flector inside the cyclotron and focused in the reaction chamber by the focusing magnet.

VI. CONCLUSIONS

A smooth curve which fits the data is given by

$$\sigma(\cos\Omega)=0.0740+0.1150\cos\Omega+0.00492\cos^2\Omega -0.1214\cos^3\Omega+0.1424\cos^4\Omega.$$

Figure 4 shows the results of the measurements made on this reaction for a number of energies. In the 10-Mev region nuclear scattering represents by far the major fraction of the scattering cross section at all angles. If one makes a reasonable extrapolation of the cross-section *vs* angle curve to 0° and 180° and then integrates this curve, the total cross section for the nuclear scattering is found to be 1.5×10^{-24} cm². This is essentially the same as the total cross section for the $n-d$ collision at the same center-of-mass energy.[15] It should be pointed out that little error is introduced in the extrapolation of the cross-section curve from 29° to 0° and from 161° to 180°, since the integrand is $\sigma(\Omega)\sin\Omega d\Omega$. The continued shift in the minimum to larger angles at our energy indicates the increased effectiveness of waves of higher order than *S*-waves. The Legendre expansion indicates that *D*-waves are in evidence.

We take pleasure in acknowledging the helpful cooperation of Dr. J. L. Fowler, Mr. Alvin M. Hudson, and the entire Los Alamos cyclotron group. For the analysis of most of the plates we are indebted to Mrs. M. Bergstresser, Mrs. R. Booth, Mrs. M. Downs, Mrs. M. Gibson, Mrs. F. Forbes, Mrs. C. Hart, Mrs. C. Lacey, Mrs. O. Milligan, Mrs. M. Osborn, Mrs. F. Peet, Mrs. V. Stovall, and Mrs. L. Tallmadge.

[15] Nuckolls, Bailey, Bennett, Bergstralh, Richards, and Williams, Phys. Rev. **70**, 805 (1946).

PHYSICAL REVIEW VOLUME 82, NUMBER 6 JUNE 15, 1951

Angular Distribution of Protons from the D(*d*, *p*)T Reaction at 10.3-Mev Bombarding Energy

J. C. Allred, D. D. Phillips, and Louis Rosen
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received February 19, 1951)

The differential cross section of the D(*d*, *p*)T reaction for 10.3-Mev bombarding deuterons has been measured by a nuclear emulsion technique, using a multiple nuclear-plate camera. Values of the cross section are given over essentially the entire range of the center-of-mass angle. The results are fitted within experimental error by the expression:

$$\sigma(\cos\Omega)=6.24P_0+8.28P_2+13.16P_4+8.24P_6+2.31P_8,$$

where Ω is the center-of-mass angle, σ is expressed in millibarns per unit solid angle, and the P_i's are Legendre polynomials. For angles between 20° and 160° the average rms absolute standard error is ±3.8 percent. For angles greater than 160° and less than 20° this error approaches ±5 percent.

I. INTRODUCTION

THE investigation of the D(*d*, *p*)T reaction is of special interest because the small number of nucleons involved in the reaction makes possible detailed theoretical treatments such as have been carried out by Konopinski and Teller,[1] Nakano,[2] and Beiduk, Pruett, and Konopinski.[3] Such theoretical analyses are likely to be most fruitful if they are based on accurate experimental data measured over as large an angular interval as possible. In the present experiment, data are taken from 10° to 172.5° in the laboratory system. This makes it possible to obtain the differential cross section as a function of angle over the entire angular range in the center-of-mass system except between 0° and 4°, where geometric conditions prevented the taking of data.

Both the D(*d*, *p*)T and D(*d*, *n*)He³ reactions have been investigated rather extensively below 3.7 Mev. The latter reaction has been investigated recently at this laboratory[4] using 10.3-Mev deuterons. It is of interest to determine whether the differential cross sections for the two reactions continue to vary with energy as they do from 1 Mev to 3.5 Mev. Furthermore, if, as one might infer from the low energy data, the two reactions are reasonably similar at 10.3 Mev, the differential cross-section curve for the reaction yielding protons might be normalized to the curve for the reaction yielding neutrons in order to make possible a prediction of the latter differential cross section between 4° and 40° in the center-of-mass system, which interval could not be investigated in the D(*d*, *n*)He³ experi-

* Work done under the auspices of the AEC.
[1] E. J. Konopinski and E. Teller, Phys. Rev. **73**, 822 (1948).
[2] Y. Nakano, Phys. Rev. **76**, 981 (1949).
[3] Beiduk, Pruett, and Konopinski, Phys. Rev. **77**, 622, 628 (1950).
[4] Erickson, Fowler, and Stovall, Phys. Rev. **76**, 1141 (1949).

ment.[4] The reaction yielding protons has been studied recently with 9.94-Mev deuterons at the University of Illinois.[5] The angular region covered in this work was 20°–90° in the center-of-mass system.

II. EXPERIMENTAL

The apparatus and techniques employed in the present experiment are the same as those described by Rosen and Allred[6] for their $d-p$ scattering investigation. The present experiment consists essentially of bombarding a thin deuterium gas target with 10.3-Mev deuterons from the Los Alamos 42-inch cyclotron and recording on photographic plates the intensity and range of the reaction particles which come off at various angles with respect to the incident deuteron beam. The purity of the deuterium gas was determined spectroscopically to be 99.5 percent. The cyclotron instrumentation is the same as that described by Curtis, Fowler, and Rosen.[7] Experimentally, one measures the integrated beam current, the pressure and temperature of the deuterium gas in the camera, the detector and slit system geometry, and the number of tracks of proper range in a rectangular swath of known width along the photographic plate. From these data, the differential cross sections at the various angles of observation can be calculated.[8]

Most of the data for the differential cross-section curves are in the laboratory interval from 65° to 172.5° and in this region elastically scattered deuterons cannot be confused with the reaction protons when range discrimination is used. Figure 1 shows a range distribution of the charged particles arriving at the 132.5° detector. At the more forward angles it is necessary to absorb the elastically scattered deuterons with aluminum foils of appropriate thickness, since here the number of deuterons is sufficient to interfere with the reading of proton tracks. These absorbers are located in front of the plates just behind the outer slit ring (see reference 6). The net effect of such absorbers is to scatter more protons out of the detectors than are scattered into them. Consequently, it is necessary to apply a correction to the number of protons observed at these forward angles where absorbers are used. This correction, which is due principally to multiple scattering, has been evaluated theoretically by Dickinson and Dodder[9] as well as empirically in a previous experiment. It varies from 9 percent at 10° to 1 percent at 40° in the laboratory system for the absorbers and proton energies used here. It was found that the cross sections measured at the forward angles, when corrected as indicated above for absorber scattering, were in statistical agreement with the corresponding cross sections measured at backward angles where no absorbers were used. (The angular distribution must be symmetrical about 90° center-of-mass.) Figure 2 shows a range distribution of the charged particles observed at 12.8° in the laboratory system, where an aluminum absorber 0.018 inch thick was used.

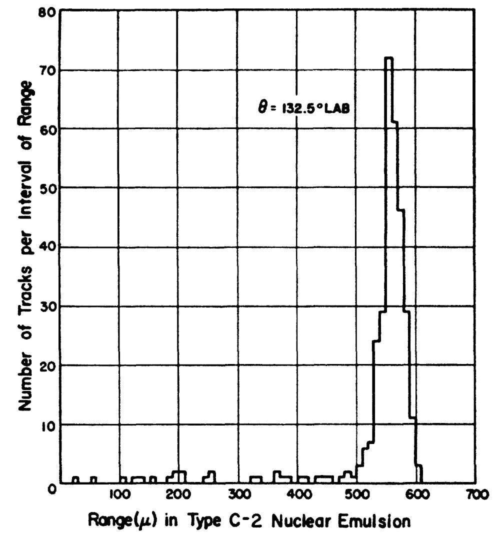

FIG. 1. Range *vs* number histogram for charged particles observed at 132.5° lab from the D(d, p)T reaction. 1018 tracks.

Deuterium gas pressures from 2 to 20 cm of Hg were used. Integrated deuteron currents from 20 to 120 microcoulombs were found to be necessary to give an adequate number of tracks per unit area of plate.

III. RESULTS AND EVALUATION OF ERRORS

The differential cross section for the reaction D+D→T+P+Q as a function of center-of-mass angle is tabulated in Table I. In the coordinate transformation

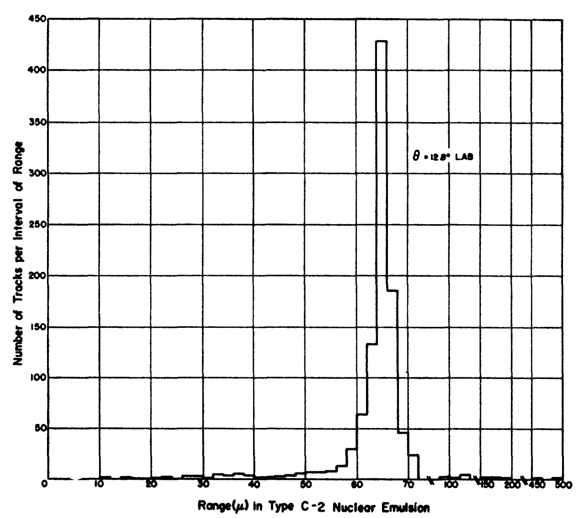

FIG. 2. Range *vs* number histogram for charged particles observed at 12.8° lab from the D(d, p)T reaction. 18-mil aluminum absorber used. 321 tracks.

[5] Leiter, Rodgers, and Kruger, Phys. Rev. **78**, 663 (1950).
[6] Louis Rosen and J. C. Allred, Phys. Rev. **82**, 777 (1951).
[7] Curtis, Fowler, and Rosen, Rev. Sci. Instr. **20**, 388 (1949).
[8] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr., to be published.
[9] W. C. Dickinson and D. C. Dodder, private communication.

TABLE I. Differential cross-section values, $\sigma(\Omega)$, at various angles, Ω, in the center-of-mass system for the $D(d, p)T$ reaction at 10.3-Mev bombarding energy.

Ω(CM) (degrees)	$\sigma(\Omega)$ (millibarns/ steradian)	Ω(CM) (degrees)	$\sigma(\Omega)$ (millibarns/ steradian)
14.3	28.5 ±1.4	134.1	2.30±0.09
17.4	23.0 ±1.1	136.1	2.38±0.09
18.3	21.2 ±1.0	138.1	2.58±0.10
21.0	18.9 ±0.75	140.0	2.82±0.11
28.5	10.3 ±0.41	141.9	3.37±0.13
35.5	4.47±0.17	143.9	4.22±0.17
35.5	4.50±0.18	145.8	4.63±0.18
49.4	2.61±0.09	147.7	6.16±0.24
56.2	3.31±0.11	149.4	7.42±0.26
56.2	3.38±0.13	151.1	9.24±0.37
62.6	4.04±0.14	152.8	10.6 ±0.42
62.8	4.08±0.16	154.4	11.7 ±0.46
72.6	4.82±0.19	156.1	14.1 ±0.49
75.8	4.95±0.20	157.8	17.1 ±0.60
75.8	4.69±0.18	159.2	18.2 ±0.72
82.0	5.00±0.20	159.4	18.6 ±0.65
85.1	5.16±0.18	160.9	21.0 ±1.1
88.0	4.70±0.16	162.3	21.5 ±1.1
88.0	5.24±0.20	162.5	22.3 ±1.0
95.2	4.53±0.18	164.0	23.6 ±1.1
99.7	4.68±0.18	165.4	28.1 ±1.4
99.7	5.03±0.20	165.5	27.4 ±1.2
105.3	4.64±0.16	167.0	28.3 ±1.3
108.1	4.62±0.16	168.3	30.3 ±1.5
110.6	4.69±0.18	168.5	28.8 ±1.3
115.6	3.87±0.15	170.0	31.5 ±1.4
115.7	4.02±0.16	171.3	33.8 ±1.5
118.1	3.92±0.16	171.4	34.2 ±1.5
120.5	3.96±0.16	172.9	35.3 ±1.6
122.8	3.59±0.14	174.1	37.9 ±1.9
125.1	3.18±0.12	174.3	37.5 ±1.7
129.8	2.69±0.10	175.9	36.4 ±1.8

from laboratory to center-of-mass system, the value of Q is taken as 4.01 Mev.

The average errors involved in the evaluation of cross sections from the data of this experiment are estimated to be as follows: statistical standard error for each angle investigated, 2.3 percent; current integrator, 1.7 percent; gas pressure and temperature, 0.5 percent; geometrical factors, 1.0 percent; microscope calibration and personal factors, 1.0 percent; background and discrimination, 2.0 percent. The average rms absolute standard error is thus ±3.8 percent for most of the angular region investigated. At CM angles larger than 160° and smaller than 20° the error may be as much as ±5 percent. At angles greater than 160°, the higher neutron induced background, which was not entirely separable from the reaction proton peak, provides the additional uncertainty. In the region below 20°, the use of relatively thick absorbers made necessary a correction for absorber scattering and this introduced some uncertainty.

The energy and direction of the deuteron beam were determined by the method of reference 6. The energy variation during the course of the experiment was less than 1 percent. The value given, 10.3 Mev, is considered to be accurate to ±1.5 percent. Part of this error is due to the uncertainty in the value of Q for the $D(d, p)T$ reaction. The absolute values of the angles are considered accurate to ±0.2 degree. Since, however, data were taken simultaneously on both sides of the incident beam direction, the errors in angle on one side of the camera will be compensated, to a large extent, by corresponding errors on the other side.

Background runs were made both with the camera evacuated and with the camera filled with deuterium gas. In the latter case, a thick absorber was placed inside the camera between the target region and the inner slit rings so as to remove charged particles produced by the action of the direct beam. The latter technique was used to investigate the possibility that recoil deuterons resulting from $n-d$ scatterings in the camera might produce tracks which would be confused with those due to the protons from the $D(d, p)T$ reaction. In both cases it was found that the background was negligible at laboratory angles of observation less than 150°. That is, the production of tracks satisfying the applied criteria of direction, range, and origin at the surface of the emulsion comprised less than 0.5 percent of the number of tracks attributed to the protons being observed. For the very large angles of observation, the proton tracks were extremely short and were more easily confused with deuteron tracks resulting from $n-d$ collisions.

When the range criterion can be applied rigorously, however, the possibility of confusing the proton tracks with those of recoil deuterons from $n-d$ collisions is severely limited. This follows from the considerations that (1) the Q for $D(d, n)He^3$ is less than that for $D(d, p)T$, and hence a neutron originating in the camera will have a lesser energy than that of a proton emitted in the same direction; (2) the recoil deuteron which such a neutron may produce can receive, at most, only eight-ninths of the energy of the colliding neutron; and (3) the range of a deuteron of given energy is less than that of a proton of the same energy by an appreciable factor.

IV. DISCUSSION

The results of the present work are in good agreement with those of Leiter, Rodgers, and Kruger[5] except at 20° CM at which angle the differential cross section obtained by them is approximately 13 percent lower than our value. Also, our data give no indication of a dip in the cross-section curve at 90° CM as is perhaps suggested by the curve given by Leiter, *et al.*[5]

An expression in terms of Legendre polynomials giving our values of the differential cross section in millibarns per unit solid angle within experimental accuracy is, for $\mu = \cos\Omega$,

$$\sigma(\mu) = 6.24P_0 + 8.28P_2 + 13.16P_4 + 8.24P_6 + 2.31P_8.$$

An additive term, $0.69P_{10}$, gives a better fit for the extrapolated cross section at zero degrees; but this term is essentially unimportant for the curve fit at other angles. If this expression is transformed to one in powers of $\cos\Omega$, it appears that the coefficients of terms

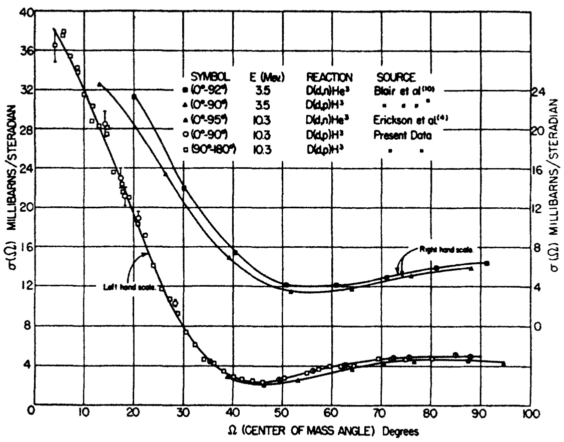

FIG. 3. Differential cross section *vs* center-of-mass angle for the D(d, p)H^3 and D(d, n)He^3 reactions for bombarding energies of 3.5 Mev and 10.3 Mev.

containing powers of cosΩ equal to or greater than two are extremely sensitive to the number of terms used in the Legendre expansion. This is due to the very large coefficients of $\cos^n\Omega$ which appear in the higher order Legendre polynomials. For this reason, the power expansion in cosΩ is not given.

In Fig. 3, the results of Blair, *et al.*[10] for a deuteron bombarding energy of 3.5 Mev are shown. It is seen that the cross section for the reaction yielding protons follows very closely the cross section for the reaction yielding neutrons for the same bombarding energy. This is also true for a bombarding energy of 10.3 Mev as can be seen by comparing our results for the D(d, p)T reaction with those of Erickson, *et al.*,[4] for the D(d, n)He^3 reaction.

Values of the differential cross section in the center-of-mass coordinate system at zero degrees for different bombarding energies are given in Table II. Assuming that the D(d, p)T reaction does indeed yield a cross-section curve which is essentially parallel to the corresponding curve for the D(d, n)He^3 reaction when the incident deuteron energy is 10.3 Mev, our zero-degree value seems to be in agreement with the results of Hunter and Richards[11] obtained for the D(d, n)He^3 reaction at deuteron bombarding energies below 3.7 Mev. It is not in agreement with the value obtained at zero degrees for the D(d, n)He^3 reaction by Erickson, *et al.*[4] However, this latter value is considered quite approximate by the authors, since it was obtained by measuring the Cu^{62} activity induced in Cu^{63} by the $n-2n$ reaction, and the method for calibrating the counters may have introduced a rather large inaccuracy.

Thanks are due Dr. J. L. Fowler and the Los Alamos cyclotron group for their cooperation during the experimental runs. For the analysis of most of the plates, we wish to thank P. Agee, M. Bergstresser, R. Booth, N. Brown, M. Downs, J. Frazer, M. Gibson, C. Hart, C. Lacey, O. Milligan, M. Osborn, F. Peet, L. Shackelford, V. Stovall, and L. Tallmadge.

TABLE II. Differential cross sections in the center-of-mass coordinate system at zero degrees using bombarding deuterons of various energies.

E (Mev)	Reaction	$\sigma(\Omega=0°)$ (millibarns/steradian)	Reference
2.54	D(d, n)He^3	26	11
3.40	D(d, n)He^3	27	11
3.69	D(d, n)He^3	36	11
10.3	D(d, n)He^3	25[a]	4
10.3	D(d, p)T	39[b]	present report

[a] This value is listed as approximate in reference 4.
[b] This value was obtained by extrapolating our results to zero degrees (Fig. 1) and is considered accurate to ±7 percent.

[10] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1599 (1948).

[11] G. T. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949)