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A STUDY OF THE HIGH ENERGY NEUTRONS FROM C^{13}
BOMBARDED BY DEUTERONS

by

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A STUDY OF THE HIGH ENERGY NEUTRONS FROM C\textsuperscript{13}

BOMBARDED BY DEUTERONS

I. Introduction

The phenomena associated with collisions between particles and nuclei are in definite contrast to those associated with collisions between particles and atoms. In an atomic collision, the interaction between the incident particle and the individual electrons in the atom is small so that the particle will most likely pass through the atom without any loss of energy. The usual effect is that the incident particle is deflected by the average field of the atom. If an electron should be excited above ionization energy, it will leave the atom quite rapidly, and no state can be defined in which an electron remains near the atom when excited to such an energy.

As the nuclear forces are very strong, giving binding energies as high as 7 to 8 Mev per particle, and have a range of the same order of magnitude as the distance between the particles constituting the nucleus, it would be impossible for a particle to enter a nucleus without interacting with it. Even in an elastic collision, where the emitted
particle is of the same type as the incident particle and the bombarded nucleus is left in its initial state, there must have been a strong interaction when the particle entered the nucleus. Furthermore, in a nuclear collision, the time required for the emission of a particle is observed to be much longer than the time it would have taken the particle to traverse the nucleus. This property of nuclear collisions holds even though the nucleus may be excited to high enough energies to emit one or more of its constituent particles.

With these facts in mind, Bohr\(^{(1)}\) proposed what is now one of the most generally accepted views of nuclear reactions. As an incident particle could not pass between two nuclear particles without interacting, he called the nucleus a "closed" system and suggested that a nuclear reaction must consist of two steps.

First, particle A collides with nucleus B and the two combine to form an intermediate nucleus C. The intermediate nucleus is initially excited by an amount equal to the fractional part of the energy of the bombarding particle given to the center of mass system plus the binding energy of the incident particle in the intermediate nucleus. The binding energy is the loss in mass of particle A when it combines with nucleus B to form the new nucleus C. This loss in mass goes into energy of the intermediate nucleus which leaves it excited.

Since there is a strong interaction between particles
in a nucleus, there is little reason to believe that this energy should be imparted to one single particle. There is a larger variety of ways that the energy could be shared by the particles in the nucleus. The chance of a particle's being emitted is the probability that sufficient energy will, by chance, be concentrated on that one particle to cause its emission. Thus the two steps are: the collision of particle A with nucleus B resulting in the formation of a new nucleus C, and the emission of a particle E, which may or may not be the same as particle A. By the emission of particle E, nucleus C transforms into nucleus D. This residual nucleus is not necessarily left in its ground state. In some cases, nucleus D is left excited and subsequently drops to its ground state by emitting a gamma-ray or other particles.

If \( A \) represents the atomic mass and \( Z \) the atomic number of a nucleus, the formula for such a reaction can be written:

\[
A^Z_A + B^Z_B \rightarrow (A^Z_{A_1} + A^Z_{A_2}) \rightarrow D^Z_{A_3} + E^Z_{A_4}
\]  

(1)

Since a nucleus has only certain discreet energy levels, the probability that it will be formed and consequently break up with the emission of a particle is dependent on its degree of excitation. If it is excited to an energy not coincident with one of its levels, the probability will be low, but finite, since the levels do have widths. As the excitation energy passes through one of the levels, the yield of a particular particle passes through a maximum. Thus resonances in the yield are indicative of levels in the intermediate nucleus.
Two factors that play an important role in the artificial disintegration of nuclei are the coulomb barriers which must be penetrated by the incident and the emitted charged particles and the angular momenta of the particles concerned. If the bombarding particle is positively charged, such as a proton, deuteron, or an alpha particle, there will be a strong repulsive force between the particle and the nucleus due to their like charges. Thus the incident particle must have sufficient energy to overcome this barrier in order to enter the region of the short-range nuclear forces. A similar condition holds if the emitted particle is positively charged. Of course, there is no such barrier presented to a neutron. The effect of the coulomb barrier is explained by means of a penetrability factor. This is the probability that a particle of energy $E$ and of angular momentum quantum number $\lambda$ can get through the barrier.

A classical explanation can be given for the effect of the angular momentum on a nuclear reaction. If the incident particle has momentum $p$ and a distance of closest approach to the nucleus $b$, the angular momentum is:

$$|\vec{r} \times \vec{p}| = bp = \lambda \hbar$$

or

$$\lambda = b \left( \frac{p}{\hbar} \right) = b \sqrt{\frac{\pi}{\lambda}}$$

(2)

where $\lambda$ is the wave length of the incident particle.

If $a$ is the range of the nuclear forces, an interaction can take place only if $b$ is less than $a$. Thus to interact with the nucleus the angular momentum of the incident par-
ticle must be such that

\[ \lambda < \frac{a}{\Lambda} \]  \hspace{1cm} (3)

Therefore, for a given energy of the incident particle, and so for a given wave length, only those values of angular momentum which satisfy the above condition will take part in the collision.

In terms of Quantum Mechanics the effect of the angular momentum is explained by the indeterminacy in position of the bombarding particle. As the angular momentum is increased the probability that the particle can be found in the region of the nucleus decreases. The chance that it will enter the nucleus and cause a reaction then decreases.

Conservation of parity and of total angular momentum must also hold if a nuclear reaction is to be possible. The parity depends upon the intrinsic parity of the particle and upon the value of the angular momentum quantum number \( \lambda \). If the intrinsic parity is even and \( \lambda \) is even, the parity is even. If the intrinsic parity is even and \( \lambda \) is odd, the parity is odd. The converse holds if the intrinsic parity is odd. Conservation of parity implies that if the initial wave function is symmetrical, or antisymmetrical, the final wave function should also be symmetrical, or antisymmetrical. The parity of a nucleus, which is a system of particles, depends upon the parity of the wave functions which represent individual particles present in the nucleus. In other words, if \( \Psi \) is the wave function representing the nucleus and if \( \Psi_i \) are the wave functions of the particles making up the
nucleus, then

$$\Psi = \Psi_1 \Psi_2 \Psi_3 \ldots$$

If the sum of the numerical values of $\lambda$ for all particles is even, the parity is even. If the sum is odd, the parity is odd. It is not an easy matter to determine the parity of a nucleus, but the rule followed is nuclei with even mass numbers have even parity, whereas nuclei with odd mass numbers have odd parity. This is valid from He$^4$ to O$^{16}$. It is evident that the intrinsic parity of fundamental particles—neutrons, protons, etc.—is even, since $\lambda = 0$ for isolated particles.

In order for the total angular momentum to be conserved, the orbital plus spin quantum numbers of the initial particles must equal the orbital plus spin quantum numbers of the final particles.

As an example, consider $^7\text{Li}$ bombarded by protons which we will assume to have an orbital momentum quantum number of $\lambda = 1$. One possible reaction is that of the intermediate $^8\text{Be}$ nucleus breaking up into two alpha particles. The reaction can be written:

$$^7\text{Li} + ^1\text{H} \rightarrow (^8\text{Be})^* \rightarrow ^4\text{He}^4 + ^4\text{He}^4$$

$$\lambda = 1$$

The spins of the proton, the $^7\text{Li}$ nucleus, and the alpha particles are known to be $1/2$, $3/2$, and 0 respectively. Since the intrinsic parity of the $^7\text{Li}$ nucleus is odd and the orbital momentum quantum number of the proton is assumed to be $\lambda = 1$, the $^8\text{Be}$ nucleus will have even parity and a total
angular momentum quantum number of I = 0, 1, 2, or 3. Consider the case where I = 1. Then for the two alpha particles, I = 1 must be so to conserve total angular momentum, but this would not conserve parity since an alpha particle has even parity. If we should make I even to conserve parity, we could not conserve the total angular momentum. Therefore, if the total angular momentum quantum number of the $^4\text{Be}^8$ nucleus is I = 1, it could not break up into two alpha particles. If I = 0 or 2, both parity and total angular momentum can be conserved.

Although conservation of spin is not essential, it may influence the reaction. If there is a large change in spin the transition will not be impossible, but it will be less probable than one involving a smaller change in spin. For example, a metastable state, or an isomer of a nucleus, has a long half life because the difference in spin between the lowest excited state and the ground state of the nucleus is very large.

The probability that a certain reaction will occur at a given bombarding energy is spoken of as the cross section for that reaction at the given bombarding energy. The cross section for disintegration is the probability that a single incident particle striking a square centimeter of a target containing one atom of the target material will produce a disintegration. This quantity has the units of area and is the effective area presented by the target nucleus to the bombarding particles.
The cross section for disintegration is given by the
single level dispersion formula: \( ^{(3)} \)

\[
\sigma = \frac{\pi \lambda^2(2J+1)}{(2s+1)(2l+1)} \frac{\Gamma_A \Gamma_D}{[(E-E_0)^2 + 1/4\lambda^2]} \tag{4}
\]

In equation (4), \( J \) is the total angular momentum quantum number of a particular compound state of the intermediate nucleus of total width \( \Gamma \); \( s \) and \( l \) are the respective spins of the incident particle and the target nucleus; \( \lambda \) is the wave length of the incident particle; \( \Gamma_A \) is the partial width due to the incident particle; \( \Gamma_D \) is the partial width due to the emitted particle; \( E \) is the energy of the incident particle and \( E_0 \) is its energy at resonance. This formula holds if neighboring resonances are well separated.

The cross section for disintegration is influenced by the coulomb barrier and the angular momenta and energies of the incident and emitted particles. These variables are included in equation (4) in the partial widths \( \Gamma_A \), \( \Gamma_D \), and the incident wave length \( \lambda \). The partial widths are equal to their respective nuclear widths times their penetration factors, \( P_A \) and \( P_B \). These penetrabilities depend upon the angular momenta and energies of the particles concerned. Division of the observed cross section by \( \frac{P_A P_B}{\lambda^2} \) allows the determination of the resonant energy \( E_0 \) and the total width \( \Gamma \). The corresponding energy level in the intermediate nucleus can then be found from the value of \( E_0 \).
II. Historical Background

When C¹³ is bombarded by deuterons, there are three competing processes which are attributed to the reactions:

\[ ^6C^{13} + ^1H^2 \rightarrow (^7N^{15}) \rightarrow ^7N^{14} + ^1H + Q_1 \]  \hspace{1cm} (5)

\[ \rightarrow ^6C^{14} + ^1H + Q_2 \]  \hspace{1cm} (6)

\[ \rightarrow ^5B^{11} + ^2He + Q_3 \]  \hspace{1cm} (7)

Two groups of neutrons from the disintegration of carbon by deuterons were observed by Bonner and Brubaker in 1936(4) and were attributed to reaction (5). By means of cloud-chamber measurements, they observed Q values of 1.2 and 5.2 \( \pm 0.4 \) Mev respectively for the two groups.

As natural carbon contains 99 percent C¹² and only 1 percent of the C¹³ isotope, one would expect the relative intensity of neutrons from C¹³ 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 C¹³ and the \(-0.281 \pm 0.003\)-Mev(5) group from C¹² to be 1, 3, and 300 respectively.

In order to explain the 5.5-Mev gamma-rays from C¹³ bombarded by deuterons, Bennett, Bonner, Hudspeth, Richards, and Watt(6) looked for a third group of neutrons from reaction (5). They obtained a target which was concentrated to 23 percent of C¹³ and found a low-energy group of neutrons with a Q value of \( 0.4 \pm 0.05 \) Mev. This group of workers also studied the 5.5-Mev gamma-rays which are emitted when C¹³ is
bombed by deuterons and obtained an excitation curve for
deuteron energies from 450 kev to 1.9 Mev. Coincident
Geiger-counter measurements were taken with sufficient ab-
sorber placed between the two counters to keep gamma-rays
of energies below 3 Mev from producing a coincident count.
Their target was 2 percent $^{13}C$ and was 30 kev thick. The
thickness was determined from the width of the 1.43-Mev $^{12}C$
resonance. The excitation curve for the 5.5-Mev gamma-rays
was rising steadily and was smooth 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.

A weak group of 50-cm. protons were observed by Bower
and Burcham(7), and independently by Pollard(8). These
protons result from reaction (6). Bennett and Bonner(6)
bombed a target containing 23 percent $^{13}C$ with 1.00-Mev
deuterons and found the Q value for this group of protons
to be $6.09 \pm 0.2$ Mev. Although a search was made, no other
groups of protons from this reaction with ranges less than
20 cm. could be found. Their observations showed that the
ratio of the intensity of this 50-cm. group from reaction
(6) to the 15-cm. group from the $^{12}C(d,p)^{13}C$ reaction was
only 0.07 percent when a natural carbon target was bombarded
by 1.22-Mev deuterons. Since natural carbon contains only
1 percent of the $^{13}C$ isotope, this means that for like num-
bers of atoms the $^{13}C$ isotope yields approximately 7 percent
as many protons as $^{12}C$ at this bombarding energy. This can-
not be taken to be very significant by itself since this does not mean that the ratio of intensities remains this small at other points of the respective excitation curves. However, this ratio agrees with that obtained in later work by Schultz and Watson\(^{(9)}\) at higher bombarding energies. They found a ratio of less than 4 percent, for like numbers of atoms, when carbon was bombarded by 2.54-Mev deuterons. Their results were obtained by means of a cloud chamber filled with enriched methane.

Humphries and Watson\(^{(10)}\) bombarded enriched \(^{13}\text{C}\) targets with 3.82-Mev deuterons and observed two groups of protons with \(Q\) values of 0.58 and 5.82 Mev. They suggested that the 5.5-Mev gamma-ray may be associated with the level in the \(^{14}\text{C}\) nucleus corresponding to the difference between the two \(Q\) values. A corresponding proton group in the work of Bennett and Bonner would have been masked by the \(^{12}\text{C}(d,p)^{13}\text{C}\) reaction.

The third competing process in the disintegration of \(^{13}\text{C}\) by deuterons is reaction (7). Bennett and Bonner\(^{(6)}\) observed that this 3-cm. group of alpha particles appeared in greater intensity when an enriched \(^{13}\text{C}\) target was bombarded than when an ordinary target was used. They thus confirmed that Cockcroft and Lewis\(^{(11)}\) had properly attributed this group of alpha particles to reaction (7). They also obtained an excitation curve for the 50-cm. protons and found a resonance at a deuteron energy of 1.55 Mev. This indicates an excited state in the intermediate \(^{15}\text{N}\) nucleus of
17.5 Mev.

The primary difficulty met in the study of reactions involving a $^{13}\text{C}$ target is inherent in the small natural abundance of this isotope. With the exception of very recent work, all experiments have been performed with either natural carbon targets or with targets enriched with from 2 to 23 percent of the $^{13}\text{C}$ isotope.

We obtained 2.55 grams of methyl iodide from the Eastman Kodak Company of Rochester, New York, in which the $^{13}\text{C}$ isotope content was 0.109 grams more than that contained in normal methyl iodide of the same weight. This means that 48 percent of the carbon atoms are $^{13}\text{C}$ and 52 percent are $^{12}\text{C}$. The targets used in this experiment were prepared by means of cracking the carbon on nickel disks. A complete description of the preparation technique is given below. With these targets and with a 20-atmosphere helium counter, it was thought practicable to look for levels in the $^{15}\text{N}$ nucleus by studying the 5.2-Mev neutrons from reaction (5).

III. Preparation of Targets

A nickel disk, 1/32 of an inch thick, was supported in a Vycor tube by means of a quartz support. The support used was a quartz tube nicked on both ends so as to facilitate pumping as well as to allow the methyl iodide vapor to flow into the outer Vycor tube. The Vycor tube was placed inside a single-turn induction coil of a Model 1-Al, RCA Electronic Power Generator with the disk at the center of the coil. An induction tuning device allowed the disk to be heated to any
desired temperature. A complete drawing of the apparatus is shown in Figure (1).

The top of the Vycor tube was closed and the bottom was made vacuum-tight by means of an "O" ring seal. From the bottom of the tube one 5/8-inch, inside diameter, brass tube led through a sylphon-bellow Hoke valve to the diffusion pump, while another led through two similar valves to the glass section containing the methyl iodide.

The methyl iodide, as purchased from the Eastman Kodak Company, was contained in an inner sealed tube. An additional inner sealed glass tube was attached in order to save the unused methyl iodide for later use.

The iron cylinder used to break the inner seal was sealed in a glass envelope to avoid the possibility of its reacting with the methyl iodide.

The glass and metal parts of the apparatus were joined by a special "O" ring seal. Its essential feature was the compression of an "O" ring so that the rubber fitted tightly between the glass and metal parts of the seal. It was found by experiment that an "O" ring has no noticeable reaction with methyl iodide over a period of two days, although the solution was found to attack rubber vacuum hose readily.

The condition of the nickel disk was found to have an effect on both the quantity and the quality of the carbon deposit. The metal should be well polished, carefully cleaned, and degassed before obtaining a carbon deposit.

The degree of heating seemed to be fairly critical, al-
though the time of heating was not. The cracking process commences at red heat, but no deposits were obtained when the nickel disk was heated to yellow heat or more. This is most likely due to evaporation of the metal or to the formation of an excessive amount of nickel iodide. In the preparation of these targets we chose to use red-orange heat.

The apparatus was evacuated to a vacuum of less than $5 \times 10^{-5}$ mm. of mercury. If the vacuum is too low, the carbon will burn, and any blackening of the disk will be merely nickel oxide.

It was found necessary in the preparation of the targets to freeze the methyl iodide by immersing the tube containing the liquid in liquid air and then pumping off oxygen which was apparently sealed in the tube with the methyl iodide.

Known amounts of methyl iodide vapor could be sent into the Vycor tube by means of the two Hoke valves placed between the solution and the Vycor tube.

After degassing the nickel, the valve to the pump was closed and the desired amount of methyl iodide vapor was allowed to enter the Vycor tube. The induction heater, which had been tuned to the proper coupling between the loop and the nickel disk during the degassing process, was turned on. Completion of the cracking was shown by a heavy deposit of iodine on the cooler parts of the Vycor tube. There should be no danger of having iodine on the target, since both
iodine and nickel iodide are in the gaseous state at the
temperature of the disk. As a precaution, starch tests
were made with targets prepared during trial runs with
ordinary methyl iodide. These tests showed no trace of
iodine.

After the desired number of targets were prepared, the
remaining methyl iodide was transferred from its original
container to the inner sealed tube attached to the appa-
ratus by immersing the latter in liquid air. This method
of preparing targets is about 30 percent efficient, and
very little methyl iodide was used in preparing seven tar-
ggets, since the amount of carbon needed is in the order of
micrograms.

An estimation of the target thickness was made from
results obtained with targets prepared from ordinary methyl
iodide. A comparison of the gamma-ray yield from these tar-
ggets with that from a natural-carbon target of known thick-
ness indicates that the thickest $^{13}$C targets have a total
thickness of about 20 kev. This corresponds to 44.8 micro-
grams/cm.$^2$.

IV. Experimental Arrangement

The Rice Institute pressure Van de Graaff generator was
used as the particle accelerator. With this machine homo-
gegeneous beams of deuterons can be accelerated up to an energy
of 2 Mev. A magnetic analyzer$^{(12)}$ calibrated by gamma-ray
resonances in Li$^7$+ p, F$^{19}$+ p, and C$^{12}$+ d determined the energy
of the deuterons.
The deuterons were accelerated along the vacuum tube, passed through an electrically-controlled shutter box, and entered an electromagnet of 26 cm. radius. For a given magnet current those deuterons of the proper energy were bent through an angle of 90 degrees. An adjustable slit, set at 0.012 inches gap width during the experiments to be described, and placed at the line where the deuteron beam is focused after being bent through 90 degrees, gave additional resolution of the deuteron energy.

The energy spread was still further reduced and a constant beam of deuterons was maintained on the slit by means of an electron gun stabilizer. The electron gun sent electrons back up the vacuum tube to the high voltage end and thus controlled the accelerating voltage. The beam of electrons from the gun was modulated by an electronic circuit which itself was controlled by the deuterons striking the slit. The time required for the electron gun to correct a shift in the deuteron beam was in the order of microseconds.

The arrangement used gave an energy spread of less than 3 kev when the bombarding energy was 1 Mev. The magnetic analyzer allowed absolute energies to be known to better than 5 kev. Specific energies could be reproduced by following the same hysteresis cycle and by always changing magnet readings by increasing the current. This enables energies to be reproduced to within 2 kev.

A counter filled to 19 atmospheres of helium and 1 at-
mosphere of argon was used as the neutron detector. The counter was operated as a proportional counter with a gas multiplication of about 50. It was first tried with a filling of 20 atmospheres of helium, but breakdowns were observed at a counter voltage of 2,200 volts. This is just a little more than half the voltage used in the experiment—4,000 volts. These breakdowns appeared to be localized in the counter itself, which would indicate breakdowns in the helium gas. For this reason, 5 percent argon was added to the gas filling and no further trouble was encountered.

Precautions were taken to insure that the counter was as free as possible from electronegative gases. These gases, notably oxygen and water vapor, are undesirable, as they capture electrons readily and thus form negative ions, which results in a smaller pulse. Although of comparatively small importance in low-pressure counters, this becomes increasingly troublesome as higher pressures are used. Because of the small amount of electron capture in argon and helium, these gases are well suited for high-pressure counters.

Approximately 100 percent pure, oil-free helium and 99.6 percent pure commercial tank argon were used to fill the counter. The counter was carefully pumped, degassed, and flushed before making the final filling.

The counter was constructed of brass with a glass Kovar seal at each end. All joints, other than the Kovar seals, were silver soldered. It was found that such a
counter could hold over 30 atmospheres pressure without showing any signs of leaking. The brass cylinder had 1/16-inch walls and an outer diameter of 2 inches. The length of the 5-mil tungsten wire measured 2 inches between ends of the two Kovar glass sleeves. This was taken as the active length of the counter.

The efficiency of the counter is not known accurately. An attempt was made to determine its order of magnitude. A standard Po-Be source was placed 50 cm. from the counter, and with 4,500 volts counter voltage the efficiency was found to be in the order of 0.1 percent when an average neutron energy of 5 Mev was assumed. Because of the wide spread in energy from such a source and the variation of the helium cross section with energy, this can be taken only as a rough order of magnitude.

The electrical components of the high voltage circuit were chosen so as to minimize background due to voltage breakdowns. The glass Kovar seals had a breakdown voltage rating of 20,000 volts. A 10,000-volt Glassmike condenser was used in the power supply filter and a ceramic condenser was used as the coupling condenser. The high voltage components were all covered sparingly with ceresin wax. The coaxial, high-voltage lead to the power supply terminated in a connector which had been designed by the Amphenol Company after a high-voltage breakdown study showed that better connectors were needed.\(^{(14)}\)

The pulses resulting from helium nuclei recoiling from
neutrons entering the counter were amplified by an Atomic Instrument Company, Model 204-B, linear amplifier. An Atomic Instrument Company, Model 101-A, scale of 64 recorded the pulses from the amplifier. A discriminator unit in the scale of 64 allowed only those pulses above the bias setting to be counted. The power supply used for the 4,000 volts counter voltage was an Instrument Development Laboratories, Model 1090, 5,000-volt regulated power supply.

A "long counter" was used to detect neutrons from the $^6\text{Li}$ reaction for deuteron energies between 200 kev and 450 kev. The counter was constructed after that built by Hanson and McKibben\(^{(15)}\) at Los Alamos. It consisted essentially of a boron trifluoride counter surrounded by a large paraffin cylinder. The paraffin cylinder of the Rice Institute counter was 28 cm. in diameter, and the counter was operated at a voltage of 1,900 volts. The pulses from this counter were amplified and detected by the same equipment that was used with the helium counter.

The above workers found this type of counter to have an equal efficiency for the detection of neutrons of energies between 10 kev and 3 Mev. The response curve was found to remain flat up to the average energy of neutrons from a Ra-Be source. They felt that their assumed value, 5 Mev, was subject to error but thought it probable that the efficiency does remain constant up to this energy. An inspection of their response curves shows that the efficiency for the detection of the high energy group of neutrons from
the $^{13}\text{C}$ reaction should not be more than about 10 percent smaller than that for the lower energy groups. The Po-Be source used to determine the efficiency of the helium counter showed the "long counter" to have about the same efficiency. The advantage of the "long counter" was the large solid angle subtended, whereas its disadvantage was that it did not discriminate against the lower groups of neutrons.

V. Experimental Procedure

Helium Counter:

When a carbon target is bombarded by deuterons, there are four groups of neutrons emitted. Three of these groups are from the $^{13}\text{C}$ reaction and have $Q$ values of 0.4, 1.2, and 5.2 Mev respectively. There is also a group from the $^{12}\text{C}$ reaction with a $Q$ value of $-0.281$ Mev. If only the high energy group of neutrons from the $^{13}\text{C}$ reaction is to be counted, the correspondence between discriminator bias voltage and neutron energy must be known in order to insure that all lower groups are biased out. This was done by taking a bias curve before each run; i.e., plotting the yield of neutrons at a given bombarding energy against the discriminator bias voltage. That point where the bias curve of a certain group of neutrons intercepts the voltage axis corresponds to the bias, in terms of energy, which will just bias out that group of neutrons.

It is not an easy task to locate the different groups of neutrons when such a bias curve consists of four different groups as is the case for carbon bombarded by deuterons. The
procedure first followed was to calibrate the discriminator before each run with a natural carbon target. The content of the $^{13}$C isotope in such a target is only 1 percent, so the neutrons from the $^{12}$C reaction will be predominant by a factor of 100. Thus that point where the $^{12}$C neutrons, whose $Q$ value is well known, are biased out can be quite readily found. Knowing the energy of the bombarding deuterons, the energy of these neutrons can be calculated.

Although satisfactory, this procedure was found to consume a large amount of time. After calibrating the discriminator it was necessary to break the vacuum and change to the target containing 48 percent $^{13}$C. For this reason a technique was devised for calibrating the discriminator using the enriched target.

The neutron counter contained 95 percent helium which has a large cross section in the region of 1 Mev. In calibrating the discriminator the energy of the bombarding deuterons was chosen so that the neutrons from the $^{12}$C($d, n$,$^1$N) reaction would have an energy in this region of large cross section. This caused the yield of neutrons from the $^{12}$C reaction to stand well above that of neutrons from the $^{13}$C reaction. This group was then used to calibrate the discriminator.

An effect that should be considered when counters are used to count high energy neutrons is the possibility that some recoils may reach the walls of the chamber before losing all of their energy. If a particle of mass $m_1$ and
energy $E_1$, in the laboratory coordinate system, bombs a nucleus of mass $m_2$, and if $m_3$ and $m_4$ are the particle and nucleus respectively resulting from the reaction, then the energy of the particle $m_3$ in the laboratory system will be

$$\frac{M E_1^{\frac{1}{2}}}{3} = \left( m_1 m_3 \right)^{\frac{1}{2}} E_1^{\frac{1}{2}} + \left( M m_4 Q + m_2 m_4 E_1 \right)^{\frac{1}{2}}$$

where $M = m_1 + m_2 = m_3 + m_4$

If we take 1 Mev as the average deuteron energy used in obtaining the excitation curve taken at zero degrees for the $^{13}$C group of neutrons whose $Q$ value is 5.2 Mev, the energy of these neutrons for this deuteron energy will be 6.1 Mev. The maximum energy given to a recoil helium nucleus in the counter will then be 3.9 Mev. An alpha particle of this energy will have a range of 2.86 cm. in air at atmospheric pressure\(^{(16)}\). This corresponds to a range in the counter of only 0.59 cm. which is about 1/10 the diameter of the counter. Therefore, any change in efficiency and distortion of the bias curve due to wall effects can be considered as negligible.

The stability of the counter was checked before each run. In some cases it was checked by placing a Ra-Be source at a known distance from the counter. In other cases it was checked by observing whether the calibration bias curve had shifted from the position found on the previous run. With these methods, the gas multiplication was found to remain constant to within 5 to 10 percent although changes as great as 20 percent were occasionally found during a day's run.
It is believed that these changes in gas multiplication were due to temperature changes, since a rare gas such as helium or argon is known to have a gas multiplication which is sensitive to pressure and therefore to temperature.

Large cans containing water saturated with borax were used to form a wall between the helium counter and the magnetic analyzer. This served to shield the counter from the high energy neutron group of the $^{13}$C reaction resulting from carbon contamination along the path of the deuteron beam.

**Long Counter:**

The "long counter" was placed as close to the target as possible and subtended a solid angle of about $2\pi$ steradians to the target. There was no background due to high voltage breakdowns or to electronic circuits associated with the counter. As this counter detected neutrons of a wide range of energies with equal efficiency, a more elaborate shielding arrangement had to be used than was used with the helium counter. With the arrangement mentioned above, the background for the "long counter" was found to be in the order of 80 percent of the total number of counts. As such a high background made it impossible to obtain worthwhile data, additional shielding was added. The shielding arrangement actually used was made up of the cans containing water saturated with borax which formed a double wall between the path of the deuteron beam and the counter. The front face of the paraffin cylinder was completely shielded by
these cans, and a sheet of cadmium was placed over the front of the boron trifluoride counter. The cadmium shield served to absorb thermal neutrons or higher energy neutrons which had been slowed down to thermal velocities after passing through the cans. With this arrangement, the percentage background was reduced to about 38 percent.

VI. Experimental Results

The enriched $^{13}$C 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 ± 28 degrees to the direction of the deuteron beam. The sensitive volume of the counter subtended a solid angle of 1.12 steradians to the target.

The excitation curve for the high energy neutron group resulting from the bombardment of $^{13}$C with deuterons is shown as curve (A) of Figure (2). For deuteron energies above 500 kev, over 3,000 single neutron counts were taken for each point of the curve. For the points between 350 kev and 500 kev about 1,500 single neutron counts were taken. Each portion of the curve was covered in at least three separate runs. The total excitation curve shown, curve (A) of Figure (2), consists of eighteen separate runs. These runs were made either over the whole curve at one time or repeatedly over those portions of the curve that showed features not so definite as the two broad resonances seen in curve (A). Those parts of the curve covered during a run were taken so that they had at least three, usually
many more, points in common with neighboring parts of the curve. This enabled an accurate normalization factor to be used. In most cases, points for normalization were selected where the curve is not rising too steeply. The curve given here is the complete weighed and normalized curve.

The background was determined by means of a target chamber containing two targets. One was the enriched $^{13}\text{C}$ target and the other was a silver blank. The positions of the $^{13}\text{C}$ target and the silver blank were controlled externally by a small magnet so that either of the two could be moved into the path of the deuteron beam.

When using the helium counter, the discriminator was set at a bias corresponding to a neutron energy of about 3 Mev. As the deuteron plus deuteron neutrons have a $Q$ value of 3.2 Mev, one would expect the greater part of the background to be due to these neutrons. However, this was not the case. The number of background counts was found to be a function of the time of bombardment only. The rate of bombardment had no apparent effect. At each bombarding energy the number of background counts was plotted against the time of bombardment, and at each energy the same straight line was obtained with a scattering of points smaller than would be expected from voltage breakdowns. This background is thought to be due to natural radioactive contamination of the brass walls of the counter. Its counting rate is too invariant to be due to high voltage breakdowns across insulators or to background counts resulting from too small a
warm-up period. The excitation curve, curve (A) of Figure (2), was corrected for background as a function of the time of bombardment.

The background was less than 10 percent of the total counts taken for all deuteron energies above 600 kev and became increasingly smaller as the deuteron energy increased because of the continual rise in the yield of neutrons. Below this deuteron energy, the percentage background increased from about 6 to 10 percent at 600 kev to almost 80 percent at 200 kev. This increase in percentage background was due to the increased length of time required to obtain enough counts to have statistical value. The neutron yield falls rapidly for lower deuteron energies.

For points taken with the "long counter", the background remained at about 40 percent over the small range of deuteron energies covered. Because of the high percentage background and its being a function of the amount of bombardment and not the time, an equal number of counts were taken with the silver blank in the path of the deuteron beam as with the C$^{13}$ target. The corrected yield obtained at a certain deuteron energy was found to agree very closely with the value obtained previously. Twenty scale-of-64 counts were taken for each of the points covered between 200 kev and 450 kev.

A small Geiger counter shielded by 1.85 cm. of lead was used to count the gamma-rays from the carbon bombarded by deuterons. As our main objective was a study of the high energy neutron group resulting from the C$^{13}$ reaction, no
steps were taken to count only a single energy gamma-ray. All gamma-rays from the $^{12}$C and the $^{13}$C reactions were counted, so not too much can be said for the resulting curve. However, the curve—Figure (3)—did show the steep rise Bennett and Bonner (6) found for the 5.5-Mev gamma-rays with the resonances of the gamma-rays from the $^{12}$C reaction superimposed on it. The resonance at 1.55 Mev was also seen, although it was not as pronounced as was that obtained by the above workers when only the 5.5-Mev gamma-ray was detected, since the yield of gamma-rays from the $^{12}$C reaction is rising in this region. An effort was made to calculate the relative yields of gamma-rays from the two carbon reactions. In the deuteron energy region between 1.2 and 1.3 Mev there appear to be between one and two times as many $^{13}$C gamma-rays as $^{12}$C gamma-rays.

VII. Discussion of Results

The excitation curve for the 5.2-Mev neutrons from the $^{13}$C(d,n)$^{14}$N reaction shows resonances at four deuteron energies. Curve (A) of Figure (2) is the observed yield. Curve (B) is curve (A) divided by $P = 0 / x^2$. The deuteron energy at resonance, $E_0$ of equation (4), as estimated from the two curves, is given in the table below.

<table>
<thead>
<tr>
<th>Curve (A)</th>
<th>Curve (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>1.80</td>
<td>1.79</td>
</tr>
</tbody>
</table>
This shows that there is a very small shift of the resonance energy for resonances with widths of this order of magnitude. If the deuteron energies at resonance are taken to be 0.6, 0.9, 1.55, and 1.80 Mev respectively, these will correspond to excited states in the intermediate \( N^{15} \) nucleus of 16.65, 16.91, 17.47, and 17.69 Mev.

In dividing curve (A) by \( P \lambda / \lambda^{-2} \), so as to find the total width and position of the nuclear energy level given by the term

\[
\frac{1}{(E-E_0)^2 + 1/4 \Gamma^2}
\]

of equation (4), only \( l=0 \) deuterons were assumed to have taken part in the reaction. Since the purpose of the correction was to examine the low energy region and the flat part of the curve near 600 kev, the choice of \( \lambda \) was of little importance. The ratio of the penetrabilities for different values of the angular momentum quantum number is constant for energies so far below the barrier height. Thus the choice of a different value of \( \lambda \) would have made no change in the shape or position of a low energy resonance. The choice of \( \lambda=0 \) deuterons is perhaps incorrect for the high energy regions yet it is interesting to note that the correction used removed the asymmetry of the 1.80-Mev resonance. The values for the penetrability factor were obtained from proton width curves of Christy and Latter. Proper corrections were made so that these curves would apply to the \( ^{13}C(d,n)N^{14} \) reaction.
It has been assumed that there would be little dependence of neutron emission on the penetrability for these neutrons. Reaction (5) shows these neutrons must have \( l = 1 \) if \( l = 0 \) for the deuterons. This must be so to conserve parity. However, for such energetic neutrons, the penetrability will be close to unity and slowly varying.

A resonance in the yield of gamma-rays resulting from the bombardment of \( \text{C}^{13} \) by deuterons was found at a deuteron energy of 1.55 Mev. As was mentioned previously, Bennett and Bonner(6) found this resonance when studying the 5.5-Mev gamma-rays from the \( \text{C}^{13} \) reaction. They also found a resonance at this energy in the yield of the 50-cm. protons from the \( \text{C}^{13} \) reaction. Since the 5.5-Mev gamma-rays, the 50-cm. protons, and the 5.2-Mev neutrons all have a resonance at 1.55 Mev, there are three competing processes at this energy. The excited \( \text{N}^{15} \) nucleus either emits a 50-cm., 6.1-Mev, proton leaving the \( \text{C}^{14} \) nucleus in its ground state; or it emits a low energy neutron, 0.4 Mev, leaving the \( \text{N}^{14} \) nucleus in an excited state which then drops to its ground state through the emission of a gamma-ray; or it emits a 5.2-Mev neutron which leaves the \( \text{N}^{14} \) nucleus in its ground state.

Data taken with the "long counter" showed the yield of neutrons to have a very slow rise between 200 kev and 300 kev, and then to start rising more rapidly for deuteron energies over 300 kev. Curve (B) therefore gives indications of a strong level corresponding to a deuteron energy below
200 kev. As this counter has a flat response over a wide range of energies, neutrons from other sources were undoubtedly counted and could have had a large effect on the curve obtained. These neutrons would have been mainly from the deuterium and C^{12} reactions. The work of Bonner and Brubaker\(^4\) shows that the cross sections for the 5.2-Mev C^{13} neutrons and the -0.281-Mev C^{12} neutrons are of the same order of magnitude. If one assumes the yields of the two groups to be equal at 1.18 Mev, an inspection of curve (A) and the work of Bonner, Evans, and Hill\(^5\) shows that the yield of C^{13} neutrons will be seven times greater than that of the C^{12} neutrons at .520 Mev. Furthermore, the C^{12} yield is dropping twice as fast as the C^{13} yield at this energy. A further inspection of the curve shows it to increase by a factor of 5 between .323 and .432 Mev, whereas the C^{12} neutron yield increases by a factor of 2,000 in this interval of energy.

Between 200 kev and 300 kev curve (A) is rising only about 50 percent faster than does the deuteron plus deuteron yield over this energy range.\(^{18}\) For deuteron energies greater than 300 kev curve (A) rises much more rapidly.\(^{19}\) Although one could conclude that there is little effect from the C^{12} neutrons, the possibility of a large percentage of the counts being deuterium neutrons can certainly not be discounted for energies between 200 kev and 300 kev. If a high percentage of the counts taken were from these neutrons, the steep slope of curve (B) would be explained. This matter
could best be cleared up by use of a natural-carbon target in place of the silver blank. This would eliminate the possibility of a greater deuterium contamination on the carbon than on the silver blank.

The table shown below gives the half widths of the resonances observed, $\Gamma$; the time that the $N^{15}$ nucleus exists before breaking up; the time it would take for a neutron of energy equal to that of the emitted neutron to traverse the nucleus; and the time it would take the bombarding deuteron to traverse the $N^{15}$ nucleus. The nuclear radius was calculated from the formula:

$$R = \frac{1}{2} \frac{e^2}{mc^2} A^{1/3}$$

<table>
<thead>
<tr>
<th>$E_0$ (Mev)</th>
<th>$\Gamma$ (Mev)</th>
<th>$t = \frac{\hbar}{\Gamma}$ (sec.)</th>
<th>$t = \frac{2R}{v_n}$ (sec.)</th>
<th>$t = \frac{2R}{v_d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.1</td>
<td>$6.6 \times 10^{-19}$</td>
<td>$2.1 \times 10^{-22}$</td>
<td>$9.2 \times 10^{-22}$</td>
</tr>
<tr>
<td>0.9</td>
<td>0.4</td>
<td>$1.7 \times 10^{-19}$</td>
<td>$2.0 \times 10^{-22}$</td>
<td>$7.4 \times 10^{-22}$</td>
</tr>
<tr>
<td>1.55</td>
<td>0.1</td>
<td>$6.6 \times 10^{-19}$</td>
<td>$2.0 \times 10^{-22}$</td>
<td>$5.7 \times 10^{-22}$</td>
</tr>
<tr>
<td>1.80</td>
<td>0.5</td>
<td>$1.3 \times 10^{-19}$</td>
<td>$1.9 \times 10^{-22}$</td>
<td>$5.3 \times 10^{-22}$</td>
</tr>
</tbody>
</table>

This shows that the intermediate $N^{15}$ nucleus exists for a time which is almost a factor of 1,000 longer than the time it would take the neutron to travel across the nucleus. It exists for a time which is a factor of several hundred longer than the time it would take the bombarding deuteron to traverse the nucleus.
An energy level diagram of the $^\text{N}^{15}$ nucleus is shown in Figure (4). This diagram is a summary by Hornyak and Lauritsen (20) of work done on the $^\text{N}^{15}$ nucleus by various workers. The solid lines represent known levels which were obtained either by resonances in excitation curves, by determinations of the energies of gamma-rays emitted by the excited $^\text{N}^{15}$ nucleus, or by the difference between $Q$ values of proton or neutron groups associated with the same nuclei. The dotted lines indicate a degree of uncertainty in the exact energy of these levels. The excitation curve and the levels found in this experiment have been added.
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REFERENCES

(1) Niels Bohr, Nature 137, 344 (1936)
(2) H. A. Bethe, Elementary Nuclear Theory, 38 (1947)
(3) H. A. Bethe and G. Placzek, Phys. Rev. 51, 450 (1937)
(4) T. W. Bonner and W. M. Brubaker, Phys. Rev. 50, 308 (1936)
(5) T. W. Bonner, J. E. Evans, and J. E. Hill, Phys. Rev. 75, 1398 (1949)
(8) E. Pollard, Phys. Rev. 56, 1168 (1939)
(9) Howard L. Schultz and William W. Watson, Phys. Rev. 58, 1047 (1940)
(13) S. J. Bame, Jr., and L. M. Baggett, Rev. Sci. Inst. 20, 839 (1949)
(14) F. M. Glass, Rev. Sci. Inst. 20, 239 (1949)
(15) A. O. Hanson and J. L. McKibben, Phys. Rev. 72, 673 (1947)
(16) H. A. Bethe, Rev. Mod. Phys. 2, 226 (1937)
(17) R. F. Christy and R. Latter, Rev. Mod. Phys. 20, 185 (1948)

(19) W. E. Bennett, C. E. Mandeville, and H. T. Richards,
    Phys. Rev. 62, 418 (1946)

(20) W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20,
    191 (1948)