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The Scattering of 10.4-Mev Deuterons by Hydrogen*

LOUIS ROSEN AND J. C. ALLRED
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
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The $d-p$ elastic scattering cross section has been measured in the angular region 30°–160° CM (center-of-mass system) by means of a nuclear multiple photographic plate camera. Thin hydrogen gas targets were bombarded by the deuterons from the Los Alamos cyclotron, the incident deuteron energy at the center of the reaction volume being 10.4 Mev. Values of the scattering differential cross section are given within an absolute standard error of ± 3 percent in the range 40°–140° CM and to ± 5 percent in the remainder of the angular range observed. Results of this measurement are in good agreement with previously reported data. The estimated total nuclear cross section, 1.5×10^{-24} cm^2, is essentially that observed for the $n-d$ collision at the same center of mass energy. A least squares curve fit indicates S-, P- and D-wave interactions to be present at this energy.

I. INTRODUCTION

THE general theoretical interest in the scattering of nuclei involving a small number of nucleons has led us to extend the measurements on the $d-p$ interaction[1] to the region of 10.4-Mev deuteron bombarding energy. A further stimulus for such measurements is to be found in the possibility of comparison between $p-d$ and $n-d$ scatterings as a means of comparing $p-p$ and $n-n$ forces in this energy region. The fact that considerable theoretical work has already been carried out on the $p-d$ and $n-d$ interactions offers encouragement in this direction.[2] Of the experimental data, the most complete are those of Sherr, *et al.* These data were analyzed by Critchfield, who concluded that in the range of energy investigated, the scattering was due principally to S- and P-wave interactions. At higher center-of-mass energies it might be expected that partial waves of higher order would make themselves evident, and it was hoped that the present investigation would provide such information at this higher energy. Preliminary results of the measurements to be discussed in this paper have already been reported,[3] and these are in good agreement with our final results. More recently Mather, *et al.*,[4] and Rodgers, *et al.*,[5] published results for the aforementioned reaction at 10.0- and 9.94-Mev deuteron energies, respectively. These results agree very well with our own results, when a slight correction is made for the small difference in deuteron bombarding energies. It is indeed very gratifying that all three sets of data, obtained by widely different techniques, show substantial agreement to well within quoted accuracies.

II. EXPERIMENTAL

The experiment essentially consists of bombarding thin hydrogen gas targets with 10.4-Mev deuterons and recording on photographic plates the numbers and ranges of the particles emitted into known solid angles. Data are taken at 2.5° intervals between 10° and 65° in the laboratory system with respect to the incident deuteron beam. In order to take data simultaneously at all angles we utilized the nuclear plate camera previously described.[6] This camera is mounted inside a vacuum chamber, at the center of which the cyclotron deuteron beam is brought to a focus by an auxiliary focusing magnet.[7] The focused beam passes through the

* Work done under the auspices of the AEC.
[1] Tuve, Heydenburg, and Hafstad, Phys. Rev. **50**, 806 (1936); R. F. Taschek, Phys. Rev. **61**, 13 (1942); Sherr, Blair, Kratz, Bailey, and Taschek, Phys. Rev. **72**, 662 (1947); Heitler, May, and Powell, Proc. Roy. Soc. (London) **190**, 180 (1947).
[2] H. Primakoff, Phys. Rev. **52**, 1000 (1937); K. Ochiai, Phys. Rev. **52**, 1221 (1937); C. L. Critchfield, Phys. Rev. **73**, 1 (1948); H. S. Massey and R. A. Buckingham, Phys. Rev. **73**, 260 (1948).
[3] J. C. Allred and L. Rosen, Phys. Rev. **79**, 227 (1950).
[4] Mather, Karr, and Bondelid, Phys. Rev. **78**, 292 (1950).
[5] Rodgers, Leiter, and Kruger, Phys. Rev. **78**, 656 (1950).
[6] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr., to be published.
[7] Curtis, Fowler, and Rosen, Rev. Sci. Instr. **20**, 388 (1949).

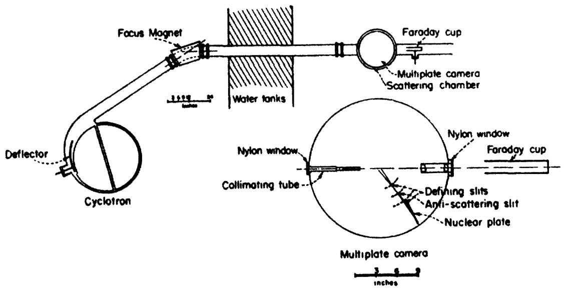

FIG. 1. Experimental arrangement, showing detail of camera geometry.

camera, which contains the hydrogen gas as well as the detectors, and into a well-insulated faraday cup. The front and back windows of the camera are of Nylon, one mil thick.

Figure 1 shows a plan view of the cyclotron and scattering chamber. At the point of entrance into the camera the deuteron beam has a maximum angular divergence of 1.2° in the horizontal plane and 0.85° in the vertical plane by virtue of the slit system geometry in the focus magnet and scattering chamber. The effective angular divergence is probably somewhat less due to the large distance (15 ft) between the cyclotron and the scattering chamber. After passing through the entrance window, the beam passes through four additional circular slits, two of which are $\frac{3}{16}$ inch in diameter and 6 inches apart, the remaining two being antiscattering slits of somewhat larger diameter. Deuterons unduly scattered by the entrance window are thus eliminated before they enter the reaction volume. The scattered particles go directly from the scattering volume to the detectors without further window traversals. Absorbers are, however, sometimes utilized in front of the detectors at the forward angles for the purpose of reducing the background due to low energy multiply-scattered deuterons from the primary beam, or to absorb the scattered deuterons so as to facilitate counting the scattered protons.

The scattering chamber is evacuated by means of an auxiliary pumping stand on which is mounted a liquid air trap and an oil diffusion pump having a pumping speed of 275 liters per second, the diffusion pump being backed by a mechanical fore pump. Without plates in the chamber a pressure of 10^{-5} mm Hg can be easily attained. When the camera is loaded for a run, it is found that four hours of pumping is adequate to give a negligible number of tracks due to scattering from the water vapor and gas liberated by the emulsion during a run. The duration of a run in the present experiment was 5 to 10 minutes, during which time an integrated current of from 12 to 30 microcoulombs of deuterons was passed through the camera. The liquid air trap is isolated from the system during the insertion of gas into the camera as well as during the actual exposure.

The pressure of gas in the camera is measured by means of a mercury manometer and cathetometer. The temperature of the gas is taken to be room temperature, which is the temperature of the camera both before and after a run.

Measurements on the ranges of the scattered deuterons and protons are made on each side of the deuteron direction, i.e., at positive and negative angles with respect to the deuteron beam. From these measurements it is possible to determine precisely the energy and direction of the beam for each run by the method outlined in a previous publication.[8]

The measurement of integrated current is made by connecting the faraday cup to an electronic current integrator. The faraday cup is maintained at a negative potential of 120 volts in order to prevent the collection of stray electrons. Two permanent magnets are mounted longitudinally along the outside of the faraday cup such that their magnetic field will provide a barrier to the outward passage of secondary electrons formed inside the cup. This cylindrical cup is 9 inches long by $1\frac{3}{4}$ inch i.d. The current integrator is calibrated before and after each run, the calibration current being measured by determining with a type K potentiometer the potential drop across a standard resistor which is connected in series with appropriate current limiting resistors between the faraday cup and ground for purposes of the calibration. The counting rate during a given experiment is monitored by a recording galvanometer. The above method of measuring current has been checked by a thermal heating experiment[9] and found to be reliable to two percent or better. Data taken on $p-p$ and $p-He^4$ scattering with the University of Minnesota van de graaff at 3-Mev bombarding energy[6] shows that, at least at this energy, the above method of measuring current is accurate to 1.5 percent.

The general features of the technique for analyzing the plates are given in references 6 and 8. For the present experiment Ilford 100-micron C2 plates were used. These plates are processed for 20 minutes in one part D-19 to three parts water. After 15 minutes in a 2 percent acetic acid stop bath, the plates are fixed for 2 hours in fresh neutral hypo, followed by 30 minutes in acid hypo. The plates are then given a $1\frac{1}{2}$-hour wash in running water, a 5-minute bath in 1 percent glycerine to prevent peeling, and then permitted to dry slowly. The developing and fixing is accompanied by good agitation. All temperatures are kept at 68 F. For most of the analysis work, Leitz Ortholux microscopes are used with 90× oil immersion apochromatic objectives and 6× compensating eyepieces. Eyepiece reticules 7.2 mm×7.2 mm divided into 100 squares are used for making range determination as well as for defining the swath width being counted. The eyepiece reticules are calibrated with stage micrometers.

[8] Rosen, Tallmadge, and Williams, Phys. Rev. **76**, 1283 (1949).
[9] Erickson, Fowler and Stovall, Phys. Rev. **76**, 1141 (1949).

III. DEUTERON-PROTON SCATTERING

For the deuteron-proton collision, the velocity of the center of mass is such that at angles greater than 30° with respect to the incident deuteron beam direction in the laboratory system, only recoil protons are observed. At angles smaller than 30°, two groups of scattered deuterons are detected, one group having quite low energy. However, all three groups were found to be well resolved, and it was therefore possible at a number of angles to obtain a value of cross section for each of three different center-of-mass angles from data at a single laboratory angle. A range distribution showing the three different groups is shown in Fig. 2. It should be mentioned that at the larger angles, the background is considerably less than that shown in Fig. 2. (At angles below 29° it is energetically possible to observe protons from the reaction $D+P\rightarrow P+P+n-2.2$ Mev.) Figure 3 is a typical number *vs* range curve for one of the larger angles. The width of the number *vs* range distribution is mainly due to the finite angular resolution (±0.9°) of the slit system geometry between the detectors and the reaction volume.

If Ω is the angle of scattering of the deuteron in the center-of-mass system and θ and ϕ are the corresponding angles in the laboratory system of the scattered deuteron and recoil proton, respectively, we have the following relationships:

$$\cot\theta=(2+\cos\Omega)/\sin\Omega \tag{1}$$

and

$$\Omega=180°-2\phi. \tag{2}$$

If one defines the scattering angle in the center-of-mass system as the angle through which the particles are deflected, Eq. (2) also gives the angle of scattering of the proton, and there is no ambiguity concerning which particle is the incident particle in the laboratory system. The laboratory angular cross sections are given by the following:

$$\sigma(\theta)=(YK\sin\theta)/n_0N \tag{3}$$

where $\sigma(\theta)$ is the laboratory cross section per unit solid angle at the angle θ, Y is the number of tracks counted, n_0 is the number of scattering nuclei per cubic centimeter, N is the number of incident particles, and $K\sin\theta$ is the geometrical term defining target volume and solid angle subtended by detector.

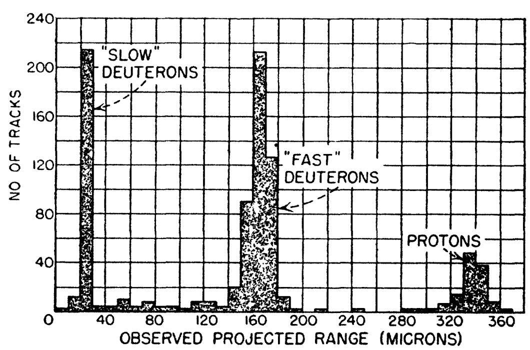

FIG. 2. Number *vs* range histogram for laboratory angle of 25°, showing three particle groups.

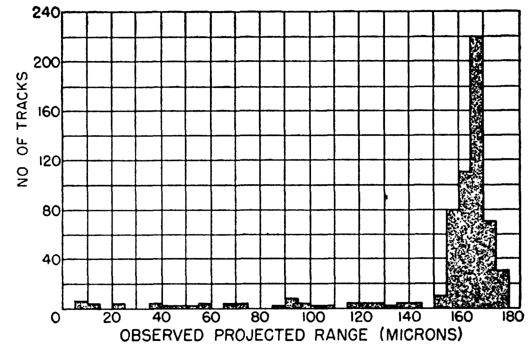

FIG. 3. Number *vs* range histogram for laboratory angle of 42.5°, showing single proton group.

The target volume seen by a given detector is a function only of the slit system geometry and the angle that the slit axis associated with that particular detector makes with the incident beam direction. The defining slits have a width of 0.0450±0.0002 inch and are 2.972 inches apart.

The solid angle subtended by the detector is determined by the slit system geometry and the total swath width on the plate over which tracks are counted. Each swath is normally about 100 microns in width, the beam current and gas pressure being adjusted such that approximately 100 tracks are recorded on each such swath. In order to obtain the statistical accuracy desired, one simply reads an appropriate number of swaths. Each plate contains about 100 usable swaths on the basis of 100 microns per swath. The equation giving an expression for the geometrical factor K in terms of the geometric parameters mentioned above was developed by Critchfield and is given in reference 6, as is also a more detailed discussion of the analysis of the photographic plates.

To convert the laboratory angular cross section, obtained from Eq. (3), to angular cross sections in the center-of-mass system, we have

$$\sigma(\Omega)\sin\Omega d\Omega=\sigma(\theta)\sin\theta d\theta.$$

Since $\sigma(\theta)$ is given by Eq. (3), using Eq. (1), we have

$$\begin{aligned}\sigma(\Omega)&=\sigma(\theta)(1+2\cos\Omega)/\sin\Omega\csc^2\theta\sin^2\Omega\\&=YK(1+2\cos\Omega)/n_0N\csc^4\theta\sin^2\Omega\end{aligned} \tag{4}$$

for the case in which Y refers to the deuterons. Similarly, when Y refers to the protons,

$$\sigma(\Omega)=YK\sin\phi/4\cos\phi n_0N.$$

IV. EXPERIMENTAL RESULTS

Table I gives the results of our measurements. The values given under run P were obtained in a slightly modified version of the experimental set up at the time

TABLE I. Experimental results for the differential cross sections in the center-of-mass system as a function of angle for $d-p$ scattering at 10.4-Mev deuteron bombarding energy.

	$\sigma(\Omega)$ (barns/unit solid angle)					
Center-of-mass-angle \ Run	O	Ξ	Γ	N	L	P
28.0		0.211[a]				
35.4		0.206[a]				
44.0		0.177[a]				
45.0	0.174		0.170			
50.0	0.163		0.162			
55.0	0.154		0.153			
60.0	0.141		0.147	0.143		0.140
61.5		0.134[a]				
65.0	0.126		0.128			
70.0	0.112		0.119	0.115		0.115
75.0	0.100	0.107[a]	0.108			0.102
80.0	0.0902		0.0961			0.092
80.8		0.0915				
81.0		0.0903[a]				
84.2		0.0821				
85.0	0.0818					
90.0	0.0707					0.073
90.8		0.0727				
95.0	0.0660		0.0694			
100.0	0.0604		0.0587			
105.0	0.0536		0.0558		0.0573	
110.0	0.0543				0.0537	
115.0	0.0526					
120.0	0.0574					
125.0	0.0612					
130.0	0.0742					
130.8		0.0800				
135.0	0.0847					
140.0	0.1077					
148.4		0.164[b]				
150.8		0.177				
151.8		0.178[b]				
155.8		0.207				
157.5		0.248[b]				
161.2		0.238				

[a] Fast deuterons.
[b] Slow deuterons.

of writing of this paper, one year after the original results were obtained.

V. EVALUATION OF ERRORS; CORRECTIONS

The internal consistency of the data for any given run indicates a relative standard deviation which is essentially that of the counting statistics. This should indeed be the case, since for any given run each of the cross sections obtained at the various angles suffers from precisely the same systematic errors. However, as will be seen from Table I, there is also good agreement from one run to the other. This is rather more encouraging, since it gives one confidence in the absolute accuracy of the results.

At each angle investigated at least 4000 tracks were counted. This implies a standard error of ± 1.5 percent due to statistics. The errors incurred because of slit penetration, slit scattering, and other background (see Fig. 2) are approximately ± 1.0 percent. Discrimination against background tracks is here achieved by counting only tracks which have the proper length and direction to have originated in the reaction volume and proceeded through the slit system to the appropriate detectors. Background runs were taken without gas in the camera and with gas in the camera, but with the reaction particles from the center of the camera being prevented from entering the detector collimating slits by an absorber of 30-mil brass placed in front of the slits nearest the reaction volume. These runs showed that errors introduced by the recording of tracks due to protons scattered by $n-p$ collisions in the gas of the chamber and neutron produced proton recoils originating near enough to the surface of the emulsion to make them indistinguishable from tracks of charged particles entering the emulsion surface were completely negligible. Some background tracks due to slit edge scattering and penetration, deuteron disintegration, and multiple scattering were observed; but most of these could be eliminated through range discrimination. Those background tracks which had sufficient length to be included in the range of particles counted were corrected for on the basis of the shape of the number *vs* range curve. This correction, however, never amounted to more than 3 percent and was usually less than 1 percent (see Fig. 3). (Deuteron disintegration could not occur at angles greater than 30°. Multiple scattering of the primary beam was negligible at angles greater than 17.5°.)

Calculations based on Critchfield's analysis of second-order geometry corrections[10] show that such corrections are entirely negligible for angles greater than 15° and amount to approximately 1 percent at 10°. No second-order geometry corrections were made, therefore. In the runs where absorbers were used at the forward angles (10°–25°) empirical corrections were applied for the scattering of the particles which were being observed. These corrections amounted to 8 percent at 10° but were less than 2 percent at 20°. These corrections account for the assignment of larger errors at the smaller angles. The largest angles also were assigned additional errors, since here the tracks were quite short and the plates were difficult to read because of considerable neutron and gamma induced background originating at the collimation slits. Also, for these angles, range straggling made the discrimination against background tracks less accurate.

The current integrator measurements are believed to be reliable to ± 1.7 percent on the basis of the previous tests[6,9] made here and at Minnesota, the above-mentioned precautions taken to avoid both neutralization of the faraday cup charge and the escape of secondary electrons and leakage tests made under the actual conditions of the experiment. The latter were performed by placing a shield in front of the faraday cup and bombarding the shield with the cyclotron deuterons. Errors due to measurements of pressure and temperature and to impurities in the gas are also approximately ± 0.5 percent. The purity of the hydrogen

[10] C. L. Critchfield and D. C. Dodder, Phys. Rev. **75**, 419 (1948).

TABLE II. H^1 pressures used and statistical counting errors for various experimental runs.

Run	O	Ξ	Γ	N	L	P
Pressure (cm Hg)	10.00	1.030	3.99	22.73	3.14	9.92
Statistical standard error (percent)	±1.5	±3	±3	±3	±3	±2

was accurately determined from the range analyses of the scattered particles. In Fig. 3, for example, O_2 impurities would have given a peak at 325 microns due to elastically scattered deuterons, and He^4 contamination would have given a peak at 230 microns. Errors introduced by geometrical factors are believed to be less than ±1.0 percent. Errors due to microscope calibration and personal factors are also estimated to be ±1.0 percent. All these give an rms absolute standard error of ±2.9 percent in the interval 40°–140° CM. The data in the intervals 30°–40° and 140°–160° are believed to have an absolute standard error of ±5.0 percent for the reasons stated above.

It is felt that negligible error is introduced by multiple small angle scatterings in the hydrogen, since data taken with 1-cm Hg pressure and 20-cm Hg pressure gave the same cross-section values. The pressures used for the various runs are given in Table II. Most of the data were taken at a pressure of 10 cm Hg. Calculations on multiple small-angle scattering using the results of Williams[11] show that in the worst cases only one percent of the protons are deviated by more than 0.005 degree.

The direction and energy of the beam for each of the runs were determined by the method previously described.[8] The direction was thus known to an accuracy of ±0.15° and the energy to an accuracy of ±1.2 percent. The range-energy curves of Lattes, Fowler, and Cuer,[12] corrected in accordance with more recent determinations of the Q values for some of the reactions which they utilized, were used for the energy determination. A check calibration was made at 14.2 Mev, using neutrons from the $D-T$ reaction. The value for the mean proton range thus obtained was in excellent agreement with the range-energy curves of Lattes, *et al.*

It should be pointed out that the very recent work of Rotblat[13] is in good agreement with the corrected results of Lattes, *et al.*, in the region in which they overlap. The fact that the accuracy in energy of the range-energy curve given by Rotblat would appear to be considerably less than ±1 percent in the 5-Mev region lends further credence to the conclusion that the error in energy for a given range in the 10-Mev energy region as deduced from the data of Lattes, Fowler and Cuer is not more than ±1 percent. Indeed, the recent data of Bradner, *et al.*,[14] bear this out. The error assigned by these authors to the range for a given energy is ±2 percent, which implies an error less than ±1 percent in energy for a given range in the 10-Mev region. Again the data of Bradner, *et al.*, is in excellent agreement with that of Lattes, *et al.*, where the two sets of data overlap. Our own range determination at 14.2 Mev in turn agrees with the value of Bradner, *et al.*, at this energy to better than 1.5 percent. It is therefore felt that the assignment of an error of ±1.2 percent to the energy in the present experiment is rather conservative.

An estimate of the homogeneity of the beam can be obtained from Fig. 3. The width at half-maximum of the peak is about 4.2 percent in energy. Consideration of the width introduced by the finite angular resolution of the slit system and the collimation system, and widening introduced by range straggling, leads to the conclusion that the energy width at half-maximum of the primary deuteron beam is not more than 0.2 Mev. This is indeed what one would expect on the assumption that deuterons from only one orbit are pulled out by the de-

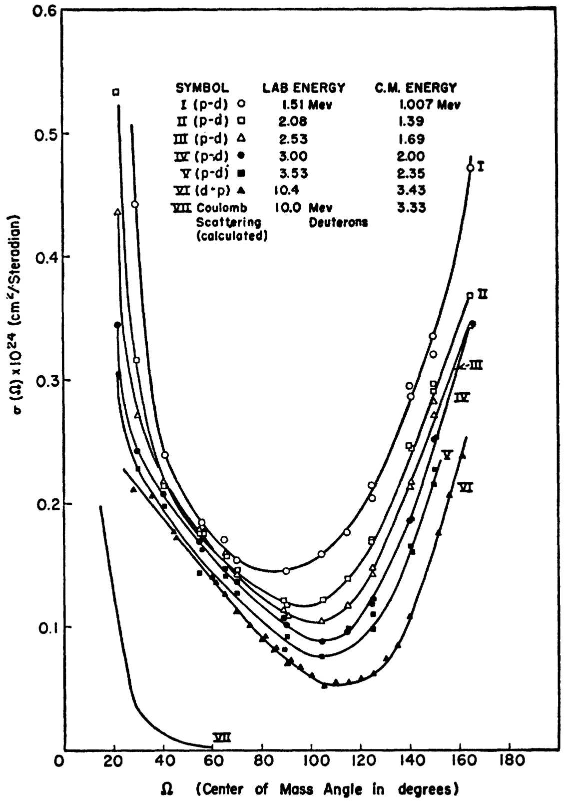

FIG. 4. Differential cross section as function of center-of-mass angle for various bombarding energies, showing present data and those of Sherr, *et al.* Curves I through IV are those of Sherr, *et al.* The present data are represented by curve VI.

[11] E. J. Williams, Phys. Rev. **58**, 292 (1939).
[12] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).
[13] J. Rotblat, Nature **165**, 387 (1950).
[14] Bradner, Smith, Barkas, and Bishop, Phys. Rev. **77**, 462 (1950).

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).

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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

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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).

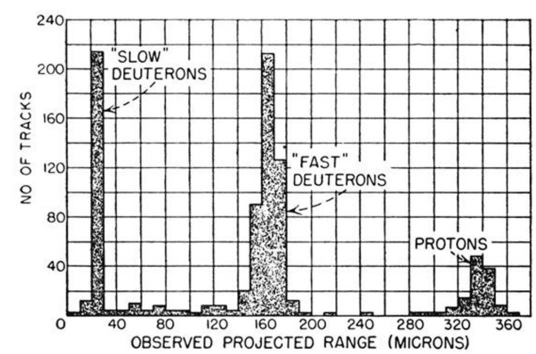

FIG. 2. Number *vs* range histogram for laboratory angle of 25°, showing three particle groups.

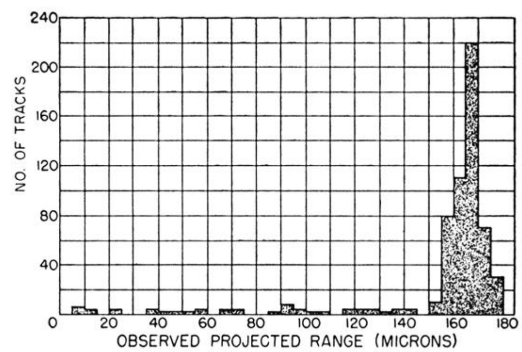

FIG. 3. Number *vs* range histogram for laboratory angle of 42.5°, showing single proton group.