Proton Resonances in the Deuteron Bombardment of Carbon

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The protons resulting from the deuteron bombardment of C^{12} have been studied in some detail, with particular emphasis on the variation of the intensity of the long-range protons with energy and angle. Excitation curves at three fixed angles, one forward, one backward, and one at 90° to the beam, show peaks which in some cases agree in energy with one another and with neutron and gamma-peaks observed in the same bombardment elsewhere. In other cases, however, there is no peak on one mode of observation at an energy where one appears in another. In some cases peaks in different modes of observation which do not quite coincide in energy are so close together that it seems reasonable to attribute them to the same virtual level of the compound nucleus, and the existence of the small energy discrepancies is discussed. Two shorter range groups of protons are studied less extensively because they penetrate the thin windows only at high bombarding energies, and their range coincides with that of the scattered deuterons at some bombarding energies. The two short range groups indicate excited states of C^{13} at 3.12 and 3.91 Mev. A possible low excited state near 0.8 Mev, suspected from an alpha-induced reaction, is not confirmed. The transition to it cannot be shown to be absent but only weak because protons indicating its existence could be masked by protons observed from an oxygen impurity. Of the three angular distributions observed in detail, the one at the lowest bombarding energy is the simplest, in keeping with the expectation that only deuterons of low angular momentum penetrate at low energies.

OBSERVATION of the various ranges of protons from the nuclear reaction $C^{12}(d, p)C^{13}$ yields information about the compound nucleus N^{14} in resonant states having an excitation of somewhat more than 10 Mev, and information about the transitions from these states of the system to the states of C^{13} plus a proton. It also yields directly information about the energy of excitation of the more interesting low states of the produce nucleus, and more indirectly it might with sufficiently penetrating interpretation yield information about other physical properties of these states.

Resonances in the production of protons, neutrons, and gammas by the deuteron bombardment of carbon have been investigated at the Rice Institute[1,2] and at the University of Minnesota.[3,4] The protons were observed[1] at 90° to the incident beam and at bombarding energies up to 1.8 Mev. Fair but not complete agreement was found between the positions of the proton, neutron, and gamma-resonances. In the most recent work of these investigations a slight discrepancy was discussed between the energies of a gamma-peak and a neutron peak which seemed to arise from resonance with the same "virtual state" of the compound nucleus N^{14}. Neutron energies were measured at two angles and the peaks of the excitation curve of forward neutrons show more resemblance to the gamma-peaks than do those of the neutrons observed at right angles to the incident beam.

In the present investigation, the excitation curves for the long range protons from deuteron bombardment of C^{12} have been observed at three different angles for bombarding energies between 0.8 and 3.6 Mev, and the resonance peaks of these curves are found to coincide in most cases with some of those observed for neutrons or gammas. More complete angular distributions of the long range protons have been observed at three energies, and the distribution in range of the protons have been observed at several bombarding energies. The latter measurements confirm the existence of two excited states of the residual nucleus C^{13}, and give their excitation energies as 3.12 and 3.19 Mev. The values previously inferred[5] from cloud-chamber work on this reaction and from the reaction $B^{10}(\alpha, p)C^{13}$ were 3.18 and 3.95 Mev. The latter reaction[6] also indicates the probable existence of an excited state of C^{13} at about 0.8 Mev, of which no trace is found either in the present or the earlier work on $C^{12}(d, p)C^{13}$.

METHOD OF MEASUREMENT

The apparatus and techniques employed in this investigation are essentially the same as used in

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1 Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
2 W. E. Bennett and T. W. Bonner, Phys. Rev. **58**, 183 (1940); T. W. Bonner, E. Hudspeth, and W. E. Bennett, Phys. Rev. **58**, 185 (1940); Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941); W. E. Bennett, and H. T. Richards, Phys. Rev. **71**, 565 (1947).
3 C. L. Bailey, M. Phillips, and J. H. Williams, Phys. Rev. **62**, 80 (1942).
4 C. L. Bailey, G. Freier, and J. H. Williams, Phys. Rev. **73**, 274 (1948).
5 W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).
6 W. Jentschke and L. Wieninger, Physik. Zeits. **41**, 524 (1940), O. Merhaut, Phys. Zeits. **41**, 528 (1940), but not observed by Joliot and Zlotowski, J. de phys. et rad. **9**, 393 (1938). Zlotowski, Comptes Rendus **207**, 148 (1938). The latter references record the long range group as more energetic than in the former references, and on this basis the value 0.6 Mev for the energy of the excited state deduced from the former references is raised to 0.8 Mev the summary chart in reference 6.

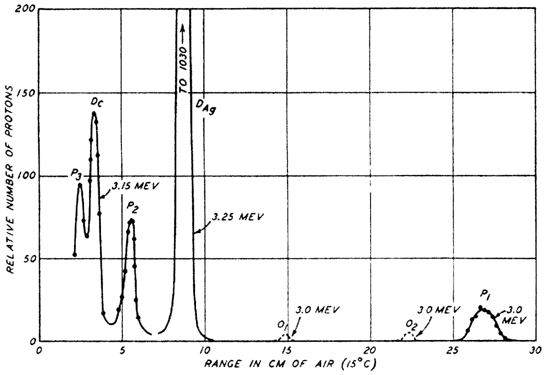

FIG. 1. Proton groups and scattered deuterons from a thin graphite target with a silver leaf backing. Reaction $C^{12}(d, p)C^{13}$, angle 132.5°.

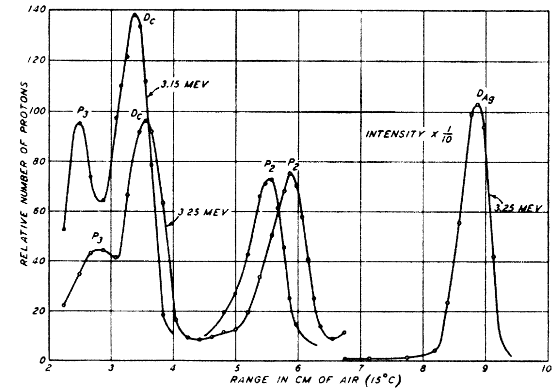

FIG. 2. Proton groups from two excited states of C^{13}, occurring in the reaction $C^{12}(d, p)C^{13*}$, for two deuteron energies, angle 132.5°.

earlier investigations[7] of the similar (d, p) reaction in O^{16} and subsequently in the (p, α) and (d, α) reactions in the two lithium isotopes. The target is contained in a circular chamber having nine thin windows at various angles, and a proportional counter having a thin window over a small aperture is mounted in such a way that the air path outside any of the windows may be accurately adjusted. The deuteron beam was obtained from the large statitron at the Department of Terrestrial Magnetism, and the accelerating potential was regulated by manual adjustment of the charging current following null indications on an oscilloscope from the generating voltmeter, after setting the comparison voltage on the generating voltmeter to the required value. The demands on the manual adjustment were much less exacting than in previous work with this statitron, because the installation of a rectifier in the dome, to supply the return charging current in place of the usual induction scheme ("current doubler"), had a marked steadying influence.

The proportional counter was for most of this work filled with argon to a pressure of 5 cm and had an air-equivalent thickness of about 3 mm. Discriminator bias was set so that the peaks in range curves for the short range proton groups of which the straggling is small were not much wider than this, which probably means that the bias required the maximum of the specific ionization curve of a given proton to be practically within the sensitive volume of the counter. Relative intensities as given in this paper are measured only by peak heights, as has also been done in earlier papers where the variation of ranges studied was not so extreme as here. With the extreme variation of ranges here encountered, the peak height is not a completely reliable measure of the relative intensity of a given proton group, because the protons of a longer range monoenergetic group have a greater spread in range, i.e. more straggling, and one would have to integrate over a wider peak of a distribution-in-range curve, or over a wider peak in a Bragg curve (with an arbitrary cut-off), to count all the protons of the group. Intensities as we give them, measured by peak heights, are thus relatively somewhat too small for the longer-range proton groups, but this does not affect the positions of resonance peaks or the survey of angular distributions.

[7] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).

OBSERVATION OF PROTON RANGES

Targets were prepared on a backing of thin silver leaf, in order to make possible observation at angles near the forward direction by penetration of the backing, and at the same time to minimize the difficulties of discriminating against scattered deuterons. In some of the early measurements, india ink was used in making the targets, but the final measurements were made on targets prepared by coating the backing with fine graphite powder suspended in very dilute shellac.

For the observation of protons down to as low an energy as possible, thinner windows than usual were mounted both on one of the windows of the target chamber and on the aperture of the proportional counter. Aluminum foil nominally 0.00025 inch thick with an air-equivalent thickness of 1.14 cm was used. The aperture of the counter was small enough that this thin foil could be used unsupported, but on the target chamber it was supported by a perforated plate.

Observations of the shorter ranges were made at a backward angle, 132.5°, because the scattered deuterons are fewer there. The intensity of the product protons and scattered deuterons at this angle as a function of their range is shown in Figs. 1 and 2. The positions and approximate intensities of the various groups are shown throughout the entire range interval 1 to 30 cm in Fig. 1. (This curve is a summary of results observed at two slightly different bombarding energies, and at neither of them were careful observations made of the peaks O_1 and O_2 which arise at least primarily from the $O^{16}(d, p)O^{17}$ reaction in an oxygen impurity, so they are drawn schematically on the basis of measurements made under other conditions.) Figure 2 shows the short range portion of such curves for two bombarding energies, 3.15 and 3.25 Mev, each high enough to permit observation of the second endoergic peak, P_3. The exoergic long range peak P_1 leading to the ground state of C^{13} is lower than the short range peaks P_2 and P_3 leading to excited states of C^{13}, but it is also broader as a result of straggling and represents a comparable number of protons. The peak marked D_{Ag} is due to the elastically scattered deuterons from the silver leaf and the peak marked D_C is due to these scattered from carbon. The peaks marked O_1 and O_2 are the protons from the reaction $O^{16}(d, p)O^{17}$ in an oxide layer that seems always to be present. The relative intensities of these two oxygen groups are well known from earlier work in this laboratory[7] and the close agreement of the ratio with that measured earlier without an appreciable amount of carbon present seems to indicate that the peaks consist entirely of protons from the oxygen reaction, without more than a very weak contribution from protons leading to a possible low excited state of C^{13}. The short range peak P_3 could be observed only through this small range of bombarding energies because of lower energies it does not penetrate the windows and at the higher attainable energies it merged with the deuteron peak. Similarly, the range of bombarding energies over which P_2 could be measured was limited on the low side at about 2.5 Mev by the approach of the deuteron peak D_C. At considerably lower energies they are separated again, and in Fig. 10 of reference 1, the peak P_2 is shown on the other side of the deuteron peak at a bombarding energy of 1.47 Mev.

EXCITATION CURVES

The excitation curve for the proton group P_2 is shown in Fig. 3, and exhibits resonances at bombarding energies of 2.72 and 3.20 Mev. The two points plotted separately on the same figure represent the intensities of the shortest range proton group P_3 at the two energies at which it was observed. Their relative position suggests the proximity of a sharp peak.

For the long range protons it was possible to make observations over wider ranges of energy and angle. Excitation curves of the long range protons have been observed over the energy interval from 0.8 to 3.6 Mev, and at the three angles 10°, 90°, and 132.5° to the incident beam. These excitation curves are shown in Fig. 4. That they are quite dissimilar is not to be considered surprising, in the light of the rather rapid changes in angular distributions that are known,[7] for example, in the analogous reaction $O^{16}(d, p)O^{17}$. It is nevertheless interesting to note that there is only one case where the same resonance energy is clearly indicated at all three angles, and that is the lowest energy peak at 0.93 Mev. Furthermore, there is no coincidence with the peaks shown in Fig. 3 for the shorter range proton group.

DISCUSSION OF THE RESONANCE PEAKS

The natural extension of the usual interpretation of excitation curves is to assume that the peaks in the various excitation curves shown in Figs. 2 and 3 each indicate the presence of virtual energy levels in the compound nucleus N^{14}, but that not all of these levels make their presence felt in the observations at each angle. On the basis of this assumption, to which we subscribe only with reservations as discussed below, the virtual energy levels indicated by the proton resonances are shown in Fig. 5, in which the excitation curves of Figs. 3 and 4 are also sketched, and the transitions from these levels to the ground state of C^{13} and to the state near 3-Mev excitation corresponding to the observed proton resonances are indicated by the sloping full lines. The sloping broken lines indicate transitions to the excited state, presumably the state at about 3-Mev excitation, inferred from the observations of gamma-resonances.[1,4] It is gratifying that most of the virtual states indicated by the proton resonances are also detected by gamma-resonances. There is one virtual level detected by a gamma-resonance but not by a proton resonance, at 1.30-

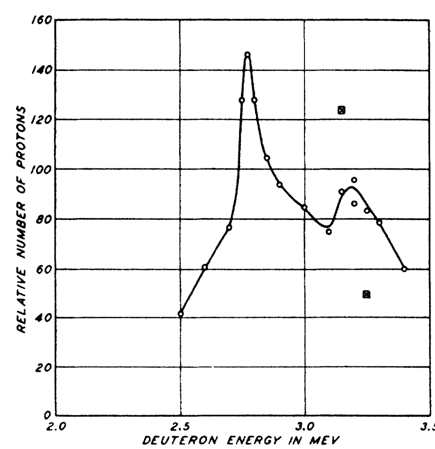

FIG. 3. Excitation curve for $C^{12}(d, p)C^{13*}$ for the short range proton group, P_2. The two points indicated by squares represent the only observations made on the proton group P_3. Observations were made at 132.5° (lab. systems of coordinates).

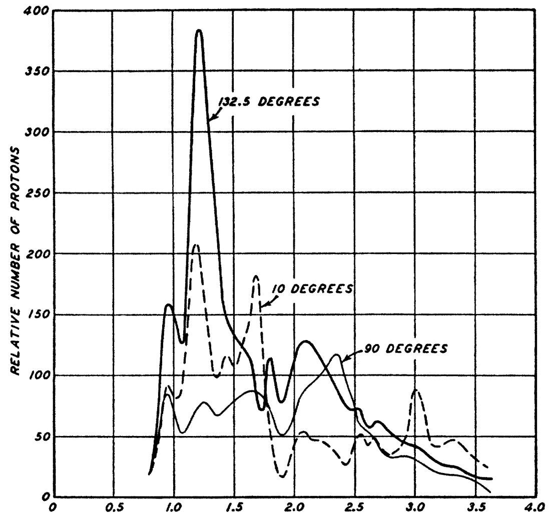

FIG. 4. Excitation curve for $C^{12}(d, p)C^{13}$ for the long range proton group, P_1. Observations were made at three observing angles, 10°, 90°, and 132.5° (lab. system of coordinates).

Mev bombarding energy, and this is shown by a broken horizontal line in Fig. 5.

COMPARISON OF RESONANCES IN THE VARIOUS REACTIONS

Although the resonances appearing in one excitation curve do not in most cases appear in all the other excitation curves obtained by observing in various ways the reactions obtained by deuteron bombardment of C^{12}, it is of some interest to note the number of instances in which the same resonance does appear several times. In Table I, the first three columns give the long range proton resonances which are the main subject of this investigation, column (1) at 10°, column (2) at 90°, and column (3) at 132.5°. Column (4) gives the two resonances observed for the short range protons. Column (5) gives the gamma-resonances, column (6) the forward neutron resonances, and column (7) the right-angle neutron resonances, as reported in reference 4. The numbers entered in columns (2) and (6) marked with an asterisk (*) are instances of resonances reported in reference 1 which did not appear as resolved peaks in the later work. Those enclosed in parentheses were not very clearly resolved in reference 1 either. The column headed E_r gives the mean energy, or resonant energy, of each group of resonances ascribed to the same level. Toward the end of the table this grouping of the observed results into levels becomes rather arbitrary, and in the most questionable case, at 2.66 Mev, four results are grouped together which cover a spread of 0.04 Mev and the distance to an adjacent level is only 0.06 Mev. In reference 4 two cases were discussed of an apparent shift of the energy at which a resonance appears in neutron observation as compared with gamma-observation. In our listing in Table I, we have removed the question in these instances by attributing the resonances to different levels, in the one case to levels 7 and 8, in the other to levels 17 and 18. This was done on the grounds of comparison with other data, mainly from reference 1, but admittedly remains open to doubt. Even if, as we assume, so many levels exist that the question does not arise in these instances, there is a similar but smaller shift in our observations of the long range proton resonances at different angles, for example in level 3 and 13, and this makes it seem likely that such shifts could in principle be found also between resonances involving different product particles.

TABLE I. Comparison of proton, gamma-, and neutron resonances.

Level	(E_r)	(1) 10°	(2) 90°	(3) 132.5°	(4) S.R., 132.5°	(5) γ	(6) N,O°	(7) N,90°
1	0.93	0.94	0.94	0.94		0.92	0.92	0.92
2	1.16	1.17	1.16*			1.15	1.16*	
3	1.23		1.24	1.22				
4	1.30					1.30	1.30	
5	1.43	1.43	(1.44)*			1.43		
6	1.66	1.66	1.66					
7	1.75		(1.74)*			1.75	(1.74)*	
8	1.80			1.80			1.79, 1.82*	1.81
9	2.09	2.09		2.08				
10	2.20	2.20				2.2		
11	2.34		2.35				2.33	
12	2.53	2.55		2.55		2.49	2.53	
13	2.66	2.64		2.68		2.67	2.65	
14	2.72				2.72			
15	2.82							2.82
16	2.90		2.91			2.89		
17	2.95						2.95	
18	3.01	3.01						
19	3.11					3.08		3.13
20	3.20				3.2			
21	3.31	3.31						

DISCUSSION OF THE SMALL DISCREPANCIES OF NEARLY COINCIDENT RESONANCES

It is apparent from the construction of Table I that there exists a legitimate question how far it is permissible to go in tolerating small differences between resonance peaks to be ascribed to the same level. In pursuing the ideal of finding complete agreement and unique specification of the levels, it should be remembered that the theoretical basis for the existence of "virtual levels" and their role in the dispersion formula leads one to expect them to manifest themselves by resonances at a unique position only when they are far apart compared with the level widths. The existence of angular distributions having a fore-and-aft asymmetry in reactions such as the one here studied is evidence of interference between the contributions of different levels and of the way this interference can be constructive in one direction, or in one mode of observation, and destructive in another at the same bombarding energy. The relative contributions of the interference terms can vary quite rapidly with energy as one passes through the neighborhood of one of the levels concerned, and this can result in the appearance of a peak in the intensity of one mode of observation on one side of an assumed level and in another mode on the other side. (In another manner of thinking of the meaning of virtual levels, they have a meaning only in terms of the mode of observation.)

In the light of the expectation that a level may manifest itself by resonance peaks at slightly different energies in different modes of observation, it seems preferable to ascribe the four resonances to level 13, as listed in Table I, for example, rather than to assume two or four different levels for the purpose. It may be that one should go further in this process of amalgamation, for example, combining levels 7 and 8 as was assumed in reference 4, but a decision on this point would involve a study of the plausibility of various assumed level widths and their behavior in the many-level dispersion formula.

One would perhaps expect the failure of a level to manifest itself in a given mode of observation to be a rarer event than it is according to the level assignment scheme of Table I, especially toward the high energy end of the observations. It would be more satisfactory if it could be shown to be plausible that the interference effects are sufficiently effective to disperse the observed resonances as widely as observed among fewer assumed levels. It might even be shown to be plausible to go so far as to attribute the peaks listed for levels 19, 20, and 21 to a single level (that is, to the predominant influence of one level interacting with its neighbors) and similarly, to combine levels 15, 16, 17, and 18 and levels 13 and 14. The spacing of peaks in a single mode of observation precludes going further in this region. Levels 2, 3, and 4 and levels 7 and 8 could perhaps be amalgamated in the lower energy region. This would leave a minimum of thirteen levels in place of the twenty-one listed.

PROTON RANGES AND ENERGY RELEASE OF THE REACTION

Proton ranges are measured to the position of the window of the proportional counter when it was set to record the maximum intensity of large pulses, which we assume to mean that the sensitive volume of the chamber straddles the maximum of the Bragg curve. Part of the path is in the two aluminum windows, and in observations of the long range group additional aluminum absorbers were used in order to keep the counter reasonably near the target for the sake of intensity. The thickness of the absorbing foil material was determined in mg/cm^2 by observing the difference in positions of the counter when set at the peak intensity of scattered protons first with and then without the absorber in place just outside the target-chamber window. The energy of the protons scattered from a silver leaf was known from the bombarding energy and scattering angle. Foil thickness was ascertained from the observed equivalent air path at the same energy by reference to the careful observations of the Wisconsin group[8] both on the range-energy relation in air and on the range-energy relation in Al. Their data and our data in air were reduced to 15°C. Their energies, presumably based on the old determination of the $Li^7(p, \alpha)$ resonance as 440 kev, were transformed to the scale[9] based on 446.5 kev, before plotting range-energy curves from their data, in order to retain consistency with our bombarding energies which are based on the newer scale.

The protons used to measure the thin foil material employed as windows had an energy of 1.454 Mev after scattering, or a range of 4.113 cm before hitting the first window (taken tentatively to have an air-equivalent thickness of 1.135 cm as observed directly for an adjacent energy interval) and an air range of 2.98 cm or energy 1.197 Mev on emerging from the first window and hitting the test absorber in one case or the equivalent air column in the other. The air difference between the two cases was 1.135 cm, which from the air range-energy curve means

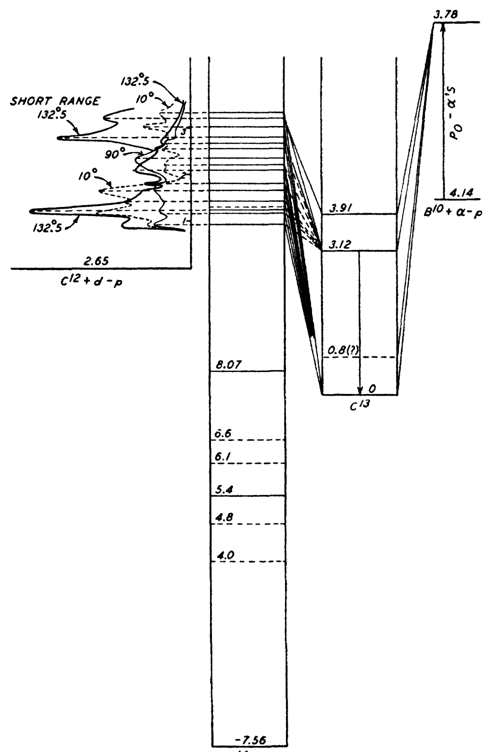

FIG. 5. Energy levels and transitions for the compound nucleus N^{14} and the final nucleus C^{13}.

[8] Parkinson, Herb, Bellamy, and Hudson, Phys. Rev. **52**, 75 (1937).

[9] A. O. Hansen and D. L. Benedick, Phys. Rev. **65**, 33 (1944).

that the protons emerged from the air-equivalent column with 0.891 Mev. The difference in Al ranges between 1.197 Mev and 0.891 Mev gives the Al thickness 0.645 10^{-3} cm, or 1.735 mg/cm^2. The corresponding figures encountered in the determination of the thickness of the thicker Al foil used as absorber are, proton energy after scattering 2.18 Mev, on emerging from window 0.645 10^{-3} cm thick, 1.99 Mev (estimated by slight extrapolation of Wisconsin data), 6.93 cm air range, 4.23 10^{-3} cm Al range; measured thickness of equivalent air column, 4.99 cm, after which air range 1.94 cm, energy 0.91 Mev, Al range 1.27 10^{-3} cm, foil thickness 2.96 10^{-3} cm or 7.98 mg/cm^2 (to be compared with 2.91×10^{-3} cm from weighing and 2.93×10^{-3} cm from micrometer measurement). At the nominal conversion factor suggested by Livingston and Bethe,[10] 1.52 (mg Al/cm^2) per cm air equivalent, this gives an air-equivalent thickness of 5.25 cm, to be compared to 4.99 cm measured directly in a region where the effects of low energy behavior are beginning to be felt. The uncorrected data are included in this discussion and in Table II below because the conversions are subject to revision after more extensive measurements are made of the range-energy relations. (These rather elaborate conversions are applied at a time when the statitron is undergoing alterations and is not available for more direct measurement of the quantities involved.)

The short range protons have energies in the range covered by the range-energy curves based on

TABLE II. Observed air ranges and conversion of foil thickness. $\theta=132.5°$.

Proton group	P_1	P_2	P_3
E_1/Mev	3.0	3.15	3.15
Foils of 7.98 mg/cm^2	4	0	0
Foils of 4.13 mg/cm^2	1	0	0
Al at end of path, mg/cm^2 including counter window, 1.74 and Al equiv. of gas in chamber 0.23	38.04	1.97	1.97
Cm air equiv. of same, at 1.52 (mg/cm^2)/(cm air)	25.01		
Correction from Fig. 34 of reference 8	0.47		
Mev on entering Al, from Wisconsin data		.608	.608
Calc. air equiv. of window+gas, cm, from Wis. data		.93	.93
Actual air path, cm, reduced to 15°C	1.12	1.27	.38
Air equiv. of target-chamber window	1.14	1.14	1.14
Peak of Bragg curve to extrap. mean range	0.20	0.20	0.20
Total air range, cm	27.94	3.54	2.65
E_2/Mev	4.46	1.33	1.11
Q/Mev	2.83	−0.43	−1.19

the Wisconsin data, and these curves are used for determining the energies of both the short range groups, as outlined in Table II. The long range protons fall outside the range of these directly measured range-energy curves, and their energies may be estimated fairly simply by use of the range-energy curve given in reference 10, after converting from Al range to air range by use of the nominal conversion factor 1.52 (mg Al/cm^2) per cm air equivalent and by application of the correction plotted in Fig. 34 of reference 10 for the variation of the air equivalent of Al with residual range. This estimate is, however, doubtful because of the gross disagreement of this curve with the Wisconsin data at low energies. The energy release for the formation of long range protons found in this way is $Q_1=2.83$ Mev as outlined in Table II. Because differences between high energy values of the aluminum-conversion correction, Fig. 34 of reference 10, are probably more reliable than the corrections themselves, we have tried to improve on this estimate by converting the lower energy end (3.65×10^{-3} cm) of the final aluminum path by use of the Wisconsin data, and the higher energy part by Fig. 34 of reference 10. This latter correction must be applied doubly in a case like this, being added for the total aluminum path and subtracted for the end of the part of the aluminum path thus converted, in keeping with footnote 4 of reference 10. This [11] gives for the long range group a range of 27.01 cm. The energy release is $Q_1=2.72$ Mev, which is to be compared with the value 2.71 Mev reported in reference 1. For the two shorter range groups, after averaging over data at two bombarding energies, we find $Q_2=-0.40$ Mev and $Q_3=-1.19$ Mev.

With these Q-values we have indication of excited states of C^{13} at 3.12 and 3.91 Mev. These are to be compared with the excitation energies 3.18 and 3.95 depicted in reference 5, presumably as an average over rather discrepent values from[6] the reaction $B^{10}(\alpha, p)C^{13}$ and from the earlier work[1,12] on the reaction $C^{12}(d, p)C^{13}$. The (d, p) reaction would seem more suitable for determining these excitation energies than the (α, p) reaction with natural alphas because of the better geometry

[10] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 245 (1937).

[11] The same method of converting aluminum path to air path has been used in a redetermination of the Q values for the two proton groups of $O^{16}(d, p)O^{17}$. For the short range group, data taken at five bombarding energies in steps of 0.5 Mev from 1.0 to 3.0 Mev, employing from zero to two aluminum foils 2.92 10^{-3} cm thick, yielded values of $Q_{s.r.}$ varying from 1.01 to 0.98 Mev, averaging 0.99 Mev. For the long range group, with four bombarding energies from 1.5 to 3.0 Mev and with two or three foils, $Q_{l.r.}$ varied from 1.89 to 1.93 Mev, averaging 1.90 Mev. These values are smaller than reported in reference 7, but within the experimental uncertainty there quoted. The best value for the excitation energy of the excited state now seems to be about 0.90 Mev.

[12] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. 154, 261 (1936).

that is practicable with accelerated particles. The present determination would seem more reliable than the earlier determination of the excitation energy of the state corresponding to P_2, which was 3.23±Mev based on $Q_1=2.71$ from reference 8 and $Q_2=0.52$ Mev from reference 1 (obtained by cloud-chamber observations), because our measurements use the same methods of observation and the same apparatus for both proton groups. The accuracy of our determination is limited mainly by the necessity of translating ranges to energies, and by uncertainty in the energy dependence of the air equivalent of Al.

The excited state at roughly 0.8 Mev above the ground state of C^{13}, the existence of which is inferred from observations of Merhaut[6] on the reaction $B^{10}(\alpha, p)C^{13}$, has failed to contribute a proton range in our observations. The oxygen peaks P_1 and P_2 occur at ranges which would correspond to about 0.7- and 1.6-Mev excitation energy, respectively, in C^{13}. In order to investigate the possibility that there is a carbon peak masked by P_1, observations of the relative intensity of P_1 and P_2 were made at a bombarding energy of 2.2 Mev, where this ratio has a minimum for an oxide target, and close agreement (within 7 percent) was obtained with the ratio previously observed in this laboratory,[7] indicating that any carbon peak in this region and at this bombarding energy must be not more than about 1 percent as intense as P_1.

ANGULAR DISTRIBUTION OF THE LONG RANGE PROTONS

In our earlier work on the similar reaction $O^{16}(d, p)O^{17}$ we concentrated on the measurement of angular distributions at reasonably small energy intervals, and from these and a 90° excitation curve could be deduced rough excitation curves at other angles. In the present work on $C^{12}(d, p)C^{13}$ we have studied in more detail the excitation curves at three angles, one forward, one backward, and one at 90°, and from these a rough indication may be obtained, by only three points, of the angular distribution curves at various energies. In either case we are trying to describe an irregular surface in space representing a function of two variables, and it is merely a question of which way we slice it to display the irregularities of the surface. In addition to the three energy cuts shown in Fig. 4, we have observed three angle cuts, that is, three angular distributions of the product protons, as shown in Fig. 6. These angular distributions were observed at the energies 1.67 Mev, which is practically the energy of the sharpest of the peaks in the 10° excitation curve, 2.82 Mev, which is in a region between peaks on the proton excitation curves but at a peak on the 90° neutron excitation curve, and 2.98, which is practically on another sharp peak

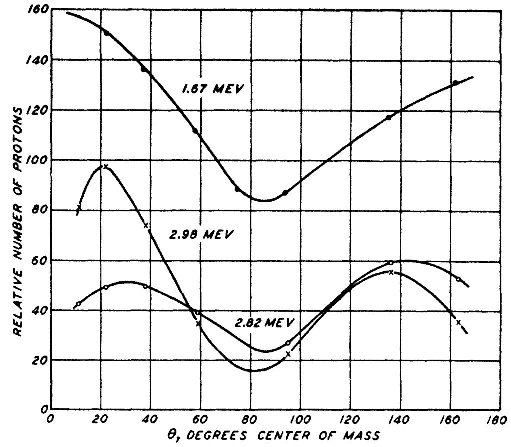

FIG. 6. Angular distributions for the long range proton group P_1 at three bombarding energies.

in the 10° excitation curve. The transformation to the center-of-mass system has been applied both to the relative intensities plotted in the excitation curves of Fig. 4 and to the angular distribution data plotted in Fig. 6.

DISCUSSION OF THE ANGULAR DISTRIBUTIONS

At the energy of the first angular distribution observed, 1.67 Mev, there is a sharp 10° peak, a less pronounced 90° peak, and in the 132.5° curve a weak indication of resonance, partly obliterated by the presence of a much stronger peak at a lower energy. This angular distribution bears semblance to a curve of the form $1+A\cos^2\theta$. This is what one might expect of a resonance with a state of the compound nucleus of odd parity: the target nucleus C^{12} is of course assumed to be even as is also the deuteron and a compound state of odd parity would require the entrance of p, f, . . . deuterons, of which only p deuterons would enter easily at the lower bombarding energies. Entering p deuterons would allow the outgoing protons to have an angular distribution no more complicated than $1+A\cos^2\theta$.

The three proton peaks of level 1 at 0.94 Mev seem to indicate an angular distribution which rises at least slightly on both sides of 90° but which is predominantly backward. This might be a resonance with an odd compound state, requiring p deuterons for its formation, but in the neighborhood of a broad even state (with $j_r=1$) formed by the penetration of s deuterons, so that the interference between the two could give rise to the fore-and-aft asymmetry. Levels 2 and 3 at 1.16 and 1.23 Mev might have angular distributions extremely strongly forward and backward, respectively, in such a way that the strong one obliterates the weak one in Fig. 4. If this is the case, it might be taken as evidence that the aforesaid broad even level is centered in this neighborhood, making the interference terms especially strong here, and it might then also contribute the slight forward emphasis of the angular distribution at 1.67 Mev.

The angular distributions at 2.82 and 2.98 Mev, in the way they bend down at the ends, show indication of the presence of a power of $\cos\theta$ at least as high as the fourth in the angular distribution. This requires the penetration of d or f deuterons, depending on the parity of the compound state, and this is not unexpected at these high bombarding energies. It is thus very satisfactory that the simplest angular distribution should appear at the lowest bombarding energy.

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Low Energy Cross Section of the $D-T$ Reaction and Angular Distribution of the Alpha-Particles Emitted*, **

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The thick-target yield of the reaction

$$T+D\rightarrow\alpha+n+17.6 \text{ Mev}$$

has been measured, using a heavy-ice target, and observations have been made on the angular distribution of the α-particles. Experiments have been conducted in the region 15-kev to 125-kev incident triton energy. Within this range the angular distribution appears to be isotropic in the center-of-gravity system. The cross section for the reaction as a function of energy has been evaluated from the thick-target yield measurements. It appears to rise more rapidly with energy than is required by a simple Gamow function.

INTRODUCTION

THE experiments described in this paper are analogous to the $D-D$ experiments which have been discussed elsewhere,[1] and the reader is referred to this earlier paper for most of the details of apparatus and procedure. Certain modifications have been made necessary by difficulties peculiar to this experiment, *viz.*, (a) the small amounts of tritium available, and (b) the steepness of the excitation function for the reaction, which makes a factor of about $2\cdot 10^4$ between the thick-target yields at the highest and the lowest energies employed. These modifications are described later in the present paper.

Measurements were confined to observations on the α-particles from the nuclear reaction. They have an energy of 3.5 Mev and a range of 2.1 cm for zero bombarding energy. They were detected with the aid of proportional counters, plus amplifying equipment.

The cross section for the reaction has been evaluated in the usual way. If the thick-target yield per unit of beam current at bombarding energy E is denoted by $N(E)$, then one has

$$\sigma(E)=(1/A)\cdot(dN/dE)\cdot(dE/dx),$$

where the constant A contains the product of the number of incident tritons per unit of beam current and the number of deuterium nuclei per cm^3 of the target. dE/dx is the rate of energy loss of the tritons in the target. Some discussion of the energy loss of hydrogen nuclei in D_2O has been presented by us elsewhere.[1,2] Numerical values were arrived at (and presented graphically in reference 1) for dE/dx in D_2O vapor. By suitable adjustment of the constant A, these values can be inserted in the above formula to determine $\sigma(E)$. One finds

$$\sigma(E)=2.38\cdot 10^{-6}\cdot(dN/dE)\cdot(dE/dx) \text{ barn},$$

where $N(E)$ = thick-target yield per microcoulomb of incident tritons,

dN/dE = change of $N(E)$ per kev change of bombarding energy, and

dE/dx = rate of energy loss in kev per cm of tritons in D_2O vapor at 1 mm of pressure, 15°C.

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** Professor H. H. Staub, now at Stanford University, joined in the direction of this research in its later stages. Considerable contributions were also made by M. J. Poole, F. G. P. Seidl, and H. L. Wiser.

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