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UMI
A STUDY OF CARBON BOMBARDED

BY DEUTERONS

A thesis submitted to the Faculty of The Rice Institute in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Gerald Cleveland Phillips
Houston, Texas
May, 1949
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I. INTRODUCTION.

A. Discussion of Nuclear Transmutations. The nuclear model proposed by Niels Bohr in 1936\(^1\) has been very useful in understanding artificial nuclear transmutations. Bohr proposed that when a target nucleus of charge \(Z\) and mass number \(A\) is struck by a projectile with energy \(E_a\), charge \(z\), and mass number \(a\), that a compound nucleus of charge \((Z + z)\) and mass number \((A + a)\) is formed in an excited state of energy \(E_x\). Symbolically this is written as

\[ Z^A + z^a \rightarrow (Z + z)^{A + a} \]

The excitation energy is just

\[ E_x = c^2 \left[ m_A + m_a - m_{(A+a)} \right] + \frac{m_{A+a} - m_a}{m_{A+a}} E_a, \]

where \(m_a\) is the mass-spectroscopic mass of the nucleus of mass number \(a\), etc.

It is known that the compound nucleus \((Z + z)\)\(^{(A+a)}\) exists longer than the transit time of the particle \(z^a\) across the field of \(Z^A\). The energy of the particle \(z^a\) is supposed to be shared with all the particles forming \((Z + z)^{(A + a)}\), and this semistable system exists until such a time as sufficient energy is concentrated on a particle \(\gamma\) to remove it from the nucleus. This relatively "long lifetime" of the compound nucleus is thought to be due to the very short range nature of the nuclear

\(^1\) Niels Bohr, Nature, 137, 344 (1936).
forces \( \sim 10^{-13} \) cm and to the saturation properties of the forces. Such a dense, strongly interacting system allows the existence of virtual energy states; that is, excitation energies \( E_x \) that far exceed the binding energy of the individual particles.

In general the compound nucleus can decompose in many different ways. It may emit various types of particles or photons. The decomposition of \((Z + z)^{(A+a)}\) by the emission of a particle \( \alpha \) is written

\[
(Z + z)^{(A+a)} \rightarrow \alpha + (Z + z - \alpha)^{(A+a-\alpha)}
\]

with a change in kinetic energy given by

\[
c^2 \left( m_\alpha + m_{(A+a-\alpha)} - m_{(A+a)} \right).
\]

In case \( E_x \) is not sufficient to remove a heavy particle (neutron, proton, alpha particle, etc.) from the nuclear field, the excitation energy \( E_x \) will be released by a gamma-ray, or several gamma-rays in cascade. In general, the probability of gamma-ray emission is much smaller than that for particle emission if \( E_x \) is greater than the binding energy of a nucleon. Another way of stating this is that gamma-ray line widths are generally very much smaller than the widths of the virtual levels. Since the width \( \Gamma \) of an energy level is related to the half life \( \Delta t \) of the state by \( \Gamma \Delta t = \hbar \), the narrow gamma-ray widths have states of relatively long lives, while the broad widths of the particle emitting states have much shorter half lives.
For nuclear reactions of the type discussed the interesting phenomena of resonance is observed. Resonance may be defined as an anomalously large increase in cross-section for the production of a certain disintegration when the excitation energy of the compound nucleus is in the region of some characteristic energy $W_2$. This phenomenon is believed to represent the formation of quantized energy-characteristic states $W_2$ in the compound nucleus. Further, it is observed experimentally, that associated with each $W_2$ there is a characteristic energy width $\Gamma_2$ between the half-maximum points on either side of the resonance. For the bombardment of heavy nuclei with neutrons of thermal energies, it is observed that there exist levels only a few volts wide and with a few volts of separation. Such levels have $E_x \sim 8$ Mev since this is the average binding energy of a nuclear particle. For higher excitation energies in light nuclei, resonances are observed that are much wider than the slow-neutron capture-levels in heavy nuclei. For example, in the bombardment of $\text{F}^{19}$ by protons the widths of the levels are $\sim 375$ kev.

Resonances have been observed in almost all the light elements when they are bombarded by neutrons, protons, deuterons, and triton or alpha particles. A recent tabulation

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4T. W. Bonner and J. E. Evans, Phys. Rev. 73, 666 (1948).
has been made by the Pasadena group.  

The variation of the cross-section $\sigma$ for a reaction

$$A + B \rightarrow C \rightarrow D + E$$

as the states $r$ in the compound nucleus $C$ are excited to the energy $E$ is given by

$$\sigma = \frac{\pi X^2}{(2j_B+1)(2S_A+1)} \sum_{J_c, J_A, I_A, I_E} \frac{\Gamma_{C,r,J_c}^{C,r,J_c}}{(E-W_r)^2 + (\Gamma_{1/2})^2} \frac{\Gamma_{D,q,j_e,l_e}^{D,q,j_e,l_e} \Gamma_{C,r,J_c}^{C,r,J_c}}{(E-W_r)^2 + (\Gamma_{1/2})^2}$$

where $W_r$ is the excitation energy of the virtual state $r$ of $C$ with total angular momentum $J_c$, formed by particle $A$ of spin $S_A$, orbital angular momentum $I_A$, and total angular momentum $j_A$ striking particle $B$ of total angular momentum $j_B$ in a state $p$ and giving $E$ an orbital angular momentum $I_E$, total angular momentum $j_E$ and leaving the residual nucleus $D$ in the state $q$. The total width $\Gamma_r$ of the state is the sum of the partial widths $\Gamma_{C,r,J_c}^{C,r,J_c} \Gamma_{D,q,j_e,l_e}^{D,q,j_e,l_e}$, etc., for the emission of the various kinds of particles $E$.

$$\Gamma_r = \sum_{D,q,j_e,l_e} \Gamma_{C,r,J_c}^{C,r,J_c} \Gamma_{D,q,j_e,l_e}^{D,q,j_e,l_e}$$

The difference in $\Gamma_r$ and the other $\Gamma_s$ is that $\Gamma_r$ represents the widths for the decay of the state $r$ into all possible types of nuclei $D$ in all their possible states $q$, while the other widths are summed over all the possible ways to form

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5 W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20, No. 1, 191 (1948).

6 W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Rev. Mod. Phys. 20, No. 1, 236 (1948).


the state \( r \) in the nucleus C from the given initial system B and final system D.

When transmutations are investigated where the bombarding particle is charged (protons, deuterons, and alpha particles are commonly used) the coulomb repulsion between the target and the projectile nuclei influences the observed effects. In the same way, the escape of charged particles from inside the nucleus is impeded. The probability of penetrating the coulomb barrier is called penetrability and has been recently calculated for all the light nuclei.\(^9\)

The radial wave equation for the scattering of a particle of reduced mass \( m \) with orbital angular momentum \( \ell \) by a center of force \( V(r) \) is

\[
\frac{\hbar^2}{2m} \frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{dU_\ell(r)}{dr} \right) + \left( E - V(r) + \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} \right) U_\ell(r) = 0
\]

The term \( \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} \) has the dimensions of energy and acts as a repulsive potential for even an uncharged particle \( m \). This term decreases the probability of capture (or emission) of a neutron by a nucleus if \( \ell > 0 \). For example, the height of the centrifugal barrier for \( \gamma N^{13} + n \) is

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>Barrier in Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>3.76</td>
</tr>
<tr>
<td>2</td>
<td>11.25</td>
</tr>
<tr>
<td>3</td>
<td>22.55</td>
</tr>
</tbody>
</table>

One may compare these values with the purely coulomb barrier heights of 2.68 Mev for $^6\text{C}^{13} + ^1\text{H}^1$ and 2.91 Mev for $^6\text{C}^{12} + ^1\text{H}^2$.

B. History of the $^6\text{C}^{12} + ^1\text{H}^2$ Reaction.

Since the experimental researches to be described are concerned with the reactions of transmutation that occur when carbon of mass number twelve is bombarded with deuterons, a brief account will be given of the known facts.

There are three reactions known to occur when carbon is bombarded with deuterons:

\begin{align*}
(1) & \quad ^6\text{C}^{12} + ^1\text{H}^2 \rightarrow ^7\text{N}^{14} \rightarrow ^6\text{C}^{13} + ^1\text{H}^1 + Q_1 \\
& \quad ^6\text{C}^{13} \rightarrow ^6\text{C}^{13} + \gamma (Q'_1) \\
(2) & \quad ^6\text{C}^{12} + ^1\text{H}^2 \rightarrow ^7\text{N}^{14} \rightarrow ^6\text{C}^{13} + ^{1}\text{O}^{1} + Q_2 \\
& \quad ^7\text{N}^{13} \rightarrow ^6\text{C}^{13} + \beta^+ + Q'_2 \\
(3) & \quad ^6\text{C}^{12} + ^1\text{H}^2 \rightarrow ^7\text{N}^{14} \rightarrow ^6\text{C}^{13} + ^1\text{H}^1 + Q_3.
\end{align*}

The three reactions will be designated by (1) (2) and (3) in all that follows. The best values for the $Q$ are

\begin{align*}
Q_1 &= -.5 \text{ Mev} \quad ^{10} \\
Q'_1 &= 3.1 \text{ Mev} \quad ^{11}
\end{align*}

\begin{footnotesize}

\begin{itemize}
\item[^{10}] Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. 59, 781 (1941).
\item[^{11}] Ibid., p. 781.
\end{itemize}
\end{footnotesize}
\[ Q_2 = -0.281 \text{ Mev} \]
\[ Q'_2 = 1.24 \text{ Mev} \]
\[ Q_3 = 2.7 \text{ Mev} \]

Historically reaction (3) was the first observed, while the gamma rays of reaction (1) were observed at about the same time. The positron emitting \( ^1\text{N} \), with a 10 minute half life, was observed by Henderson et al. for reaction (2), while the neutrons were found by Crane and Lauritsen.

In a series of experiments at the Rice Institute the first deuteron induced resonances observed were found for all three of the reactions. To date, probably the best excitation curves for energies below 2 Mev are those of J. C. Harris. For higher energies the most recent determination are those of the groups at the University of Minnesota.

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12 T. W. Bonner, J. E. Evans, J. E. Hill (to be published).
17 Henderson, Livingston and Lawrence, Phys. Rev. 45, 428 (1934).
23 C. L. Bailey, G. Freier, and J. H. Williams, Phys. Rev. 73, 274 (1948).
and the Carnegie Institute D.T.M. 24

C. Purpose of the Present Experiments.

The shape of the excitation curves for reactions (1) and (2) had been previously determined; however there was some doubt as to the absolute value of the cross-sections. These cross sections needed to be determined accurately.

The excitation curve for reaction (3) had only been determined at the one angle of 90° to the beam direction, and so it was felt excitation curves at other angles should be obtained in view of a possible angular asymmetry of the disintegrations.

Because of this possibility of angular asymmetry the angular distributions for reactions (2) and (3) appeared to be of interest.

Because of these considerations experiments were performed to determine: (a) the cross-section for reaction (1); (b) the cross-section for reaction (2); (c) the excitation curve and cross-section of reaction (3); (d) the angular distribution of the neutrons of reaction (2); and (e) the angular distribution of the long range protons of reaction (3).

The Rice Institute Van de Graaff electrostatic generator was used to accelerate the deuterons. This machine and its voltage regulation by means of "counter-flow" electron feedback has been described. 25,26 The possible

voltage regulation is better than $\pm 0.05\%$. A neon discharge tube integrator was used to measure the number of magnetically analyzed deuterons that struck the target.\textsuperscript{27}

II. DETERMINATION OF THE TOTAL GAMMA RAY CROSS-SECTION

The shape of the excitation curve for reaction (1)

$$^{6}\text{C}^{12} + _{1}\text{H}^{2} \rightarrow ^{7}\text{N}^{14} \rightarrow ^{6}\text{C}^{13} + _{1}\text{H}^{1} - 0.5 \text{ Mev}$$

$$^{7}\text{C}^{13} \rightarrow ^{7}\text{C}^{13} + \gamma (3.1 \text{ Mev})$$

had been previously determined in this laboratory;\textsuperscript{28,29} however there was some doubt about the accuracy of the cross-section determinations, and so a new experiment was performed to determine the cross-section for a particular energy of the bombarding deuterons.

To measure the cross section, a small Eck and Krebs copper cathode Geiger counter was placed 17 cm from the target and was surrounded by 1.4 cm of lead. A "thick" target, consisting of a slab of pure graphite was bombarded with 1.30 Mev deuterons. Since the thin target relative yield of gamma rays as a function of energy was known, the cross-section for gamma ray production could be calculated from the observed "thick" target yield by integrating the "thin" target yield.


\textsuperscript{28}J. C. Harris, \textit{op.cit.}

\textsuperscript{29}Bonner, Evans, Harris, and Phillips, Phys. Rev. (to be published in May, 1949).
from 0 to 1.30 Mev. An efficiency of 1.65 per cent was
assumed for the 3.1 Mev gamma rays.\textsuperscript{30} The transmission of
the lead, under identical geometrical conditions, was
determined experimentally by means of the 2.62 Mev gamma rays
from mesothorium and was found to be 48 per cent. These data
gave a cross section at 1.30 Mev of 0.39 barns. The relative
yields of gamma rays were all adjusted to this value and are
shown on Figure 1.

The angular distribution of the gamma rays was investi-
gated at 1.73 Mev for a thin target. To do this, it was
necessary to rotate the small Geiger counter about the target
at a distance greater than that previously used for the
excitation curve determinations, so that the background count
due to extraneous gamma rays was \textasciitilde 10 per cent of the true
counts. No asymmetry was found greater than 10 per cent—the
background counting rate.

III. DETERMINATION OF THE TOTAL NEUTRON CROSS-SECTION

Although the total cross-section for reaction (2)

\[
^6\text{C}^{12} + ^1\text{H}^2 \rightarrow ^{\alpha}_{7}\text{N}^{14} \rightarrow ^{\beta}_{7}\text{N}^{13} + ^1\text{H}^1 - 281 \text{ Mev}
\]

\[
^{\beta}_{7}\text{N}^{13} \rightarrow ^6\text{C}^{13} + ^1\beta^+ + 1.24 \text{ Mev}
\]

had been previously determined in this laboratory\textsuperscript{31} by

\textsuperscript{30} Bradt, Gugelot, Huber, Medigaus, Preiswerk, and Scherrer,

\textsuperscript{31} J. C. Harris, op. cit.
counting the positrons from the radioactive $^{13}\text{N}$, it was realized that an important point had been overlooked in these determinations that put them in error. This error resulted from the backscattering of the positrons from the thick target backing and the walls of the adjacent target chamber, thus increasing the observed yield of positrons. This error, by geometrical considerations only, might increase the cross-section by as much as 50 per cent.

To eliminate the backscattering from the target backing, special thin targets of carbon on thin silver foils (7.75 mg/cm$^2$) were constructed. (See Section V for the method of preparation.) The silver foil was thin enough that it did not scatter many of the positrons, but was thick enough so that it stopped the deuterons.

The thickness of the pure carbon target on the thin foil was obtained by comparing ratios of the gamma rays from this target and the thick target described in Section II. These data, which were all taken at 1.30 Mev with several geometrical arrangements of the Geiger counter about the targets, gave the same ratios within 10 per cent. The thickness for this target was determined to be 23.5 $\mu$gms/cm$^2$.

A quantity of $^{13}\text{N}$ was then prepared by placing the target normal to the deuteron beam and bombarding at an almost constant rate for 20 minutes (two half lives of the $^{13}\text{N}$). The target was then quickly removed from the vacuum
system and placed over the axis of a bubble window Geiger counter, of window thickness 3 mg/cm². The only absorbing material in the path of the positrons (end point energy 1.24 Mev) was the few centimeters of air and the counter window, and so nearly 100 per cent of the positrons reached the sensitive region of the counter. The backscattering was negligible because of the thin target backing and the isolation of the target back from objects that might have scattered the positrons. Five independent measurements were taken at 1.30 Mev with different target-counter separations; cross-sections calculated from these measurements agree within 10 per cent.

If $\frac{dN}{dt}$ is the number of $N^{13}$ atoms decaying at the end of the bombardment of 20 minutes, and $n$ is the number of $N^{13}$ atoms formed per second during the bombardment, then

$$n = -\frac{4}{3} \left(\frac{dN}{dt}\right),$$

so that

$$\frac{\sigma_{N^{13}}}{N^{13}} = 1200 \left(\frac{4}{3}\right) \left(\frac{\beta}{\sec}\right)_{1200} \frac{4\pi}{\omega} \frac{1}{C \cdot D}$$

where $D$ is the number of deuterons that struck the target during the bombardment, $C$ is the number of carbon atoms/cm², and $\omega/4\pi$ is the fraction of the total solid angle subtended at the counter aperture. The experimental determination of $\left(\frac{\beta}{\sec}\right)_{1200}$ was obtained by plotting the number of Geiger counts in 100 second intervals versus the time for at least one half life after cessation of bombardment. The
points were plotted 53 seconds from the beginning of each 100 second interval because this is the time at which the average decay rate for the interval would be expected. A line with a slope corresponding to a 10 minute half life was drawn through the points and extended back to 1200"--the time when bombardment ceased. This intercept gave \((\sigma/\text{sec})_{1200}\).

These measurements gave a cross-section of 0.192 barns at 1.30 Mev for the production of \(N^{13}\). The previously determined relative yield curve was adjusted to this value and is shown in Figure 1.

In addition to the determination of the total cross-section, measurements were repeated to obtain the cross-section at the higher deuteron energies. The cross-sections for the production of \(N^{13}\) for deuteron energies above 1.30 Mev, shown in Figure 1, are these new determinations.

IV. THE NEUTRON ANGULAR DISTRIBUTIONS.

The neutrons from reaction (2)

\[ ^{12}\text{C} + ^1\text{H} \rightarrow ^{14}\text{N} \rightarrow ^{13}\text{N} + ^1\text{n} \rightarrow 0.28 \text{ Mev} \]

have been examined for departures from spherical symmetry because of the differences noted in the shape of the excitation curves for the production of neutrons at \(0^\circ \pm 30^\circ\) and the production of \(N^{13}\).
A. The Neutron Counter. To count the neutrons at the various angles about the direction of the bombarding deuterons, a special proportional counter was constructed. This counter was made of heavy brass tubing of inner diameter 4.4 centimeters and was 14.5 centimeters long with soldered end plates as is shown in Figure 2. The anode was a 2 mil tungsten wire 4.4 centimeters long supported at the center of the cylinder by 31 gauge nickel wires vacuum sealed through the end plates with Kovar-glass insulators. The counter was filled with about an atmosphere of tank hydrogen to which was added 2 per cent methane. The counter was found to operate satisfactorily as a proportional counter with the wire held at 1920 volts. The small voltage pulses that appeared across the counter when an ionizing event occurred were amplified by means of an Atomic Instrument Company 101-A Linear Amplifier. The pulses were then counted by means of a discriminator and a scale-of-64 scaling circuit. The discriminator allowed the counting of only those voltage pulses that were greater than the bias voltage $V_B$, and this ascertained that only ionizing events that released an energy $E$ Mev, or more, inside the counter were recorded.

The overall gain of the system was checked for constancy from day to day by means of counting the gamma rays from a radium source with a standard geometrical
arrangement, a counter voltage, an amplifier gain, and a discriminator bias. At the bias settings used when neutrons were being counted, the counter was insensitive to gamma rays.

Two curves of discriminator bias - versus neutrons counted per deuteron were taken for neutrons of three different energies. Since the neutron-proton cross-section is known to be spherically symmetrical at these neutron energies, one would expect that the curves would be of the linear form

\[
\text{neutrons/deuteron} = A \left( E_n - B \right),
\]

where \( E_n \) is the monoenergetic neutron energy. However, for a counter of finite depth there is a larger probability that a low energy (short range) recoil proton will be sufficiently inside the counter gas to release the bias energy \( B \), than for a long range proton to be sufficiently inside. This distorts the straight line upwards at low biases. Nevertheless, the cut off bias is determined uniquely, and so one is able to correlate the discriminator bias setting in volts to a neutron energy \( B \) in Mev. From the two experimental curves in Figure 3 it follows that the bias setting of 15 volts (which was used throughout the subsequent experiments) corresponded to a neutron energy of 0.15 Mev.
B. The Efficiency of the Neutron Counter

(1) Calculated Efficiency. The efficiency of the counter has been calculated, by an extension of the method of Barschall and Bethe. If the number of neutrons emitted into unit solid angle in the direction of the counter is \( N \), the number of neutrons counted is \( n \), and the solid angle subtended by the counter is \( \omega \), then the counter efficiency \( F \) is just

\[
F = \frac{n}{N \omega}.
\]

Now \( F \) is the probability that a count will result if a neutron passes anywhere through the counter. If the average neutron traverses \( D \) centimeters of the gas, the probability of giving a count is

\[
F = \sigma_0 E_n^{-\frac{1}{2}} N DP,
\]

where \( \sigma_0 \) is the neutron proton cross-section at 1 Mev, \( E_n^{-\frac{1}{2}} \) gives the variation of the neutron-proton cross-section with energy, \( N \) is the number of hydrogen atoms per cubic centimeter, and \( P \) is the probability that a recoil proton of energy \( E_p = E_n \cos^2 \theta \) recoiling at an angle \( \theta \) to the direction of the neutron will produce ionization enough to give a pulse above the bias energy \( B \).

32 G. C. Phillips and J. C. Harris, to be published.
Now defining a quantity $p$ as the probability that a recoil proton of energy $E_p$, starting anywhere within the gas of the counter, will release $B$ Mev to the counter, and $L(E_p, B)$ as the length of track in centimeters of a recoil of energy $E_p$ necessarily inside the counter to release the bias energy $B$, we have that

$$p = V_1/V.$$  

Here $V$ is the volume of the sensitive region of the counter (assumed spherical), and $V_1$ is the intercepted volume between two such spheres with centers displaced by $L(E_p, B)$. Then

$$p = 2 \pi \int_{r/2}^r (r^2 - x^2) \frac{d\varphi}{\sqrt{2}} \frac{\pi r^3}{\sqrt{2}} = 1 - \frac{3}{2} \left( \frac{L}{2r} \right) + \frac{1}{2} \left( \frac{L}{2r} \right)^3.$$  

The function $L(E_p, B)$ has been obtained from the range-energy relationship for protons for a bias of $B = 0.15$ Mev and from the known stopping power of hydrogen gas. To within 5 per cent for $0.2 \lesssim E_p \lesssim 2.0$ Mev, and $B = 0.15$ Mev that

$$L(E_p, B) = a + b E_p,$$

where $a = 0.7$, $b = -1.85$ (See Figure 4).

Since the numbers of protons, $\Sigma$, scattered into all unit solid angles in the c. of g. coordinates are equal, the number scattered between c. of g. angles $\varphi$ and $\varphi + d\varphi$ is $2 \pi \Sigma \sin \varphi \ d\varphi$. For neutron-proton scattering the

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$^{34}$M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 268 (1937).
laboratory angle $\Theta$ is related to the c. of g. angle $\phi$ by

$$2 \Theta = \phi.$$  

Thus the number scattered between $\Theta$ to $\Theta + d\Theta$ is

$$8 \pi \varphi \cos \Theta \sin \Theta d\Theta,$$

while the total number scattered is $4\pi \varphi$. Thus

$$P = \int_{\Theta}^{\Theta_0} 2 \varphi \cos \Theta \sin \Theta d\Theta,$$

where $\Theta_0$ is the maximum angle of recoil counted, defined by

$$B = E_n \cos^2 \Theta_0,$$

since $E_p = E_n \cos^2 \Theta$ for neutron-proton scattering. Noting that $dE_p = -2E_n \cos \Theta \sin \Theta d\Theta$, we have that

$$E_n^{1/2} P = E_n^{-3/2} \int_{B}^{E_n} p \, dE_p,$$

so that

$$E_n^{1/2} P = E_n^{-3/2} \int_{B}^{E_n} \left[1 - \frac{3}{2} \left(\frac{a+bE_p}{2n}\right) + \frac{1}{2} \left(\frac{a+bE_p}{2n}\right)^3\right] dE_p,$$

and on setting $\alpha = a/2n$, $\beta = b/2n$ we obtain

$$E_n^{1/2} P = \frac{E_n^{-3/2}}{2} \left\{ (1 - 3\alpha + \alpha^3) [E_n - B] - \frac{3\beta}{2} (1 - \alpha^2) [E_n - B^2] + \alpha \beta^2 [E_n - B^3] + \frac{\beta^3}{4} [E_n - B^4] \right\}.$$  

Since we know the values of all quantities:

\begin{itemize}
  \item $a = .7$ cm
  \item $b = -1.85$ cm/Mev
  \item $B = 0.15$ Mev
  \item $c = 4.16 \times 10^{-24}$ cm$^2$
  \item $k = \frac{273^0C}{293^0C} \times \frac{26}{30}$ atmos $\times 2 \times 2.69 \times 10^{19}$ H molecules cm$^{-3}$
  \item $= 4.33 \times 10^{19}$ H atoms cm$^{-3}$
  \item $D = ((4/3)r) = (4/3) 2.2$ cm $= 2.92$ cm,
\end{itemize}
we obtain the efficiencies shown by the smooth curve of Figure 5.

It should be noted that the above analysis does not strictly apply for $E_n \gg 2$ Mev because in this case it is impossible for head-on-collision recoils to produce a count; only protons at angles $\Theta$ great enough to give $E_p \leq E_n \cos^2 \Theta$ (where $E_n = 2$ Mev) will count.

Thus

$$E_n^{-3/2} P = \int_0^2 \text{MeV} \ f_p = \text{constant} \times E_n^{-3/2}$$

The consideration of the geometrical probability of a recoil's being sufficiently inside to count decreases the efficiency in this case by about a factor of two over that expected by the analysis of Barschall and Bethe, which only considers the variation with bias energy. Those authors derived

$$F = \sum_0 E_n^{-1/2} kD \left( \frac{E_n}{E_n} \right)$$

which is shown by the dashed curve of Figure 5.

(2) Experimental Efficiency. The efficiency of the counter was also determined experimentally. If the total cross-section $\sigma_t(E_d)$ is known for the production of neutrons of average energy $(E_n)_{av}$ by bombardment with deuterons of energy $E_D$, and if the experimentally observed angular distribution function $Y(\cos \phi, E_D)$ is known, it is possible to calculate the average efficiency $F_{av} \left[ (E_n)_{av} \right]$ for the counting of neutrons of average energy $(E_n)_{av}$. We have
\[ \sigma_t(E_d) = \frac{2\pi}{F_{av.}[(E_n)_{av.}]} \int_{-1}^{+1} Y(\cos \varphi, E_d) \, d(\cos \varphi). \]

Thus
\[ F_{av.}[(E_n)_{av.}] = \frac{2\pi}{\sigma_t(E_d)} \int_{-1}^{+1} Y(\cos \varphi, E_d) \, d(\cos \varphi). \]

From the known values of $\sigma_t(E_d)$ (See Section III.) and the nine determinations of $Y(\cos \varphi, E_d)$ at nine values of $E_d$ it was possible, by graphical integration, to obtain nine average values of the efficiency. These are shown by $x^S$ in Figure 5. It is noted that the experimental values agree with the $F$ calculated by considering the geometrical probability of a count to within about 15%. However, the disagreement with the values of $F$ obtained by the formula of Barschall and Bethe is $\sim 100\%$. In all that follows, when the counter efficiency $F$ is referred to, it will mean the values calculated by the theoretical method considering geometrical effects.

C. The Geometry of the Experiment. The beam of deuterons emerged from the analyzing magnet of the Rice Institute Van de Graaff generator in a 1-1/8 inch glass tube about 40 centimeters long. The end of the tube was terminated with a cup of light brass construction that contained the carbon target. The target was a thin, uniform layer of cerasine wax of 135 $\mu$gms/cm$^2$ that had been
evaporated onto a 10 mil thick silver disk. The target was placed at right angles to the deuteron beam which struck the target in the center on a spot less than 1.5 centimeters in diameter. The neutron counter was mounted on a rotatable table whose axis projected through the center of the target and was at right angles to the deuteron beam. The counter axis was parallel to the table axis, 10 centimeters from the target center, and the center of the sensitive volume of the counter was at the same height above the table as was the target center. The experimental arrangement is shown in Figure 6.

Using this arrangement, the counter subtended an angle of $\pm 12.6^\circ$ in the laboratory system of coordinates.

D. **Corrections for Center of Gravity Motion.**

Consider a reaction involving particles of mass $m_0$, $m_1$, $m_2$, $m_3$ and with an evolution of energy $Q$:

$$m_0 + m_1 \rightarrow M \rightarrow m_3 + m_2 + Q.$$  

To conserve momentum the center of gravity has velocity

$$V_{cg} = \frac{1}{M} \sqrt{2m_1E_1}$$

and energy

$$E_{cg} = \frac{m_1}{M} E_1.$$  

In coordinates where the center of gravity is at rest (c.g. coordinates) the energy available to the particles
2 and 3 is \( \mathcal{E} = E_1 + Q - E_{cg} = \frac{m_0}{M} E_1 + Q \). In these coordinates, to conserve momentum, particles 2 and 3 recoil at 180° to each other, and so \( \mathcal{E}_3 = \frac{m_2}{m_3} \mathcal{E}_2 \) and

\[
\mathcal{E} = \frac{m_0}{M} E_1 + Q = (1 + \frac{m_2}{m_3}) \mathcal{E}_2 \quad \text{or}
\]

\[
V_{2cg}^2 = \sqrt{\frac{2m_2}{m_2M} \left( \frac{m_0}{M} E_1 + Q \right)}
\]

gives the velocity of particle 2 in the c.g. system.

Now an angle \( \Theta \) in the laboratory is related to an angle \( \phi \) in the c.g. system by \( V_{2cg}^2 \sqrt{V_{cg}} = \frac{\sin \Theta}{\sin (\phi - \Theta)} \).

Thus

\[
\sin (\phi - \Theta) = \sqrt{\frac{m_1 m_2}{m_3 M}} \sqrt{\frac{E_1}{\frac{m_0}{M} E_1 + Q}} \sin \Theta.
\]

In reaction (2) \( m_0 = 12, m_1 = 2, m_2 = 1, m_3 = 15, M = 14 \)

\( Q = -0.281 \) so that

\[
\sin (\phi - \Theta) = \sqrt{\frac{E_1}{78 E_1 - 25.5}} \sin \Theta.
\]

In this way the transformation of the two angles may be calculated for any deuteron energy \( E_1 \).

The solid angle \( \omega \) subtended by the counter is also a function of this c.g. motion since it is defined by a different \( \Delta \phi \) at different c.g. angles \( \phi \). One has

\[
\omega = \frac{4.5 \text{ cm}}{(10 \text{ cm})^2} \times 2 \times 10 \text{ cm} \times \tan \frac{\Delta \phi}{2} = 0.9 \tan \frac{\Delta \phi}{2}.
\]
The data \( Y(\cos \Theta, E_D) \) was corrected for the center of gravity motion in this way.

E. **Calculations of the Cross Sections.** The yield of neutrons per deuteron was taken every 15° in the laboratory system. The procedure in taking data was to go several times back and forth through the angles. The data was then averaged. By the scatter in the values of \( Y(\cos \Theta, E_D) \) it is believed that the averages are correct to \( \pm \) 10 per cent. During all the runs, the background count of neutrons was frequently determined. The background neutrons were principally due to some of the deuterons striking carbon on surfaces in other parts of the vacuum system other than the target. To determine the background, the beam was held just on the low energy side of the defining slits at the exit of the analyzing magnet, so that no beam fell on the target but had essentially the same path in the rest of the vacuum system. A correction was made for these background neutrons, but they never exceeded 10% of the true counts.

The cross-section in barns per unit solid angle at the c.g. angle \( \Theta \) for the production of neutrons is given by

\[
\sigma(\cos \Theta, E_d) = \frac{Y(\cos \Theta, E_d) \omega(\Theta, E_D)}{F(\Theta, E_d)},
\]

where \( Y(\cos \Theta, E_d) \) is the number of neutrons counted per unit solid angle per deuteron per carbon atom at the angle \( \Theta \).
Now if \( N(\theta, E_d) \) is the number of neutrons counted at the laboratory angle \( \theta \) for \( I \) deuterons falling on \( C \) carbon atoms per cm\(^2\), then \( Y(\cos \theta, E_d) = \frac{N(\theta, E_d)}{I_G} \), so that

\[
\Sigma_c(\cos \varphi, E_d) = \frac{\omega(\theta, E_d)}{I_G \cos^2 \theta (E_d)} N(\theta, E_d).
\]

These quantities have been discussed and are all measurable. In this way the cross-sections were calculated. The final data are shown in Figure 7, where the elementary cross-sections \( \Sigma_c(\cos \varphi, E_d) \) are plotted as a function of the c.g. angle \( \varphi \) for the nine deuteron energies used: \( E_d = 0.77, 0.89, 0.99, 1.16, 1.20, 1.26, 1.35, 1.55 \) and \( 1.72 \).

V. THE LONG RANGE PROTON EXCITATION CURVES.

A. The Proton Counter. To count the long range protons from reaction (3):

\[
^6C^{12} + ^1H^2 \rightarrow ^5N^{14} \rightarrow ^6C^{13} + ^1H^1 + 2.7 \text{ Mev}
\]

a special proportional counter was constructed. The counter was formed of a brass cylinder 8 centimeters long and 5/8 inch inside diameter with soldered brass end plates. Through holes in the end plates Kovar glass-to-metal seals were soldered, and each served to support a short length of 31 gauge nickel wire. A 5 mil tungsten wire formed the collecting anode and was stretched between the nickel wire stubs. At the center of the counter a 0.5 centimeter
diameter hole was drilled, normal to the counter axis, through the cylinder wall. The hole was covered with a thin, hole free, aluminum foil that was 17.1 mg/cm². The counter was constructed integral with the preamplifier. The construction of the counter is shown in Figure 8.

The counter was found to operate satisfactorily at a pressure of 4 inches of tank Argon. The anode was maintained at 1100 volts positive, and the pulses developed across the counter, when a proton entered through the foil and traversed the gas, were amplified and counted by the same electronic system as was used for the detection of the neutrons.

A set of slots in front of the counter window allowed the insertion of various amounts of aluminum absorbers into the path of the protons. This technique was employed so that only the protons from reaction (3) would enter the counter and that no protons by the (d,p) reaction of the possible contamination of O¹⁶ would enter. Further, the foils were used to adjust the proton range so that only about a centimeter of range remained after passing through the counter gas; this assured that a large end-of-range energy release would result in a pulse well above the bias voltage. Typical counting rate versus bias and counting rate versus absorber curves are shown in Figure 9. At the bias settings used no gamma rays were counted from reaction (1).
B. The Geometry. A special target chamber was constructed so that the protons of reaction (3) could be observed at various angles. The chamber consisted of a brass cylinder 18 centimeters inside diameter and was 9 centimeters high. A bottom plate was silver soldered to the cylinder, and below this was a close fitting plate that carried the counter and could turn freely about the axis of the chamber. One-half inch holes were drilled every 15° about one side of the chamber (from 0° to 150°) and were covered with thin aluminum windows (~ 6 centimeters air equivalence). The target was placed on the axis of the cylinder and at the height of the exit holes. The target was carried by a ball-bearing support and could be rotated to calibrated angles by means of a permanent magnet external to the chamber. The aperture of the counter was 13.6 centimeters from the target center and at the height of the exit holes. The deuteron beam entered the chamber through a copper tube and collimating hole 0.5 centimeters in diameter in the same plane as the target center, the exit hole center, and the counter aperture center. When the target was placed at 45° to the beam direction, the beam fell on a spot on the target never exceeding 1 centimeter in diameter. Protons coming from anywhere on the bombarded spot saw essentially the same solid angle at the counter. The solid angle in laboratory coordinates was thus

\[ \omega_{\text{lab}} = \frac{\pi (0.5)^2}{4} / (13.6)^2 = 1.064 \times 10^{-3} \]
The geometry of the experiment is shown in Figure 10.

C. Target Preparation, Calibration, and Cross-Section Calculation.

The target employed to count the long range protons of reaction (3) and the positrons from the N^{13} (Section III) was prepared by cracking benzene vapor onto thin silver foils. Target blanks were prepared by spot welding silver foils (\(\sim 7 \text{ mg/cm}^2\)) between rings of 20 mil silver. The blanks were placed inside a Vycor combustion tube with one end sealed and with the other end connected to a mechanical vacuum pump and to a flask of benzene. The Vycor tube was evacuated and the vapor pressure of the benzene allowed to reach equilibrium inside it. The tube was isolated and then inserted into an electric furnace at 1500°F. When the tube had been in the furnace 5 to 10 minutes, it was removed and allowed to cool before opening to the air. Target blanks, on removal, had smooth layers of pure carbon on them. The thinnest targets made (\(\sim 7 \mu \text{ gms/cm}^2\)) were quite blue, while thicker targets (\(\sim 25 \mu \text{ gms/cm}^2\)) were jet black.

The target used to determine the excitation curves and the proton angular distributions was calibrated in terms of the yield of positrons (reaction (2)) for which the cross section had been accurately determined. The target,
placed at 45° to the incident deuterons, was exposed for 20 minutes at an energy of 0.99 Mev. The thin wall β-ray counter used previously was at 90° to the beam direction and had \(\frac{4\pi}{\omega} \ \beta\text{-ray counter} = 10^4\). An extrapolated \((\beta/\text{sec})_{1200"} = 8.32\) was observed for \(8.32 \times 10^{14}\) deuterons. Now at 0.99 Mev \(\Sigma_{N13} = 0.09 \times 10^{-24}\) cm². This gave for the thickness (at 45°): 35.5 μ gms/cm².

At the same time the bombardment for this data was made, the protons at 0° to the bombarding deuterons were counted. \(5.9 \times 10^{-11}\) protons per deuteron were observed considering the correction to the laboratory solid angle; this gave \(\Sigma_P(0.99\text{ Mev}) = 0.028\) barns/unit solid angle.

Using this cross section at 0°, the relative yields were plotted as cross sections in barns for the excitation yield curves taken at 0°, 90°, and 150° to the bombarding deuteron direction. These data are shown on Figure 11. It will be noted that all the resonances shown by reactions (1) and (2) occur for this reaction (3) as well as a previously unknown resonance at 1.13 Mev. However, the relative intensities of the resonances as shown by the three reactions are not the same.

VI. THE PROTON ANGULAR DISTRIBUTIONS.

A. Experimental Arrangement. To obtain the angular distribution of the protons of reaction (3), the same experimental
arrangement was employed as that used to obtain the excita-
tion curves for those protons (Section V). The main
difference in technique was that the protons were counted at
every 15° in the interval 0° to 150° about the beam direction.
The ratio of number of protons per deuteron was taken at each
angle in turn. The sequence of angles was gone through
several times and the yields averaged. The scatter about the
average was very small, ~ 2 to 3 per cent.

B. Corrections for the Center of Gravity Motion.

The motion of the compound nucleus \(^{14}_7\)N tends to
throw the protons in the direction of its motion. This
results in the center of gravity angle \(\phi\) being larger than
the laboratory angle \(\Theta\) by the relation

\[
\sin (\phi - \Theta) = \sqrt{\frac{E_1}{78 E_1 + 249 \sin \Theta}} = f (E_1, \Theta).
\]

Now if \(\omega\) is the laboratory solid angle, \(r\) the
counter aperture radius, \(R\) the target to counter separation,
then at the c.g. angle \(\phi\) the counter will subtend a solid
angle \(\omega_{c.g.}\) that is defined by an ellipse of axes \(b\) and
\(r\) at the distance \(R\). Thus \(\omega_{c.g.} = \pi rb/R^2\). Now since
the aperture is small (~ 2°), then \(b \ll R \Delta \phi\) and \(r \approx R \Delta \Theta\),
so that

\[
(b - r) = R[\Delta \phi - \Delta \Theta] = R [(\phi_2 - \Theta_2) - (\phi_1 - \Theta_1)]
\approx R f(E, \Theta) \Delta \Theta \cos \Theta.
\]
Thus

\[ \omega_{cg} = \omega \left[ 1 + 2 f(E, \theta) \cos \theta \right] = \omega \left[ 1 + S(E, \theta) \right]. \]

The functions \( f(E, \theta) \) and \( S(E, \theta) \) have been plotted and are shown on Figure 12. The correction for the center of gravity motion was taken from such graphs.

C. The Proton Ranges. It was necessary to know the variation of the proton ranges with the energy \( E_1 \) and the angle \( \theta \) so that the proper absorbing foils could be used. The calculation of the proton energy was made using the relation of Section IV:

\[ E_{\text{proton}} = \frac{1}{196} \left[ \sqrt{2 E_d \cos \theta + \sqrt{49 + 56 E_d - 2 E_d \sin^2 \theta}} \right]^2. \]

From the \( E_{\text{proton}} \) calculated in this way the ranges were obtained from the range versus energy curves.\(^{35}\) The ranges versus \( E_d \) are shown at several angles in Figure 13.

D. Calculation of the Cross Sections. The elementary cross-sections \( \sigma_{\text{proton}}(E, \phi) \) for the production of protons into unit solid angle at the c.g. angle \( \phi \) for deuterons of energy \( E \) were calculated from the observed yields by applying the corrections for center of gravity motion and the value of known target thickness. These cross-sections as a function of \( \phi \) are shown in Figure 14 at the five deuteron energies \( E_d = 0.75, 0.91, 0.99, 1.09, \) and 1.06 Mev.

\(^{35}\) M. S. Livingston and H. A. Bethe, op. cit., p. 268.
VII. **ANALYSIS OF THE ANGULAR DISTRIBUTIONS.**

A. **Theoretical Discussion.** In considering radioactive decay of the compound nucleus, it is supposed that the disintegrated system may be represented by a wave function $\psi(r, \theta, \phi, t)$ that satisfies the wave equation with the time:

$$i\hbar \frac{d\psi}{dt} = -\hat{H} \psi,$$

where $\hat{H}$ is the Hamiltonian operator of the system. Energy characteristic values $\mathcal{W}$ representing bound states of the system will have a representation

$$\psi \sim e^{\frac{i\mathcal{W}t}{\hbar}} U(r \theta \phi),$$

while radioactive states of half width $\Gamma/2$ will have the form

$$\psi \sim e^{\frac{i\mathcal{W}t}{\hbar}} e^{-\frac{rt}{2\hbar}} U(r \theta \phi).$$

When the time is removed, we have

$$\hat{H} U(r \theta \phi) = \mathcal{W}' U(r \theta \phi); \quad \mathcal{W}' = \mathcal{W} + i\frac{\Gamma}{2}.$$

We may quite generally assume that

$$U(r \theta \phi) = \frac{e^{ikr} f(\theta)}{r}$$

since the system will be symmetrical in $\phi$. The scattering cross-section $\sigma(\theta, E)$ into unit solid angle at the c.g. angle $\Theta$ is then

$$\sigma(\theta, E) = |f(\theta, E)|^2.$$
Now if \( f(\Theta, E) \) is assumed to be a function of bounded variation, we may expand it in Legendre polynomials of the first kind:

\[
f(\Theta, E) = \sum_{l} a_{l}(E) e^{i\alpha_{l}(E)} P_{l}(\cos \Theta).
\]

Thus we have

\[
\Sigma(\Theta, E) = \sum_{n} A_{n}(E) P_{n}(\cos \Theta).
\]

It will be indicated later how certain theories correlate the integers \( l \) with the angular momentum quantum number \( l \).

Any quantum mechanical treatment of disintegrations indicates that states in the system of angular momentum \( l \hbar \) will not be excited if the distance of closest approach \( b \) for that angular momentum exceeds the range of the nuclear forces \( r \).

Thus only if

\[
l \hbar < \frac{\hbar}{\chi} r,
\]

or for

\[
l < \frac{r}{\chi},
\]

where \( \chi = \frac{\hbar}{2 \pi m v} \). Thus one expects that the sum of Legendre polynomials should terminate. The effect of the coulomb barrier between the deuteron and the carbon nucleus increases this effect since the large values of \( l \) of the system will give a small probability of the interacting of the systems.
The coefficients $A_n(E)$ have been determined for
the angular distributions of reactions (2) and (3) by a
method that will be indicated later.

If $H = \frac{\hbar^2}{2\mu} \nabla^2 + V(r)$ is written in the wave
equation without the time, one obtains, upon separating
variables, the radial wave equation

$$\frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{dU_2(r)}{dr} \right) + \left( k^2 - \frac{l(l+1)}{r^2} + \frac{2\mu V(r)}{\hbar^2} \right) U_2(r) = 0,$$

where $k^2 = \frac{2\mu E^2}{\hbar^2}$, $\mu$ is the reduced mass of the system, and
$E$ is the kinetic energy, and $l$ is an integer. Here it has
been assumed that there is no spin in the system and that
the disintegrating system can be treated as particles
scattered by a center of force with potential $V(r)$. This
has the asymptotic solution for large $r$

$$U_2(r) \sim \frac{e^{-ikr}}{kr} - \frac{e^{i\eta_{2l}(k)}}{kr},$$

where $\eta_{2l}(k) \equiv e^{2i\gamma_{2l}(k)}$ is Heisenberg's $^{36}$ $S$
matrix element, and $\gamma_{2l}(k)$ is the phase shift introduced into
the solution by the presence of the term with $V(r)$. Following
the discussion given by several authors, $^{37,38,39,40,41,42}$

$^{36}$ W. Heisenberg, Zeit. f. Physik, 120, 513 (1943).
$^{37}$ Ning Hu, Phys. Rev. 74, 131 (1948).
$^{38}$ W. Heitler and Ning Hu, Proc. Roy. Irish Acad. 51A, No. 9
(1947).
$^{39}$ W. Heitler and Ning Hu, Nature 159, 776 (1947).
$^{40}$ C. Møller, Kgl. Danske Vid. Sels. Math-Fys. Medd 23, No. 1
(1945).
$^{41}$ Ibid, 22, No. 19 (1946).
$^{42}$ C. Møller, Nature 158, 403 (1946).
it should be noted that the bound states of the system require a wave function that is $\sim e^{\alpha r}$ where $\alpha$ real $\geq 0$. This requires that $S_{\ell}(k)$ have a pole or a zero along the imaginary axis of the $k$ plane. The radioactive states of the system require a function $\sim e^{i\beta r} e^{\alpha r}$ where $\alpha$ real $\geq 0$ and $\beta$ real. This necessitates that $S_{\ell}(k)$ have poles or zeroes at complex values of $k$. These authors show that all the observable properties of the nuclear system are determined by the type and position of the poles and zeroes of the functions $S_{\ell}(k)$.

Ning Hu reports to have shown that $S_{\ell}(k)$ can have only simple zeroes and poles in the finite plane if the range of the nuclear forces is smaller than the wave length of the particle. He obtains the general form for $S_{\ell}(k)$

$$ S_{\ell}(k) = e^{\pm ick} \prod_m \frac{(k-k_m^*)}{(k-k_m)} \prod_n \frac{(k-k_n^*)(k+k_n)}{(k-k_n)(k+k_n^*)} $$

where $e^{\pm ick}$ represents the possible essential singularity at infinity. The set $\{k_n\}$ are the location of the poles at complex values of $k$ and correspond to the virtual states of the system. The set $\{k_m\}$ gives the location of the poles for pure imaginary values of $k$ and correspond to the bound states of the system.

In the particular case where there is only one pole at $k_n = k_{\ell}$ he obtains the Breit and Wigner "one level formula"
\[ \sigma(E) \propto \frac{(\Gamma_{3/2})^2}{E \left[ (E-W_l)^2 + (\Gamma_{3/2})^2 \right]} \]

when he sets \( k_{l}^2 = \frac{2 \mu E}{\hbar^2} = \frac{2 \mu}{\hbar^2} (W_l - \frac{1}{2} i \Gamma_l) \).

The wave function in \( \Theta \) becomes, in general,

\[ \phi(\Theta) = \frac{1}{2 \sqrt{k}} \sum_l (2l+1) \left[ e^{i\pi \delta_{l,m}} S_l(k) - 1 \right] P_l(\cos \Theta). \]

In the case of two levels, one at \( W_l = 0 \) and one at \( W_l = 1 \), we obtain

\[ \sigma(E,E) = \left\{ \left[ \phi_0(E) + 3 \phi_1(E) \right] P_0(\cos \Theta) + 6 \left[ \phi_0(E) \phi_1(E) \right] P_1(\cos \Theta) \right\}, \]

where

\[ \phi_{l}(E) = \frac{4}{\mu} \frac{(\Gamma_{3/2})^2}{E \left[ (E-W_l)^2 + (\Gamma_{3/2})^2 \right]} \]

and

\[ \delta_{l,m}(E) = \pm \frac{\mu}{8E} \frac{1}{(\Gamma_{3/2})^2} \frac{(E^2-W_l^2)(E^2-W_m^2)}{(E^2-W_m^2)}. \]

These formulae allow one to predict the exact shape of the \( A_n(E) \) functions when a set of numbers \( \{W_l, \Gamma_l \} \) are assumed for each of the virtual levels. Since perhaps \( W_l \) and \( \Gamma_l \) can be determined from the shape of the excitation curve, one may be able to determine the \( l \) for the level. It should be noted, however, that a more extensive theory is needed--particularly to include the spin--since the weighting factors are most likely not as simple as the theory would
indicate. Nevertheless, at the time of this writing, work is in progress to perform such fitting.

Perhaps the most significant feature of the discussion is that in actuality it appears that \( l \) may be determined for each level by much simpler considerations. If the highest \( l \) that appears in the function \( f(E, \Theta) \) for a certain range of \( E \) is \( l' \), which arises from a level \( W_{l'} \) in the range of \( E \), then the highest order \( A_n(E) \) that will appear in \( \sigma'(E, \Theta) \) is \( A_{2l'}(E) \). Since the analysis on the S matrix is probably very nearly sound physically (in spite of some apparent mathematical errors), it appears that such an \( A_{2l'}(E) \) must go through a positive maximum in the region of \( W_{l'} \). If, however, there is a contribution to \( f(\Theta, E) \) for values of \( l > l' \), then \( A_{2l'}(E) \) will contain interference terms that may even make \( A_{2l'}(E) \) negative in the region of \( W \).

B. Technique of the Analyses of the Angular Distributions.

If it is assumed, as in the previous section, that the cross-section may be expanded as

\[
\sigma(E, \cos \Theta) = \sum_n A_n(E) P_n(\cos \Theta)
\]

then multiplying by \( P_m(\cos \Theta) \, d(\cos \Theta) \) and integrating one has

\[
I_n = \int_{-1}^{+1} \sigma(E, \cos \Theta) \, P_m(\cos \Theta) \, d(\cos \Theta) = \int_{-1}^{+1} \sum_n A_n(E) P_n(\cos \Theta) P_m(\cos \Theta) \, d(\cos \Theta)
\]
For a finite sum

\[ I_n = \frac{2}{2n + 1} A_n(E) \]

because of the orthogonality of the Legendre functions. Thus the coefficients \( A_n(E) \) are given by

\[ A_n(E) = \frac{2n + 1}{2} I_n \]

To evaluate the integrals \( I_n \), the experimentally determined cross-sections \( \sigma(E, \cos \Theta) \) were multiplied by the successive Legendre functions and integrated graphically. In this way the \( A_n(E) \) were determined for the two reactions (2) and (3). \( A_n(E) \) coefficients contributing less than the estimated experimental error were ignored. The coefficients \( A_n(E) \) are shown in Figures 15 and 16 for the neutrons and protons respectively. It is noted that no polynomials of order higher than \( P_6(\cos \Theta) \) were needed to fit the neutron data, and none higher than \( P_4(\cos \Theta) \) were needed for the proton data. The proton data are the more accurate \( (\sim 3\%) \), and so the fitting within the small experimental error is an impressively successful application of quantum mechanical principles to a nuclear phenomenon.

VIII. DISCUSSION OF RESULTS.

A. Comparison of the Competing Reactions. The three reactions may be compared in several ways as will be discussed below. One hopes to be able to attribute to each
level \( r \) in the compound \( ^{14}N \) nucleus an energy position \( W_\ell \), a total width \( \Gamma_\ell \) and to say what angular momentum \( \ell \hbar \) creates the state. In the discussion that follows, the influence of the penetrabilities for the two proton groups on the various reaction features will be discussed. For this purpose the penetrabilities of the two proton groups have been obtained from Christy and Latter's curves for deuterons of energy \( E_d \) and are shown below.

### Short Range Proton Penetrabilities

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<th>( P_{\ell = 1} ) ( \times 10^{-3} )</th>
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### Long Range Proton Penetrabilities

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<th>( P_{\ell = 0} )</th>
<th>( P_{\ell = 1} )</th>
<th>( P_{\ell = 2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>.7</td>
<td>.69</td>
<td>.44</td>
<td>.154</td>
</tr>
<tr>
<td>1.3</td>
<td>.71</td>
<td>.51</td>
<td>.200</td>
</tr>
</tbody>
</table>
The "penetrability" of the neutrons is assumed throughout to be one.

1.) The Position of Resonances. If one supposes that the anomalous cross-sections for disintegrations are due to a set of levels occurring at excitation energies $W_2$ of the $N^{14}$ nucleus, it appears that most of the observed phenomena may be described by saying that the excitation of each level gives a resonance for each of the reactions. Actually, not all of the observed resonances are shown by all of the reactions, but this need not invalidate the theory. However, Heydenburg, et al, have apparently doubted the validity of the competing mechanism$^{43}$ for this reaction. It will be shown that there is strong experimental evidence that competition occurs. There are several resonances that do not occur for all of the three reactions; however, this may be explained by assuming the operation of some form of selection rules. The 1.435 Mev resonance occurs only for reactions (1) and (3) as far as can be determined; the 1.13 Mev resonance only for reaction (3). The 1.73 Mev resonance for gamma rays (reaction (1)) very likely is the same level as the 1.76 Mev resonance for reaction (2). The 1.62 Mev resonance for reaction (2) is not known for reaction (1) but may occur in reaction (3).

$^{43}$Heydenburg, Inglis, Whitehead, and Hafner, op. cit.
In general, however, the levels appear to show competition at the 0.91, 1.16, 1.30 Mev resonances.

The positions at which the resonances occur do not come at exactly the same energy. This may be explained by the form of the widths \( \Gamma^C_r, J_C \) that occur in the numerator of the dispersion formula (Section I). These widths have as a factor the penetrability for entrance (or exit) of the particle P, and this penetrability is a function of the relative energy of P and the angular momentum of P. Thus, for example, if the penetrability increases sufficiently rapidly across the level, the resonance shape will be distorted, and the maximum will occur at a higher energy. The shift of the 1.16 Mev level for reaction (2) up to \( \sim 1.20 \) Mev for reaction (3) does not appear to be explained in this way, since if the long range protons have \( l = 0 \), their penetrability will change \( \sim 3\% \) per 100 kev in the region of 1.16 Mev. This would not seem to be enough to shift the peak \( \sim 40 \) kev. We should expect an even larger shift for the short range protons of reaction (1) for the 1.16 Mev resonance, for in this region the penetrability changes by a factor of about 3 in going across the resonance. No shift of the 1.16 resonance for reaction (1) with respect to reaction (2) is observed.

In a similar way the resonance shown at 0.91 Mev by all three reactions would be expected to be shifted. At
0.91 Mev the short range protons have their penetrability changing by a factor of 6 in going across the resonance, while the penetrability of the long range protons shows a change of only a few per cent. It appears that the long range protons may show a slight upward shift $\sim 10$ kev, while the short range protons do not seem to be shifted at all. This is certainly not what would be expected.

The resonance at 1.30 Mev exhibits the same contradiction, for the short range proton penetrabilities increase by about 40%, while their resonance occurs at the same voltage as that of the neutrons. The long range proton penetrabilities change by only a few per cent, yet their resonance is perhaps shifted upwards around 10 kev.

The most striking examples of the shifting of resonance position are when particles are observed at different angles across a resonance. The 1.435 Mev resonance shows a shift $\sim 15$ kev from $0^\circ$ to $150^\circ$. However, this is an entirely different phenomenon from that discussed above and should not be confused with it. This shift, due to the angle of observation, may be simply explained as interference of the protons from the state corresponding to 1.435 Mev deuterons with the "background" protons.

The best estimates of the positions of the resonances $W_l$ are shown in Table I.
2.) **The Intensity of Resonances.** The intensity of a resonance is determined by the statistical weighting factor \( (2J_c + 1)(2J_B + 1)(2S_A + 1) \), by the widths for excitation of the state \( r \) in \( N^{14} \), and also by the "background", due to the contributions of overlapping levels. As was mentioned above, the widths for formation are functions of the penetrabilities of the reaction products and so may be different for competing reactions from the same state \( r \) in \( N^{14} \). This fact, in principle, would allow one to estimate the angular momentum of the reaction products. For example, if we assume that the levels at 0.91 and 1.16 Mev are identical for reactions (2) and (3) except for the penetrability of the protons of reaction (3), we may deduce the angular momentum of the protons and neutrons. It is found that \( \sigma_p(0.91)/\sigma_n(0.91) \approx 4.6 \), while \( \sigma_p(1.16)/\sigma_n(1.16) \approx 7.3 \); and this indicates that the protons at 0.91 have about half the chance of getting out as those at 1.16 Mev have. The penetrabilities of these protons for bombarding deuteron energies in the range 0.9 to 1.2 Mev are: \( P_{l=0} \approx .7, P_{l=1} = .45 \rightarrow .46, P_{l=2} = .16 \rightarrow .17 \). Thus we may, for example, assume that the level at 0.91 has \( l_n,p = 1 \) neutrons and protons and the level at 1.16 has \( l_n,p = 0 \) and explain the observed ratio sufficiently well. One might also choose \( l_{n,p} = 2 \) at 0.91 and \( l_{n,p} = 1 \) at 1.16 Mev.
In a similar way it may be estimated that
\[ \sqrt{p(1.30)} / \sigma_n(1.30) \approx 1/6. \] Thus we may say that the penetrability at 1.30 Mev for the protons is 1/6 x 1/1.4 \approx 1/10 of the penetrability at 1.16 Mev. This would be consistent with a level at 1.30 Mev having \( l_{n,p} = 2 \) or \( l_{n,p} = 3 \).

If it is assumed that the only factor influencing the ratios of cross-sections for the competing reactions is the penetrabilities of the protons, one would expect that the short range protons of reaction (1) would show a much steeper rise at the 0.91 Mev resonance than reactions (2) or (3), since on the low energy side of the resonance there are no other resonances contributing strongly to the cross-sections. One would expect, for example, that

\[
\frac{\sigma^{(1)}(0.8 \text{ Mev})}{\sigma^{(2)}(0.8 \text{ Mev})} / \frac{\sigma^{(1)}(0.91 \text{ Mev})}{\sigma^{(2)}(0.91 \text{ Mev})} = \frac{P^{(1)}(0.8 \text{ Mev})}{P^{(2)}(0.8 \text{ Mev})} / \frac{P^{(1)}(0.91 \text{ Mev})}{P^{(2)}(0.91 \text{ Mev})}
\]

where \( \sigma^{(1)}(0.8 \text{ Mev}) \) and \( P^{(1)}(0.8 \text{ Mev}) \) are the cross-section and penetrability respectively for the protons of reaction (1) at a bombarding energy of 0.80 Mev, etc. The quantity on the left is \( \frac{0.065}{0.030} / \frac{0.28}{0.12} = 0.93 \). The ratio on the right for \( l = 0 \) protons is \( \frac{0.0065}{1} / \frac{0.02}{1} = 0.32 \), and for \( l = 1 \), protons is \( \frac{0.82 \times 10^{-3}}{1} / \frac{2.76 \times 10^{-3}}{1} = 0.30 \). The ratios do not check by a factor of three.
Comparing reactions (1) and (3) in a similar way, one finds the cross-section ratio is equal to 1, while the penetrability ratio for $\ell = 0$ or $\ell = 1$ is 0.3. These again differ by a factor of three.

The same type of comparison for the 0.91 Mev resonance for reactions (2) and (3) gives the cross-section ratio 1.11, while the penetrability ratios for $\ell = 0$ and $\ell = 1$ are 1.02. These ratios check within the estimated experimental errors of the determinations.

Since the cross-section measurements have an estimated error of only 10% and since the ratios of the penetrabilities for reactions (1) to (2) and (1) to (3) disagree with the ratios of the cross-sections by a factor of three, it seems certain that there must be something other than the penetrability influencing the emission of the short range protons at the 0.91 Mev resonance. The discrepancy will become less at the higher levels since the penetrabilities tend to one. However, in the range 0.7 to 1.3 Mev, where the neutron yield stays constant within a factor of 2, the short range proton penetrabilities vary by a factor of 10. The gamma ray reaction (1) remains constant within a factor of 2 in the region, completely disagreeing with the large calculated penetrability increase.

The ratios of intensities of the reactions (1), (2) and (3) show the difficulty in explaining these intensities.
In Table I the normalized estimated intensities $I$ (above background) for the resonances are given. The column marked $Y$ is a normalized "corrected intensity", the estimated intensity of the level divided by the penetrability of the proton with the assumed angular momentum $\Omega$. The most striking feature of this table is that reaction (1) is $10^3$ to $10^4$ more intense than would be expected.

In searching for an explanation of this seeming discrepancy, one notes that in conserving parity and total angular momentum in reactions (2) and (3) that $l_{n,p} = l_d + 1$, but that the spin changes across the reaction. This follows from the known spins (deuteron, 1; carbon, 0; $^1$C$^{13}$, 1/2; $^1$N$^{13}$ probably 1/2) and the assumed even parity of $^2$C$^{12}$ and the odd parity for $^1$C$^{13}$ and $^1$N$^{13}$. The spin must change from 1 on the left of the reaction to 0 on the right. Spin-orbit interaction would allow such a change. Now in reaction (1) one knows nothing about the parity of $^1$C$^{13}$; and if it is assumed to have odd (spin 1/2 or 3/2), one gets the same situation described above. However, if it is assumed that $^1$C$^{13}$ has even parity (spin 1/2 or 3/2), it follows that $l_p = l_d$, $l_d + 2$; and in either case the spin can be transferred unchanged. Thus it would appear that by invoking a strong selection rule for spin conservation (forbidding spin-orbit interaction), one may explain why reaction (1) is so much stronger than (2) and (3).
Another possible explanation is that in some way the deuteron forms a $^14N$ nucleus without the proton in the deuteron having to penetrate all of the coulomb barrier.

The cross-sections at resonance are given in Table I along with the estimated relative intensities of the levels. This latter number is somewhat subject to error as it involves estimating the resonance contribution above the background. These intensities are normalized to the cross-section for reaction (2) at 0.91 Mev.

3.) The Widths of the Resonances. The width $\Gamma_r$ of the state $r$ of $^14N$ is determined by the modes of decay of the state, and should, according to theory, be the same for competing reactions from the same state $r$. However, in practice one estimates $\Gamma_r$ from the excitation curves, and when the widths for formation, in the numerator of the Breit-Wigner formula, vary appreciably in the energy range $\Gamma_r$ about $W_r$, then the shape is distorted from that to be expected from the total width $\Gamma_r$ alone. This perhaps accounts for the variation in widths in reactions (1) and (3) at 1.16 Mev. However, the small magnitude of the variation lends credence to the belief that $\Gamma_r$ is the same for the competing processes.

The estimated values of $\Gamma_r$ are shown in Table I.

4.) Comparison of the Angular Distributions. The angular distributions for the reactions (2) and (3) are
perhaps the most interesting phenomena to be compared. The striking similarities of the distributions add credibility to the compound-nucleus, competing-process hypothesis.

As was discussed in Section VII, the angular distributions should indicate the angular momentum state in the \( N^{14} \) nucleus. However, because of the spins of the particles it is not clear to just what the \( \ell \) in the coefficients \( A_{2\ell}(E) \) refers. There are apparently two ways of discussing this problem. It will first be assumed that \( \ell \) is the quantum number of a neutron or proton possessing angular momentum \( \ell \hbar \) about the residual nucleus. For this discussion it will be assumed that \( C^{12} \) in its ground state has even parity. \( C^{12} \) is known to have spin zero. The deuteron has spin 1. One knows that \( C^{13} \) has spin 1/2 and it will be assumed that \( N^{13} \) has spin 1/2 and that they both have odd parity. If these assumptions are true, it may be concluded that there should be no major differences in the angular distributions of reactions (2) and (3) except for intensity differences caused by the coulomb barrier penetration of the protons in reaction (3). This seems to be verified; for the plots of \( A_n(E) \) coefficients of both reactions, as are shown in Figures 15 and 16, are strikingly similar in the common energy region where they have been determined. As was indicated in Section VII, one expects the angular momentum of the proton or neutron to be shown
by an anomaly in the coefficient $A_2 l (E)$ in the region of the level $W$. Now for both reactions the level at 0.91 Mev is shown principally by the $A_0$ coefficient, but it may also show an anomaly in $A_2$. The level at 1.16 Mev is shown strongly by $A_0$ and $A_2$ for both reactions. The presence of $A_4$ and $A_6$ coefficients might be explained as due to higher lying levels, but $A_4$ probably does show the 1.30 Mev resonance for the neutrons.

If a table of allowed values of $l_{n,p}$ is constructed, one obtains:

<table>
<thead>
<tr>
<th>$l_d$</th>
<th>$l_{n,p}$</th>
<th>$f(\Theta)$</th>
<th>$\nabla(\Theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\pm 1$</td>
<td>$P_1(\cos\Theta)$</td>
<td>$P_0, P_2$</td>
</tr>
<tr>
<td>1</td>
<td>0, $\pm 2$</td>
<td>$P_0(\cos\Theta), P_2(\cos\Theta)$</td>
<td>$P_0, P_2, P_4$</td>
</tr>
<tr>
<td>2</td>
<td>$\pm 1, \pm 3$</td>
<td>$P_1(\cos\Theta), P_3(\cos\Theta)$</td>
<td>$P_0, P_2, P_4, P_6$</td>
</tr>
</tbody>
</table>

This is based on the relation which was mentioned above that $l_{n,p} = l_d \pm 1$, which follows from the conservation of total angular momentum and parity. The column marked $f(\Theta)$ indicates the Legendre polynomials that would be expected to arise in the wave function, and the column marked $\nabla(\Theta)$ indicates the Legendre polynomials that should appear in the elementary cross-section. By these considerations one may
conclude that the levels at 0.91 and 1.16 Mev are due either
to \( l_d = 0 \), or \( l_d = 1 \), giving respectively either \( l_{n,p} = 1 \),
or \( l_{n,p} = 0 \). It appears impossible to decide between these
two possibilities on the basis of the angular distributions
alone. However, the argument about intensities in the pre-
ceding section may determine this uniquely. Since angular
distributions of the protons have not yet been obtained above
1.16 Mev, one has only the neutron angular distributions to
consider. The neutrons show anomalies in \( P_0 \), \( P_2 \) and probably
\( P_4 \) at 1.30 Mev which might be attributed to \( l_d = 1 \) and
\( l_n = 2 \). This again agrees with the possible \( l_{n,p} \) for this
level obtained by the intensity argument. One may consider
the excitation curve for the protons in this region as giving
three points on an angular distribution. The large backward
asymmetry indicates a large negative \( A_1 \) and possibly a large
\( A_3 \), both of which are shown by the neutrons. Thus the scant
extent data for the protons do not invalidate the argument.

The arguments for the angular momentum values are
summed up in the table below and in Table I. These are only
provisional values.

<table>
<thead>
<tr>
<th>Resonance Energy Mev</th>
<th>( l_{np} ) by Intensity</th>
<th>( l_{np} ) by Angular Distributions</th>
<th>Probable ( l_{np} )</th>
<th>Probable ( l_d )</th>
<th>( J(N^{14}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>1</td>
<td>0 or 1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1.16</td>
<td>0 or 1</td>
<td>0 or 1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.30</td>
<td>2 or 3</td>
<td>1 or 2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
In direct contradiction to the above conclusions one may argue that since the system is unpolarized, if S deuterons only contribute to the first level, the angular distribution of the system should be spherically symmetric. However $l_{n,p} = \pm 1$. Critchfield and Teller,\textsuperscript{44} in referring to the $\text{Li}^7 + \text{H}^1 \rightarrow 2 \text{He}^4$ reaction, said, "Since the bombarded nuclei are completely unpolarized, and since the spins of the incident protons are also unpolarized the emitted beam cannot show more complicated transformation properties under the rotation of coordinates than those of the orbital momentum of the incident beam." If such an argument applies to the $\text{C}^{12} + \text{H}^2$ reaction, it will, of course, invalidate all of the previous arguments about the "meaning" of the numbers $l$. And would perhaps indicate that the $l$ refers to the angular momentum of the deuterons and not to the disintegrating system. This contradiction is not resolved at the time of this writing.

B. Conclusions. It may be concluded that the experimental data for the $\text{C}^{12} + \text{H}^2$ reaction, with its three modes of decomposition, indicate that, in general, levels of the compound $\text{N}^{14}$ nucleus compete. These levels in $\text{N}^{14}$ show the same widths and have similar angular distributions where investigated. No definite conclusions have been obtained as

\textsuperscript{44}C. L. Critchfield and E. Teller, Phys. Rev. 60, 10 (1941).
to the angular momentum of the states, but rather a very interesting contradiction is indicated.

More angular distributions at higher bombarding energies are needed for the long range protons, and the high energy neutron angular distributions must be analyzed. The contradictions that occur in comparing the intensities of the reactions show that the consideration of penetrabilities alone is not sufficient to explain the phenomena. It appears that the short range protons do not have to penetrate the coulomb barrier and yet that the intermediate nucleus $^14N$ is formed as in the other two reactions.

It is hoped that further study of these competing reactions will resolve some of the confusion.

C. Acknowledgments.

I wish to thank Professor T. W. Bonner for his suggestion of this interesting problem and for his helpful direction of its pursuit. For discussions of the theory of angular distributions and dispersion I am indebted to Professors H. A. Wilson and W. V. Houston. To Professors C. W. Heaps and J. R. Risser I owe thanks for many helpful suggestions. Finally I wish to thank the many people who have assisted in the operation of the electrostatic generator. From Mr. J. E. Richardson I received valuable aid in the construction of the thin carbon targets on
silver foils. Dr. J. E. Evans and especially Dr. J. C. Harris assisted in the determination of the neutron angular distributions. The proton chamber and counter were constructed jointly and used jointly with Mr. Ward Whaling. Mr. Van der Henst and Mr. de Vries help in the construction of apparatus is appreciated. I wish to thank my wife for help in correcting the manuscript.

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BRASS TARGET CUP

TARGET

GLASS TUBE

NEUTRON COUNTER

~40 CM.

10 CM.

ANALYZING MAGNET

GEOMETRY FOR THE NEUTRON ANGULAR DISTRIBUTIONS
\[ \sigma^-(\phi) = |F(\phi)|^2 = \sum_{\omega} A_{\omega} \rho_{\omega}(\phi) \]

CROSS SECTION - BARN/UNIT SOLID ANGLE

DEUTERON ENERGY - MEV

FIG. 16
<table>
<thead>
<tr>
<th>Deuteron Energy at Resonance (Mev)</th>
<th>W (Mev)</th>
<th>Probable Value of</th>
<th>J(N14) (Mev)</th>
<th>Estimated Relative Intensities</th>
<th>Relative Intensities (Corrected)</th>
<th>Y(Y)</th>
<th>Y(3)</th>
<th>Y(3)/Y(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>11.04</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>.200</td>
<td>2.5</td>
<td>1.0</td>
<td>4.6</td>
</tr>
<tr>
<td>1.13</td>
<td>11.23</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>&lt;.030</td>
<td>0</td>
<td>0</td>
<td>7.1</td>
</tr>
<tr>
<td>1.16</td>
<td>11.25</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>.200</td>
<td>2.5</td>
<td>1.0</td>
<td>7.3</td>
</tr>
<tr>
<td>1.30</td>
<td>11.37</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>.080</td>
<td>2.5</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>1.435</td>
<td>11.49</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>.0055</td>
<td>2.5</td>
<td>&lt;0.1</td>
<td>&lt;8</td>
</tr>
<tr>
<td>1.62</td>
<td>11.65</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>.200</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.73</td>
<td>11.74</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>.200</td>
<td>9.0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

(nd means no data or not enough data)
The Neutrons and Gamma-Rays from the Disintegration of C\textsuperscript{12} by Deuterons

T. W. Bonner, J. E. Evans, J. C. Harris, and G. C. Phillips

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(Received January 17, 1949)

The excitation curves for the production of gamma-rays and neutrons resulting from the bombardment of carbon by deuterons have been determined over the deuteron energies 0.7 to 1.9 Mev. A careful study of the very narrow gamma-ray resonance occurring at 1.435 Mev has shown that the half-width of the resonance is 5.5 kev and the cross section is 0.62 barn at resonance. Other gammaray resonances were observed at 0.91, 1.16, 1.30, and 1.73 Mev with cross sections, respectively, of 0.29, 0.34, 0.39, and 0.97 barn. No resonance for the production of neutrons has been observed at, or near, 1.435 Mev. Resonances for the production of neutrons were observed at energies of 0.91, 1.16, 1.30, 1.62, and 1.75 Mev with the total cross section at resonance, respectively, of 0.12, 0.14, 0.19, 0.19 and 0.22 barn. The angular distributions of the neutrons have been studied; the distributions are quite complex and vary radically with changes in the bombarding energy. At 1.26 Mev there are about five times as many neutrons at 160° as at 0° to the direction of the deuteron beam.

INTRODUCTION

RESONANCE yields occurring in the deuteron bombardment of carbon were first observed in 1940 by Bennett and Bonner. In a series of experiments done at the Rice Institute\textsuperscript{5,6} and at the University of Minnesota\textsuperscript{5,6} the excitation yields for the various disintegration products were determined. The nuclear reactions occurring in C\textsuperscript{12} and the energy released in each reaction are

\begin{align*}
&\text{(1)} \quad ^{2}\text{C} + ^{2}\text{H} \rightarrow ^{4}\text{He} + ^{14}\text{N} + ^{1}\text{H} + 2.7 \text{ Mev},^{7} \\
&\text{(2)} \quad ^{2}\text{C} + ^{2}\text{H} \rightarrow ^{4}\text{He} + ^{14}\text{N} + ^{1}\text{H} + 0.5 \text{ Mev},^{8} \\
&\text{(3)} \quad ^{2}\text{C} + ^{2}\text{H} \rightarrow ^{4}\text{He} + ^{14}\text{N} + ^{1}\text{H} + 0.281 \text{ Mev}.^{8}
\end{align*}

The gamma-rays emitted from the excited \(^{2}\text{C}\) of reaction (2) have been determined to have an energy of 3.11 Mev,\textsuperscript{9} which is to be compared to a value of 3.2 expected from the measured values of the energy released in reactions (1) and (2). The energy of the gamma-ray involved in the very narrow resonance at 1.435 Mev was checked and found to be about 3 Mev,\textsuperscript{7} the same as for the other broader resonances.

One of the objects of the present experiment was to obtain the natural width of the sharp resonance at 1.435 Mev. In the previous experiments the observed width of this resonance was 10 kev, but since this was the width expected from the spread in energy of the beam of deuterons, the data showed only that this level was narrower than 10 kev. With the improved resolution of our apparatus, the natural width could be obtained.

Another object of these experiments was to find if neutrons from reaction (3) showed a resonance at 1.435 Mev. The earlier experiments indicated no resonance, but a careful search for resonant effects is important since it is very difficult to understand theoretically why any level in the excited \(^{14}\text{N}\) nucleus, no matter what its parity and angular momentum, cannot break up into \(^{14}\text{N}\) and a neutron.

A study of the angular distribution of the neutrons of reaction (3) has been prompted by the somewhat different form of excitation curves obtained by measurements of the positron activities of \(^{14}\text{N}\) (a measure of total neutron production over all angles) and curves obtained by direct detection of the neutrons emitted in a small solid angle from a carbon target. Similarly Bailey, Freier, and Williams\textsuperscript{5} have discovered a very marked difference between the excitation curves for the production of neutrons taken at 0° and 90° to the bombarding deuteron direction.

APPARATUS

The Rice Institute Van de Graaff generator was used to accelerate the deuterons. Regulation of the beam-analyzing electromagnet (supplied now by a bank of high capacity storage batteries instead of a generator as in previous descriptions\textsuperscript{10}), in combination with a potential stabilizer used to modulate an electron beam to the central electrode, gave a deuteron beam with an estimated resolution of 0.01 percent, or less, of the operating voltage. A beam current integrating device, designed by B. E. Watt,\textsuperscript{11} gave a count on a mechanical register for each 0.0416 microcoulomb of deuteron charge collected at the target.

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\textsuperscript{14} Bennett, Bonner, Mandeville, and Watt, Phys. Rev. 70, 882 (1946).
\textsuperscript{15} B. E. Watt, Rev. Sci. Inst. 17, 334 (1946).
Some of the carbon targets were prepared by heating small volumes of ceresin wax in a vacuum and collecting a thin film of the wax on a polished silver disk. The target thickness in $\mu$ g/cm$^2$ was determined by weighing the wax deposit on a microbalance. These targets did not collect carbon or deuterium in quantities sufficient to be detected as an increase in gamma-rays or neutrons. However, ceresin wax targets when deposited on very thin silver foils and exposed to the deuteron beam in a vacuum were found to become thinner. More satisfactory targets of pure carbon were made by cracking benzene in an atmosphere of helium onto the surface of silver foils.\textsuperscript{12}

The counter used to determine the angular distribution of the neutrons was a cylindrical proportional counter of 4.5-cm inner diameter and a sensitive length of 4.5-cm, with a one mil tungsten wire. The counter was filled with one atmosphere of hydrogen and two percent methane, and operated at 1920 volts with an Atomic Instrument Company type 204-B Linear Amplifier.

\textsuperscript{12} G. C. Phillips and J. Richardson (to be published).

DETERMINATION OF THE EXCITATION CURVES

The Gamma-Rays

In order to study the gamma-rays that accompany the short range proton group of reaction (2), a thin-walled, argon-filled Geiger counter was placed at about 8 cm from the center of the target and at about 90° to the direction of the deuteron beam. Large lead blocks were used to shield the counter from stray gamma-rays originating from carbon contamination along the beam path. In addition, about an inch of lead was placed around the counter to absorb scattered x-rays coming from the high voltage electrode of the Van de Graaff generator and annihilation radiation coming from the N$^2$. The counting rate for this arrangement of the Geiger counter became too great above 1.5 Mev. To keep the counting rate of the background radiation a small percentage of the total counting rate, a much smaller Geiger counter was used in preference to moving the original counter farther from the target. Background determinations were usually made by allowing the entire beam to fall just on the low energy side of the analyzing slit system, thus blocking the beam from the target, but giving essentially the same amount of radiation from carbon.
contamination elsewhere along the beam path. Under these conditions this background counting rate was about 10 percent of the total rate for a very thin target that was only 3.0 \( \mu \) g/cm\(^2\) of ceresin. For the thicker targets, which were ordinarily used, the background was correspondingly less.

To determine accurately the cross section for the production of gamma-rays, a thick, pure graphite target was bombarded with deuterons of 1.30-Mev energy. Since the "thin" target relative yield of gamma-rays as a function of energy was known, the cross section for gamma-rays could be calculated from the observed thick target yield by integrating the thin target curve from 0 to 1.30 Mev. A small counter with a copper cathode was placed 17 cm from the target and surrounded by 1.4 cm of lead. A counter efficiency of 1.65 percent was assumed for the 3.1-Mev gamma-rays.\(^{13}\) The transmission of the lead under identical geometrical conditions was determined experimentally by means of 2.62-Mev gamma-rays from mesothorium and found to be 48 percent. These data gave a cross section at 1.30 Mev of 0.39 barn. The gamma-ray data of Fig. 1 are all adjusted to this cross section. It is to be noted that in Fig. 1 the narrow resonance at 1.435 Mev does not have its true cross section indicated since the target was much thicker than the true resonance width.

The 1.435-Mev gamma-ray resonance has been observed in the present experiment with ceresin targets varying in thickness from 3 to 80 \( \mu \) g cm\(^2\), which correspond to the range of 1 to 27 kev for deuterons of 1.4 Mev. Just previous to one of these observations with a 6-kev target, the beam analyzing magnet was calibrated using the narrow gamma-ray resonances found in the bombardment of fluorine by protons for reference energies.\(^{14}\) The resonances at 0.669 and 0.8735 Mev were studied using the molecular beam, and so calibrations were obtained at 1.338 and 1.742 Mev. With this calibration the peak of the narrow resonance, which had previously been designated as the 1.43-Mev resonance,\(^{15}\) was found to occur at 1.435 Mev.

The shape of the 1.435-Mev resonance was determined with good resolution by using a 1-kev thick ceresin target and by changing the bombarding energy in 1-kev steps (see Fig. 2). The energy width measured midway between the dotted line of Fig. 2 and the resonance peak was found to be 5.5 kev. This is thought to be nearly the natural width since the energy spread in the beam was less than 1.4 kev and the target was very thin. The asymmetry observed on the sides of this resonance has been observed in all of the twelve separate examinations of the resonance made during this experiment. By using a 1-kev target, the ratio of yields at the peaks of the 1.30-Mev and the 1.435-Mev were carefully determined to be 1.58 so that the cross section at resonance peak for the 1.435-resonance is 0.62 barn.

The angular distribution of the gamma-rays was investigated at 1.73 Mev with the small Geiger counter. To do this it was necessary to rotate the counter about the target at a distance greater than had been used for the excitation curves. The background count was \( \approx 10 \) percent of the true counts. No asymmetry was found greater than 10 percent, the background counting rate.

The \( ^{12} \)N\(^+\) Positrons

The total yield of neutrons integrated over all angles can be obtained by observing the positron activity of the residual \( ^{14} \)N nucleus of reaction (3). To determine the relative number of positrons as a function of energy a quantity of \( ^{13} \)N was prepared by deuteron bombardment for a half-life (600 seconds) of a thin ceresin target on a thick silver disk placed at \( 30^\circ \) to the beam. Immediately after this bombardment the positron activity was observed through an aperture of 0.5-cm diameter at a distance of 6.7 cm from the target and at right angles to the beam. A thin-walled Geiger counter

\[\text{Cross-section for production of gamma-rays in Mev} \]

\[\text{Energy of deuterons in Mev}\]

Fig. 2. Experimentally determined cross section in barns for the production of gamma-rays from a thin (1-kev) ceresin target at the narrow 1.435-Mev resonance.


\(^{14}\)Bernet, Herb, and Parkinson, Phys. Rev. 54, 398 (1938); R. G. Herb (1948) private communication.

\(^{15}\)Harris, Bonner, Evans, and Phillips, Phys. Rev. 73, 649 (1948).
and a scale of 64 units were used to detect and record the number of positrons passing through the aperture. These measurements could not be used to determine the cross section because of backscattering of the positrons by the thick target backing, but the measurements gave relative yields. The cross section was determined by using a pure carbon target of 23.5 μ g/cm² on a thin silver foil (7.75 mg/cm²). The target was placed normal to the beam and was bombarded for two half-lives (20 minutes). It was then quickly removed from the vacuum system and placed over the axis of a bubble-window Geiger counter, of window thickness 3 mg/cm². The only absorbing material in the path of the positrons (end-point energy 1.24 MeV) was from the few centimeters of air and the counter window, and so nearly 100 percent of the positrons reached the sensitive region of the counter. The backscattering was negligible because of the thin target backing. Five independent measurements were taken at 1.30 Mev, with different target-counter separations; cross sections calculated from these measurements agreed within 10 percent.

If \( dN/dt \) is the number of \( N^{19} \) atoms decaying at the end of the bombardment of 20 minutes and \( n \) is the number of \( N^{19} \) formed per second during the bombardment, then

\[
n = -4/3(dN/dt).
\]

The experimental determination of \( dN/dt \) was obtained by plotting the logarithms of the number of Geiger counts obtained in 100-sec. intervals versus the time, for ten or so intervals after the cessation of bombardment. The times at which the points were plotted were 53 sec. from the beginning of each interval; i.e., the time at which the average number of positron counts over an interval would be expected. A line with a slope corresponding to a 10-minute half-life was drawn through the experimental points and extended back to the time bombardment ceased, thus obtaining \( dN/dt \) at \( t = 1200 \) sec.

The thickness of the pure carbon target on the silver foil was obtained by comparing the ratios of the gamma-rays from this target and the thick target previously mentioned. These data were taken at 1.30 Mev with several geometrical arrangements of the counter about the targets, and gave the same ratio of yield to within 10 percent.

These measurements gave a cross section of 0.192 barn at 1.30 Mev for the production of \( N^{19} \). The cross section for \( N^{19} \) production as a function of deuteron energy is shown in Fig. 1.

Table I gives the collected data pertaining to the neutron and gamma-ray resonances which were observed.

### Table I. Data pertaining to the neutron and gamma-ray resonances.

<table>
<thead>
<tr>
<th>Position of resonance Mev</th>
<th>Width at half-height kev (gamma-ray and neutron resonances)</th>
<th>Cross section at resonance peak in barns</th>
<th>Estimated relative intensity</th>
<th>Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td>200</td>
<td>0.29</td>
<td>0.12</td>
<td>2.5</td>
</tr>
<tr>
<td>1.16</td>
<td>200</td>
<td>0.34</td>
<td>0.14</td>
<td>2.5</td>
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<td>1.30</td>
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<td>0.19</td>
<td>2.5</td>
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<tr>
<td>1.435</td>
<td>5.5</td>
<td>0.62</td>
<td>0.19</td>
<td>2.5</td>
</tr>
<tr>
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<td>0.19</td>
<td>0.19</td>
<td>9.0</td>
</tr>
<tr>
<td>1.73</td>
<td>200</td>
<td>0.97</td>
<td>0.22</td>
<td>9.0</td>
</tr>
</tbody>
</table>

The Neutrons

The yields of neutrons at 0° (±30°) as shown in Fig. 1 were obtained using a proportional counter 6 cm long and 1.6 cm in diameter filled with ethane at a pressure of 43 cm of Hg. The counter had a 4-mil wire and was operated in the proportional region at 2200 volts. These data are relative yields and not absolute cross sections.

The protons recoiling from the neutrons entering the counter were counted if their energy exceeded 300 kev, a value set by means of a discriminator attached to the output of a 204-B linear amplifier and before the input of an Atomic Instrument Company scale of 64. Gamma-rays from reaction (2) were not observable at this bias. A discussion of this type of counter has been given by Bethe and Barschall,\(^{17}\) who show that the counter sensitivity (assuming a proton track length small in relation to the counter diameter) is relatively insensitive to neutron energy.

Stray fast neutrons were partially shielded from the ethane counter by means of paraffin blocks interspersed among the lead blocks used to shield the gamma-ray counter. The counter was placed to subtend the largest solid angle possible at the target and was surrounded by about 5 cm of paraffin except on the side adjacent to the target. The paraffin shielding was effective in reducing the background counting rate.

The region in the vicinity of the 1.435-Mev gamma-ray resonance has been investigated for neutron resonances by means of the hydrogen-filled counter at laboratory angles of 45°, 90°, and 160°, and by means of the ethane counter at 0°. These data are shown in Fig. 3. There is no evidence for a sharp neutron resonance in this energy region.

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The Neutron Angular Distributions

Neutron angular distributions were taken at nine deuterion energies. The hydrogen-filled proportional counter with a linear amplifier, discriminator, and scaler was used to count the fast neutrons. This counter was non-directional and the bias setting corresponded to 0.15-Mev recoil protons as was determined by 3 bias versus counting rate curves for neutrons of different known energies. The counter was insensitive to the gamma-rays when set at its standard bias. By lowering the bias the over-all gain of the system was checked frequently with a radium source in a standard position. The counter was rotated about the target at a distance of 10 centimeters and it subtended a laboratory angle of ±12° at the target. The data was taken in 15° steps in the laboratory system. The carbon target was 1.35 μ g/cm² of ceresin wax on a thick silver disk. Data was taken by going seven times through the angles and averaging. These averages are believed to be correct to within 10 percent. The background count was obtained by letting the beam fall on the defining slits only. The background was less than 10 percent.

The laboratory angles θ were converted into center of gravity angles ϕ by the relation

\[ \sin(\phi - \theta) = \left( \frac{E_{\text{deuteron}}}{78 E_{\text{deuteron}} - 25.5} \right) \sin \theta \]

and the counting rates at each c.g. angle ϕ were corrected because of the variation of the solid angle subtended by the counter in the center of gravity coordinates.

The counting rates at each deuteron energy, and at each angle, were also corrected for the efficiency of the counter. The efficiency of the counter is given by

\[ F = \sigma_o N D P E_n^{-1} \]

where \( \sigma_o = 4.16 \times 10^{-24} \) cm² is the neutron-proton cross section at 1 Mev, \( E_n \) is the neutron energy in Mev, \( N \) is the number of hydrogen atoms/cm², \( D \) is the effective depth of hydrogen gas that the neutrons see, and \( P \) is the probability that if a recoil occurs inside the counter it will be counted as a pulse above the bias. \( P \) is not a function of bias energy (the size of the “cone” of recoiling protons that will release the bias energy) but also of the ratio of proton track length \( L \) to counter radius \( R \). \( P \) and \( F \) have been calculated for the counter.\(^{18}\)

The efficiency of the hydrogen counter may also be experimentally determined. By integration of the observed angular distribution curves and comparison of this total yield into 4π-radians with the yield of \( N^{13} \) as determined from the positron measurements an efficiency of the counter for the average neutron energy in that distribution is obtained. These experimental determinations agreed with the theoretical within about 15 percent. The corrections in yield were made using the theoretical efficiency. The angular distributions are shown in Fig. 4 and are believed to be correct to within 10 percent. A subsequent paper will analyze the neutron angular distributions.

CONCLUSIONS

In general, reactions (2) and (3) are competing reactions, and at the three lower resonances there are about equal probabilities of breaking up with the emission of neutrons or short range protons. However, certain marked differences in the resonance phenomenon of reaction (2) and (3) can be noted. There are resonances for neutron emission at 1.62 and 1.76 Mev that do not correspond to the large gamma-ray resonance at 1.73 Mev. It is interesting that the 1.73-Mev gamma-ray resonance occurs at the point of maximum slope of the neutron cross section suggesting that the neutrons show something akin to dispersion about this point. Although the resonance at 1.62 Mev was not observed at 0°, similar curves when counting neutrons at 90° have been obtained by Williams et al.\(^4\) for this region.

At the 1.435-Mev resonance there is no indication of a neutron resonance within the limits of the experiment. If a neutron resonance exists it must be relatively weak and \( \sigma_1/\sigma_{\text{neut.}} > 25 \). The shape of the 1.435 resonance for gamma-rays is markedly asymmetrical; this resonance has been observed many times with different targets and different experimental arrangements and so it is certain that the asymmetry is real. It is interesting that a

\[ \text{FIG. 3. The yields of gamma-rays and neutrons at 0°, 45°, 90°, and 160° at the narrow 1.435-Mev resonance. The 45°, 90°, and 160° neutron counting rates are correct ratios while the 0° counting rate is arbitrary.} \]

\(^{18}\) J. C. Harris and G. C. Phillips (to be published).
superposition of resonance and dispersion formulas will produce this shape. Similar shapes have been observed in the resonances associated with the bombardment of fluorine by protons.

The ratio of the cross sections for reactions (2) and (3) are several orders of magnitude different from what would be expected if the deuteron is captured by the C\textsuperscript{12} nucleus and the excited *N\textsuperscript{14} nucleus subsequently breaks up with the emission of either a short-range proton or a neutron. At the 0.91-Mev resonance the ratio of the number of short-range protons to neutrons is $\sigma_{\gamma}/\sigma_n \approx 2.5$. At this bombarding energy the short-range protons have only an energy of 230 kev in the center of mass coordinates; the penetrability through the Coulomb barrier for $l=0$ is only approximately $10^{-4}$. The effect of the Coulomb barrier should make the emission of neutrons far more likely than the emission of short-range protons; and indeed the cross section for reaction (2) should be much smaller than is observed.

In the case of the narrow resonance at 1.435 Mev the penetrability of the short-range protons is approximately 1/30, while the observed ratio $\sigma_{\gamma}/\sigma_n > 25$, and so the discrepancy in the expected number of neutrons and short range protons is $> 750$.

Since the discrepancies are so large in the cross sections, it seems possible that the assumed mechanism of disintegration is wrong. There is the possibility that the entire deuteron does not enter the C\textsuperscript{12} nucleus in the case of low energy proton emission. The difficulty in proposing an Oppenheimer-Phillips reaction to interpret the results is that sharp resonances like the 1.435 Mev should not be observed. The lifetime of the nucleus would be expected to be of the order of the transit time of the proton across the nucleus, or about $5 \times 10^{-19}/10^9 = 5 \times 10^{-22}$ sec. From the relation $\Delta E \cdot \Delta t \approx h$, a width of 1.3 Mev is obtained, and this is completely incompatible with the sharp resonance that is observed. In view of this difficulty in the width of the level it seems that some other mechanism must be sought.

Critchfield has suggested an explanation in terms of a special model of the excited *N\textsuperscript{14} nucleus with a large rotational angular momentum. If the *C\textsuperscript{13} has high rotational angular momentum the probability of transition from *N\textsuperscript{14} to *C\textsuperscript{13} may be much greater than to a N\textsuperscript{13} nucleus without this high angular momentum.

This work was supported by the Research Corporation and by the joint program of the ONR and AEC.