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Yield and Angular Distributions from the
$^{11}\text{Be}(d,n)^{12}\text{C}$ and $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ Reactions

by

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A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Houston, Texas
June, 1956
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The $^\text{11}\text{B}(d,n)^{12}\text{C}$ Reaction

I. Introduction

Several theories have been proposed to explain the details of nuclear reactions. "A nuclear reaction is a process that occurs when a nuclear particle (nucleon or nucleus) gets into close contact with another."\(^1\) The eventual confirmation of any theory will require a knowledge of the energies of the nuclear energy states, their spins, parities, multipole moments, modes of decay, and the cross sections for their formation by various processes. A theory which seems to explain the results obtained in one experiment may fail to explain the effects observed in a similar experiment. Hence, it takes several theories to explain all the observed effects. The aim of the nuclear spectroscopist is to test the theories with appropriate experiments in order to verify or disprove these theories.

One theory that has been proposed by N. Bohr\(^2\) to explain nuclear reactions is the compound nucleus theory. A compound nucleus is formed when two nuclear particles come near enough to one another to be within the range of nuclear forces. They form a system in which the two initial particles lose their identity and form an entirely new "compound" nucleus. This theory divides the nuclear reaction into two parts: (a) the formation of the compound nucleus, and (b) the disintegration of the compound nucleus into the products of the reaction. Bohr assumed that "the mode of disintegration of the compound nucleus depends only on its energy, angular momentum, and parity, but not on the specific way in which it has been produced."\(^3\)

If $A$ and $B$ represent the two particles before the formation of a
compound nucleus C, and if the compound nucleus breaks up into two particles D and E, the reaction may be written as:

\[ A + B \rightarrow C \rightarrow D + E \]

If a beam of monoenergetic particles, A, impinge upon a target composed of particles B, and if particles E are detected, then the differential cross section, \( \sigma(\Theta) \), for a single resonance level is given by:

\[ \sigma(\Theta) = \sum L R_L P_L (\cos \Theta) \]  

(1)

Where \( \Theta \) is the angle between the velocity vectors of A and E in the center of mass system; \( P_L \) is the usual Legendre polynomial of order \( L \); and \( R_L \) is a constant. Blatt and Biedenharn give a method for evaluating \( R_L \). For a single resonance level the sum in (1) contains only even values of \( L \). Also, \( L \) cannot be greater than twice the orbital angular momentum of either A or E, nor can \( L \) be greater than twice the spin of C. The sum in (1) is therefore finite and gives a function which is symmetric about \( \Theta = 90^\circ \).

If particle A is a deuteron and if E is a neutron or a proton, then the reaction may take place by a process which Butler has called stripping. Stripping depends on the deuteron's large radius and small binding energy. According to this theory, one of the deuteron's nucleons, for example, the proton, may come within the range of the nuclear force of B, while the other nucleon (the neutron) does not. If this happens, the proton may be captured by B, and the neutron will continue in approximately the same direction that it was traveling before the proton was "stripped" from the deuteron. Thus, the differential cross section should have a forward maximum. The differential cross section as a function of the absorbed proton's orbital angular momentum \( l_p \) is given by:
\[ \sigma(\theta) = \text{const} \ G^2(K) \sum_{l_p} \sum_{l_p} \left[ j_{l_p}(kR) \right]^2 \]

\[ k^2 = (k_d - \frac{M_i}{M_f} k_n)^2 + 4 \frac{M_i}{M_f} k_n k_d (\sin \frac{\phi}{2})^2 \]

\[ G(K) = \frac{1}{\alpha^2 + (k_n - \frac{1}{2} k_d)^2 + 2 k_n k_d (\sin \frac{\phi}{2})^2} \]

\[ \alpha = 0.23 \times 10^{13} \text{ cm}^{-1} \]

Where \( M_i \) and \( M_f \) are the masses of the initial and final nuclei respectively; \( k_d \) is the wave number of the deuteron and the initial nucleus in the laboratory system; \( k_n \) is the wave number of the neutron and final nucleus relative to the center of gravity of the final nucleus; \( \Phi \) is the angle between \( \vec{k}_n \) and \( \vec{k}_d \); \( R \) is the nuclear radius plus the range of nuclear forces; \( j_{l_p} \) is the spherical Bessel of order \( l_p \); and \( \sum_{l_p} \) is a nuclear matrix element that can be estimated by statistical methods.\(^7\)

\( l_p \) is governed by two selection rules that limit the number of terms appearing in (2) and can often reduce the sum to one term. The selection rules are\(^6\) (a) the spin of the final nucleus must be obtainable by vector addition of the spin of the initial nucleus, the orbital angular momentum of the absorbed proton, and the latter's spin angular momentum, and (b) \( l_p \) must be even or odd depending on whether the parities of the initial and final nuclei are the same or different. If the stripping theory is applicable to a reaction, \( l_p \) is determined by finding the value of \( l_p \) which makes the theoretical curve best fit the experimental points. This value is usually unique.

The yield and differential cross section in any direction are proportional to one another. Therefore, by measuring the yield of a nuclear
reaction as a function of the angle between the velocity vectors of the
bombarding and escaping particles, one should be able to determine
whether the reaction is taking place by compound nucleus formation or
by stripping.

Due to the difficulties of neutron spectroscopy with the techniques
available in the past, fewer (d,n) than (d,p) angular distributions have
been measured. Only about a dozen (d,n) angular distributions have
been reported in the literature: see, for example, the Be\textsuperscript{9}(d,n)B\textsuperscript{10} and
O\textsubscript{16}(d,n)F\textsubscript{17} reactions by Ajzenberg;\textsuperscript{8,9} the Cl\textsubscript{13}(d,n)N\textsubscript{14} and Cl\textsubscript{12}(d,n)N\textsubscript{13}
reactions by Benenson;\textsuperscript{10} and the H\textsubscript{3}(d,n)He\textsubscript{4} reaction by Stratton and
Freier.\textsuperscript{11} Of the (d,n) angular distributions that have been reported,
nuclear emulsions were generally used to detect the neutrons.\textsuperscript{8,9,10}
This method permits excellent resolution of the neutron groups, but the
labor of track counting and analysis limits the statistical accuracy of
the data and the range of angular measurements. Usually the neutrons
were detected only at angles less than 90°.\textsuperscript{8,9,10} Obviously, this did
not test the compound nucleus theory since the symmetry around Θ = 90°
could not be ascertained. Also, the angular distribution measurements
have usually been carried out at only a single deuteron energy and the
validity of the stripping or compound nucleus theory has not been inves-
tigated over a wide range of energies. The theories of nuclear reactions
should be valid for all energies; thus, experiments to test the theories
should be carried out at several energies.

Since stripping had been reported for the B\textsubscript{11}(d,n)C\textsubscript{12} reaction at
1 and 8.1 MeV,\textsuperscript{12,13} this reaction was chosen to test the stripping theory
over a range of energies.
II. Some Constants of the $^{11}\text{B}(d,n)^{12}\text{C}$ Reaction

When $^{11}\text{B}$ is bombarded with deuterons, one of the possible reactions yields neutrons, $^{12}\text{C}$, and some energy, $Q$. For this reaction $Q$ has four definite values which are: 13.7, 9.3, 6.2, and 4.1 Mev. When the reaction has a $Q$ of 13.7 Mev, the neutrons will be designated as ground state neutrons because the $^{12}\text{C}$ nucleus is left in its ground state. Similarly, if $Q$ is 9.3 Mev, the neutrons will be designated as first excited state neutrons since the $^{12}\text{C}$ nucleus is left in its first excited state.

A neutron and three alpha particles can also be produced when a deuteron and a $^{11}\text{B}$ nucleus come together. This reaction has a $Q$ of 6.4 Mev. The kinetic energy of the neutron can vary from zero to a maximum which is a function of the bombarding energy.

The parity of the $^{11}\text{B}$ nucleus is odd and its spin is three-halves. $^{12}\text{C}$ has even parity and its spin is zero or two depending on whether it is in its ground or first excited state. The deuteron has a spin of one and the neutron's spin is one-half. For compound nucleus formation, the incoming channel spins are five-halves, three-halves and one-half. The outgoing channel spin is one-half if the $^{12}\text{C}$ nucleus is left in its ground state, or five-halves and three-halves if it is left in its first excited state. Since the parities of the initial and final systems are different, the orbital angular momentum of the deuteron and neutron must differ by an odd integer in order to conserve parity.

If the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction proceeds by stripping, rule (b) forces $l_p$ to be odd. The lowest value of $l_p$ that satisfies rule (a) is one. This would be the most probable value and it would produce a maximum in the differential cross section at about 30°.
III. Apparatus

A neutron detector of fair energy resolution and efficiency was needed to study the individual neutron groups from the $\mathrm{B^{11}(d,n)C^{12}}$ reaction over a range of deuteron energies. The neutron spectrometer described below appeared suitable. Briefly, it operates as follows: recoil protons from a thin hydrogenous radiator exposed to the neutron flux are counted in coincidence by a gas proportional counter and a crystal scintillation counter. A simplified drawing of the spectrometer is shown in Fig. 1. The coincidence pulse gates a multichannel pulse height analyzer which records the spectrum from the scintillation counter. Use of the coincidence arrangement makes it possible to count neutrons in the presence of gamma rays. Since this spectrometer was able to resolve the neutrons from the ground and first excited states in the $\mathrm{B^{11}(d,n)C^{12}}$ reaction, the excitation curve and angular distributions of these two groups were studied.

To minimize scattering, the neutron spectrometer was built in an eccentrically bored aluminum envelope, A. (See Fig. 1) The wall in the forward direction was less than one-sixteenth of an inch thick. The envelope was a circular cylinder four and one half inches in diameter and three inches high.

The radiator, B, was a thin sheet of polyethylene which is fourteen percent hydrogen by atomic weight. The polyethylene molecules consist of a chain of carbon atoms with two hydrogen atoms linked to each carbon atom. The radiator was one inch in diameter and was mounted on a carriage. A soft iron bar mounted on the carriage allowed it to be rotated with a magnet from the outside of the envelope.
NEUTRON SPECTROMETER

FIG. 1
The carriage has four positions, of which B is the first. The first position has a "thick" radiator; the second is blank; the third has a small Po(RaF) alpha source; and the fourth position contains a "thin" radiator. The "thick" radiator (40 mg/cm$^2$) is used to detect the ground and first excited state groups of neutrons simultaneously. The blank is used to measure the background. The alpha particles from the polonium source are used to check the resolution of the crystal and phototube assembly. The "thin" radiator (16 mg/cm$^2$) was used to check some of the first excited state data in a manner which will be described later. The four carriage positions were accurately determined by a ball and socket arrangement.

The crystal and phototube assembly are mounted on the envelope opposite the radiator. The phototube assembly consists of the phototube, E, glass light-pipe, C, teflon vacuum seal, and brackets to hold the light-pipe and phototube in position. The light-pipe was surrounded by a layer of magnesium oxide which acted as a light reflector. The crystal, D, was mounted in a recess in the light-pipe. The NaI(Tl) crystal was three-fourths of an inch in diameter and 0.65 gm/cm$^2$ thick. The crystal was thin enough so that electrons would not lose much energy in it, but still thick enough to stop the highest energy protons that were made in the radiator. (18 Mev protons were about the highest energy protons that were encountered in this investigation.) The optical joint between the light-pipe and phototube was made with Dow Corning 200 fluid.$^{17}$

The electrodes of the gas proportional counter are the brass cylinder, F, and the tungsten wire, G. A recoil proton from the radiator could
reach the crystal only by passing through this counter. There were
two holes (three centimeters in diameter) in the brass cylinder which
permitted the protons to travel through the gas counter.

The envelope was thoroughly outgassed before being filled to
insure stability over a long period of time. A mixture of argon and
five percent carbon dioxide gas was used in the counter at a pressure
of one atmosphere. Teflon and polyethylene were found to have very
low vapor pressures so the gas was not contaminated by organic materials.

Since the distance between the radiator and the crystal is 8.75 cm
and one argon atom is equivalent in stopping protons to 0.96 of an
air molecule, this distance corresponds to 8.4 cm of air at standard
conditions. The lowest energy proton that the first excited state
group of neutrons produced in the radiator had an energy of about
7 Mev. These low energy protons lost 500 Kev\(^{18}\) or seven percent of
their energy, in the gas before reaching the crystal. Higher energy pro-
tons will lose a smaller percentage of their energy in the gas.\(^{18}\)
Different proton paths vary in length by approximately three percent;
therefore, the ionization energy along various paths differs by a
negligible amount. The gas counter will detect a great number of low
energy electrons since the pulse created by a 10 Kev electron reaching
the end of its range in the gas is about one-half as large as the pulse
from a 10 Mev proton going straight through the counter. The low energy
electrons cause small pulses in the scintillation counter which can
be biased out; thus, they produce only accidental pulses. The gas
counter was usually run at 3000 volts. However, some of the excited
state data was checked with a somewhat lower voltage and with the thin
BLOCK DIAGRAM OF ASSOCIATED ELECTRONICS

FIG. 2
PULSE HEIGHT DISTRIBUTION FROM THE $\text{H}^3(d,m)\text{He}^4$ REACTION

ALPHA PEAK

**Fig. 3**

- Pulse Height (arbitrary units)
- Yield (arbitrary units)
- 16%

**Fig. 4**

- Pulse Height (arbitrary units)
- Yield (arbitrary units)
- 10%
TYPICAL PULSE HEIGHT DISTRIBUTION
FROM THE $B^{11}(d, n)C^{12}$ REACTION

$E = 2.4$ MEV $\theta = 0^\circ$

FIG. 5
radiator. Because slower protons make larger pulses in the gas counter, the voltage could be reduced, which in turn reduces the number of small pulses not biased out. This lowered the background and accidental counting rates, and with the improved resolution due to the thin radiator, a more accurate pulse height distribution could be obtained.

When a coincidence circuit is employed, it will be triggered accidentally at a rate $a$ which is given by:

$$a = 2tn_1n_2$$

where $n_1$ and $n_2$ are the counting rates of the two input channels and $t$ is the resolving time of the circuit. The counting rate of the scintillation counter was low and most of the undesired pulses were small; hence, the accidental coincident rate was negligible in the region of the pulses produced by the two highest energy neutron groups when the gas counting rate was less than about $10^4$ per second.

The electronics were connected as shown in the block diagram in Fig. 2. The coincident circuit used a 6BN6 vacuum tube in a circuit similar to the ones described by Smaller and Avery, and Adler. It had a resolving time of one microsecond. The amplifiers, discriminators, and pulse height analyzer were commercial products. Both preamps were single-stage cathode followers. The pulse shapers were shorted stubs of RG-65U delay line twelve feet long which gave square topped pulses one microsecond long since the delay time one way was one-half microsecond. The delay between the gate and scintillation counter's amplifier was secured by using RG-65U delay line. The rise times of the pulses from the gas and scintillation counters were about five-tenths and three-tenths microseconds respectively. The gate was about eight
microseconds long so that pulses would not be affected by the trailing edge of the gate. The linear pulses were delayed two to three microseconds to allow for any uncertainty of the triggering time of the discriminator circuits, which causes some uncertainty in the leading edge of the gate.

Fig. 3 shows a spectrum from the $^3\text{H}(d,n)^4\text{He}$ reaction given by the neutron spectrometer, and Fig. 4 shows the polonium alpha spectrum measured with the scintillation counter. A typical spectrum from the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction is shown in Fig. 5. An energy resolution of ten percent was obtained from the alpha particles, and the neutrons from the $^3\text{H}(d,n)^4\text{He}$ reaction gave a resolution of sixteen percent. For the spectrum shown in Fig. 5, the resolution for the ground and first excited state neutron groups was fifteen and twenty-one percent respectively.

The resolution of the spectrometer is determined solely by the pulse height spread from the scintillation counter. The difference between the resolution of the alpha particles and the neutrons is due to several factors. One important factor is the neutron's spread of energy due to the size of the crystal and radiator. The alpha particles are very nearly monoenergetic when they reach the crystal, but the crystal will accept recoil protons from the radiator with a range of angles from zero to a maximum angle, $\phi_m$, where $\phi$ is the angle between the velocity vectors of the neutron and proton. Fig. 6 depicts the extreme case. The energy of the recoil proton, $E_p$, is given by:

$$E_p = E_n \cos^2 \phi$$
$E_n$ is the energy of the incident neutron. If $\phi_m$ and $\beta$ are determined for the geometry of the spectrometer and the target, $\phi_m$ is $23^\circ$ and $\beta$ is $11^\circ$. For a maximum $\alpha$, $E_p$ can range from $0.85E_n$, to $0.96E_n$. Thus, a monoenergetic neutron source would produce an energy spread of eleven percent in the recoil proton's energy. Since this is the extreme case, the most probable energy spread will be less. Taking into account the distribution of areas in the crystal and radiator, a more probable energy spread in the recoil protons amounts to about six percent.

The protons had an energy spread because they came from all depths in the radiator. If the protons produced by the ground state neutrons went through the entire thick radiator, they would lose about 1.5 Mev or ten percent of their energy.\textsuperscript{18} The protons from the other neutron group would lose about 2.5 Mev or twenty-eight percent of their energy in the thick radiator, but only 1.0 Mev or thirteen percent of their energy in the thin radiator.\textsuperscript{18} The above values were calculated for the slowest neutrons that were detected in each group. As the proton energies are increased, they will lose less energy in the radiator and the resolution will be improved. The difference in the resolutions of the ground and first excited states as shown in Fig. 5 bears this out.
Another factor to consider is the spread in energy of the neutrons entering the radiator. This spread is due to the fact that the neutron energy is a function of the angle, \( \alpha \), between the velocity vectors of the deuteron and the neutron. The radiator accepts neutrons with all values of \( \alpha \) from zero up to a maximum. This maximum for the spectrometer was 90°. Livingston and Bethe have derived an expression that gives the neutron energy, \( E_n \), as a function of the angle \( \alpha \) and of the deuteron's energy, \( E_d \).\(^{22}\) This expression is:

\[
M E_n^{1/2} = (m_d m_n E_d)^{1/2} \cos \alpha + (M m_f Q + m_i m_f E_d - m_d m_n E_d \sin^2 \alpha)^{1/2}
\]

The quantities \( m_n, m_d, m_i, \) and \( m_f \) are the masses of the neutron, deuteron, initial and final nuclei respectively; \( Q \) is the energy liberated in the reaction; and \( M = m_d + m_i \approx m_n + m_f \). For the values of \( Q, \alpha \), and \( E_d \) pertaining to this experiment, the energy spread was calculated to be less than one percent. The neutrons also had a slight energy spread because the target was relatively thick. This energy spread amounted to one percent at 2.0 Mev and less at higher energies.

If the radiators were made thinner, the resolution could be improved, but the efficiency would be decreased. To estimate the efficiency of the spectrometer, consider first the probability, \( p \), of a 15 Mev neutron producing a recoil proton. (All of the data was normalized to the neutron-proton cross section at 15 Mev.)

\[
p = \frac{2dN}{W} \sigma
\]

d is the thickness of the polyethylene radiator in grams per square centimeter; \( W \) is the molecular weight of polyethylene (14); \( N \) is Avogadro's number; and \( \sigma \) is the total neutron-proton cross section. (At 15 Mev, \( \sigma \) is 0.64 barns.) For the thick radiator, \( p \) is 2.2 \times 10^{-3}.
\( \sigma \) decreases as \( E_n \) increases, therefore, the efficiency decreases although the resolution is improved. If the radiator is thin enough so that its stopping power is nearly constant, then the energy loss of the proton in the radiator is approximately equal to a constant times \( p \).

At this energy, the neutron-proton cross section is very nearly isotropic in the center of mass system. Thus, the differential cross section will vary as \( \cos \alpha \) in the laboratory system. The probability, \( P \), that a proton from the center of the radiator will hit the crystal is given by:

\[
P = \frac{\int_0^\alpha \sin \alpha \cos \alpha \, d\alpha}{\int_0^{\frac{\pi}{2}} \sin \alpha \cos \alpha \, d\alpha} = \sin^2 \alpha
\]

As long as the neutron-proton scattering is spherically symmetric in the center of mass system, the energy spread of the recoil protons will be directly proportional to \( P \). For this experimental geometry, \( P \) is 0.025 since \( \alpha \) is 90°. \( P \) will be nearly constant over the whole radiator. Then the total probability of a 15 Mev neutron being detected is \( pP \) or 3.2 x 10^{-5}. This means that only one out of every 3.1 x 10^4 neutrons with an energy of 15 Mev impinging upon the radiator will be detected.

The target was made by evaporating finely powdered natural boron from a tantalum strip onto a tantalum backing. The backing was three-fourths of an inch in diameter and fifty mils thick. The target thickness was determined by comparing the neutron yield from the target with the yield from an infinitely thick boron carbide target. The neutrons were detected with a long counter which allowed the excitation curve
given by Burke, Risser, and Phillips\textsuperscript{11} to be used for this determination. By this method the target was found to be about 70 Kev thick for 1.9 Mev deuterons.

The yield of a nuclear reaction, $Y$, is given by:

$$Y = \sigma (\Theta) N t \cdot \omega$$

$\sigma (\Theta)$ is the differential cross section for the reaction; $N$ is the number of particles striking the target; $t$ is the number of target atoms per square centimeter; and $\omega$ is the solid angle subtended by the detector with respect to the target. It is of interest to calculate the counting rate expected from the $^{11}$B(d,n)$^{12}$C ground state neutrons with an estimated cross section of ten millibarns per steradian.\textsuperscript{12} For a deuteron beam of one microampere incident upon the target, $N$ is $6.25 \times 10^{12}$ per second. Using 85 Kev for the target thickness, $t$ is $1.5 \times 10^{19}$ atoms per square centimeter. The radiator subtends a solid angle of $6.25 \times 10^{-2}$ with respect to target. Thus, $Y$ is $0.6 \times 10^{5}$ neutrons per second. Since the spectrometer's efficiency is $3.2 \times 10^{-5}$, it should detect about 2.0 neutrons per second.

The deuterons were accelerated by the Rice Institute's 5.5 Mev positive ion accelerator. The deuteron beam was magnetically analyzed and the energy resolution is about one kilovolt. The target chamber was a thin copper tube two inches in diameter with brass end plates. The target was mounted on the axis of the tube which was perpendicular to the deuteron's velocity vector. A three-fourths inch hole admitted the deuterons into the target chamber. The target and a piece of quartz were mounted in a manner such that either the target or quartz could be placed in the path of the deuteron beam without opening the vacuum system. The quartz
was used to check the alignment of the target chamber. The spectrometer was mounted on a platform that could be rotated about an axis that coincided with the axis of the copper tube. To increase the yield, the normal to the target was turned at an angle of $35^0$ with respect to the deuteron's velocity vector. This increased the target thickness to 85 Kev.
IV. Results

Each point was obtained by a numerical integration of the area under the appropriate peak in the pulse height distribution. The total error includes an allowance for the uncertainty in determining this area, as well as the statistical error for random counting. The points have been corrected for background and the non-constant neutron-proton cross section. The background was negligible for the ground state neutrons, but it amounted to about ten percent for the excited state neutrons at the higher bombarding energies.

Fig. 7 shows the zero degree excitation curves for the ground and first excited state neutron groups for the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction. Fig. 7 is plotted in the laboratory system of coordinates. The average differential cross section in the forward direction is estimated to be 0.15 millibarns per steradian per ordinate unit.

The ground state excitation curve exhibits two resonances, one at about 1.65 Mev and the other at about 3.9 Mev. Two resonances are also indicated for the excited state neutrons; one at 3.9 Mev and a very broad one extending from 1.3 to 2.7 Mev. The broad one may be two resonances close together; one centered at about 1.65 Mev and the other at about 2.3 Mev.

The angular distributions of the ground and first excited state neutrons from the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction were measured at nine deuteron energies between 1.6 and 4.7 Mev. For each determination, data was taken at both positive and negative values of $\Theta$ to help offset errors due to misalignment. $\Theta$ is the angle between the velocity vector of the deuteron and a line through the centers of the radiator and crystal. The angular
ZERO DEGREE EXCITATION CURVE FOR THE $^1H(d,\alpha)^{12}C$ REACTION

YIELD (ARBITRARY UNITS)

$Q = 9.3$ MEV

$Q = 13.7$ MEV

$E_d$ (MEV)

FIG. 7
distributions are shown in Figs. 8-11 and are plotted in the center of mass system. The angular distributions are definitely a function of the deuteron's energy, especially the ground state group.

It does not seem very likely that any significant information about a single level can be obtained from any of the angular distributions except those taken with bombarding energies between 3.5 and 4.7 Mev. Using the available deuteron energies, the excitation energy of the compound nucleus is about 20 Mev and many interfering levels would be expected. However, the angular distributions taken with bombarding energies between 3.5 and 4.7 Mev appear capable of yielding some information. They are not isotropic and are roughly symmetric around \( \theta = 90^\circ \).

From the excitation curve it appeared as though the angular distribution taken with a bombarding energy of 4.1 Mev was due more to a single level than any of the other angular distributions. The single resonance theory for compound nucleus formation as worked out by Blatt and Biedenharn\(^4\) might be expected to apply here. This theory gives the angular dependence of the differential cross section as a sum of Legendre polynomials. (See equation 1.)

To find the relative amount of each Legendre polynomial needed to fit the data at 4.1 Mev a least squares calculation was done. From this it was found that polynomials through the sixth order were needed in order to fit the data reasonably well. This implies that a spin of 7/2 is needed for the compound nucleus.

If a compound nucleus is formed with a positive parity and a spin of 7/2, then the angular momentum of the neutron would be 4 and that of the deuteron would be 1, 3, or 5. For a negative parity the angular mo-
mentum of the neutron would be 3 and that of the deuteron would be 2, 4, or 6.

One might expect that every possible value of the deuteron's angular momentum $l_d$, in all incoming channels would contribute to the total angular distribution. One might also think that the contribution due to the various values of $l_d$ would be in proportion to their penetration factors. However, if this assumption is made, a minimum is found at $90^\circ$ and the curve rises continuously to a maximum at $0^\circ$ and $180^\circ$. It was found impossible to fit the experimental peak at small angles by using all the possible values of $l_d$ and channel spins simultaneously, no matter how the contributions from various channels and $l_d$ values were weighted.

Since the observed half width of this resonance and the Wigner limit are both about 1 Mev, a single particle state for the neutron might exist. This might make one feel that it is more reasonable to make up this state from special values of the channel spins instead of mixing all of them. Therefore, one might assume that the resonance is due to a single value of $l_d$ in a single entrance channel. On this assumption, it is found that the curve which best fits the data is obtained by using the five-halves channel spin with an $l_d$ of five. This gives a curve which has a peak at small angles but does not drop quite as fast as the data in the $40^\circ$ to $60^\circ$ region. If $l_d$ is five, the impact parameter of the deuteron would be $5 \times$. Since $5 \times$ is about twice as large as the radius of the $^1_1$ nucleus, it does not seem very likely that a deuteron with an $l_d$ of five would interact with the nucleus. Also, the penetration factor is only 0.01 for an
\( l_d \) of five as compared to 1.0 for a \( l_d \) of zero.

Another combination which was found to fit the 4.1 Mev data reasonable well involved channel spins of one-half and three-halves, with an \( l_d \) of three in both channels. For the solid curve shown in Fig. 12, the channel with a spin of three-halves contributes about three times as much to the total curve as the channel with a spin of one-half. The impact parameter for this case is \( 3 \times 10^{-\frac{1}{2}} \) which is nearly equal to the radius of the \( B^{11} \) nucleus and the penetration factor is about 0.3. It would appear that the reaction should take place more readily with an \( l_d \) of three than with an \( l_d \) of five.

The theoretical distribution predicts a small bump at \( \Theta = 90^\circ \) that was not found. No combination of channel spins and \( l_d \) values were found that would eliminate the bump at 90\(^\circ\) without destroying the other characteristics of the curve, such as the dip at 0\(^\circ\) and the rapid drop between 40\(^\circ\) and 60\(^\circ\). On the other hand, it is unreasonable to expect that the assumption of a single level would give more than a first approximation to the data, since there must be many levels near enough to affect the experimental angular distribution. The fact that there is some slope in the angular distributions strengthens this idea.

Recently another theory has been proposed that might be used to explain the angular distributions. This theory is known as the "heavy particle stripping theory."\(^{24}\) This theory predicts a peak at backward angles between 90\(^\circ\) and 180\(^\circ\). By combining the heavy particle stripping theory and the regular stripping theory, an angular distribution that has both a forward and a backward peak
$E_d = 4.1$ MEV

- Compound nucleus
  \[ \sigma(\theta) \sim 1 + 0.90P_2 + 0.16P_4 - 0.41P_6 \]
- Butler stripping
- Heavy particle stripping

**Figure 12**

**Yield (Arbitrary Units)**

\[0, 2, 4, 6\]

\[0, 30, 60, 90, 120, 150, 180\]

**Theta (CMS)**
can be obtained. The dashed line in Fig. 12 is the result of such a calculation. The two stripping theories contain a somewhat arbitrary parameter in the radius of interaction, and the relative amount of each of the stripping theories used to fit the data is determined by fitting each theory individually to about one-half of the total angular distribution. The smaller number of arbitrary parameters involved in the compound nucleus theory and the fact that the compound nucleus theory fits the whole angular distribution might indicate that the $^8\text{Be}(d,n)^{12}\text{C}$ reaction takes place predominately by compound nucleus formation at 4.1 Mev.

The angular distribution measured at 1.6 Mev is antisymmetric and Legendre polynomials of odd order would be needed to secure a reasonable fit to the data. On the compound nucleus picture, this could indicate interference between two resonances. Another possibility is that the angular distribution at 1.6 Mev might indicate stripping at lower energies since stripping has been reported at 600 Kev.25

The first excited state angular distributions do not show as radical change with energy as the ground state angular distributions. A theoretical fit of this data would not yield any additional information since the ground state parameters plus some additional ones would be involved. All of the excited state angular distributions appear to be roughly symmetric around $\Theta = 90^\circ$, although the ones produced with a deuteron energy of less than 3.5 Mev have a minimum at $100^\circ$ to $110^\circ$. This effect could be caused by the interference of two resonances which would support the hypothesis that
that the broad resonance is actually two narrower ones close together.

If a pure $B^{11}$ target is used, the possibility of resolving the other excited state neutron groups should be increased. Natural boron contains twenty percent $B^{10}$ which can yield neutrons with a Q of 6.47 and 4.62 Mev$^{13,14}$ which could not be resolved from the $B^{11}$ neutrons with Q values of 6.2 and 4.1 Mev$^{13,14}$. There would still be a great number of gamma rays present as well as the continuum of low energy neutrons from the $B^{11}(d,n\beta\alpha)$ reaction.
The $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ Reaction

I. Introduction

Since the alpha particle has no spin, there is only one incoming channel spin for this reaction, and, when $^{12}\text{C}$ is left in the ground state, there is only one outgoing channel spin. Thus, it should be possible to obtain some significant information about energy levels of the compound nucleus from the measurement and analysis of the neutron angular distributions.

The target nucleus, $^{9}\text{Be}$, and the compound nucleus, $^{13}\text{C}$, both contain $4n+1$ nucleons. In both cases the extra particle is a neutron. It is of interest to investigate whether or not there are any significant features of this reaction that might result from this fact. Direct interaction for this reaction has been postulated by Mandansky and Owen.\textsuperscript{24} In this process, which they call "heavy particle stripping" the extra neutron should be emitted predominately in the backward direction.

Since the $^{9}\text{Be}$ nucleus has a spin of three-halves, the incoming channel spin is three-halves. The spin of $^{12}\text{C}$ is either zero or two depending on whether it is in its ground or first excited state. The outgoing channel spin is one-half if the $^{12}\text{C}$ nucleus is left in its ground state, and either five-halves or three-halves if it is left in its first excited state. Since the parity of $^{9}\text{Be}$ is odd and the parity of both levels in $^{12}\text{C}$ is even, the angular moments of the neutron and alpha particle must differ by an odd integer.

By using the available deuteron energies to bombard $^{11}\text{B}$, $^{13}\text{C}$ could be produced with excitation energies of 19.8 to 22.9 Mev.\textsuperscript{15}
Thus, different levels in $^{13}\text{C}$ could be examined by these reactions.

The $\text{Be}^9(\alpha,n)^{12}\text{C}$ reaction has $Q$ values of 5.71 and 1.28 Mev.\textsuperscript{15} The neutrons formed by the $\text{Be}^9(\alpha,n)^{12}\text{C}$ reaction with a $Q$ of 5.71 and 1.28 Mev will be designated as the ground and excited state neutron groups respectively.
II. Apparatus

Except for the ground state excitation data, the neutrons were detected with a modified spectrometer which greatly resembled the neutron spectrometer used for the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction. The modified spectrometer was also of the recoil proton type, and the recoil protons were counted in coincidence by a gas proportional counter and scintillation counter. The modified spectrometer incorporated some new design features and was used to do some necessary experimenting on this type of detector without interrupting the other experiment in progress. CsI was used for the crystal in the scintillation counter to avoid assembling the counter in a dry box. Also, the light-pipe was eliminated in hopes of improving the resolution.

A simplified drawing of the modified spectrometer is shown in Fig. 13. The modified spectrometer was also built in an eccentrically bored aluminum envelope, A. The envelope was a circular cylinder five and one half inches high and four and one half inches in diameter. Since the modified spectrometer was longer in proportion to its diameter than the original spectrometer, the electric field in the proportional counter more nearly approached the idealized case of an infinitely long cylinder. The wall thickness in the forward direction was about one-sixteenth of an inch. The polyethylene radiators were one inch in diameter and were mounted on a carriage, B, that could be turned from outside the envelope with a magnet. There were four carriage positions which were accurately determined.
MODIFIED NEUTRON SPECTROMETER

FIG. 13
by a ball and socket arrangement. The carriage held three radiators of different thicknesses (15, 10, and 5 mg/cm²) and a blank.

The phototube assembly consists of a Du Mont 6291 photomultiplier, C, and a soft iron shield, D. The phototube was waxed to the shield at E, and a teflon ring made the seal between the shield and the envelope.

The CsI(Tl) crystal, H, was held in place by spring clips, J. To avoid gas contamination, nothing was used for the optical joint between the phototube and the crystal except the mechanical contact. The crystal was one inch long, three-fourths of an inch wide, and about one-sixteenth of an inch thick.

The brass cylinder, F, and the tungsten wire, G, formed the electrodes of the gas proportional counter which was filled with a mixture of argon and five percent carbon dioxide gas to a pressure of one third of an atmosphere. The radiator to crystal distance is 10.28 cm which is equivalent to 3.3 cm of air under normal conditions. A 3 Mev proton will lose about 400 Kev, or about thirteen percent of its energy, in the gas between the radiator and the crystal.¹⁸ (The energy of the slowest proton encountered in this investigation was about 3 Mev.) The ionization energy along various proton paths differs by a negligible amount because different proton paths vary in length by approximately three percent. The high voltage was usually around 1500 volts for the ground state group and about 1300 volts for the excited state group. The high voltage and the amplifier gain were adjusted until decreasing the amplifier gain by a factor of two would not reduce the coincident counting rate.

The electronics were the same as those used for the original spectrometer. The accidental counting rate was negligible when the gas counter detected less than 10⁶ events per second.
A pulse height distribution from the modified spectrometer for the $^3\text{H}(d,n)^4\text{He}$ reaction is shown in Fig. 14 and two typical pulse height distributions for the $^9\text{Be}(\infty,n)^{12}\text{C}$ reaction are shown in Fig. 15. The resolution improves for higher neutron energies as Fig. 15 shows. The modified spectrometer acts like the original spectrometer in this respect.

For the modified spectrometer, $\phi_m$ and $\beta$ are $21^\circ$ and $7^\circ$ respectively. (See Fig. 6) Thus, $E_p$ can vary from $0.98E_n$ to $0.87E_n$ which is an energy spread of eleven percent. By considering the areas of the crystal and radiator, a more probable energy spread of six percent can be calculated. A 3 Mev proton will lose 700 Kev, or twenty-three percent of its energy, if it goes through the thin radiator and a 6 Mev proton will lose 900 Kev, or fifteen percent of its energy, if it goes through the thick radiator.\(^{18}\) Thus, the energy resolution for the slow neutrons is rather poor and this places a limit on the slowest neutrons that can be accurately detected.

For the modified spectrometer, the probability, $p$, that a 10 Mev neutron will produce a recoil proton in the radiator is $1.6 \times 10^{-3}$. (The data was all normalized to the neutron-proton cross section at 10 Mev.) The probability, $P$, that a proton from the radiator hits the crystal is $1.5 \times 10^{-2}$. The total efficiency of the modified spectrometer is then $pP$, or $2.4 \times 10^{-2}$. The probabilities $p$ and $P$ are discussed on pages 12 and 13.

An anthracene crystal detector was used to obtain the excitation curve of the ground state neutrons. The anthracene crystal
PULSE HEIGHT DISTRIBUTION FROM
THE $^3\text{H}(d,n)^4\text{He}$ REACTION

FIG. 14
TYPICAL PULSE HEIGHT DISTRIBUTIONS
FROM THE Be\(^9\) (\(\alpha\),n)C\(^{12}\) REACTION

\[ E_\alpha = 4.3 \text{ MEV} \quad \theta = 0^\circ \]

**Q = 1.28 MEV**

**Q = 5.7 MEV**

YIELD (ARBITRARY UNITS)

PULSE HEIGHT (ARBITRARY UNITS)

FIG. 15
detector was used to obtain the excitation curve of the ground state neutrons. The anthracene crystal was a sphere eight millimeters in diameter which gave a good rectangular pulse height distribution. Taylor, Lonsjo, and Bonner have discussed this type of counter.\textsuperscript{26} Since this type of counter is more efficient than either of the neutron spectrometers, more points with better statistics from thinner targets could be taken using this counter than using one of the spectrometers. The ground state group was well resolved since an anthracene sphere eight millimeters in diameter separates neutrons up to about 10 Mev very well from high energy gamma rays because of the relative ranges of electrons and recoil protons in this energy region. The photomultiplier was connected through a preamplifier, amplifier, and pulse height analyzer to a scaler. The preamplifier was a single stage cathode follower. The other electronic apparatus was obtained from the Atomic Instrument Company.\textsuperscript{21}

The alpha particles were secured from the Rice Institute's 5.5 Mev positive ion accelerator. The modified spectrometer was mounted on the same platform as the original spectrometer, and the same target chamber was used for both the $^{11}\text{B}(d,n)^{12}\text{C}$ and the $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ reactions. The targets were prepared by evaporating beryllium from a tantalum strip onto a thin tantalum backing.
III. Results

Every point was obtained by finding the area under the appropriate peak in the pulse height distribution. The total error was estimated to be about ten percent for most of the angular distribution and excitation curve points. The data has been corrected for the varying neutron-proton cross section and background has been subtracted. The background was negligible for the ground state group, and it was less than twelve percent for the excited state group.

The zero degree excitation curves for the ground and first excited state neutron groups are shown in Fig. 16. The coordinates are in the laboratory system and the average differential cross section in the forward direction is estimated to be 4.7 millibarns per steradian per ordinate unit. The ground state curve has two peaks. The lower one appears to consist of three resonances centered at approximately 1.9 and 2.3, and 2.6 Mev, and the other one is probably composed of resonances at 4.0 and 4.3 Mev. These values were taken from the work of Schiffer, Bonner, Kraus and Marion, in which a gamma-ray excitation curve was taken with thinner targets than those used in this work. The excited state yield increases with bombarding energy except for a comparatively narrow resonance at about 4.0 Mev.

The angular distributions are shown in Figs. 17-20. Angular distributions of the ground state neutrons were measured at eleven alpha particle energies between 2.08 and 5.20 Mev, and the excited state angular distributions were measured at four alpha energies between 4.05 and 5.20 Mev. The resolution of the modified spectro-
FIG. 16. The target that was used to obtain the upper curve was 120 Kev thick for 4 Mev alpha particles. The upper curve has been corrected for the background which was less than twelve percent, but no correction was made for the target thickness. The gamma ray yield was taken with the same target as the neutron yield, but they were not measured simultaneously. In order to have the gamma ray yield appear with the neutron yield, the scale for the gamma ray yield differed from the scale of the neutron yield by about a factor of four. A target that was 70 Kev thick for 2 Mev alpha particles was used to obtain the lower curve which has been corrected for the target thickness by reducing the abscissa by one-half of the target thickness. No correction for the background was made in the lower curve since the background was negligible.
\( \text{Be}^9(\alpha, n) \text{C}^{12} \)

Q = 1.28 MEV

Q = 5.71 MEV

FIG. 16
Be$^{9}(\alpha, n)\text{Cl}^{12}$

$Q = 5.7$ MEV

$E_\alpha = 3.95$ MEV

$E_\alpha = 3.75$ MEV

$E_\alpha = 2.75$ MEV

YIELD (ARBITRARY UNITS)

$\theta$ CMS

FIG. 17
$Be^9(\alpha, n)C^{12}$

$Q = 5.7$ MEV

$E_\alpha = 2.33$ MEV

$E_\alpha = 2.08$ MEV

FIG. 18
meter was not good enough to resolve accurately excited state neutron
groups at large angles with any lower alpha particle energy.

The 3.3 Mev angular distribution has a very distinctive shape
which is nearly symmetric around $\Theta = 90^\circ$. The symmetry suggests
that compound nucleus formation is taking place. If it is assumed
that this distribution is due mainly to a tail of one resonance either
above or below it, it is found that a curve which will roughly fit
the data can be calculated from the compound nucleus theory. Using
reasonable values of compound nucleus spin and alpha particle orbital
angular momentum, $l_\infty$, the only combination that produced a peak at
$90^\circ$ was a spin of three-halves and an $l_\infty$ of one.

The calculation of a theoretical angular distribution between 3.8
and 5.0 Mev is somewhat complicated by the overlapping of several
resonances. However, a theoretical calculation which assumed a five-
halves even state at about 4 Mev, a broader overlapping three-halves
even state at about 4.4 Mev and a seven-halves even state above 5 Mev
will give curves that roughly fit the data.

Below 3.3 Mev, the ground state angular distributions are peaked
in the forward direction. This is probably due to interference between
several levels since there appears to be at least three resonances in
this region. Haefner has tentatively assigned a spin of five-halves
to the resonance at an alpha energy, $E_\infty$, of 1.9 Mev from theoretical
considerations.28 James, Jones and Wilkinson29 postulate a spin of
seven-halves and odd parity for the 1.9 Mev resonance, and a spin of
one-half and odd parity for a resonance at higher energy. These values
were inferred from angular distribution data taken below 1.4 Mev. The
present angular distributions are the first experimental distributions
taken in the 1.9 to 2.6 Mev energy region. They do not substantiate these hypotheses, but indicate interference between levels of spin one-half and three-halves with opposite parity. The fitting does not appear to be unique.

The excited state angular distributions have a shape which can be obtained from the compound nucleus theory, but several combinations of parameters will give a curve that fits the data equally well. Therefore, it was felt that no significant information would be secured by fitting the data with a theoretical curve.

The compound nucleus theory seems adequate to explain qualitatively the experimental angular distributions. No stripping of the type postulated by Mandansky and Owen is demanded, but we cannot rule out the possibility that a small part of the yield arises in this manner. Although there is some tendency for the neutrons to be emitted backwards, this can easily be explained in terms of compound nucleus formation.
References


17. Dow Corning Corporation, Midland, Michigan.


Acknowledgements

The author wishes to express his sincere appreciation to Dr. J. R. Risser and Dr. C. M. Class who directed this research and made many valuable suggestions during the course of this work. The grand cooperation of the men in the Physics Department shop under the direction of J. F. Van der Henst is also very greatly appreciated.