam. Two solid-state-detector telescopes were used to detect the two protons from the reaction ^{2}H$(p, 2p)n$ in coincidence. One telescope was held fixed at an angle of $\theta_3 = 27.1$ deg. The other telescope was positioned at various points along the symmetric constant-relative-energy locus corresponding to $\theta_3 = 27.1$ deg, $E_3 = 17.87$ MeV, $E_{35} = E_{45} = 14.37$ MeV.[7] Each telescope contained a ΔE detector for timing and particle identification, an E detector to measure the total energy of the breakup protons, and a veto detector to reject elastic protons. Data were accumulated in a computer as two 64×64-channel E_3-versus-E_4 arrays, one for genuine plus accidental coincidence events and one for accidental coincidence events. The differential cross section $d^5\sigma/d\Omega_3 d\Omega_4 dE_3$ as a function of E_3 was obtained from the 64×64 arrays using the measured target-gas pressure and a Faraday-cup integration of the incident beam current. The measured value of the cross section at $E_3 = 17.87$ MeV in each $d^5\sigma/d\Omega_3 d\Omega_4 dE_3$ spectrum corresponds to one point on the ($\theta_3 = 27.1$ deg) constant-relative-energy locus. The data near the desired value of E_3 were smoothed using a polynomial fit to ten data points. The cross sections extracted in this way are plotted in Fig. 2 along with the appropriate model calculations for the locus. The error bars indicate 1 standard deviation due to statistics. Systematic effects cause an additional overall normalization uncertainty of ±4%. Because of the finite acceptance of the detector system, each experimental cross section is the average in a region of ±0.40 MeV about the nominal E_5 values.

At large values of E_5, the data agree with the calculation for the MT13 potential. This is the most realistic of the three s-wave NN potentials in that it predicts approximately correct values for the $^3S_1$ and $^1S_0$ NN phase shifts up to 300 MeV and the triton binding energy.[2] In the region of the interference minimum the data are considerably larger than predicted by the MT13 potential. The data are in complete agreement with the data of Rogers[9] within the larger experimental uncertainties of those earlier data. These results supersede those presented in a preliminary version of this work.[10]

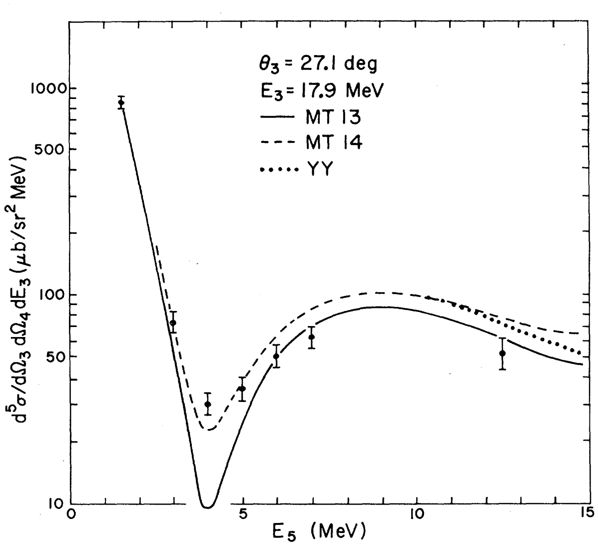

FIG. 2. Data and calculations along a constant-relative-energy locus.

One possible reason for the discrepancy between the MT13 potential and the data in the region of the minimum is the contribution to the breakup cross section from scattering amplitudes involving interacting NN pairs with nonzero orbital angular momentum ($l \neq 0$). All currently available breakup calculations ignore NN interactions for $l \neq 0$, so a precise calculation of this contribution is not possible. However, one can roughly estimate the size of the possible effect using the simple impulse approximation (SIA).[11]

If we divide the model breakup amplitudes into single-scattering and multiple-scattering parts, the breakup cross section has contributions from the squares of the single-scattering parts, the squares of the multiple-scattering parts, and the interference terms between single-scattering and multiple-scattering parts.[6] Along our constant-relative-energy loci only M_{d2} is significantly nonzero so the three contributions are essentially from this one amplitude. The single-scattering term in the model amplitude contains the target-deuteron momentum wave function, which causes the familiar peak in the breakup cross section at $E_5 = 0$. In s-wave model calculations such as those shown in Fig. 1, the deuteron wave function is a pure $^3S_1$ bound state as opposed to a more realistic deuteron wave function which is a mixture of $^3S_1$ and $^3D_1$ states.

The SIA gives a prediction for the fraction of the single-scattering contribution to the cross section which comes from the D-state component of the deuteron wave function. For the deuteron wave function derived from the Reid soft-core potential[12] the D state contributes about 8% to the square of the wave function at the position of the minimum in Fig. 2. If a small part of the D-state contribution to the single-scattering amplitude is not canceled by multiple scattering at the position of the minimum it would account for the difference between the MT13 calculation and the data in this region. Such a filling in of the minimum would occur if the $^3D_1$ contribution to the single-scattering amplitude has a different phase than the $^3S_1$ contribution. Whether or not such a phase difference actually exists can only be answered by a more realistic calculation, including at least the NN tensor force.

Measurements near destructive interference minima such as those presented here make such calculations especially desirable because it is possible that the deuteron D state may have a sizable effect on the cross section near the interference minima even at lower bombarding energies (i.e., energies at which the s-wave models are generally thought to predict the breakup cross section fairly well[13]). This hypothesis is reinforced by Doleschall's recent work[14] in calculating $N+d$ elastic polarization observables at 22.7 MeV. He found that the calculated polarization observables are much more sensitive to the low-energy behavior of the NN tensor force than to the high-energy characteristics of the NN interaction.

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[4]M_{d2} is the amplitude describing the scattering state in which the three nucleons have total spin $\frac{1}{2}$ and the two identical nucleons (the protons in our case) have relative spin 0. In the s-wave models it is the only amplitude which can be nonzero for a scattering state in which the two identical particles are in parity-inverse momentum states. For example, in kinematic situations in which two protons emerge with momenta of the same magnitude and make the same angle with the beam direction, M_{d2} is the only nonzero amplitude.

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