THE RICE INSTITUTE

RESOLVED NEUTRONS FROM THE
Be\(^9(\alpha,n)\)C\(^{12}\) REACTION

by

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Acknowledgements
I. INTRODUCTION

If beryllium is bombarded with α particles, neutrons are obtained by the reaction:

\[ ^{4}\text{Be}^9 + ^{2}\text{He}^4 \rightarrow ^{6}\text{C}^{13} \rightarrow ^{6}\text{C}^{12} + ^{0}\text{n}^1 + Q \]

The Q value for the neutrons to the ground state of C\text{\textsubscript{12}} is equal to 5.71 Mev. For the neutrons to the first excited state of C\text{\textsubscript{12}}, Q is equal to 1.28 Mev. The ground states of Be\text{\textsubscript{9}} and C\text{\textsubscript{12}} have total angular momenta 3/2 and 0 respectively. The ground state of Be\text{\textsubscript{9}} has odd parity, whereas the ground state of C\text{\textsubscript{12}} has even parity.\textsuperscript{1}

This thesis describes additional experimental results for α particle energies above 4 Mev of the type recently reported by Risser, Price, and Class.\textsuperscript{2} At the time of publication there were several gaps in the energy range studied in which little or no data had been obtained, and the angular distributions had not been given least-square fits in terms of angular functions. It was therefore the purpose of this thesis project to secure additional angular distributions such as to fill in some of the gaps for the ground state neutrons and to obtain least-square fits to the angular distributions previously reported. In addition, excitation curve data were taken for the ground state neutrons extending the previous work to higher α particle energies.

The subject reaction is of interest because it is
commonly used as a neutron source, and knowledge of the
differential cross-section as a function of angle and energy
is useful. Also, since the spin of the \( \alpha \) particle and the
ground state of \( ^{12}\text{C} \) are both zero, it may be expected that
angular distributions of the ground state neutrons will
yield unambiguous information about states of \( ^{13}\text{C} \), the com-
pound nucleus.

The larger of the two Rice Institute Van de Graaff
accelerators was used in the experiment. Satisfactory ex-
citation curve and angular distribution data for the ground
state neutron group were obtained by means of the neutron
spectrometer described by Arthur Cole in his master's
thesis, 1953. Attempts to use this detector for the reso-
lution of the neutrons to the first excited state of \( ^{12}\text{C} \)
proved unsuccessful at angles greater than 90° for
energies less than 4 Mev. The possibility of resolving the
low energy group by means of a hydrogen-filled proportional
counter was investigated. Such a counter was designed and
constructed, and separation of the low energy group neutrons
by this method is planned for the near future.

Results included in this thesis are the angular dis-
tributions of the ground state neutrons at \( \alpha \) energies
4.14, 4.38, and 4.87 Mev, and the excitation curve for the
same neutron group in the bombarding energy range 3.8 to
5.5 Mev. Also included is a table of coefficients of
Legendre polynomials of least-square fits to angular
distributions previously reported. Results pertaining to the neutrons to the first excited state of Cl² are included in the master's thesis of W. L. Anderson, who also studied the Be⁹(α, n) reaction as a thesis subject.
II. EXPERIMENTAL METHOD

A. Neutron Detectors, General

The two most commonly used neutron detectors are the gas-filled counter and the scintillation counter. Two such detectors are combined to form the neutron spectrometer used in the experiment. Before discussing the spectrometer, it is perhaps well to consider each type individually.

Both type detectors depend on ionization from moving charged particles for the production of pulses which are amplified and analyzed electronically. In the gas-filled counter a charged particle is produced by either a nuclear reaction or by means of a scattering collision between a neutron and a "recoil nucleus". Ions are collected at the central electrode and thereby form a pulse.

The gas-filled counter, when operated with a suitable voltage has the favorable aspect that it produces pulses which are proportional to the specific ionization of the recoiling charged particles. A pulse will be proportional to the energy of the recoil particle if the particle path begins and ends in the counter. A monoenergetic neutron group, however, gives rise to a broad distribution of pulse heights corresponding to all scattering angles from 0° to 90°.

Sometimes a difficulty in the use of gas-filled counters arises from the slow rise time of the pulses. The principal voltage pulse is due to the motion of the positive ions.
near the central electrode. The collection time for these ions depends on the pressure but is generally on the order of $10^{-3}$ seconds. If a faster counting rate is required, this difficulty may be circumvented at the cost of pulse height by clipping the pulses with an appropriate R-C time constant or delay line. A clipped pulse on the order of 1 microsecond duration can generally be obtained.

If the gas counter is filled with a gas of low atomic number, such as hydrogen or deuterium, high gas pressures are required in order that a sufficiently large percentage of recoil nuclei be completely stopped in the counter. The addition of a noble gas, such as argon, reduces the pressure required but causes an increase in the positive ion collection time.

Gamma radiation accompanying neutrons produces in a gas counter high energy electrons by means of pair formation or by the production of photoelectrons from the walls of the chamber. Most electrons will not effect as much ionization as recoil nuclei that expend all their energy in the gas, and the pulses due to the electrons may to a large extent be biased out by means of a discriminator component of the amplifier.

The scintillation counters are divided into two classes according to the type of scintillator: (a) Organic phosphor, (b) Inorganic crystals. The pulse height for both types is
a non-linear function of the recoil particle energy, and each such detector must therefore be calibrated.

Scintillation counters using organic phosphors are analogous to gas counters containing hydrogenous gases in that the recoil nuclei are protons. The high density of the phosphor compared to that of a gas causes a greater efficiency. Moreover, the phosphor is highly effective in stopping the recoils so that total recoil energy is expended in the scintillator. For the neutron energies involved in this experiment the theoretical distribution of the number of recoil protons as a function of their energy is a constant from zero to the maximum recoil energy; thus, analysis of the data is somewhat simplified. The rise time of pulses from phosphors is usually short (∼10^{-8} seconds or less), and the pulse durations are correspondingly short.

Inorganic crystals are effective in detecting heavy charged particles originating outside the counter. Such crystals yield relatively high pulses from charged particles as compared to organic scintillators, and they produce only low energy recoils from neutrons. In both types of scintillation counters the pulses from high energy electrons may be of the same order of magnitude as the pulses due to recoil protons. A crystal may be reduced in size (within limits) in order to minimize the proportion of the electron range within the crystal.
B. Neutron Spectrometer

The neutron spectrometer used in the experiment combines a gas and inorganic crystal counter and provides a fair degree of energy resolution for neutrons above 4 Mev. The spectrometer consists of a proportional counter and crystal counter mounted in series and connected electronically in coincidence. Its chief advantage is that X-ray background can be eliminated since the proportional counter in conjunction with a discriminator circuit can distinguish between the specific ionization of electrons and protons of the same energy. The spectrometer, on the other hand, has the undesirable characteristic of low counting efficiency due to the geometry of the arrangement.

A schematic diagram of the spectrometer is shown in Figure 1. The gas proportional counter is enclosed in a cylindrical aluminum shell which contains in its back face a thin CsI crystal in contact with the window end of a photomultiplier. The photomultiplier tube extends from the back of the aluminum can. Mounted concentrically to the shell is a 1 mm thick brass cylinder which defines the active volume of the proportional counter. Along the axis of symmetry through the photomultiplier, 3 cm holes in the brass cylinder allow the passage of recoil protons from the radiator to the crystal. Several thicknesses of polyethylene and a blank radiator frame are made available through the use of a
Figure 1. A CsI crystal and 1 atmosphere of argon + 5% CO₂ used in resolving neutrons from the Be⁹(α,n) reaction.
radiator carriage which can be rotated as desired from the outside by means of a magnet. For the detection of the ground state neutrons, a radiator 15 mg/cm² thick was used. The crystal scintillator is located 10 cm from the radiator. The brass cylinder and a 5 mil tungsten wire form the electrodes of the proportional counter. For detection of ground state neutrons, the aluminum can was filled to 1 atmosphere of argon plus 5% CO₂.

The five most important factors that determine the energy resolution of the neutron spectrometer are: (1) Target thickness, (2) Radiator thickness, (3) The variation of the angle at which the neutron is emitted, (4) The variation in the angle at which the recoil protons are scattered, (5) Non-linearity of crystal pulse height as a function of recoil proton energy.

The neutron yield of the target was compared to that of a standard Be⁹ target of known weight. The thickness thus determined was 213 µg/cm². This corresponds to thicknesses of 160, 153, and 142 kev at bombarding energies 4.14, 4.38, and 4.87 Mev respectively. These values were obtained using the experimental results of S. D. Warshaw for the stopping power of beryllium for protons. The above thicknesses expressed in kev give a measure of the difference in energy of the neutrons which originate at the front and back surfaces of the target. The maximum energy spread due to this effect was calculated to be 4%.
A spread in proton energy results from the variation of radiator thickness traversed. The radiator consisted of 3 layers of polyethylene, each 5 mg/cm² thick. A 10 Mev proton loses approximately 0.6 Mev in passing through the entire radiator. This value was determined by considering the stopping power of a CH₂ unit of polyethylene equal to that of 1 atom (average) of air.

The third factor affecting the energy resolution results from the variation of neutron energy with the angle between the beam direction and the neutron path. Let this angle be designated as \( \theta \). It may be readily shown that

\[
E_{p}\frac{1}{\beta} = \left( \frac{\cos\theta (m_\alpha m_n E_\alpha)^{1/3}}{m_c + m_n} \right) + \left( \frac{m_\alpha m_n E_\alpha \cos^2 \theta + (m_c + m_n) \left[ m_c Q + (m_c - m_\alpha) E_\alpha \right]}{m_c + m_n} \right)^{1/3}
\]

where
- \( m_c \) = mass of C¹² nucleus
- \( m_\alpha \) = mass of \( \alpha \) particle
- \( m_n \) = mass of neutron

The maximum \( \theta \) for this experiment was 7.2° at \( E = 4.87 \) Mev. Using \( Q = 5.71 \) Mev, the maximum spread due to this effect was calculated to be less than 1%.

A large factor was that due to the finite widths of the crystal and radiator. The energy of the recoil proton, \( E_p \), is found by the relation

\[
E_p = E_n \cos^2 \theta
\]

where \( \theta \) is the angle between the incident neutron path and
the proton path after collision. The maximum angle $\theta$ in the experiment was $19^\circ$. It follows that $E_p$ for this extreme case is $0.89E_n$ such that the maximum energy spread from this effect alone was 11%.

Other factors which affect energy resolution are the differences in distance travelled by recoil protons through the gas counter and the non-linearity of crystal pulse height with proton energy. Both of these effects were small for the high energy neutrons of this experiment.

In order to convert the number of neutrons counted for a particular set of conditions to differential cross-section, it is necessary to know the efficiency of the counter; i.e., the number of neutrons analyzed per number incident on the radiator. The probability of interaction between an incident neutron and a proton is

$$p = \frac{2t \sigma N\rho}{A}$$

where $t$ is the radiator thickness, $A$ is the molecular weight of polyethylene (14), $N$ is Avogadro's number, and $\sigma$ is the n-p cross-section. The only energy dependent factor is $\sigma$. The efficiency is then given by the relation

$$\text{Efficiency} = (8.61 \times 10^{-5})t \rho \sigma \cdot G$$

$G$ is a geometrical factor, and $t \rho$ is expressed in $mg/cm^2$ of polyethylene.

The geometrical factor was determined using the fact
that n-p scattering for the neutron energies of the experiment is isotropic in the center-of-mass frame of coordinates. The fraction of recoil protons striking the crystal was calculated by numerical analysis to be 0.014. The above expression then becomes

\[
\text{Efficiency} = (1.21 \times 10^{-4}) \epsilon \sigma
\]

In order to resolve low energy neutrons it is necessary to decrease the thickness of the proton radiator, causing a decrease in the counter efficiency. Although the neutron-proton cross-section increases with the lower neutron energy, the overall change in efficiency is downward with decreasing energy.

When detecting low energy neutrons, the background is found relatively high. Those background counts due to protons from brass or aluminum cannot be discriminated against. Many of the background counts, however, are due to electrons. Since the low energy protons passing through the gas have higher specific ionization, the bias of the gas counter discriminator can be raised as a counter measure.

A block diagram of the electronic network associated with the spectrometer is shown in Figure 2. The pulse from each counter was sent through a cathode follower stage to a linear amplifier. The discriminator of each amplifier was set at 10.0 volts. A 3/8 microsecond delay line was added at the scintillation side discriminator output in order to
BLOCK DIAGRAM OF ASSOCIATED ELECTRONICS

PULSE SHAPER → COINCIDENCE CIRCUIT → PULSE SHAPER → PULSE SHAPER

DISCRIMINATOR

3/8 μSEC DELAY

AMPLIFIER

PREAMPLIFIER

PROPORTIONAL COUNTER

HIGH VOLTAGE

SCINTILLATION COUNTER

HIGH VOLTAGE

TO MULTICHANNEL ANALYSER

Figure 2.
compensate for the slower pulses from the proportional counter. Both amplifier output pulses were differentiated by means of delay lines before entering a 6BN6 coincidence circuit.\textsuperscript{5,6} A square pulse generated by the coincidence circuit "opened" a gate circuit and allowed the passage of a delayed pulse from the CsI amplifier.

The output of the gate circuit was fed to a 20-channel analyser. The base line of the analyser was set at 20 volts throughout the experiment. Each channel had a width equal to 0.5 volts. By choosing suitable amplifier gain settings, it was always possible to resolve the ground state neutrons within 15 or less channels. As the angle of observation was increased, it was always necessary to increase the CsI amplifier gain in order to keep the pulses in the channels. The gas counter amplifier gain was held constant for an entire angular distribution. To determine the amount of background, data were observed with and without the radiator in the forward position.

For determining the neutron yield as a function of angular distance from the incident $\alpha$ beam, data were taken at convenient 10° and 15° intervals from 0° to a maximum of 150°. The total yield at each angle was observed for a fixed number of bombarding $\alpha$ particles, which was determined by means of a charge integrator. In so far as time permitted, data for angles about either side of the target
were observed and averaged in order to reduce alignment errors.

Excitation curve data were taken with the spectrometer directly in line with the incident \( \alpha \) beam. The neutron yield was recorded at intervals of approximately 60 keV bombarding energy. To determine the energy of the \( \alpha \) particles incident on the front face of the target, use was made of an analyzing magnet associated with the Van de Graaff accelerator. The field of this magnet was measured with a Li\(^7\)-moment magnetometer.

C. Hydrogen Counter

Because of the poor results obtained in the effort to resolve the low energy group neutrons with the spectrometer, a gas counter was designed and constructed to detect neutrons of less than 5 MeV energy. A high-pressure hydrogen-filled ionization chamber has been reported successful in measuring neutron spectra up to approximately 13 MeV.\(^7\) The use of deuterium was considered in order to reduce the pressure requirement. However, for neutron energies greater than 2.5 MeV, n-d scattering is anisotropic.\(^8\) It was therefore decided to design a hydrogen-filled counter to hold pressures as high as 70 atmospheres.

A cross-section of the hydrogen counter is shown in Figure 3. The counter consists of a brass cylinder mounted inside a \( \frac{1}{4} \)" thick steel pipe which is sealed at both ends.
HYDROGEN COUNTER

Figure 3. Dotted areas represent teflon insulation. Pressure meter and filling connections not shown.
by means of lead gaskets embedded in 5/8" steel plates. The brass cylinder and a .046" diameter tungsten wire comprise the cathode and central electrodes respectively. Connections to the central electrode are made by means of a spark plug to which the tungsten wire is soldered. Concentric to the electrodes at either end of the counter is a brass "field tube" which is mounted for the purpose of eliminating end-effects resulting from non-uniform fields. The cylindrical active volume is 3 3/4" in diameter and 4" long.

The range of 5 Mev protons in hydrogen at 50 atmospheres is 1.4". Practical considerations of weight and size prevented making the counter longer. In order to reduce wall effects the diameter of the counter was made large relative to the proton range. Since the gas should have as high a stopping power as possible, the use of a mixture of hydrogen and a heavy noble gas is under consideration.

To obtain a uniform radial electric field, the length of the field tubes should be made at least equal to the radius of the cylinder. The potential of the tubes should be equal to the potential at a distance from the center of the tungsten wire equal to the radius of the field tube. The ratio of resistors connecting the field tubes to the central electrode and the cathode was chosen such that regardless of the voltage applied, the field tubes will be at the proper potential.
A copy of the type A1 preamplifier designed by Bell and Jordan was constructed for use with the hydrogen counter. It consists of a 3 stage feed-back group, using 6AK5 tubes, followed by a cathode-follower output tube. The preamplifier was mounted on a frame which connects to the back plate of the counter.
III. RESULTS

The angular distributions of neutrons obtained in the laboratory were corrected for the variation in n-p cross-section with energy and converted to differential cross-section in the center-of-mass coordinate system. Figure 4 shows the graph of $\frac{d\sigma}{d\Omega}$ vs $\theta_{cm}$. The lengths of the vertical lines through the experimental points represent the errors in the observations.

Figure 5 shows the excitation curve of the ground state neutrons for α energies ranging from 3.75 to 5.5 Mev. The closed circles and crosses are points previously reported. The closed circles are a result of data taken with an 8-mm-diameter spherical plastic scintillator, and the crosses were taken by means of the neutron spectrometer. The open circles are points obtained in this experiment, also with the neutron spectrometer. These data are expressed as differential cross-section in the laboratory system.

The angular distributions previously reported were given least square fits in powers of $\cos \theta_{cm}$ at Los Alamos by means of an IBM computer. The equations thus obtained have the form

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6$$

where $x = \cos \theta_{cm}$ and $y$ is proportional to $\frac{d\sigma}{d\Omega}$. Fits were obtained with both five and seven terms; i.e., fourth
and sixth degree polynomials. It was then possible to convert these equations into similar equations in terms of Legendre polynomials, such as

\[ y = \alpha_0 + \alpha_1 P_1(x) + \alpha_2 P_2(x) + \alpha_3 P_3(x) + \alpha_4 P_4(x) + \alpha_5 P_5(x) + \alpha_6 P_6(x) \]

Table I lists the coefficients \( \alpha \) for both five and seven term expansions for each distribution. The \( \omega \) bombarding energy, listed in the first column, designates the angular distribution.

Another method of fitting angular distributions with Legendre polynomials consists of choosing \( n \) points on the experimental curve, equating the ordinate at each point equal to an expansion consisting of \( n \) Legendre polynomials, and solving the resulting simultaneous equations for the \( n \) unknown coefficients. These calculations were carried out for the general case for \( n = 5 \) polynomials. Table II gives the equations for the coefficients as a function of the neutron yield (or differential cross-section) at each of the five angles chosen. These equations are given for two sets of angles. The choice of angles depends on the nature of the curve to be fitted. Equations such as these are useful when there is no access to a computer. The equations of Table II were used by the author in fitting experimental distributions obtained from the \( C^{13}(\omega,n)0^{16} \) reaction.
Figure 4. Angular distributions of neutrons from the Be$^9(\alpha,n)$ reaction. Alpha-particle energies refer to center of target.
Figure 5. Excitation curve of neutrons obtained from the Be\(^9\)(α,n) reaction. Alpha-particle energies refer to center of target.
TABLE I

Coefficients of Legendre Polynomials for Least-Square Fits to Angular Distributions

A. Ground State Neutrons

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TABLE I. (continued)

B. First Excited State Neutrons

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<th>( \alpha_1 )</th>
<th>( \alpha_2 )</th>
<th>( \alpha_3 )</th>
<th>( \alpha_4 )</th>
<th>( \alpha_5 )</th>
<th>( \alpha_6 )</th>
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TABLE II.
Equations for the Coefficients of Legendre Polynomials

In the equations listed below the $\phi$'s represent the neutron yield or differential cross-section at the corresponding center-of-mass angles.

A. $\phi_1 \rightarrow 0^0; \phi_2 \rightarrow 55^0; \phi_3 \rightarrow 70^0; \phi_4 \rightarrow 110^0; \phi_5 \rightarrow 125^0$

$\alpha_0 = 0.1516\phi_1 - 0.3558\phi_2 + 0.9310\phi_3 - 0.4716\phi_4 + 0.7448\phi_5$

$\alpha_1 = 1.3853(\phi_4 - \phi_3) + 1.9856(\phi_2 - \phi_5)$

$\alpha_2 = 0.4627\phi_1 - 1.0705\phi_2 + 1.3001\phi_3 - 2.9604\phi_4 + 2.2882\phi_5$

$\alpha_3 = 1.6443(\phi_2 - \phi_3) + 2.7577(\phi_4 - \phi_3)$

$\alpha_4 = 0.3357\phi_1 - 2.2035\phi_2 + 2.3949\phi_3 - 1.1740\phi_4 + 0.5969\phi_5$

B. $\phi_1 \rightarrow 0^0; \phi_2 \rightarrow 30^0; \phi_3 \rightarrow 70^0; \phi_4 \rightarrow 110^0; \phi_5 \rightarrow 150^0$

$\alpha_0 = -0.0057\phi_1 + 0.1794\phi_2 + 0.3247\phi_3 + 0.3313\phi_4 + 0.1702\phi_5$

$\alpha_1 = 0.3465(\phi_3 - \phi_4) + 0.4405(\phi_2 - \phi_5)$

$\alpha_2 = -0.0207\phi_1 + 0.5711\phi_2 - 0.5496\phi_3 - 0.5153\phi_4 + 0.5234\phi_5$

$\alpha_3 = 0.3648(\phi_2 - \phi_5) - 0.9238(\phi_3 - \phi_4)$

$\alpha_4 = 1.0353\phi_1 - 1.5559\phi_2 + 0.8021\phi_3 - 0.3932\phi_4 + 0.1116\phi_5$
REFERENCES


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