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THE $^3$He($d,n)^{12}$ REACTION AND
A CALORIMETRIC DOSAGE CALIBRATION AND
A DETERMINATION OF ABSORBED DOSE FOR PROTON IRRADIATION

by

PETER RICHARD ALMOND

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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DOCTOR OF PHILOSOPHY

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PART I

THE $^{{\text{B}}_{11}}(d,n)^{\text{C}}_{12}$ REACTION
I. INTRODUCTION

Several investigations of the \( B^{11}(d,n)C^{12} \) reaction have previously been made\(^{1-11} \). Ames \textit{et al.}\(^{7} \) studied the reaction for the ground state neutrons up to deuteron bombarding energies of 1.15 Mev and measured several angular distributions in this region. Price\(^{6} \) studied the range of bombarding energies from 1 to 5 Mev and measured nine angular distributions in this region for both ground state and first excited state neutrons. With the advent of the Tandem Van de Graaff, deuteron energies up to 12 Mev became available, and it was decided to extend these investigations up to this energy. Several groups\(^{1,5,9,10} \) have taken angular distributions in this region but no excitation curves have been measured.

It is of interest to determine how this reaction proceeds. There are two general theories that might be used to explain the results: the compound nucleus theory and the direct interaction or stripping theory.

Many experimental observations of nuclear reactions have been successfully explained in terms of the compound nucleus model. In this model the incident particle is assumed to interact with the nucleus as a whole, and the two initial particles lose their identity and form a compound nucleus. This theory divides the nuclear reaction into two parts; (1) the formation of the compound nucleus and (2) the disintegration of this compound nucleus into the
products of the reaction. The mode of disintegration is assumed to depend only on the energy, angular momentum, and parity and not on the way the compound nucleus was formed.

Let $A$ represent the target nucleus, $b$ the incident projectile, $C$ the compound nucleus, and if it breaks up into two particles, let $d$ represent the particle which is normally observed and $E$ the residual nucleus. The reaction may then be written as:

$$A + b \rightarrow C \rightarrow d + E.$$ 

$C$ is assumed to have a mean life and a definite energy of excitation which is governed by the kinetics of the reaction. The mean life of the compound nucleus is assumed long compared to the transit time of the incident projectile across the radius of the target nucleus.

At low energies of excitation the yield curve for the observed particles may show sharp resonances due to individual states in the compound nucleus. The differential cross section in the center-of-mass coordinate system for such a single resonance level is given by\textsuperscript{12}:

$$\sigma(\Theta) = \sum_{L} R_{L} P_{L}(\cos \Theta)$$

where $\Theta$ is the angle between the velocity vectors of $b$ and $d$ in the center-of-mass system. $R_{L}$ is a constant and $P_{L}$ is the Legendre Polynomial of order $L$. $L$ is limited by the orbital angular momenta of $b$ and $d$ and the total angular
momentum \( J \) of \( C \). The sum is therefore finite. For an isolated resonance level \( L \) can only have even values and gives a function—which is symmetric about 90 degrees.

In the intermediate region of excitation where the average level density in the compound nucleus increases, interference between two or more levels becomes possible. If the levels are of opposite parity the angular distributions may show marked asymmetry about 90 degrees, and the angular distributions will, in general, change rapidly as a function of bombarding energy.

At high energies of excitation the levels in the compound nucleus are closely spaced and the level widths \( \Gamma \) are usually much greater than the level spacings \( D \). Ericson\textsuperscript{13} has pointed out that when the resolution \( \Delta E \) of the incident beam is less than or of the order of \( \Gamma \) we should expect (1) strong fluctuations in the cross sections with spacings of the order of \( \Gamma \) and (2) angular distributions asymmetrical with respect to 90 degrees. This effect is due to interference of the levels of the compound nucleus and is strongest when only a few final states are involved. When \( \Delta E > \Gamma \) we would again expect a smoothly varying behaviour of the cross section and symmetrical angular distribution with respect to 90 degrees.

For direct reactions as opposed to compound nucleus reactions, it is assumed that the transition from the initial
configuration (target plus projectile) to the final configuration (observed particle plus recoil nucleus) is instantaneous. The direct-interaction explanation for the angular distributions of neutrons from \((d,n)\) reactions at high bombarding energies was given by Serber\(^{14}\) in 1947. He was interested, however, in the total angular distribution of all the observed particles without regard to the final states of the residual nuclear systems, and the history of the proton after the interaction was ignored. The theories of deuteron stripping of Butler\(^{15}\) and Bhatia\(^{16}\) took into account proton capture into definite final states at incident energies comparable to or less than the \(Q\) value of the reaction. In this model it is assumed that the deuteron is a sufficiently extended system so that only one of the two nucleons comprising the deuteron is captured by the target nucleus. For example, the proton which is loosely bound in the deuteron (2.23 Mev) might be stripped off by the nuclear forces from the target. The neutron would then pass on as the observed particle. These ideas led to the very important result that the angular distribution was directly related to the capture angular momentum \(\lambda_p\) of the proton by the target nucleus.

The simple theory assumed that: (1) all effects of Coulomb repulsion and nuclear scattering of the deuteron and outgoing particle may be neglected; (2) there is no
compound nucleus formation; (3) the captured particle reacts with the target nucleus only on the surface of a sphere of radius $R$. A simple sketch of the theory as developed by Bhatia\textsuperscript{16} will now be given. The possible values of $\ell_p$ are restricted by conservation of angular momentum and parity. If $J_1$ and $J_e$ are respectively the spins of the target nucleus and the particular state in which the residual nucleus is left, then:

$$|J_1 - J_e| - 1/2 \leq \ell_p \leq J_1 + J_e + 1/2.$$  

The values of $\ell_p$ are further restricted to be either even or odd depending on whether the parities of the initial and final nuclei are the same or different. The differential cross section in the center-of-mass system is given by:

$$\sigma(\theta) = \mathcal{T}(K_h) \frac{\mathcal{P}_p \mathcal{L}_p}{\mathcal{L}_p} (k_p),$$  

(1)

where $\mathcal{T}(K_h)$ is the probability that the neutron has the momentum contribution $K_h \hbar$ from the internal motion of the deuteron, $\mathcal{L}_p$ is the centrifugal barrier factor of a proton with angular momentum $\ell_p \hbar$ and linear momentum $k_p \hbar$, and $\mathcal{P}_p$ is the probability that the proton will be captured if it reaches the "surface" of the target nucleus with angular momentum $\ell_p \hbar$. By using the zero range approximation to the deuteron wave function,
\[ \pi(K_n) = \left(\frac{\alpha}{\pi^2}\right)(\alpha^2 + k_n^2)^2, \]

with \( \alpha = 2.3 \times 10^{12} \text{ cm}^{-1}. \)

The barrier factor \( I_{\ell_p}(k_p) \) is given by:

\[ I_{\ell_p}(k_p) = 4\pi(2\ell_p + 1)j_{\ell_p}^2(k_pR), \]

where \( j_{\ell_p} \) is a spherical Bessel function of order \( \ell_p \) and \( R \) is the radius at which the proton is captured. \( R \) is usually used as a parameter in fitting experimental curves. \( P_{\ell_p} \) contains kinematical and statistical factors and a factor dependent on the properties of the initial and final nuclear levels.

The diagram shows the relation between \( K_n, k_p, \) and the propagation vectors \( k_d \) and \( k_n \) of the incident deuteron and outgoing neutron respectively, required by momentum conservation:
\[ \bar{K}_n = \bar{K}_n - \bar{K}_d / 2, \]
\[ K_n = \left[ \left( k_n - k_d / 2 \right)^2 + 2 k_n k_d \sin^2(\theta / 2) \right]^{1/2}, \]
\[ \bar{K}_p = \bar{K}_d - \left( m_t / m_r \right) \bar{K}_n, \]
\[ k_p = \left[ \left( k_d - (m_t / m_r) k_n \right)^2 + 4 (m_t / m_r) k_n k_d \sin^2 \theta / 2 \right]^{1/2}, \]
\[ k_d = \left[ m_t / (m_d + m_r) \right] \left[ 2m_d E_d \right]^{1/2} / h, \]
\[ k_n = \left[ 2 m_t m_r / (m_t + m_r) \right] \left[ Q + E_d m_t / (m_t + m_d) \right]^{1/2} / h, \]

where \( m_t, m_r, m_n, \) and \( m_d \) are the masses of target nucleus, residual nucleus, neutron, and deuteron respectively, \( E_d \) is the bombarding energy (laboratory system), and \( Q \) is the \( Q \) value for the final state \( e \).

It is usually possible to fit the first peak in the angular distributions with this theory if the distribution has a strong forward maximum and the bombarding energy is not too low. Then \( \ell_p \), and hence the relative parity of states \( i \) and \( e \), is determined, and limits are placed on the value of \( J_e \) if \( J_i \) is known. Usually the value of \( \ell_p \), which makes the theoretical curve best fit the experimental, is unique. An increase in bombarding energies will cause the angular distribution peaks to shift to low angles and the peaks will become narrower. The excitation curve should be a smooth function of energy.

This analysis has implied that the free particles are
represented by plane waves. It cannot, therefore, account for distortions arising from the specific nature of the interaction. Consequently, these results would only give a qualitative picture of the behaviour of the differential cross section. In the calculations made in this thesis "distorted wave functions" rather than plane wave functions were used. These distortions arise from the Coulomb field and the nuclear optical potential. The distorted wave functions are wave functions of the incident deuteron and outgoing neutron in the Coulomb and optical potentials.

The $^B_{11}(d,n)^{C_{12}}$ Reaction

Figure 1 shows an energy level diagram describing the $^B_{11}(d,n)^{C_{12}}$ reaction. Three facts can be seen immediately from this diagram: (1) the energy in the compound nucleus is high, of the order of 20 to 30 Mev; (2) the Q values for the reaction are high, 13.731 Mev to the ground state of $^{C_{12}}$; and (3) the ground and first three excited states at 4.43 Mev, 7.656 Mev, and 9.64 Mev are separated by a few Mev. A neutron spectrometer of low resolution can be expected to resolve the neutron groups from the ground and first two excited states.

A neutron and three alpha particles can also be produced when a deuteron and $^B_{11}$ nucleus react. This reaction has a Q value of 6.45 Mev, and the kinetic energy of the neutrons can vary from zero to a maximum which is a function of the
FIGURE CAPTION

Fig. 1  Energy level diagram describing the $^{11}\text{Be}(d,n)^{12}\text{Be}$ reaction. The levels and $J^\pi$ values are from T. Lauritsen and F. Ajzenberg-Selove, Nuclear Data Sheets, Sets 5 and 6, 1961\textsuperscript{17}.
bombarding energy.

The experimental results given in this thesis are for the neutrons to the ground and first two excited states of $\text{C}^{12}$. The neutrons will be designated as ground state, first excited state, and second excited state neutrons when $\text{C}^{12}$ is left in each of these states. If $\text{C}^{12}$ is left in the 9.64 Mev level, the neutrons will be called third excited state neutrons.

The parity of the $\text{B}^{11}$ nucleus is odd and its spin is three halves. $\text{C}^{12}$ has an even parity and spins 0, 2, and 0 for the ground and first two excited states respectively as can be seen from Fig. 1. The deuteron has a spin of one with even parity and the neutron a spin of one-half. If compound nucleus formation is assumed, the incoming channel spins are five-halves, three-halves, and one-half. The outgoing channel spin is one-half if the $\text{C}^{12}$ nucleus is left in the ground state or second excited state and five-halves or three-halves if it is left in its first excited state. In order to conserve parity the orbital angular momentum of the deuteron and neutron must differ by an odd integer since the parities of the initial and final systems are different for all three groups.

If we assume that the reaction goes by stripping and consider the selection rules for $\ell_p$ given above, we find that (1) $\ell_p$ must be odd and (2) the lowest value that it can take
for either $^1_{2}$ in its ground state or first excited state is one. This would be its most probable value and it would produce a maximum in the differential cross section at about 30 degrees.

**Previous Investigations**

As was mentioned above, several investigations of the $^{11}_{\text{B}}(d,n)^{12}_{\text{C}}$ reaction have already been made and several ways of detecting the neutrons have been used. The usual method has employed photographic nuclear emulsions$^{1-4}$. This method permits excellent resolution of the neutron groups but the labour of analyzing and counting the tracks limits the statistical accuracy of the data and the range of angular measurements. Ames et al.$^7$ studied this reaction by means of recoil detection in stilbene scintillation crystals. The first two neutron groups, which are separated by approximately 4 Mev, were very well resolved in the energy range up to 1.15 Mev. The effective resolution of the apparatus at these energies was probably 1-2 Mev, and the principal limitations arose from the crystal and phototube statistics. However, in this reaction there are high energy $\gamma$-rays which produced an appreciable background in the vicinity of the first excited state group, and it is unlikely that higher state groups could be resolved by this method. The scintillator had to be shielded by one-quarter of an inch of lead to stop the high energy electrons from the $^{11}_{\text{B}}(d,p)^{12}_{\text{B}}(\beta)^{12}_{\text{C}}$ reaction.
This lead also reduced the $\gamma$-ray background.

Some investigators have studied the reaction using time-of-flight techniques $^{19,20}$. These, however, have been limited to angular distribution measurements in the energy region up to about 3 Mev. Only the neutron groups leaving $C^{12}$ in excited states at 4.43 Mev and 12.75 Mev have been observed to be coincident with $\gamma$-rays $^{21}$, in agreement with gamma-ray measurements $^{22}$. Therefore, most of the time-of-flight measurements have been on the first excited state neutron groups.

Zeidman $^{9}$, Maslin $^{5}$, and Price $^{6}$ have used counter telescopes to study the reaction. Zeidman studied the reaction at 10 Mev whereas Price used bombarding energies between 1 and 5 Mev, as has already been indicated. The energy resolution and efficiency of these types of spectrometers will be discussed in the next chapter.

It was observed in the work of Price $^{6}$ that the neutron yield increased at angles greater than 90 degrees unlike that for deuteron stripping. It may be possible to explain this on the basis of compound nucleus formation or distorted wave direct interaction theory, but Owen and Madansky $^{23}$ proposed an explanation, which they called "heavy particle" stripping, within the framework of direct interactions. They assumed that the emitted neutron could originate from the target nucleus while the incident deuteron would be
captured as a whole by the core of the target nucleus. Heavy particle stripping would enhance the probability of producing neutrons at large angles, since the nuclei from which the neutrons are stripped would be travelling in the direction predominantly opposite to the deuteron beam in the center-of-mass system. An approximation to the differential cross section can be obtained from Eq. 1 by replacing $\Theta$ with $\Pi - \Theta$ and changing the definition of the momenta. $\Pi(K_n)$ would now be the momentum distribution of a neutron in the outer shell of the target nucleus. Instead of $L_p$ the angular momentum parameter would be $L_x$, the angular momentum with which the deuteron is captured by the core. The form of $\Pi(K_n)$ depends on the nuclear model, and it is generally assumed that the neutron is in a square well whose parameters fit the neutron binding energy. If the final state wave function describing the outgoing neutron and the residual nucleus is constructed to be antisymmetric under exchange of neutrons, the resulting differential cross section contains the deuteron and heavy particle stripping terms as well as a strong interference term. This theory has now been used to fit the data from 0.6 to 10 Mev with only $\lambda_2/\lambda_1$, which is the measure of the relative amplitudes of deuteron and heavy particle stripping, and the radius of interaction as variable parameters. Since this latter parameter must simulate the various distortions
of the wave functions, which are certainly energy dependent, it is not unreasonable that it should vary as it does from $3.8 \times 10^{-13}$ cm. for the low energy data to $5.9 \times 10^{-13}$ cm. for the high energy data\(^9\). However, it has been pointed out\(^{24}\) that the Distorted Wave Born Approximation theory (D.W.B.A.)\(^{25}\) has been successful in many cases in explaining the largest part of the backward peaking. This would throw some doubt on the need for postulating heavy particle stripping.

Price\(^6\) fitted an angular distribution at 4.1 Mev with both compound nucleus and heavy particle stripping. This is in a region where the excitation function shows resonance-like structure. Both the predicted distributions fitted the data fairly well and were similar in shape up to the greatest background angle measured, 150 degrees. At this angle the compound nucleus distribution peaked and then dropped off, but the heavy particle stripping curve continued to rise smoothly with angle.

Kuan et al.\(^{26}\) have measured the excitation curve of the 15.1 Mev gamma-ray from the $^6B(d,n^\gamma)^{12C^*}$ reaction. They found resonances at 2.18 and 3.08 Mev agreeing with previous data\(^{22}\) and two new resonances at 3.70 and 4.41 Mev. These resonances correspond to levels in $C^{13}$ at 20.52, 21.28, 21.81, and 22.41 Mev respectively.

It was therefore decided to study further the
$^{11}\text{B}(d,n)^{12}\text{C}$ reaction in the energy range 1-12 Mev. Excitation functions were measured and angular distributions were taken on and off the resonance-like structures that were found. It was then hoped to find from all the data available which theory would best explain the experimental results. It was also hoped to compare the excitation functions with the 15.1 Mev gamma-ray excitation curve.
II. APPARATUS

The Neutron Spectrometer

Introduction. The neutron detector used in the \( {\text{B}}^{11}(d,n){\text{C}}^{12} \) experiment was of the recoil telescope type. The history, design, and use of recoil telescope neutron detectors have been described by C. H. Johnson\(^{66} \). Early models consisted of hydrogenous radiators with two or more gas proportional counters or ionization chambers arranged in tandem and used in coincidence to detect recoils\(^{67} \). An example was the arrangement of Nereson and Darden\(^{27} \). It was a double coincidence telescope in which the first counter was a thin (1 cm.) proportional counter and the second was a long (36 cms.) Frisch grid ionization chamber, and the pulses were analyzed by a 12-channel analyzer gated by double coincidences.

The main problem in the design of Nereson and Darden arose from the fact that the two counting systems were basically of the same type (gas filled) but much different in physical thickness. The introduction of a solid scintillator offers an ideal solution to this problem. Instead of making the counters physically of such different thicknesses, one can simply make them of different materials, a gas and a solid. About 1954, results of experiments using telescopes with gas filled \( dE/dx \) counters in coincidence with solid scintillators were published almost simultaneously from at
least four different laboratories. In these telescopes most of the proton recoil energy is dissipated in a NaI(Tl) or CsI(Tl) scintillation counter operating in coincidence with one or more gas filled proportional counters.

Two of the most successful telescopes were triple-coincidence telescopes (two gas filled dE/dx proportional counters and a scintillation counter) used for experiments at Los Alamos and Oak Ridge. The Los Alamos telescope, built by Bame et al.\(^{32}\), was of a large angle design and was used for measurements of flux from monoenergetic neutron sources. The Oak Ridge telescope was a high resolution telescope designed by Johnson and Trail\(^{33}\). If the source-to-radiator distance is set equal to the radiator-to-scintillator distance for each counter, the geometric resolutions are 1.56 per cent for the Oak Ridge counter and 16 per cent for the Los Alamos counter. If the radiator thicknesses are chosen appropriately for these resolutions, the ratio of efficiencies is roughly 10\(^3\), i.e. the ratio of the resolutions to the third power.

Basic Design of the Rice Spectrometer. The neutron detector used for the study of the neutron groups from the \(^{11}\text{B} (d,n)\text{C}^{12}\) reaction was a proton recoil telescope previously used by Cole\(^{68}\), Price\(^6\), and Risser et al.\(^{30}\). It consisted of a hydrogenous polyethylene radiator with two counters in tandem. They operated in coincidence to detect the protons
which recoiled within a small solid angle $\psi_p$ to the neutron flux. One counter was a dE/dx gas proportional counter and the other a CsI(Tl) scintillation counter to measure the proton-recoil energies. By using the two counters in coincidence good discrimination against background was obtained. Since the n-p scattering cross section is precisely known as a function of neutron energy, it was possible to calculate accurately the neutron detection efficiency from the composition of the radiator and the solid angle of the detector. Since the scintillator subtended a limited range of forward recoil angles, a group of recoil protons of limited energy spread were incident on the scintillator from each monoenergetic neutron group. The energy spread of the protons depended on the range of recoil angles accepted and the thickness of the radiator. The energy resolution depended, in turn, on the energy spread of the recoils and the resolution of the scintillator and photomultiplier tube. The proton recoil telescope therefore offered a neutron spectrometer of known efficiency and good background discrimination. However, it had a low efficiency since the radiator had to be relatively thin for energy resolution, and the scintillator could only subtend a small solid angle at the radiator. Also due to the resolution of the scintillator and phototube, as well as the finite radiator thickness required for efficiency, the energy resolution was only fair
but was good enough to separate the first four groups from the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction as the low lying energy levels in $^{12}\text{C}$ are each separated by a few Mev. It was possible with this spectrometer to keep the energy resolution and efficiency fairly constant over a wide range of neutron energies by increasing the radiator thickness with increasing neutron energy.

**Design Used in the Experiments with 1-5.8 Mev Deuterons.**

In the energy range of the bombarding deuterons, 1-5.8 Mev, the spectrometer was the same as used by Price and Risser et al. in the study of the $^{9}\text{Be}(\alpha,n)^{12}\text{C}$ reaction. A simplified drawing of this spectrometer is shown in Fig. 2. It was built in an eccentrically bored aluminum envelope A. The envelope was a cylinder with a diameter of four and one-half inches and was five and one-half inches high. The thickness of the wall in the forward direction was about one-sixteenth of an inch. This envelope was mounted in an aluminum support that contained the gas counter and crystal counter preamps.

The radiators used in the spectrometer were of pure polyethylene which was obtained from a sample booklet of Visqueen foils supplied by the Visking Corporation of Terre Haute, Indiana. It was found possible to construct radiators of all the required thicknesses from foils supplied in this booklet. The radiators were mounted on a movable carriage B. There was room for radiators of three
different thicknesses and a blank position with no radiator present. A soft iron bar was mounted on the carriage, and this allowed the radiators to be rotated from the outside of the envelope with a magnet. The four carriage positions were accurately determined by a ball and socket arrangement. The radiator thicknesses varied from 15 mg/cm$^2$ to 60 mg/cm$^2$ depending on the neutron energies under observation. The radiators were clamped to the front of brass supports, and their areas were defined by one inch circular holes cut in the brass.

The crystal used in this spectrometer was a one inch diameter CsI(Tl) crystal. It was held against the photomultiplier tube by three spring clips J, and Dow Corning 200 fluid was used to couple the crystal to the tube. In the energy range, 1-5.8 Mev deuterons, a 100 mil thick crystal was used. This thickness was just enough to stop the highest energy protons to be detected, as estimated using Nuclear Data Tables, Part 3$^{34}$. Use of a thin crystal helped to minimize the background noise in the crystal due to $\gamma$-rays. The crystal was covered on the sides and top with 5 mil thick aluminum foil to help improve the light-collecting efficiency of the crystal counter.

The photomultiplier tube was a DuMont 6291 tube and was waxed to a soft iron shield D. The shield was bolted directly onto the aluminum envelope, and a teflon ring made the
seal between the shield and the envelope.

The proportional counter consisted of a brass cylinder F and a tungsten wire G. There were two holes in this cylinder. One of these, which was opposite the radiator, was one and one-quarter inches in diameter, and the other, opposite the crystal, was one and three-eighths inches in diameter. These holes were at the same height as the radiator and crystal and allowed the recoil protons to pass from the radiator into the proportional counter and onto the crystal. The diameter of the wire was 5 mils. Anderson\textsuperscript{35} has made calculations studying the change of rise time of the pulse with increasing wire diameter. A smaller diameter would decrease the rise time by increasing the velocity of positive ions away from the wire; however, it would reduce the electric field at a given radius for a given voltage and increase the electron collection time. The value of the diameter used was a good compromise between these two factors.

To insure low background counts no hydrogenous contamination should be present inside the spectrometer. The inside of the spectrometer was therefore thoroughly cleaned with fine wire wool after which no contact was made with the inside of the counter. The envelope was then outgassed, generally for about two days. It was later flushed out with argon and allowed to pump out for an additional day. The counter was filled with a mixture of argon and carbon dioxide.
Figure 3 shows a graph of the drift velocities of electrons in tank argon, with various percentages of CO$_2$, as a function of E/P$^{36}$. Figure 4 shows a graph of E/P, the ratio of voltage gradient to pressure, versus $r$, the distance from the center electrode, under two different operating conditions. The proportional counter should operate throughout its effective volume with E/P above the knee of the drift velocity curve and with as large a drift velocity as practical. The effective radius of the proportional counter was about 1.27 cms., and therefore the percentage of CO$_2$ in the argon to satisfy the above condition was 1 per cent. The counter was usually filled to 2-1/3 atmospheres. Because of the low counting efficiency of the spectrometer, constancy of gas gain over long time intervals was important. Risser et al.$^{30}$ had found that the tight envelope with teflon gasket seals and careful gas filling achieved constancy over periods of several months for pressures up to 1 atmosphere for this spectrometer. To check the constancy at the higher pressure the spectrometer was tested for gas leaks over a period of several days. The counter was filled to 2-1/3 atmospheres and was left on the test gauge for two or three days. No drop in pressure was noticed during that time. Both teflon and polyethylene have very low vapour pressures so the gas was not contaminated by organic materials.

As the faster protons gave smaller pulses in the propor-
tional counter than the slower ones, it was necessary at all times to make sure all the protons were detected. Therefore, with the deuteron bombarding energy constant, the gas voltage was varied and the number of protons detected in the crystal in coincidence with the gas counter was noted. When the gas voltage was too low the number of protons detected increased as the gas voltage increased until a maximum in the number detected was reached. This maximum stayed constant as the voltage was further raised. The gas voltage was then set just above the value at which this maximum number was obtained. This voltage check was made at regular intervals as the deuteron bombarding energy was increased. By using as low a voltage as allowable, the number of small pulses not biased out was reduced, which lowered the background and accidental counting rates.

**Difficulties and Attempted Modifications.** Since the specific ionization of fast recoil protons was low, the gas counter gain was sufficiently high so that the gas counter could detect a great number of low energy electrons. For example, the pulse created by a 100 Kev electron reaching the end of its range in the gas counter is about one-fifth as large as the pulse from a 20 Mev proton going straight through the counter from radiator to crystal. These electrons will only cause small pulses in the scintillation counter which can be biased out, but their detection in the gas
counter increased the accidental coincidence rate. An attempt was made to decrease the active volume of the gas counter for electrons without appreciably decreasing the total proton-recoil path by placing a grid in the counter. A thin aluminum cylinder of diameter one and one-half inches was placed concentric with the brass cylinder. It had two holes cut in it level with those in the brass cylinder to allow the protons to reach the scintillator and was held at about 250 volts negative. The protons passing straight through the counter should be counted while the electrons between the grid and the brass outer electrode would not be. Unfortunately, it was found that the gas counter rate was not appreciably cut down. A considerable part of the rate was due to radioactivity which built up in the gas counter. A decay study was made of this radioactivity, and it was found to have a half-life of 11.7 minutes. Due to the large neutron flux inside the counter, it was assumed that the majority of this radioactivity came from the reactions:

\[
^{13}\text{Al}^{27} + ^0\text{N}^1 \rightarrow ^{12}\text{Mg}^{27} + ^1\text{H}^1 - 1.81 \text{ Mev}
\]

\[
\rightarrow ^{11}\text{Na}^{24} + ^2\text{He}^4 - 3.137 \text{ Mev.}
\]

\(^{27}\text{Mg}\) decays by \(\beta^-\) and \(\gamma\) radiation with a half-life of 9.6 minutes and \(^{24}\text{Na}\) decays by \(\beta^-\) and \(\gamma\) radiation with a half-life of 14.9 hours. The grid could have been made of another material, but due to its small diameter and the large holes
cut in it (approximately one and one-half inches diameter), the cylinder presented surfaces by which small-angle scattered protons could enter the scintillator. Therefore, another design was undertaken which will be described below after discussing the limitations imposed on the design by considerations of proton-recoil scattering in the gas and from metal surfaces.

The problem of scattering in recoil telescope detectors has been dealt with by C. H. Johnson\textsuperscript{37}. Multiple scattering in the telescope materials can change the efficiency either by scattering out protons which normally reach the detector or by scattering in protons that normally miss it. The inscattered protons will distort the spectrum if they originate in large angle n-p scattering or if they lose energy during multiple scattering. There are three main sources of scattering; scattering in the radiator, multiple scattering in the counter gas, and multiple scattering from the walls and apertures.

Corrections to the efficiency for multiple scattering of protons in the radiator are negligible for radiators that cause no more than 15 per cent energy loss\textsuperscript{32,38}. The reason is that the protons scattered out of the detector's solid angle are compensated by those scattered in. Although the compensating protons scattered into the detector have their origin in larger angle n-p scattering, there is negligible
distortion of the energy spectrum because the multiple scattering angles are small compared to the usual n-p scattering angles. The radiators used in this spectrometer caused much less than 15 per cent energy loss, and thus these effects could be neglected.

Scattering in the gas counter presents a difficult analytical problem but can be avoided if inscattering is allowed to compensate for protons scattered out. This occurs if the apertures do not limit the inscattering. For this reason any apertures between the radiator and exit should be approximately 10 per cent larger in diameter than the radiator or exit, which is the case for this spectrometer as seen in Fig. 2.

Protons which strike the walls or aperture edges can be scattered through large angles into the detector. This could happen in this spectrometer. The protons can be scattered from the wall of the brass cylinder F and also from the edges of the apertures which defined the radiator areas.

**Design Used in the Experiments with 5-11 Mev Deuterons.** For the study of the $^6\text{Li}(d,n)^{12}\text{C}$ reaction in the energy range of 5.8 to 11 Mev deuterons, when it was required to resolve the third excited state neutron group, some modifications were made to the spectrometer. They were made for three reasons: (1) to overcome the scattering from the aperture edges and from the wall; (2) to cut down on the low energy
distortion of the energy spectrum because the multiple scattering angles are small compared to the usual n-p scattering angles. The radiators used in this spectrometer caused much less than 15 per cent energy loss, and thus these effects could be neglected.

Scattering in the gas counter presents a difficult analytical problem but can be avoided if inscattering is allowed to compensate for protons scattered out. This occurs if the apertures do not limit the inscattering. For this reason any apertures between the radiator and exit should be approximately 10 per cent larger in diameter than the radiator or exit, which is the case for this spectrometer as seen in Fig. 2.

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**Design Used in the Experiments with 5-11 Mev Deuterons.**
For the study of the $^11\text{B}(d,n)^{12}\text{C}$ reaction in the energy range of 5.8 to 11 Mev deuterons, when it was required to resolve the third excited state neutron group, some modifications were made to the spectrometer. They were made for three reasons: (1) to overcome the scattering from the aperture edges and from the wall; (2) to cut down on the low energy
noise in the gas counter by accurately defining its volume; and (3) to increase the resolution. Figure 5 shows a diagram of the modified spectrometer. To overcome the scattering of the protons from the edges of the circular apertures that defined the areas of the polyethylene radiators, the polyethylene in this spectrometer was mounted directly onto tantalum backings. The radiators were mounted by gently heating the previously weighed metal backing and allowing the polyethylene to define its own area. The amount of radiator was then given by again weighing. To overcome scattering from the walls, the brass cylinder was replaced by a slit system. The widths of the slits were about 10 per cent wider than the diameters of the radiator and scintillator so that in-scattering was not limited. As can be seen from the diagram it was impossible for any proton striking the walls of the counter to be scattered into the scintillator. Protons scattering from the aluminum wall would be stopped by the slits, and only those protons passing from the radiator through the slits would reach the scintillator. However, in this rectangular slit arrangement, as opposed to the cylindrical arrangement, the electric field was not known. It was assumed that in the region through which the protons passed, that is close to the center wire, the electric field was not very different. The advantages gained by reducing the scattering from the walls and lowering the active
FIGURE CAPTIONS

Fig. 2  Schematic diagram of the unmodified spectrometer. A is the aluminum envelope and B the radiator. F is the brass cylinder which formed the outer electrode of the proportional counter and G is the center wire. The J's are the clips that held the CsI(Tl) scintillator H in place. C is the photomultiplier tube waxed at E to a soft iron shield D.

Fig. 3  Drift velocities of electrons in tank argon with various percentages of CO₂ as a function of E/P, the ratio of voltage gradient to pressure<sup>36</sup>.

Fig. 4  The voltage gradient to pressure, E/P, versus r, the distance from the center electrode. Two cases are shown: (1) for 500 volts at 1 atmosphere and (2) 2-1/3 atmospheres at 2,000 volts.

Fig. 5  Modifications to the spectrometer. The A's are the slits placed inside the aluminum envelope. B shows the radiator mounted directly onto tantalum backing, and the C's are the field tubes surrounding the center electrode D.
volume of the gas counter outweigh the disadvantages introduced by the worsening of the electric field.

The effective volume of the gas counter was limited by the use of field tubes. The potential on the field tubes is appropriate to its position in the electric field and is given by:

\[ V = V_0 \frac{\log r_p/a}{\log b/a} \]

where \( a \) is the radius of the wire, \( b \) the radius of the outer electrode (in this case an average distance was taken as the radius), \( r_p \) the radius of the field tubes, and \( V_0 \) the applied counter voltage. A separate power supply was used to supply the voltage \( V \). This arrangement gave an effective volume for the gas counter of 3.0 cm\(^3\) compared with about 15.0 cm\(^3\) for the other spectrometer. It was found that with this arrangement the gas counter singles rate was greatly reduced, which consequently reduced the accidental counting rate.

To help improve the scintillation counter resolution, a premium DuMont tube number K-1242 was used. This tube was mounted in an aluminum holder of the same dimensions as the one of soft iron and was bolted directly onto the envelope as before. The aluminum holder was then surrounded with a mumetal magnetic shield.

**Electronics**

A coincidence circuit is triggered accidentally at a rate "a" which is given by:
\[ a = 2n_1n_2 \]

where \( n_1 \) and \( n_2 \) are the counting rates of the two input channels and \( t \) is the resolving time of the system. The counting rate of the scintillation counter was low, and most of the undesired pulses were small and could be biased out. It was found that the accidentals in the region of the spectrum investigated were negligible if the gas counting rate was \( 10^4 \) counts per second or lower. In most cases the gas singles rate was of the order of \( 10^3 \) counts per second.

A block diagram of the electronics is shown in Fig. 6. The coincidence circuit has been described by Smaller and Avery\(^40\) and Adler\(^41\) and uses a 6BN6 vacuum tube. It has a resolving time of one microsecond. The scintillator preamp was a two-stage cathode follower. The last stage was a 6AG7 tube to send the pulse through the long cable back to the control desk. The preamp for the gas counter was built by the author and closely follows the design of the Hamner preamp model N-357. It consisted of a double triode input circuit or cascode circuit\(^42\), two amplification stages, and a cathode follower output. A circuit diagram is shown in Fig. 7. To reduce the noise due to microphonics the preamp was suspended from the counter by elastic bands. The noise level was found to be negligible compared with the pulses from the proportional counter.

The Atomic amplifiers were modified to give a pulse of
the required shape from the discriminator output circuit. The pulses out of the discriminating circuit were then of a constant height of a few volts and were one microsecond long, and these pulses were fed into the coincidence circuit. The pulses out of the coincidence circuit went into a univibrator which was used to trigger the gating circuit. A three microsecond delay line was necessary between the linear output of the crystal amplifier and the gating circuit to insure that the crystal pulses arrived in the middle of the gate.

The timing parameters, delays and resolving time, may be adjusted with the aid of time resolution curves which show the coincidence rate versus delay in the scintillation and gas channels. As the resolving time of this counter was fixed at one microsecond, only the delay lines in the scintillation and gas counter channels were varied. Delay lines were put in the circuit between the two cathode followers of the crystal preamp or immediately after the preamp of the gas counter. The delay line was terminated at both ends with a 1K resistor to reduce "ringing" effects. This was done with all delay lines used in the circuit. Figure 8 shows a typical time resolution curve and compares well with those taken by Anderson\textsuperscript{35}, who found that the optimum delay was about one-tenth of a microsecond in the scintillation channel but that there was no loss in counts with
zero delay in either channel. Figure 7 shows that this was the case here, and the spectrometer was used under these conditions. This was checked at various energies to make sure that the maximum counts were always recorded.

Two analyzers could be used with the spectrometer, the Nuclear Data ND-150F analyzer or the T.M.C.400 channel analyzer. The linear output from the amplifier was a 30-40 volts positive pulse and was therefore fed directly into the 0-100 volt input of the Nuclear Data analyzer, which was used in the 256 channel mode. The T.M.C. analyzer took negative pulses of less than 10 volts. The pulses to be analyzed had to be attenuated and inverted. A potentiometer divider was used to reduce the size of the pulses, and they were inverted by means of a pulse transformer. The correct pulse size was set with the aid of an oscilloscope.

The Rice I.B.M. 1401 computer was used in preliminary reduction of the data. It is necessary with this kind of spectrometer to make one run with the radiator in and another with the radiator out to give a background spectrum. This background spectrum had to be subtracted from the one obtained with the radiator in. The data was stored on magnetic tapes. The spectra with the radiator in were designated with one thousand plus the run number, and the background spectra were designated with just the run number. A program was written that (1) subtracted the run number
FIGURE CAPTIONS

Fig. 6  Block diagram of the electronics. The amplifiers were Baird-Atomic Model 218 Linear Amplifiers.

Fig. 7  Circuit diagram of the proportional counter preamp, as designed and built by the author. Unless otherwise stated, the capacitors are in $\mu$farads.

Fig. 8  Time resolution curve. The variation in yield versus delay (in $\mu$secs.) in both gas and scintillator channels is shown. The delay line used was RG-65/U.
from the same run number plus one thousand; (2) summed every 5 channels for the Nuclear Data and every 8 channels for the T.M.C. analyzers; and (3) plotted the spectrum normalized to any chosen channel number. In both cases a spectrum of 50 channels was obtained. Nothing was gained by using a larger number of channels because of the energy resolution of the spectrometer. In this investigation of the first four neutron groups from the $^{11}\text{B}(d,n)^{12}\text{C}$ reaction, it was found necessary to use at least two different radiators at a given energy to detect and resolve the groups.

It was found that for the highest energy group the background was about 15 per cent of the total counts, and for the next highest group it was about 25 per cent. As was indicated above, the lowest background was obtained when the counter had been thoroughly cleaned with fine wire wool, completely outgassed, and carefully filled.

**Energy Resolution and Efficiency**

This discussion will be limited to the efficiency and resolution inherent in the basic components, the radiator thickness and detector aperture, which are illustrated in Fig. 8.

The energy of the recoil protons is given by

$$E_p = E_n \cos^2 \psi_p$$

where $\psi_p$ is the laboratory proton recoil angle. Therefore, if we had made the radiator and detector radii very small, i.e. $\psi_p \approx 0^\circ$, and the radiator thickness negli-
gible, the recoil protons would have had the same energy as the neutrons. In that case the resolution would have been limited only by the resolution of the detector itself but the efficiency would have also been negligible. In order to increase the efficiency it was necessary to increase the radiator thickness and the solid angle acceptance, and both of these contributed to the width of the resolution function.

**Radiator Thickness Energy Resolution.** The resolution function introduced by the foil was essentially rectangular in width equal to the energy loss in the foil. As the geometric energy resolution could be determined and the detector resolution was measured, the foil thicknesses were calculated to give an over-all energy resolution of about 10 per cent for the highest energy neutron groups at all bombarding energies. As was indicated above, the thickness of the foils was found by weighing, and as their areas were known the thicknesses in mg/cm$^2$ were calculated. These thicknesses were in agreement with those given in the sample booklet of Visqueen foils.

**Geometric Energy Resolution.** To have a finite efficiency the counter had to accept a range of recoil angles with a corresponding range of proton energies. The crystal would accept recoil protons from the radiator with a range of angles from zero to a maximum angle $\psi_m$, where $\psi$ was the
angle between the velocity vectors of the neutron and proton. For the geometric arrangement most often used, i.e. a target-radiator distance of 10 cm., \( \psi_m \) was 21.5 degrees, and

\[
E_p = E_n (0.93)^2 = 0.87 E_n,
\]

or about a 13 per cent variation in the proton energy.

This, of course, was for the extreme case of a proton originating at the edge of the radiator and being detected on the opposite edge of the crystal. In order to calculate the geometric resolution an integration has to be done over both radiator and detector. This has been done\(^ \text{43} \) for equal radiator and detector radii and equal source-to-radiator and radiator-to-detector spacings. It was found that the geometric resolution function is non-symmetric and has a width approximately equal to \( (\psi_p^0)^2 \) where \( \psi_p^0 \) is the angle for the protons passing from the edge of the radiator to the center of the detector. This yields a resolution of 6 per cent for this spectrometer.

**Scintillation Counter Resolution.** The resolution of the scintillation counter was measured with \( \alpha \) particles. One of the radiators was replaced by a Po\(^{210} \) alpha particle source, and with a vacuum in the gas counter, the resolution of the scintillation counter was investigated for the 5.3 Mev \( \alpha \) particles. It was found to be 10 per cent. If it is assumed that the resolution is inversely proportional to the
square root of the energy, the resolution of the scintillation counter can be calculated for any given energy.

Figure 10 shows a typical computer output. It shows the spectrum obtained for 8 Mev bombarding deuterons at 75 degrees using a 60 mg/cm² thick radiator. The energies of the ground state and first excited state neutrons were 19.53 and 15.36 Mev respectively, and the energies of the protons reaching the scintillator were 17.20 and 13.46 Mev. The calculated resolution of the scintillation counter for these two energies was therefore 5.4 per cent and 6.1 per cent respectively. The energy resolution due to the radiator thickness was 8.2 per cent for the ground state neutrons and 12.5 per cent for the first excited state neutrons. Combining the geometric, radiator, and scintillator resolutions yielded over-all energy resolution factors of 11.5 per cent and 14.9 per cent respectively for the ground and first excited state neutrons. These values compared well with the measured resolutions of 12.5 per cent and 16.5 per cent for the two neutron groups.

There were two factors which were not taken into account in the energy resolution calculations. First was the spread in neutron energies reaching the counter, i.e. the neutron energies were a function of the angle $\alpha$ (Fig. 19). In these experiments $\alpha$ was always 7 degrees or less, and this only introduced an error of less than 1 per cent. Secondly,
the neutrons would also have an energy spread due to the
target thickness. This was again less than 1 per cent at
low bombarding energies and decreased as the deuteron
energy increased.

**Efficiency.** The real value of the recoil telescope rests
largely on the fact that its efficiency could be accurately
determined from the geometry, composition of the radiator,
and the differential n-p scattering cross section.

The differential n-p scattering cross section was found
from the total n-p cross section. For low neutron energies
(≤ 5 Mev) the center-of-mass scattering is isotropic so that:

\[ \sigma_n (E, \psi_p = 0) = \frac{\sigma_n (E)}{\pi}, \]

where \( \sigma_n (E) \) is the total cross section. At higher energies
the scattering becomes progressively nonisotropic, and this
anisotropy is not accurately known from 5 to 30 Mev but is
small. Gammel\(^4^4\) has reviewed this problem and Johnson\(^4^5\) gives
two sets of values for a normalization constant \( A \) defined by:

\[ \sigma_n (E, \psi_p = 0) = \left( \frac{A}{\pi} \right) \sigma_n (E). \]

I have used the average of these two sets of values for \( A \).

The efficiency is defined as the number of protons enter-
ing the detector aperture per neutron/steradian at the source.
If the telescope had only accepted small angle recoils the
efficiency would have been:
\[ \mathcal{E} (\text{small angles}) = \left( \frac{\pi r_1^2}{d_1^2} \right) \left( \frac{\pi r_2^2}{d_2^2} \right) P (A/\pi) \sigma_n (E), \]
\[ = A \pi \left( \frac{r_1 r_2}{d_1 d_2} \right)^2 P \sigma_n (E), \]
where \( P \) is the number of hydrogen atoms/cm\(^2\) in the radiator.

For accurate efficiencies the calculations should include the dependence of effective radiator thickness on incident neutron angle and the dependence on angle for n-p scatterings. Fortunately, these calculations have been done by computer for a range of parameters \( r_1, r_2, d_1, \) and \( d_2 \) for 4 to 30 Mev neutrons emitted from an isotropic point source. Johnson\(^{46}\) has reproduced these results in tables of \( G \) values which are accurate to 0.1 per cent. Interpolations were made for the various experimental arrangements used. The efficiency is then equal to:

\[ \mathcal{E} = G A \pi \left( \frac{r_1 r_2}{d_1 d_2} \right)^2 P \sigma_n (E). \]

Values of \( \sigma_n (E) \) were obtained from Neutron Cross Sections\(^{47}\). The weight of the polyethylene was found as described above, and the radiator was assumed to be pure CH\(_2\) although it is not a definite chemical compound. The dimensions \( r_1, r_2, \) and \( d_2 \) are fixed by the geometry of the counter and \( d_1 \) was determined from the experimental arrangement. Usually it was set equal to \( d_2 \) at 10 cm.

The values of \( G, A, \) and \( \sigma_n (E) \) versus the neutron energy are shown in Fig. 11.
The differential cross section is then given by:

\[
\frac{d\sigma}{d\theta} = \frac{Y}{Nt^2}
\]

where \(Y\) is the yield of neutrons as measured by the counter, \(N\) is the number of particles striking the target and \(t\) is the number of target atoms/cm\(^2\). The measurement of the target thickness is described below. Curves for \(Nt^2\) versus neutron energy are shown in Fig. 12 for the four radiator thicknesses used. It was possible to choose the right radiator thickness for a given neutron energy so that the efficiency and resolution could be maintained fairly constant over the whole range of neutron energies encountered.

Energy Absorption

There are three sources of energy absorption in the counter: (1) the radiators, (2) the gas, and (3) the aluminum foil over the crystal. If we assume that the average proton originates in the center of the radiator, then the average absorption will be due to half the radiator thickness. The proton energy losses in the polyethylene (\(C_nH_{2n}\)) radiator were calculated from a table given by Johnson.\(^{48}\) The relative stopping power for argon is 0.96 that of air. The pressure used in the gas chamber was 2-1/3 atmospheres, and the path length between the radiator and crystal was 10 cm. This resulted in an equivalent path of 22.4 cm. of air at normal temperature and pressure. The
stopping power of protons in air was taken from Bethe and Ashkin's graphs in Experimental Nuclear Physics. The thickness of the aluminum foil was 0.5 mils, and the energy loss of protons in aluminum was obtained from Nuclear Data Tables Part 3.4.

The total energy loss versus energy was calculated for the four radiator thicknesses used and graphs were drawn. These are shown in Fig. 13. As can be seen the absorption varies rapidly with energy in the low energy range but begins to level off at the high energy end. It was necessary to calculate these curves in order to identify the peaks found in the spectrum.

The neutron energies were calculated by computer for a given energy, angle, and Q value from the reaction kinematics formula given by Marion in Nuclear Data Tables Part 3.4. The zero point in the spectrum was found by calibration with a pulse generator and an oscilloscope, and due to the low level cutoff on the analyzer, it was usually below the zero channel. The peak corresponding to the highest energy protons was then assumed to be due to the neutrons to the ground state. Its energy was taken to be that of the computed neutron energy minus the calculated average absorbed energy in the counter on the assumption that the laboratory proton recoil angle was zero and that the protons passed through the counter via the shortest route. This point was
then used to form an energy scale for the spectrum which enabled the energies of the other peaks to be measured. By comparing these values with the results obtained from the kinematic calculations and absorption curves, the peaks were identified. A typical spectrum is shown in Fig. 14. It was found that as the energy of the bombarding deuterons or the angle was varied the position of the peaks changed as predicted, so that their identification was definitely established.

**Target and Detector Geometry**

The target holder described by Price\(^6\) was used for the experiments carried out on the 5.5 Mev Van de Graaff accelerator. This consisted of a thin copper tube two inches in diameter with brass end plates. The target and a quartz were mounted on the axis of the tube which was perpendicular to the deuteron beam. They were mounted in such a way that they could be rotated about the axis and either the target or the quartz could be brought into the beam path. A scale on the top end plate enabled the target to be set at any desired angle to the deuteron velocity vector. A small window in the side of the tube enabled the quartz to be viewed when it was in the path of the beam. The beam was lined up with low energy protons. The target holder was adjusted until the beam hit cross-wires on the quartz. By means of stops on the target holder the target could then be placed
FIGURE CAPTIONS

Fig. 9 Basic geometry for a thin radiator proton recoil telescope. The neutrons were assumed to come from a point source.

Fig. 10 Computer output. The energy of the bombarding deuterons was 8.0 Mev and the neutrons were measured at a laboratory angle of 75 degrees. The calculated neutron energies for the ground and first excited state neutrons were 19.53 and 15.36 Mev respectively. The absorptions with the H\textsuperscript{1} radiator were calculated as 1.56 and 1.90 Mev and the energies actually measured were 17.97 and 13.46 Mev for the two groups. The resolution was measured as 12.5 per cent for n\textsubscript{0} and 16.5 per cent for n\textsubscript{1}.

Fig. 11 The factors G\textsuperscript{46}, A\textsuperscript{45}, and $\sigma_{n}(E)$\textsuperscript{47} versus neutron energy.

Fig. 12 NTt for four radiator thicknesses versus neutron energy. The factor NTt was calculated with a target distance of 10 cm., a target thickness of 300 $\mu gms/cm^2$, and a total charge collected of 370.3 $\mu$coulombs.
Fig. 13  The absorption of proton energy in the counter versus proton energy. This is shown for the four radiators used. $H^1$ was 60 mg/cm$^2$ thick, H was 45 mg/cm$^2$, M was 30 mg/cm$^2$, and L was 15 mg/cm$^2$.

Fig. 14  Computer output. The energy of the deuterons was 7.6 Mev and the neutrons were measured at zero degrees. The calculated energies were 21.29, 16.89, 13.67, and 11.67 Mev for the first four neutron groups. The absorptions with the $H^1$ radiator were 1.42, 1.74, 2.10, and 2.37 Mev respectively. The energies measured were 19.87, 15.15, 11.57, and 9.30 Mev. The energy scale was calculated assuming 19.87 Mev as the energy of the ground state neutrons. The other three points on the calibration line are the positions calculated with this assumption.
$E_d = 8.0 \text{ MeV}$  $\theta(\text{LAB}) = 75^\circ$

H' RADIATOR

$E_{n_0} \text{ measured } = 17.97 \text{ MeV}$

$E_{n_1} \text{ } = 13.46$
$E_d = 7.6\text{ MeV} \quad \theta \text{(LAB.)} = 0^\circ$

H' RADIATOR

$E_{n_0} \text{ measured} = 19.87\text{ MeV}$

$E_{n_1} \quad = 15.15 \quad "$

$E_{n_2} \quad = 11.57 \quad "$

$E_{n_3} \quad = 9.30 \quad "$

FIGURE 14
in the exact position of the quartz.

Due to the more energy-dependent beam path in the Tandem Van de Graaff, it was impossible to align the chamber with low energy protons and then be sure that the higher energy deuterons would strike the target. Certain modifications were made to the chamber so that the beam of high energy deuterons could be directly lined up on the quartz. A larger window was cut in the tube with a diameter equal to that of the lens on the closed circuit television camera. With the quartz in the bombarding position and with a light shining on the quartz, the position of the cross-wires could be seen on the television screen at the control desk. The beam could then be lined up on the cross-wires. In the modification, the quartz and target were insulated from the rest of the chamber. This was done by replacing the top brass end plate with a nylon one and having the bottom of the target holder rest in a nylon bearing. The charge was then collected from the target holder and the rest of the chamber was used as a suppressor. A brass scale was inserted in the nylon end plate so that the angle of the target could again be read. A cross section view of the modified chamber is shown in Fig. 15.

As the aim of part of this investigation was to extend the angular distributions to backward angles, the one inch diameter tube connecting the target chamber to the accelerator
vacuum tube was lengthened to eighteen inches. As used by Price the maximum backward angle that could be viewed with usable efficiencies was 150 degrees in the laboratory. By lengthening this tube the backward angle obtainable was increased to 160 degrees.

The spectrometer was mounted on a platform that could be rotated about an axis that coincided with the axis of the target chamber. Great care was taken in aligning these two axes, and the yield of neutrons at 90 degrees on either side of the beam was measured to check the alignment. When angular distributions were taken the target was usually set at 45 degrees to the beam. The forward angles were used on one side and the backward angles on the other side (Fig. 15). The experimental set-up of the target chamber and spectrometer is shown in Fig. 16, photographs a and b.

**Accelerators**

The deuteron beam was accelerated by the Rice University Van de Graaff accelerators. For energies up to 5 Mev the 5.5 Mev accelerator was used, and for the higher energies the 12 Mev tandem accelerator was used. The beam energies were determined using the 90 degrees analyzing magnets which were calibrated in terms of the frequencies of proton and lithium moment magnetometers, using the Li⁷(p,n)Be⁷ and the C¹³(p,n)N¹³ thresholds. These calibrations have been checked with a magnetic spectrograph⁵⁰.
FIGURE CAPTIONS

Fig. 15 Cross section view of modified target chamber and the experimental arrangement of the chamber and spectrometer.

Fig. 16 Photographs of the experiment arrangement. In photograph (a) the placement of the spectrometer, target chamber, and television camera can be seen. The flashlight was used to illuminate the quartz inside the target chamber. In (b) the stand on which the spectrometer was placed can be seen. The gas counter preamp suspended by elastic bands is also evident.
Targets

Two targets were used throughout these experiments. One was made by evaporation at Rice University. The other was obtained from A.E.R.E. Harwell.

The Rice target was made by evaporating natural boron from a tantalum strip onto a tantalum backing which was three-quarters of an inch in diameter and fifty mils thick. The other target from Harwell was obtained from the Electromagnetic Separation group. The $^{11}$B was deposited on a 2 x 2 cm. tantalum backing that was 5 mils thick. The nominal thickness of this target was quoted as 300 $\mu$gms/cm$^2$.

The actual target thicknesses were measured by comparing the neutron yield from the targets with the yield from an infinitely thick boron target. This infinitely thick boron target was made by compressing powdered natural boron into a solid and mounting onto a tantalum backing. It was approximately 166 mg/cm$^2$, whereas the range of 5.6 Mev deuterons in boron is about 15 mg/cm$^2$ $^{34}$ so that all the deuterons were stopped in the target. The yield of neutrons from a small layer in the boron is given by:

$$dy = \sigma(E) \rho dx.$$  

The total yield will be given by:

$$Y \sim \int_0^{R(F_{max})} \sigma(E) \rho dx,$$
where \( R(\text{E}_{\text{max}}) \) is the range of the deuterons in the boron, \( \sigma(E) \) is the cross section, and \( \rho \) is the density. Now \( \text{dE} = \text{dx}(\text{dE/}\text{dx})_{\text{E}} \) and we can write the yield as:

\[
Y \sim \int_{0}^{\text{E}_{\text{max}}} \sigma(E) \frac{\text{dE}}{(\text{dE/}\text{dx})_{0-\text{E}_{\text{max}}}}
\]

and for the thin target the yield will be given by:

\[
Y' \sim \int_{E'}^{\text{E}_{\text{max}}} \sigma(E) \frac{\text{dE}}{(\text{dE/}\text{dx})_{E'-\text{E}_{\text{max}}}}
\]

The highest deuteron energy used for these comparisons was 5.2 Mev. The ground state neutrons are still fairly well separated from the first excited state neutrons at 5.2 Mev. The yields from the two targets were, therefore, measured and normalized to the same collect beam charge. The integration from 0 to \( \text{E}_{\text{max}} \) was then done manually using a planimeter.

The excitation curve from 0 to 1 Mev was obtained from Burke et al.\(^{11}\) and Ames et al.\(^{7}\). However, the relative variation of \( (\text{dE/}\text{dx})_{\text{E}} \) in boron must be taken into account. The value of \( (\text{dE/}\text{dx})_{0-\text{E}_{\text{max}}} \) was obtained by interpolation from Whaling's data\(^{51}\) and then normalized to unity at \( \text{E}_{\text{max}} \).

The excitation curve was then divided by \( (\text{dE/}\text{dx})_{0-\text{E}_{\text{max}}} \) and the integration done again with a planimeter. As the ratio of \( Y/Y' \) was measured the value of \( E^{1-\text{E}_{\text{max}}} \) was easily calculated. The Harwell target was found to be approximately 22 kev thick at 5.2 Mev or 187 \( \mu \)g/cm\(^2\). The Rice target
was measured at two different bombarding energies, 1.8 Mev and 4.8 Mev, and the average thickness was found to be $275 \, \mu g/cm^2 \pm 50 \, \mu g/cm^2$.

Two factors have been ignored in these calculations: (1) the change in counter efficiency with change in neutron energies and (2) the presence of $^{10}B$ in natural boron. The variation in efficiency was due to the energy dependence of the $n$-$p$ cross section. When 5.2 Mev bombarding energy deuterons were stopped in the infinitely thick target, the range of neutron energies was 13.7 to 18.8 Mev. In this region the efficiency did not vary by more than 25 per cent. The infinite boron target was made from natural boron, which is 18 per cent $^{10}B$. Therefore, these target thicknesses were only good to within about 35 per cent. However, the cross sections measured using both targets agreed well within the error.
III. CALCULATIONS

Deuteron Stripping Distorted-Wave Calculation

In the introduction a simple discussion of the direct interaction as developed by Bhatia was described. The distorted-wave approximation to the theory will be discussed here. In this type of interaction the proton is stripped from the incoming deuteron by the target nucleus, leaving the neutron as the outgoing particle.

The general matrix element for this process can be written in terms of the n-p force.

\[ M_{f1} = \int \psi_f^* \psi_{np} \psi_1 \, d\tau, \]

and the cross section is proportional to the square of the matrix element:

\[ \sigma(\theta) \propto |M_{f1}|^2, \]

where \( \psi_1 \) and \( \psi_f \) are the initial and final-state wave functions.

The wave function \( \psi_1 \) will, in general, be a complicated many body wave function describing the complete interaction of the system, which is initially a plane-wave deuteron incident on the target nucleus. For the distorted-wave approximation \( \psi_1 \) is written as:

\[ \psi_1 = \varphi_d (\vec{r}_p - \vec{r}_n ) \chi_d (\vec{r}_d - \vec{r}_t) \]
where $\phi_d(\vec{r})$ is the internal wave function of the deuteron, 
$\vec{\rho} = \vec{r}_p - \vec{r}_n$, $\chi_d(\vec{r})$ describes the relative motion of the
deuteron and the target, and $\vec{r}_d$ is the center-of-mass
coordinate of the deuteron, i.e. $\vec{r}_d = (\vec{r}_p + \vec{r}_n)/2$. $\chi_d(\vec{r})$ is
calculated using the optical model (complex potential well)
to describe the deuteron target interaction and is solved
subject to the outgoing-wave boundary condition:

$$
\chi_d(\vec{r}) \xrightarrow{r \to \infty} \frac{1}{K_d \cdot \vec{r}} e^{ik_d r} + f(\theta) \frac{e^{ik_d r}}{r} .
$$

In this representation of $\psi_1$, the internal wave function
of the deuteron is assumed to be unchanged by the deuteron-
target interaction. The matrix element involves the short-
range potential $V_{np}$, and it may be expected that the short-
range parts of $\phi_d(\vec{r})$ are not seriously modified by the
distortion. This approximation must be used because the
three-body problem which is present without it has not been
solved.

Since we are dealing with low residual states, we assume
that the use of the optical model is valid. The optical
model assumption neglects the contribution of complicated
inelastic collisions to the stripping process. These collis-
sions result in a transfer of energy to the target and, in
general, will lead to highly excited final states. The low
excited final states will only receive small contributions
from such inelastic collisions. Inelastic collisions are to
be classified as compound nucleus processes whose contribution is neglected in direct interaction theory.

The wave function for the final state is approximated by:

\[ \psi_f = \int_p (\overline{r}_p - \overline{r}_t) \chi_n (\overline{r}_n - \overline{r}_r), \]

where \( \int_p \) is the wave function of the captured proton, \( \chi_n \) describes the relative motion of the neutron and the residual nucleus, and \( \overline{r}_r \) is the center-of-mass coordinate of the residual nucleus, i.e. \( \overline{r}_r = (m_t \overline{r}_t + m_p \overline{r}_p) / m_r \). \( \chi_n \) is again calculated using a complex potential well to describe the neutron-nucleus interaction and is solved subject to the ingoing-wave boundary condition.

\( \chi_n^*(\overline{r}) \) is a solution for a complex potential with a negative imaginary well satisfying the boundary condition:

\[ \chi_n^*(\overline{r}) \rightarrow e^{-iK_n \cdot \overline{r}} + g(\theta) \frac{e^{iK_n \overline{r}}}{r}, \]

when there are only central forces in the optical potential. \( \chi_n^* \) is the function which actually appears in the matrix element \( M_{fi} \). It should be noted that the complex conjugation has changed \( K_n \) to \( -K_n \) and the ingoing wave to an outgoing wave.

It is general in stripping calculations to assume that the n-p force has zero range.

\[ V_{np} (\overline{r}_p - \overline{r}_n) \neq V_o \delta (\overline{r}_p - \overline{r}_n). \]
This is valid if the actual range of the force is small compared to the size of the deuteron and the inverse of the momentum transfer $|\vec{K}_d/2 - \vec{K}_n|$. The effect of this zero-range approximation is that the calculated differential cross section will fall off less rapidly with increasing angle than in the actual case of finite range.

Therefore, with this approximation and measuring all coordinates relative to the target, we obtain:

$$M_{fi} = \int d^3r_p d^3r_n \sum_p^* \frac{(\vec{r}_p)}{(\vec{r}_n - \frac{m_p}{m_r} \vec{r}_p)} \chi_n (\vec{r}_n) \frac{m_p}{m_r} \chi_p (\vec{r}_p)$$

$$V_{np}(\vec{r}_p - \vec{r}_n) \phi_d(\vec{r}_p - \vec{r}_n) \chi_d \left( \frac{\vec{r}_p + \vec{r}_n}{2} \right)$$

$$= V_0 \phi_d(0) \int d^3r \sum_p^* \chi_n \left( \frac{m_r}{m_p} \frac{\vec{r}_p}{\vec{r}_n} \right) \chi_d(\vec{r}) .$$

The computer program used in the calculations evaluated this overlap integral which involves (1) the scattering function of the deuteron, (2) the scattering function of the neutron, and (3) the bound-state function of the captured proton\(^{52}\).

$V_0$ is defined by $V_{np}(\vec{p}) \equiv V_0 \delta(\vec{p})$, so that

$$\int d^3p \ V_{np}(\vec{p}) \ \phi_d(\vec{p}) = V_0 \ \phi_d(0)$$

and the integral is taken as the definition of $V_0 \phi_d(0)$.

The deuteron wave function satisfies the Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m_{pn}} \nabla^2 + V_{np}(\vec{p})\right] \phi_d(\vec{r}) = -\epsilon_d \ \phi_d(\vec{r}) ,$$
where $E_d = 2.226$ Mev and $m_{pn}$ is the reduced mass of the $n-p$ system.

According to the divergence theorem,

$$\int d^3\rho \nabla^2 \varphi_d(\bar{\rho}) = \int dS_\rho \nabla \cdot \varphi_d(\bar{\rho}) = 0$$

since $S_\rho$ is the surface at infinity and $\varphi_d(\bar{\rho})$ vanishes on that surface. Then,

$$V_o \varphi_d(0) = \int d^3\rho V_{np}(\bar{\rho}) \varphi_d(\bar{\rho}) = -E_d \int d^3\rho \varphi_d(\bar{\rho}) .$$

For a Hulthén function

$$\varphi_d(\bar{\rho}) = \left[ \frac{\alpha\beta(\alpha+\beta)}{2\pi(\alpha-\beta)^2} \right]^{1/2} \frac{e^{-\lambda\rho}}{\rho} $$

$$
\therefore V_o \varphi_d(0) = -\sqrt{8\pi} E_d \left( \frac{\alpha+\beta}{\alpha\beta} \right)^{3/2} .$$

Here

$$\lambda = \sqrt{\frac{2m_{nd}E_d}{\hbar^2}} = 0.238 \text{ fm}^{-1} \text{ and } \beta = 7\lambda = 1.67 \text{ fm}^{-1} .$$

There are several well known approximations to the overlap integral. In the Born approximation

$$\chi_d(\vec{r}) = e^{iK_d \cdot \vec{r}}$$

$$\chi_n \left( \frac{m_t}{m_r} \right) = e^{i(m_t/m_r)\vec{K}_n \cdot \vec{r}} ,$$

where $\vec{K}_d$ and $\vec{K}_n$ are the initial and final center-of-mass momenta.
\[ K_d = \sqrt{\frac{2m_{dt}}{h^2}} \frac{m_{dt}}{m_d} E_d, \quad K_n = \sqrt{\frac{2m_{nr}}{h^2}} \left( \frac{m_{dt}}{m_d} E_d + Q \right). \]

\( E_d \) is the laboratory energy of the deuteron; \( m_{dt} \) and \( m_{nr} \) are the initial and final reduced masses.

In this stripping calculation it is assumed that the proton is captured into a single-particle level having a well defined orbital angular momentum \( \ell \). Then

\[ \int_p \langle \hat{r} \rangle = \frac{\hbar \ell(r)}{r} Y_{\ell m}(\theta, \varphi), \]

where \( \hbar \ell(r)/r \) is the radial wave function of the bound state. With this assumption and using the Born approximation,

\[ M_{fi} = V_o \varphi_d(0) \sqrt{4\pi (2\ell+1)} \delta^{\ell}_{m_0} \int_0^\infty r dr \ h_\ell(r) \ j_\ell(Q_r), \]

where \( Q = | \frac{K_d - m_t/m_n K_n} \) is the momentum transferred to the target by the captured proton. \( j_\ell(Q_r) \) is the spherical Bessel function of order \( \ell \).

In the cut-off or Butler approximation, the lower limit on the integral is replaced by \( R \), so that

\[ M_{fi} \propto \int_R^\infty r dr h_\ell(r) j_\ell(Q_r). \]

This is to simulate the damping of the incident wave due to absorption out of the incident beam. This is accomplished by the imaginary potential in the distorted wave form.

As we have seen for the Bhatia approximation, it is assumed that the integrand, including inner damping and
outer fall-off of the bound state, is sharply peaked at a radius $R$, in which case

$$M_{r1} \propto J(QR).$$

In most cases these two approximations give very similar angular distributions.

**Heavy Particle Stripping**

As has been indicated some of the angular distributions found in the literature have been fitted using heavy particle stripping theory\(^7,^{23}\). This theory was discussed briefly in the introduction. A complete outline of this theory can be found in the paper by Owen and Madansky\(^{23}\) and only their final results will be discussed here. As was mentioned above, their treatment is based upon a Born approximation. Their final wave function for the outgoing neutron, which is antisymmetric for the exchange of the neutron from the deuteron and the outer shell neutrons of the $^{11}_B$, includes the probability of heavy particle stripping. The exchange wave function for the final state neutrons also introduces interference between the deuteron stripping and heavy particle stripping. This interference is large below the Coulomb barrier.

Their final expression for the differential cross section can be written as:
\[
\frac{d\sigma}{d\Omega} = C(E) \left| G_d(K_1) J_1(k_1 R_1) + \frac{\lambda}{\lambda'} \frac{2}{1} G_H(K_2) J_0(k_2 R_2) \right|^2
\]

\[
K_1 = \left[ k_n^2 + \frac{1}{4} k_d^2 - k_n k_d \cos \theta \right]^{1/2}
\]

\[
k_1 = \left[ k_d^2 + \left( \frac{11}{12} k_n^2 \right)^2 - \frac{11}{6} k_n k_d \cos \theta \right]^{1/2}
\]

\[
K_2 = \left[ k_n^2 + \left( \frac{1}{11} k_d^2 \right)^2 + \frac{11}{11} k_n k_d \cos \theta \right]^{1/2}
\]

\[
k_2 = \left[ k_d^2 + \left( \frac{1}{6} k_n^2 \right)^2 + \frac{1}{3} k_n k_d \cos \theta \right]^{1/2}
\]

\(k_n\) = center-of-mass wave number of the outgoing neutron,
\(k_d\) = center-of-mass wave number of the incident deuteron,
and \(\theta\) is the angle between \(\vec{k}_n\) and \(-\vec{k}_d\)(= + \(\vec{k}_{11}\)). These relations are shown in the following diagrams:
\[ G_D(K_1) = \frac{2(2\pi \alpha_d)}{\alpha_d^2 + K_1^2} \]

\[ G_H(K_2) = \left\{ \frac{\alpha_B^2}{\alpha_B^2 - K_2^2} + \frac{1.9\beta_B^2}{\beta_B^2 + K_2^2} \right\} \times \left\{ 0.535 \sin(K_2r_B) + j_1(K_2r_B) \right\} \]

\[ \alpha_d = \sqrt{\frac{m}{\hbar^2} E_B} \quad \alpha_B = \left[ \frac{2M}{\hbar^2} (E-V) \right]^{1/2} \quad \beta_B = \left[ \frac{2M}{\hbar^2} |E| \right]^{1/2} \]

\[ r_B = 3.4 \times 10^{-13} \text{ cm} \]

The \( j_{\ell}(kR) \) terms are the spherical Bessel functions of order \( \ell \), and \( M \) is the reduced mass of the neutron-\( ^{10}\text{B} \) system. \( E \) is the binding energy of the neutron in \( ^{11}\text{B} \), and \( E_B \) is the binding energy of the deuteron.

\( \lambda_2/\lambda_1 \) is proportional to the ratio of the amplitudes of the exchange term and the deuteron term. It is usually taken as the principal adjustable parameter of the analysis along with the interaction radii \( R_1 \) and \( R_2 \) of the centrifugal barrier terms \( j_1(k_1R_1) \) and \( j_0(k_2R_2) \). These radii are usually set equal. As has been said before, the use of the interaction radius in the Born approximation is a method of introducing the equivalence of distortions in the plane waves.

**Compound Nucleus Formation**

Price\(^6\) has discussed in this thesis the possibility of compound nucleus formation in the region 3.5 to 4.7 Mev where both the excitation curves and angular distributions
suggest this form of reaction. He suggested that the single resonance theory for compound nucleus formation, as worked out by Blatt and Biedenharn\textsuperscript{12}, might be expected to apply here.

No details of the theory will be given, but a brief indication of how the calculations are carried out will be presented. The expression for the differential cross section is proportional to:

$$\frac{d\sigma}{d\sigma_0} \propto \sum \mathcal{Z}(l_1,l_1',s) \mathcal{Z}(l,l',j_1,j') P_{j}(\cos \theta) ,$$

$s=$ incoming channel spin, $l=$ orbital angular momentum of incident particle, $s'=\text{outgoing channel spin}, l'=\text{orbital angular momentum of outgoing particle, and } J=\text{spin of compound nucleus state}$. The $\mathcal{Z}$ coefficients were obtained from revised tables by L. C. Biedenharn\textsuperscript{53}.

First, least squares Legendre Polynomial fits to the angular distribution data were obtained. By comparing the coefficients of $P_{j}$ obtained from the least squares fits with those given by the tables, an indication of the spin of the compound nucleus state could be obtained.

It is unreasonable, however, 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 distributions.
.IV. RESULTS

Excitation Curves

As was indicated in the introduction, it was desired to measure excitation functions for this reaction for the energy range 1-12 Mev. The Q values for the $^\text{11}\text{Be}(d,n)^\text{12}\text{C}$ reaction are 13.731, 9.297, 6.074, and 4.091 Mev respectively for the first four neutron groups. The Q values for the first two groups from $^\text{10}\text{Be}(d,n)^\text{12}\text{C}$ reaction are 6.466 and 4.66 Mev. Therefore, in order to resolve the higher energy excitation groups, pure $^\text{11}\text{Be}$ targets had to be used. Due to the background of low energy neutrons, the neutrons of the discrete spectrum could only be resolved when they had energies in excess of 8 Mev. Therefore, the excitation functions for the second and third excited state neutrons start at about 2 and 5.5 Mev respectively. Due to the fact that the radiators used were generally chosen to give good resolution for the first two groups, the energy resolution of the other groups was not especially good and was of the order of about 30 per cent. Coupled with this was the fact that the background increased for the low energy neutron groups. The errors in the cross section measurements were, therefore, greater for these groups and especially the third excited state neutrons where it was often difficult to separate them from the continuum of low energy neutrons. The error bars shown in the figures for the excitation curves are standard
deviations from the mean as these measurements were repeated a number of times.

**Ground State Neutrons.** Figure 17 shows the ground state neutron excitation function at 0 degrees. In the region 1 to 5 Mev it agrees with the curve given by Price\(^6\), although he does not resolve the two peaks at 3.6 Mev and 4.25 Mev, but both curves show the large peak around 1.6 Mev. The cross section drops off very quickly above 4.5 Mev and reaches a minimum at 7 Mev. From 8 to 11 Mev the curve again begins to show some structure with peaks at around 9.6 and 10.4 Mev. Where no error bar is shown it means that the point was only measured once. The other points are averages of between four to six measurements. Most of the low energy points were taken using the Rice target and the high energy points using the Harwell target. The cross sections were calculated using the target thicknesses quoted above, and no normalization was used between the two measurements.

**First Excited State Neutrons.** Figure 18 shows the excitation curve obtained for the first excited state neutrons at zero degrees. Again the curve agrees quite well with the one obtained by Price\(^6\) in the energy region 1 to 5 Mev. There is a broad peak between 1 and 2.4 Mev. Both curves show a minimum at 3.4 Mev but Price\(^6\) measures a peak around 3.9 Mev, whereas Fig. 18 shows a peak around 4.1 Mev. Again
the cross section drops off with increasing energy to a minimum around 8.0 Mev. However, there is evidence of some structure from 5 to 11 Mev with a strong peak at 9.6 Mev again. This curve was taken at the same time as the excitation function for the ground state neutrons so the points are averages of between four and six measurements.

Second Excited State Neutrons. In Fig. 19 is shown the excitation curve for the second excited state neutron group at zero degrees. Due to the fact that it was difficult to resolve this group at the low energies, the error bars for the low energy points are rather large. The cross section in this energy range is much smaller than for the two higher groups but in the higher energy region the cross section is comparable to that of the ground state neutrons. Due to the large errors it is not possible to specify details of structure except that there is evidence of peaks again at 3.6, 4.1, 9.6, and 10.4 Mev. On the whole the cross section tends to be fairly constant over the entire energy range. These cross sections were measured using the Harwell target and are the averages of about four different measurements.

Third Excited State Neutrons. Figure 20 shows the zero angle excitation curve for the third excited state neutrons. As indicated this group could only be resolved above about 5.5 Mev. As can be seen from the diagram, the cross section
FIGURE CAPTIONS

Fig. 17  The excitation function at zero degrees for the ground state neutrons from the reaction $^{11}_{\text{B}}(d,n)^{12}_{\text{C}}$. The points are averages of between four and six measurements, and the error bars are the standard deviations from the mean.

Fig. 18  The excitation function at zero degrees for the first excited state neutrons. The points are again averages of between four and six measurements, and the error bars are standard deviations.

Fig. 19  The excitation function at zero degrees for the second excited state neutrons. Here the points are averages of four different measurements. The error bars indicate standard deviations from the mean.

Fig. 20  The excitation function at zero degrees for the third excited state neutrons. As for the second excited state neutrons, the points are averages of four measurements, and the error bars are standard deviations.
starts off quite small but at the higher energies it becomes comparable to the cross section for the first excited state neutrons. The large error bars in this curve make it unrealistic to claim any specific structure but there appear to be a number of resonance-like peaks, and the one around 9.6 Mev can also be seen in this curve. These cross sections were measured at the same time as the second excited state group and are, therefore, averages of about four different measurements.

**Angular Distributions**

As the energy of the neutrons depended on the laboratory angle at which they were measured, only the angular distributions for the ground and first excited state neutrons were measured. In general, the energy of the neutrons at the backward angles for the second and third excited state neutrons became too low to resolve from the background. In the figures for the angular distributions the error bars represent the statistical error calculated from $\sqrt{N}/N$, where $N$ is the total number of counts. The figures also show angular distributions from the literature and, where possible, these have been normalized to the present data.

**Ground State Neutrons.** Table 1 gives a list of the angular distributions measured for the neutron group and indicates the method by which the data was taken and ways in
which fits to the data have been attempted. Figure 21 shows most of these angular distributions. As can immediately be seen, there are several different types of behaviour, depending on the bombarding energy. The low energy distributions show little structure, and the cross sections drop off with increasing angle. At 7.0 Mev and above, the distributions are typical of stripping and are strongly peaked around 20 degrees. In the intermediate energy region between 2.0 and 5.5 Mev, the angular distributions tend to be symmetrical around 90 degrees. It is also in this region that the excitation curves show resonance-like peaks so that possibly compound nucleus formation is indicated.

**First Excited State Neutrons.** Table 2 lists the angular distributions for the first excited state neutrons, and most of them are plotted in Fig. 22. They show the same general trend as the ground state neutron angular distributions. At 4.7 Mev and above, some of the distributions show a backward peak around 150 degrees to 140 degrees. In the intermediate region the distributions tend to be a little less symmetric around 90 degrees than those for the ground state.

**Second and Third Excited State Neutrons.** Although angular distributions for these groups have not been measured in this investigation, several of them have been reported in
the literature $^{2,3,5,8}$, and for completeness they have been included here. Table 3 lists them and they are shown in Fig. 23.
<table>
<thead>
<tr>
<th>Energy (Mev)</th>
<th>Method of Observation</th>
<th>Type of Analysis</th>
<th>Observers</th>
<th>Figures</th>
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<tr>
<td>0.5</td>
<td>Stilbene crystal detector</td>
<td>Heavy particle stripping</td>
<td>Ames et al.</td>
<td>7</td>
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<tr>
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**SECOND EXCITED STATE NEUTRON GROUP**

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<td>Maslin et al.$^5$</td>
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FIGURE CAPTIONS

Fig. 21  Angular distributions for the ground state neutrons from the reaction $^6\text{Li}(d,n)^7\text{Be}$. The references to the distributions are given in Table 1. Where they were available, the error bars have been shown.

Fig. 22  Angular distributions for the first excited state neutrons. The references to these distributions are given in Table 2.

Fig. 23  Angular distributions for the second and third excited state neutrons. The references to these distributions are given in Table 3.
FIGURE 23
V. DISCUSSION OF CALCULATIONS AND RESULTS

Compound Nucleus

As was stated in the introduction, Price investigated the angular distribution of the ground state neutrons at 4.1 Mev by means of the compound nucleus theory. He found that polynomials through the sixth order were needed in order to fit the data. This implied that the spin of the compound state was at least 7/2 and that \( \ell_d \) and \( \ell_n \) were at least three. He found that the combination which fitted the data reasonably well involved deuteron channel spins of one-half and three-halfes, with an \( \ell_d \) of three in both channels and an \( \ell_n \) of four. However, the calculated curve gave a small peak at 90 degrees which was not measured experimentally.

It is evident from the present data that there is a peak in the excitation curve of the ground state neutrons at 4.25 Mev. For the angular distribution at this energy, polynomials through the fourth order only were needed to fit the data. This implied a spin of at least 5/2 for the compound nucleus with the value of \( \ell_d \) and \( \ell_n \) each being at least two. The best calculated fit to the data with this assumption was given by a deuteron channel spin of one-half, \( \ell_d \) equal to three, and \( \ell_n \) equal to two. Again a peak at 90 degrees is present which was not measured experimentally. If one took a deuteron channel spin of three-halfes, an \( \ell_d \) of four, and an \( \ell_n \) of three, the peak at 90 degrees disappeared. Figure
24(b) shows these two calculated distributions, and it can be seen that the agreement with experiment is quite good in both cases.

The difference between the orders of polynomials needed to fit Price's data at 4.1 Mev and the present data at 4.25 Mev depended solely upon the cross section measurement at zero degrees. Price measured a decrease in the cross section at zero degrees compared to the cross section at 20 degrees. He also found a similar decrease for the cross sections measured at 4.7 Mev. No such effect was seen at 4.25 Mev in the present data. The cross sections at 0 and 20 degrees were measured as equal.

Heavy Particle Stripping

It is apparent from Tables 1 and 2 in Chapter IV that heavy particle stripping has been used to fit many of the ground and first excited state angular distributions. Table 4 lists the adjustable parameters used in the calculations to fit the measured ground state angular distributions\(^7,9,23\). All the calculations were made with \( \ell_p = 1, \ell_\lambda = 0 \). \( \ell_\lambda \) is the angular momentum with which the deuteron is captured by the core. Since the ground state of \(^{12}\text{C}\) is even, the deuteron has even parity, and the \(^{10}\text{B}\) core has even parity, the captured angular momentum must be even.

The radius of interaction varies with energy as expected and so does the parameter \( \lambda_2/\lambda_1 \). Owen and Madansky\(^{23}\) have
given a possible explanation of the variation of $\frac{\lambda_2}{\lambda_1}$ for the ground state neutrons. The heavy particle stripping amplitude requires that the center-of-gravity of the deuteron reach the nuclear surface, and the probability for this obviously depends critically upon the energy of the incident deuteron relative to the Coulomb barrier. One would therefore expect a reduction of the heavy particle stripping amplitude relative to the deuteron stripping amplitude at lower energies, since the latter only requires the proton to reach the nuclear surface. Figure 25 shows $\frac{\lambda_2}{\lambda_1}$ versus deuteron energy, with the Coulomb barrier indicated. The curve does indeed reach a maximum around the Coulomb barrier and then stays fairly constant.

Figure 24 shows calculated distributions compared with three measured angular distributions at 3.8, 4.25, and 7.0 Mev. For the distribution at 3.8 Mev two calculations are shown with different $\frac{\lambda_2}{\lambda_1}$. At 7.0 Mev the variation of the calculated distributions with changes in the interaction radii and $\frac{\lambda_2}{\lambda_1}$ is shown.

The agreement with experiment for the distribution at 3.8 Mev is quite good for both calculations. At 4.25 Mev the calculated distribution predicts a secondary peak at 45 degrees which seems to be measured experimentally. At 7.0 Mev the calculations and experiment agree for the forward peak but in the region 60 to 130 degrees the calculations predict a
### TABLE 4

HEAVY PARTICLE STRIPPING PARAMETERS FOR GROUND STATE NEUTRON ANGULAR DISTRIBUTIONS

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<th>$R_2$(fm)</th>
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FIGURE CAPTIONS

Fig. 24 Heavy particle stripping and compound nucleus fits for three ground state neutron angular distributions. (a) shows two heavy particle fits at 3.8 Mev using \( \lambda_2/\lambda_1 = 1 \) and \( \lambda_2/\lambda_1 = 0.8 \). \( R_1 = R_2 = 4.5 \) fm in each case. (b) shows two compound nucleus fits and one heavy particle stripping fit at 4.25 Mev. (c) shows two heavy particle stripping calculations for the distribution at 7.0 Mev. For one \( R_1 = R_2 = 4.5 \) fm, \( \lambda_2/\lambda_1 = 1.0 \) and for the other \( R_1 = R_2 = 4.7 \) fm and \( \lambda_2/\lambda_1 = 0.8 \). Also shown is a D.W.B.A. calculation with a cut-off radius of \( R = 5.2 \) fm. The error bars represent statistical errors calculated from \( \sqrt{N}/N \), where \( N \) is the total number of counts.

Fig. 25 \( \lambda_2/\lambda_1 \) versus energy for the ground state neutron angular distributions. The Coulomb barrier is also indicated.
FIGURE 24
much smaller cross section than was measured.

**Distorted Wave Born Approximation Calculations**

It has been suggested recently by several investigators\(^{55,24}\) that the backward rise in \(d,n\) reaction angular distributions can be explained by distorted wave analysis as opposed to heavy particle stripping. It would, therefore, seem reasonable to suppose that this reaction could be explained with D.W.B.A. theory. The analysis of \(B^{11}(d,n)C^{12}\) for a deuteron energy of \(5.53\) Mev has been carried out by Nagarajan and Arya\(^{55}\). They found striking agreement between the theory and experiment for the angular distribution and the \(n-\gamma\) correlations using distorted wave theory, which further suggests that the rest of this reaction may be analyzed in this way.

The calculations were done as indicated in Chapter III using a computer\(^{52}\).

The optical parameters used were\(^{56}\):

\[
\begin{align*}
V_D &= -55 \text{ Mev} \\
R_D &= 3.4 \text{ fm} \\
W_D &= -4 \text{ Mev} \\
a_D &= 0.5 \text{ fm}
\end{align*}
\]

for the incident channel, and

\[
\begin{align*}
V_N &= -55 \text{ Mev} \\
R_N &= 2.85 \text{ fm} \\
W_N &= -3 \text{ Mev} \\
a_N &= 0.5 \text{ fm}
\end{align*}
\]

for the outgoing channel.
Figures 26 and 27 show the predicted angular distributions compared with nine ground state and nine first excited state distributions. It is evident that the over-all agreement is quite good. Above 5.5 Mev a cut-off radius R was necessary to give good agreement with experiment, and the value of R is written by each curve. Below this value no cut-off radius was required. There are two exceptions to this statement. At 2.4 Mev for the ground state neutrons, the best fit was obtained using a cut-off radius R = 4.0 fm as indicated. The fit was quite good up to a backward angle of 130 degrees center-of-mass. Beyond that angle the theory predicted an increasing cross section whereas it was measured as decreasing. The agreement, however, is much better than that predicted without a cut-off radius. In that case there is a minimum in the distribution at 120 degrees center-of-mass, and the cross section increases at forward and backward angles. The other exception is at 8.8 Mev for the first excited state neutrons. From Fig. 22 it can be seen that the distribution does not have a large maximum at 20 degrees as the other distributions in this region. The best agreement with the experimental results came when the D.W.B.A. calculations were done without a cut-off radius.

The D.W.B.A. calculations did not give a good agreement with the distributions in the region 4 to 6 Mev although the general shape of the curves are predicted. They do show the
FIGURE CAPTIONS

Fig. 26  D.W.B.A. calculations for nine ground state neutron angular distributions. Where a cut-off radius has been employed, it has been indicated by the appropriate distribution. The error bars are statistical errors.

Fig. 27  D.W.B.A. calculations for nine first excited state neutron angular distributions. Again the cut-off radius is indicated by each curve when it has been used. The calculations using the different bound state wave function are shown by a broken line. The error bars are again statistical errors.
peak at forward angles beginning to appear at 5.5 Mev. M. A. Nagarajan\textsuperscript{57} has pointed out that the shape of the angular distributions is quite dependent on the bound-state wave function of the captured proton. He analyzed the first excited state angular distribution of Garg et al.\textsuperscript{10} at 5.35 Mev using a bound-state that was calculated from a Saxon well of the form:

$$V = V_0 \frac{1}{1 + \exp \left( \frac{r-R}{a} \right)}$$

with $V_0 = 35$ Mev, $R = 3.2$ fm, and $a = 0.5$ fm. He obtained excellent agreement with the experimental results. He kindly undertook to analyze the present data at 3.8, 4.25, and 5.5 Mev using a similar bound-state wave function calculation. His results are also shown in Fig. 27. The improvement in the fits can be seen.

**Excitation Functions**

In Fig. 28 is shown a comparison between the excitation curve of the 15.1 Mev gamma-ray from the reaction $^{11}$B*(d,n$^\gamma$)$^{12}$C, as given by Kuan\textsuperscript{54}, and the excitation curves for the first three neutron groups. The energy in the compound nucleus $^{13}$C is also indicated.

Although it is difficult to be sure of any specific structure in the neutron curves, due to the rather large errors, it is possible to distinguish certain prominent peaks.
Both the ground and first excited state neutron curves show a large peak around 1.6 Mev which probably corresponds to several levels in $^{13}C$ around 20 Mev. The first excited state curve has a very large peak at 4.1 Mev which also appears in the second excited state curve. In the ground state curve there is a peak at 4.25 Mev. As both this peak and the one in the $n_1$ curve are fairly wide, it is likely that they are due to a couple of levels in $^{13}C$ around 22.2 Mev. The ground state and second excited state curves show broad resonances around 3.4 Mev or 21.6 Mev in $^{13}C$. The gamma-ray curve has a resonance at 3.7 Mev which gives a level in $^{13}C$ at 21.8 Mev and a large peak at 3.08 Mev giving a level in $^{13}C$ at 21.28 Mev. These levels probably contribute to the peaks in the $n_0$ and $n_2$ curves at 3.4 Mev. The $n_2$ curve has a broad resonance around 5.0 Mev, and the $n_1$ curve has a narrower one at 5.4 Mev or 22.9 and 23.2 Mev in $^{13}C$ respectively. There also appears to be a small peak in the gamma-ray curve at 5.4 Mev.

Above 5.4 Mev only three resonances stand out. There is one at 9.7 Mev which appears in all four neutron excitation curves. This would correspond to a level in $^{13}C$ at 26.9 Mev. The ground state, second excited state, and third excited state curves all have a peak at 10.4 Mev or 27.5 Mev in $^{13}C$. The $n_3$ curve also shows a broad resonance at 7.7 Mev which would give a level in $^{13}C$ at 25.2 Mev.
Fig. 28  Comparison of the excitation curves for the first three neutron groups with the excitation curve of the 15.1 Mev gamma-ray from the $^{12}$C reaction $^{12}(d,n)^{15}$ reaction. The energy in the compound nucleus $^{13}$C is also shown.
Discussion

It is apparent that above 6 Mev bombarding energy, this reaction takes place by a stripping mechanism for the ground and first excited state neutrons. The angular distributions between 6 and 10 Mev are typical of such reactions. They show a large peak in the forward direction, around 20 degrees center-of-mass, and have been fitted quite well with D.W.B.A. calculations using a cut-off radius.

At the lower energies, 0.6 to 1.6 Mev, the shape of the angular distributions are generally antisymmetric. Stripping has again been used to explain their shapes. Where heavy particle stripping has been employed in this region, it was found that the deuteron stripping in the forward direction was the dominant component in determining the shape of the distributions.

In the region 2 to 6 Mev, the shape of the angular distributions tend to be symmetric about 90 degrees which might suggest compound nucleus mechanism. As previously mentioned Price\(^6\) analyzed the 4.1 Mev ground state distribution, and the 4.25 Mev ground state distribution has been analyzed here. These analyses were done using single level compound nucleus theory. To explain the backward rise in the angular distributions with a direct interaction mechanism, Owen and Madansky\(^{23}\) proposed the heavy particle stripping theory. Price\(^6\) again analyzed the 4.1 Mev distribution with this
heavy particle stripping theory which was also used for the 4.25 Mev distribution here. At both energies the agreements with the experimental results were about the same for the two theories.

It has been shown here that the shape of the distributions between 2 and 6 Mev can be predicted using a D.W.B.A. calculation. The agreement with experiment in most cases was good. Where the bound state wave function of the captured proton was determined using a Saxon-type well, the agreement became very good. It was, therefore, possible to explain the shape of the distributions between 2 and 10 Mev using a D.W.B.A. stripping calculation. It was not found necessary to use either compound nucleus or heavy particle stripping theory to explain the data in this energy region.
PART II

A CALORIMETRIC DOSAGE CALIBRATION AND
A DETERMINATION OF ABSORBED DOSE FOR PROTON IRRADIATION
I. CALORIMETRIC DETERMINATION OF ABSORBED DOSE FROM
Co-60 AND Cs-137 $\gamma$-RAYS AND 22 MEV X-RAYS

Introduction

The determination of absorbed dose for various kinds of radiation is of medical and biophysical importance, and the calibration of radiation sources is often required so that meaningful comparisons can be made. It is generally recognized that the most satisfactory way of expressing radiation dose is a statement of the energy locally absorbed. This may be expressed as the amount of energy imparted by ionization particles to unit mass of the irradiated material at the point of interest. In 1953 the International Commission on Radiological Units defined the rad as the unit of dose; 1 rad is 100 ergs of energy absorbed per gram of irradiated material.

It was decided to make absolute measurements of the absorbed energy from three of the radiation sources at M. D. Anderson Hospital and Tumor Institute. These were the Co-60 and Cs-137 $\gamma$-ray teletherapy units and the 22-Mev X-ray betatron. The results were then compared with the dose determined indirectly from measurements of the ionization in a cavity-type chamber.

Calorimetry

The energy absorbed from X or $\gamma$-radiation will appear
as heat unless there is chemical activity. Such activity is not expected in low atomic number elements but can be expected in compounds\textsuperscript{59}. An absolute measurement of this absorbed dose can be made with a calorimeter which measures the small temperature rise imparted to a thermally isolated absorber. This temperature rise may be compared to that produced when a known quantity of heat is introduced by electrical means. Ideally adiabatic conditions should be maintained during these processes but in practice this is difficult. For example, the temperature sensing element may introduce a continuous background heating rate due to the measurement current through it. However, it can be arranged so that steady state conditions are maintained and the rate of heat loss from the sensing element and absorber is equal to this background rate. The temperature of the absorber, which is higher than the environs, will then remain constant. Then when a small amount of additional heat is introduced at comparable or greater heating rates, the absorber temperature will rise only slightly above the steady state value. The rate of heat loss from the absorber will, therefore, only increase by a small fraction of its initial steady state value, resulting in a correspondingly small loss from the absorber of the heat added during this period. The system thus acts approximately adiabatically in regard to the absorption of small amounts of energy.
This restricted adiabatic condition is indicated when the graph of temperature plotted against time shows no slope before or after a small quantity of heat is added. If the plot shows a slope during these periods, the temperature rise corresponding to adiabatic conditions may be estimated accurately by a simple extrapolation correction of the heating curve as suggested by Skarsgard et al.\textsuperscript{60}

Although a water or tissue equivalent calorimeter would be of biological interest, it is simpler to estimate the energy that these materials would absorb from a radiation source that has been calibrated with an aluminum calorimeter. This involves a comparison of the energy mass absorption coefficients of the two materials considered for the spectrum of radiation incident in each case. In the range between 150 kev and 25 Mev photon energies, the ratio of water absorption to that of aluminum remains within 15 per cent of unity and can be estimated to about \(\pm 1\) per cent in particular cases.

\textbf{Apparatus}

Two different calorimeters were used in these measurements. A compact calorimeter, illustrated in Fig. 29, was used to calibrate the Co-60 and Cs-137 \(\gamma\)-ray sources. A larger prototype design, built by Ewing and Bramble\textsuperscript{61} and illustrated in Fig. 30, was used to calibrate a 22-Mev betatron and also the Co-60 \(\gamma\)-ray source. The design of
the two calorimeters is similar except for size and the means of controlling the temperature of the immediate environment. In the smaller unit, a controlled heater coil was placed directly on the outer aluminum surface, whereas the larger unit was placed within a temperature controlled oil bath. Specific details will only be given for the compact design but apply in principle to the larger unit.

A schematic drawing of the associated circuitry for the compact unit is given in Fig. 31. The aluminum absorbing disk was approximately 1 mm. thick with a radius of 1 cm. and weighed 0.86069 grams (with less than 1 per cent of material other than aluminum). A $10^5$-ohm thermistor, Veco 51A32, attached to the disk with glyptal, was the temperature sensing element. Its resistance changed about 4 per cent per °C. Typical resistance changes were 6.5 ohms for the Co-60 measurements and 10.5 ohms for the Cs-137 measurements. These represented temperature changes of $2.7 \times 10^{-3}$ °C and $4.5 \times 10^{-3}$ °C respectively. For a 6 ohm change, a $12 \times 10^{-6}$ volt signal was presented to the D. C. amplifier. The noise and drift levels had to be less than about $12 \times 10^{-8}$ volts to achieve the desired resolution. Low-noise, high-impedance cables, a fully shielded detector system independently grounded at the amplifier input, and a D. C. chopper amplifier were employed. Low-thermal e.m.f. solder and soldering flux were used in making joints in
order to achieve the necessary stability.

Nickel-chromium resistance wire, wound around the absorber, formed the heat calibration source. Input power was determined by the accurate measurement of resistance and voltage and the accurate weighing of the absorber.

The absorber was suspended on nylon threads within an aluminum baffle, which was in turn suspended within an isothermal shield as shown in Fig. 29. The control heater coils, which surrounded the shield, maintained the temperature constant within about $10^{-3} \, ^\circ C$. Further thermal insulation was provided by a styrofoam block covered with aluminum foil. A vacuum greater than $10^{-4} \, \text{mmHg}$ was maintained within the calorimeter during measurements.

Measurements

The period required for the calorimeter to reach thermal equilibrium was fairly long. However, the calorimeter was usually turned on in the laboratory the day before the desired measurements. When the calorimeter was transferred to the irradiation room, a period of only two to three hours was required for it to reach thermal equilibrium in the new environment. The equilibrium temperature was determined by the heater control circuit.

The output signal was linear over a suitable range of input energies as shown in Fig. 32. Figures 33, 34, and 35 show typical heating curves. Figure 33 represents the heating
by a 1.25-Mev γ-ray beam for 4 minutes from the Co-60 unit, which delivered about 92.5 rads per minute to the absorber. Figure 34 represents the heating by the nickel-chromium element at $16.21 \times 10^{-6}$ watts for 4 minutes (equivalent to 460 rads). Figure 35 shows typical heating curves for the large calorimeter. The ratio of the corrected deflections gave the ratio of the absorbed energies.

Table 5, column 2, lists the absorbed dose in aluminum measured with the calorimeter for three Co-60 (1.25 Mev) studies, one Cs-137 (0.663 Mev) study, and three betatron (22 Mev) studies. For the Co-60 measurements, the energy determinations are believed correct to ± 1 per cent; for the Cs-137 measurements, ± 2 per cent; and for the betatron, 22-Mev X-ray measurements, ± 1.5 per cent. In order to determine the energy absorption that these beams would produce in water and to compare results with Victoreen and Baldwin-Farmer ion chamber standardized calibrations, a number of conversion factors were determined.

**Conversion Factors**

Cobalt-60. The calorimeter was exposed to a 10 x 10-cm. field at 58.5 cm. from the source. The standardized ion chamber calibration arrangement determined energy absorption in water at 0.5 cm. depth for a 12.5 x 12.5-cm. field at 75-cm. S.S.D. (Source to Surface Distance) and did not include backscatter contributions in these measurements.
Therefore, to compare the calorimeter to ion chamber measurements, the calorimeter determinations had to be multiplied by the following factors:

A. Ratio of the mass energy absorption coefficient of water to that of aluminum for 1.25-Mev photons. This was found to be \( 1.14 \pm 1 \) per cent\(^6\).

B. Ratio of the exposure dose at the standardized arrangement (75.5-cm., 12.5 x 12.5-cm. field without backscatter) to the exposure dose at the absorber in the calorimeter arrangement (58.5-cm. and 10 x 10-cm. field). This ratio included corrections for distance, buildup, backscatter, scatter from the cone face, and absorption. It was measured by comparing the ionization currents produced in a small cylindrical ionization chamber placed in both the calorimeter and standardized arrangements and was found to be \( 0.582 \pm 2.0 \) per cent. The total conversion factor was:

\[
K_{\text{Co-60}} = 0.582 \times 1.14 = 0.663 \pm 2.5 \text{ per cent.}
\]

Cesium-137. The calorimeter was exposed to an open field at 17.3-cm. S.S.D. The standardized ion chamber calibration arrangement utilized a 10 x 10-cm. field at 30-cm. S.S.D. The comparison required a determination of the following conversion factors:

A. Ratio of the mass energy absorption coefficient of water to that of aluminum for 0.663-Mev photons. This was
found to be $1.135 \pm 1$ per cent$^{62}$.

B. Ratio of the exposure dose at the standardized arrangement to the exposure dose at the absorber in the calorimeter arrangement. This ratio, which included distance, buildup, backscatter, and sidescatter, was again measured using the small ion chamber in the two arrangements. It was found to be $0.325 (\pm 2.5$ per cent). The total conversion factor became $K_{\text{Cs-137}} = 0.325 \times 1.136 = 0.369 \pm 3.0$ per cent.

Betatron (Large Calorimeter). The calorimeter was exposed to a 5-cm. diameter field at 84 cm. from the target while the reference ion chamber arrangement (10 x 10-cm. field chamber at 84 cm. from the target centered in an 8-cm. Lucite cube) provided a value of energy absorption 4 cm. deep in a water phantom at 80-cm. T.S.D. (Target to Surface Distance). The comparison required a determination of the following conversion factors:

A. Ratio of the energies deposited in water and aluminum. The relatively large equilibrium depth produced by the long range of the secondary electrons generated by the betatron radiation complicated the comparison. However, it may be pointed out that at equilibrium depth (4 cm. in water), the energy deposited locally by the available electron flux is closely equal to the energy abstracted in that region from the incident photon beam$^{63}$. Thus, for two materials having
the same buildup thicknesses, density, and geometry, the ratio of energy deposited locally at the equilibrium depths is simply the ratio of the mass-energy photon absorption coefficients times the ratio of photon fluxes at that depth. The ratio of the mass-energy absorption coefficient of water to that of aluminum was calculated by a weighted averaging of absorption data of N.B.S. Handbook 62 and N.B.S. Circular 583 with an X-ray spectrum for 22-Mev X-radiation passed through a beam flattening compensator. The value obtained was $0.950 \pm 1$ per cent. The ratio of the incident photon fluxes at a depth of 4 cm. was 1.005. The ratio of energy absorption became $0.955 \pm 1$ per cent.

B. Correction for different geometries. The calorimeter presented a rather different geometry due to the smaller equilibrium thickness of aluminum and the 5-cm. diameter field used. The electron flux available in a "unit density" aluminum reference phantom (made by stacking perforated aluminum sheets) with field size, geometry, and density equivalent to the water reference was compared to the electron flux available at the calorimeter absorber. These measurements were made with thin wall mylar cylindrical and disk ion chambers. They showed that the ratio of electron flux in the aluminum reference system to that in the calorimeter was $1.04 \pm 1$ per cent. (This factor included a field size factor of 1.09 and a density effect
factor of 0.95.) In order to account for incomplete electronic equilibrium and absorption due to the top cover of the large calorimeter, additional factors of 1.005 for series 800 and 300 and 1.015 for series 1100 were required. These provided flux ratios of $1.045 \pm 1$ per cent and $1.055 \pm 1$ per cent respectively.

The over-all conversion factors accounting for the different materials ("unit density" aluminum and water) and the different geometries and densities became:

$$K_{\text{Bet.}} = 0.955 \times (1.045 \text{ or } 1.055) = 0.999 \text{ (series 300 and 800)}$$

$$1.008 \text{ (series 1100)}$$

both $\pm 1.5$ per cent.

**Results**

Column 4 in Table 5 gives the calorimetric calibrated energy absorptions in water. Column 5 gives the expected energy absorptions in water determined by ion chamber measurements. It can be seen that the reproducibility of the runs, as determined by consistency of calorimeter to ion chamber ratios, was within $\pm 1$ per cent. The accuracy of the converted calorimeter determinations agreed well within the experimental error. It may be noted that the calorimeter results were about 1 per cent higher than the ion chamber calibrations, but as they all agreed within the
experimental error, it was impossible to say if this was significant.

Conclusion

Although the calorimeter gave an accurate absorbed dose in aluminum, the extra errors introduced by the conversion factors to the ion chamber calibrations made the measurements only slightly better than the ion chamber measurements. A long time was also required to calibrate a radiation source, a 24 hour period to allow the calorimeter to come into equilibrium, 2 to 3 hours to make the actual runs, plus the time needed to calculate the output from the data and measure the correction coefficients. It, therefore, seems likely that the standardized ion chambers will remain the main means of calibrating radiation sources since they are reliable and measurements can be made quickly. However, the calorimeter can provide an accurate absolute calibration of the ion chambers from time to time.

Calorimeters have also been developed to calibrate electron beams, and the small calorimeter is at present being adapted for such use.
<table>
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<th>Experiment</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>Co-60 (Small Calorimeter)</td>
<td></td>
<td>Measured Radiation</td>
<td>Conversion Factor to</td>
<td>Calculated Absorption</td>
<td>Ionization Chamber</td>
<td>Ratio to Ion Chamber</td>
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<td></td>
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<td>Water Standardization</td>
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<td>Series 900-A</td>
<td></td>
<td>92.4±0.5% rads/min</td>
<td>0.663±2.5%</td>
<td>61.25±2.75% rads/min</td>
<td>60.6 rads/min</td>
<td>1.011</td>
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<td>Series 900-B</td>
<td></td>
<td>92.4±0.5% rads/min</td>
<td>0.663±2.5%</td>
<td>61.3±2.75% rads/min</td>
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<td>1.011</td>
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<td>Series 2100-C</td>
<td></td>
<td>90.9±1.0% rads/min</td>
<td>0.663±2.5%</td>
<td>60.22±3.0% rads/min</td>
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<td>Cs-137 (Small Calor.)</td>
<td></td>
<td>100.0±2.0% rads/min</td>
<td>0.369±3.0%</td>
<td>36.9±4.0% rads/min</td>
<td>36.4 rads/min</td>
<td>1.013</td>
</tr>
<tr>
<td>Beta-otron (Large Calorimeter)</td>
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<td>152.9±1.0% rads</td>
<td>1.008±1.5%</td>
<td>153.1±2.0% rads</td>
<td>153.0 rads</td>
<td>1.001</td>
</tr>
<tr>
<td>Series 800</td>
<td></td>
<td>152.2±2.0% rads</td>
<td>0.999±1.5%</td>
<td>152.0±2.5% rads</td>
<td>150.3 rads</td>
<td>1.013</td>
</tr>
<tr>
<td>Series 300</td>
<td></td>
<td>153.2±1.5% rads</td>
<td>0.999±1.5%</td>
<td>153.0±2.5% rads</td>
<td>150.0 rads</td>
<td>1.020</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Fig. 29  Cross sectional drawing of compact calorimeter.

Fig. 30  Cross sectional drawing of large calorimeter.

Fig. 31  Associated electronic circuitry for the calorimeter.

Fig. 32  Plot of output deflection versus input energy for compact calorimeter.

Fig. 33  Compact calorimeter heating curve for a 1.25 Mev $\gamma$-ray beam, 92.5 rads per minute for four minutes.

Fig. 34  Compact calorimeter heating curve for the calibration heater delivering $16.21 \times 10^{-6}$ watts for four minutes.

Fig. 35  Large calorimeter heating curves for a 22 MeVp X-ray beam delivering about 153 rads in two minutes and forty seconds (curve marked Rad) and the calibration heater delivering $27.0 \times 10^{-6}$ watts in three minutes (curve marked Cal.).
ALUMINUM ABSORBED DOSE CALORIMETER

1 cm Scale

FIGURE 29
ALUMINUM ABSORBED DOSE CALORIMETER

FIGURE 30
MEASURING CIRCUIT

LOW NOISE CABLES

51A32 THERMISTOR

RESISTANCE BOX

10K

10K

100K

40K

LISTON BECKER D.C. AMP

SPEED-O-MAX CHART RECORDER

CALIBRATION CIRCUIT

374.9Ω

NICHROME HEATER WIRE

RESISTANCE BOX

MERCURY CELL

1.35V

TIMER SWITCH

TEMPERATURE CONTROL CIRCUIT

34AI THERMISTOR

RESISTANCE BOX

3K

6K

6K

MODIFIED BROWN AMP

HEATING WIRE 300Ω

VOLT-METER

FIGURE 31
Sensitivity 8
Bridge balance 45.968K
Heater control resistance 5.095K
SERIES B 906 "RAD"
CO 60 4 MINS. 370 RADS
SENS. 8.

FIGURE 33
SERIESB 907 "CAL".
HEATER 6K. 4MINS. 16.21 µWATTS
SENS. 8.

FIGURE 34
II. PROTON IRRADIATION OF T2r BACTERIOPHAGE

Introduction

Recently the 5.5 Mev Van de Graaff at Rice University has been used for biophysical experiments. The effect of cysteine upon the radiation sensitivity of T2r bacteriophage under several physical conditions was investigated to determine the radiation protective action of cysteine at various linear energy transfers (L.E.T.). Different L.E.T.'s can be obtained by using particles at different energies, and, for these preliminary investigations, protons were used. The dose required to reduce survival to 37 per cent ($D_{37}$ dose) was taken as the measure of radiation sensitivity. It was, therefore, necessary to calculate the dose that a given number of particles at a fixed energy would impart to the biological solution. It is this calculation that will be described here.

Calculations

First it was necessary to determine the energy of the protons entering the solution. The protons from the accelerator were monoenergetic. Their energies could be determined to an accuracy of several kilovolts. The protons passed through a thin "Havar" foil from the accelerator into the irradiation vessel, and the energy loss of the particles through this foil was determined. It was assumed that the
foil was pure iron and the dE/dx values for protons in iron were obtained from Whaling's data. The thickness of the foil in milligrams per square centimeter was accurately determined by weighing and measuring the area of a sample of the foil used. The energy loss was given in terms of kev-cm²/mgms, and the total energy loss for the particles passing through the foil was easily calculated. The initial energy of the particles was determined by the magnetic analyzer of the Van de Graaff, and thus the energy of the particles in the solution was found.

The thickness of the solution was such that the particles were completely stopped in it. Since the energy of the particles was known, the amount of energy per particle deposited in the solution in ergs was calculated from the relationship 1 ev. = 1.602 x 10⁻¹² ergs on the assumption that all the proton energy went into making ion pairs.

The volume of the solution was accurately measured with a pipette, and as the density was that of water, the weight of the solution was known. During irradiation the solution was vigorously stirred, and it was assumed that the solution was uniformly irradiated. This was supported by measurements using ferrous sulphate dosimetry. Since the weight of the solution in grams and the amount of energy per particle deposited in ergs were known, the dose in rads deposited by each particle could be calculated. It was generally required
to give doses of the order of 50 to 150 kilorads (1 kilorad = \(10^3\) rads), and since the dose per particle was known, the number of particles required to yield these doses was found.

Since the Havar foil and irradiation vessel acted as the Faraday cup, the total charge deposited by the particles could accurately be measured with an integrator. Therefore, the charge in microcoulombs required to deposit a given dose could be accurately obtained.

For example, 6.65 ml. of solution irradiated with 4.74 Mev protons required \(4.313 \times 10^{12}\) particles to deposit 50 kilorads. This represents a total charge of .691 microcoulombs. Since each unit of the integrator represented 0.0416 microcoulombs, a total of 17 units on the integrator was required.

In order to calculate the \(D_{37}\) dose, a series of irradiations had to be made on the same solution, and 0.1 ml. or 1 ml. samples were removed after every given dose. The volume of the solution decreased as the experiment progressed which reduced the amount of charge to be collected for a given dose. For example, the volume at the beginning of a run might be 6.65 ml. but for the last irradiation it might be down to 6.15 which is a factor of nearly 10 per cent. This had to be taken into account for the dosage calculations.
Discussion

These calculations have been made with the following assumptions: (1) that the solution is uniformly irradiated and (2) that the total energy of the particle is deposited in the solution. As was stated above, the solution was vigorously stirred in order to obtain uniform irradiation. The speed of stirring was increased until the graph of speed versus dose showed a plateau. It was then assumed that the irradiation was uniform throughout the solution.
ACKNOWLEDGEMENTS

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