# The Disintegration of Carbon by Deuterons

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The excitation curves for the emission of $\gamma$-rays, neutrons, and protons from the disintegration of $C^{12}$ by deuterons were investigated. Resonances for $\gamma$-ray emission were found at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. The resonance at 1.43 Mev has a half-width less than 10 kev while the other resonances are considerably broader. Resonances for neutron emission were found at 0.92, 1.16, 1.30, 1.74 and 1.82 Mev. Resonances for proton emission are found at 0.92, 1.16, 1.23 and 1.74 Mev. The $\gamma$-rays from $C^{12}$ were shown to come from the reaction $C^{12}(d, p)C^{13*}$. The short range protons from this reaction were observed and had a range of 1.1 cm. The $Q$ value for this 1.1-cm proton group is $-0.52\pm0.07$ Mev. The excitation curves for the emission of $\gamma$-rays and protons from the disintegration of $C^{13}$ by deuterons were investigated. Both curves showed a resonance at 1.55-Mev deuteron energy. The $\gamma$-rays from $C^{13}$ have an energy of 5.5 Mev and come from the reaction $C^{13}(d, n)N^{14*}$. The low energy group of neutrons from this reaction were found when a 23-percent $C^{13}$ target was used. The $Q$ value for this group of neutrons is 0.40 Mev. The relative and absolute yields of the various reactions were determined.

The protons from the disintegration of carbon by deuterons were observed by Cockcroft and Walton[1] in 1934. When they bombarded carbon with 0.5-Mev deuterons they observed protons with a range of 14 cm which they attributed to the reaction:

$$C^{12}+H^2\rightarrow(N^{14*})\rightarrow C^{13}+H^1+Q_1. \qquad (1)$$

This reaction has been extensively studied since that time and the value of $Q_1$ is now accurately known to be $2.71\pm0.05$ Mev.[2]

Radioactive nitrogen from the bombardment of carbon by deuterons was simultaneously observed by Crane and Lauritsen[3] and by Henderson, Livingston and Lawrence.[4] The production of radioactive nitrogen was attributed to the reaction:

$$C^{12}+H^2\rightarrow(N^{14*})\rightarrow N^{13}+n+Q_2. \qquad (2)$$

Tuve and Hafstad[5] found that the neutrons produced in this reaction were of low energy. Later Bonner and Brubaker[6] obtained an accurate measurement of the range of the recoil protons produced by these neutrons in a cloud chamber. From the range-energy curve for protons which was available at that time a value of $Q_2=-0.37$ Mev was obtained. Later, when a more accurate range-energy curve for protons was obtained from the experiments of Parkinson, Herb, Bellamy and Hudson,[7] a recalculation[7a] from these data gave a value of $Q_2=-0.25\pm0.03$ Mev. Another value of $Q_2$ was obtained by Lewis and Burcham[8] from the observation that the formation of $N^{13}$ begins at 0.32 Mev. This gives a value of $Q_2=-0.28$ Mev which is in good agreement with the value of Bonner and Brubaker.

Bonner and Brubaker also found a neutron group representing about 1 percent of all the neutrons from carbon for which a $Q$ value of 5.2 Mev was determined. They also observed another weak group of neutrons corresponding to a $Q$ value of 1.2 Mev. The production of these two high energy groups of neutrons was attributed to the $C^{13}$ isotope according to reaction:

$$C^{13}+H^2\rightarrow(N^{15*})+N^{14}+n+Q_3. \qquad (3)$$

Gamma-rays from the bombardment of carbon by 0.8-Mev deuterons were first reported by Lauritsen and Crane.[9] From absorption experi-

* Now at Bartol Research Foundation.

[1] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **144**, 704 (1934).

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

[3] H. R. Crane and C. C. Lauritsen, Phys. Rev. **45**, 430 (1934).

[4] M. C. Henderson, M. S. Livingston and E. O. Lawrence, Phys. Rev. **45**, 428 (1934).

[5] M. A. Tuve and L. R. Hafstad, Phys. Rev. **48**, 106 (1935).

[6] T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

[7] D. B. Parkinson, R. G. Herb, J. C. Bellamy and C. M. Hudson, Phys. Rev. **52**, 75 (1937).

[7a] T. W. Bonner, Phys. Rev. **53**, 496 (1938).

[8] E. Bretscher, *Kernphysik* (J. Springer, Berlin, 1937), p. 74.

[9] C. C. Lauritsen and H. R. Crane, Phys. Rev. **45**, 345 (1934).

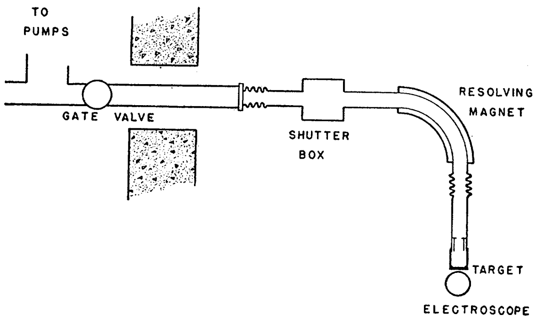


FIG. 1. Diagram of the observational end of the Rice pressure Van de Graaff generator.

ments they estimated that rays of 3.5 Mev were produced. The $\gamma$-rays were later studied by McMillan[10] who carried out absorption measurements in various elements. From these measurements he deduced a $\gamma$-ray energy of 3 Mev. Other experiments on the $\gamma$-rays from carbon bombarded by deuterons were carried out by Tuve and Hafstad.[11] From cloud-chamber studies of the Compton electrons, they obtained evidence for a strong line at about 2.7 Mev and a much weaker one extending up to 4 Mev or higher. It was at first thought that the $\gamma$-rays from carbon might accompany the emission of the 14-cm protons of reaction (1). At this time the mass of $C^{13}$ was considerably in error and the energy of the $\gamma$-ray had to be added to the energy of the 14-cm protons to give a $Q$ value consistent with the isotopic masses. Later, in calculating the masses from disintegration data, Bethe found[12] that a consistent set of masses was obtained only if the $\gamma$-ray energy was not added to the proton energy. When the masses of $C^{12}$ and $C^{13}$ were accurately determined by Bainbridge and Jordan,[13] it was certain that the energy of the 14-cm protons alone gave the proper value of $Q_1$.

The weak $\gamma$-rays of 4 Mev (or higher) were attributed by Bonner and Brubaker to reaction (3) involving $C^{13}$. There is sufficient energy available in this reaction for these $\gamma$-rays to come from an excited $N^{14}$ after the emission of a low energy group of neutrons.

The discovery of a weak group of 48-cm protons from carbon bombarded by 0.8-Mev deuterons was made by Bower and Burcham.[14] The protons come from the reaction:

$$C^{13}+H^2\rightarrow(N^{15*})\rightarrow C^{14}+H^1+Q_4. \qquad (4)$$

This reaction was also independently observed by Pollard[15] at higher bombarding voltage.

Recently we have reported in a *Letter to the Editor* in *The Physical Review* that the excitation curve for the emission of $\gamma$-rays from carbon bombarded by deuterons shows resonances.[16] Resonances were reported at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. Furthermore it was found[17] that the neutrons from reaction (2) showed some of these same resonances; namely, those at 0.92, 1.16, and 1.30 Mev and an additional resonance at 1.80 Mev. Further experiments[18] showed that the 14-cm protons from reaction (1) also showed the resonance at 0.92 Mev. A later Letter[19] gave results on the yield of the high energy protons from $C^{13}$. The present paper is a report of extended results on the yield of the products from carbon bombarded by deuterons.

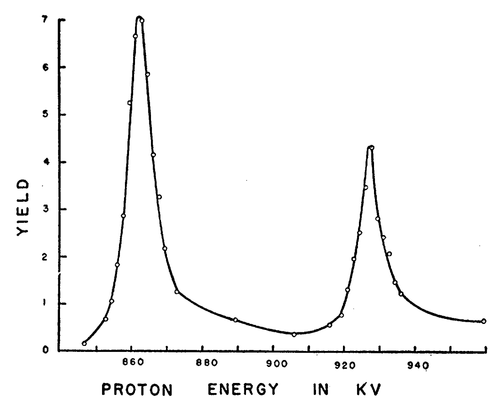


FIG. 2. Gamma-ray resonances from $F^{19}+H^1$ which were used in calibrating the electrostatic voltmeter of the Van de Graaff generator. The observed 8.5-kev half-width is thought to be chiefly experimental and represents the minimum width which could be obtained for other resonances.

[10] E. McMillan, Phys. Rev. **46**, 868 (1934).
[11] M. A. Tuve and L. R. Hafstad, Phys. Rev. **48**, 106 (1935).
[12] H. A. Bethe, Phys. Rev. **47**, 633 (1935).
[13] K. T. Bainbridge and E. B. Jordan, Phys. Rev. **51**, 384 (1937).
[14] J. C. Bower and W. E. Burcham, Proc. Roy. Soc. **A173**, 379 (1939).
[15] E. Pollard, Phys. Rev. **56**, 1168 (1939).
[16] W. E. Bennett and T. W. Bonner, Phys. Rev. **58**, 183 (1940).
[17] T. W. Bonner, E. Hudspeth and W. E. Bennett, Phys. Rev. **58**, 185 (1940).
[18] M. M. Rogers, W. E. Bennett, T. W. Bonner and E. Hudspeth, Phys. Rev. **58**, 186 (1940).
[19] W. E. Bennett, T. W. Bonner, E. Hudspeth and B. E. Watt, Phys. Rev. **58**, 478 (1940).

## Experimental Arrangement

The Rice Institute pressure Van de Graaff machine was used in the experiments on the disintegration of carbon by deuterons. A complete description of the apparatus will be published elsewhere. For a description of the present experiment, it is sufficient to say that the machine is of the same general type as the pressure machine developed by Herb and collaborators[20] at the University of Wisconsin.

A schematic diagram of the observational end of the high voltage apparatus is given in Fig. 1. The ion beam passes through a gate valve after emerging from the accelerating tube. Then the beam passes through a box which contains an electrically operated shutter. After passing through the shutter box the beam is bent through 90° by a large electromagnet, which resolves the beam into different components, corresponding to the different values of $e/m$ for the positive ions. The current then enters a Faraday cage before falling on the target. The ion current on the target is measured by a current integrator of the neon discharge type.[21] The voltage at the high potential center electrode is measured by means of an electrostatic voltmeter. This voltmeter was calibrated by observing the resonances for the emission of $\gamma$-rays from the bombardment of fluorine by protons. The $\gamma$-rays were detected by a Wulf type electroscope filled with argon at a pressure of 70 atmospheres. Figure 2 gives the results that were obtained when a thin target of $CaF_2$ was bombarded with protons. The resonances at 0.862 and 0.927 Mev were used to obtain the value of the constant of the electrostatic voltmeter. The resonances[22] at 0.660 and 1.363 Mev were also observed and each resonance voltage gave very nearly the same voltmeter constant. The subsequent readings of the voltmeter were thought to be reliable to at least 20 kev. In order to stabilize the voltage and to facilitate making small changes in the voltage, a corona current of from 50 to 100 microamperes from the central electrode to an adjustable probe was used. This current passed from the probe to ground through a variable high resistance balanced against the e.m.f. of a battery. Small changes in the voltage could be noted by observing the change in the corona current from the high potential electrode. Over a region of about 0.10 Mev the change of corona current was found to be proportional to the change in voltage, and so could be used to measure the change in voltage.

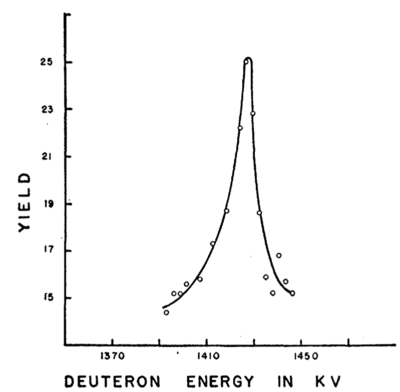


FIG. 3. The $\gamma$-ray resonance at 1.43 Mev obtained by using a carbon target $\frac{1}{3}$ as thick as the thin one used for the excitation curve of reference 16. While this shows that this 10-kev half-width is not due to target thickness, comparison with the half-width obtained in Fig. 2 for the fluorine $\gamma$-ray resonances indicates that this may really be a much narrower excitation level.

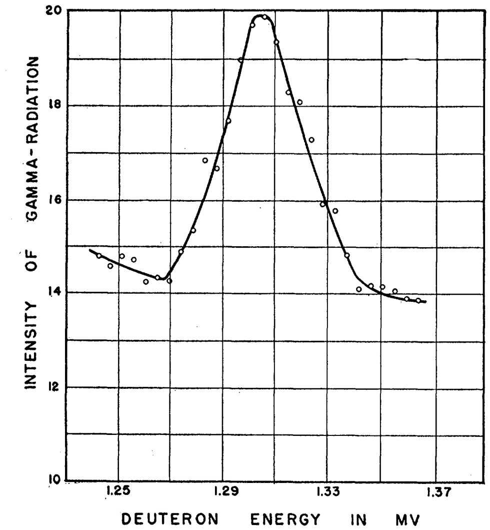


FIG. 4. Sample data of the detailed study which was made of the $\gamma$-ray resonances of the curve of reference 16.

[20] R. G. Herb, D. B. Parkinson and D. W. Kerst, Phys. Rev. **51**, 75 (1937).

[21] B. E. Watt, Rev. Sci. Inst. in press.

[22] E. J. Bernet, R. G. Herb and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

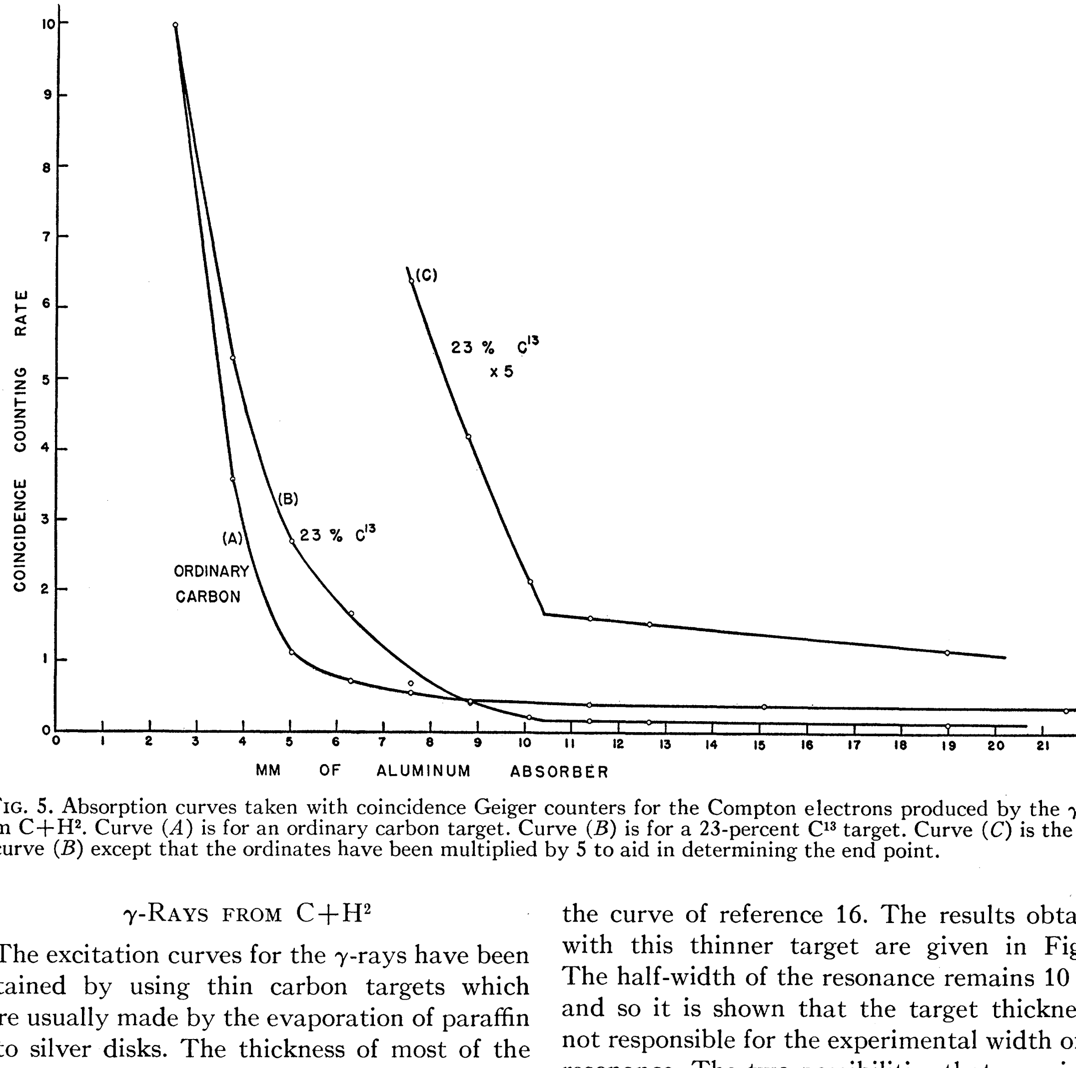


FIG. 5. Absorption curves taken with coincidence Geiger counters for the Compton electrons produced by the $\gamma$-rays from $C+H^2$. Curve (*A*) is for an ordinary carbon target. Curve (*B*) is for a 23-percent $C^{13}$ target. Curve (*C*) is the same as curve (*B*) except that the ordinates have been multiplied by 5 to aid in determining the end point.

## $\gamma$-Rays from $C+H^2$

The excitation curves for the $\gamma$-rays have been obtained by using thin carbon targets which were usually made by the evaporation of paraffin onto silver disks. The thickness of most of the targets was only a few thousand volts. The $\gamma$-rays were detected by means of coincidences of Geiger counters and by measurements with the Wulf type electroscope filled with argon at 70 atmospheres. Since the electroscope gave a greater accuracy for a given time of observation than the counters, it was used in most of the work. Figure 1 of reference 16 gives the excitation curve for the $\gamma$-rays from 0.55 up to 2.0 Mev. This curve shows resonance at 0.92, 1.16, 1.30, 1.43 and 1.74 Mev. The experimental half-widths of the resonances vary from about 0.25 Mev for the resonance at 1.74 Mev to 10 kev for the resonance at 1.43 Mev. The narrow resonance at 1.43 Mev was investigated further by using a target $\frac{1}{5}$ as thick as that used to get the curve of reference 16. The results obtained with this thinner target are given in Fig. 3. The half-width of the resonance remains 10 kev, and so it is shown that the target thickness is not responsible for the experimental width of the resonance. The two possibilities that remain are that the 10-kev width is due to the spread in the energy of the deuterons, or that the real width of the resonance level is 10 kev. Since this is about the same width as we obtained for the resonances from $F+H^1$, we are inclined to think that at least most of the 10-kev experimental width is due to the spread in the energy of the deuterons, and so the real width of the level might be considerably less.

We have studied the excitation curve for $\gamma$-rays in more detail than is shown in reference 16. Figure 4 gives a sample set of such data which were taken in the energy interval 1.24 to 1.36 Mev. This curve shows that the level at 1.30 Mev has a half-width of about 40 kev.

It is difficult to be certain how the $\gamma$-rays originate without information about their energy. Consequently a series of absorption experiments on the $\gamma$-rays were made at each of the resonances. We found that the absorption coefficient in Pb was near the theoretical minimum value and that the $\gamma$-rays from each of the resonances had the same absorption coefficient. We have also measured the energy of the $\gamma$-rays at each of the resonances by determining the range of the Compton electrons produced by the $\gamma$-rays. We used a similar technique to that described in the following paper.[23] Curve ($A$) of Fig. 5 gives the average results of the coincident Geiger-counter measurements on the $\gamma$-rays from an ordinary carbon target. The results for each resonance agreed within the probable error with this average curve. The absorber thickness at which the number of coincident counts falls to half-intensity indicates a $\gamma$-ray energy of roughly 3 Mev, but the actual end point of the curve indicates an energy of about 5.1 Mev. This suggests that there is a strong $\gamma$-ray with an energy of 3.0 Mev and a weak $\gamma$-ray with an energy of 5.1 Mev. Similar results were obtained from a cloud-chamber study of these $\gamma$-rays by Bonner, Becker, Rubin and Streib[24] in Pasadena. When a potential of 1.0 Mev was used they found a $\gamma$-ray with an energy of $3.0\pm0.2$ Mev and another $\gamma$-ray with approximately 5 percent relative intensity near 5.5 Mev. Using separated isotopes they found that the 5.5-Mev $\gamma$-ray comes from $C^{13}$. We have also carried out some experiments with 23-percent $C^{13}$ which has been kindly supplied to us by Professor H. C. Urey. Curve ($B$) of Fig. 5 shows the absorption in aluminum of the secondary electrons produced by the $\gamma$-rays. A thick carbon target was used for this experiment and the bombarding deuterons had an energy of 1.5 Mev. It is apparent from curves ($A$) and ($B$) that the average quantum energy of the $\gamma$-rays is considerably higher for the 23-percent $C^{13}$ target. This confirms the results quoted above that the higher energy component of the $\gamma$-radiation is from $C^{13}$, and the curve gives a more accurate value of

[23] W. E. Bennett, T. W. Bonner and B. E. Watt, Phys. Rev. 59, 793 (1941) (this issue).

[24] T. W. Bonner, R. A. Becker, S. Rubin and J. F. Streib, Phys. Rev. 59, 215A (1941).

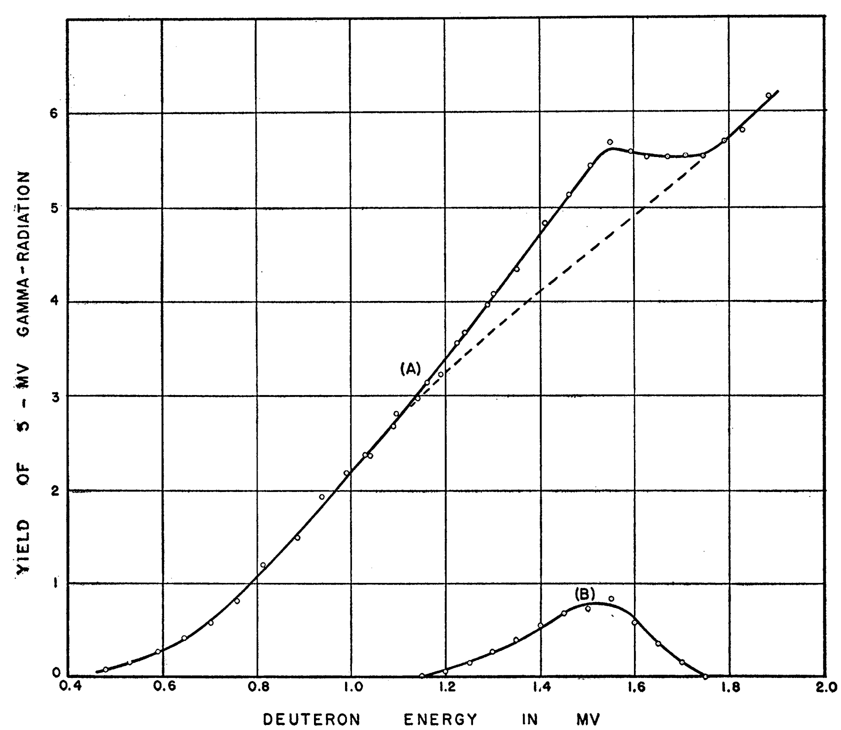


FIG. 6. Excitation curve for the 5.5-Mev gamma-radiation from $C^{13}+H^2$. Curve ($B$) is obtained by subtracting the dotted curve from curve ($A$). Curve ($B$) then represents the shape of a resonance which is superposed upon the general rise in the excitation function.

the maximum range of the Compton electrons than we obtained before. This maximum range is 10.3±0.3 mm of aluminum. From the range-energy relation for such electrons,[23] we find that this corresponds to a quantum energy of 5.5 ±0.2 Mev. This is in good agreement with the cloud-chamber results of Bonner, Becker, Rubin and Streib.[24]

Since the γ-ray excitation curves of Figs. 3, 4, and of reference 16 were obtained using ordinary carbon targets, it is apparent that about 95 percent of the γ-rays recorded there were from the bombardment of $C^{12}$. We have carried out a separate experiment to get the excitation curve for the γ-rays from $C^{13}$. We were able to count γ-rays from $C^{13}$ by using coincident Geiger counters with sufficient absorber between them to prevent 3-Mev rays from producing coincident counts. A target of 2-percent $C^{13}$ was used in these experiments. It was prepared by one of us (B.E.W.) from methane in which $C^{13}$ had been concentrated by thermal diffusion. Its thickness was found to be about 30 kev from

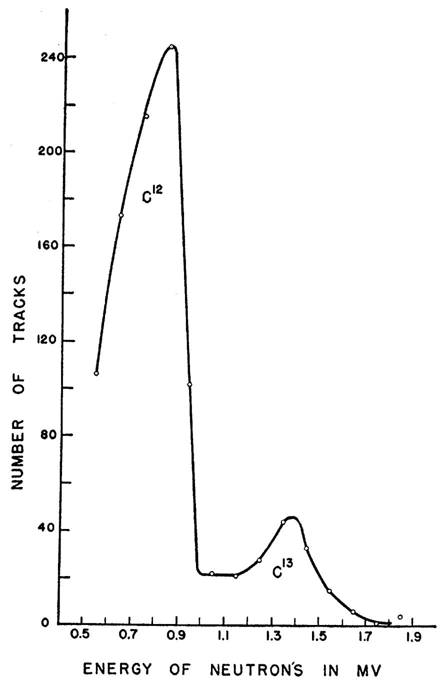


FIG. 7. Energy distribution of the neutrons from $C+H^2$ as inferred from recoil protons in a methane-filled cloud chamber. A target containing 23-percent $C^{13}$ was bombarded with 1.4-Mev deuterons.

the observation that the resonance at 1.43 Mev showed a width of 30 kev. Figure 6 shows the excitation curve for γ-rays with an energy of 5.5 Mev. The curve is smooth except for a resonance at 1.55 Mev which will be discussed in detail later in this paper.

Since it seemed possible that the 1.43-Mev resonance for γ-rays was of a different character from the other broader levels, we thought that the γ-rays from that level might have a different quantum energy. We carefully searched for a sharp resonance in the yield of high energy γ-rays at 1.43 Mev but found no effect. To further investigate the energy of the γ-rays from the 1.43-Mev resonance, we put sufficient absorber between two coincidence counters to prevent 2.5-Mev γ-rays from producing coincident counts. We then investigated the resonance at 1.43 Mev and obtained the same resonance curve as before. This showed that the γ-rays from the 1.43-Mev resonance have an energy greater than 2.5 Mev and the previous experiment had already shown that the γ-rays from the resonance were less than 4 Mev. All these results indicated that the radiation from the 1.43-Mev level is from $C^{12}$ and that the γ-rays have the same energy as those from the other broader levels.

The intensity of the γ-rays from a thick graphite target was compared with that obtained from the bombardment under similar conditions of a thick crystal of $CaF_2$ by 1.5-Mev protons. The γ-rays from $C+H^2$ were found to be 3.0 times as intense as those from $CaF_2$ when an electroscope shielded by one cm of iron was

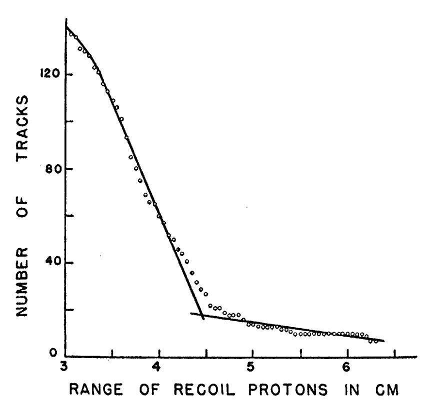


FIG. 8. Integral range curve for recoil protons from the neutrons of $C^{13}+H^2$, (Fig. 7).

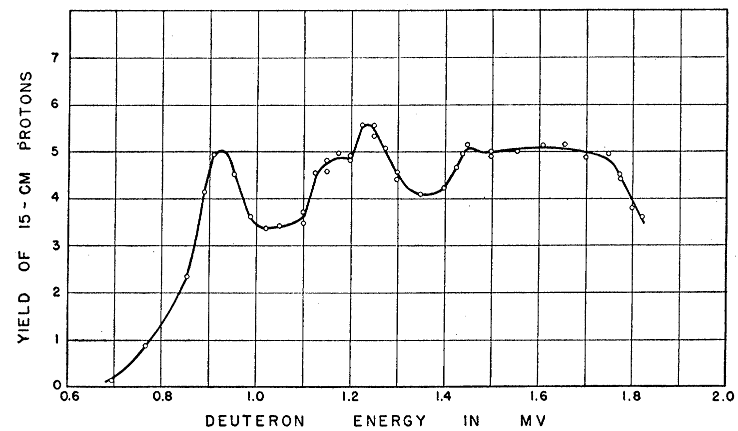


FIG. 9. Excitation curve for the 15-cm protons from $C^{12}+H^2$.

used to detect the $\gamma$-rays. The absolute yield of the $\gamma$-rays from carbon was determined at 1.0 Mev by the use of a Geiger counter, assuming that it counted $\gamma$-rays with an efficiency of two percent. For 1.0-Mev deuterons the yield of $\gamma$-rays from carbon was $17\times10^6$ quanta per micro-coulomb of deuterons. This shows that the $\gamma$-rays have about 4 times the intensity of those from $CaF_2+H^1$ at this same bombarding voltage.

### THE NEUTRONS FROM $C+H^2$

We have investigated the excitation curve for the neutrons from carbon bombarded by deuterons. To detect the neutrons we have used a Wulf type electroscope filled with hydrogen at a pressure of 7 atmospheres. We have also studied the radioactive $N^{13}$ which is formed whenever a neutron is emitted according to reaction (2). The electroscope was placed in the forward direction to the incident deuteron beam and it gave, therefore, the excitation curve for neutrons in the forward direction. The amount of radioactive $N^{13}$ formed in a thin paraffin target was measured by means of a thin-walled Geiger counter placed outside a thin window on the target tube. The procedure was to bombard the target for ten minutes, then shut off the high voltage and follow the activity of the target. The half-life of the $N^{13}$ activity was found to be ten minutes in agreement with the known half-life of 9.93 minutes.[25]

Figure 1 of reference 17 shows the excitation curves obtained from the ionization currents in hydrogen and from the radioactivity of the $N^{13}$. Since some of the ionization in hydrogen is due to $\gamma$-rays, a correction had to be made to compensate for this effect. By using a radium source filtered by 1.0 cm of lead, we found that the $\gamma$-ray intensity measured by the electroscope filled with hydrogen was only 4.75 percent that of the argon-filled electroscope which was used in the $\gamma$-ray experiments. The total intensity from a carbon target bombarded by 1.525-Mev deuterons was measured by using the electroscope filled with argon and then with hydrogen. From the ratio of the two ionization effects it was possible to calculate that the $\gamma$-rays were responsible for 19 percent of the ionization in hydrogen at 1.525 Mev. A corresponding correction was made at all other voltages. Curve (3) gives this corrected ionization due to the neutrons alone. Both curves (1) and (3) show resonances at 0.92, 1.16 and 1.30 Mev. These are the same resonances as those found for the emission of $\gamma$-rays. However the $\gamma$-ray resonance at 1.43 Mev does not show up as a resonance for neutron emission. Above 1.43 Mev the hydrogen ionization data show a resonance at 1.74 Mev and 1.82 Mev. The resonance at 1.74 Mev partially disappears after the $\gamma$-ray correction is made, and it is uncertain whether the resonance at 1.74 Mev is truly a resonance for neutron emission.

Although curves (1) and (3) of reference 17 agree in showing the same resonances, the relative heights of the resonances are different. The differences might be explained by supposing that

[25] A. G. Ward, Proc. Camb. Phil. Soc. **35**, 523 (1939).

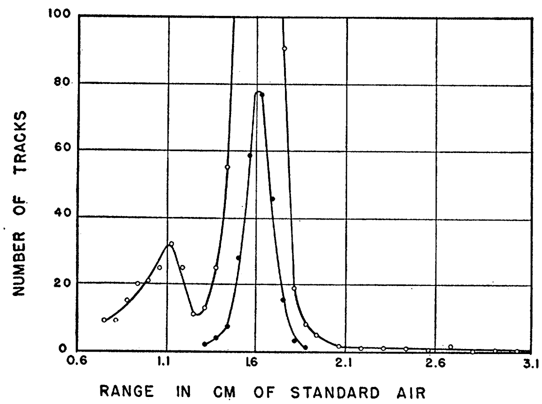


FIG. 10. Short range (1.1 cm) protons from $C^{12}+H^2$. The intense group of particles at 1.6 cm are deuterons from the incident beam which have been scattered at 90° into the cloud chamber. The closed circles have ordinates 6 times the value shown on the graph.

neutrons from the different excited levels of the intermediate nucleus have different angular distributions; whereas curve (1) gives the total yield of $N^{13}$ (and neutrons), curve (3) gives the yield of neutrons only in the forward direction. Experiments to study these angular distributions would be of interest.

Since it seemed likely that the 5.5-Mev $\gamma$-rays from $C^{13}$ were produced in reaction (3), we looked for low energy neutrons when a thick target of 23-percent $C^{13}$ was bombarded by 1.4-Mev deuterons. The neutron energies were measured by the method of finding the energy distribution of the recoil protons photographed in a cloud chamber containing methane. The neutrons were observed at an angle of $90\pm10°$ to the direction to the deuteron beam. Two thousand stereoscopic photographs were taken on which there were numerous recoil protons. One thousand and ten of these protons were in the forward direction (0–10°) and their track lengths were measured. The energy distribution of these recoil protons is given in the curve of Fig. 7. The group of neutrons at 0.9 Mev is the group from reaction (2) which was previously measured by Bonner and Brubaker. The $Q$ value obtained in the present experiment was $-0.19\pm0.05$ Mev. This agrees with the value of $Q_2=-0.25$ Mev which was obtained by Bonner and Brubaker. The group of neutrons at 1.5 Mev was not observed by Bonner and Brubaker in their original experiments. For this reason and because of energy considerations this group must be from $C^{13}$. An accurate calculation of the $Q$ value for this group of neutrons was calculated by the method of Livingston and Bethe.[26] The integral number *vs.* range curve of the recoil protons is given in Fig. 8. The extrapolated range of the recoil protons is $4.4\pm0.2$ cm of standard air. The energy of the neutrons coming from the surface of the target at 90° to the incident beam was found to be $1.49\pm0.03$ Mev. The disintegration $Q$ value was then calculated from the relation $Q_3^*=(15/14)E_n-(6/7)E_D$. $Q_3^*$ was found to be $0.40\pm0.05$ Mev. The best value of the energy evolved in reaction (3), when the products are left unexcited, is that calculated from the masses of the atoms concerned and these give $Q_3=5.5\pm0.2$ Mev. The neutron group at 1.5 Mev must then leave the $N^{14}$ nucleus in an excited state at $5.1\pm0.3$ Mev. This excited $N^{14}$ nucleus would give a $\gamma$-ray of this energy when it returns directly to the ground state. This group of neutrons from $C^{13}$ then seems to explain the $5.5\pm0.2$ Mev $\gamma$-rays which are also produced in the disintegration of $C^{13}$.

## PROTONS FROM $C+H^2$

Since the $\gamma$-rays and neutrons from the bombardment of carbon by deuterons show many of the same resonances, we might expect the 15-cm protons from reaction (1) also to show the same resonances. These resonances correspond to excited states in the intermediate $N^{14*}$ nucleus, and we might expect the emission of neutrons, protons and $\gamma$-rays to be competing processes.

The excitation curve for the emission of 15-cm protons was studied with an ionization chamber 2.5 cm in depth connected to a linear amplifier. Such a deep chamber was used so that the protons would give large pulses and would be counted far from the end of their range. This was useful because the range of the protons from reaction (1) changes with bombarding energy. As an additional precaution to insure the counting of all protons, absorbers were added as the bombarding voltage was increased so that the protons were always counted at the same distance from the end of their range. Figure 9

[26] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 281 (1937).

gives the excitation curve for the 15-cm protons from reaction (1). The curve shows the resonances at 0.92 Mev and 1.16 Mev that were found in the emission of $\gamma$-rays and neutrons. The proton curve shows a resonance at 1.23 Mev which did not appear for $\gamma$-rays or neutrons. The resonance at 1.30 Mev which was shown by both neutrons and $\gamma$-rays appears to be missing in the proton excitation curve. Above 1.35 Mev the proton curve shows a rise of about 25 percent and then stays nearly horizontal up to 1.7 Mev, where it begins to decrease rapidly.

The relative yield of 15-cm protons and neutrons at 0.92-Mev bombarding energy was obtained by counting the number of $N^{13}$ atoms formed and comparing it with the number of protons from the same thin target. At 90° to the bombarding direction, the ratio of protons to positrons from $N^{13}$ is 1.9. The number of $\gamma$-rays in comparison to the number of protons was also obtained at 1.60 Mev. The number of counts produced by $\gamma$-rays in a single Geiger counter was obtained at the same time that the 15-cm protons were counted by the linear amplifier. After allowing for the differing solid angles and for the efficiency of the Geiger counter for counting 3-Mev $\gamma$-rays (2 percent), we obtained 1.0 as the ratio of the number of $\gamma$-rays to the number of protons. This shows that all three processes, the emission of neutrons, of 15-cm protons, and of 3.0-Mev $\gamma$-rays are about equally probable.

The apparent explanation of the 3-Mev $\gamma$-rays from $C^{12}$ is that they come from a $C^{13}$ nucleus which is left excited to 3 Mev after the emission of a short range proton group. Consequently, we have looked for such a group of protons. The $Q$ value for this group of protons should be equal to $Q_1-E_\gamma$ which is numerically equal to $2.71-3.0=-0.29\pm0.25$ Mev. Since the expected proton group would have a range less than that of the scattered deuterons, we used an experimental arrangement which could detect particles with shorter ranges than the scattered deuterons. The deuteron beam was allowed to pass through an aluminum foil with a stopping power of 6.5 mm of air into a gas target chamber which was filled with methane at a pressure of 2.5 cm. The protons and scattered deuterons were observed in a cloud-chamber at an angle of 90° to the direction of the deuteron beam. The disintegration particles entered the cloud chamber through a Nu-Skin foil which had a measured stopping power of 1.3 mm of air. The cloud chamber was operated at a pressure, when expanded, of 0.5 atmosphere of helium and water vapor. The high voltage apparatus was adjusted to give a beam of 1.7-Mev deuterons during this experiment, and the deuterons, after passing through the aluminum foil and 3.9 cm of methane, had an energy of 1.47 Mev at the center of the gaseous target. The part of the gaseous target from which it was possible to get disintegration particles entering the cloud chamber was 1 cm deep in the direction of the deuteron beam; thus the $CH_4$ target had a thickness equivalent to approximately 0.03 cm of air.

At this bombarding voltage we obtained about one track per expansion coming from the gaseous target. The scattered deuterons had an actual track length of 10.2 cm in the cloud chamber. We took a total of 4000 cloud-chamber pictures with this experimental arrangement and on these photographs we measured 2030 tracks. The length of the tracks in helium was converted to range in standard air by taking the stopping power of He equal to 0.20. To the range in the cloud chamber was added 0.39 cm, which was the air equivalent of the Nu-Skin foil and the thickness of methane absorber between the deuteron beam and the foil. The resulting range distribution of the tracks in terms of standard air is given in Fig. 10. The 15-cm protons from $C^{12}$ were observed in the cloud chamber, but

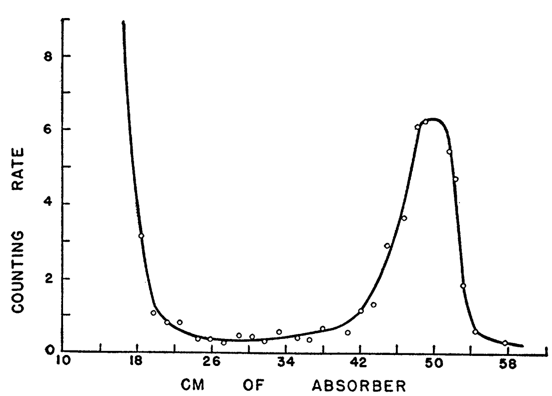


FIG. 11. Long range protons from a 23-percent $C^{13}$ target bombarded by 1.00-Mev deuterons. The rise at 18-cm range is from the long range (15 cm) protons from $C^{12}+H^2$.

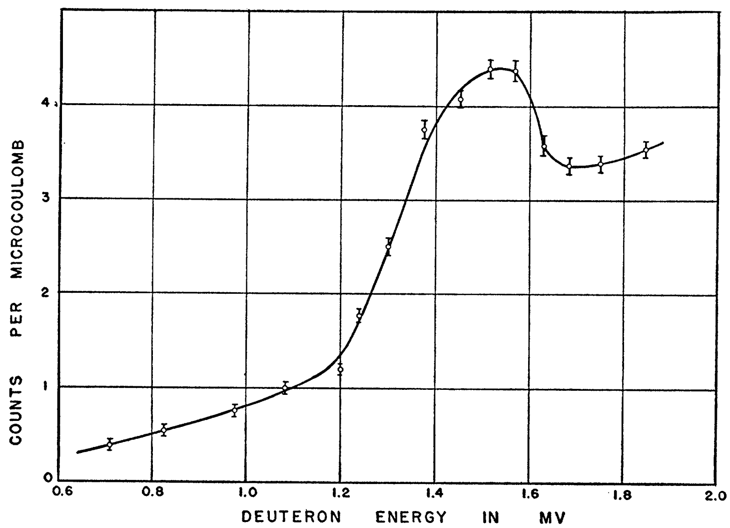


FIG. 12. The excitation curve for the long range (50 cm) protons from $C^{13}+H^2$.

these went entirely across the chamber, so they are not indicated on the curve of Fig. 10. The group of particles with a range of 1.61 cm are the scattered deuterons. The expected range of the scattered deuterons was computed using the 1938 Cornell range-energy relation and was found to be 1.50 cm which agrees to within 7 percent with the experimental range of this group. The group of scattered deuterons appears to be symmetrical and has a half-width of 0.18 cm of standard air. Besides the strong group of scattered deuterons there is a weaker group of particles with a range of 1.10±0.10 cm. The ratio of the number of 1.1-cm particles to the number of 15-cm protons was found to be 0.44. Since we previously found that the number of $\gamma$-rays was 1.0 times the number of 15-cm protons, we should have expected that there would have been 1.0 times as many short range protons as 15-cm protons, if the short range proton groups had a spherical angular distribution. The fact that the experimental ratio is 0.44 indicated that the number of short range protons must be a factor of 2 to 3 greater in the forward direction. Another possible explanation of the 1.1-cm group is that it arises from a small amount of molecular hydrogen ions in the beam of mass 2. We found that our ratio of current in the mass 2 beam was usually about 2 to 3 times as large as the current in the mass 4 beam. We also had 7 percent as many protons (mass 1 beam) as deuterons (mass 2). Consequently we would expect that about 1 percent or less of the mass 2 beam was composed of molecular hydrogen atoms each of which had half the bombarding energy. The energy of these molecular hydrogen ions at the scattering target was calculated, and the range of these scattered protons was computed to be 0.70 cm of air. This eliminates the possibility that the group at 1.10 cm could be caused by scattered molecular hydrogen ions.

The $Q$ value corresponding to this 1.10-cm group of protons was calculated from the relation: $Q_1^* = (14/13)E_H - (11/13)E_D$ and a value of $-0.52\pm0.07$ Mev was obtained. From these data the energy of the $\gamma$-ray should be $2.71+0.53 = 3.24\pm0.08$ Mev which agrees with the experimental value of 3.0±0.2 Mev. Since each low energy proton is accompanied by a quantum of $\gamma$-radiation, the excitation curve for the production of low energy protons is the same as for the 3-Mev $\gamma$-rays (reference 16).

It is interesting to note that the ratio of disintegration protons from carbon to the number of scattered deuterons was 0.37, which indicates that at this angle a disintegration is nearly as probable as an elastic scattering.

We have also investigated the protons that come from $C^{13}$ according to reaction (4). In order to be able to count weak groups of particles in the presence of neutrons we have used a deep ionization chamber (2.5 cm) connected to a linear amplifier. When the bias is set so that only the largest pulses are counted, the background due to neutron recoils is found to be very small. We bombarded a thick target of 23-percent $C^{13}$ with 1.00-Mev deuterons and obtained the curve shown in Fig. 11. The group of protons from $C^{13}$ has an extrapolated range of $53.7\pm2.6$ cm. The value of $Q_4$ was found from this value of the extrapolated range to be $6.09\pm0.2$ Mev. This agrees with the value of $Q_4$ calculated from the masses which is $6.13\pm0.19$ Mev.

No other group of particles from $C^{13}$ was obtained with ranges greater than 20 cm although a group with an intensity of $\frac{1}{10}$ that of the 50-cm group could have been detected. We also looked for protons from $C^{13}$ below the 15-cm group of protons from $C^{12}$. No groups were observed, but only groups considerably more intense than the 50-cm group could have been detected in this region. The experiment indicates that there are probably no excitation levels in $C^{14}$ below 2.8 Mev. The 3-cm group of alpha-particles from carbon was observed both with an ordinary carbon target and with a 23-percent $C^{13}$ target. Since the number of alpha-particles was much greater from the $C^{13}$ target this definitely shows that this group had been properly attributed[27] to the reaction:

$$C^{13}+H^2\rightarrow(N^{15*})\rightarrow{}_5B^{11}+{}_2He^4+Q_5. \quad (5)$$

The ratio of the intensity of the 50-cm group of protons to the 15-cm protons from $C^{12}$ was determined with a target in which the $C^{13}$ had been concentrated. With this target and 1.22-Mev deuterons, the ratio of the intensity of the 55-cm group to the intensity of the 15-cm group of protons was 0.11 percent. A target in which the $C^{13}$ was depleted by approximately the same factor was then bombarded and the ratio was only 0.029 percent. This showed that the $C^{13}$ had been concentrated in the first target relative to the second by a factor of 3.8, whereas the separation factor had been calculated from the dimensions of the thermal diffusion apparatus as 3.7. The average of these two ratios (0.07 percent) is consequently the ratio of the yields from ordinary carbon at 1.22-Mev bombarding energy. This ratio would vary considerably with different bombarding voltages since the yields for both groups of protons show resonances.

[27] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **A154**, 261 (1936).

The excitation curve has also been obtained for the 50-cm protons. A target of 2-percent $C^{13}$ prepared from methane and with a thickness of 30 kev was used in this experiment. The deep ionization chamber was again used to count protons, and the bias on the recording circuit was made low enough to count all protons passing through the ionization chamber. Absorbers were also added as the bombarding voltage was increased to insure that the protons were always counted at the same distance from the end of their range. The excitation curve is given in Fig. 12. The indicated error is the statistical error increased by a factor of two, since it was necessary to make observations in two separate runs, which were joined at 1.45 Mev. The curve shows a maximum at 1.52 Mev. This may be interpreted as a resonance in the yield which would indicate an excited state in the intermediate nucleus ($N^{15*}$) at 17.5 Mev.

## Discussion of the Results

### $C^{12}$

The sharp resonances obtained from the disintegration of $C^{12}$ by deuterons are surprising because of the fact that the intermediate nucleus ($N^{14}$) is excited to 11 Mev and might be expected to emit a neutron or a proton in such a short time that the level in $N^{14*}$ would be wide. The width of the level is given by the uncertainty relation $\Delta E\Delta T\approx\hbar$. The level at 1.30 Mev had a width of 40 kev and consequently the intermediate $N^{14*}$ nucleus must exist for a time

$$\Delta T=\frac{1.04\times10^{-27}}{1.60\times10^{-6}\times0.040}=1.6\times10^{-20}\text{ sec.}$$

This shows that it takes more than $1.6\times10^{-20}$ sec. to emit a neutron with an energy of 0.8 Mev from the excited $N^{14*}$ nucleus. The lifetime of the intermediate $N^{14*}$ nucleus can be estimated from the relation

$$\Delta T=R/v,$$

where $v$ is the velocity of the neutron in the $N^{14*}$ and $R$ is the nuclear radius. If we take $R=4\times10^{13}$ cm and a neutron velocity of 1/20 that of light, we get a value of $\Delta E=1.2$ Mev. This is more than 30 times the observed width and so it may be necessary to invoke a selection rule to explain this result. The emission of neutrons and 15-cm protons from the 1.43-Mev resonance level in $N^{14*}$ must have a strong selection rule forbidding such modes of disintegration.

The experiments with $C^{12}$ show what the three modes of disintegration, the emission of (1) a neutron, (2) a 15-cm proton, and (3) a short range proton, are all about equally probable from the levels in $N^{14*}$ corresponding to the resonances at 0.92 and 1.16 Mev. However the 15-cm protons show a resonance at 1.23 Mev which is not shown by either of the two competing processes. It seems possible, however, that this level may be the same as that shown for neutron and $\gamma$-ray emission at 1.30 Mev. A shift in the position of the maximum of 0.07 Mev might be produced through a different interference with the background, or it might be caused by the theoretical considerations discussed by Breit.[28]

The 15-cm proton group seems to show the resonance at 1.74 Mev as shown by the sharp decrease in the curve above 1.74 Mev, and another broad resonance at from 1.5 to 1.6 Mev. A broad resonance in this region is probably needed to explain the plateau which is experimentally observed from 1.45 to 1.75 Mev.

## $C^{13}$

In the disintegration of $C^{13}$ by deuterons the competing processes are reaction (3), (4) and reaction (5). Unlike the case of $C^{12}$ the three competing processes for $C^{13}$ have very unequal probability. The 5.5-Mev $\gamma$-rays (consequently 1.5-Mev neutrons) are approximately 70 times as numerous as are the 50-cm protons. The alpha-particles from reaction (5) were found to be roughly 50 times as probable as the 50-cm protons. Thus it seems that the emission of low energy neutrons and alpha-particles from $C^{13}$ are about equally probable but that the emission of 50-cm protons is very unlikely.

The excitation curves for 5.5-Mev $\gamma$-rays and 50-cm protons both show the same resonance at 1.55-Mev bombarding voltage. This indicates that an excited state in the intermediate ($N^{15*}$) nucleus at 17.5 Mev may break up either into low energy neutrons or 50-cm protons. It is surprising that an isolated resonance at this high excitation of the intermediate $N^{15}$ nucleus is observed.

The principal difference in the excitation curves for 50-cm protons and 5-Mev $\gamma$-rays is that the emission of $\gamma$-rays appears to come mainly from a continuum, while the emission of 50-cm protons comes mainly from the resonance at 1.55 Mev. The fact that very few of the 50-cm protons come from the continuum may explain why this reaction is so much more improbable than the emission of 5-Mev $\gamma$-rays.

The width of the level in the $N^{15*}$ at 17.5 Mev may be calculated as was done for the level in $N^{14*}$ by the relation $\Delta E \Delta T \approx \hbar$ and $\Delta T = R/v$. The width of this level is fixed by the neutron emission which is the most probable reaction. A calculation gives the value of $\Delta E = 1.7$ Mev for the width of this level. It may not be necessary to invoke the use of selection rules forbidding disintegration into neutrons and protons from this level to explain the experimental half-width of this level as 0.25 Mev. It is reasonable that the actual width of the level is smaller than the estimated width because the estimate does not take into account the internal rearrangements necessary for concentrating the necessary energy on either a neutron or a proton.

It would be interesting to determine the excitation curve for the alpha-particles to see if they show the same resonance at 1.55-Mev bombarding energy since they come from the same $N^{15*}$ nucleus.

[28] G. Breit, Phys. Rev. **58**, 1068 (1940).