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The D$-$He^4 Interaction for 10.3-Mev Deuterons*

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Elastic scattering and disintegration of 10.3-Mev deuterons bombarding He^4 have been studied by means of a multiple nuclear plate camera. The reaction $D+He^4 \rightarrow He^4+p+n-2.2$ Mev was observed with a total cross section of 0.3±0.1 barn. The protons show a marked tendency to emerge in the forward direction, and there is some, not very strong, evidence for the formation of He^5 as an intermediate product. The differential elastic scattering cross section was measured at intervals of 2.5° in the laboratory system from 12.5° to 140°. The shape of this cross-section curve can be inferred from the following approximate values (angles in CM system and differential cross sections in millibarns per unit solid angle): 29.4°, 186; 58.4°, 9.7; 97.7°, 69; 129.3°, 37; 157.4°, 82.4.

I. INTRODUCTION

As part of our program for studying light particle interactions, we have recently investigated the angular distribution of the charged products arising from the D$-$He^4 interaction when 10.3-Mev deuterons are the bombarding particles.

Although the number of nucleons involved in this reaction is larger than desirable for direct theoretical interpretation of the results, the experiment was felt to be worthwhile for the following reasons:

A. Low energy data are already available for this reaction.[1] The use of electronic computers and the low energy data may make interpretation of the results from the present experiment entirely feasible.

B. The bombarding energy available is sufficiently high to afford an opportunity to learn something about the unstable nucleus He^5 and/or the disintegration of the deuteron in its more conventional sense.

The Los Alamos cyclotron served as the accelerator and photographic emulsions as the detectors in the present experiment. Both the experimental arrangement for utilizing the cyclotron beam and the nuclear plate camera (which contains the scattering gas as well as the detectors) have been fully described in previous publications.[2–5]

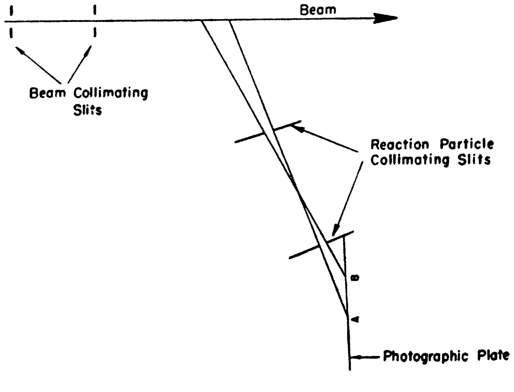

FIG. 1. Slit system-detector geometry.

II. EXPERIMENTAL PROCEDURE

The procedure for making a run is identical to that previously described,[3,4] as is also the method for determining the energy and direction of the projectile deuterons. The range and intensity distribution of the charged products from the subject reaction were recorded every 2.5° in the laboratory interval between 12.5° and 140° with respect to the beam direction.

The angular resolution of the incident beam was ±1.2° in horizontal direction and ±0.8° in vertical direction. The angular resolution of detection was ±0.9°.

Helium pressures of 5 to 20 cm Hg were utilized in order to obtain proper track intensities on the plates as well as to check the effects of multiple scattering in the gas. Beam currents of approximately 0.1 microampere were utilized for times varying from 3 to 10 minutes, depending upon the gas pressure in the camera and the angular region in which good statistics were desired in the particular run. Although spectroscopically pure He^4 was used, the usual range analyses were investigated to determine the extent of impurities present in the scattering gas during the run.

Because of the large inelastic cross sections which the data from this reaction seemed to indicate, the techniques for analyzing the data are somewhat more specialized for this experiment than those previously described. This is caused by the necessity for verifying that the tracks of ranges other than those predicted from conservation of energy and momentum on the basis of elastic scattering are actually representative of reaction products originating in the reaction volume seen by a particular slit system and not due to some kind of background. In order to discuss in detail the method of analyzing the present plates so as to preclude confusion from spurious or background tracks, it will

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[1] Blair, Freier, Lampi, and Sleator, Phys. Rev. **75**, 1678 (1949).

[2] Curtis, Fowler, and Rosen, Rev. Sci. Instr. **20**, 388 (1949).

[3] Rosen, Tallmadge, and Williams, Phys. Rev. **76**, 1283 (1949).

[4] L. Rosen and J. C. Allred, Phys. Rev. **82**, 777 (1951).

[5] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr. **22**, 191 (1951).

be necessary to review briefly some of the features of the technique used for taking data in this type of scattering and disintegration experiment.

As has been described previously,[3,4] the photographic plates are mounted around the periphery of the 18-inch i.d. scattering chamber, each plate being mounted behind its own slit system, the axis of which intersects the incident beam axis at the center of the scattering chamber. Figure 1 illustrates the slit system-detector geometry. Each plate can be mounted so that the plane of each emulsion and the long edge of the plate make an angle of either 6° or 12° with the axis of its slit system. In either case, the plate extends lengthwise beyond the region defined by the slit system as seen from the reaction volume. To analyze a plate it is necessary to

1. Make a range analysis of all tracks starting on the surface and proceeding into the emulsion with initial orientation corresponding with origin of the particles in the reaction volume defined by the slits.
2. Count the number of tracks in any desired range interval within an accurately measured width of swath extending lengthwise over the entire region of the plate exhibiting tracks. Examples of range distributions at various angles for the D – He^4 interaction are shown in Fig. 2. Tracks in the groups *b* and *c* correspond to elastically scattered alpha-particles and deuterons respectively. The differential cross section for elastic scattering at an angle corresponding with a given plate can be determined from the number of such tracks, corrected for background where necessary, observed in a swath of known width, say 1000 microns, together with the slit system-detector geometry, the pressure and temperature of the gas in the camera, and the integrated beam current. The number of swaths counted is determined by the statistical accuracy desired.

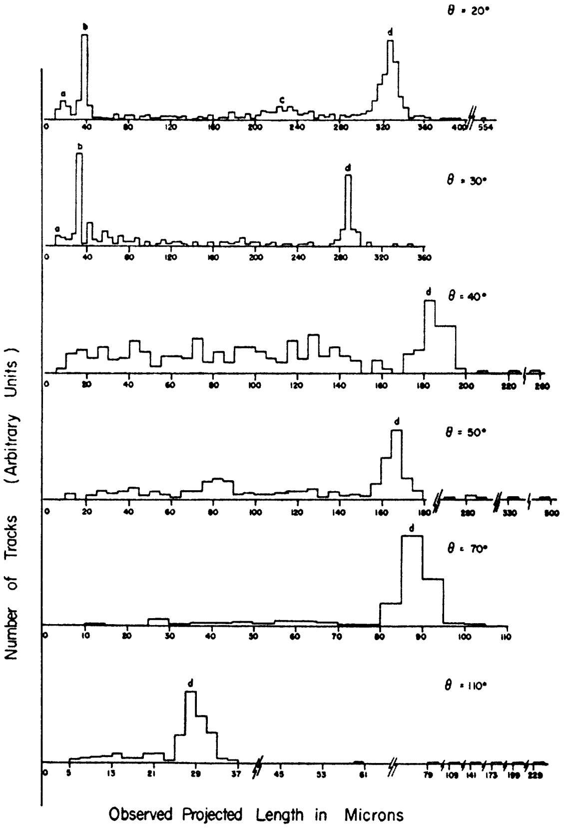

FIG. 2. Histograms of measured track lengths. Groups (b) and (d) represent the elastically projected alpha-particles and scattered deuterons, respectively. Group (a) consists of alpha-particles from either reaction B or reaction C. Other tracks (c) are protons from deuteron disintegration.

Usually, observing the range and direction criteria mentioned above is sufficient precaution to take against counting spurious tracks. However, it can be seen from Fig. 2 that there exists a considerable number of tracks of range other than that attributable to elastically scattered deuterons and alpha-particles, and it is not possible to apply energy and momentum considerations to these tracks in order to have assurance that they are not spurious. It is, therefore, desirable to use another criterion based on the density distribution of the tracks on the plate. As can be seen from Fig. 1, all of the particles which arise in the reaction volume and proceed in such a direction as to pass through a particular slit system must impinge upon the plate in the region *AB* and produce tracks whose lengths bear a fixed relation to the energy of the particles. Tracks which arise by other mechanisms, such as slit scatterings, reactions in the slit system, and neutron induced reactions in the plates or in the gas surrounding the plates, will have a density distribution which, in general, will not be confined to the region *AB* on the plate. Furthermore, the density distribution of such tracks along the plate will not correspond to that predicted by the slit system-detector geometry. Thus, in cases exhibiting broad range distributions, as in the present experiment, it is desirable to plot the density distribution of each range of tracks of interest at each angle investigated. Such density distributions for $\theta = 20°$ are shown in Fig. 3 for the scattered deuterons, *d*, the recoil alphas, *b*, the almost continuous spectrum of protons from D^2 disintegration, *c*, and reaction alphas, *a*. The track density distributions plotted in Fig. 3 show prac-

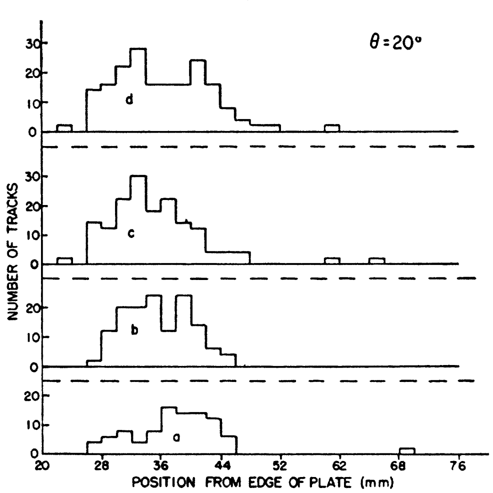

FIG. 3. Density distribution of track groupings designated (a), (b), (c), and (d) in Fig. 2.

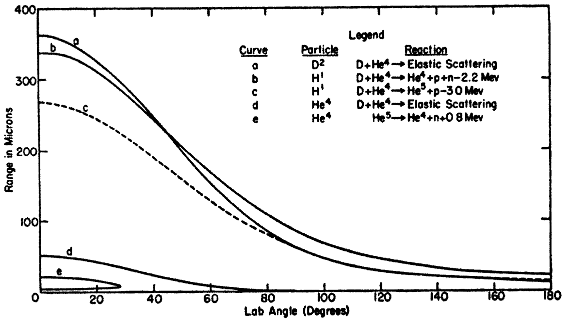

FIG. 4. Calculated ranges in Ilford C2 emulsion of reaction products from $D-He^4$ interaction. Curve (b) applies to the maximum proton range (He^4 and neutron go off in the same direction). Curve (e) applies to the average He^4 range.

tically no evidence of particles arriving at the plate in nonconformity with the slit system geometry. Thus, in this case essentially all of the tracks in a given range interval counted in a swath along the plate must have arisen within the reaction volume defined by the slit system. This technique has proved to be a powerful one for evaluating the authenticity of inferred particle groups from a given reaction. In the case of a continuous spectrum the range distribution may, of course, be subdivided into any arbitrary number of range groups and the density distribution test applied to each group.

Standard background runs without gas in the camera were made to determine corrections necessary because of primary beam interactions with slits, diaphragms, or water vapor and other gases from plates and camera.

III. THE $D-He^4$ INTERACTION

A high energy deuteron can, in principle, interact with an alpha-particle in the following ways:

A. $D+He^4 \rightarrow D+He^4$ (elastic scattering),

B. $D+He^4 \rightarrow He^4+p+n-2.2$ Mev (deuteron disintegration),

C. $D+He^4 \rightarrow He^5+p+Q_1$; $He^5 \rightarrow He^4+n+Q_2$,

where $(Q_1+Q_2=-2.2$ Mev). (If process "C" takes place, one would expect a Q_1 of approximately -3 Mev on the basis of an 800-kv negative binding energy for He^5.[6,7]

Reaction "A" will of necessity yield monoenergetic groups of deuterons and alpha-particles, their energy at any angle being determined only by the incident deuteron energy. Reaction "B" might be expected, at any given angle, to yield protons of more or less continuous energy up to a certain maximum, which maximum is again determined by the incident deuteron energy and the binding energy of the deuteron. For maximum proton energy the neutron and alpha-particle must go off together, the proton recoiling in the opposite direction in the center-of-mass system.

Reaction "C" might be expected to yield monoenergetic groups of protons. On the other hand, the He^5 nuclei will decay into alpha-particles and neutrons long before they reach the detectors.[8] Since the neutrons will come off in all directions and with energies of approximately 0.64 Mev, the corresponding He^4 nuclei will have a considerable spread in energy at any given angle in the laboratory system.

Let us now consider the collision mechanics of the $D-He^4$ interaction for the various possibilities mentioned. Suppose that an incident nucleus of mass m_1 and energy E_0 reacts with a target nucleus of mass m_2 initially at rest, giving rise to two nuclei of masses M_3 and M_4 and energies E_3 and E_4 where the subscript (3) refers to the lighter nucleus. Let θ and ϕ denote the angles which M_3 and M_4, respectively, make with the incident beam direction in the laboratory system of coordinates, and let Ω denote the angle of emission of M_3 in the center-of-mass coordinate system. It can be shown quite generally, on the basis of conservation of energy and momentum, that[8]

$$E_3=E_TA_1\{\cos\theta\pm[(B_1/A_1)-\sin^2\theta]^{\frac{1}{2}}\}^2, \tag{1}$$

$$E_4=E_TA_2\{\cos\phi\pm[(B_2/A_2)-\sin^2\phi]^{\frac{1}{2}}\}^2, \tag{2}$$

$$\sin\theta=\{M_4(E_4/E_T)/M_3[1-(E_4/E_T)]\}^{\frac{1}{2}}\sin\phi, \tag{3}$$

$$\sin\theta=(B_1E_T/E_3)^{\frac{1}{2}}\sin\Omega, \tag{4}$$

$$\begin{aligned}\cos\Omega&=[E_3/(E_TB_1)]^{\frac{1}{2}}\cos\theta-(A_1/B_1)^{\frac{1}{2}}\\&=-[E_4/(E_TB_2)]^{\frac{1}{2}}\cos\phi+(A_2/B_2)^{\frac{1}{2}},\end{aligned} \tag{5}$$

where

$$\begin{gathered}A_1=m_1M_3(1-Q/E_T)/(M_3+M_4)^2,\\A_2=m_1M_4(1-Q/E_T)/(M_3+M_4)^2,\\B_1=m_2M_4(1+m_1Q/m_2E_T)/(M_3+M_4)^2,\\B_2=m_2M_3(1+m_1Q/m_2E_T)/(M_3+M_4)^2,\\E_T=E_0+Q.\end{gathered}$$

Further, it can be shown from geometrical considerations that the intensities per unit solid angle for particle emission in the center-of-mass system and in the laboratory system are related by the following:

$$\begin{aligned}I(\Omega)/I(\theta)&=\sin\theta d\theta/\sin\Omega d\Omega\\&=(A_1B_1)^{\frac{1}{2}}(B_1/A_1-\sin^2\theta)^{\frac{1}{2}}E_T/E_3,\end{aligned} \tag{6}$$

$$\begin{aligned}I(\Omega)/I(\phi)&=\sin\phi d\phi/\sin\Omega d\Omega\\&=(A_1B_1)^{\frac{1}{2}}(B_2/A_2-\sin^2\phi)^{\frac{1}{2}}E_T/E_4.\end{aligned} \tag{7}$$

Now for the case of elastic scattering (Case A), we have $Q=0$, $m_1=M_3=2$, $m_2=M_4=4$. For the case of simple deuteron disintegration (Case B) we have $Q=-2.2$ Mev. Since this is a three-body problem, we can evaluate the case only if the neutron and alpha-particle go off in the same direction. For this case $m_1=2$, $m_2=4$, $M_3=1$, $M_4=5$, and the proton energy will be a maximum. For Case C, where we assume the formation of a short-lived He^5 nucleus, we have, for

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[6] Williams, Shepherd, and Haxby, Phys. Rev. **51**, 888 (1937).

[7] Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. (London) **190**, 196 (1946).

[8] Carlson, Goldstein, Rosen, and Sweeney, Los Alamos Report 723 (unpublished).

ground-state formation, $Q=-3.0$ Mev with the remaining notation identical to that for Case B.

Figure 4 shows the calculated variations of the range with angle in C2 emulsion for the various particles in all three cases. The values obtained differ somewhat from the measured values, since no account is taken of the absorption of energy by the gas in the camera or by absorbers placed in front of plates. Also, the observed values represented projected ranges rather than absolute ranges. It can be seen, however, that the various particle groups to be expected are, for the most part, sufficiently separated in range as to be resolvable. The range-energy relations of Lattes, Fowler, and Cuer[9] were used for these calculations.

IV. RESULTS

The results obtained for the differential elastic scattering cross section as a function of angle are given in Table I. Wherever possible, projected He^4 particles as well as scattered deuterons were counted; and, in this way, two points on the cross-section curve were obtained from a single plate. Wherever such checks were made, reasonably good agreement was obtained.

The absolute accuracy of the elastic scattering cross sections is not as good as one might wish, owing to some confusion about counting protons in the deuteron peak. Although corrections were applied for this effect on the basis of the shapes of number *versus* range curves, it is felt that significant errors still remain. These errors depend upon the extent of this so-called background which varies with angle.

No second-order geometry corrections were made. It was, however, necessary to make corrections at 12.5° and 15° for scattering from oxygen in water vapor from the plates. This effect is exaggerated at the small angles because of the low gas pressure used and the relatively high coulomb scattering cross section at forward angles. Coulomb scattering was assumed for the deuterons on oxygen; and, from observations at angles of 20° and 22.5°, where deuterons scattered from oxygen are clearly distinguishable from those scattered by helium, corrections for the effect of oxygen contamination were calculated at smaller angles. These corrections were 8 percent at 12.5° and 4 percent at 15°. At the forward angles it was necessary to apply a further correction for absorbers which were used in some of the exposures to remove alpha-particles and/or background resulting from multiple scattering of the primary beam. This correction was a maximum of 10 percent at 12.5° but less than 1 percent for angles larger than 20°. At angles above 20°, runs were made with and without absorbers and these agreed quite well. The corrections for absorbers were determined empirically and are believed to be accurate to ±15 percent. Calculations by D. C. Dodder and W. C. Dickinson on the basis of multiple small angle scattering agreed well with the empirical corrections.

TABLE I. Deuteron-helium elastic scattering cross section per unit solid angle in the center-of-mass coordinate system. The cross sections are given in units of 10^{-24} cm². These data were obtained from three experimental runs.

Ω CM angle (degrees)	σ(Ω) barns per unit solid angle	Ω CM angle (degrees)	σ(Ω) barns per unit solid angle
18.4	0.452 ±0.036	109.2	0.0616±0.0028
22.0	0.356 ±0.021	110.6	0.0587±0.0026
23.0	0.326 ±0.020	112.4	0.0576±0.0026
29.4	0.186 ±0.011	114.6	0.0519±0.0023
34.0	0.143 ±0.009	119.8	0.0434±0.0020
36.6	0.112 ±0.007	119.8	0.0445±0.0020
36.6	0.111 ±0.007	119.8	0.0455±0.0027
40.8	0.0761±0.0046	120.6	0.0418±0.0019
43.8	0.0571±0.0034	124.6	0.0378±0.0017
48.2	0.0369±0.0022	127.2	0.0362±0.0016
51.0	0.0223±0.0013	129.3	0.0370±0.0017
55.4	0.0105±0.0006	133.6	0.0374±0.0017
58.4	0.0098±0.0006	133.6	0.0329±0.0020
58.4	0.0097±0.0006	133.6	0.0343±0.0017
62.5	0.0118±0.0007	133.6	0.0371±0.0017
65.4	0.0171±0.0010	134.4	0.0371±0.0017
69.4	0.0217±0.0013	137.8	0.0400±0.0018
72.2	0.0250±0.0011	140.6	0.0436±0.0035
72.2	0.0257±0.0012	141.7	0.0440±0.0035
76.1	0.0343±0.0015	141.7	0.0506±0.0040
78.8	0.0396±0.0024	145.3	0.0454±0.0036
78.8	0.0427±0.0026	145.3	0.0477±0.0038
82.6	0.0467±0.0023	147.4	0.0522±0.0042
82.6	0.0495±0.0030	147.4	0.0551±0.0044
85.2	0.0548±0.0025	149.0	0.0596±0.0048
85.4	0.0570±0.0026	149.0	0.0573±0.0046
85.4	0.0587±0.0026	152.3	0.0683±0.0055
91.6	0.0629±0.0028	152.3	0.0729±0.0058
95.2	0.0694±0.0031	154.1	0.0700±0.0056
97.7	0.0691±0.0031	154.1	0.0755±0.0060
100.6	0.0679±0.0031	155.4	0.0729±0.0058
101.2	0.0709±0.0032	155.4	0.0756±0.0060
103.6	0.0646±0.0029	157.4	0.0824±0.0066
103.6	0.0690±0.0031	158.6	0.0861±0.0069

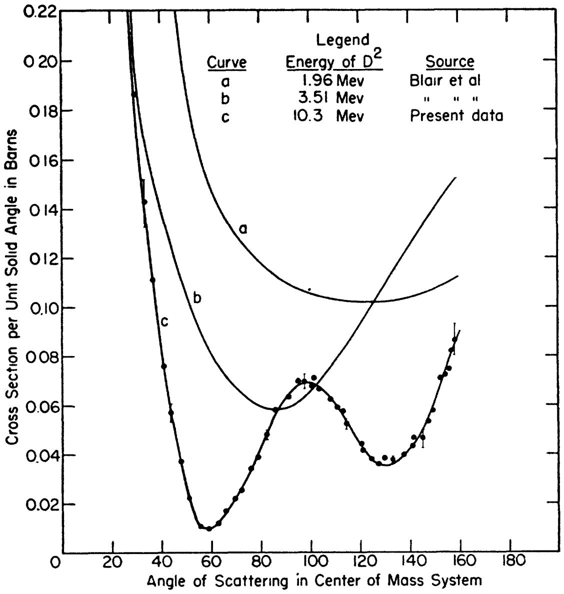

FIG. 5. D–He⁴ differential elastic scattering cross section in the center-of-mass coordinate system for various deuteron energies in the laboratory system of coordinates.

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[9] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).

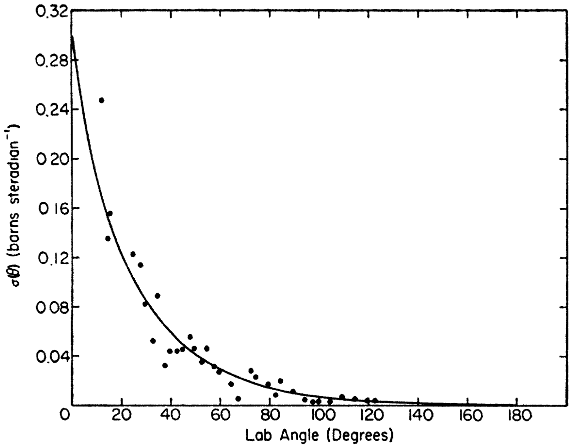

FIG. 6. Differential cross section in the laboratory coordinate system for deuteron disintegration when 10.3-Mev deuterons are incident upon helium. No distinction is made here between reactions B and C.

The root-mean-square standard error estimated from the measurements of temperature, integrated current, geometry, and counting statistics is in most cases less than 4 percent. Since, however, disintegration protons introduced rather large errors, it is estimated that the over-all accuracy of the cross sections at the angles investigated is 18°–22.5°, ±8 percent; 22.5°–70°, ±6 percent; 70°–140°, ±4.5 percent; 140°–160°, ±8 percent. The data of Table I are based on three runs. The deuteron bombarding energy averaged over all three runs is 10.3±0.5 Mev. The maximum variation in energy between runs was 0.1 Mev.

Figure 5 shows the results of the present experiment together with the low energy data of Blair, *et al.*[6] The data of Guggenheimer, *et al.*,[7] were not plotted, since their cross-section values are not given in absolute units. We have learned via private communication that data on the $D-He^4$ interaction have recently been obtained by Rotblat[10] and Gibson[11] at approximately 8-Mev deuteron bombarding energy, and that these data show the same sort of variation of the elastic scattering with angle as our own. These data further show that at this lower energy the differences in cross section between the two valleys and the central peak are not as pronounced as at 10.3 Mev and furthermore that these dips and peaks are shifted to somewhat smaller angles.

Figure 6 shows the angular variation of cross section for deuteron disintegration, including both cases B and C, which immediately give rise to two and three residual nuclei, respectively. This cross-section curve should be considered only approximate because statistical accuracies were sometimes no better than ±15 percent. Moreover, it was quite impossible to subtract accurately the neutron background and that due to slit edge scattering and penetration. The total cross section for deuteron disintegration over the angular region investigated is $0.3\pm0.1\times10^{-24}$ cm². This is to be compared with a total cross section of $1.01\pm0.06\times10^{-24}$ cm² for elastic scattering over the same angular region.

V. DISCUSSION

An interesting feature of the number *versus* range curves at small angles is the presence of a group of particles of charge two, lower in energy than the elastically projected He^4 particles. The second group of particles of charge two may result from either reaction *B* or reaction *C*. If these are alpha-particles from reaction *B*, it follows that they are being produced by virtue of some preferential mode of disintegration of the compound Li^6 nucleus. On the other hand, energy grouping would be expected for helium particles arising from reaction C. For example, at 20° in the laboratory system, the He^4 particles would have an average energy of 3.8 Mev and a width at half-maximum of approximately 1.6 Mev. This is not incompatible with the energy and width of the low energy group of alpha-particles observed at this angle (Fig. 2, Group a). It should, however, be pointed out that even a line spectrum of alpha-particles at this low energy would be recorded as a group of approximately this same width.

Before the inelastic part of the $D-He^4$ interaction can be interpreted with certainty, it will be necessary to perform a coincidence experiment in which the energies of the He^4 particles and protons are observed simultaneously.

No serious attempt has been made to interpret, theoretically, the observed variation with angle of the differential elastic scattering cross section for deuterons on helium; the experimental curve has not even been fitted by a power series in the cosine of the scattering angle. However, it is obvious that the experimental results shown in Fig. 5, taken together with those of Rotblat and Gibson mentioned earlier, form a self-consistent picture in which the angular moments involved in the scattering process progressively increase to higher order as the energy increases.

The authors are indebted to the following personnel of the nuclear plate laboratory for analyzing the many plates from which the present data were taken: E. Agee, M. Bergstresser, R. Booth, F. Forbes, M. Gibson, C. Hart, C. Lacey, O. Milligan, M. Osborn, F. Peet, V. Stovall, and L. Tallmadge. The authors wish also to acknowledge the help of Miss Leona Shackelford in the calculation and compilation of the data as well as in the preparation of the manuscript.

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