The writers are indebted to E. S. Robinson and his colleagues in the Radiochemistry Group at Los Alamos for their collaboration in the preparation and handling of the tritium samples, and they gratefully acknowledge the assistance of G. G. Everhart in the operation of the electrostatic accelerator.

APPENDIX

TABLE I. Proton-triton scattering; experimental results for differential cross sections in both laboratory and center-of-mass systems as a function of angle in barns per unit solid angle.

		$E_p=0.708$ Mev		$E_p=0.990$ Mev		$E_p=1.108$ Mev		$E_p=1.236$ Mev		$E_p=1.45$ Mev		$E_p=1.678$ Mev		$E_p=1.90$ Mev		$E_p=2.117$ Mev		$E_p=2.335$ Mev		$E_p=2.548$ Mev	
θ_{lab}	ϕ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}	σ_{lab}	σ_{CM}
45	58.8	0.571	0.381					0.215	0.144	0.235	0.157					0.306	0.204				
50	65.7	0.475	0.330	0.292	0.203	0.204	0.142	0.195	0.135	0.204	0.142	0.210	0.146	0.218	0.152	0.240	0.167	0.256	0.171	0.264	0.183
60	77.5	0.338	0.256	0.219	0.166	0.184	0.140	0.167	0.127	0.169	0.128	0.171	0.130	0.173	0.131	0.176	0.133	0.185	0.140	0.193	0.147
70	90.0			0.202	0.170	0.170	0.143	0.155	0.130	0.152	0.128	0.150	0.126	0.147	0.124	0.143	0.120	0.142	0.119	0.148	0.125
80	98.5			0.194	0.184	0.162	0.154	0.150	0.142	0.146	0.138	0.142	0.135	0.136	0.129	0.129	0.122	0.124	0.118	0.120	0.114
90	109.4					0.160	0.170	0.149	0.158	0.145	0.154	0.140	0.148	0.134	0.142	0.127	0.135	0.120	0.127	0.113	0.120
100	118.8							0.153	0.184	0.147	0.176	0.141	0.169	0.135	0.162	0.130	0.156	0.124	0.149	0.115	0.138
110	128.									0.144	0.196	0.140	0.191	0.136	0.185	0.132	0.180	0.126	0.171	0.117	0.159
120	136.8											0.137	0.210	0.134	0.206	0.131	0.199	0.126	0.193	0.118	0.181
130	144.8											0.134	0.229	0.131	0.225	0.128	0.219	0.124	0.213	0.116	0.199
135	148.5											0.132	0.237	0.129	0.232	0.126	0.227	0.121	0.218		
55	71.1			0.251	0.182																
65	83.7			0.208	0.166	0.176	0.140			0.160	0.127										
75																0.135	0.120				
85										0.149	0.149									0.115	0.115
95										0.152	0.171										

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Cross Section as a Function of Angle for the D(*d*,*n*)He^3 Reaction for 10-Mev Bombarding Deuterons*

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By counting He^3 particles with a proportional counter, the differential cross sections for the reaction D(*d*,*n*)He^3 have been measured at laboratory angles from 16.5 degrees to 38.2 degrees (39.3 degrees to 95.0 degrees in center of mass system), for an incident deuteron energy of 10.3 Mev. In the center of mass system, the differential cross section is 4.5×10^{-27} cm² at 90 degrees, decreasing to a minimum of 2.2×10^{-27} cm² at about 45 degrees, and rising steeply at lower angles. By determining the neutron yield with $Cu^{63}(n,2n)Cu^{62}$ detectors, the differential cross section at zero degrees is found to be about five times that at 90 degrees (center of mass).

I. INTRODUCTION

SINCE the discovery of the $D+D\rightarrow He^3+n$ reaction by Oliphant, Harteck, and Rutherford,[1] a number of investigations[2–11] of the yield and the angular distribution of the products have been made for bombarding energies below five Mev. The earlier measurements on the angular distribution were made at zero and 90 degrees to the beam direction and the differential cross section in the center of mass system was fitted to a $(1+A(E)\cos^2\theta)$ law. This law has been found to hold[12–17] at a number of angles for the competing reaction, $D+D\rightarrow H^3+H^1$.

For the D(*d*,*n*)He^3 branch of the reaction in the bombarding energy region above one Mev, more recent work[18–19] shows that terms up to $\cos^6\theta$ must be included in the Fourier expansion of the differential cross section

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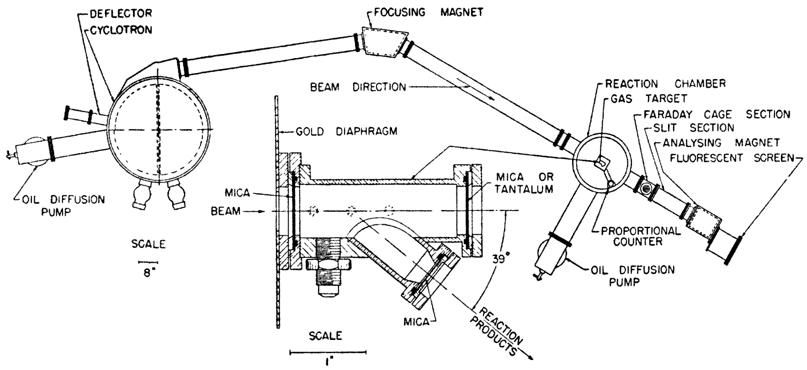

FIG. 1. Apparatus assembly.

as a function of angle. Konopinski and Teller[20] have formed a qualitative theory of the angular variation of this reaction showing how $A(E)$ (the coefficient of the first term of the Fourier expansion) should change with the energy of the bombarding deuterons.

For bombarding energies above five Mev, very little experimental or theoretical research has been done on this reaction. Preliminary work in this laboratory at 10 Mev over limited angular range has been previously reported.[21] The thick target yield of neutrons from this reaction has been obtained with 10-Mev deuterons.[22]

The present experiment consists of bombarding a thin deuterium gas target with 10-Mev deuterons from the Los Alamos 42-inch cyclotron and counting the number of reaction particles which come off at various angles per coulomb of beam current. From these values and the geometry of the system, the differential cross section is calculated. Since the cyclotron does not hold the energy of the deuterons constant (see Table II), this energy is measured at frequent intervals and all data corrected to 10.3 Mev. For center of mass angles larger than 39 degrees the He^3 particles were counted by means of a proportional counter. For zero degrees the neutrons from the reaction were counted indirectly by measuring the 10-minute activity produced in copper foils by a $Cu^{63}(n,2n)Cu^{62}$ reaction. The essential results of this research have been reported in a Letter to the Editor in the *Physical Review*.[23]

TABLE I. Summary of the results of analysis for possible excited states of the He^3 nucleus.

Lab angle between He^3 and beam	Energy of main He^3 peak Mev	Energy region examined for He^3 group Mev	Limit of required He^3 excitation levels to fall in column 3 Mev
31.4°	7.4	4.8–6.8	3.1–0.9
26.7°	8.6	4.8–7.7	4.5–1.0
22.4°	9.1	7.2–8.7	3.2–0.9
19.5°	9.6	7.7–9.2	3.2–0.9
16.5°	10.2	7.8–8.7	3.8–2.6

II. APPARATUS

The equipment used in this experiment was, in general, the same as that described by Curtis, Fowler, and Rosen.[24] The general outline of the apparatus is shown in Fig. 1. The 10-Mev deuteron beam passes from the focusing magnet and thence into a six-foot length of six-inch diameter tubing. Gold defining slits, together with an antiscattering slit in this tubing, collimate the beam to ± 0.6 degree as it enters the $\frac{1}{4}$-inch diameter mica window of the gas target. In order to cut down on background due to neutrons, and also to confine the source of neutrons (Section IV) the gas targets were designed as short as possible consistent with the condition that the volume defined by the slit of the counter not include any material being bombarded by the deuteron beam except the deuterium gas. Rutherford scattering in the front mica window of the target was small for 10-Mev deuterons; the measured effective spread of the beam after passing through the window was increased from ± 0.6 degree to ± 0.8 degree; less than one deuteron in 10^5 in the beam was scattered at such an angle as to strike the target wall in front of the proportional counter slit system. After passing through the gas target, the beam entered the Faraday cage which was used with a current integrator to monitor the beam. The cage could be moved to allow the beam to continue to the analyzing magnet for energy measurements.

The slit system defining the He^3 particles consisted of a $\frac{1}{8}$-inch vertical slit attached to the target immediately in front of the target window and a $\frac{1}{8}$-inch hole in the proportional counter. Since there was nothing between the target and an absorber foil immediately in front of the counter to produce scattering of particles into the counter (Fig. 1), an antiscattering slit between the target and the counter was unnecessary. Reaction volume and solid angle calculations were made in essentially the same manner as suggested by Herb, Kerst, Parkinson and Plain.[25] Pulses from the proportional counter were fed to a linear amplifier and thence to a ten-channel pulse amplitude analyzer from which the data were recorded.

[20] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).
[21] Curtis, Rosen, and Fowler, Phys. Rev. **73**, 648 (1948).
[22] L. W. Smith and P. G. Kruger, Phys. Rev. **74**, 1258 (1948).
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[24] Curtis, Fowler, and Rosen, Rev. Sci. Inst. **20**, 388 (1949).
[25] Herb, Kerst, Parkinson, and Plain, Phys. Rev. **55**, 998 (1939).

In an effort to improve the effective resolution of the proportional counter, several additions and improvements were made to the equipment described by Curtis, Fowler, and Rosen.[24] The most important of these was the addition of a selsyn controlled foil system mounted on the reaction chamber lid so that one hundred combinations of foil thicknesses were available for slowing down the reaction particles to make the ends of their paths lie in the counter. The proportional counter was redesigned with a 0.005-inch collecting wire offset $\frac{1}{4}$ inch from the center of the counter. A palladium leak was added to the target filling system in order to improve the purity of the deuterium in the target.

The beam spread and position was measured by using the proportional counter, with a $\frac{1}{8}$-inch diameter entrance window, as an ionization chamber (with about one atmosphere of argon pressure and minus 135 volts on the center wire). This counter was set at various positions near zero degrees and the amount of ionization (and hence the beam strength) was obtained as a function of angle. Since the beam was defined by a $\frac{1}{4}$-inch diameter diaphragm at the position of the target entrance window (Fig. 1), and since the distances involved were known, it was possible to calculate the angular spread of the beam from this measurement. The measurement was repeated after the target was in place in order to determine the scattering effect of the two mica windows.

The current integrator and Faraday cage were checked by measuring, by thermocouple, the temperature rise of an 83-gram piece of copper faced with 15 grams of gold which was placed in the beam just in front of the Faraday cage. The beam was monitored by the He^3 particles from the $D(d,n)He^3$ reaction which had in turn been calibrated against the current integrator. From the temperature rise of the block while it was in the beam, the specific heat of the block, and from the beam energy, the total charge striking the block was computed and compared with the charge indicated by the He^3 particles passing through the counter. Results of this test indicate agreement between these two measurements within three percent.

III. DISTRIBUTION OF HE^3 PARTICLES

The procedure used in taking the primary data was quite similar for all these points. At the beginning of each day of operation the ten-channel amplitude analyzer was calibrated against an automatically variable pulse generator; the current integrator was calibrated against known constant leakage currents; and the target and counter were flushed and refilled with fresh gas. The counter voltage was adjusted to give a gas multiplication of ten. When a usable cyclotron beam was obtained, the absorber foils in front of the counter were adjusted to give the best He^3 peak on the ten channel analyzer and the amplifier gain was set to cause this peak to occur at a convenient position on the analyzer. When these adjustments had been completed, a data run was made, usually consisting of about 128 current integrator counts (i.e., about 14 microcoulombs). The raw data consisted of the number of pulses recorded in each channel of the ten-channel pulse amplitude analyzer and the number of current integrator counts obtained. The cyclotron beam was such that a normal run usually required about two minutes. On the completion of a data run, the absorber foil wheels were adjusted so that they would completely stop the He^3 particles and a background run was made. Immediately after such a set of runs (and without turning off the cyclotron), the Faraday cage was moved and the

TABLE II. Summary of results for the differential cross section of the $D(d,n)He^3$ reaction.

Lab. angle degrees	Energy of deuterons Mev	Differential cross section in lab. system $cm^2 \times 10^{-26}$
16.5	10.0	1.55
16.5	10.2	1.54
19.5	9.9	1.12
19.5	10.3	1.13
22.4	10.0	1.33
22.4	10.3	1.37
26.7	10.5	1.90
26.7	10.6	1.91
29.2	10.4	2.11
29.2		2.14
31.4	10.5	2.17
31.8	10.1	2.21
35.9	9.7	2.22
35.9	9.8	2.16
35.9	10.2	2.13
38.2	9.7	1.98
38.2	10.2	2.04
38.3	10.3	2.18

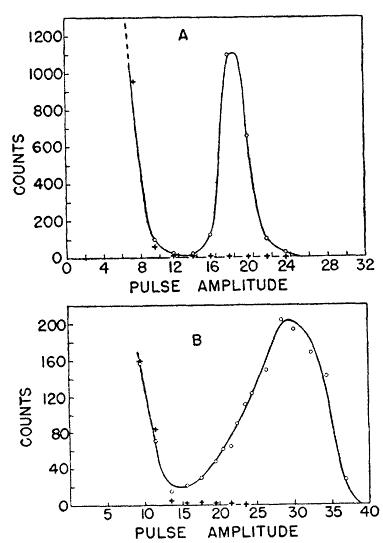

FIG. 2. Distribution of pulses from proportional counter due to He^3 particles. Curve A is for He^3 particles which make an angle of 16.5 degrees with the deuteron beam. Curve B is for He^3 particles which make an angle of 38.2 degrees with the deuteron beam. The crosses represent the background obtained by stopping the He^3 particles before they reach the counter.

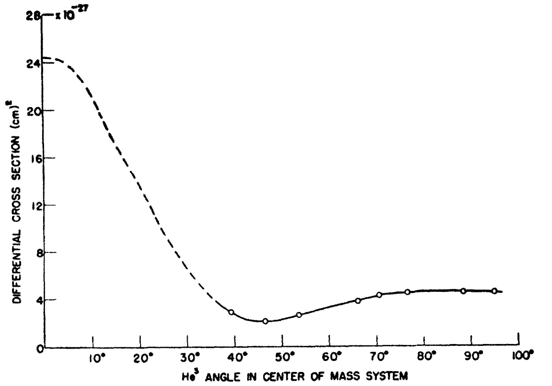

FIG. 3. Differential cross section of D(d,n)He^3 reaction in center of mass system.

energy of the beam was measured by means of magnetic deflection.

Figures 2A and 2B give typical distribution of pulses from the proportional counter as obtained during data runs. By comparison of the pulse amplitudes with pulses from plutonium alphas, one determines that the peaks are due to doubly charged particles. That the peaks are due to He^3 particles from the reaction $D+D\rightarrow He^3+n+3.3$ Mev[26] is demonstrated by the amount of absorber, between the counter and the target, required to obtain maximum peak height and best resolution from background. The air equivalent of the absorbers plus the mica windows and gas in the target and counter corresponded to the expected range of the He^3 particles.

For laboratory angles from 16.5 degrees to 32.0 degrees, the low energy tail of the distribution is of the order of one percent of the maximum peak as in Fig. 2A. Near 40 degrees to the beam, where the range of the He^3 particles approaches the air equivalent of the mica windows, the resolution of the peak is not as complete (Fig. 2B). For all the curves used to obtain the data in this report the low energy tail was less than 12 percent of the peak.

The curves similar to Fig. 2A provide information on the possibility of excited states of the He^3 nucleus. The width of the minimum between the peak and background sets a limit to the energy region in which no secondary He^3 peak exists (at least to one part in forty compared to the main He^3 peak). From the energy of the main He^3 group which is lost in the counter, one can calculate the energy of a group which would fall in the minimum between the peak and background. Table I gives a summary of the results of this analysis. Columns one and two give, respectively, the laboratory angle and the energy of the He^3 particles in the main peak. Column three gives the energy region corresponding to the minimum in which peaks could be detected if they were present. Column four gives the limits of the excitation levels of the He^3 nucleus which would be required to give groups in the energy region tabulated in column three. Since these groups were not found, the interpretation of Table I is: at the angles listed there are not energy levels, detectable by this method, above the ground state of the He^3 nucleus between the limits listed in column four.

The total number of counts in the He^3 peak per coulomb of beam current (corrected for background as mentioned above), together with geometrical factors, and the pressure and temperature of the gas in the target, allows one to calculate the differential cross section of the D(d,n)He^3 reaction at the various angles at which data were taken. Table II gives a summary of the results. Column one gives the angle defined by the slit system between the He^3 particles and the deuteron beam. The maximum angular spread defined by the slits and counter window is ± 1.1 degrees for angles near 40 degrees and is ± 1.3 degrees for angles near 20 degrees. The effective angular spread of the deuteron beam including Rutherford scattering of the deuterons in the front window of the target is ± 0.8 degree. Rutherford scattering of the He^3 particles by the mica windows in the side port adds to the angular spread. This scattering was calculated for the foils and energies involved. Near 20 degrees only about three percent of the He^3 particles were scattered between one and two degrees by the mica. Because the energy of the He^3 particles is less near 40 degrees, about nine percent are scattered between one and two degrees in this angular region. Such scattering introduces a negligible error in the differential cross section, providing the cross section does not vary rapidly over angular intervals of about two degrees. This follows from the fact that, under the above conditions, as many particles are scattered into the counter as are scattered out of it.

Column two of Table II records the deuteron beam energy as measured directly after data and background runs as described above. While the accuracy of this measurement is about two percent, relative measurements are good to about one percent so that an appreciable part of the variation of the energy (given in column two) is real. This variation has been correlated with changes in the cyclotron such as oscillator frequency, etc.

The measured differential cross section for production of He^3 by the D(d,n)He^3 reaction is given in column three. This is the cross section per unit solid angle, in units of 10^{-26} cm^2. Since no two measurements at the same angle were taken on the same day, the data appear to be very reproducible under different conditions. The statistical error expected from the number of counts in each run is about one percent or less. For most of the runs the error involved in estimating the background is less than one percent, although for the runs near 38 degrees the error may be as large as three percent. The error in the geometrical factor (including the error in measurement of the angle to the beam) is about two percent. The Faraday cage measurement of the deuteron current is possibly in error by two percent. The

[26] H. V. Argo, Phys. Rev. 74, 1293 (1948).

check of the beam current discussed in Section II agrees to about this accuracy when the error of the energy measurement is taken into consideration. Treating the errors as random, the estimated accumulated standard error in the figures in column three is about four percent over most of the range. Near 40 degrees these errors may be about six percent. The differential cross section as measured is the average value over an angular region of about $\pm$ two degrees in the laboratory system. Thus, if this differential cross section varies rapidly over an angular region of this size the variation will not be resolved.

IV. NEUTRONS AT ZERO DEGREES

The differential cross section of the $D(d,n)He^3$ reaction, for the case in which the neutron emerges at zero degrees to the direction of the deuteron beam, was measured by allowing the neutrons to irradiate copper foils, and by means of Geiger counters, determining the number of copper atoms so activated. The deuteron beam was monitored by counting He^3 particles with the proportional counter. The copper activity has a half-life of ten minutes and is produced by the reaction $Cu^{63}(n,2n)Cu^{62}$. Two separate runs were made with deuterium in the target and one run with hydrogen. The latter run was made to correct for background neutron flux which was found to be about 14 percent at zero degrees.

The Cu^{62} activity has been produced elsewhere in this laboratory by a known flux of 14-Mev neutrons[27] and with the cyclotron by a known flux of neutrons from the threshold to 12.6 Mev.[28] Combining this information it is possible to estimate the activation cross section for 13.3-Mev neutrons (obtained with the present set-up) and hence arrive at an estimate of the flux of the $D-D$ neutrons at zero degrees. This involved an intercalibration of the various Geiger counters used in the different measurements. This calibration was carried out by using a standard thermal neutron flux to produce five-minute Cu^{66} by the $Cu^{65}(n,\gamma)Cu^{66}$ reaction, with activity was counted on the various Geiger counters. The beta-ray from the Cu^{66} has about the same energy as the beta-ray from Cu^{62} (2.6 Mev).[29]

Using this method of detecting neutron flux, one obtains an estimate for the $D(d,n)He^3$ cross section at zero degrees. This value is not very accurate, mainly because of the unreliability of the estimate of the activation cross section of the Cu^{63} at 13.3 Mev, which may be in error by 30 percent. The result, translated into differential cross section, is plotted in Fig. 3.

[27] R. W. Davis and D. D. Phillips (private communication).
[28] J. L. Fowler and J. M. Slye, Phys. Rev. **76**, 169 (1949).
[29] J. Mattauch, *Nuclear Physics Tables* (Interscience Publishers, Inc., New York).

V. CONCLUSIONS

The data given in Table II have been plotted as a function of beam energy and from this family of curves the cross sections for 10.3-Mev beam energy obtained. These values of the differential cross section (corrected for the intensity per unit solid angle in the laboratory system compared to the intensity per unit solid angle in the center of mass system) have been plotted in Fig. 3 as a function of angle in the center of mass system. The measurements, when translated to the center of mass angles, extend from 39.3 degrees to 95.0 degrees. Below 39.3 degrees the dotted curve indicates a rough extrapolation on the basis of neutron measurements using the $Cu^{63}(n,2n)Cu^{62}$ threshold detector as explained in Section IV. The symmetry of the reaction in the center of mass system makes the curve in Fig. 3 symmetrical about 90 degrees. The data in Fig. 3, the differential cross section as a function of angle in the center of mass system, has been analyzed, by least squares, in terms of normalized Legendre polynomials of even order. The result is:

$$\sigma = 7.13P_0 + 3.29P_2 + 4.22P_4 + 1.83P_6 + 0.18P_8$$

in millibarns. The last term is about equal to the estimated uncertainty in the data.

Preliminary measurements made over a somewhat limited angular region and with much less precision[21] gave values of the differential cross section of 3.5×10^{-27} cm^2 in rough agreement with the results of Fig. 3 for angles near 90 degrees in the center of mass system. These measurements, however, did not extend over a large enough angular region nor were they precise enough to detect the minimum which shows up in Fig. 3 nor the maximum at zero degrees (center of mass system). This minimum in the differential cross-section curve begins to appear at bombarding energies of 2.5 Mev and is very pronounced at 3.5 Mev.[18] The total cross section obtained by integrating the curve of Fig. 3 over the entire solid angle is 0.07×10^{-24} cm^2. The steep rise in the cross section below 40 degrees makes the total cross section somewhat higher than the value reported earlier (0.04×10^{-24} cm^2)[21] which was obtained from differential cross section measured in the more or less flat region of the curve near 90 degrees. The value of 0.07×10^{-24} cm^2 fits the cross section *versus* energy curve extrapolated from measurements which extend to 3.5 Mev.[18]

We wish to acknowledge the assistance of members of the cyclotron group at Los Alamos who helped run the cyclotron while the data for this experiment were being taken. We wish to thank Dr. J. H. Williams for his aid in installing the palladium leak, and for several helpful suggestions relative to this problem.