Differential Cross Sections for the $C^{12}(d,p)C^{13}$ and $C^{13}(d,t)C^{12}$ Reactions*

H. D. HOLMGREN,† J. M. BLAIR, B. E. SIMMONS, T. F. STRATTON, AND R. V. STUART
University of Minnesota, Minneapolis, Minnesota
(Received June 14, 1954)

The differential cross section for the $C^{12}(d,p)C^{13}$ reaction has been measured for 3.29-Mev deuterons over an angular range from 5° to 140°. It was found to have a maximum near 25°, a minimum near 80°, and another increase at higher angles. Over the same angular range, the $C^{13}(d,t)C^{12}$ reaction has a differential cross section for 3.29-Mev deuterons which shows a maximum at 12°, a minimum at 57°, and a small rise at higher angles. For 2.19-Mev deuterons the structure of $C^{13}(d,t)C^{12}$ differential cross section is broader, with the maximum occurring at 17°. The experimental results have been compared with the results theoretically expected for stripping reactions.

INTRODUCTION

THE deuteron stripping theory developed by Butler[1] has recently been extended to (d,t) and (t,d) reactions by Butler and Salpeter[2] and Newns.[3] On the basis of this theory, the differential cross sections for the (d,t) and (t,d) reactions may be expressed in terms of l, the angular momentum carried into or out of the target nucleus by the neutron involved; R, an effective nuclear radius; and the momentum distribution of the neutron in the triton, considering the triton as a neutron bound to a deuteron-like core. Butler and Salpeter have suggested the possibility of obtaining information about the triton wave function by measuring the differential cross sections for the following reactions:

$$(A+1)+d\rightarrow A+t \quad (1)$$

and

$$A+d\rightarrow (A+1)+p \quad (2)$$

or

$$(A+1)+p\rightarrow A+d. \quad (3)$$

From the (d,p) or (p,d) observations one can, in principal, determine l and R. According to Butler and Salpeter, it is expected that these same values of l and R should be applicable for the (d,t) reaction. A measurement of the differential cross sections for reactions (1) and (2) or (3) should enable one to determine the form of the momentum distribution of the neutron in the triton. Newns has shown that the angular distribution for a (d,t) reaction is rather insensitive to the form of the space wave function of the triton. It is also somewhat questionable whether one should expect the same value of R to be applicable to both reactions on the basis of the Born approximation theory of stripping reactions.[4,5] In addition, Horowitz and Messiah[6] have shown that by taking into account the interaction of the outgoing proton with the final nucleus in a (d,p) reaction the absolute magnitude of the differential cross section may change by as much as a factor of 6 from that predicted by Butler's original formula. It was thus uncertain as to the amount of information which might be obtained from such a series of experiments, considering the present state of the theory. However, in the interest of stimulating theoretical work towards the improvement of the deuteron stripping theory and the extension of this theory to triton reactions, it was felt a study of reactions (1) and (2) would be justified.

With the limited energy available from the Minnesota electrostatic generator, it was necessary for the atomic number of the target nucleus to be less than 10 in order to satisfy the assumption of the theory that Coulomb effects may be neglected. In addition, it was desirable for the Q's of the reactions to be greater than zero. On the basis of these restrictions, the only reactions which could be studied were the following:

$$Be^9(p,d)Be^8 \quad \text{and} \quad Be^9(d,t)Be^8, \quad (4)$$

$$C^{12}(d,p)C^{13} \quad \text{and} \quad C^{13}(d,t)C^{12}, \quad (5)$$

$$O^{16}(d,p)O^{17} \quad \text{and} \quad O^{17}(d,t)O^{16}. \quad (6)$$

The $Be^9(d,t)Be^8$ reaction has already been rather thoroughly investigated.[7–10] The investigation of reactions (6) would have been very difficult since the highest enrichment of O^{17} available was less than one percent. Therefore the carbon reactions were studied.

The M.I.T. group first reported the $C^{13}(d,t)C^{12}$ reaction.[11] Their measurements gave a Q value of 1.310 ±0.006 Mev for the $C^{13}(d,t)C^{12}$ reaction and a Q value of 2.716±0.005 Mev for the $C^{12}(d,p)C^{13}$ reaction. The differential cross sections for the $C^{12}(d,p)C^{13}$ reaction have been measured by Phillips[12] at 8 energies over the energy range extending from 0.75 Mev to 1.32 Mev and

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Atomic Energy Commission Fellow during the preliminary parts of this work. Present address: Naval Research Laboratory, Washington 25, D. C.

[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[2] S. T. Butler and E. E. Salpeter, Phys. Rev. **88**, 133 (1952).
[3] H. C. Newns, Proc. Phys. Soc. (London) **A65**, 916 (1952).
[4] Bhatia, Huang, Huby, and Newns, Phil. Mag. **43**, 485 (1952).
[5] P. B. Daitch and J. B. French, Phys. Rev. **87**, 900 (1952).
[6] J. Horowitz and A. M. L. Messiah, Phys. Rev. **92**, 1326 (1953).
[7] F. A. El-Bedewi, Proc. Phys. Soc. (London) **A64**, 947 (1951).
[8] Fulbright, Bruner, Bromley, and Goldman, Phys. Rev. **88**, 700 (1952).
[9] P. Cuer and J. J. Jung, Phys. Rev. **89**, 1151 (1953).
[10] D. R. Bach and P. V. C. Hough, Phys. Rev. **91**, 463 (1953).
[11] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).
[12] G. C. Phillips, Phys. Rev. **80**, 164 (1950).

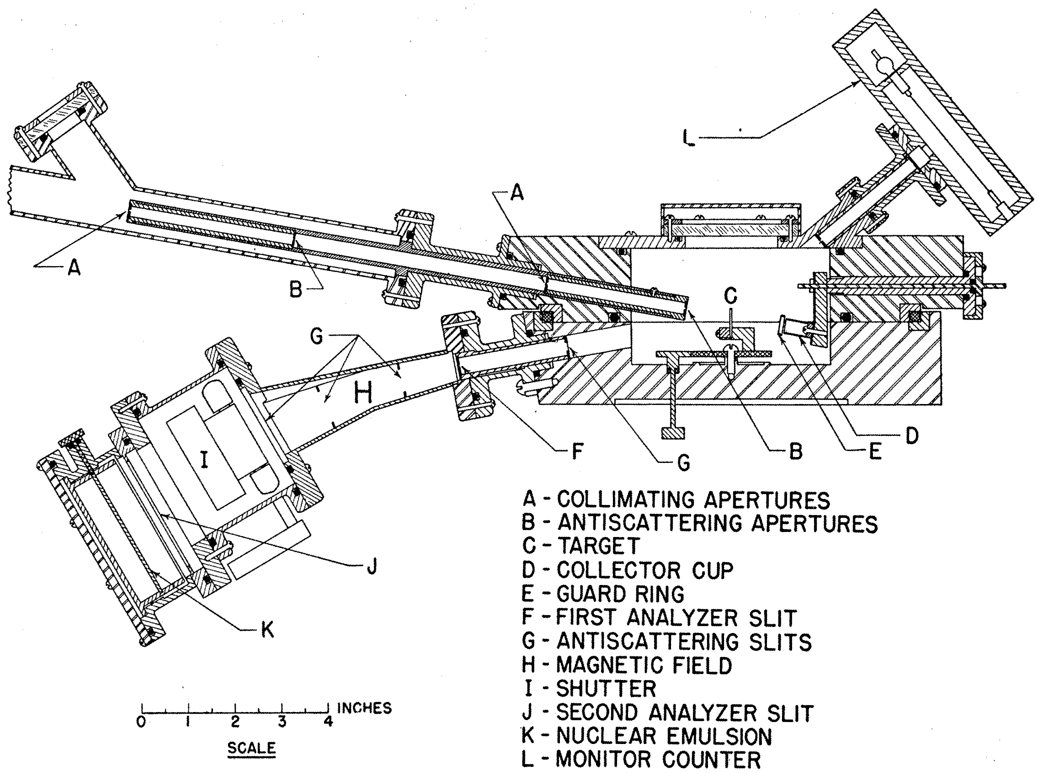

FIG. 1. Sectional drawing of the reaction chamber. The section is through the center of the chamber with the analyzer in the 160° position.

at 7.8 Mev by Rotblat.[13] The angular distributions of the protons emitted in this reaction have also been studied for 3.89-Mev,[14] 4.0-Mev[15] and 14.5-Mev[16] incident deuterons. The experimental data at all energies above 3 Mev indicated that the neutron carries one unit of angular momentum into the target nucleus.

The highest energy at which it was feasible to make the present study of the $C^{13}(d,t)C^{12}$ reaction was 3.29 Mev. The differential cross section of the $C^{12}(d,p)C^{13}$ reaction had not been determined previously at this energy, so it also was measured at this time. For purposes of studying the influence of the Coulomb interaction the $C^{13}(d,t)C^{12}$ differential cross section also was measured at a lower energy, 2.19 Mev.

REACTION CHAMBER

In the study of the $C^{13}(d,t)C^{12}$ reaction, it was necessary to employ a combination of momentum analysis in a magnetic field and range measurements in nuclear emulsions in order to distinguish the tritons from the other reaction products or the scattered deuterons. The reaction chamber which was used to observe this reaction is shown in Fig. 1.

[13] J. Rotblat, Nature **167**, 1027 (1951).
[14] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[15] D. A. Bomley and L. M. Goldman, Phys. Rev. **86**, 790 (1952).
[16] C. L. Black, Phys. Rev. **87**, 205 (1952).

The chamber consisted of two circular aluminum sections, each 9 in. in diameter. The upper section in Fig. 1 contained the diaphragms for collimating the incident ion beam from the electrostatic generator. The lower section, which could be rotated with respect to the upper section, contained the analyzer system. Proper alignment between the two was maintained by a ring of steel balls trapped between steel races. The rotating vacuum seal between the two sections was formed by an "O-ring." The axes of both the collimating system and the analyzer system were at angles of 10° with respect to the plane of the chamber. These axes intersected the axis of rotation of the chamber at the same point; thus, the angle between the axes of the two systems could be continuously varied from 0° to 160°.

The collimating system consisted of two beam-defining apertures (A), 9 in. apart, each with an antiscattering aperture (B) 3 in. behind it. The diameters of the collimating apertures were 0.058 in. The first antiscattering aperture was 0.065 in. in diameter, and the second was 0.100 in. in diameter.

The target assembly was mounted in the lower section of the chamber in such a manner that it could be rotated about the axis of the chamber. The plane of the target contained the axis of the chamber and the intersection of this axis with the axes of the collimating and analyzer systems. It was thus possible to vary the angle of incidence of the beam on the target in order to obtain the maximum resolution of the analyzer.

The targets used in this experiment were sufficiently thin to allow the beam to pass through them and be stopped in the insulated collector cup (D). The cup was 0.350 in. in diameter and was mounted one in. from the center of the target on the axis of the collimating system. Between the target and the collector cup there was a guard ring (E) to which was applied a potential of -90 volts to repel the secondary electrons produced in the target and to prevent the secondary electrons formed in the collector cup from escaping.

The first analyzer slit (F) determined the angular spread of the group of particles which traveled from the target through the analyzer system. This slit was 0.032 in. wide and 5.92 in. from the center of the target. After passing through the slit (F), the particles entered the region of the magnetic field (H) which served to separate the various types of particles according to their momenta. The magnetic field, usually 10 500 gauss, was impressed in a direction parallel to the edge of the slit (F). Some of the particles deflected by the magnetic field passed through the second analyzer slit (J). This slit, 0.140 in. wide, was at right angles to the slit (F) and the magnetic field. The distance from the target to slit (J) along the trajectories of the particles was a function of the radius of curvature ρ of the particles in the magnetic field; thus, the solid angle subtended by the detector at the target was also a function of ρ. However, it was shown that, for values of ρ of interest in this experiment, the solid angle varied by less than $\frac{1}{2}$ percent from its average value of 5.58×10^{-5} steradian.

Directly behind the slit (J) there was located an Ilford C2 nuclear emulsion plate (K). This plate was in such a position that all the particles which passed through the slit (J) struck the surface of the emulsion at an angle of 10°. The amount of deflection of the particles by the magnetic field could be determined from the positions of the particle tracks in the emulsion. The plate holder contained six plates which could be positioned, one at a time, behind the second analyzer slit without opening the plate holder to the atmosphere.

Since the radius of the collector cup subtended an angle of 11° from the center of the target, it was necessary to remove the cup and monitor the beam with the proportional counter (L) when making observations at small angles. The axis of the slit system for the counter (L) was at an angle of 55° to the axis of the beam collimating system and intersected this axis at the center of the target.

TARGETS

During the course of this experiment, it was found that targets in which the incident deuterons lost 100 to 200 kev provided a practical compromise between the incompatible goals of maximizing the yield of particles from the reactions and minimizing their spread in energy. To make possible observation of the reactions at low angles, the targets were made with thin backings. Satisfactory targets were prepared by cracking methyl iodide[17] onto 0.005-mil nickel foils (Chromium Corporation of America, Waterbury 20, Connecticut). Details of target preparation have recently been described.[18] Ordinary methyl iodide was employed to make the C^{12} targets, and methyl iodide in which the carbon had been enriched to 63 percent C^{13} was used to prepare the C^{13} targets.

The number of target nuclei per cm^2 was determined from measurements of the energy loss which protons suffered upon passing through the target. The accelerating potential necessary to reach the threshold of the $Li^7(p,n)Be^7$ reaction was measured for protons which had passed through a bare nickel backing foil; then the measurement was repeated after the deposition of carbon on the foil. The difference between the two accelerating potentials was combined with the rate of energy loss of protons in carbon, as determined by Aron,[19] to obtain the number of target nuclei per cm^2. These measurements were repeated on at least four parts of each target foil in order to study the nonuniformities and obtain an average thickness of each target.

EXPERIMENTAL PROCEDURE

The charge accumulated by the collector cup was measured by a current integrator designed by Brown.[20] This current integrator was found to be accurate to within $\frac{1}{2}$ percent for currents in the range from 0.001 to 1 microampere.

The charge collection efficiency of the collector cup was determined by placing a one-inch diameter annular cup around the collector cup and then measuring the charge accumulated by this annular cup relative to that received by the collector cup. In this manner, it was found the smaller cup collected more than 98 percent of the incident deuterons.

For angles less than 15° the collector cup was removed, and the beam strength was monitored with the proportional counter mentioned above. The amplified pulses from this counter were analyzed by means of a 10-channel pulse-height analyzer so that it was possible to count only the deuterons elastically scattered from the target. The monitor sensitivity was calibrated with the current integrator for each target at the energy used for the plate exposure.

At low observation angles and a bombarding energy of 3.29 Mev, the protons from the $C^{12}(d,p)C^{13}$ reaction had about the same momentum as the elastically scattered deuterons. Since the flux of scattered deuterons was several orders of magnitude larger than the

[17] G. C. Phillips and J. E. Richardson, Rev. Sci. Instr. **21**, 885 (1950).

[18] Holmgren, Blair, Famularo, Stratton, and Stuart, Rev. Sci. Instr. (to be published).

[19] W. A. Aron, University of California Radiation Laboratory Report UCRL-1325, 1951 (unpublished).

[20] R. J. S. Brown, Rev. Sci. Instr. (to be published).

flux of reaction protons, it was necessary to prevent these deuterons from reaching the nuclear emulsion plate. The range of protons was about four times the range of the deuterons; thus it was possible to stop all the deuterons without losing a significant number of protons by placing an aluminum foil of suitable thickness between the second analyzer slit and the nuclear emulsion plate. However, to prevent some protons from missing the plate, because of small-angle scattering in the aluminum foil, it was necessary to tip the plates so that the particles entered the emulsion at an angle of 45°. It was also found that by wrapping the plates in 2.5-mil aluminum foil the scattered deuterons could be completely removed without appreciably broadening the group of protons.

A group of particles, having a given momentum, produced tracks in the emulsion in a narrow band parallel to the one-in. dimension of the 1- ×3-in. plates. The slit (J) defined the region across the plate which could be struck by the particles so that small variations in the position of the plates would be unimportant. The bands varied from 3 mm to 6 mm in width, depending upon the energy spread of the particles emitted from the target.

The number of particle tracks having the required length in a particular band was counted using a microscope having a net micrometer disk inserted in one eyepiece. For all of the plates exposed with the 45° plateholder and for 6 of the plates obtained with the 10° plateholder, the total number of particle tracks having the required length in the band was counted. However, to facilitate the more rapid accumulation of data, the remainder of the plates were analyzed by counting all tracks having the required length in a measured fraction of the area of the band. A comparison of the two methods showed satisfactory agreement.

The entire experimental procedure was tested by measuring the differential cross sections for the elastic scattering of 3.10-Mev incident deuterons by gold and nickel foils. These measurements agreed with the calculated values of the Coulomb cross sections to within 3 percent, which is less than the estimated errors.

In order to obtain the minimum spread in energy of the particles entering the analyzer, it was necessary to rotate the target as the angle of the analyzer was changed. Because of this, the apparent thickness of the target and the number of target nuclei per cm^2 were a function of the analyzer angle. The angle of incidence of the beam on the targets increased from a minimum of 10° for low angles to 47° for analyzer angles in the region of 90°. The number of target nuclei per cm^2 can be expressed as $N_0/\cos\alpha$, where N_0 is the number of target nuclei per cm^2 observed for normal incidence, and α is the angle of the incidence. The surfaces of the targets were observed to be slightly wrinkled. Because of these wrinkles, it was necessary to express the angle of incidence as $\alpha=\alpha_0+\delta$, where α_0 is the angle of incidence calculated from the rotation of the target assembly, and δ is the correction due to the wrinkles. The corrections δ were determined for each target by measuring the yield of reaction particles at a fixed analyzer angle as a function of the calculated angle of incidence α_0 and then fitting the experimental points with a curve of the form $1/\cos(\alpha_0+\delta)$. These corrections δ were found to be of the order of 5°. It was believed, on the basis of this work, that the angle of incidence α could be determined to less than 1°.

Because the angular distribution at low angles was of particular interest, four to ten plates were exposed for each angle in the region from 5° to 40° to provide a check on the consistency of the results. At least 2 exposures were taken for each angle greater than 40° for the $C^{13}(d,t)C^{12}$ reaction.

It was found that observations could not be made for angles less than 5° because of the presence, in this region, of large numbers of deuterons scattered by the edges of the analyzer slit (F). In the case of the $C^{13}(d,t)C^{12}$ reaction at these angles, the tritons could not be separated from the scattered deuterons by the use of absorbers, since their ranges were nearly the same. The protons from the $C^{12}(d,p)C^{13}$ reaction could pass through an absorber foil sufficiently thick to stop the scattered deuterons, but the nuclear emulsions were completely blackened in the region reached by the protons because of the x-rays produced when the deuterons were stopped in the foil.

ERRORS AND RESULTS

Since the theory is more sensitive to the angular distributions than to the absolute magnitude of the differential cross sections, the errors in this experiment were divided into two groups. This allows the theoretical predictions to be compared more critically with the experimental results. The first group of errors included those which affected only the angular distributions. These errors consisted of the statistical errors, the plate reading errors, the errors in the relative calibration of the current integrator scales, and the errors in the determination of the angle of incidence of the beam on the targets. At low angles, where a number of exposures had been taken, the errors due to the combination of the statistical errors and the plate reading errors were replaced by the errors determined from the reproducibility of the data. From this, it could be estimated that the plate reading errors were in the order of 1 percent. For angles greater than 40°, the statistical errors were about 3 percent. The relative current integrator error was less than $\frac{1}{2}$ percent and was thus negligible. The errors in the angle of incidence were believed to be 1°. On this basis, it was necessary to assign 2- to 3-percent relative errors at low angles and errors of the order of 5 or 6 percent in the region of 90°. The second group of errors was composed of the errors in the quantities which entered into the calculation of

TABLE I. The center-of-mass differential cross sections σ for the $C^{12}(d,p)C^{13}$ reaction for 3.29-Mev incident deuterons as a function of the center-of-mass angle θ. The cross sections are in millibarns (10^{-27} cm^2).

θ (deg)	σ (mb)
5.4	11.6±0.3
10.8	13.9±0.4
16.2	17.8±0.4
21.6	19.3±0.4
27.0	21.1±0.5
32.3	18.5±0.7
43.0	14.1±0.4
53.6	9.4±0.3
64.0	6.9±0.3
74.4	5.9±0.2
84.6	5.9±0.3
94.6	6.2±0.3
109.5	9.1±0.6
124.0	10.9±0.5
138.3	11.9±0.6

the absolute differential cross section. In addition to the relative errors, this group consisted of the absolute current integrator calibration error, the errors in the measurement of the solid angle of the analyzer system, and the errors in the determination of the number of target nuclei per cm^2. On the basis of the measurement of the elastic scattering differential cross sections for gold and nickel, it was assumed that the combination of the first two errors was less than 3 percent. The errors

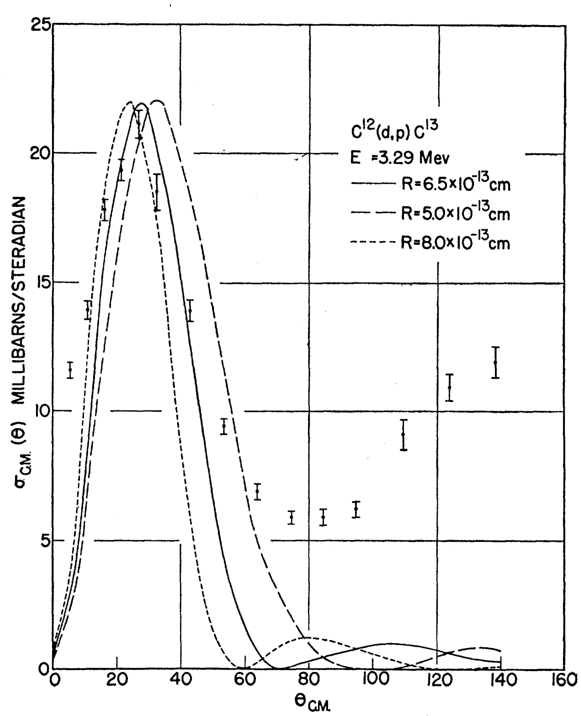

FIG. 2. Center-of-mass differential cross sections for the $C^{12}(d,p)C^{13}$ reaction *vs* center-of-mass angle, for incident deuterons of 3.29-Mev energy. Points represent experimental determinations. Curves are theoretical angular distributions on the basis of Butler's formula for $l=1$ and $R=5.0\times10^{-13}$, 6.5×10^{-13}, and 8.0×10^{-13} cm. The curves were normalized to the observations at their maximum values.

in the determination of the number of target nuclei per cm^2 consisted of a 3 percent error in the value of the rate of energy loss of protons in carbon and about an 8 percent error in the measurement of the thickness of the targets. The errors in the thickness measurements were estimated by comparing the yields for three targets. On this basis, it was necessary to assign an absolute error of the order of 9 percent at low angles and about 10 percent at higher angles.

The center-of-mass differential cross section for the $C^{12}(d,p)C^{13}$ reaction for 3.29-Mev incident deuterons is

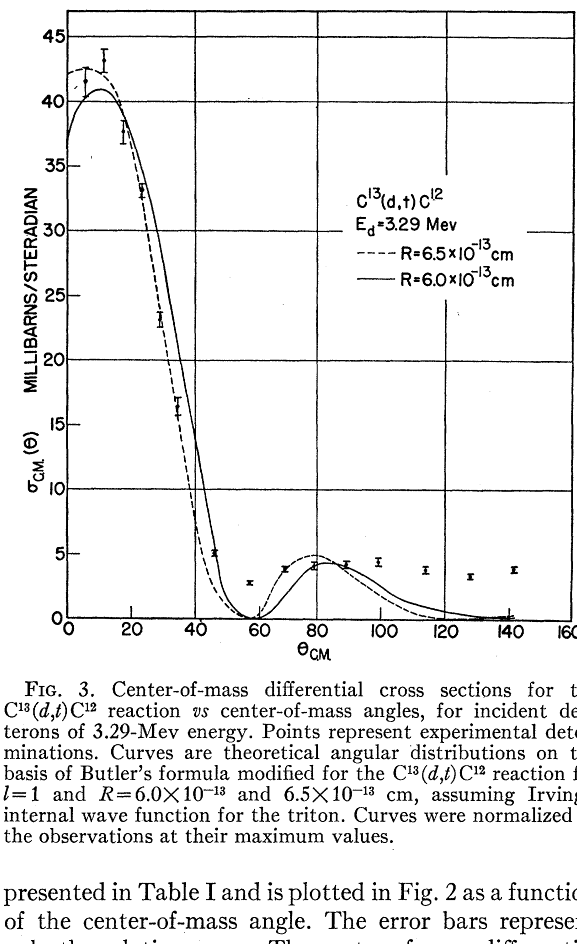

FIG. 3. Center-of-mass differential cross sections for the $C^{13}(d,t)C^{12}$ reaction *vs* center-of-mass angles, for incident deuterons of 3.29-Mev energy. Points represent experimental determinations. Curves are theoretical angular distributions on the basis of Butler's formula modified for the $C^{13}(d,t)C^{12}$ reaction for $l=1$ and $R=6.0\times10^{-13}$ and 6.5×10^{-13} cm, assuming Irving's internal wave function for the triton. Curves were normalized to the observations at their maximum values.

presented in Table I and is plotted in Fig. 2 as a function of the center-of-mass angle. The error bars represent only the relative errors. The center-of-mass differential cross sections for the $C^{13}(d,t)C^{12}$ reaction are plotted as a function of the center-of-mass angle for 3.29-Mev incident deuterons in Fig. 3 and for 2.19-Mev incident deuterons in Fig. 4. The values of the cross sections for the $C^{13}(d,t)C^{12}$ reaction are presented in Tables II and III.

DISCUSSION OF RESULTS

In Fig. 2 the theoretical angular distributions determined on the basis of Butler's formula with $l=1$ for three values of the parameter R are compared with the experimentally observed center-of-mass differential cross section of the $C^{12}(d,p)C^{13}$ reaction for 3.29-Mev incident deuterons. The theoretical curves in Fig. 2 are normalized at the first maximum to the maximum value of the observed cross sections. Only curves for $l=1$ are shown in Fig. 2, since this is the only value of l for which the theoretical angular distribution has a maximum in the region of the observed maximum.[13–16] The theoretical curve for $R=6.5\times10^{-13}$ cm has a maximum at about the same position as the observed differential cross sections; however, this theoretical curve does not agree with the experimental points for either higher or lower angles. The disagreement is particularly noticeable for angles greater than 80°.

Theoretical angular distributions for the $C^{13}(d,t)C^{12}$ reaction at 3.29 Mev are compared with the experimental differential cross section in Fig. 3. The curves are calculated from Butler's formula modified for (d,t)

TABLE II. The center-of-mass differential cross sections σ for the $C^{13}(d,t)C^{12}$ reaction for 3.29-Mev incident deuterons as a function of the center-of-mass angle θ. The cross sections are in millibarns (10^{-27} cm²).

θ (deg)	σ (mb)
5.8	41.5 ±1.1
11.6	43.1 ±0.9
17.4	37.6 ±0.9
23.2	33.1 ±0.5
28.8	23.1 ±0.6
34.7	16.4 ±0.6
46.0	5.10±0.15
57.1	2.80±0.10
68.1	3.84±0.16
78.8	4.12±0.20
89.2	4.36±0.20
99.3	4.45±0.27
114.0	3.82±0.19
128.1	3.35±0.15
141.6	3.91±0.15

reactions and employing Irving's internal space wave function for the triton.[3] Two values of the parameter R are used with $l=1$. It may be seen that a value of R in the region of 6.25×10^{-13} cm would produce excellent agreement between the theoretical curve and the experimental points. The agreement between this value of R and the one obtained from the $C^{12}(d,p)C^{13}$ reaction may be only fortuitous.

In Fig. 4 the theoretical angular distributions for three values of the parameter R with $l=1$ for the $C^{13}(d,t)C^{12}$ reaction at 2.19 Mev are compared with the experimental observations. It may be seen that $R=5.5\times10^{-13}$ cm produces about the best agreement; however, it is not possible to obtain as good agreement at this energy as at the higher energy. The experimental results are in qualitative agreement with results of Butler and Austern,[21] who have attempted to take into account the Coulomb effects for a (d,n) reaction. Their results indicate that the increased importance of the

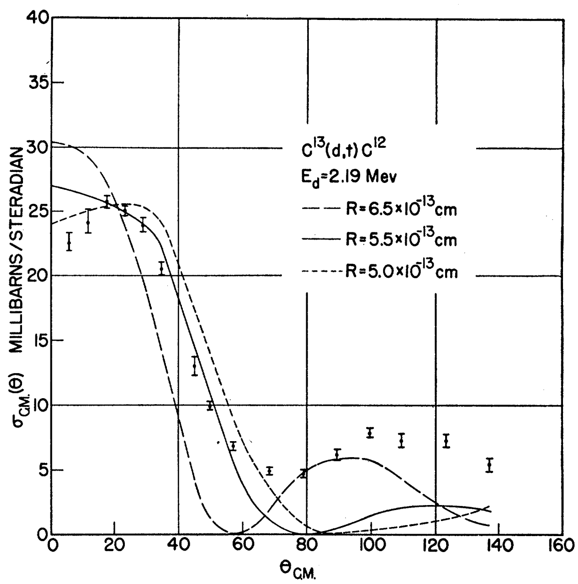

FIG. 4. Center-of-mass differential cross sections for the $C^{13}(d,t)C^{12}$ reaction *vs* center-of-mass angle, for incident deuterons of 2.19-Mev energy. Points represent experimental determinations. Curves are theoretical angular distributions on the basis of Butler's formula modified for the $C^{13}(d,t)C^{12}$ reaction for $l=1$ and $R=5.0\times10^{-13}$, 5.5×10^{-13}, and 6.5×10^{-13} cm, assuming Irving's internal wave function for the triton. Curves were normalized to the observations at their maximum values.

Coulomb effect at the lower energy causes the distribution to broaden and shift to higher angles if the same R is used as at the higher energy.

The observed discrepancies between the experimental points and the theoretical curves for the $C^{13}(d,t)C^{12}$ reaction may be expected to be eliminated by refinements in the theoretical calculations for the pick-up process. However, it appears that it will be impossible to account for the observed discrepancies in the $C^{12}(d,p)C^{13}$ reaction merely with refinements in the calculations based on a stripping process alone, and

TABLE III. The center-of-mass differential cross sections σ for the $C^{13}(d,t)C^{12}$ reactions for 2.19-Mev incident deuterons as a function of the center-of-mass angle θ. The cross sections are in millibarns (10^{-27} cm²).

θ (deg)	σ (mb)
5.8	22.6±0.7
11.6	24.2±0.9
17.4	25.7±0.5
23.2	25.0±0.4
29.0	23.9±0.6
34.7	20.5±0.5
45.1	13.0±0.7
49.9	9.9±0.3
57.2	6.8±0.2
68.2	4.9±0.2
78.9	4.7±0.3
89.3	6.2±0.4
99.4	7.8±0.3
109.3	7.3±0.5
123.5	7.3±0.5
137.2	5.5±0.3

[21] S. T. Butler and N. Austern, Phys. Rev. **93**, 355 (1954).

that it will be necessary to include contributions from other fundamental nuclear processes such as compound nucleus formation. At present it is not clear how the compound-nucleus and stripping processes interfere. In the case of (d,t) reaction one would expect a very small contribution from the compound-nucleus process, since in order for this process to contribute to the reaction, it would require the simultaneous appearance of two neutrons and a proton at the nuclear surface, all with sufficient energy to escape.

ACKNOWLEDGMENTS

We would like to express our appreciation to Professor J. H. Williams for his advice and encouragement throughout the course of the experiment. We should also like to thank Dr. K. Famularo, Dr. D. M. Van Patter, and Dr. W. B. Cheston for their help and suggestions. Finally, we wish to thank Mr. R. B. Thorness for his supervision of the construction of the reaction chamber and Mr. D. Schifferl for his exceptionally accurate work in the construction of the chamber.

PHYSICAL REVIEW VOLUME 95, NUMBER 6 SEPTEMBER 15, 1954

Low-Energy Photofission Yields for U^{238}†

HAROLD G. RICHTER* AND CHARLES D. CORYELL
Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received June 9, 1954)

The pattern of mass number dependence of fission yield has been determined in the photofission of natural uranium (U^{238}) by 16-Mev electrons from the linear accelerator. The effective photon energies were principally 9–14 Mev. Yields were determined by quantitative radiochemical isolation and close approximation to absolute β counting for 19 chains. The peak-to-valley ratio is 110, the highest found yet outside of low-energy neutron studies. A spike in fission yields was found near mass number 133. Yields were also obtained for a number of chains in photofission with 10-Mev electrons.

I. INTRODUCTION

As part of an extended study of the pattern of fission yields as a function of energy and nature of the nucleus undergoing fission, a detailed study has been made of the yields in the photofission of natural uranium (essentially the photofission of U^{238}). It is well known that low-energy fission gives principally asymmetric mass division, with peak yields near mass numbers 97 and 138, and a deep valley for masses near symmetric division ($\sim$117). The dependence of the peak-to-valley yields on the energy available to the fissioning nucleus has been the subject of considerable interest. An attempt was made to determine the energy dependence of the very low yields of symmetrical fission using the photons produced by electrons of 10 Mev and 16 Mev impinging on a cylinder of uranium salt. In addition, interest is attached to fission yields in the mass region 131-138 where a fission yield spike occurs, presumably related to closed-shell effects in the primary fission products.[1–4] Photofission yields for masses 132, 133, and 134 are correlated with yield for other fission processes.

II. EXPERIMENTAL PROCEDURE

A. Irradiation Procedure

The M.I.T. linear accelerator[5] accelerates electrons to a maximum energy of about 16 Mev, with those electrons reaching the end of the machine having a spread of energy of about $\pm$0.6 Mev. The machine terminates, in the target chamber, in a thin aluminum window through which the electrons can be passed essentially unimpeded. On rapid deceleration in a heavy metal target, the electrons give rise to a spectrum of photons ranging in energy from zero to the maximum electron energy. This diverging beam of x-rays is customarily the source of photons for irradiations.

Since the sample irradiated in this study was the salt of a heavy metal, it seemed more conservative of the photons to produce them in the immediate vicinity of the target nuclei by absorbing the electrons directly in the 20-gram uranium salt sample in a cylinder 10 cm long and 1.4 cm in diameter. The fission rate was increased by more than an order of magnitude employing this method over that of placing the sample in a lead-produced photon beam. Such an increase of

† This research was supported in part by the U. S. Atomic Energy Commission.

* Presented in partial fulfillment for the Ph.D. degree in the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts. Present address: Department of Chemistry, University of Oregon, Eugene, Oregon.

[1] L. E. Glendenin, Massachusetts Institute of Technology Laboratory for Nuclear Science and Engineering, Technical Report No. 35, December, 1949 (unpublished).

[2] Wiles, Smith, Horsely, and Thode, Can. J. Phys. **31**, 419 (1953).

[3] A. C. Pappas, Massachusetts Institute of Technology Laboratory for Nuclear Science, Technical Report No. 63, September, 1953 (unpublished).

[4] D. R. Wiles, Ph.D. thesis in Chemistry, Massachusetts Institute of Technology, November, 1953 (unpublished); D. R. Wiles and C. D. Coryell (to be published).

[5] P. T. Demos, Massachusetts Institute of Technology Laboratory for Nuclear Science and Engineering, Technical Report No. 50, May, 1951 (unpublished).