Proton-deuteron breakup cross sections in collinear geometry at 28.6 MeV

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Deuteron breakup cross sections induced by 28.6 MeV protons have been measured in collinear and noncollinear geometry and the results compared with an exact three-body calculation using the Doleschall code. This calculation includes two-body interactions in S and P waves and, in addition, a tensor force. The agreement with experiment in all cases is excellent. No evidence is seen for a collinearity enhancement.

[NUCLEAR REACTIONS ^{2}H(p,2p)n, E=28.6 MeV; measured cross section in collinear geometry; compared with exact three-body calculation.]

There has been some speculation recently as to whether an enhancement in the cross section for breakup can be observed at the kinematic conditions for collinearity of three final state particles, and whether such an enhancement can be the experimental manifestation of a fundamental physical phenomenon. In the collinear situation one of these particles is left at rest in the center of mass system, the reaction products being detected therefore in coplanar geometry.

The existence of a "collinearity enhancement" was first suggested by the data of Berovic *et al.*[1] in the study of d-d breakup at 12 MeV. The final state in this case consists of a proton, a neutron, and a deuteron. The problem in understanding this reaction is, however, that no exact calculation of theoretical cross section for breakup is yet possible for this system because of the four-body nature of the three-body final state.

Exact calculations are possible, however, in the three-nucleon system. The Faddeev[2] three-body equations have been solved by several groups both for nucleon-deuteron elastic scattering and for nucleon-deuteron breakup. While many early exact three-body calculations used S-wave nucleon-nucleon interactions (see, e.g., Ref. 3), others[4-6] have included higher partial waves. Good agreement with cross section and polarization data at 10, 14.1, and 22.7 MeV has been obtained using both local[5] and nonlocal separable[4,7] interactions including S, P, and D partial waves. With similar interactions, satisfactory results have been obtained[6] for nucleon-deuteron breakup cross sections at 22.7 MeV in the vicinity of the quasifree and final state interaction peaks. These theoretical predictions are confirmed by the experimental data despite the neglect of Coulomb effects in the calculations. It is therefore of interest to carry out detailed studies of cross sections at such energies in regions of phase space far removed from two-body enhancements, in particular for the collinearity condition. In the absence of two-body enhancements, there may be increased sensitivity to small effects arising from differences in the off-energy shell extension of the two-body t matrix or a possible three-body potential. The collinearity configurations may be peculiarly sensitive to the latter due to the partial shielding of the two-body interaction. Since we are seeking small effects, it is important to compare precise data with an accurate calculation which includes the higher partial waves in the two-body interaction.

Ohlsen[8] in a recent review comments on the experiments of Lambert *et al.*[9] and Fujiwara *et al.*[10] on pd breakup at 23 and 156 MeV, respectively. He concludes that there is no direct evidence of an enhancement in the data from the first of these experiments, although a weakly defined peak appears in the ratio of experimental to theoretical breakup cross sections when the Ebenhöh code with a separable S-wave nucleon-nucleon potential is used as input for three-body calculations. The question as to whether Fujiwara *et al.*[10] observed a real peak or a statistical fluctuation is still open to speculation. Clearly no exact calculation is available for comparison at this energy.

In order to investigate further the spectra of pd breakup in collinear geometry, it was decided to perform a precise experiment at the University of Manitoba Cyclotron Laboratory with a view to providing data of sufficient quality that, when compared with an exact calculation using the highly successful Doleschall code (see the theoretical section which follows), would identify accurately any unexpected enhancement in the breakup cross section in the kinematic region of collinearity. Preliminary data for this reaction were presented recently.[11]

The ^{2}H(p,2p)n reaction was studied using the University of Manitoba Spiral Ridge Cyclotron Facility in a kinematically complete experiment at an incident proton energy of 28.6 MeV. The two

outgoing protons were detected in coincidence in ΔE-E telescopes located on either side of the beam at three different pairs of angles. Two of the angle pairs (58.5°–58.5° and 54.6°–62.5°) correspond to collinear geometry at one point on the breakup kinematic locus, and the third angle pair (54.6°–54.6°) has no collinear point. The angular resolution was ±2.1° for the first angle pair and ±1.1° for the second and third pairs of angles. ΔE and E signals for both telescopes and the time difference ΔT between left and right ΔE pulses were stored on-line on magnetic tape. Timing resolution between detectors was 3 ns full width at half maximum (FWHM), allowing timing within a beam burst. Proton events in each telescope were selected from displays of ΔE against E; setting of windows on the time-difference spectrum allowed selection of prompt plus random and random events. The random coincidence background was less than 0.6% of the true coincidence rate in the region of the deuteron breakup kinematic locus. Data were also accumulated with an empty target and a target filled with air; no significant background was seen arising from target windows or air contamination. The hydrogen content of the deuterium gas was <0.5%.

Events lying on the kinematic locus for breakup, projected onto the locus, are plotted in Figs. 1–3 as a function of arc length. The arc length is the distance (in MeV) measured along the kinematic locus, the zero being at the collinearity point for the angle pairs 58.5°–58.5° and 54.6°–62.5°, and at the equal proton energy point for the angles 54.6°–54.6°.

The numerical solution of the Faddeev[2] three-body equations is greatly simplified if the two-body interaction is separable [see Eq. (1)], in which case the Faddeev equations reduce to a set of coupled one-dimensional integral equations of the Lippmann–Schwinger type. Doleschall[4,12] has succeeded in providing separable representations of the nucleon-nucleon interaction which not only give excellent fits to the nucleon-nucleon scattering phase shifts[13] up to pion-production threshold, but also yield results for neutron-deuteron elastic scattering cross sections and polarization observables in good agreement with data[4,7] at 10, 14.1, and 22.7 MeV.

We have used the computer program developed by Doleschall[12] for a calculation of the nucleon-deuteron breakup cross section in the collinearity region studied in the present experiment. The nucleon-nucleon potential is taken as a sum of separable terms,

$$\langle p(LS)J|V|p'(L'S')J\rangle = \sum_n g_{n(LS)J}(p)\lambda_n g_{n(L'S')J}(p'). \quad (1)$$

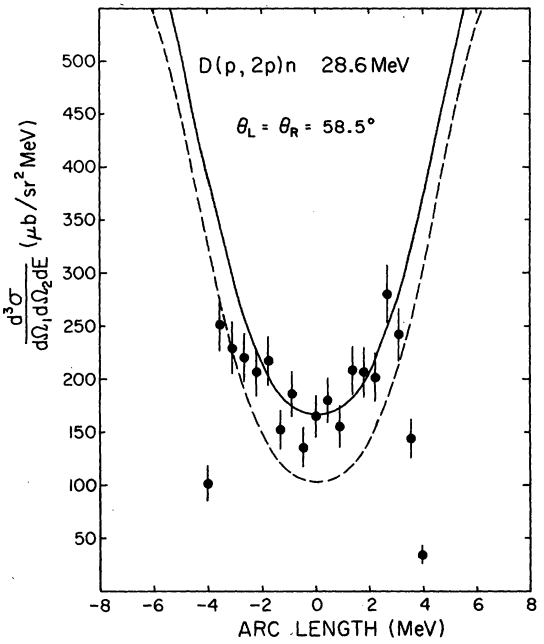

FIG. 1. Cross sections for proton-deuteron breakup in collinear geometry, with $\theta_L = \theta_R = 58.5°$. The abscissa is the arc length along the kinematic locus measured in MeV, the zero being at the collinearity point. Dots with error bars: data; solid line: full three-body calculation; dashed line: S-wave calculation.

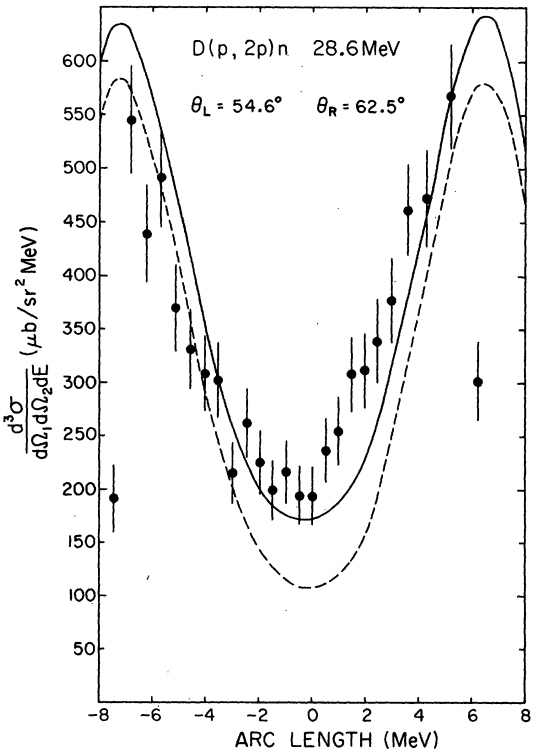

FIG. 2. Cross sections for proton-deuteron breakup in collinear geometry, with $\theta_L = 54.6°$, $\theta_R = 62.5°$. See caption to Fig. 1.

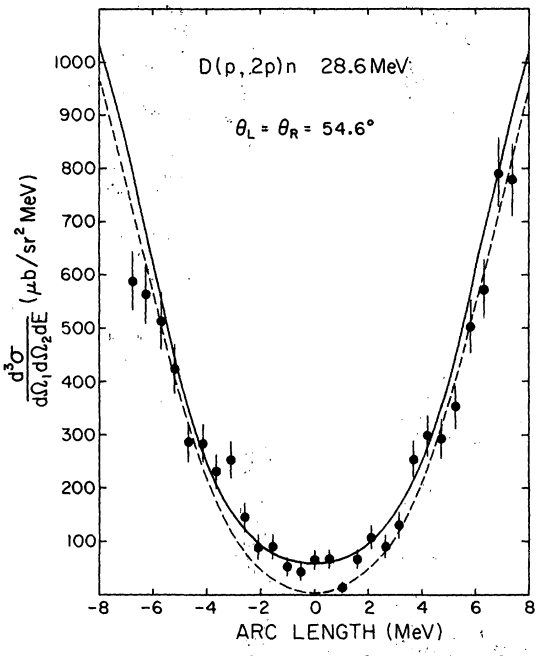

FIG. 3. Cross sections for proton-deuteron breakup in noncollinear geometry, with $\theta_L = \theta_R = 54.6°$. The zero is the equal energy point for the two detected protons. See caption to Fig. 1.

Here L, S, and J are the two-body orbital, spin, and total angular momenta. The two-body relative momentum p is defined in the way introduced by Lovelace,[14] so that p^2 is the two-body relative energy. Thus, p has the units $(\text{MeV})^{1/2}$. In the interaction of Refs. 4 and 12 the sum on n has at most 2 terms. The form factors g are taken[4] to be

$$g_{n(LS)J}(p) = \kappa_{nL} p^L \frac{1+\sum_{i=1}^{N} \gamma_{nLi} p^{2i}}{\prod_{i=0}^{N+L}(1+\beta_{nLi} p^2)} . \quad (2)$$

The interaction used in this work consists of an $^1S_0$ (Yamaguchi $N=0$) interaction,[12] the one-term $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$ interactions of Ref. 4 ($N=1$), and a two-term $^3S_1 - ^3D_1$ interaction,[15] denoted[16] 2T4. The parameters of this interaction are given in Table I. Higher partial waves were omitted to save computer time. The time required for a breakup calculation grows very rapidly with the number of two-body partial waves. At the energy of this experiment, this is not a severe truncation of the two-body interaction. Because of its long range, the Coulomb force cannot be included in the Faddeev formalism. In all the exact calculations, therefore, the Coulomb force has been deliberately omitted, or treated in some rough, and generally untested, approximation. In the calcula-

TABLE I. Parameters in the separable interactions, Eqs. (1) and (2), used in the three-body calculation.

	Partial wave	β_{nLi} (MeV^{-1})	γ_{nLi} (MeV^{-i})	κ_{nL} ($\text{MeV}^{-L/2}$)	λ_n ($\text{MeV}^{-1/2}$)
	$^1S_0$	1.7518×10^{-2}		1.0	-1.5549×10^{-1}
$n=1$	$^3S_1$	2.089×10^{-2}	2.6670×10^{-2}	1.0	-1.6817×10^{-1}
		1.939×10^{-2}			
	$^3D_1$	2.500×10^{-2}	5.4545×10^{-2}	-1.1987×10^{-2}	
		2.245×10^{-2}			
		1.221×10^{-2}			
		0.0			
$n=2$	$^3S_1$	2.438×10^{-2}	-8.7740×10^{-3}	-1.0	1.2800×10^{-1}
		1.522×10^{-3}			
	$^3D_1$	4.892×10^{-2}	2.499×10^{-2}	-2.8300×10^{-2}	
		1.146×10^{-2}			
		2.959×10^{-3}			
		1.631×10^{-3}			
	$^1P_1$	2.2203×10^{-1}	5.4695×10^{-2}	1.0	1.6933×10^{-2}
		1.8889×10^{-3}			
		1.8860×10^{-3}			
	$^3P_0$	1.3317×10^{-1}	8.0240×10^{-2}	1.0	-5.4941×10^{-3}
		1.6727×10^{-2}			
		9.5283×10^{-3}			
	$^3P_1$	1.0363×10^{-1}	2.4827×10^{-2}	1.0	1.9899×10^{-2}
		1.2209×10^{-3}			
		1.1877×10^{-3}			
	$^3P_2$	9.1349×10^{-3}	3.2659×10^{-3}	1.0	-5.3872×10^{-4}
		1.8673×10^{-3}			
		1.4039×10^{-3}			

tion described here the Coulomb force is excluded completely.

The form of the equation solved and the calculational techniques used are described in Ref. 12. We will here show only the results for the three kinematic conditions used in this experiment. The calculations were done both with the full interaction described above and also with only the $^1S_0$ and $^3S_1$ parts[17] of it. As most earlier work suggesting the existence of an enhancement of the cross section in the collinearity region had invoked only S waves, it was felt important to examine the effects of higher partial waves. The results of the comparative calculations are shown in Figs. 1–3. It is clear that the full calculation agrees very well both in absolute magnitude and shape with the data. It must be emphasized that no parameter in the calculation has been varied to fit the data and that there has been no overall renormalization of either the theory or the data. Clearly the S-wave calculation underestimates the cross sections in the collinear regions. If the ratio of the data to the S-wave theory were taken, as has been done in other work,[9] a peak would appear at the condition of collinearity. No evidence of such a peak is seen when the comparison is made with an exact calculation including higher partial waves and the tensor force.

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[16]The, as yet unpublished, $2T4$ interaction is similar in form ($N=2$) to the interactions denoted $2T4D$ and $2T4M$ in Ref. 4 but gives a better fit to both the $^3D_1$ phase and the ϵ_1 mixing parameter than either of them. The notation used for these interactions is that of Doleschall (Refs. 4 and 15): $T4$ signifies a tensor force giving a 4% D-state probability; the 2 before the T is the rank, or number of terms in Eq. (1), and the D or M indicates that either the D-wave phase or the mixing parameter was more strongly weighted in the fit to data.

[17]The $^3S_1$ is in this case not just taken as the S-wave part of $2T4$, but is a one-term interaction fitted (Ref. 12) to only the $^3S_1$ phase shift.