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Compound Nucleus Effects in Deuteron Reactions: $C^{13}(d,p)C^{14}$†

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By using an angular distribution chamber with observation ports at 5° intervals from 5° to 165°, the $C^{13}(d,p)C^{14}$ reaction has been studied as a function of the bombarding energy and angle of observation over the range of deuteron energy from 0.6 Mev to 3.0 Mev. A CsI crystal, with a resolution of 4.5 percent for the ground state protons from $C^{13}+d$, was used as a detector. Excitation curves were obtained at angles of 20° and 135°. A number of broad maxima were observed, the most pronounced effects occurring near $E_d \cong 1.4$ Mev. Twelve angular distributions were measured, at $E_d=0.64$, 0.78, 0.87, 0.98, 1.23, 1.39, 1.48, 1.58, 1.74, 1.99, 2.36, and 2.84 Mev. Those distributions obtained below 1.5 Mev are well described by a power series expansion in $\cos\theta$, involving terms up to $\cos^4\theta$. The variation with energy of the angular distributions suggests that for these low bombarding energies the major part of the cross section is probably due to compound nucleus formation. For energies above 1.7, a maximum in the distributions occurs near $\theta \cong 25°$. This peak becomes more pronounced at the higher energies and indicates that for $E_d \gtrsim 1.7$ Mev, the stripping process becomes increasingly important.

INTRODUCTION

As the first step in a program designed to investigate compound nucleus effects in deuteron reactions, the $C^{13}(d,\alpha)B^{11}$ and $C^{13}(d,t)C^{12}$ reactions were studied[1] in an effort to learn something of the properties of the N^{15} nucleus at high excitation energies. Additional details concerning these energy states as well as information regarding the competition between compound nucleus formation and the stripping process may be obtained through an investigation of the $C^{13}(d,p)C^{14}$ reaction.

Previously, a rather thorough study of this reaction had been made in the range of deuteron energy from 0.2 Mev to 0.7 Mev by Endt and his co-workers.[2] An excitation curve at 90° from 0.7 Mev to 1.9 Mev was obtained by Bonner and the Rice group.[3] The present measurements extend the region of detailed investigation up to 3 Mev; in the range of bombarding energy from 0.6 Mev to 3.0 Mev, twelve angular distributions and excitation curves at 20° and 135° were obtained.

In the (d,α) and (d,t) experiments it was necessary to use magnetic analysis to separate the desired reaction products. The investigation of the protons from $C^{13}+d$ was not undertaken with the magnetic spectrometer since the Q-value for the $C^{13}(d,p)C^{14}$ reaction is sufficiently high (5.944 Mev) to make possible the separation of the ground state proton group with pulse-height analysis in a crystal scintillator. The energy release in the $C^{12}(d,p)C^{13}$ reaction is only 2.723 Mev, so that no difficulty is encountered in the use of a target which is a mixture of C^{12} and C^{13}.

EXPERIMENTAL PROCEDURE

A. Angular Distribution Chamber

The extension of the $C^{13}+d$ experiments to include an investigation of the ground state protons required the construction of a suitable angular distribution chamber. The features which were desired in the chamber were: (a) a wide range of possible observation angles, (b) ease and accuracy of beam alignment, (c) accurate positioning of targets, (d) reproducibility of detector positions, and (e) secondary observation ports subtending large solid angles at the target position.

The diameter of the chamber body is 8 inches and 33 observation ports, $\frac{1}{8}$ in. in diameter, are located at 5° intervals from 5° to 165°. These ports are covered with a 0.9-mg/cm² Mylar foil. Secondary observation ports, $\frac{1}{2}$ in. in diameter, are located at 15° intervals from 15° to 150° in the opposite wall of the chamber. Into these holes are inserted plugs through which were drilled $\frac{1}{4}$-in. holes and are covered with 0.8-mil aluminum foil. In order to use a $\frac{1}{2}$-in. port, the plug is removed and a detector housing is inserted with O-ring seals. For normal operation, with the $\frac{1}{8}$-in. and $\frac{1}{4}$-in. ports, a CsI crystal and photomultiplier tube are enclosed in a steel housing located entirely outside the chamber. In order to allow the detector to rotate to 165° without interfering with the beam tube, the crystal is mounted off-center on the phototube face and the tube housing is correspondingly offset from the axis of the supporting arm. A quartz window waxed into the chamber wall at 0° permits accurate beam and target alignment. The beam is stopped on a 20-mil piece of tantalum which is insulated from the chamber by a Koroseal bushing. The beam-stop may be rotated out of the path of the beam when it is desired to view the beam spot on the quartz. Positioning pins at several locations insure the reproducibility of both target and detector geometry.

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[1] J. B. Marion and G. Weber, Phys. Rev. **102**, 1355 (1956).
[2] Koudijs, Valckx, and Endt, Physica **19**, 1133 (1953).
[3] Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).

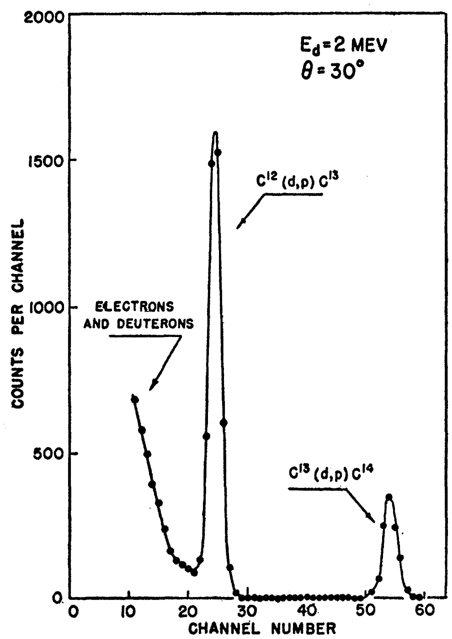

FIG. 1. Pulse-height distribution in the CsI crystal of the ground-state protons from the $C^{12}(d,p)$ and $C^{13}(d,p)$ reactions. The target was a 30-kev carbon foil, enriched to 60% C^{13}. The bombarding energy was 2.00 Mev and the observation angle was 30°. The resolution of the $C^{13}(d,p)$ peak is 4.5%.

B. CsI Detector

A thallium-activated CsI crystal, attached to a DuMont 6291 photomultiplier tube, was used as a detector. An 80-mil-thick piece of CsI, $\frac{7}{16}$-in. in diameter, was cut in a mill. The surfaces of the crystal cut in this manner were quite rough and it was found that the resolution was considerably improved by careful polishing. This was accomplished by rubbing the crystal with the fingers under running water. Since CsI is soluble in water, a gentle rubbing suffices to produce a smooth surface. About 10 mils of material was removed during the polishing procedure and the crystal was quickly dried to prevent pitting by water spots remaining on the surface. The crystal was mounted on the phototube with vacuum grease and covered with 0.2-mg/cm² aluminum leaf which acted as a light shield.

A pulse-height distribution taken with the crystal prepared in the above manner is shown in Fig. 1. The target was a 30-kev thick carbon foil enriched to 60 percent C^{13} and the pulse-height peaks are due to the ground-state proton groups from the $C^{13}(d,p)C^{14}$ ($Q = 5.944$ Mev) and $C^{12}(d,p)C^{13}$ ($Q = 2.723$ Mev) reactions. The bombarding energy was 2.00 Mev and the angle of observation was 90°. A 3-mil aluminum foil was inserted between the target and detector to remove the deuterons, so that the protons had to traverse 0.9 mg/cm² of Mylar, about 0.5 cm of air, and 3 mils plus 0.2 mg/cm² of aluminum before reaching the detector. Even under these conditions, the resolution of the $C^{13}(d,p)$ group was 4.5%. For protons of higher energy, the resolution is even better. Under the same conditions, the protons from the $B^{10}(d,p)B^{11}$ (ground state) reaction ($E_p = 9.95$ Mev) gave a resolution of 3.2%.

C. C^{13} Target

The target used in this experiment was the same as that used in the investigation of the $C^{13}(d,\alpha)$ and

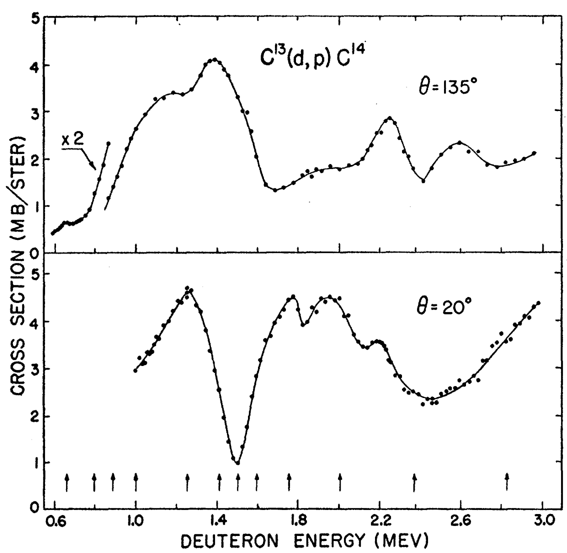

FIG. 2. Excitation curves for the ground-state protons from the $C^{13}(d,p)$ reaction at observation angles of 20° and 135°. The target thickness varies from 38 kev at 1 Mev to 22 kev at 3 Mev and the energy scale is uncorrected for target thickness. The arrows indicate the energies at which angular distributions were measured.

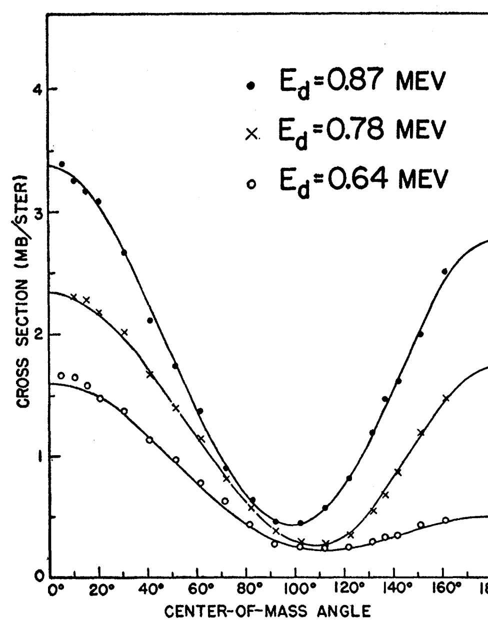

FIG. 3. Angular distributions of the ground-state protons from the $C^{13}(d,p)$ reaction at deuteron energies of 0.64, 0.78, and 0.87 Mev. The curves were calculated from the coefficients listed in Table I.

$C^{13}(d,t)$ reactions. The measurements of the target thickness and C^{13} enrichment have been described previously.[1] The thickness to 1.00-Mev deuterons was 38 kev when the target was oriented at 45° to the beam direction. The C^{13} enrichment was 60%.

RESULTS

Using the apparatus described previously, excitation curves for the $C^{13}(d,p)C^{14}$ (ground state) reaction were measured at 135° for the range of bombarding energy from 0.6 Mev to 3.0 Mev and at 20° for $E_d=1.0$ Mev to 3.0 Mev. The $\frac{1}{8}$-in. ports were used (angular resolution ±0.9°). These curves are shown in Fig. 2. Angular distributions over the range of observation angle from 5° to 160° were measured at the twelve bombarding energies indicated by the arrows along the abscissa of Fig. 2. These angular distributions are shown in Figs. 3, 4, and 5. The energies indicated on the latter curves are the bombarding energies minus one-half of the target thickness and therefore correspond to the deuteron energies at the center of the target. The excitation curves and the angular distributions were internally consistent to better than 2% and no normalization has been made. The differential cross sections were transformed from the laboratory system to the center-of-mass system by using the tables of Marion and Ginzbarg.[4]

The angular distributions of Figs. 3 and 4 have been fitted with a power series expansion in $\cos\theta$ up to $\cos^4\theta$ and the coefficients are given in Table I. The data obtained at the higher bombarding energies (Fig. 5) could not be well represented by using terms only up to $\cos^4\theta$ and a further fit was not attempted. The solid curves of Figs. 3 and 4 are those obtained from the coefficients listed. The dotted portions of the curves in Fig. 4 represent what are considered to be significant departures from the $\cos^4\theta$ expansion. The angular distribution taken at 0.64 Mev is in good agreement with that obtained by Endt[2] at the same bombarding energy.

An excitation curve for $\theta=90°$ was constructed from the angular distribution data and the points are shown

TABLE I. Values of the total cross sections and the coefficients in the expansion $\sigma(\theta)=\sum_{n=0}^{4} a_n \cos^n\theta$ for the $C^{13}(d,p)C^{14}$ reaction.

E_d[a]	σ_t (mb)	a_0	a_1	a_2	a_3	a_4
0.64	7.2±0.4	0.33	0.55	0.72	...	...
0.78	11.4±0.6	0.42	0.98	1.26	−0.67	0.36
0.87	16.3±0.8	0.49	0.70	2.20	−0.39	0.38
0.98	21.9±1.1	0.55	−0.32	3.20	−0.73	0.60
1.23	32.9±1.6	1.10	0.45	4.00	−1.38	0.94
1.39	37.7±1.9	2.40	0.67	1.31	−3.16	0.78
1.48	35.8±1.8	3.00	0.15	−1.19	−2.43	1.25
1.58	33.0±1.6					
1.74	25.6±1.3					
1.99	27.4±1.4					
2.36	23.8±1.2					
2.84	26.3±1.3					

[a] Corrected for target thickness.

[4] J. B. Marion and A. S. Ginzbarg, "Tables for the Transformation of Angular Distribution Data from the Laboratory System to the Center-of-Mass System." Shell Development Company, Houston, 1955 (unpublished).

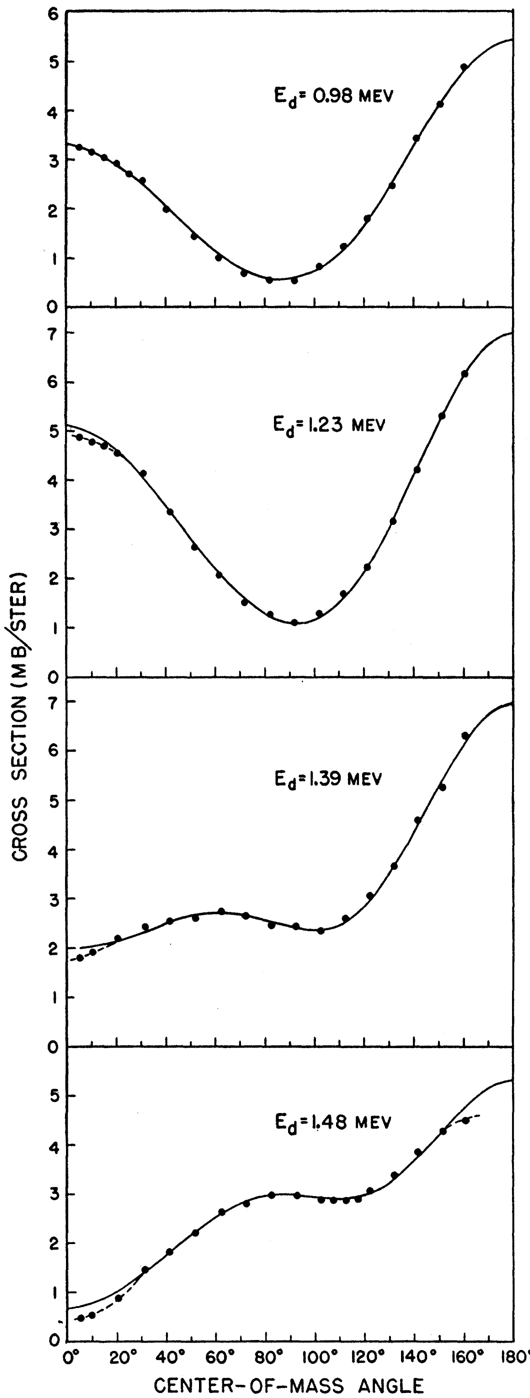

FIG. 4. Angular distributions of the ground-state protons from the $C^{13}(d,p)$ reaction at deuteron energies of 0.98, 1.23, 1.39, and 1.48 Mev. The solid curves were calculated from the coefficients listed in Table I and the dotted portions indicate what are considered to be significant deviations from the $\cos^4\theta$ expansion.

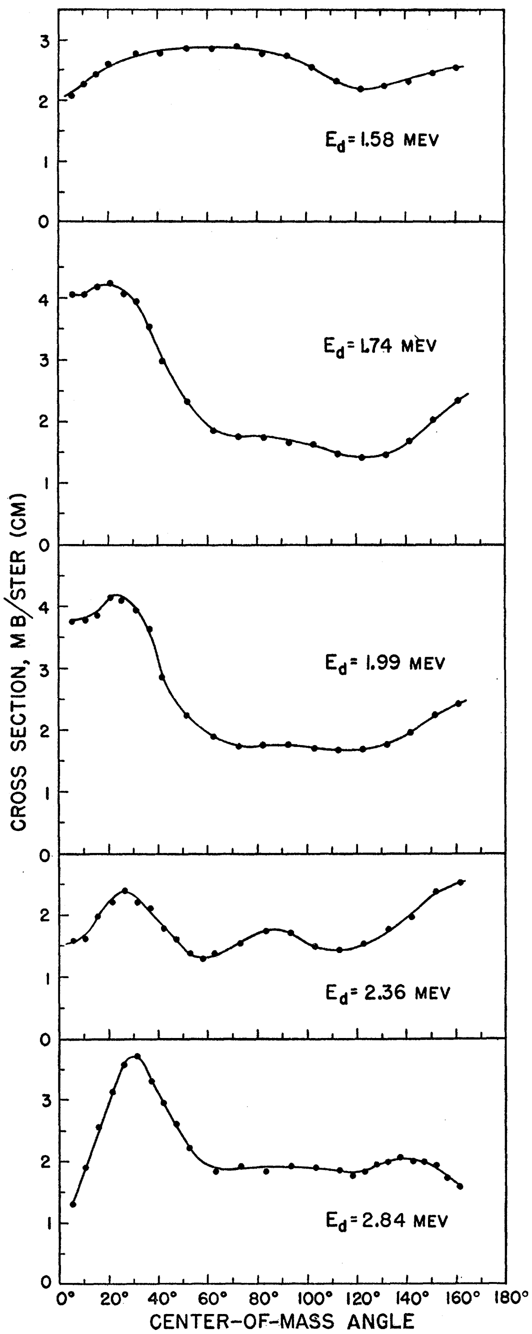

FIG. 5. Angular distributions of the ground state protons from the $C^{13}(d,p)$ reaction at deuteron energies of 1.58, 1.74, 1.99, 2.36, and 2.84 Mev. These distributions could not be well represented with a $\cos^4\theta$ expansion and the curves are merely drawn through the experimental points.

in Fig. 6. The solid curve is the normalized data of Bonner's group.[3] Both experiments indicate a maximum near 1.5 Mev, but the peak is more pronounced in the present work.

The differential cross sections of Figs. 3, 4, and 5 were integrated to obtain the variation of the total cross section with the bombarding energy. The result is shown in Fig. 7 and the values are listed in Table I. A pronounced maximum occurs at $E_d = 1.40 \pm 0.04$ Mev with a peak cross section of 38 mb. At 0.64 Mev, the cross section is 7.2 mb. This value is larger by a factor of 8.5 than that obtained by Endt.[2]

The uncertainty in the absolute cross sections is compounded from the uncertainties in the target thickness (3%[1]), stopping power of carbon (2%[5]), C^{13} enrichment (assumed 3%[1]), current integrator calibration (1%[1]), and counting statistics (generally 2 to 3%). The solid angle of the observation ports in the chamber is precisely known. Therefore, the resultant probable error in the absolute cross sections is approximately 5%. The uncertainties in Figs. 6 and 7 were drawn accordingly; the relative errors in these points are determined only by the counting statistics and consequently amount to about half of the indicated errors.

DISCUSSION

Angular distributions of the ground state protons from $C^{13}+d$ have previously been measured by Bromley and Goldman[6] and by Benenson[7] at $E_d = 4$ Mev and by McGruer, Warburton, and Bender[8] at $E_d = 15$ Mev. These results showed the typical Butler-type stripping peak corresponding to the capture of neutrons with one unit of angular momentum. None of the measurements was extended to the backward hemisphere where cross sections larger than those predicted on the basis of the stripping theory would have indicated the effects of compound nucleus formation. It is perhaps significant in this connection that the 4-Mev data show only a factor of 3 decrease between the differential cross section at the stripping peak and that at $\theta(\text{c.m.}) = 90°$, indicating that the contribution to the total cross section from the backward hemisphere is probably large.

The low-energy angular distributions measured by the Dutch group[2] showed forward and backward maxima. Since the minimum moved to smaller angles and the backward maximum became less pronounced as the bombarding energy was increased up to 0.7 Mev, it was suggested that this indicated the increasing importance of the stripping process. The present data, however, demonstrate that this trend does not continue beyond $E_d = 0.7$ Mev and that, in fact, the forward maximum completely disappears near 1.5 Mev. No systematic increase of a forward maximum persists for deuteron energies up to 1.7 Mev and all of the angular distributions in this energy range can be well represented by a power series expansion in $\cos\theta$ involving terms only up to $\cos^4\theta$. The stripping process (with Coulomb effects neglected) cannot account for these distributions and it appears that the cross section for these low bombarding energies is dominated by compound nucleus formation.

[5] Reynolds, Dunbar, Wenzel, and Whaling, Phys. Rev. **92**, 742 (1953).
[6] D. A. Bromley and L. M. Goldman, Phys. Rev. **86**, 790 (1952).
[7] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[8] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

For deuteron energies above about 1.7 Mev, a consistent maximum in the differential cross section occurs near θ(c.m.)$=25°$. This peak becomes more prominent as the bombarding energy is increased and almost certainly indicates that stripping becomes increasingly important for $E_d \gtrsim 1.7$ Mev. Even at the highest energy studied ($E_d=2.84$ Mev), however, there is still a relatively large cross section for angles in the backward hemisphere. This suggests that compound nucleus formation still plays a strong role even at these higher energies.

The excitation curves shown in Fig. 2 indicates a very complicated resonance structure. The weak maximum at $E_d=0.63$ Mev in the 120° excitation curve measured by Endt[2] was also observed at this energy at $\theta=135°$. A careful search was made for a narrow resonance at $E_d=2.20$ Mev since it is known[1] that the $C^{13}(d,\alpha)$ reaction is resonant at this energy. The level width, as determined from the (d,α) reaction, is 22 ± 4 kev. No narrow resonance was found near this energy in the (d,p) reaction, although a broader maximum was observed at 2.23 Mev. This latter resonance probably corresponds to that found at this energy in the $C^{13}(d,t)$ reaction.[1] The maximum in the 135° curve near 2.6 Mev may be associated with the (d,α) resonance at 2.55 Mev [1] and perhaps with the (d,n) resonance at 2.45 Mev.[9] It is possible that the 1.80-Mev resonance, known to occur in the (d,α) and (d,t) reactions,[1] is responsible for the narrow dip in the (d,p) cross section at $\theta=20°$ at this energy. The 90° excitation curves shown in Fig. 6 indicate a resonance at 1.55 Mev. When the integrated angular distributions are plotted as a function of energy,

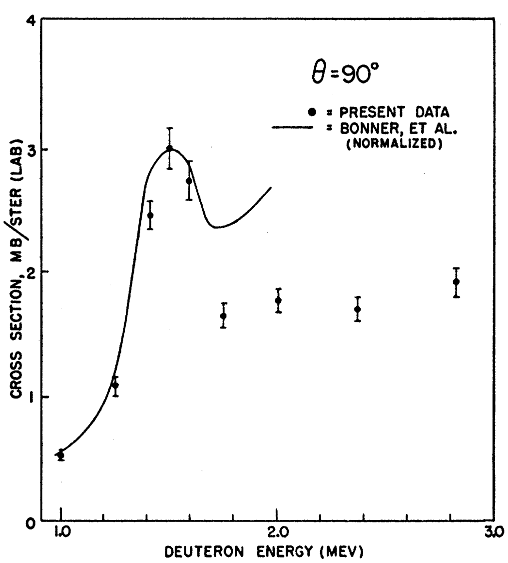

FIG. 6. Excitation curve for the ground-state protons from the $C^{13}(d,p)$ reaction at $\theta=90°$, constructed from the angular distributions of Figs. 4 and 5. The solid line represents the normalized data of Bonner *et al.*, reference 3.

[9] Marion, Bonner, and Cook, Phys. Rev. **100**, 847 (1955).

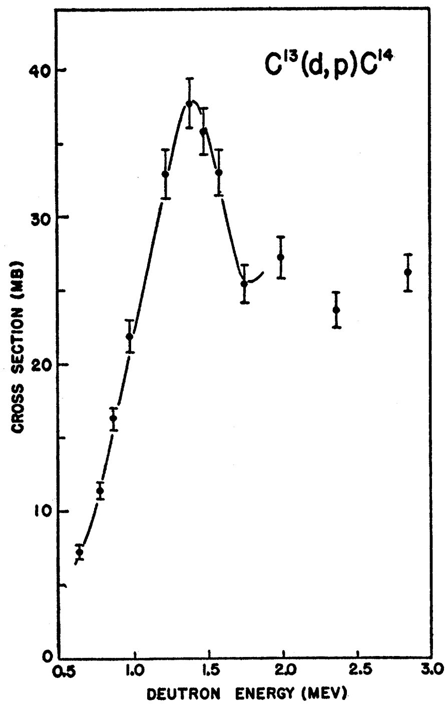

FIG. 7. Total cross section for the ground-state protons from the $C^{13}(d,p)$ reaction as a function of the deuteron energy, obtained by integrating the angular distributions of Figs. 3, 4, and 5. The cross-section values are also given in Table I.

however, the peak is shifted to 1.40 Mev. Resonances in the (d,α) and (d,t) reactions also occur at this energy.[1] A compilation of the various resonances observed in the $C^{13}+d$ reactions has been given previously[1] and includes results from this work.

The accuracy to which the (d,p) cross sections have been measured is approximately 5%; the (d,α) cross sections have been measured to an accuracy of about 10%.[1] The possibility of systematic error between these measurements was reduced by using the same target for both experiments. Therefore, the relative cross sections may be compared with some confidence. The total cross section for the (d,p) (ground-state) reaction at 2.36 Mev is 24 mb while the (d,α) (ground-state) cross section[2] at 2.28 Mev is 150 mb. Furthermore, the cross sections for the emission of protons[7] and α particles[1] to excited states are smaller than the ground-state transition cross sections. This large ratio of the (d,α) to the (d,p) cross section is maintained over the entire energy range studied. Since the emitted protons and α particles have approximately the same energy, it is quite difficult to understand the relatively large (d,α) yield compared to that from the (d,p) reaction.

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