of the rate of lowering of the Fermi level. When this level has reached the halfway point, the conduction process is intrinsic. Now, however, before appreciable hole conductivity can occur, the Fermi level must be lowered still further to very near the top of the filled band. When this happens all the electrons must be in traps or acceptors near the top of the filled band. From the time at which hole conductivity shows up, about four hours in Fig. 2, one concludes that the rate of formation of this last group of levels is at least 19 per alpha-particle. This is twice the initial value for hole production. One can explain the latter fact several ways. Each alpha-particle produces 19 acceptor levels but they are so far above the filled band that only half of them are ionized to give holes at room temperature could be one explanation. The other possible explanations would involve a combination of electrons traps and acceptors near the top of the filled band or a combination of acceptors and hole traps or some combination of all three. The important point is that the p-type conductivity due to alpha-particle bombardment is not the simple case of the formation of acceptor levels each producing a conduction hole at room temperature.

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The High Energy Neutrons from the Disintegration of C^{13} by Deuterons*

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An excitation curve for the 5-Mev neutrons resulting from C^{13} bombarded by deuterons has been obtained for neutrons emitted at $0°\pm 28°$ to the direction of the deuteron beam. The curve covers deuteron energies from 200 kev to 2.1 Mev. Resonances in the yield were observed at deuteron energies of 0.6, 0.9, 1.55, and 1.80 Mev with half-widths of 0.1, 0.4, 0.1, and 0.5 Mev respectively. These correspond to excited states in the intermediate N^{15} nucleus of 16.7, 16.9, 17.47, and 17.69 Mev.

I. INTRODUCTION

TWO groups of neutrons from the disintegration of carbon by deuterons were observed by Bonner and Brubaker[1] in 1936 and were attributed to the reaction:

$$C^{13}+H^2\rightarrow(N^{15*})\rightarrow N^{14}+n^1+Q_1. \quad (1)$$

By means of cloud-chamber measurements, they observed Q-values of 1.2 and 5.2±0.4 Mev respectively for the two groups.

As natural carbon contains 99 percent C^{12} and only one percent of the C^{13} isotope, one would expect the relative intensity of neutrons from C^{13} to be very weak when a natural carbon target is bombarded by deuterons. Using such a target and a methane-filled cloud chamber, they observed the relative intensities of the 5.2- and 1.2-Mev groups from C^{13} and the −0.281 ±0.003-Mev group[2] from C^{12} to be 1, 3, and 300 respectively.

In order to explain the 5-Mev gamma-rays from the disintegration of carbon by deuterons, Bennett, Bonner, Hudspeth, Richards, and Watt[3] looked for a third group of neutrons from reaction (1). They obtained a target which was enriched to 23 percent of C^{13} and found a low-energy group of neutrons with a Q-value of 0.4 ±0.05 Mev.

A weak group of 50-cm protons from carbon was observed by Bower and Burcham,[4] and independently by Pollard.[5] These protons result from the reaction:

$$C^{13}+H^2\rightarrow(N^{15*})\rightarrow C^{14}+H^1+Q_2. \quad (2)$$

Bennett and Bonner[3] bombarded a target containing 23 percent of C^{13} with 1.00-Mev deuterons and found the Q value of this group of protons to be 6.09±0.2 Mev. Using a target enriched to two percent C^{13}, they obtained an excitation curve for these protons with the counter placed at 90° to the direction of the deuteron beam. The curve showed a maximum at a deuteron energy of 1.55 Mev which may be interpreted as a resonance in the yield. This would indicate an excited state in the intermediate N^{15} nucleus at 17.47 Mev.

This group of workers also studied the 5-Mev gamma-rays and obtained an excitation curve for

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deuteron energies from 450 kev to 1.9 Mev. A two percent C^{13} target was used which was 30-kev thick. Coïncident Geiger-counter measurements were taken with an arrangement such that gamma-rays of energies below 3 Mev would not produce a coincident count. The excitation curve was rising steadily up to a deuteron energy of 1.55 Mev. At that point a resonance was observed where the curve remained flat and started rising again at 1.75 Mev.

Humphries and Watson[6] bombarded enriched C^{13} targets with 3.82 Mev deuterons and observed two groups of protons with Q values of 0.58 and 5.82 Mev, respectively. Thus the 5-Mev gamma-rays can be explained by either of the above reactions.

The object of the present experiment was to study the high energy group of neutrons from reaction (1) using a carbon target containing 48 percent C^{13}. It was thought to be practicable to detect this group of neutrons by use of a counter filled with 20 atmospheres of helium and five percent argon, if the discriminator was biased to record only large pulses.

II. APPARATUS

The Rice Institute pressure Van de Graaff generator was used to accelerate the deuterons. The magnetic analyzer,[7] used with an electron gun stabilizer,[8] gave an energy spread of the order of one kev when the bombarding energy was one Mev. The magnetic analyzer, calibrated by gamma-ray resonances in $F^{19}+p$ and $C^{12}+d$, allowed absolute energies to be known to better than 5 kev.

The targets were prepared from enriched methyl iodide which was purchased from the Eastman Kodak Company of Rochester, New York. A complete description of the method used in preparing the targets will be published elsewhere. It consists essentially by cracking carbon from the methyl iodide vapor onto nickel disks. The targets are estimated to be about 20-kev thick for 1.4-Mev deuterons and contain 52 percent C^{12} and 48 percent of the C^{13} isotope. This thickness corresponds to 60 micrograms of carbon per cm^2.

The counter used for deuteron energies above 350 kev was a cylindrical proportional counter with a 5-mil tungsten wire. The inner diameter of the counter was 2 inches and the sensitive length of the counter was also 2 inches. It was filled with 19 atmospheres of helium and one atmosphere of argon and was operated at 4000 volts with 5000 volt regulated power supply. Pulses from the counter were amplified by a linear amplifier and were recorded by a scale of 64. Calculations and experimental determinations show the counter to have an efficiency of the order of 0.3 percent for 5-Mev neutrons.

A "long counter" filled with enriched boron trifluoride was used as the neutron detector for deuteron energies between 200 kev and 450 kev. The counter was constructed after that built by Hanson and McKibben.[9] The pulses from this counter were amplified and detected by the same equipment as was used with the helium counter. Its efficiency, as determined by a standard Po-Be source, was 0.1 percent.

III. EXPERIMENTAL RESULTS

The enriched C^{13} targets were bombarded with homogeneous beams of deuterons of energies ranging from 200 kev to 2.09 Mev. The helium counter was placed at $0°(\pm 28°)$ to the direction of the deuteron beam. The sensitive volume of the counter subtended a solid angle of 0.98 steradians to the target.

Helium nuclei recoiling from neutrons entering the counter were counted if the neutron energy was greater than 3 Mev. This value was determined by the bias setting of a discriminator unit which was a part of the scale of 64. Only the high energy group of neutrons from reaction (1) should be counted. The maximum range in the counter of the highest energy neutrons detected was slightly greater than one-tenth of the counter diameter. Thus there should be little trouble from wall effects.

For data taken between 200- and 450-kev bombarding deuteron energy, the "long counter" was placed as close to the target as was possible and subtended a solid angle of 2π-steradians to the target. As this counter would count low energy as well as high energy neutrons, cans containing water saturated with borax were used to form a wall between the counter and the magnetic analyzer. This served to minimize background counts.

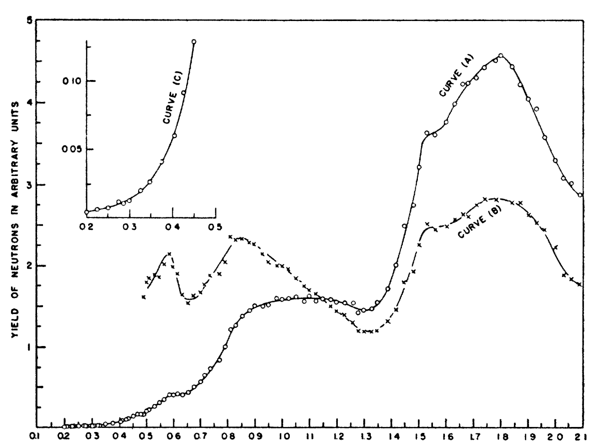

FIG. 1. Curve (A) is the yield of the high energy neutrons observed at $0°\pm 28°$ from the reaction $C^{13}(d,n)N^{14}$. Curve (B) is curve (A) divided by the penetrability of the deuterons times the square of their wave-lengths. Curve (C) is an enlargement of curve (A) in the region of low deuteron energies.

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TABLE I. Data concerning the resonances. Total cross sections were computed assuming spherical symmetry.

	E_0 (Mev) Curve (A)	E_0 (Mev) Curve (B)	Γ (Mev)	σ (barns) for $Q=5.2$ Mev
(1)	0.58	0.58	0.1	6.6×10^{-3}
(2)	0.90	0.85	0.4	2.4×10^{-2}
(3)	1.55	1.55	0.1	6.3×10^{-2}
(4)	1.80	1.78	0.5	8.0×10^{-2}

For deuteron energies above 500 kev, over 3000 single neutron counts were taken for each point of the curve. For points below 500 kev, about 1500 neutron counts were taken. The background was determined by means of a target chamber containing two targets. One was the enriched C^{13} target and the other was a silver blank. The positions of the two were controlled externally by a small magnet so that either could be moved into the path of the deuteron beam.

The background with the helium counter was found to be less than 10 percent of the total number of counts for deuteron energies above 600 kev and became increasingly smaller as the deuteron energy increased. For points taken with the "long counter," the background remained at about 40 percent over the small range of deuteron energies covered. An equal number of counts were taken with the silver blank in the path of the deuteron beam as with the C^{13} target.

A small Geiger-counter shielded by 1.85 cm of lead was used to count the gamma-rays. All gamma-rays from the C^{12} and the C^{13} reactions were counted as no precautions were taken to count only gamma-radiation of a single energy. The excitation curve was consistent with the results of Bennett and Bonner.

The excitation curve for the high energy neutrons from reaction (1) is shown as curve (A) of Fig. 1. An enlargement of the low energy region is also given as curve (C). Curve (A) indicates several pronounced resonances. Since the cross section for disintegration, as given by the Breit-Wigner formula, is strongly influenced by the barrier penetration of the deuteron, the observed cross sections have been divided by the product of the penetrability of the deuterons times the square of their wave-length. The resulting curve (B) should show the true resonance shapes if the interference between neighboring resonances is negligible.

IV. CONCLUSIONS

The excitation curve for the 5-Mev neutrons from the $C^{13}(d,n)N^{14}$ reaction shows resonances at four deuteron energies. The deuteron energy at resonance, E_0, as estimated from the two curves of Fig. (1), is given in Table I. The half-widths of the resonances and the cross sections at these energies, calculated from the experimental arrangement, are also given. Because of uncertainties in absolute neutron intensities, the cross sections are not very precise and may be in error by as much as 50 percent.

Curves (A) and (B) show that there is a very small shift of the peaks in the resonance curves because of changing deuteron penetrability for resonances with widths of this order of magnitude. The resonances correspond to excited states in the intermediate N^{15} nucleus of 16.7, 16.9, 17.47, and 17.69 Mev.

Since the 5-Mev gamma-rays, the 50-cm protons and the 5-Mev neutrons all show a resonance at 1.55 Mev, there are three competing processes at this energy. The resonances at 0.9 Mev and 1.8 Mev were not observed for the long range protons. This is difficult to understand since the neutrons and protons have comparable amounts of energy and it is possible for the compound nucleus, in a particular state, to break up either way and conserve angular momentum and parity. It is possible that the long range protons observed at 0°, instead of 90°, would show similar resonances. It would be very puzzling if reactions (1) and (2) were not competitive.

Data taken with the "long counter" showed the yield of neutrons to have a very slow rise between 200 and 300 kev, and then to start rising more rapidly for deuteron energies above 300 kev. When corrected for penetrability and energy, the curve shows a steep rise as the energy decreases in the neighborhood of 200 kev. As this counter has a flat response over a wide range of energies, neutrons from other sources could be counted. The yield of neutrons from reaction (1) is very low in the energy region between 200 and 300 kev, and although this is below the threshold for C^{12} neutrons, those from the deuteron on deuterium reaction may have caused a large percentage of the counts. Between 200 and 300 kev, curve (A) is rising only 50 percent faster than does the deuterium plus deuteron yield over this energy range.[10] For deuteron energies greater than 300 kev, curve (A) rises much more rapidly than does the $D(d,n)He^3$ reaction.[11] Thus it seems to be likely that most of the neutrons counted below 300 kev were due to deuterium contamination, although the possibility of another resonance in this region cannot be ruled out.

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