The Angular Distributions of the Products of the D – D Reaction: 1 to 3.5 Mev

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Cross sections per unit solid angle for the reactions $H^2+H^2\rightarrow He^3+n$ and $H^2+H^2\rightarrow H^1+H^3$ have been measured at various angles for incident deuterons of energies from 1 to 3.5 Mev. The dependence of the cross sections on angle is nearly the same for the two reactions, and it can be represented by an expression of the form $A(1+B\cos^2\phi+C\cos^4\phi)$, where ϕ is the angle of observation in the center of mass coordinate system. A increases from 4×10^{-27} cm^2 at 1 Mev to 6×10^{-27} cm^2 at 3.5 Mev; B decreases from approximately 1 at 1 Mev to -3.5 at 3.5 Mev; C increases from 1.5 at 1 Mev to 7 at 3.5 Mev. The total cross sections for the two reactions are approximately constant at 10^{-25} cm^2 throughout this energy range.

THE nuclear reaction $H^2+H^2\rightarrow He^3+n$ has long been used as a source of fast neutrons, but because of the difficulty of measuring a flux of neutrons and the prevalent use of targets composed of a thick layer of heavy ice there is little accurate data on the variations in yield and angular distribution of the disintegration products for deuterons of various energies. The competing reaction, $H^2+H^2\rightarrow H^3+H^1$, has been carefully investigated with thin targets for deuteron energies up to 400 kev. These data have been summarized and some remarks about the theory of the deuteron-deuteron reaction have been made by Konopinski and Teller,[1] and the many references to previous work given in their paper will not be repeated here.

It seemed probable that information of some importance about the deuteron-deuteron interaction could be obtained from a further study of the angular distributions of the reaction products. Such an investigation was carried out at the higher energies available with the Minnesota electrostatic generator, and with the accuracy attainable by means of the gas-filled scattering chamber technique.[2] The present paper is a report on this work.

EXPERIMENTAL PROCEDURE

During the process of measuring the cross section for elastic scattering of deuterons on deuterons[3] it was necessary to determine the numbers of He^3 and H^3 entering the proportional counter in order to apply them as corrections to the observed data. From a study of the bias curves obtained while making that measurement (see Fig. 1 in reference 3) it was seen that the reactions $H^2+H^2\rightarrow He^3+n+3.25$ Mev and $H^2+H^2\rightarrow H^1+H^3+3.98$ Mev had cross sections which were of the order of one or two percent of the elastic scattering cross section. The relatively small counting rate obtained from these disintegrations made it unprofitable to obtain accurate data on their cross sections with the same counter which had been used for the proton-proton[2] and deuteron-deuteron scattering. Increasing the counting rate by increasing the beam current or gas pressure in the chamber were not feasible procedures, so a separate set of measurements was made using a proportional counter with a larger window and an analyzing slit system with wider slits. The width of the first slit (designated $2b$ in Fig. 1 of reference 2) was increased to 0.2067 cm, and the diameter of the defining hole immediately in front of the counter window was increased to 0.4847 cm. The other dimensions of the slit system remained the same. This increased the geometrical factor G (see reference 2, Eq. (1)) by a factor of approximately 9, to a value of 2.8400×10^{-4} cm. The half angle spread of the particles which could enter the counter was increased to 2.6°.

From the information obtained during the measurement of deuteron-deuteron scattering[3] it was known that the He^3 nuclei entering the

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[1] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).

[2] For examples see J. M. Blair, G. Freier, E. Lampi, W. Sleator, and J. H. Williams, Phys. Rev. **74**, 553 (1948).

[3] See preceding paper by the same authors.

TABLE I. Cross sections per unit solid angle in the center-of-mass coordinate system for the reaction $H^2+H^2 \rightarrow H^3+n$ for various deuteron energies and at various angles in the center-of-mass system. The cross sections are in units of 10^{-27} cm².

0.96 Mev		1.49 Mev		2.01 Mev		2.51 Mev		3.02 Mev		3.50 Mev	
φ	σ	φ	σ	φ	σ	φ	σ	φ	σ	φ	σ
16° 18′	15.6 ±.45	17° 29′	18.6 ±.30	18° 23′	21.1 ±.30	19° 7′	20.9 ±.25	19° 43′	22.9 ±.30	20° 14′	23.3 ±.20
24° 25′	13.1 ±.35	26° 11′	15.6 ±.35	27° 34′	16.0 ±.35	28° 39′	15.3 ±.28	29° 34′	14.9 ±.30	30° 21′	14.0 ±.20
32° 30′	11.1 ±.33	34° 52′	12.4 ±.30	36° 42′	10.9 ±.25	38° 11′	9.79±.22	39° 24′	8.36±.15	40° 30′	7.43±.14
40° 17′	9.63±.27	43° 29′	9.38±.23	45° 48′	7.65±.19	47° 4′	6.13±.15	49° 15′	5.43±.10	50° 38′	4.53±.10
48° 26′	8.06±.23	52° 1′	7.24±.18	54° 50′	6.12±.14	57° 8′	5.11±.13	59° 4′	4.46±.07	60° 48′	4.15±.10
56° 16′	6.29±.20	60° 29′	5.81±.15	63° 49′	5.10±.12	66° 33′	4.88±.14	68° 52′	4.87±.11	70° 58′	4.92±.12
		68° 49′	5.48±.16	72° 41′	5.15±.13	75° 54′	5.65±.15	78° 39′	5.54±.15	81° 9′	5.90±.14
		74° 0′	5.22±.14	81° 27′	5.82±.16	85° 10′	5.72±.15	88° 24′	6.35±.17	91° 23′	6.40±.16
		77° 2′	4.78±.12	86° 36′	5.59±.15			98° 6′	6.08±.17		

TABLE II. Cross sections per unit solid angle in the center-of-mass coordinate system for the reaction $H^2+H^2 \rightarrow H^3+H^1$ for various deuteron energies and at various angles in the center-of-mass system. The cross sections are in units of 10^{-27} cm².

0.96 Mev		1.49 Mev		2.01 Mev		2.51 Mev		3.02 Mev		3.50 Mev	
φ	σ	φ	σ	φ	σ	φ	σ	φ	σ	φ	σ
11° 55′	12.2 ±.30	12° 17′	15.9 ±.38	12° 35′	20.7 ±.40	10° 15′	22.8 ±.30	13° 0′	23.9 ±.36	13° 11′	24.5 ±.55
23° 47′	11.0 ±.33	24° 3′	13.2 ±.33	25° 5′	14.9 ±.40	12° 48′	21.1 ±.30	25° 56′	15.7 ±.40	26° 16′	15.4 ±.35
35° 32′	8.31±.36	36° 36′	8.73±.33	37° 26′	9.25±.38	25° 32′	14.9 ±.40	38° 4′	7.47±.23	39° 11′	6.85±.35
47° 7′	6.63±.25	48° 30′	5.88±.27	49° 34′	5.78±.24	38° 7′	8.26±.35	51° 12′	4.24±.20	51° 50′	3.52±.23
58° 30′	5.41±.32	60° 9′	4.93±.23	61° 26′	4.47±.22	50° 27′	5.48±.40	63° 23′	4.28±.23	64° 9′	3.84±.32
69° 37′	4.57±.31	71° 29′	4.26±.40	72° 57′	4.62±.26	62° 29′	4.36±.21	75° 10′	4.54±.20	76° 2′	5.10±.26
		82° 40′	4.67±.22	84° 20′	4.49±.53	74° 7′	4.26±.40	86° 29′	6.03±.25	88° 0′	5.93±.28
						85° 30′	5.12±.27				

counter could be counted separately from the other particles entering simultaneously because the pulses which they produced were so much larger than those produced by the H^3, H^2, and H^1. Therefore, to obtain the cross section for the He^3 reaction the amplifier gain and discriminator bias settings were adjusted so as to record only the number of pulses in the group of largest pulses. Under these conditions data were taken in the manner previously described[2] in the energy range from 1 to 3.5 Mev. Due to the relatively great amount of ionization produced by the He^3 passing through the proportional counter, amplifier noise and the various sorts of background pulses did not influence these data.

The cross section for the competing disintegration was obtained by counting the H^1 nuclei produced. These could be distinguished from all the other disintegration products and scattered particles by means of their much greater range. To take advantage of this fact, the thin Nylon window on the proportional counter was replaced by one of aluminum. For bombarding energies of 2 million volts and greater, the window was 0.0055-inch thick. For the lower energy range a window 0.0035-inch thick was used. These windows satisfactorily eliminated the charged particles other than the desired H^1, but it was found that, because of the greater amplification necessary to record the fast protons, there were counts being recorded due to the recoil argon atoms in the counter produced by neutrons generated when the deuterons collided with deuterons. Although the cross section for the production of neutrons is comparable to that for the productions of H^1, the H^1 which are counted can originate only in a relatively small volume in the center of the scattering chamber, whereas the neutron production occurs throughout the path of the deuterons across the deuterium filled chamber. The number of counts due to these neutron produced pulses could be obtained by making a run during which a small brass shutter was swung into place over the end of the slit system in front of the counter. (This shutter was the one which held the LiF covered screen used for voltage calibration during the proton-proton scattering experiments.[2]) It prevented the entrance of any charged particles into the counter, but did not affect the passage of the beam through the chamber, nor the number of neutrons entering the counter.

The neutrons passing through the counter had energies from 2 to 7 Mev, and the argon recoils could receive a maximum of 10 percent of this energy. With the counter filling (14.5 cm Hg pressure of argon) used for the scattering and He^3 measurements the maximum energy lost by a recoil argon atom is comparable to the energy lost by the relatively fast H^1 in passing through the counter. This made it difficult to get a bias curve flat enough to obtain reproducible data. By increasing the pressure of argon in the counter to about 40 cm Hg the pulses due to the H^1 were increased in size due to the additional energy lost as the H^1 crossed the counter, whereas the maximum pulse due to an argon recoil was the same size because some of the recoils completed their paths in the counter in either case. To maintain the necessary gas amplification in the counter with a reasonable voltage the central wire was reduced from 0.010 to 0.003 inch in diameter. Under these conditions there was still an appreciable counting rate when the shutter was over the entrance to the counter, but by taking appropriate numbers of runs with the shutter in place and with it out of the way the net counting rate due to the H^1 could be determined in a reliable manner.

CORRECTIONS

As mentioned above, no background correction to the data taken on the H^3 was necessary because no other particle was present which would produce as large a pulse as a He^3.

The background counting rate during counts of the H^1 varied from 10 percent to 25 percent of the total counting rate, but was always measured along with the H^1 rate by means of the shutter so that it could be directly subtracted to get the net yield of H^1 counts. Even with the shutter open no charged particles but H^1 from the reaction could get into the counter.

As was the case in the experiment on deuteron-deuteron scattering,[3] there was a correction of 0.3 percent in the beam current measurement because of HH+ ions in the deuteron beam, and a correction of 1.1 percent to be applied to the gas pressure measurement due to the hydrogen contamination in the deuterium in the chamber.

RESULTS

The cross sections per unit solid angle for various angles in the center-of-mass coordinate system and for various deuteron energies are presented in Tables I and II and Figs. 1 and 2. The angle of observation in the center-of-mass coordinate system, ϕ, was obtained from the

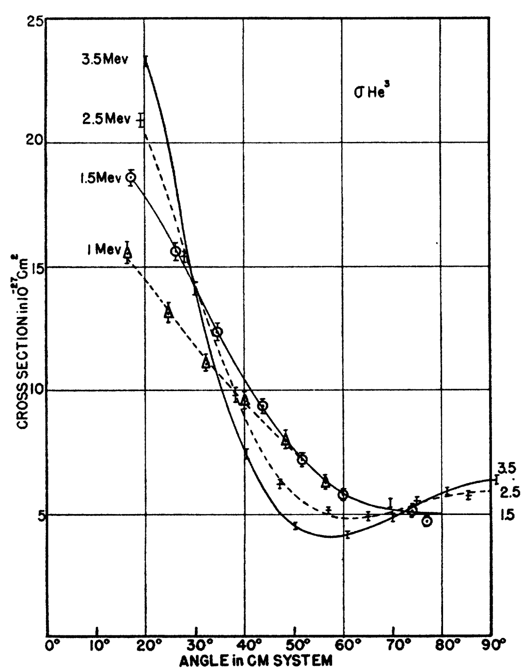


FIG. 1. Cross section per unit solid angle in the center-of-mass coordinate system for the reaction $H^2+H^2 \rightarrow He^3+n$ for deuterons of various energies.

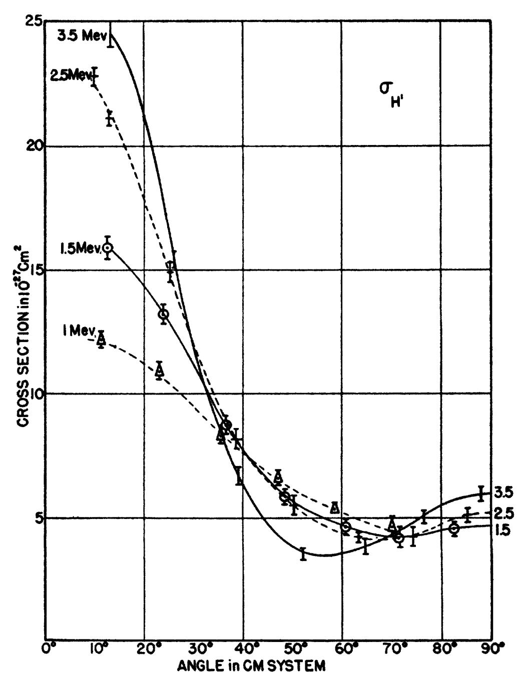


FIG. 2. Cross section per unit solid angle in the center-of-mass coordinate system for the reaction $H^2+H^2 \rightarrow H^3+H^1$ for deuterons of various energies.

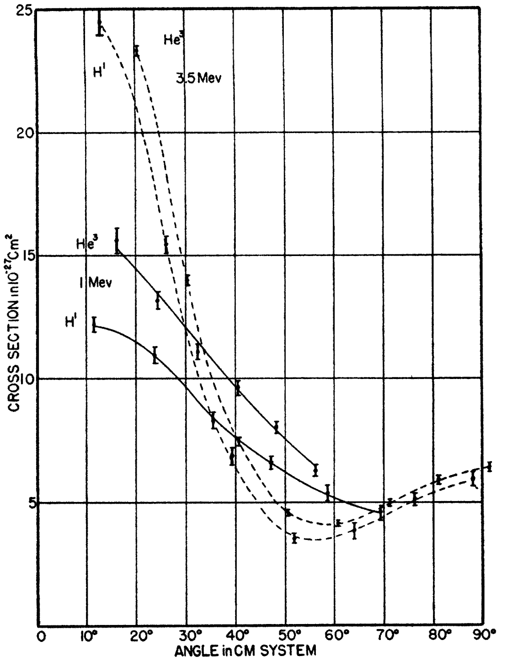


FIG. 3. Comparison of the cross sections per unit solid angle in the center-of-mass coordinate system for the reactions $H^2+H^2\rightarrow He^3+n$ and $H^2+H^2\rightarrow H^3+H^1$ at 1 Mev and 3.5 Mev.

angle of observation in the laboratory, θ, by $\phi=\theta+\sin^{-1}(\sin V\,\mathrm{cm}/V)$ where V cm is the velocity of the center-of-mass of the particles undergoing the disintegration and V is the velocity in the center-of-mass coordinate system of the observed particle. The cross section per unit solid angle in the center-of-mass coordinate system, $\sigma(\phi)$, was obtained from the cross section in the laboratory by

$$\sigma(\phi)=\sigma(\theta)\cos(\phi-\theta)\cdot(\sin\theta/\sin\phi)^2=\sigma(\theta)\cdot g(\theta).$$

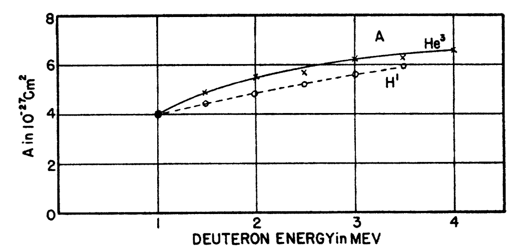
Unlike the elastic scattering case, the factors $g(\theta)$ and $V\,\mathrm{cm}/V$ are also functions of the energy of the incident deuterons.

The probable errors quoted in Tables I and II are those caused by the expected statistical fluctuations in the number of counts obtained at each point. In addition there is a probable error, common to all the points, of about 1.7 percent which enters in the factors used for converting the observed numbers of counts to cross sections.

The curves for 1 Mev and 3.5 Mev deuterons for both reactions are redrawn in Fig. 3 to facilitate a comparison of the two reactions. If a similar comparison of the data for the other energies were made it would be seen that in each case the two curves would lie practically parallel, as in the case of the 3.5 Mev curves in Fig. 3. It is only at low energies that the angular distributions of the products of the two reactions differ appreciably.

Since the earlier low energy data on the angular distribution of the products of these reactions were found to be represented by a curve of the form $A(1+B\cos^2\phi)$,[1] a similar analysis was attempted on the data given above. It was soon found that an additional term, $C\cos^4\phi$, was required. The variations of the coefficients A, B, and C with energy for the two reactions are shown in Fig. 4. The size of the symbols on each curve at each deuteron energy represents the approximate uncertainty in that value of the coefficient. Due to the uncertainties in the original data and the fact that this equation does not seem to provide a perfect representation of these data at the higher energies, there is some leeway in the values to be assigned to the coefficients for a "best" fit.

The short curve labeled "B" at the low energy end of the axis is taken from Fig. 1 of the sum-



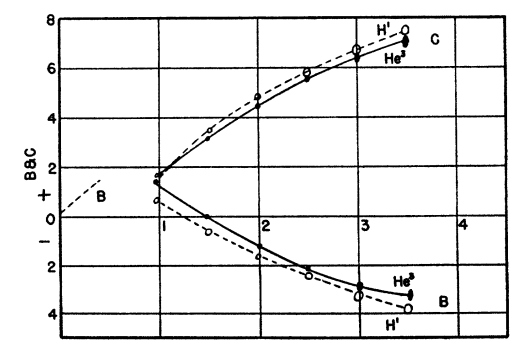


FIG. 4. Values of the coefficients A, B, and C in the equation $\sigma=A(1+B\cos^2\phi+C\cos^4\phi)$ for incident deuterons of various energies. The curves marked He^3 apply to the reaction $H^2+H^2\rightarrow He^3+n$. The curves marked H^1 apply to the reaction $H^2+H^2\rightarrow H^3+H^1$. The low energy curve marked B is taken from reference 1.

mary of the low energy data by Konopinski and Teller.[1] It may be considered as a low energy extension of the B curve for the H^1 data. In this low energy range a term involving $\cos^4\phi$ has been found unnecessary for a representation of the data,[1] so apparently C goes to zero between $\frac{1}{2}$ and 1 Mev deuteron energy.

The measurements of Bennett, Mandeville, and Richards[4] on the angular distribution of the neutrons from the $H^2+H^2\rightarrow He^3+n^1$ reaction are not in contradiction to our data, although they represented their data in terms of $1+B\cos^2\phi$. Their measurements were made only at two angles, $\phi=0°$ and $\phi=90°$, so the more detailed data necessary for a comparison with our results are not available. However, the value of the coefficient given in Fig. 3 of their paper can be compared with the algebraic sum of B and C in our analysis, and the two numbers are found to agree within the accuracy one might expect considering the difficulty of measuring a flux of neutrons.

From the data presented in Figs. 1 and 2 one can compute the values of the total cross section for each of the reactions. This was obtained from $\sigma_T=4\pi\sum_i\sigma(\phi_i)\sin\phi_i\cdot\Delta\phi$ for each energy of incident deuterons. The summations were taken for values of ϕ_i in 10° steps from 5° to 85°. The results of these computations are shown in Fig. 5. From these curves it is apparent that, in this energy range, increasing the deuteron energy does not greatly affect the total number of disintegrations occurring, even though, as shown by Figs. 1 and 2, the angular distributions change in a marked fashion.

The dots and crosses in the low energy region in Fig. 5 represent the data for the total cross sections for these two reactions taken by Manley, Coon, and Graves[5] using a thick heavy ice target. They counted the protons emitted at three angles for the $H^2+H^2\rightarrow H^3+H^1$ reaction and integrated the neutron production from the $H^2+H^2\rightarrow He^3+n^1$ reaction with a $MnSO_4$ bath. Except for the 300 kev neutron point, their data appear to lie in line with extensions of our curves to lower energies.

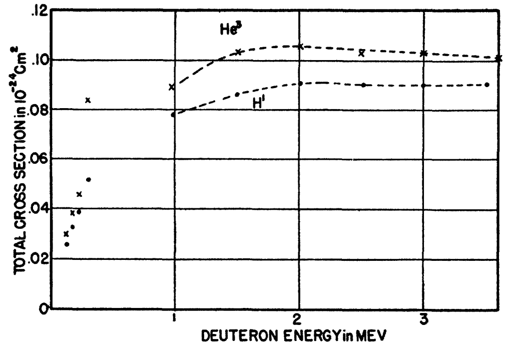


FIG. 5. Total cross sections for the reactions $H^2+H^2\rightarrow He^3+n$ (curve marked He^3) and $H^2+H^2\rightarrow H^3+H^1$ (curve marked H^1) for deuterons of various energies. The low energy points are taken from the work described in reference 5.

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[4] W. E. Bennett, C. Mandeville, and H. Richards, Phys. Rev. **69**, 418 (1946).

[5] J. H. Manley, J. H. Coon, and E. R. Graves, Phys. Rev. **70**, 101A (1946).