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Range Distribution of the Charged Particles from the D–D Reactions for 10-Mev Deuterons: Differential Elastic Scattering Cross Section at 40 Degrees, 60 Degrees, and 80 Degrees in the Center-of-Mass System*

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Microphotographic techniques have been used to obtain the range distribution of the charged particles resulting from the D–D reactions at center of mass angles of 40 degrees, 60 degrees, and 80 degrees for 10-Mev deuterons. At 80 degrees all of the groups of charged particles from the above reactions are clearly resolved. The differential D–D elastic scattering cross sections have been obtained for the same angles and for these angles the cross sections per unit solid angle in the center-of-mass system are in the ratios of 1.00:0.51:0.42, respectively. Only one group of protons is observed from the D(d,H)H^3 reaction, thus indicating that the H^3 nucleus is not formed in an excited state for the energy region investigated when He^4 is the compound nucleus.

ALTHOUGH a large number of investigators[1] have studied the D–D reactions, practically all this work has been done with relatively low incident deuteron energies. The only investigations in an energy region comparable to the energy region available to us in the present experiments were carried out by Guggenheimer, Heitler, and Powell.[2] These experiments were concerned with D–D elastic scattering and no attempt was made to resolve the various groups of charged particles arising from the D–D reactions. In fact, the differential scattering cross sections themselves are given in relative units.

In the present experiments photographic plate detectors were utilized to obtain the range distribution of the charged particles resulting from the D–D reactions and also to make absolute determinations of the D–D elastic scattering cross section at angles of 20 degrees, 30 degrees, and 40 degrees with respect to the incident beam in the laboratory system for 10-Mev deuterons from the Los Alamos cyclotron. The general instrumentation for this paper is the same as that described in a forthcoming paper by Curtis, Fowler, and Rosen.[3] The experimental arrangement is given in Figs. 1 and 2. The experiment consisted of bombarding thin gas targets with 10-Mev deuterons and simultaneously recording on photographic plates the numbers and ranges of the disintegration particles and scattered deuterons emitted into a known solid angle in a given direction.

Deuterium gas of 99.4 percent purity at an accurately determined pressure in the region of 20 cm Hg was contained in the gas targets by thin mica windows: beam entrance and exit windows, and one window on each side of the target for the emergence of the reaction products at the desired angle (in the case of the 40 degree target only one such window was used for the emergence of the scattered particles). The beam, focused at approximately the center of the gas target, was diaphragmed to a diameter of $\frac{1}{4}$ inch immediately in front of the target. Additional slits defined the beam to an angular divergence of 1.2 degrees in the horizontal direction and 0.85 degree in the vertical direction. Coulomb scattering by the entrance target windows never caused more than 2.5 percent of the incident deuterons to be scattered through an angle greater than 1.0 degree. The deuteron current which passed through the target was collected in a nine-inch long Faraday cage and integrated with an electronic current integrator.

Three different gas targets were used, one for each of the angles investigated, the reaction products being simultaneously recorded by two cameras, one on each side of the target, with the exception of the 40 degree target for which only one camera was used. Each camera contained a 100-micron Ilford C-2 plate behind a thin aluminum window at the front of the camera. The plates made angles of approximately seven degrees with the axes of the slit systems.

The cameras were set at accurately determined angles with respect to a 0–180 degree line, which line corre-

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[1] T. W. Bonner and W. M. Brubaker, Phys. Rev. **49**, 19 (1936); Kempton, Browne, and Massdorp, Proc. Roy. Soc. **A157**, 386 (1936); H. Neuert, Physik Zeits. **38**, 122, 618 (1937); T. W. Bonner, Phys. Rev. **52**, 685 (1937); R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937); R. B. Roberts, Phys. Rev. **51**, 810 (1937); R. Dopel, Ann. d. Physik **28**, 1, 87 (1937); T. W. Bonner, Phys. Rev. **53**, 711 (1938); H. Neuert, Zeits. f. tech. Physik **19**, 12, 576 (1938); A. Ellett and R. D. Huntoon, Phys. Rev. **54**, 87 (1938); Hoxby, Allen, and Williams, Phys. Rev. **55**, 140 (1939); N. P. Heydenburg and R. B. Roberts, Phys. Rev. **56**, 1092 (1939); E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971 (1940); Huntoon, Ellett, Bayley, and Van Allen, Phys. Rev. **58**, 97 (1941); T. W. Bonner, Phys. Rev. **59**, 237 (1941); Manning, Huntoon, Myers, and Young, Phys. Rev. **61**, 371 (1942); Bennett, Mandeville, and Richards, Phys. Rev. **69**, 418 (1946); Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948); H. V. Argo, Phys. Rev. **74**, 1293 (1948); Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1594, 1599 (1948).

[2] Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **190**, 196 (1947).

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

sponded to the axis of the beam direction to within 0.3 degree. The angular resolution of the camera-target slit system geometry (Fig. 2) was ±1.4 degrees for the 20 degree target, ±1.2 degrees for the 30 degree target, and ±1.0 degree for the 40 degree target. When the scattered deuterons were recorded simultaneously on each side of the target, as was the case for the 20 degree and 30 degree targets, both the energy and the direction of the beam were determined from the mean ranges of the deuteron groups. By using the range-energy relations given by Lattes, Fowler, and Cuer[4] and making allowance for the loss in range which the particles suffer in traversing the target window, target gas, and camera window, the average energy of the beam prevailing during all the exposures was calculated to be 10.0 Mev ±0.3 Mev at the center of the gas targets.

The direction of the beam which prevailed during the exposures was accurately determined from the mean scattered deuteron ranges at two angles with respect to the incident beam (see Fig. 6). The measurements of the ranges of the scattered deuterons were made by the same observer using the same equipment, the two sets of tracks having been recorded on plates which came from the same batch. Under such conditions the ratio of the mean ranges could be determined to an accuracy of ±1.5 percent. It is noteworthy that it is necessary to know neither the absolute ranges nor the absolute value of the energy in order to accurately determine the beam direction from this method, for from Fig. 2:

$$R_1(\theta)=K_1E_0\cos^2\theta,$$

$$R_2(\theta'-\theta)=K_2E_0\cos^2(\theta'-\theta),$$

and

$$R_1/R_2=K_1/K_2\times\frac{\cos^2(\theta)}{\cos^2(\theta'-\theta)},\tag{1}$$

where E_0 = incident deuteron energy at center of target, R_1 and R_2 are the ranges of the deuterons at their respective angles, corrected for the absorbers between the center of the target and the photographic plate, and K_1/K_2 is determined from the range-energy relations (1). The direction of the beam determined in this manner for the 30 degree point was calculated to be accurate to ±0.25 degree. The beam maintained this direction during the 20 degree exposures and was

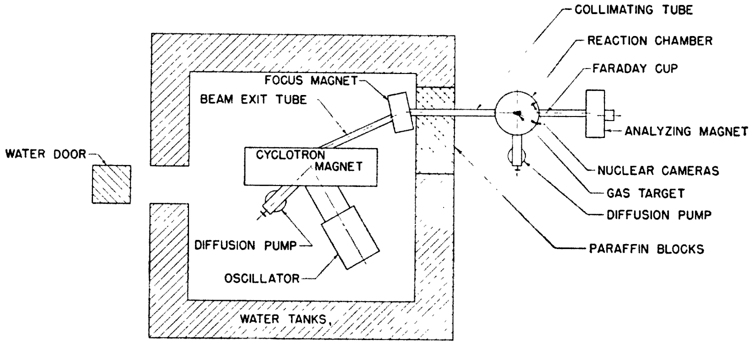

FIG. 1. Plan view of experimental arrangement.

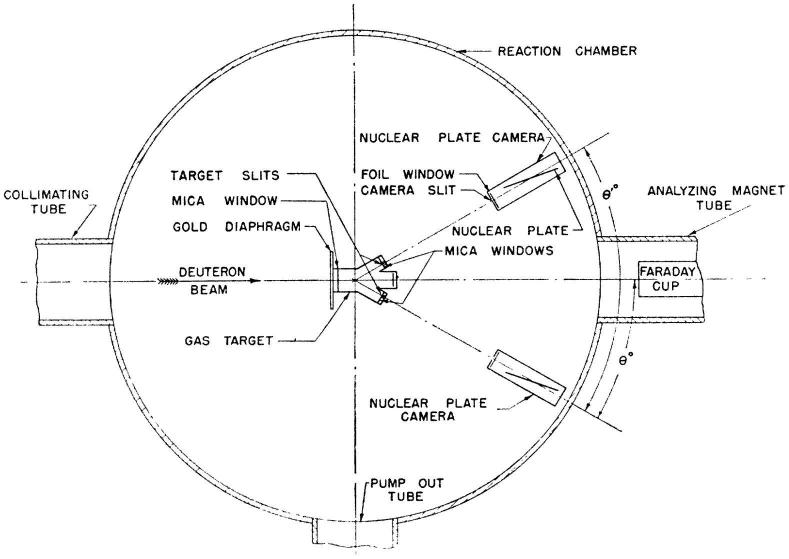

FIG. 2. Plan view of reaction chamber.

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[4] Lattes, Fowler, and Cuer, Nature **159**, 301 (1947).

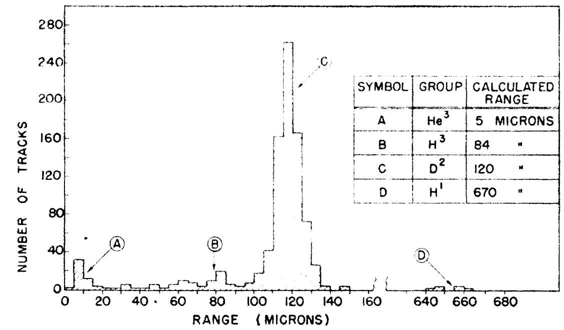

FIG. 3. Range distribution of charged particles from D—D reaction. Ten-Mev deuterons. Forty degrees (laboratory system).

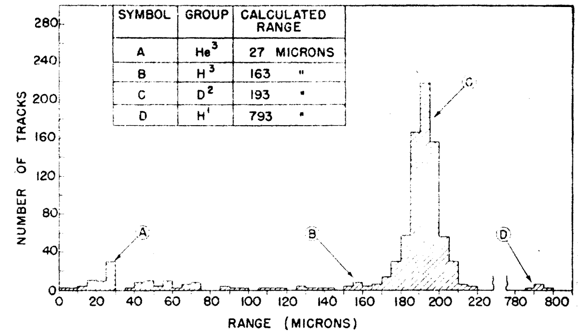

FIG. 4. Range distribution of charged particles from D—D reaction. Ten-Mev deuterons. Thirty degrees (laboratory system).

therefore assumed to have this same direction during the 40 degree exposures.

The experimental procedure for making the range and cross-section measurements was quite simple and straightforward. It consisted of lining up the cameras with respect to the center of the target and axis of the beam, pumping down the vacuum chamber, Fig. 2, and then turning on the cyclotron with the focus magnet off, thus preventing the beam from reaching the scattering chamber during the "warm-up" period. When a steady external beam of the proper magnitude was obtained, the focus magnet was turned on and a beam of approximately 0.2 microampere was permitted to pass through the target. With such a beam an exposure of one to three minutes gave an ample track density in our geometry.

The gas temperature in the target was taken to be the same as the temperature of the water cooling the target. Since the cyclotron was on for a very short time this temperature never changed measurably during an exposure.

Since many particles besides elastically scattered deuterons are produced when high energy deuterons impinge upon a deuterium target, protons and tritons from the reaction $D+D\rightarrow H^3+H^1$, He^3 particles from the $D+D\rightarrow He^3+n$ reaction and possibly protons from the disintegration of the deuteron ($Q=-$ 2.2 Mev), it was felt desirable, in order to accurately determine the D—D scattering cross section, to make range analyses of the charged particles which come off at each of the angles investigated. Only tracks starting on the surface of the emulsion and traveling in the proper direction were included in this range analysis, thus effectively eliminating all background due to proton recoils from neutrons as well as all charged particle background which did not originate from the gas target. It was necessary to eliminate about two percent of the tracks which started on the surface of the emulsion because they did not travel in the proper direction. These tracks were caused by particles which either did not originate inside the gas target or else suffered scattering by the slit systems. In either case the tracks due to such particles were justifiably eliminated. The probability of the change of direction of scattered deuterons by Coulomb scattering in the target and camera windows and in the target gas to such an extent that they would not be counted was calculated to be completely negligible. Figures 3–5 give the results of range analyses at laboratory angles of 40.3 degrees, 30.0 degrees, and 20.1 degrees with respect to the incident beam direction. All of the charged particle groups from the D—D reactions are seen to be clearly resolved at 40 degrees. At 20 degrees the triton peak cannot be resolved from the deuteron peak, for at this angle the mean ranges of the two groups of particles differ by only 2.5 percent. It should be pointed out that some of the short range tracks (tracks whose length is less than that to be expected for elastically scattered deuterons) were undoubtedly caused either by the scattering of deuterons from the walls of the target or by slit penetration. Others of these short range tracks, however, may have been caused by protons arising from deuteron disintegration. The various groups are labeled with the particles producing them and with their calculated residual*** ranges in the emulsion. The energy widths at half-maximum of

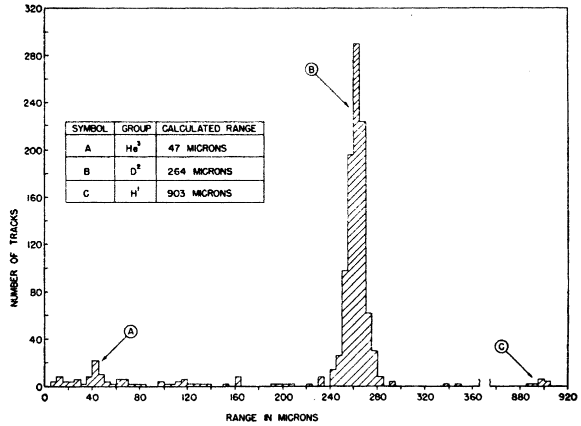

FIG. 5. Range distribution of charged particles from D—D reaction. Ten-Mev deuterons. Twenty degrees (laboratory system).

*** Range which particle has left after passing through the absorbing materials in its path on the way to the detector—D^2 gas, mica window in target, and aluminum window in camera.

TABLE I. D−D scattering cross sections per unit solid angle in the laboratory and center-of-mass coordinate systems.

θ (lab)	$\sigma(\theta)$ (cm²)	ϕ (cm)	$\sigma(\phi)$ (cm²)
40.3°±0.25°	$0.324\pm0.020\times10^{-24}$	80.6°±0.5°	$0.106\pm0.006\times10^{-24}$
30.0°±0.25°	$0.456\pm0.027\times10^{-24}$	60.0°±0.5°	$0.132\pm0.008\times10^{-24}$
29.7°±0.25°	$0.467\pm0.029\times10^{-24}$	59.4°±0.5°	$0.134\pm0.008\times10^{-24}$
20.1°±0.25°	$0.955\pm0.057\times10^{-24}$	40.2°±0.5°	$0.254\pm0.015\times10^{-24}$
19.7°±0.25°	$0.980\pm0.059\times10^{-24}$	39.4°±0.5°	$0.260\pm0.016\times10^{-24}$

TABLE II. Comparison of the present data with those of other observers.

	E_d	σ(40 degrees)/σ(80 degrees)
Present data	10 Mev	2.40
Guggenheimer *et al*	6.6 Mev	3.58
Blair *et al*	3.5 Mev	2.02
Blair *et al*	2.5 Mev	2.05

the deuteron peaks are approximately three percent of the scattered deuteron energy which is quite close to what one expects from the geometry in these experiments. From such a range analysis it is a simple matter to determine with rather high precision the total number of tracks which are due to the properly collimated elastically scattered deuterons. (At 20 degrees a two percent correction was applied for the tritons which were counted in the deuteron peak.) Having made such a determination, the procedure was adopted of counting all tracks originating in a swath of accurately known width, again only tracks being counted which originated on the surface of the emulsion and which proceeded in the proper direction. The charged particles coming from the target were collimated by two slits of accurately known dimensions, which slits were sufficiently narrow such that all the tracks in a swath were clustered approximately at the center of the plate. In order to make an absolute cross-section determination it was necessary to accurately determine the following: the number of tracks per swath, width of swath, diameter of slits and their relative geometry with respect to the center of the plate and the center of the target, the number of target gas atoms per unit volume, the angle of the axis of the slit system with respect to the incident deuteron beam and the integrated beam current. The equation giving the absolute cross sections in terms of the above was developed by Dr. C. L. Critchfield. The geometrical factors which enter into this equation for the 30 degree points are illustrated in Fig. 6. The equation is as follows:

$$Y=NI\sigma(\theta)n_0, \tag{2}$$

$$I=\frac{4abw}{Ll\sin\theta}\left\{1-\frac{a^2+b^2}{2l^2}-\frac{Pa^2+b^2\cot\alpha}{3l^2}+\frac{P^2a^2+Q^2b^2}{3l^2}\right\}, \tag{3}$$

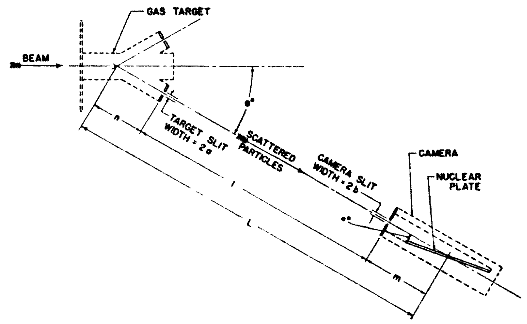

FIG. 6. Geometrical factors which enter into cross-section determinations.

where

$$P=\frac{m[\cot\alpha-\cot\theta]}{L},\quad Q=\frac{(m+l)[\cot\alpha-\cot\theta]}{L},$$

Y = number of tracks appearing on a swath of width w, N = number of incident beam particles that passed through the target, n_0 = number of scattering centers per unit volume, and $\sigma(\theta)$ = differential cross section in laboratory system.

By diaphragming the scattered particles so that they are concentrated about the center of the plate, the necessity for making accurate measurements of the angle that the surface of the emulsion makes with the direction of the scattered deuterons was eliminated. This technique also essentially eliminated errors due to surface irregularities in the emulsion.

The errors in the measurements which enter into the cross-section determination (Eq. (2)) were determined to be as follows:

Quantity	Y	ab	w	Ll	$\sin\theta$	n_0	N
Error (± percent)	3.5	1.5	1.0	2.0	1.0	0.5	3.5

Since the first term in the expansion for I (Eq. (3)) determined approximately 99.5 percent of I for our geometries, the remaining terms need not be considered as far as errors are concerned. It is therefore seen that the r.m.s. of all the above errors, which enter linearly into our cross-section determination is approximately ±5.5 percent.

The D^2 gas used was specified as 99.4 percent pure by the manufacturer. As a check on the purity with respect to heavy atoms (i.e., O_2 and N_2), it is noticed that, in Fig. 5, deuterons scattered by such atoms would have formed a peak at 328±7 microns and deuterons scattered by protons would have formed a peak at 193±4 microns. It is therefore seen that the number of tracks due to scattering from heavy nuclei for which the Coulomb scattering cross sections would be many times the D−D cross section indicates that the total amount of impurities in the D^2 gas from heavy elements is completely negligible. For D−P scattering, on the other hand, the cross section at 20 degrees is probably about one-half the D−D cross section. If this be so it would indicate a maximum hydrogen impurity of less than one percent, in good agreement with the manufacturer's specifications.

In order to check the contribution made to the elastically scattered deuteron peak by deuterons scattered from the walls of the target, the deuterium gas was replaced by hydrogen and a run made at a scattering angle of 20 degrees. An analysis of the plate showed that less than one percent of the particles recorded had a range between 240 and 280 microns which would correspond to the range of deuterons scattered elastically through 20 degrees by deuterons.

Several of the plates were analyzed by two observers using different microscopes and calibration equipment. It was a gratifying verification of the method to find that the number of tracks recorded per unit swath width always agreed to within the statistical accuracy of the determinations.

The results for the D—D scattering cross sections are given in Table I. Figure 7 gives the differential cross-section values as a function of angle in the center-of-mass system and also the differential cross sections for Coulomb scattering as a function of angle in the same coordinate system.

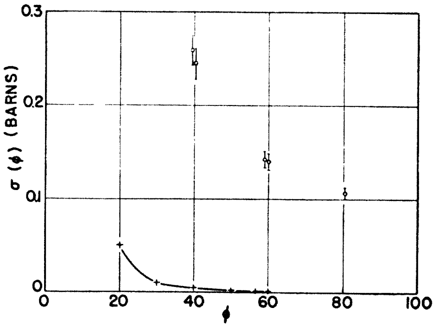

FIG. 7. Upper curve: Differential D—D scattering cross section in the center-of-mass coordinate system. Lower curve: Calculated differential cross section for Coulomb scattering in the center-of-mass coordinate system.

The present data may be compared to the results of Guggenheimer, Heitler, and Powell[2] for 6.6-Mev deuterons and Blair *et al*[1] for 3.5- and 2.5-Mev deuterons. The results of Guggenheimer *et al.* are given in arbitrary units for the cross section and a comparison can only be made by considering the ratios of the cross sections at two scattering angles, $\phi=40$ degrees and 80 degrees. The results of such a comparison are shown in Table II. The marked disagreement with the 6.6-Mev data is disturbing.

Although both theoretical and experimental evidence[5,6] suggest the non-existence of excited levels in the H^3 nucleus, it was felt worth while to investigate this possibility in the energy region available to us, since this region is considerably higher than that heretofore utilized for this investigation.

The method employed to look for energy levels in the H^3 nucleus consisted of determining the energy distribution of the protons from the $H^2+H^2\rightarrow H^3+H^1$ reaction, since a group of protons of energy below that of the primary group would constitute strong proof of the existence of an excited state of the H^3 nucleus.

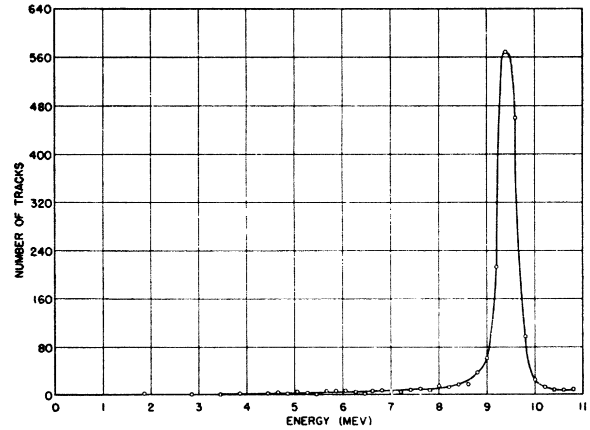

FIG. 8. "Residual" energy distribution of protons from $D(d,p)H^3$ reaction at 20 degrees.

The experimental arrangement was identical with that illustrated in Fig. 2. Since, however, the cross section for elastic scattering of deuterons is much higher than for the production of protons by the reaction $D(d,H)H^3$, it is necessary, in order to record a suitable number of proton tracks without simultaneously obscuring them with deuteron tracks, to prevent the elastically scattered deuterons from being recorded by the photographic detector. This was accomplished by utilizing an aluminum absorber of appropriate thickness between the camera windows and the photographic plate. The proton tracks were recorded at 20 degrees to the incident beam direction.

The plates having been exposed and developed, a range analysis of the tracks on the plate yielded a number *vs.* range curve for the protons from the above reaction which was then converted to a number *vs.* energy curve, the energy representing the residual energy of the protons after penetrating the target gas, target, camera window, and absorber. Figure 8 shows such a curve, an analysis of which brings one to the conclusion that, to within one percent of the primary group intensity, no second group of protons exists which would correspond to an energy level of the H^3 nucleus between one and 5.2 Mev.

In view of the apparent success of the above experiments, a camera is now being constructed for recording the ranges and intensities of the products of nuclear disintegrations and scatterings at 2.5 degree intervals from 10 degrees to 170 degrees with respect to the incident beam. When this is completed, we hope to repeat the D—D elastic scattering experiment over a much larger range of angles and with higher absolute precision.

We wish to thank Mrs. Virginia Stovall and Mrs. Lois Tallmadge for analyzing most of the plates from which were taken the data for this paper. We wish to express our indebtedness to the Los Alamos cyclotron group, and in particular to Dr. J. L. Fowler for the use of the cyclotron.

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[5] S. S. Share, Phys. Rev. **53**, 875 (1938).

[6] F. E. Myers and L. M. Langer, Phys. Rev. **54**, 90 (1938).