THE Li$^7 (\alpha, \gamma)$ B$^{11}$ REACTION

and

SOME OTHER TOPICS

by

PRITHE PAUL SINGH

B.Sc., Agra University (India), 1949
M.Sc., Agra University (India), 1951

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PHYSICS

We accept this thesis as conforming

to the required standard

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November, 1959
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Date 10th November, 1959
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Theory of Measurements .................. A. M. Crocker
Nuclear Physics ......................... K. C. Mann
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Other Studies:

Theory and Applications of Differential Equations .................. T. Hull
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Analogue Computers ................ E. V. Bohn

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PRITHE PAUL SINGH

B.Sc., Agra University, India, 1951
M.Sc., Agra University, India, 1953

IN ROOM 301, PHYSICS BUILDING

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California Institute of Technology
THE Li\(^{7}\) (\(\alpha\), \(\gamma\)) B\(^{11}\) REACTION AND SOME OTHER TOPICS

ABSTRACT

The University of British Columbia Van-De-Graaff generator was used to study the resonant capture of \(\alpha\)-particles by Li\(^{7}\) to form B\(^{11}\) in the three excited states at 8.92 Mev, 9.19 Mev and 9.28 Mev. B\(^{11}\), being in the middle of the \(p\) shell, has been rather extensively studied in the past decade, with considerable disagreement between results obtained from the Li\(^{7}\) (\(\gamma\), \(\gamma\)) B\(^{11}\) and B\(^{10}\) (\(d\), \(p\)) B\(^{11}\) reactions. With seven particles outside the closed shell theoretical calculations are difficult and the calculations of Kurath have been limited to the negative parity states only.

The energies, intensities and angular distributions of the gamma-rays which de-excite the three states of B\(^{11}\) have been studied. It was found that the 9.28 and 9.19 Mev states cascade through the 6.76 Mev and 4.46 Mev states and negligibly, if at all, through the 6.81 Mev state. The gamma-ray widths for many of the gamma-ray transitions have been obtained and compared with the average radiative widths reported by Wilkinson. On the basis of the angular distribution results spins and parities have been assigned to some of the B\(^{11}\) levels up to an excitation of 9.28 Mev. The results are in good agreement with recent work on the B\(^{10}\) (\(d\), \(p\)) B\(^{11}\) reaction. Tentative speculations concerning the nature of some of the transitions have been made, although no detailed comparison with theory seems possible at the moment.

The assignments based upon the present work are

<table>
<thead>
<tr>
<th>B(^{11}) level</th>
<th>Spin and Parity</th>
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<tr>
<td>9.28 Mev</td>
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</tr>
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<td>5/2(^{-}), 5/2(^{+})</td>
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The 4.46 MeV level assignment of 5/2\(^{-}\) was previously well known. For the 8.92 MeV level the present work favours the assignment of 5/2\(^{-}\) which is supported by the recent stripping work on the B\(^{10}\) (\(d\), \(p\)) B\(^{11}\) reaction; however, the present results do not rule out the possibility of this level being 5/2\(^{+}\).

Using this counter the yield and angular distribution of neutrons was measured from thick and thin heavy ice targets bombarded with protons below the D (\(p\), \(n\)) 2\(p\) threshold. The yield and the angular distribution data fit very well with theoretical results calculated by Y.I. Ssu on the hypothesis that neutrons are produced by deuterons, scattered in the target by incident protons, which, then, collided with other target deuterons producing D (\(d\), \(n\)) He\(^{3}\) neutrons.

A semi-empirical method has been developed to calculate the gamma-ray detection efficiency of NaI (TI) crystals for gamma-rays from 0.5 Mev to 12 Mev. The results were compared with the experimental efficiencies at 0.5 Mev, 1.25 Mev, 4 Mev, 6 Mev and 12 Mev, independently determined by absolute methods at 0.5 Mev, 1.25 Mev and 6 Mev and by relative comparison at 4 Mev and 12 Mev. The agreement is within 5% up to 6 Mev. The effects of scattered gamma-rays by lead shielding was also investigated.

remaining kinetic energy of the pair electrons with moderate accuracy gives the energy of the gamma-rays with considerably greater percent-
age accuracy. The present results are,

\[
\begin{align*}
\text{Zn}^{65} \text{gamma-ray Energy} & \quad 1.1124 \pm 0.0019 \text{ Mev} \\
\text{Na}^{22} \text{gamma-ray Energy} & \quad 1.2736 \pm 0.0018 \text{ Mev}
\end{align*}
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ABSTRACT

The University of British Columbia Van De Graaff generator was used to study the resonant capture of α-particles by Li$^7$ to form B$^{11}$ in the three excited states at 8.92 Mev, 9.19 Mev and 9.28 Mev. B$^{11}$, being in the middle of the p shell, has been rather extensively studied in the past decade with considerable disagreement between results obtained from the Li$^7$ (α, γ) B$^{11}$ and B$^{10}$ (d, p) B$^{11}$ reactions. With seven particles outside the closed shell theoretical calculations are difficult and the calculations of Kurath have been limited to the negative parity states only.

The energies, intensities and angular distributions of the γ-rays which de-excite the three states of B$^{11}$ have been studied. It was found that the 9.28 and 9.19 Mev states cascade through the 6.76 Mev and 4.46 Mev states and negligibly, if at all, through the 6.81 Mev state. The γ-ray widths for many of the γ-ray transitions have been obtained and compared with the average radiative widths reported by Wilkinson. On the basis of the angular distribution results spins and parities have been assigned to some of the B$^{11}$ levels up to an excitation of 9.28 Mev. The results are in good agreement with recent work on the B$^{10}$ (d, p) B$^{11}$ reaction. Tentative speculations concerning the nature of some of the transitions have been made, although no detailed comparison with theory seems possible at the moment.
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The assignment of 5/2\textsuperscript{-} to the 4.46 Mev state was well known previously. For the 8.92 Mev state the present work favours 5/2\textsuperscript{+} and in this is supported by recent results from the stripping reaction B\textsuperscript{10} (d, p) B\textsuperscript{11} which suggests positive parity for the level; however, the present results do not rule out the possibility of 5/2\textsuperscript{-} and formation of the state by d-wave α-particles.

A three crystal pair spectrometer was used to determine accurately the energies of the γ-rays from Zn\textsuperscript{65} and Na\textsuperscript{22}. The energies of these γ-rays are above 1.022 Mev and since the accurately known rest mass of the pair electrons is subtracted from each incident photon by pair production, a measurement of the small remaining kinetic energy of the pair electrons with moderate accuracy gives the energy of the γ-rays with considerably greater percentage accuracy. The present results are,

\textbf{Zn}\textsuperscript{65} γ-ray Energy \hspace{1cm} 1.1124 \pm 0.0019 Mev

\textbf{Na}\textsuperscript{22} γ-ray Energy \hspace{1cm} 1.2736 \pm 0.0018 Mev
The pulse height spectrum and absolute efficiency of a ZnS-lucite fast neutron counter, consisting of a number of thin sheets of lucite coated with zinc sulphide and sandwiched together to form a rectangular block, was investigated using neutrons with energies from 280 KeV to 16 MeV and γ-rays with energies of 1 MeV and 6 MeV. At a bias setting where the absolute neutron detection efficiency varied from 0.15% for 2 MeV neutrons to 0.3% for 4 MeV neutrons, the 6 MeV γ-ray sensitivity was less by a factor of 10^9.

Using this counter the yield and angular distribution of neutrons was measured from thick and thin heavy ice targets bombarded with protons below the D (p, n) 2p threshold. The yield and the angular distribution data fit very well with theoretical results calculated by Y.I. Ssu on the hypothesis that neutrons are produced by deuterons, scattered in the target by incident protons, which, then, collided with other target deuterons producing D (d, n) He^3 neutrons.

A semi-empirical method has been developed to calculate the γ-ray detection efficiency of NaI (TI) crystals for γ-rays from 0.5 Mev to 12 Mev. The results were compared with the experimental efficiencies at 0.5 Mev, 1.25 Mev, 4 Mev, 6 Mev and 12 Mev, independently determined by absolute methods at 0.5 Mev, 1.25 Mev and 6 MeV and by relative comparison at 4 Mev and 12 Mev. The agreement is within 5% up to 6 Mev. The effects of scattered γ-rays by lead shielding was also investigated.
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Chapter I

INTRODUCTION

1. Aims and Aspirations.

"Nuclear spectroscopy aims on the one hand to help to develop, on the other hand to get along without, a detailed knowledge of the nature of nuclear 'forces'. This seeming contradiction arises from the great difficulty of uncovering the profound laws of nature, and the hope of doing so in a stepwise fashion. It is too much to hope in the near future to calculate the energy levels of $^{11}$B, say, on the basis of a completely satisfactory meson theory of nuclear structure. Instead one hopes to divide the problem up into a phenomenological one in which the interactions between the nucleons are assumed to have one of the several possible simple forms, it being determined by trial which form seems to have the greatest empirical validity, and a second step in which the phenomenological interaction thus selected is to be understood on the basis of a theory of the structure of the nucleons themselves, akin to the present meson theories which as yet are not entirely free from divergences."

Dr. D.R. Inglis (1953) in his review article on the energy levels and the structure of light nuclei thus summed up the motivation behind low energy experimental nuclear physics, to provide consistent data about the energy
of levels, their spins and parities and their modes of decay, checked and rechecked by entering a given nuclear level through as many channels as possible so that this information can be used to test the predictions of empirical models.

Already there is enough information available in the case of light nuclei (Ajzenberg and Lauritsen, 1955) that many serious attempts have been made to understand the nature of the interaction between nucleons, such as those of Feenberg et al (1937), Inglis (1953) and Kurath (1952, 1956). Though the predictions of the intermediate coupling model (Kurath, 1956) for the nuclei at the beginning and at the end of the 1 p-shell are quite satisfactory in some respects, it is not so for the nuclei in the middle of the shell such as B^{11} and C^{11}. Unfortunately, experimental information available about the nuclei in the middle of the shell is in many respects insufficient and also inconsistent. Therefore further experimental investigation is required for nuclei such as B^{11}, which is the subject of the present study.

2. Previous Work on B^{11}.

(1) \( \text{Li}^7(\alpha, \gamma)B^{11} \) reaction.

Historically Bennett et al (1950) were the first to observe the resonant capture of \( \alpha \)-particles by \( \text{Li}^7 \) forming \( B^{11} \) in three excited states at 8.92, 9.19 and 9.28 Mev, corresponding to the resonant \( \alpha \)-particle energies of 400, 820 and
FIG. 1 ENERGY LEVEL DIAGRAM
960 kev respectively. The gamma rays were observed by a pair of coincident beta-counters. Due to the limitations of this device they could not identify the individual radiations and therefore little could be said about the decay scheme of the excited $^{11}$B states. They, however, did estimate the width of each resonance from the slope of the excitation functions obtained with thick targets. An upper limit of 1 kev was placed on the width of the lower and the middle resonances while the width of the upper resonance was measured to be 6 kev. They also made rough estimates of the total radiative width of each resonance by comparing the yield of the $^{7}$Li$(p,\gamma)^{8}$Be reaction to the $^{7}$Li$(a,\gamma)^{11}$B yield. Values of $(\omega \Gamma)$ for the lower, middle and upper resonances were .04, 0.6 and 4.7 ev respectively, where $\omega$ is the statistical factor and $\Gamma$ is the gamma ray width.

Using NaI (TII) crystals Jones and Wilkinson (1952) observed the $\gamma$-rays emitted as the three excited states of $^{11}$B decayed to the ground state, directly or through some of intermediate levels. On the basis of their angular distribution data and some "reasonable assumptions" they assigned the spins and parities to the $^{11}$B levels up to 9 Mev, shown in Fig. 1, on the assumption that these levels were those of the odd proton in $^{11}$B.

Heydenberg et al (1954) also observed the gamma rays from $^{7}$Li$(a,\gamma)^{11}$B and reported that the widths of the .82
and 0.96 Mev resonances were 6 and 11 kev respectively.

Next Meyer-Schutzmeister and Hanna (1957) studied the angular distribution of most of the gamma rays from the three resonances and suggested the spins and parities which are also shown in Fig. 1. In the same year Phillips (1957) of this laboratory studied the reaction in detail using 2.5" diameter by 3.5" long NaI crystal. From his angular distribution data he assigned \( \frac{5}{2}^+ \) to the 9.28 Mev level and made tentative assignments to some of the other levels as shown in Fig. 1.

Ferguson et al. (1957) reported the gamma ray decay schemes for the first nine states of \( ^{11}B \) excited by the \( ^{9}Be \ (He^3, p\gamma) \ ^{11}B \) reaction and by observing the \( \gamma \)-rays from each state in coincidence with proton groups. However, the 6.76 and 6.81 Mev states were not resolved. They observed ground state transitions for all levels in addition to the cascade through the first excited state from the 5.03, 7.30, 7.99, 8.57 Mev states and the unresolved doublet around 6.8 Mev with an intensity comparable with that of the corresponding ground state transition. From the particle spectrum coincident with \( \gamma \)-rays of energy greater than 7.5 Mev, it was inferred that the gamma ray width of the 8.92 Mev level is comparable to its \( \alpha \)-particle width.
(ii) $^{10}\text{B}(d,p^7)^{11}\text{B}$ stripping reaction.

Perhaps the only other way by which the $^{11}\text{B}$ system has been investigated is the stripping reaction $^{10}\text{B}(d,p^7)^{11}\text{B}$. As a matter of fact the levels of $^{11}\text{B}$ were first determined accurately by Van Patter et al (1951) and Elkind (1953) by identifying proton groups. Because of the competing process $^{11}\text{B}(d,n^7)^{11}\text{C}$ and the complex contribution in the pulse height spectrum by neutrons from the $^{11}\text{B}(d,n)^{11}\text{C}$ reaction, the study of gamma rays associated with $^{10}\text{B}(d,p^7)^{11}\text{B}$ (Bent et al, 1955) is difficult. The study of proton angular distributions from this reaction has led to valuable information about $^{11}\text{B}$. All the levels below 7 Mev seem to be formed (Ajzenberg and Lauritsen, 1955) by p-wave neutrons, thus restricting these states to odd parity and their total angular momentum to values between $3/2$ and $9/2$.

The ground state ($3/2^-$) proton group shows a well defined p-wave stripping pattern for all deuteron energies greater than 2 Mev, though stripping seems to predominate even below this energy. Also the relatively large neutron capture probability would suggest a single particle character for the ground state. The single particle shell model (Mayer and Jensen, 1955) suggests $3/2^-$ ($1p3/2$) for the ground state of $^{11}\text{B}$ which is consistent with the nuclear magnetic moment and with the stripping data.

The angular distribution of protons corresponding to the $^{11}\text{B}$ 2.14 Mev state produced in the $^{10}\text{B}(d,p)^{11}\text{B}$ reaction
indicates that this state is formed by p wave neutrons which would imply that the total angular momentum \( J \) for this state is between \( \frac{3}{2}^- \) and \( \frac{9}{2}^- \). This is in contradiction to the shell model expectation of \( \frac{1}{2}^- \) for this level. This difficulty can be resolved if one assumes first, that in the \( \text{B}^{10}(d,p)\text{B}^{11} \) reaction the outgoing proton reverses its spin and transmits the extra unit of angular momentum to the remaining nucleus as suggested by French (Evans, 1954) or second, that the outgoing proton comes from the target nucleus and not from the deuteron as ordinarily believed (Evans, 1958).

Hensel et al (1958) observed that the polarization of the protons in the \( \text{B}^{10}(d,p)\text{B}^{11} \) reaction going to the first excited state is opposite to that of the proton group going to the ground state and point out that this is consistent with both of the above hypotheses which increase the possible range of angular momentum values for this state from \( \frac{1}{2}^- \) to \( \frac{11}{2}^- \).

The isotropic \( p-\gamma \) correlation in the \( \text{B}^{10}(d,p\gamma)\text{B}^{11} \) reaction through the 2.14 Mev state (Cox and Williamson, 1957) and the isotropic distribution of the \( \gamma \)-rays in the \( \text{B}^{11}(p,p\gamma)\text{B}^{11} \) reaction (Blair et al, 1955) can only be explained by an assignment \( \frac{1}{2}^- \) leading to M1 radiation or \( \frac{3}{2}^- \) leading to pure E2 radiation. In order to distinguish between these two possibilities Wilkinson (1957) measured an upper limit of \( 4 \times 10^{-14} \) sec for the life time of the 2.14 Mev state and more recently Hensel et al (1958) measured the mean life time of \( 4.6 \times 10^{-15} \) sec for this state, which is much too fast for an
E2 transition. Thus it appears that all the experimental information is consistent with $1/2^-$ for the 2.14 Mev level as predicted by the shell model. In fact Kurath (1957) on the intermediate coupling model calculated a mean life time of $(2.5 \text{ to } 5) \times 10^{-15}$ sec for this state.

The 4.46 Mev state has also been studied by the $^{10}\text{Be}(d,p)^{11}\text{Be}$ reaction. The proton angular distribution indicates that this state is formed by p wave neutrons. Also the p-γ angular correlation is isotropic to within 5% (Cox et al, 1957). This favours $3/2^-$ or $5/2^-$ consistent with the assignment of Meyer-Schutzmeister and Hanna (1957). Phillips (1957) rules out $3/2^-$ on the basis of angular distribution measurement made with the $^7\text{Li}(α,γ)^{11}\text{Be}$ reaction. The mean life time measured by Rasmussen et al (1957), using the $^{11}\text{Be}(γ,γ)^{11}\text{Be}$ reaction for the 4.46 Mev $^{11}\text{Be}$ state, is $T_m = 1.17 \times 10^{-15}$ sec, assuming $J = 5/2$ for this state. This is in good agreement with calculations done by Kurath (1957) on the intermediate coupling model which also predicts $5/2^-$ for this state.

From the proton angular distribution obtained from the $^{10}\text{Be}(d,pγ)^{11}\text{Be}$ reaction forming the 6.76 Mev $^{11}\text{Be}$ state Cox et al (1957) concluded that this state is also formed by p-wave neutrons, restricting its parity to an odd value and its spin to a value between $3/2$ and $9/2$. From their p-γ angular correlation they ruled out $3/2^-$ and suggested that $9/2^-$ is unlikely.
From this review of the experimental data the following conclusions seem to be justified.

(a) For the ground state and the first and the second excited states we know the spin and parities with some confidence.

(b) The data available for the other levels is neither complete nor consistent enough to permit drawing any firm conclusions about the spins and parities of these levels.

(iii) Theoretical investigations.

On the theoretical side many attempts to understand the energy level schemes of the light nuclei have been made and it soon became apparent that one cannot obtain a satisfactory picture, consistent with the experimental facts, with either the L-S model (Peenberg et al., 1937) or with the j-j model (Kurath, 1952). This left the hope that perhaps the true picture lies between these two extremes, that is to say in the region of intermediate coupling. Inglis in 1953 presented an interpolated estimate of level schemes for the p-shell nuclei on this picture. Recently Kurath (1956) using the intermediate coupling model has computed the energy level schemes of all the nuclei in the 1 p-shell as a function of the three parameters, a/K, L/K, and K, where a/K measures the relative spin-orbit and central energy contribution, L/K depends on $p$, the ratio of nuclear size to range of nuclear forces and K is the parameter chosen to match the level scheme with the experimental energy scale. For B$^{11}$, the theoretical
spin assignments for the negative parity states are 3/2, 1/2, 5/2 and 7/2, and 3/2 for one of the states at 6.8 Mev. These are shown in Fig. 1. In addition the model predicts a 5/2 state somewhere around 11 Mev. There are many difficulties (Kurath, 1957) in identifying this 5/2 state with any of the states around 9 Mev in $^{11}$B. Thus no doubt that by considering the various possible combinations of $a/K$, $L/K$ and $K$ values one may be able to obtain a scheme which compares reasonably well with the experimental information for low lying levels of $^{11}$B, it is already apparent that there is not much hope of this relatively simple model explaining all the facts, especially those pertaining to the region of higher excitation. This may be because these calculations do not take into consideration

(a) excitation of two nucleons from the 1p into the 2s and 1d shells.

(b) possibilities of collective motion of the nucleus.

(c) that coupling parameters may vary with excitation energy.

It may be instructive to conclude this section with two quotations from Kurath (1956 and 1957). "The over-all picture for the 1p-shell shows that the intermediate coupling model gives considerable improvement over the models of extremely weak or strong spin-orbit coupling. One can even begin to make quantitative comparison with experiment using what is conceptually a very simple model. While the agree-
ment with the complicated $^{10}$Be nucleus is very encouraging, one will have to wait for more experimental identifications in the neighbouring $^9$Be and $^{11}$Be nuclei to test the model further."

"The predictions of this intermediate-coupling model do not give a satisfactory picture of the experimental evidence concerning gamma transitions in the 1 p-shell. There are some cases of good agreement, a few unexplained contradictions and a number of cases which suggest that introduction of some collective motion might bring them into agreement with observation. In addition there are transitions observed for which there are not enough data to draw any conclusions. This is particularly true of the low lying states in $^{11}$Be, ------ ."

This thesis deals with the problem of the spins and parities of the states of $^{11}$Be as well as with the gamma-ray transition probabilities.
FIG. 2 HELIUM GAS FILLING SYSTEM
CHAPTER II

APPARATUS

1. Van-De-Graaff Generator.

A beam of singly ionized helium atoms, hereafter referred to as α-particles, was obtained by ionizing the helium gas in a conventional radio-frequency ion source and accelerated by means of the Van de Graaff generator at the University of British Columbia.

(i) Helium Filling System.

Since a small contamination of hydrogen or of deuterium in the helium gas will be preferentially ionized due to their lower ionization potentials, (H - 13.6 ev; He - 24.6 ev; He⁺ - 54.4 ev; Kaye and Laby, 1956), the 99.99% pure helium gas, from the Matheson Corporation, was cleaned of such contaminations by slowly passing it through a liquid nitrogen cooled charcoal trap. The block diagram of the filling system is shown in Fig. 2. The charcoal adsorbs the hydrogen gas especially at lower temperatures. To start with, the stainless-steel charcoal trap was outgassed by heating it under vacuum until further heating of any section did not raise the pressure as seen by the pirani gauge. It was then cooled and kept immersed in a dewar
FIG. 3 DISCHARGE TUBE
of liquid nitrogen. On cooling the pressure dropped further. If it did not rise in five minutes, when isolated from the pump, the system was considered to be vacuum tight. The vapours from the pump were kept away from the charcoal trap by an intermediate liquid nitrogen trap. The helium gas then was allowed to pass through the charcoal trap and into the storage bottle very slowly. It took about one hour to fill the helium bottle to 60 lbs. gauge. Due to the limited quantity of charcoal in the trap, 60 lbs. of helium was about the maximum amount that could reliably be cleaned without outgassing the trap again.

The helium gas from the bottle leaks into the manifold, which is also connected to hydrogen and deuterium bottle outlets, through a thermal leak (see Appendix I) enclosed in the helium bottle and a solenoid shut-off valve. From the manifold the gas passes to the radio-frequency ion source.

(ii) **Beam Extraction.**

Fig. 3 shows the base of the discharge tube, the aluminum extractor canal, the quartz sleeve and the glass skirt. Positive charge collected on the insulating quartz sleeve as a result of probe voltage applied at the top of the discharge space results in the formation of a dark space between the plasma region and the extractor canal. Most of
FIG. 4 SIDE ARM

- Liquid N₂ Cooled Trap
- Target
- Mo Stop
- Lucite
- Glass Window
- Quartz and CaF₂ Target
- Beam Stabilizing Probes
- Gold Stop
- Beam Chopper
- Magnet
- Magnet Shims
- Valve
- V.D.G. Generator
the probe voltage appears across this space and results in a focusing of the ions from the plasma into the central hole of the extractor. Therefore it is essential that the quartz sleeve be accurately aligned axially with respect to the extractor canal. Also it is important that the top of the quartz be smooth and accurately parallel to the top of the extractor. Whenever these conditions were not met the extraction was a matter of luck (mostly bad luck!). The top of the aluminum canal was tapered to reduce the amount of aluminum sputtered onto the quartz due to the beam bombardment. Aluminum sputtered onto the quartz destroyed its insulating properties, thus reducing the amount of beam that could be extracted. Poor alignment had the same effect. The best height of the quartz above the aluminum canal was 3 mm. Slight variations in this height could be offset by adjusting the height of the tank coil for optimum performance.

(iii) Bending of the Beam.

A well focused beam of 40-50 microamperes in a circular spot of 3 mm. diameter, was allowed to enter the magnet box where it was bent through 90 degrees by a large electromagnet so that it emerged horizontally into the side arm tube, shown in Fig. 4. The vertical spread of the beam was limited by molybdenum beam stabilizing probes. It could be sharply focused in the horizontal direction by means of the magnet shims. A gold stop with 1 cm. diameter hole,
located before the solenoid operated beam shutter, and two others of molybdenum (3/8 in. x 3/16 in.) placed in the side arm of the target chamber defined the beam. The last two stops were geometrically so placed that the beam passing the front stop did not hit anywhere except the target, while the second stop trapped secondary electrons from going to the target. By viewing through a small (1/16 in.) glass window in the target pot, the three stops, molybdenum sniffers and the exit hole of the magnet box were aligned optically. The beam was focused on the beam chopper before letting it through to the target. When the beam landed on the target it was sufficiently defocused that it filled the hole through the stops, thus avoiding any serious local heating of the target.

The target, insulated from the rest of the chamber, was kept at 90 volts positive to recover the secondary electrons knocked out of the target by the beam. The beam was measured by means of a current integrator (Edwards, 1950) which was calibrated occasionally during the period of the experiments using a standard voltmeter, 1% resistors and a 90 volt battery. Over a period of a few months this calibration remained constant to within 1%. For the 1 microfarad scale, which was used throughout this work, the average calibration gave 110 micro coulombs per integrator count.
(iv) **Lithium Target Preparation.**

The target chamber built by Phillips (1957) was provided with an upper side arm, shown in Fig. 4, which contained an externally heated stainless-steel furnace into which metallic lithium could be placed. Two small pieces of lithium metal (.4 cm. cube) were cut under benzol and quickly transferred to the lithium furnace. The target chamber was then evacuated, first by a backing pump through one of the flat valves in the side arm and then by the magnet box diffusion pump. The furnace was heated at low heat (30 watts) for about half an hour to outgas the furnace and the lithium of all adsorbed vapours including benzol. The power was then gradually increased over a period of five minutes to 100 watts. Soon a black deposit, presumably of lithium oxide, appeared on the wall of the target chamber facing the furnace tube exit which later turned into pale white. At this stage the copper rod carrying the target backing was raised to face the furnace exit. A black uniform deposit of lithium appeared which turned to grey and then white as the thickness increased. The thickness of a target was determined by running an excitation function over the desired resonance. More lithium could be easily laid on in a few minutes if required.

The yield from the target decreased steadily with time, perhaps due to oxidation or nitride formation of
lithium partly under beam bombardment and partly due to finite air leak. This change was rather erratic in the first half hour of the bombardment, because of fluctuations in the beam position different portions of the lithium targets were undergoing above mentioned changes. These fluctuations in the yield were less troublesome in the case of thicker targets and bombarding energies about 20-40 kev higher than the resonance energy so that the resonant reaction was taking place a little inside the target and not on its surface. This would indicate that the reduction in yield is not solely due to beam bombardment.

Besides the lithium targets various other targets were used. $^{11}$B, isotopically separated and deposited on a .002 inch thick gold foil (kindly supplied by the electromagnetic separator group at Harwell), was used to obtain $4.43$ Mev $\gamma$-ray spectra from the reaction $^{11}$B ($p, \gamma$) $^{12}$C for the energy calibration of the counter. Calcium fluoride targets, locally prepared, were used to obtain $6$ Mev $\gamma$-rays from the $^{19}$F ($p, \alpha\gamma$) $^{16}$O reaction. A $^{13}$C target (also supplied by Harwell) was used to obtain calibration spectra at $8$ and $9$ Mev.

2. **Gamma Ray Detection.**

(i) **Scintillation Counters.**

Two scintillation counters were used during these experiments. One consisted of a NaI (TlI) crystal 2.5 inches
FIG. 5 CIRCUIT DIAGRAM OF CATHODE FOLLOWER

P. T. = Pulse Transformer
VALOR PT. 530 D

D. L. = 1 µ Sec. Delay Line
Type H.H 2500
in diameter and 3.5 inches long (Harshaw) mounted on a Dumont 6363 photomultiplier. The second NaI crystal, 2.75 inches in diameter and 4.5 inches long, was mounted on a Dumont KL213 photomultiplier. In both cases the crystal, photomultiplier, resistance chain and cathode follower, were mounted in brass cylinders 3.5 inches in diameter, 15 inches long and 4 inches in diameter by 16.5 inches long respectively. Fig. 5 shows the circuit diagram of the cathode follower. An adjustable diode limiter in the cathode follower circuit prevented severe overloading of the pulse amplifier by cosmic ray pulses.

High voltage for both photomultipliers was supplied by an Isotopes Development Limited type 532 E.H.T. unit and a potentiometer with a separate adjustment for each counter. Both multipliers were operated at +900 Volts. At higher operating voltages they showed signs of gainshift with high counting rates. No appreciable changes in the high tension power supply were noticed over the course of a few days. A Lambda model 28 regulated power supply fed both cathode followers.

The negative pulses from the cathode follower of the 4.5 inch counter were carried by means of a long 100 ohm cable to a pre-amplifier which drove a Dynatron Radio Limited amplifier type 1430 A. Positive output pulses from the amplifier were fed into a 100 channel transistorised kick-
sorter (Computing Devices of Canada) for pulse height analysis. The output of the amplifier was also fed into a scale of 100 Dynatron type 1009 A scaler in parallel with the kicksorter. The block diagram of Fig. 6 shows this arrangement. The 3.5 inch counter was only used as a monitor. The negative output pulses from its cathode follower were fed directly into a 'Dynatron' amplifier and then into a 'Dynatron' scaler, with the bias set just above the 2.62 Mev gamma ray level.

(ii) **Background and Shielding.**

(a) **Background.**

There are two sources of counter background. The first is the room background due to cosmic rays, contamination of radioactive material in the walls, floor and shielding lead. This is completely time dependent and for a given counter geometry can be accurately determined. The second is the beam dependent background. This is partly due to X-rays produced by electrons from the reverse electron gun stabilising system, hitting the top of the Van de Graaff generator. This source is not very serious below 1 Mev. bombarding energy since the X-rays are soft and are readily absorbed in the lead shield. The other source of beam dependent background is the nuclear reactions produced by alpha particles, protons and neutrons in the unresolved beam through reactions such as $^{13}C (\alpha, n) ^{16}O$, $^{12}C (d, n\gamma) ^{13}N$ or $^{12}C (p, \gamma) ^{13}N$. The carbon contamination
Fig. 7 γ-Ray spectra; Na\textsuperscript{22}, Co\textsuperscript{60} and RdTh

- Na\textsuperscript{22}: 0.51 Mev, 1.28 Mev
- Co\textsuperscript{60}: 1.33 Mev
- RdTh: 2.62 Mev

Axes: CHANNEL NUMBER - COUNTS
inside the magnet box, and on the stops and walls of the glass tube and sometimes on the target came mostly from the diffusion pump oil vapours and the grease used in the sealing gaskets and O-rings. Neutrons are the most serious source of background due to the complex shape of the pulse height spectrum produced by them in the counter.

(b) **Shielding.**

Most of the room background could be easily removed by shielding the counter (all around) with 4 to 5 inches of lead; this also eliminates most of the soft X-rays produced by the machine. To keep the background produced by nuclear reactions to a minimum, it was essential, first to have a liquid nitrogen trap on the magnet box pumping system, second to use the minimum amount of vacuum grease on the sealing gaskets and O-rings and third to clean the magnet box with hot dilute nitric acid and steel wool at least once every two weeks. Use of a second liquid nitrogen trap in the beam tube (Fig. 4) kept the vapour pressure down in the neighbourhood of the target. The beam stabilising sniffers generally ran hot enough under beam bombardment to prevent appreciable carbon from depositing on them. The Hydrogen and Deuterium bottles in the V.D.G. generator were disconnected from the manifold to reduce to a minimum the deuteron and proton contents of the α beam, therefore minimising the background produced by proton and deuteron induced reactions.
Fig. 8 γ-Ray spectra; 4.43, 6.14 and 9.18 MeV

4.43 MeV Spectrum

6.14 MeV Spectrum

9.18 MeV Spectrum

CHANNEL NUMBER
The counter and shielding were mounted on a steel 'dexion' trolley on top of which were mounted two steel plates separated by quarter inch ball bearings so that the upper plate could be moved freely on the lower one. Adjusting screws were provided to facilitate the relative positioning between the plates. The front end of the trolley could be jacked up leaving it free to rotate about a universal bearing mounted on a degree circle placed on the floor. The centre of the target was placed vertically above the centre of the universal bearing. As the floor was not exactly level small adjustments of the upper steel plate were required to bring the counter axis into line with the centre of the target and to keep the counter target distance constant as the angle was changed. The counter could be rotated up to 135° on either side of the incident beam direction. The counter was mounted in a cylindrical hole through four interlocking lead bricks (6" x 6" x 6") which were lined with quarter inch thick iron tubing to provide additional magnetic shielding over that obtained from a light mu-metal shield placed over the photomultiplier. Three inches of additional lead shielding was placed around this whole assembly. To shield the counter from the neutron and γ-ray background, produced in the magnet box, a lead and paraffin wall was constructed in front of the magnet box so that the counter did not see any portion of the box.
FIG. 9 GAMMA RAY EFFICIENCY CURVES

\[ \varepsilon_{1/2} \]

\[ (1-e^{-\mu L}) \]

\[ (1-e^{-\mu L}) \left( \frac{\pi + \tau + \sigma_{1/2}}{\mu} \right) \]

\begin{align*}
\text{EFFICIENCY} & \quad \% \\
\text{GAMMA RAY ENERGY (MEV)} & \quad 0 \quad 4 \quad 8 \quad 12 \quad 16
\end{align*}
(iii) **Counter Energy Calibration.**

Since the pulse height response of the NaI (TlI) crystals is linearly proportional to the energy of the incident γ-rays, the energy calibration of the counter could easily be effected by means of γ-rays of known energies and a standard pulse generator. The standard pulse generator (Robertson 1957) used during these experiments had a linearity better than 0.1%. The pulses from this device had the same rise time as a typical NaI pulse (0.25 microsecond) and were of sufficiently low level to be fed directly into the photomultiplier cathode follower. This provided an independent check on the linearity of the electronic equipment used after the cathode follower. The gamma rays emitted by radioactive sources of Na$^{22}$, Co$^{60}$ and Rd Th were used for calibration at energies of 0.51, 1.33 and 2.62 Mev respectively and for obtaining representative γ-ray spectra. The B$^{11}$ (p, γ) C$^{12}$ reaction was used to obtain 4.43 Mev and 12 Mev γ-rays, the F$^{19}$ (p, αγ) O$^{16}$ reaction provided 6.14 Mev γ-rays and the C$^{13}$ (p, γ) O$^{14}$ reaction was used to obtain 9.18 Mev γ-rays. This covered the whole range of γ-rays encountered in the present study of the Li$^{7}$ (α, γ) B$^{11}$ reaction. A detailed knowledge of the shape of gamma ray spectra as a function of energy is required for separating the individual components from a complex spectrum. Typical spectra obtained for this purpose are shown in Fig. 7 (0.5, 1.33 and 2.62 Mev) and Fig. 8 (4.43, 6.14 and 9.18 Mev).
FIG. 10  9.28 MEV LEVEL SPECTRUM

YIELD

2.52 Mev
4.82 Mev
6.76 Mev
9.28 Mev

CHANNEL NUMBER
Scintillation Counter Efficiency.

In order to obtain absolute $\gamma$-ray intensities from the complex kicksorter spectra it was necessary to have a knowledge not only of the spectrum shape but also of the absolute efficiency of the scintillation counter for detecting gamma rays as a function of energy. This information was obtained from an independent theoretical and experimental study of the efficiency of several scintillation counters, including those used in the present study, as outlined in appendix IV. This study covered the gamma ray energy range from 0.5 Mev to 20 Mev and included absolute measurements at energies of 0.5, 1.25 and 6.14 Mev as well as the comparison of the scintillation counter efficiency curve with the efficiency curve for a standard Geiger counter of the type used by Barnes et al. (1952). The effects of scattering due to the presence of the counter shield and mounting were also investigated. In this study, the efficiency has been defined as the ratio of the number of counts in the gamma ray spectrum above a bias equivalent to half the $\gamma$-ray energy to the number of gamma rays incident on an area equal to the area of the face of the X-tal. It was assumed that this area was placed at the effective centre of the crystal. The effective centre being taken as that point in the crystal from which measurements of source to crystal distance were made in order to give an inverse square relation between counting rate and distance. The reasons for this choice of efficiency definition are given in appendix IV. Fig. 9 shows the curve
FIG. II  9.19 MEV LEVEL SPECTRUM

- 1 to 5 Spectrum
- 5 to 9.5 MeV Spectrum

YIELD

CHANNEL NUMBER

2.43 Mev
4.73 Mev
6.76 Mev
of efficiency to half energy bias obtained from the above mentioned study for the 2.75 inch by 4.5 inch crystal used in the present work when that crystal is in its 4 inch thick lead shield.

The efficiency, $\xi_b$, at any other bias could be empirically determined in terms of the efficiency at the half energy bias, $\xi_{1/2}$, and the experimental $\gamma$-ray spectrum shape using the relation,

$$\xi_b = \xi_{1/2} \times \frac{\text{No. of counts above bias } b}{\text{No. of counts above half energy bias}}$$

In this work due to the complex nature of the $\gamma$-ray spectra obtained, it was not always possible to observe the complete spectrum of a particular gamma ray down to its half energy point because of the presence of other gamma rays. Consequently for higher energy gamma rays an efficiency to a bias 2 Mev below the peak gamma ray energy has been used. This efficiency as obtained by the above mentioned method is also shown as a function of gamma ray energy in Fig. 9.
CHAPTER III

EXPERIMENTAL

1. Decay Scheme.

Three excited states of $^\text{11}$ have been produced by the resonant capture of $\alpha$ particles in Li$^7$. These are 9.28 Mev produced by 960 kev $\alpha$ particles, 9.19 Mev produced by 820 kev $\alpha$ particles and 8.92 Mev formed by 400 kev $\alpha$ particles. The gamma ray spectra obtained from each of these resonances are shown in Figs. 10, 11, and 12 which cover an energy range of about 1.5 Mev to 9.5 Mev. From the spectra it is apparent that the 8.92 Mev level decays chiefly to the ground state and a small fraction of the 9.28 Mev level decays to the ground state but there is no evidence for any significant fraction of the 9.19 level decaying to the ground state. These spectra also show that the upper two levels decay to one of the two levels of the doublet around 6.8 Mev which in turn primarily decays to the ground state giving a $\gamma$-ray of about 6.8 Mev. For the 9.28 and 9.19 levels the most prominent transition is the cascade through the 4.46 level giving two gamma rays of about equal energy. The separation of this part of the spectrum into its two components is discussed in section 2 of this chapter. For the 8.92 level, there is an indication that a small fraction of the decay goes via the 4.46 Mev state.
FIG. 13 2 MEV SPECTRUM—9.28 MEV LEVEL

YIELD

CHANNEL NUMBER

1.3 MeV  1.5 MeV  2.3 MeV  2.53 MeV
In order to determine the energy of the 2.5 Mev transition from the 9.28 Mev level to one of the levels of the doublet around 6.8 Mev, γ-ray spectra covering the range 1 Mev to 3 Mev were obtained as shown in Fig. 13. The width of a kicksorter channel was 20 kev for these runs. Using the linear pulse generator and the 2.62 Mev Rød Th line, the energy of the prominent peak was determined to be 2.52 ± 0.015 Mev. This gamma ray must therefore be assigned to the transition from the 9.28 Mev level to the 6.76 level. A transition to the 6.81 level would lead to a γ-ray of energy 2.47 Mev which is outside the experimental error for the observed energy. There are no other possible transitions between known levels of Bi to which this γ-ray could be assigned.

A similar analysis for the 9.19 level led to an energy of 2.43 ± 0.015 Mev, again consistent with the decay of the 9.19 Mev level to the 6.76 Mev level.

The second peak to the left of the 2.52 Mev peak was determined to have an energy of 2.30 ± 0.02 Mev and was therefore identified with the partial decay of the 6.76 Mev state to the 4.46 Mev level and not to the decay of the 4.46 level to the 2.14 Mev level because there was no evidence of the subsequent 2.14 Mev transition in the γ-ray spectrum. This was confirmed by absolute intensity determinations of the 2.52 Mev, 2.3 Mev and 6.76 Mev γ-rays, which are referred to later, in which the intensity of the 2.52 Mev γ-ray was
FIG. 14 DECAY SCHEME
found to be approximately equal to the sum of the intensities of the 2.3 Mev and 6.76 Mev gamma rays.

The determination of the energy of the 6.76 Mev γ-rays from spectra covering an energy range of 5 Mev to 7 Mev for both the 9.28 and 9.19 levels, using the 6.14 Mev γ-ray obtained from the $^{19}_P^\text{p, αγ}$ reaction and the linear pulse generator, further confirmed the above conclusion that both these states decay to the 6.76 Mev level and not to the 6.81 Mev level.

Table I lists the γ-rays identified at each resonance.

| TABLE I |
|-----------------|-----------------|-----------------|
| 400 kev Resonance | 820 kev Resonance | 960 kev Resonance |
| (8.92 Mev $^\text{B}^{11}$ state) | (9.19 Mev $^\text{B}^{11}$ state) | (9.28 Mev $^\text{B}^{11}$ state) |
| 8.92 Mev | 6.76 Mev | 9.28 Mev |
| 6.76 Mev | 4.73 Mev | 6.76 Mev |
| 4.46 Mev | 4.46 Mev | 4.82 Mev |
| 2.14 Mev | 2.46 Mev | 4.46 Mev |
| 2.3 Mev | 2.3 Mev | 2.53 Mev |

The decay scheme as suggested by these results is shown in Fig. 14, which also shows the branching ratios which are obtained in a later section of this chapter.
2. Angular Distribution.

(i) General.

Thin targets ranging in thickness from 100 kev to 200 kev were used in the angular distribution measurements. The maximum permissible thickness, with the condition that only one resonance was excited at a time, was used for each of the three resonances. The bombarding $\alpha$-particle energies were chosen somewhat above the resonance energy so that the yield was relatively independent of small changes in the bombarding energy. The yield at the beginning of the runs on a fresh target showed some fluctuation and a decrease in the yield as a function of the target bombardment. Therefore the measurements taken in the first half hour of the bombardment were not used in the analysis. This was necessary because during the angular distribution measurements at the 9.19 Mev and 8.92 Mev resonances no separate monitor counter was used due to the relatively low yield from the resonance.

The trolley carrying the counter mounted in the shield was placed near to the target so that it could be rotated around as described in section 2 of the last chapter. In order to ensure that the beam hit the centre of the target, measurements were made with the counter at $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$ and with the normal to the target plane at $45^\circ$ to the left and then to the right of the incident beam. The angular distribution measurements were taken on both sides of the beam.
as a further check on the target counter symmetry. Several measurements were made at each angle and an estimate of the change in target yield was made by plotting yield versus bombardment time curves for each angle. Typical curves are given in Fig. 15a which show the change of yield with bombardment time. Using these curves all the measurements could be normalised to the same bombardment time. In general, the slope of the curves for different angles is the same and if a particular point lay far off the appropriate curve, it was rejected. For the 9.28 Mev level where the yield is relatively high, a 3.5 inches long NaI crystal, hanging vertically above the target, was used as a monitor. This provided an additional reference for normalising the measurements. The experimental data were analysed, details of the analysis are given below for each resonance, and the experimental angular distribution function for each γ-ray line was expressed in the general form,

\[ F(\theta) = A (1 + A_2 \cos^2 \theta + A_4 \cos^4 \theta) \]  

(1)

The ratio of the number of counts at various angles for each γ-ray was used to determine \( A_2 \) and \( A_4 \). For example, the experimental ratios

\[
\frac{N_0}{N_{90}} = 1 + A_2 + A_4
\]

\[
\frac{N_{45}}{N_{90}} = 1 + 0.5 A_2 + 0.25 A_4
\]

\[
\frac{N_0}{N_{45}} = \frac{1 + A_2 + A_4}{1 + 0.5 A_2 + 0.25 A_4}
\]
gave sufficient information to determine $A_2$ and $A_4$. Only in a few cases was $A_4$ found to be as big as 5% of $A_2$ and since this is about the order of error in $A_2$, $A_4$ has been neglected in the analysis of the results. The measurements at 135° were taken to detect any forward backward asymmetry about 90°. Within the statistical errors no significant difference between the 45° and 135° measurement was detected. To put the counter at 135° quite a bit of lead shielding had to be removed which resulted in additional background contributions. Therefore these measurements were not used in the analysis of angular distributions. The angular distribution coefficients were corrected for finite solid angle of the counter. The corrections were in no case greater than 10%.

(ii) 9.28 Mev $^1\text{H}$ State.

(a) Angular Distribution of 9.28 Mev and 6.76 Mev $\gamma$-Rays.

The angular distribution of 9.28 Mev ground state gamma rays and 6.76 Mev ground state gamma rays were determined from the spectra taken covering an energy range from 5 Mev to 9.5 Mev. The angular distribution of the 9.28 Mev $\gamma$-ray was easily determined from the total number of counts, after correcting for the background, in the energy range from 7.28 Mev to 9.5 Mev as there was no contribution from any other $\gamma$-rays in this range.
Fig. 15  A. Yield vs. time curves

B. 6.76 Mev and 9.28 Mev γ-ray spectrum
To determine the angular distribution of 6.76 Mev γ-ray the spectra from each measurement were plotted and from an empirical knowledge of the shape of the 9 Mev spectra obtained at the 1.76 Mev resonance of the C^{13} (p, γ) N^{14} reaction, the tail of the 9.28 Mev γ-ray spectrum was extrapolated under the 6.76 Mev γ-ray spectrum (Fig. 15 b). The ratio of the 9.28 Mev contribution under the 6.76 Mev peaks to the 9.28 Mev contribution above the 6.76 Mev peaks was obtained for each of the curves. This ratio should be constant for all angles. Due to statistical fluctuations and the uncertainty in shape of the spectra the ratio was not exactly constant and therefore a mean value was obtained. On the basis of this mean value and the number of counts in the 9.28 Mev peak in each spectrum, the 9.28 Mev tail under the 6.76 Mev spectrum was subtracted. The angular distribution of the remaining part, attributed to 6.76 Mev γ-rays, was then obtained.

A second method was employed to check the consistency of the above method. The angular distribution of the total number of counts in the 6 Mev region, that is 5 Mev to 7.28 Mev, was obtained. This is, of course, a combination of the angular distributions of the 6.76 Mev γ-rays and the 9.28 Mev γ-rays and can be expressed as

\[ A_T (1 + A_T^2 \cos^2 \theta) = (A^9 + A^6) + (A^9 A_2^6 + A_2^6 A^6) \cos^2 \theta \]  

(3)

where the angular distributions of the total, the 9.28 Mev γ-rays.
and the 6.76 Mev γ-rays are all expressed in the form,

\[ N^1_6 = A^1 (1 + A^1_2 \cos^2 \theta) \]

and the superscript 1 takes on values 1, 9 and 6 referring to the total counts in the spectrum range from 5 Mev to 7.28 Mev or the contribution to the counts in the same range from 9.28 and 6.76 Mev γ-rays.

From this relation it follows that

\[ \frac{N^T_6}{N^T_{90}} = 1 + A^T_2 = \frac{(K + 1) + KA^9_2 + A^6_2}{K + 1} \tag{4} \]

where \( K = \frac{A^9}{A^6} \) and determines the relative contribution of the two γ-rays, in a given energy region, at 90°. This last relation leads to the result

\[ A^T_2 = \frac{KA^9_2 + A^6_2}{K + 1} \tag{5} \]

Thus, knowing \( A^T_2 \) and \( A^9_2 \), if \( K \) does not correspond to the correct tail of the 9.28 Mev γ-rays under the 6.76 Mev peaks, then \( A^6_2 \) determined from relation (5) will not agree with the value of \( A^6_2 \) calculated by the first method. By requiring that the two methods give a consistent value for \( A^6_2 \) it was possible to get a more accurate estimate of the contribution from the 9.28 Mev tail under the 6.76 Mev region than would have been possible from a priori knowledge of the spectrum shape alone.
FIG. 16 4 MEV SPECTRUM

Observed Spectrum

4.46 Component

4.82 Mev Component

CHANNEL NUMBER

YIELD
(b) **Angular Distribution of 4.82 Mev and 4.46 Mev γ-rays.**

The angular distribution of the 4.82 and 4.46 Mev γ-rays was determined from the analysis of experimental spectra taken covering the energy range from 2.5 Mev to 5 Mev. One such spectrum is shown in Fig. 16 a. It was assumed that the shapes of the 4.82 Mev and 4.46 Mev γ-ray spectra were the same as that of the 4.43 Mev spectra obtained from the $^11_B(p, γ)^{12}_C$ reaction.

The contributions from the 6.76 and 9.28 Mev γ-rays and the background under the 4 Mev spectra were subtracted. A 4.43 Mev spectrum, normalised to the number of counts in the upper part of the photopeak of the 4.82 Mev γ-rays, was subtracted from the complex experimental 4 Mev spectrum. The shape of the residual 4.46 Mev spectrum was matched with that of 4.82 Mev spectrum. If the two decomposed 4 Mev spectra were not approximately of the same shape, then slight adjustments were made to the shape of the 4.43 Mev standard spectrum so that the decomposition did result in two spectra of the same shape. These adjustments were required in the low energy end of the standard spectrum, largely because the a priori knowledge of this shape obtained from the $^11_B(p, γ)^{12}_C$ reaction was not very accurate since a fairly large 12 Mev tail had to be removed from the experimental spectrum to obtain the 4.43 Mev spectrum. Fig. 16 shows a typical spectrum decomposed into 4.82 and 4.46 Mev components.
After the separation of all the experimental spectra into two components, the angular distributions of the two 4 Mev $\gamma$-rays were determined by using both the methods outlined in subsection (a) of this section.

(c) Angular Distribution of the 2.52 Mev $\gamma$-Rays.

A typical spectrum covering the range from 0.7 Mev to 3.5 Mev, as used in the angular distribution measurements of the 2.52 Mev $\gamma$-rays, is shown in Fig. 13. The tail of the 4 Mev $\gamma$-rays under the 2.52 Mev spectrum was subtracted for all the spectra and the angular distribution for 2.52 Mev was determined from the counts in its photopeak to avoid any contribution due to 2.3 Mev $\gamma$-rays. In this case also both methods were used to check the consistency of the level of the 4 Mev tail subtracted from the complex spectra.

The results of these measurements are tabulated in table II.

(iii) 9.19 Mev $^\text{11}B$ State.

The angular distribution of the 6.76 Mev, 4.73 Mev, 4.46 Mev and 2.43 Mev $\gamma$-rays emitted by decay of the 9.19 Mev $^\text{11}B$ state were determined essentially in the same way, as for the 9.28 Mev level described above. The results for this level are also listed in table II.
(iv) **8.92 Mev B** State.

Due to very low yield of this resonance, only the angular distribution of the 8.92 Mev γ-rays could be determined with any accuracy. The value of \( A_2 \) in this case is also shown in table II.

**TABLE II**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>9.28 Mev state</th>
<th>9.19 Mev state</th>
<th>8.92 Mev state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( A_2 )</td>
<td>( A_2 )</td>
<td>( A_2 )</td>
</tr>
<tr>
<td>9 Mev</td>
<td>-0.41 ± 0.04</td>
<td>0.37 ± 0.04</td>
<td>-0.25 ± 0.1</td>
</tr>
<tr>
<td>6.76 Mev</td>
<td>+0.7 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8 Mev</td>
<td>+0.56 ± 0.1</td>
<td>-0.26 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>4.46 Mev</td>
<td>-0.07 ± 0.03</td>
<td>-0.08 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>2.5 Mev</td>
<td>-0.38 ± 0.04</td>
<td>+0.60 ± 0.10</td>
<td></td>
</tr>
</tbody>
</table>

3. **Gamma-Ray Yields.**

(1) **Relative Yields and Branching Ratios.**

The measurements of the relative yields of the gamma rays were made with thin targets of the same specifications as described in section one of this chapter. In general the number of counts observed, \( N_0 (\theta) \), for a given γ-ray and target geometry is given by

\[
N_0 (\theta) = N_\xi \times \omega \times \xi_b \times A (1 + A_2 \cos^2 \theta)
\]  \hspace{1cm} (6)
where $N_t$ is the total number of gamma rays emitted by the target per count of the current integrator corresponding to a fixed number of $\alpha$-particles incident on the target, $\omega$ is the solid angle subtended by the counter at the target, $\xi_b$ is the gamma-ray detection efficiency of the NaI crystal for a bias $b$, $(1 + A_2 \cos^2 \theta)$ is the angular distribution function for the $\gamma$-ray under investigation and $A$ normalizes this function to unity over the total solid angle such that

$$\int_0^{4\pi} (1 + A_2 \cos^2 \theta) \, d\omega = 1$$

Equation (7) on integration gives

$$A = \sqrt[4]{4\pi (1 + A_2/3)}.$$

On substituting for $A$ and $\omega$ and rearranging the Equation (6) we get

$$N_t = \frac{N_0 (0^\circ) 16\pi r^2 (3 + A_2)}{3 R^2 \xi_b (1 + A_2)}$$

where $N_0 (0^\circ)$ is the number of counts observed above the bias $b$ with the counter at zero degrees placed at an effective distance $r$ from the centre of the target and $R$ is the radius of the cylindrical NaI crystal.

Using Equation (8), experimentally determined angular distribution coefficients $A_2$ and the number of counts $N_0 (0^\circ)$ per count of the current integrator, the yield of individual gamma rays for each resonance was determined. Except for the
2.5 Mev γ-rays, for which a half energy bias was used, the bias b chosen was two Mev below the γ-ray energy. The number of counts $N_0 (0°)$ for all the γ-rays, from the three resonances, were individually determined by separating the contribution of each γ-ray from the complex γ-ray spectra, for each resonance taken at 0 degrees, in the manner described in section two of this chapter. These observed counts were corrected for absorption in the 1/16 inch thick brass wall of the target pot and 1/64 inch thick target backing of copper. The calculated results for relative γ-ray intensities in percent are given in table III and shown in Fig. 14.

<table>
<thead>
<tr>
<th>γ-ray Transition</th>
<th>9.28 Mev Level</th>
<th>9.19 Mev Level</th>
<th>8.92 Mev Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Mev to ground state</td>
<td>18%</td>
<td>&lt;0.5%</td>
<td>85%</td>
</tr>
<tr>
<td>9 Mev to 6.76 Mev</td>
<td>8%</td>
<td>9%</td>
<td>~5%</td>
</tr>
<tr>
<td>9 Mev to 4.46 Mev</td>
<td>73%</td>
<td>90.5%</td>
<td>5%</td>
</tr>
<tr>
<td>6.76 Mev to 4.46 Mev</td>
<td>15%</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>6.76 Mev to ground</td>
<td>85%</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>4.46 Mev to ground</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

(ii) Absolute Yield.

The absolute yields were determined by using freshly laid targets of about 500 kev thickness and obtaining γ-ray spectra at zero degrees covering an energy range from 1 to 9.5 Mev
for accurately known counter geometry.

During the measurements of the thick target yield for the 9.28 Mev level both the resonances, at 960 kev and 820 kev, were excited and therefore the total \( \gamma \)-ray spectra contained contributions from both the levels. Since the 9.19 level does not decay to the ground state directly, there was no contribution from the 9.19 level under the 9.28 Mev \( \gamma \)-ray spectrum from the upper level. Thus by determining the absolute thick target yield of the 9.28 Mev \( \gamma \)-ray, the absolute thick target yield for the other \( \gamma \)-rays from the 9.28 Mev level were determined relatively by using the percentage yields of table III. The results are given in table IV and are expressed as thick target yields of \( \gamma \)-rays per incident \( \alpha \)-particle. For the 9.19 Mev level, the absolute yield of 6.76 Mev \( \gamma \)-rays was determined and the absolute thick target yields of other \( \gamma \)-rays were obtained using the relative yield results. Similarly for the 8.92 Mev level the absolute thick target yield of the 8.92 Mev \( \gamma \)-rays was obtained and used to evaluate the absolute thick target yields of other transitions. In all these measurements the half angle subtended by the counter at the centre of the target was 9 degrees.

As a check, the spectra obtained with thick targets were analysed independently, as described in the section on relative yields for the 9.28 and 9.19 levels. Since the targets were very thick the \( \gamma \)-ray spectrum obtained for the 9.28 level contained contribution from the 9.19 level. After subtracting
this contribution these results agreed well with those described above.

**TABLE IV**

Thick Target Absolute $\gamma$-Ray Yields.
(totat $\gamma$-rays per incident $\alpha$-particle)

<table>
<thead>
<tr>
<th>$\gamma$-Ray Transition</th>
<th>9.28 Mev Level</th>
<th>9.19 Mev Level</th>
<th>8.92 Mev Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 to ground</td>
<td>$7.2 \pm .2 \times 10^{-11}$</td>
<td>$&lt;0.04 \times 10^{-11}$</td>
<td>$0.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>9 to 6.76</td>
<td>$2.8 \pm .1 \times 10^{-11}$</td>
<td>$0.6 \pm .05 \times 10^{-11}$</td>
<td>$0.03 \times 10^{-11}$</td>
</tr>
<tr>
<td>9 to 4.46</td>
<td>$29.2 \pm 1 \times 10^{-11}$</td>
<td>$7.0 \pm .2 \times 10^{-11}$</td>
<td>$0.03 \times 10^{-11}$</td>
</tr>
<tr>
<td>6.76 to 4.46</td>
<td>$0.2 \times 10^{-11}$</td>
<td>$0.09 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>6.76 to ground</td>
<td>$2.6 \pm .1 \times 10^{-11}$</td>
<td>$0.5 \pm .05 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td>4.46 to ground</td>
<td>$29.2 \pm 1 \times 10^{-11}$</td>
<td>$7.0 \pm .2 \times 10^{-11}$</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$39.3 \pm 1 \times 10^{-11}$</td>
<td>$7.67 \pm .5 \times 10^{-11}$</td>
<td>$0.6 \times 10^{-11}$</td>
</tr>
</tbody>
</table>
4. \( \alpha \) and \( \gamma \)-ray Widths.

In general an excited state of a nuclear system may decay by the emission of either \( \gamma \)-rays or particles or both. The life time of the system is generally described in terms of the level width which is proportional to the decay probability, that is, the reciprocal of the life time. This is convenient because the total level width, \( \Gamma \), can be expressed as the sum of the partial widths for decay through various energetically possible channels. Thus

\[
\Gamma = \sum \Gamma_{\gamma} + \sum \Gamma_{\text{particle}}
\]

For the three states of \(^{11}\text{B}^1\) formed by \( \alpha \)-particle capture in \(^{7}\text{Li}^1\), the only energetically possible modes of decay are re-emission of the \( \alpha \)-particle and \( \gamma \)-ray decay to various lower states of \(^{11}\text{B}^1\). So for these states we can write

\[
\Gamma = \Gamma_{\alpha} + \sum \Gamma_{\gamma}
\]

Knowledge of the \( \gamma \)-ray partial widths when compared with theoretical values gives some information concerning the character of the decaying states.

(1) Partial Radiation Width, \( \Gamma_{\gamma} \).

In most cases, where energetically possible, it has been found that the particle widths are considerably greater than the radiation widths, although, this is not
always true. Where this is true, the partial radiation width of a level for decay to another level can be determined directly from the absolute thick target yield of the appropriate \( \gamma \)-ray as follows. Consider the differential \( \gamma \)-ray yield from a thin layer of thickness \( dx \) inside a thick lithium target. This yield can be expressed as

\[
dN_\gamma = \sigma(E) N_1 dx
\]

or as

\[
dN_\gamma = \sigma(E) N_1 \frac{dx}{dE}
\]

(10)

where \( \sigma(E) \) is the cross section per \( \alpha \)-particle of energy \( E \) per target nucleus, \( N_1 \) is the number of lithium atoms per cubic centimeter and \( dx \) is the reciprocal of the stopping power for \( \alpha \)-particles in lithium which can be considered to be constant over the narrow resonances encountered in this work.

In order to obtain the total thick target yield the differential yield must be integrated over the path of the \( \alpha \)-particle in the thick target or by introducing the stopping power, as done above, the integration can be performed over the energy of the \( \alpha \)-particle as it slows down in the thick target. This is convenient because for narrow resonances, the energies which give appreciable contribution to the total yield lie in a narrow region about the resonance energy.
Thus integrating (10) we get,

\[ N_I = N_1 \frac{dx}{dE} \int_{0}^{E_i} \sigma^-(E) \, dE \]  

(11)

where \( E_i \) is the incident particle energy. Substituting for \( \sigma(E) \) the Breit-Wigner, single level, resonance cross section

\[ \sigma^-(E) = \frac{\pi \hbar^2 \omega_{\alpha \gamma}}{(E - E_{\alpha})^2 + (\Gamma/2)^2} \]

and integrating between the limits zero and infinity, Equation (11), becomes,

\[ N_I = N_1 \frac{dx}{dE} 2\pi^2 \hbar^2 \omega_{\alpha \gamma} \frac{\Gamma_{\alpha} \Gamma_{\gamma}}{\Gamma} \]  

(12)

where \( \hbar \) is the De-Broglie wavelength of the \( \alpha \)-particles of energy \( E \),

\[ \omega_{\alpha \gamma} = \frac{(2J + 1)}{(2S + 1)(2J_i + 1)} \]

is the statistical weighting factor. \( s, J_1 \) and \( J \) are the spins of the incident \( \alpha \)-particles initial state of lithium and compound state of \( B^{11} \) respectively.

Since the incident \( \alpha \)-particle energy, \( E_i \), used in this work, was higher than resonance energy by at least ten times the total width of the resonance, for all resonances, the upper limit of \( E_i \) in the integral can be replaced by infinity because the contribution from the Breit-Wigner formula for energies above \( E_i \) is in the worst case not more than \( 2\% \) of the total yield.
In cases where \( \Gamma_{\alpha} \gg \Gamma_{\gamma} \) we can put \( \Gamma_{\alpha} = \Gamma_{\gamma} \) in (12) which then relates the \( \gamma \)-ray width directly to the thick target \( \gamma \)-ray yield as follows:

\[
N_{\gamma} = N_1 \frac{dx}{dE} 2 \pi \tilde{x}^2 \omega_{\gamma} \Gamma_{\gamma}
\]

(13)

The number of lithium atoms per cubic centimeter, \( N_1 \), can be determined in terms of Avogadro's number, \( n \), the density of lithium, \( d \) (0.534 grams per cubic centimeter), and the atomic weight of lithium, \( M \) (6.94), by the relation

\[
N_1 = \frac{nd}{M} = 4.64 \times 10^{22} \text{ atoms per cubic centimeter.}
\]

The stopping power for \( \alpha \)-particles in lithium, \( \frac{dE}{dx} \), for the three \( \alpha \)-particle resonance energies was obtained by extrapolating from the compilation of Whaling (1958) and from calculations suggested by Bethe (1937) as described in appendix III.

Using the absolute thick target yield of each gamma ray given in table IV, and the statistical weighting factor, taking for the \( B^{11} \) compound state spins \( J \) the values obtained from the angular distribution data (see the chapter on discussion), the values of \( \Gamma_{\gamma} \) were calculated for the transitions to the ground state, 4.46 Mev state and 6.76 Mev state, for each resonance. The results are given in table V.

Weisskopf, on the basis of the single particle model, has calculated the life times of excited states, against decay by gamma radiation for various multipole radiations. The
partial radiation widths for dipole radiation obtained by Weisskopf (Weisskopf, 1955, and Moszkowski, 1955) are given by

\[ \Gamma_\gamma (E1) = 0.11 E_\gamma^3 A^{2/3} \text{ ev.} \]
\[ \Gamma_\gamma (M1) = 0.019 E_\gamma^3 \text{ ev.} \]  

(14)

Wilkinson (1955), having surveyed over 100 transitions in light nuclei, chiefly dipole, concluded that E1 transitions have a most probable speed of about 0.032 times the Weisskopf values with a spread in speed of about a factor of seven either way and that the corresponding quantities for M1 transitions have values 0.15 times the Weisskopf values with a spread factor of 20 either way. The difference between the Weisskopf single particle values and the experimental values have been qualitatively discussed by Wilkinson (1955) in terms of various shell model assumptions. The values calculated from the Weisskopf relation (14), the average values suggested by Wilkinson's survey and the present experimental values are shown in the columns a, b and c respectively of Table V.
TABLE V

Partial Radiation Widths
(in ev.)

<table>
<thead>
<tr>
<th>Transition</th>
<th>9.28 Level</th>
<th></th>
<th>9.19 Level</th>
<th></th>
<th>8.92 Level</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>to ground</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El state</td>
<td>322</td>
<td>10.3</td>
<td>0.96</td>
<td>312</td>
<td>9.98</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>M1</td>
<td>15.2</td>
<td>2.3</td>
<td></td>
<td>14.7</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>to 4.46 Mev</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Mev</td>
<td>45.1</td>
<td>1.44</td>
<td>3.9</td>
<td>42.1</td>
<td>1.36</td>
<td>0.84</td>
</tr>
<tr>
<td>M1</td>
<td>2.1</td>
<td>0.32</td>
<td>0.3</td>
<td>2.0</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>to 6.76 Mev</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Mev</td>
<td>6.5</td>
<td>0.21</td>
<td>0.38</td>
<td>5.8</td>
<td>0.19</td>
<td>0.08</td>
</tr>
<tr>
<td>M1</td>
<td>0.31</td>
<td>0.05</td>
<td>0.0</td>
<td>0.27</td>
<td>0.04</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Total $\Gamma$  

|         | 5.24 |       | 0.92 |       | .18  |

For the 9.28 Mev and 9.19 Mev levels the experimental resonance widths are greater than the total radiation widths. Therefore the assumption that $\Gamma_\alpha = \Gamma$ is justified. But for the 8.92 level, the experimental evidence by itself suggests that $\Gamma_\alpha$ may be of the same order as $\Gamma_\gamma$. So the radiation widths listed for this level on the assumption that $\Gamma_\alpha$ is greater than $\Gamma_\gamma$ must be considered to be minimum values. This point is discussed further in the next chapter.
(ii) **Reduced \( \alpha \)-Particle Width.**

The reduced \( \alpha \)-particle width \( \gamma_\alpha^2 \), which is a measure of the emission probability for \( \alpha \)-particles from the nucleus in the absence of the coulomb and centrifugal barriers, was calculated from the relationship

\[
\gamma_\alpha^2 = \frac{\Gamma}{2k v_1 R}
\]

where \( k \) is the wave number of the incident particles.

\( v_1 = \frac{1}{A_1^2} = \frac{1}{(F_1^2 + G_1^2)} \), where \( F_1 \) and \( G_1 \) are coulomb functions depending upon the height of the coulomb barrier and the angular momentum of the incident \( \alpha \)-particles. Values of \( A_1^2 \) were calculated from the tables of Block et al. (1951) and from the graphs of Sharp et al. (1953). \( R \) is the interaction radius and is given by \( R = r_o (A_\alpha^{1/3} + A_{Li}^{1/3}) \), where \( r_o = 1.45 \times 10^{-13} \) centimeter.

From a series of experiments with \( \alpha \)-particles bombarding a large range of different target nuclei it has been found that interaction radius can be expressed as \( R = r_o A_\alpha^{1/3} + b \), where \( r_o = 1.414 \times 10^{-13} \) centimeter and \( b = 2.2 \times 10^{-13} \) centimeter. (Annual Progress Report of Cyclotron Research Group, 1957, U. of Washington.) The two formulae give \( R = 5.07 \times 10^{-13} \) centimeter and \( R = 4.89 \times 10^{-13} \) centimeter respectively. An average value of \( R = 4.98 \times 10^{-13} \) centimeter was used. \( \Gamma \) is the total width of the resonance. For the 960 kev. resonance an upper limit of 8 kev. is assigned by Phillips (1957) which is in agreement with the measurements of Bennet et al. (1951).

Recently Meyer-Schutzmeister and Hanna (1958) from their study
of resonant absorption of gamma rays report that total width of the 9.19 Mev level is 100 ev. The presently available experimental data of Bennet et al. (1951) and Phillips (1957) indicate that the total width of this resonance is less than their experimental resolution of about 1 kev. The values of the reduced \( \alpha \)-particle widths for the 9.28 level and the 9.19 level, considering that these two states are formed by p and f waves respectively, as indicated by the angular distribution data discussed in the next chapter, are

9.28 Mev level \( \gamma_\alpha^2 = 260 \text{ kev.} \)
9.19 Mev level \( \gamma_\alpha^2 < 1.1 \text{ Mev} \)

For the 8.92 Mev level the reduced \( \alpha \)-particle width cannot be calculated since the laboratory width is much smaller than experimental resolution. However, the reduced width is given below in terms of the unknown laboratory width for p, d and f wave ingoing \( \alpha \)-particles.

p wave \( \gamma_\alpha^2 = 2 \times 10^4 \times \Gamma \text{ ev.} \)
d wave \( \gamma_\alpha^2 = 3.5 \times 10^5 \times \Gamma \text{ ev.} \)
f wave \( \gamma_\alpha^2 = 8 \times 10^5 \times \Gamma \text{ ev.} \)
By comparing the experimental angular distribution coefficient $A_2$ for each $\gamma$-ray with the theoretically calculated values (see appendix IV) one can get information about the spins and parities of the levels involved in the transition. For example, in a general case the systematics of the reaction can be represented as follows:

\[
\text{Li}^7 + \alpha = \text{B}^{11} \rightarrow \gamma\text{-ray} + \text{B}^{11}
\]

where:  
- $3/2^-$ is the spin and parity of the Li$^7$ ground state (Ajzenberg and Lauritsen, 1959).
- $I_\alpha$ is the orbital angular momentum carried in by the $\alpha$-particles. The intrinsic spin of the $\alpha$-particles is zero.
- $J$ is the total angular momentum of the excited state of B$^{11}$.
- $I_\gamma$ is the orbital angular momentum carried away by the photon which has intrinsic spin of 1.
- $J_2$ is the total orbital angular momentum of the final state of B$^{11}$.
In general the case where an α-particle is captured and a radiative transition goes directly from the compound state formed to any other lower state, will be referred to as a two stage process, for which the sequence of angular momenta can be written as follows:

$$3/2 \ (l_\alpha) \ J \ (l_\gamma) \ J_2$$

In particular if the transition goes directly to the ground state then $J_2 = 3/2^-$ (Mayer and Jensen, 1955, and Ajzenberg and Lauritsen, 1959). For the cases where the decay cascades through an intermediate state the sequence for the corresponding three stage process can be written as

$$3/2 \ (l_\alpha) \ J \ (l_\gamma_1) \ J_{\text{int}} \ (l_\gamma_2) \ J_2$$

where $l_\gamma_1$ and $l_\gamma_2$ are the angular momenta carried away by the two $\gamma$-rays and $J_{\text{int}}$ is the total angular momentum of the intermediate state.

If it is assumed that we are dealing with isolated resonances then the angular distributions for the $\gamma$-rays corresponding to the above sequences can be expressed in the form

$$f (\theta) = 1 + A_2 \cos^2 \theta + A_4 \cos^4 \theta + \cdots$$

For various possible values of the parameters in the above sequences, the angular distribution coefficients $A_2$ and $A_4$ were calculated using Wilkinson's Method (1954) and the
tables of Biedenharn and Rose (1953). The results are given in appendix II for \( l_a = 0, 1, 2 \) and 3 and for \( l, \gamma = 1 \) and 2, in addition a number of cases are included where \( E2 \) and \( M1 \) radiations are mixed. Since for the three resonances, observed in the \( \text{Li}^7 (\alpha, \gamma) \text{B}^{11} \) reaction, the gamma ray angular distributions were not isotropic, \( l_a = 0 \) is ruled out because it necessarily leads to isotropic distributions only.

Comparison of the experimental angular distribution coefficients with the theoretical values severely restricts the possible values of the parameters, \( l_a, l, J, J_{\text{int}} \) and \( J_2 \) as discussed below. (see also appendix IV B) Further because the parities of the ground states of \( \text{Li}^7 \) and \( \text{B}^{11} \) and the 4.46 Mev \( \text{B}^{11} \) state are well known (see chapter I) and the parity associated with \( l_a \) is \((-1)^l a\), one can in many cases decide on the magnetic or electric character of a particular \( \gamma \)-ray from the knowledge of the electromagnetic selection rules. In some cases, however, there is not sufficient information concerning the parities of the levels involved. In these cases it may be possible to determine the parity by first determining the character of the radiation by comparing the absolute radiative transition probability with theoretical values obtained on the assumption of the single particle shell model (Weisskopf, 1951, and Wilkinson, 1955) and second by using the selection rules to relate the character of the radiation to the parity change.

(i) 960 Kev. Resonance.

(a) 9.28 Mev \( \text{B}^{11} \) Level.

Comparison of the experimental coefficient \( A_2 \) for
the 9.28 Mev $\gamma$-ray with the theoretical possibilities limits

$$ I_\alpha \text{ to } 1 \text{ or } 3; \ J \text{ to } 3/2^+ \text{ or } 5/2^+ \text{ and } l_\gamma \text{ (9 Mev) to 1.}$$

A similar comparison for the 4.82 Mev $\gamma$-rays, produced by the decay of the 9.28 Mev level to the 4.46 Mev level, limits

$$ I_\alpha \text{ to 1; } J \text{ to } 5/2^+ \text{ and } l_\gamma \text{ (4.8 Mev) to 1.}$$

In this comparison it was assumed that the ground state of $^{11}$B is $3/2^-$ and the 4.46 Mev state is $5/2^-$ (see chapter I). From these two comparisons one is led to the conclusion that the 9.28 Mev state is formed by p-wave $\alpha$-particles and has a spin of $5/2$ and even parity and decays to the ground state and to the 4.46 Mev state by electric dipole radiations. This conclusion is supported by a comparison of the experimental partial radiation width (3.9 ev.) with the theoretical Wilkinson value (1.44 ev.) for the 4.82 Mev transition to the 4.46 Mev state, which suggests that this transition is a favoured electric dipole. This conclusion also requires the parity of the 9.28 Mev state to be positive. The reduced p-wave $\alpha$-particle width (260 kev.) for this resonance is an appreciable fraction of the Wigner limit (about 2 Mev) suggesting that the level has some single $\alpha$-particle character.

The present spin assignment is in agreement with the assignment of Phillips (1957). The recent stripping work of Bilaniuk and Hensel (1958), who measured the proton angular distributions from the reaction $^{10}$B (d, p) $^{11}$B, indicates that
the 9.28 Mev state is formed with S-wave ingoing neutrons, thus limiting its parity to positive and its spin to 5/2 or 7/2. A similar conclusion was drawn for the 9.19 Mev level. Considering these two levels as a spin doublet the stripping intensity ratio for the two levels favours $5/2^+$ for the 9.28 Mev level and $7/2^+$ for the 9.19 Mev level which is in agreement with our assignment for the 9.28 Mev level. Further, the high neutron capture probability in the $^{10}$B$(d, p)$ $^{11}$B reaction would suggest that this state is a single particle neutron state formed by direct neutron capture into $1d - 2s$ shell. Recent work of Ferguson et al. (1958) with the $^{7}$Li$(\alpha, \gamma)$ $^{11}$B reaction also supports the assignment $5/2^+$ for the 9.28 Mev state.

(b) 6.76 Mev Level.

A comparison of the experimental angular distribution coefficient $A_2$ of the 2.52 Mev $\gamma$-rays with the theoretical possibilities, in the light of the known facts about the $^{11}$B system and the conclusion drawn above (the 9.28 Mev state is $5/2^+$), limits the 6.76 Mev state to 3/2 or 7/2. But a similar comparison for the 6.76 Mev $\gamma$-ray, produced by the decay of the 6.76 Mev state to the ground state, is not consistent with the 3/2 assignment but is in agreement with the other possible assignment of 7/2 for this state. The partial radiation width for the 2.52 Mev transition is found to be 0.38 ev. which is slightly bigger than Wilkinson's adjusted value of 0.21 ev.
This strongly suggests that the transition is electric dipole in character and therefore leads to the conclusion that the 6.76 Mev state is of odd parity. Hence, this state is $7/2^-$. 

Recently Bilaniuk and Hensel (1958) reported that the angular distribution of protons resulting from the neutron capture to the 6.76 Mev state in the reaction $^{10}$B(d, p) $^{11}$B (resolved for the first time from those corresponding to the 6.81 Mev state) corresponds to a p-wave ($l_n = 1$) neutron capture pattern. Thus suggesting negative parity for this state which is in agreement with our conclusions and also in agreement with Cox et al. (1957) (see Introduction). This, however, limits its spin to a value between $3/2$ and $9/2$. From their $p-\gamma$ correlation study Cox et al. (1957) ruled out $3/2$ and suggested that $9/2$ is very unlikely. Thus favouring $5/2$ or $7/2$. Now if this state was $5/2^-$, then the angular distribution of the 2.52 Mev $\gamma$-rays, from the 9.28 Mev state to the 6.76 Mev state, should be the same as that of the 4.82 Mev $\gamma$-rays, from the 9.28 Mev state to the 4.46 Mev state. This is not in agreement with the present experimental results, which rules out $5/2^-$ and therefore strongly favours $7/2^-$ for the 6.76 Mev state. The only objection to this assignment is the weak magnetic dipole transition to the 4.46 Mev state as compared to the relatively strong electric quadrupole transition to the ground state. This difficulty is resolved if one accepts the theoretical prediction of Kurath based on the intermediate coupling model. These calculations show that in this case the M1 matrix element for the $7/2^-$ to $5/2^-$ transition vanishes (Kurath, 1957, and Ferguson et al., 1958).
(c) **4.46 Mev Level.**

The angular distribution of 4.82 Mev γ-rays, produced by the decay of the 9.28 Mev level to the 4.46 Mev level, is consistent with the favoured assignment of 5/2⁻ (see chapter I) for the 4.46 Mev state. The angular distribution of 4.46 Mev γ-rays show a significant mixing of E2 with M1. Present results give an E2/M1 amplitude ratio of 0.15. This is in excellent agreement with the work reported by Ferguson et al. (1958), 0.14, and with the prediction of Kurath (1957), 0.21, thus supporting the assignment of 5/2⁻ for this state and the predictions of Kurath concerning the character of the state.

(d) **2.14 Mev Level.**

No transition to the 2.14 Mev state was observed. Therefore nothing in particular can be said about this state. In general, the absence of any transition to this level from the 9.28 Mev 5/2⁺ state will rule out spin assignments greater than 1/2, because otherwise "the missing El transition would have |M|² 2 x 10⁻⁴, which is much less than one usually cares to envisage in the light nuclei if there is no inhibition by the isotopic spin selection rule", (Wilkinson, 1957). This supports the now accepted assignment of 1/2⁻ for this state.

From the present work and that of Bilaniuk and Hensel (1958) it would appear that the 9.28 Mev state has both a single α-particle and a single neutron character. Since the γ-ray transitions to the 6.76 Mev and 4.46 Mev states show possible
single particle transition probabilities in comparison with the Wilkinson adjusted values, it is interesting to speculate as to whether it is the odd proton or a neutron which makes the single particle transition. The results of Bilaniuk would suggest that it is the neutron which makes the transition. Thus it may be possible to explain the smaller radiative transition possibility from the 9.28 Mev state to the ground state in terms of the fact that both the proton and the neutron must change their state in making this transition. Whereas transitions to the 6.76 Mev and to the 4.46 Mev states may require a change in the orbital motion of the neutron only.

In the case of $\alpha$-capture it would appear, then, that the formation of the 9.28 Mev state must result in one of the $l_p$-neutrons of Li$^7$ being promoted to the positive parity 2$s$-1$d$ shell in $B^{11}$, whereas there is no further change in the state of the $\alpha$-particle during the subsequent radiative decay. These qualitative speculations may, however, be too crude to describe the motion of seven particles in the $l_p$ shell.

(ii) 820 Kev. Resonance.

(a) 9.19 Mev Level.

Comparison of the experimental angular distribution of the 4.73 Mev $\gamma$-rays, produced by the decay of the 9.19 Mev level to the 4.46 Mev level ($5/2^-$), with the theoretical possibilities limits

$1\alpha$ to 3 and $J$ to 7/2.

This is further confirmed by a similar comparison
for the 2.43 Mev γ-ray, produced by the decay of the 9.19 Mev level to the 6.76 Mev level, on the assumption that the 6.76 Mev level is 7/2⁻ as concluded above. The partial radiation width of 0.85 ev. for the transition to the 4.46 Mev state compares very well with the Wilkinson value of 1.3 ev. for electric dipole radiation. The partial radiation width of 0.08 ev. for the transition to the 6.76 Mev state also compares favourably with the corresponding Wilkinson value of 0.19 ev. for an El radiation. These facts and the above result that the 9.19 Mev state is formed by f-wave (lα = 3) ingoing α-particles show that this state has positive parity and spin 7/2. The reduced α-particle width, for f-waves, is less than or equal to 1.1 Mev which is a large fraction of the Wigner limit. This suggests that the 9.19 Mev state also has a single α-particle character.

These conclusions are in agreement with the results from the stripping work of Bilaniuk and Hensel (1958) which favours a 7/2⁺ assignment for this level, as discussed in section (i) of this chapter. The large neutron capture probability observed for this level also points to its single neutron character.

(b) 6.76 Mev Level.

As stated above the angular distribution coefficient (A₂ = +0.6 ± 0.1) for the 2.43 Mev γ-rays, produced by the
decay of the 9.19 Mev level to the 6.76 Mev level, is explained by the theoretical value of the sequence $3/2 \ (3) \ 7/2 \ (1) \ 7/2$, which is $A_2 = +0.57$. The only other sequence, consistent with the assignment $7/2$ for the 9.19 Mev level, which gives a value of $A_2$, $(A_2 = +0.77)$, close to the experimental value, although outside its error, is $3/2 \ (2) \ 7/2 \ (1) \ 7/2$. However, on comparing the experimental angular distribution of the 6.76 Mev $\gamma$-ray, produced by the decay of the 6.76 Mev state to the ground state, with the theoretical values, the sequence corresponding to $l_\alpha = 2$ is ruled out while the sequence $3/2 \ (3) \ 7/2 \ (1) \ 7/2 \ (2) \ 3/2$ agrees with the experimental results. This further confirms the above findings that the 9.19 Mev state is formed by $f$-wave $(l_\alpha = 3)$ $\alpha$-particles and also that the 6.76 Mev state is $7/2^-$. 

(c) **4.46 Mev Level.**

Here also the experimental distribution of the 4.46 Mev $\gamma$-rays showsthat the electric quadrupole radiation (E2) is mixed with magnetic dipole (M1) in the same amplitude ratio (0.15) as in the decay of the 9.28 Mev level. This checks the consistency of the assignment to this level and also the consistency of the method used in the analysis.

(d) **2.14 Mev Level.**

No transition to this level was observed.
(e) **Ground State Transition.**

No significant amount of the ground state transition was observed. This is not surprising in the light of the assignment $7/2^+$ for the 9.19 level, because it would require a magnetic quadrupole radiation which would compete very unfavourably with the strong electric dipole transitions to other levels.

(iii) **400 Kev. Resonance.**

(a) **8.92 Mev Level.**

This resonance has a very low yield (a factor of 100 less than the 960 kev. resonance) and the 8.92 Mev level predominantly decays to the ground state. Hence only the angular distribution of the 8.92 Mev $\gamma$-rays could be determined with any accuracy. A comparison of the experimental angular distribution coefficients, $A_2 = -0.25 \pm 0.1$, with the theoretical values limits $J$ to $5/2$ but cannot distinguish between $l_\alpha = 1, 2$ or 3. Unfortunately there is no other experimental angular distribution available to eliminate further values of $l_\alpha$. Thus this state is either $5/2^+$ or $5/2^-$. The reduced $\alpha$-particle width of this level cannot be determined due to the lack of any knowledge about its total width, except that it is certainly less than 1 kev. If the width of the 8.92 Mev level is about 10 ev. or more, then a comparison of the reduced $\alpha$-particle width with theoretical widths favours the formation of this
level by p-wave α-particles over d-wave α-particles, because the latter corresponds to an α-particle reduced width of 3.5 Mev or more. This is much bigger than the Wigner limit.

However, if the total resonance width of the 8.92 Mev level is about 1 ev. or less, then the above argument is weakened and d-wave formation is as acceptable as p-wave formation.

The recent study of the B\textsuperscript{10} (d, p) B\textsuperscript{11} reaction by Bilaniuk and Hensel (1958) shows that this state is formed by d-wave (l\textsubscript{n} = 2) neutrons with a small admixture of s-wave (l\textsubscript{n} = 0) neutrons. This would imply that the state has even parity and a spin of 5/2 or 7/2. Since in the present work this state is found to decay mostly to ground state (85\%), an assignment of 7/2\textsuperscript{+} to this level would imply a favoured magnetic quadrupole transition over possible electric dipoles to either the 4.46 Mev state or the 6.76 Mev state, which seems unlikely. Thus combining the results of the present investigation and those of Bilaniuk and Hensel one would favour the assignment 5/2\textsuperscript{+} for the 8.92 Mev level. However, this assignment would imply that the ground state radiation is electric dipole. The relatively small value of the radiation width, as compared to the corresponding Wilkinson value, does not give a confirmation of the assignment with any high degree of certainty.

Since the ratio (8.92/4.46)\textsuperscript{3} (85/5), the ratio of the intensities of the γ-rays from the 8.92 Mev level to the
ground state and to the 4.46 Mev state, it would appear that the two transitions are about equally favoured dipole transitions.

2. Conclusions.

From the present investigation it is concluded that the 9.28 Mev state is $5/2^-$, the 9.19 Mev state is $7/2^+$, the 6.76 Mev state is $7/2^-$ and the 8.92 Mev state is either $5/2^+$ or $5/2^-$. However, the assignment of $5/2^+$ for the 8.92 Mev state is favoured. This investigation also confirms the assignment $5/2^-$ for the 4.46 Mev state and indirectly supports the assignment $1/2^-$ for the 2.14 Mev state.

The general similarity in the decay patterns of the 9.28 Mev and the 9.19 Mev states may indicate that these two states form a spin doublet. Also since the 8.92 Mev state decays predominantly to the ground state, unlike the 9.28 Mev and 9.19 Mev states which decay predominantly to the 4.46 Mev state, probably the 8.92 Mev state is formed by a single particle (likely neutron) transition from the ground state configuration. Similarly the 9.28 Mev and 9.19 Mev states may be formed by single particle (likely neutron) transitions from the 4.46 Mev state which has a different p-shell configuration than the ground state.
PART B

1. The Energies of $\text{Zn}^{65}$ and $\text{Na}^{22}$ $\gamma$-Rays.

The three crystal pair spectrometer built by H.W. Dosso (1957) was used to determine the energies of the $\gamma$-rays emitted by $\text{Zn}^{65}$ and $\text{Na}^{22}$. The results of this work have been published in the Canadian Journal of Physics, Vol. 37, 1055, 1959, and a reprint is attached to the following page.
THE ENERGIES AND RELATIVE PAIR PRODUCTION CROSS SECTIONS
FOR Zn$^{65}$ AND Na$^{22}$ GAMMA RAYS

P. P. SINGH, H. W. DOSSO, AND G. M. GRIFFITHS

For gamma rays just above 1.02 Mev a three-crystal pair spectrometer of
even moderate resolution can be used to determine the gamma-ray energies
very accurately. Since exactly the rest mass of the pair electrons is subtracted
from each incident photon by pair production, a measurement of the small
remaining kinetic energy of the pair electrons establishes the energy of the
gamma rays with considerably greater accuracy than that of the kinetic
energy measurement. This method has been used to determine the energies of
the gamma rays from Zn$^{65}$ and Na$^{22}$ sources. The spectrometer consists of three
sodium iodide (ThI) crystals as shown in Fig. 1. The annihilation of the

![Block diagram of the three-crystal spectrometer.](image)

positron after the pair event in the center crystal (1.75 cm × 4 cm × 4 cm)
gives two .51-Mev quanta which leave the center crystal in opposite directions.
The colinear .51-Mev annihilation quanta are detected in coincidence in the


1055
side crystals (2 in. long and 1.4 in. diameter). The pulses produced in the side channels enter single-channel differential discriminators which select only those pulses which correspond to .51-Mev absorption in the side crystals. The output from the side-channel analyzers and the pulses from the center channel pass into a triple coincidence circuit. The triple coincidence output pulses open a gate which allows coincident center channel pulses to enter the 30-channel kicksorter. The differential discrimination in the side channels greatly reduces the background due to coincidences from multiple scattering, double Compton events, and cascade gamma rays and so increases the resolution of the apparatus.

The three NaI (ThI) crystals were mounted on RCA 6342 photomultipliers and had a resolution of about 8.3% for 1.3-Mev gamma rays. A 0.2-in. diameter collimated beam of radiation, obtained with a 31-cm long lead collimator, was incident along the center crystal axis. The collimation improved the resolution significantly. Photomultiplier gain changes were kept to a minimum by using stabilized power supplies and relatively low counting rates. No significant gain shifts were recorded over a period of 1 day. The kicksorter spectrum was recorded after every 2 to 3 hours and thus a regular check was kept on the gain shifts. Linearity of the center crystal was established to better than 0.1% for the energy range from 40 kev to 500 kev by the use of a standard pulse generator and gamma-ray sources of known energies from Cs, Eu, and Na.

Typical spectra produced by Co alone, and by Co with Na, and by Co with Zn are shown in Fig. 2. Since the Co lines have been established to better than 1 kev (1.3325±.0003 and 1.1728±.0005 Mev), using a double-focusing spectrometer (Lindstrom 1953) to compare the Co lines with the accurately known RaC 1.4158±.0002 Mev transition, the energies of the Na and Zn γ-rays can be obtained from the present experiment to better than 2 kev.

The individual peaks for each of the gamma rays were isolated graphically by subtracting the typical Co spectrum and the background from the composite spectra as shown in Fig. 2. Assuming a Gaussian shape for the peaks, the mean energy and the variance of each peak was computed with the help of the University of British Columbia Alwac IIIE Computer. The statistical uncertainty in the mean energy for each peak was also calculated from the variance and total number of counts in the peak; in all cases this uncertainty was not greater than 1 kev. A more realistic estimate of the uncertainty in the mean gamma-ray energies was obtained by calculating the standard deviation in the measured means from seven runs for the Na and Zn sources. Since the Na and Zn gamma-ray energies were determined by simultaneous measurement with respect to the Co gamma rays, gain shifts and other systematic errors were effectively cancelled out. The final results of the present experiment are

\[ \text{Zn}^{66} \text{gamma-ray energy} = 1.1124±.0019 \text{ Mev}, \]
\[ \text{Na}^{22} \text{gamma-ray energy} = 1.2736±.0018 \text{ Mev}. \]
NOTES

FIG. 2. Typical spectra obtained with three-crystal pair spectrometer. Curve (c) is for Co\textsuperscript{60}, curve (b) for Co\textsuperscript{60} and Zn\textsuperscript{65}, and curve (a) for Co\textsuperscript{60} and Na\textsuperscript{22} gamma rays.

The present results for Zn\textsuperscript{65} gamma rays agree, to within the errors, with those reported by Johanson (1956), 1.112±.003 Mev, and Waggoner (1950), 1.112±.007 Mev; and they are significantly different from those of Hedgran (1950), 1.125 Mev, and Good (1951), 1.127±.009. The Na\textsuperscript{22} gamma-ray energy agrees with that of P. Marmier as reported by Ajzenberg (1955), 1.275±.005. In both cases our estimated errors are less than those reported earlier.

**Relative Pair Production Cross Sections**

We have also measured the relative pair production cross sections for \(\gamma\)-rays of Zn\textsuperscript{65}, Na\textsuperscript{22}, Co\textsuperscript{60}, and RdTh, using the pair spectrometer. For a source of cascade gamma rays such as Co\textsuperscript{60} the relative pair production cross section is simply obtained from the ratio of the number of counts in the two pair peaks since the number of gamma rays of each energy is the same. This method has been used by Griffiths and Warren (1952) for Co\textsuperscript{60} and Na\textsuperscript{24} gamma rays. West (1956), with much-improved apparatus and a detailed study of the overall efficiency of the three-crystal spectrometer, was able to obtain absolute pair cross sections for the same gamma-ray cascades in both sodium iodide and anthracene. In the present work we have extended the energy range of the measurements of the relative pair production cross sections in sodium iodide by using Zn\textsuperscript{65}, Na\textsuperscript{22}, Co\textsuperscript{60}, and RdTh sources of known strength in exactly the same geometry. Since some of these sources emit only single gamma rays above
1.02 MeV it was necessary to know the relative strengths of the sources in order to obtain relative pair production cross sections. The strength of the sources was independently measured to better than 5% with a sodium iodide scintillation counter employing a crystal 2\(\frac{1}{4}\) in. in diameter by 3\(\frac{1}{4}\) in. long whose efficiency as a function of gamma-ray energy had been studied in some detail in this energy range. (Details of this work will be published.) The ratio of pair production cross sections obtained for the gamma-ray energies given in brackets are:

\[
\frac{\sigma(2.62)}{\sigma(1.33)} = 16.8 \quad \frac{\sigma(1.33)}{\sigma(1.17)} = 5.1 \quad \frac{\sigma(1.17)}{\sigma(1.11)} = 4.22
\]

If we take the absolute cross section for the 1.33-Mev gamma rays of Co\(^{60}\) from the work of West (1956) as \((6.81 \pm 0.17) \times 10^{-26}\) cm\(^2\) then these ratios lead to the following absolute pair production cross sections in sodium iodide:

\[
\begin{align*}
(1.11) &= (0.32 \pm 0.03) \times 10^{-26}\text{ cm}^2 \\
(1.17) &= (1.34 \pm 0.12) \times 10^{-26}\text{ cm}^2 \\
(2.62) &= (116 \pm 10) \times 10^{-26}\text{ cm}^2
\end{align*}
\]

The errors of about 10% include that quoted by West for the 1.33-Mev gamma ray (about 2.5%) plus statistical and estimated systematic errors introduced by our ratios. The ratios obtained here for pair production by Co\(^{60}\), Na\(^{22}\), and RdTh gamma rays are in good agreement with the results collected by West (1956) and the Zn\(^{65}\) result combined with the absolute values given by West for Co\(^{60}\) gamma rays provides a measurement of the pair production cross section in sodium iodide at an energy about 90 kev above the pair production threshold.

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2. The Performance of a Simple $\gamma$-Ray Insensitive Fast Neutron Counter.

The performance of a zinc sulphide-lucite counter assembled by Y.I. Ssu (1955), was investigated by using neutrons and gamma rays of various energies. The details are given in the attached reprint published in the Canadian Journal of Physics, Vol. 37, 858, 1959.
A SIMPLE GAMMA-RAY INSENSITIVE FAST-NEUTRON COUNTER

G. M. Griffiths, P. P. Singh, Y. I. Ssu, and J. B. Warren
A SIMPLE GAMMA-RAY INSENSITIVE FAST-NEUTRON COUNTER1

G. M. GRIFFITHS, P. P. SINGH, Y. I. SSU, AND J. B. WARREN

ABSTRACT

A gamma-ray insensitive fast-neutron counter is described which consists of a number of thin rectangular sheets of lucite coated with zinc sulphide and sandwiched together to form a rectangular block which is mounted on a photomultiplier. Pulse height spectra and absolute efficiency curves are presented for neutrons from 300 kev to 15 Mev.

INTRODUCTION

Chadwick in 1932 first identified fast neutrons by observation of the knock-on protons ejected from hydrogenous materials. Since that time many neutron counters have used the same neutron-proton interaction in either hydrogen-filled proportional counters (Coon and Nobles 1947), ionization chambers (Stafford 1948), or solid hydrogenous materials. Bell (1948) and Segel et al. (1954) employed organic phosphors successfully; however, these suffer from the fact that they are gamma-ray sensitive if the volume used is sufficiently large to give good neutron-detection efficiency. A thin layer of zinc sulphide powder placed on the face of a photomultiplier has been used to detect proton recoils from a layer of plastic resulting in a neutron counter with a very low gamma-ray sensitivity; however, the neutron efficiency is also small. Hornyak (1952) made a great improvement in detection efficiency while maintaining low gamma-ray sensitivity by using a molded button of lucite with zinc sulphide powder dispersed in it. As zinc sulphide is opaque to its own radiation the useful size of this device is limited. Since then several attempts have been made to improve the neutron-detection efficiency without increasing the gamma-ray sensitivity (Emmerich 1954; Brown and Hooper 1958). Recently a method, based on the fact that the ratio of the intensity of the slow light decay component to that of the fast component is different for protons and electrons in organic scintillators, has been used to discriminate between gamma rays and neutrons (Litherland et al. 1959; Owen 1958).

Below we describe the properties of a counter used in our laboratory for several years, which has an efficiency comparable to others we have seen reported, along with an excellent gamma-ray rejection ratio and simplicity of construction.

COUNTER CONSTRUCTION

The counter consists of a number of thin rectangular lucite sheets coated with zinc sulphide over their large faces and then sandwiched together to form a rectangular block which is mounted on an RCA 6342 photomultiplier. Pro-

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Contribution from the Department of Physics, University of British Columbia, Vancouver, B.C.

tons knocked out of the lucite produce light in the thin zinc sulphide layers and the lucite plates conduct the light to the photomultiplier. To make the block, the lucite sheets were dipped in ethyl formate and while still wet a weighed quantity of zinc sulphide powder was sprinkled on evenly through a fine mesh nylon cloth. Then the plates were stuck together under pressure until dry. The block was then polished on a face perpendicular to the plane of the sheets and this face was mounted on the photomultiplier with Dow-Corning silicone oil. The other faces of the block were smoked with burning magnesium ribbon. The construction of a typical phosphor block is shown in Fig. 1.

![Fig. 1. The lucite–zinc sulphide sandwich block.](image)

Both Patterson D and RCA 33-Z-20A zinc sulphide phosphors were tested. With a radium-beryllium neutron source the RCA phosphor gave about 30% more counts above a selected bias than the Patterson D phosphor and so was used for all further work. Tests to determine the optimum thickness of the zinc sulphide powder indicated that for thicknesses greater than 12 mg/cm$^2$ the gamma-ray sensitivity becomes appreciable and thicknesses less than 10 mg/cm$^2$ gave a satisfactory neutron response. Several lucite sheet thicknesses were tried and it was found that for radium-beryllium neutrons the efficiency decreased for thicknesses greater than 0.125 inch. The plate thickness determines a limit to the height of the block that can be usefully employed, since for a given height the light from the top of the block will not reach the photomultiplier as efficiently with thin plates as it would with thicker ones due to absorption in the zinc sulphide. Thus with increasing height a decreasing proportion of the light will get into the photomultiplier and after a certain height, which depends on the plate thickness, any additional height contributes very little light. However, greater plate thickness, although it means that the detector may be made longer, does not necessarily mean greater efficiency since for thicker plates more of the protons lose all their energy in the lucite. Protons stopped in lucite alone produce very small
pulses which are lost in the noise. A check on the transmission of light down the block was made by preparing a plastic sandwich with 0.125 inch thick plates 5 inches long mounted on a photomultiplier. A radium–beryllium source was placed 25 cm away to one side and the counting rate was observed, as a function of the length, which was altered by cutting sections from the end of the sandwich block. Little change in counting rate was observed until the length was reduced to 3 inches and the counting rate became roughly proportional to length for lengths less than 1.5 inches.

A rectangular block consisting of 1/8 inch square lucite rods packed together with zinc sulphide powder on all internal faces was made and tested. Its efficiency per unit volume for neutron detection was little if any better than that of the flat sheet assemblies and as it was more difficult to construct no further ones of this type have been made.

Tests were performed to find out whether the neutron-detection efficiency of the counter (using radium–beryllium neutrons) depended on the direction of neutron entrance (i.e., parallel or perpendicular to the lucite sheets). One might expect such an effect since the protons are scattered forward in the laboratory system, but within the errors of about 10% no effect was found either in the shape of the spectrum or in the number of counts obtained above a given bias.

Two blocks with the following characteristics were tested in some detail:

<table>
<thead>
<tr>
<th></th>
<th>Block I</th>
<th>Block II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucite thickness</td>
<td>1/32 inch</td>
<td>1/16 inch</td>
</tr>
<tr>
<td>Length</td>
<td>1 cm</td>
<td>2 cm</td>
</tr>
<tr>
<td>Cross section</td>
<td>4.2X4.2 cm</td>
<td>4.4X4.4 cm</td>
</tr>
<tr>
<td>No. of plates</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>ZnS thickness</td>
<td>7 mg/cm²</td>
<td>7 mg/cm²</td>
</tr>
</tbody>
</table>

The efficiency per unit volume for block I was 1.75 times that for block II. However, since its volume was less than half of that of block II it gave fewer counts for a given neutron flux. The results described below were obtained with block II.

COUNTER PERFORMANCE

(a) Pulse Height Spectra

The pulse height spectra and absolute efficiencies for the neutron counter were measured for neutrons of energies from 225 keV to 4.4 MeV using neutrons from the $T(p, n)He^3$ and $D(d, n)He^3$ reactions and for 17-Mev neutrons from the $T(d, n)He^4$ reaction. The differential pulse height spectra are shown in Figs. 2 and 3 along with spectra for photomultiplier noise and $\gamma$-rays of 1 MeV from Co$^{60}$ and 6.14 MeV from the $F^{16}(p, \alpha, \gamma)O^{16}$ reaction. The pulse height scale is the same for all curves but the vertical scale is arbitrary and the curves are not normalized to each other.

(b) Absolute Efficiency

The absolute efficiencies were determined from knowledge of the neutron fluxes from the targets used. The tritium content of the tritium–zirconium
FIG. 2. Pulse height spectra for low-energy neutrons and for gamma rays. The curves are not normalized with respect to each other.

FIG. 3. Pulse height spectra for high-energy neutrons. The curves are not normalized with respect to each other.
target, kindly supplied by the Oak Ridge National Laboratory, was measured in terms of the absolute gamma-ray yield from the $T(p, \gamma)He^4$ reaction at 800 kev, using absolute differential cross-section data of Perry and Bame (1955) for this reaction and theoretical estimates of the scintillation counter efficiency. Low-energy neutrons from 280 kev to 940 kev were produced by the $T(p, \alpha)He^3$ reaction and high-energy neutrons were produced by the $T(d, n)He^4$ reaction using the same target. Intermediate energy neutrons from 1.9 Mev to 4.2 Mev were produced by $D(d, n)He^3$ reactions using a heavy ice target of known thickness. The $D_2O$ targets were made by condensing heavy water vapor from a constant volume dispenser onto a liquid air cooled gold plate. The dispenser–target system was calibrated by observing the shift in the 340-kev resonance of the $F^{16}(p, \alpha', \gamma)O^{16}$ reaction after a given pressure of vapor was deposited on a thin $F^{19}$ target. From the measured energy loss of protons in passing through the ice layer and from the stopping power data given by Whaling (1958) the number of target deuterons per square centimeter was calculated. Neutron yields were obtained from cross-section data given by the review article of Fowler and Brolley (1956).

The neutron-detection efficiency for the counter is dependent on the neutron energy as shown in Fig. 4. Curve (a) shows the angular distribution of $D(d, n)He^3$ neutrons for 1.0-Mev incident deuterons as obtained by Hunter

![Fig. 4](image-url)

**Fig. 4.** The angular distribution of $D(d, n)He^3$ neutrons at 1.0 Mev. Curve (a): The distribution of Hunter and Richards (1949) obtained with a long counter. Curve (b): The distribution as seen by the lucite–zinc sulphide sandwich counter. Curve (c): The ratio of the curves (b) and (a), which are normalized to each other at zero degrees.
FIG. 5. Absolute efficiency vs. discrimination level for the low-energy neutrons. The ordinate for the gamma-ray curves should be multiplied by $10^{-2}$.

FIG. 6. Absolute efficiency vs. discrimination level for the high-energy neutrons.
and Richards (1949) using a long counter and making small corrections for the change in efficiency with neutron energy as given by Hanson and McKibben (1947). Curve (b) shows the curve obtained with the present counter normalized to curve (a) at zero degrees. The ratio between the curves is shown by the upper line and indicates the decrease in efficiency for decreasing neutron energies. The absolute intrinsic efficiencies defined as the number of counts observed divided by the number of neutrons incident on the front face of the counter for various neutron energies as a function of discriminator bias level (integral bias curves) are shown in Figs. 5 and 6. The efficiency falls off rapidly for neutrons with energies less than 300 kev and is very small for thermal neutrons. It should be noted that the efficiency figures given here are smaller by a factor $A$, equal to the area of the front face of the counter, than those quoted by some authors who give the number of counts per unit neutron flux at the position of the counter. Figure 5 also shows on an expanded vertical scale the absolute efficiencies for $^{60}$Co and 6-Mev gamma rays. Note that for the gamma-ray curves the ordinates should be multiplied by $10^{-2}$. The curves indicate that a bias may be chosen without serious loss of neutron counts to give gamma-ray efficiencies of $10^{-8}$ to $10^{-10}$ of the neutron efficiency at that bias.

As a crude first approximation one would expect the neutron-detection efficiency to be proportional to the neutron-proton scattering cross section, $\sigma$, and the mean range, $R$, of the scattered protons in the lucite, since for

![Fig. 7. Absolute efficiency vs. neutron energy for various biases. The thick curve shows a rough theoretical estimate of efficiency with energy on an arbitrary vertical scale.](image)
all energies studied here the proton ranges are smaller than the thickness of the lucite plates. The validity of this assumption is indicated in Fig. 7, which shows experimental absolute efficiencies as a function of neutron energy for several discriminator levels and also shows a curve of the product $\sigma \cdot R$ as a function of neutron energy with arbitrary vertical normalization. The agreement in shape of the curves is quite good; the theoretical curve is rather flatter than the experimental ones suggesting that for lower-energy neutrons a larger proportion of the pulses are lost in the noise.

This counter has been used to detect the small yield of secondary neutrons produced by proton bombardment of heavy ice targets below the $D(p, n)$ threshold in the presence of a much larger yield of 6-Mev $\gamma$-rays, and as a general monitor for fast neutrons.

ACKNOWLEDGMENT

One of us (P.P.S.) gratefully acknowledges the receipt of a National Research Council Studentship.

REFERENCES

Bell, P. R. 1948. Phys. Rev. 73, 1405.
Owen, R. B. 1958. Nucleonics, 16 (6), 54.
3. The Neutron Yield From Heavy Ice Targets Bombarded With Protons Below the D \( (p, n) \ 2p \) Threshold.

Using the fast neutron counter described earlier the yield and angular distributions of neutrons produced, when both thin and thick heavy ice targets were bombarded with protons, were studied. The proton energies used were below the D \( (p, n) \ 2p \) threshold. The results were compared with the theoretical computations carried out by Y.I. Ssu (1955). This work has also been published in the Canadian Journal of Physics, Vol. 37, 866, 1959, and a reprint is attached to the next page.
THE NEUTRON YIELD FROM HEAVY ICE TARGETS
BOMBARDED WITH PROTONS BELOW THE
\textit{D(p, n)2p} THRESHOLD

P. P. Singh, G. M. Griffiths, Y. I. Ssu, and J. B. Warren
THE NEUTRON YIELD FROM HEAVY ICE TARGETS
BOMBARDED WITH PROTONS BELOW THE
D(p, n)2p THRESHOLD

P. P. SINGH, G. M. GRIFFITHS, Y. I. SSU, AND J. B. WARREN

ABSTRACT

In connection with some experiments on the gamma-ray yield from the
D(p, γ)He³ reaction using heavy ice targets a considerable yield of neutrons was
found even for proton bombarding energies well below the D(p, n)2p threshold
of 3.3 Mev. The yield, excitation function, and angular distribution of this
neutron yield have been investigated both experimentally and by means of
theoretical calculations. These studies confirm the suggestion that the neutrons
are produced by a secondary reaction in which deuterons, scattered in the
target by incident protons, collide with further target deuterons to produce
D(d, n)He³ reactions.

INTRODUCTION

The production of neutrons when heavy ice targets are bombarded with
protons below the D(p, n)2p threshold has been reported by Jennings et al.
(1950), who suggested that the neutrons arise from deuterons, scattered by
incident protons, colliding with other target deuterium atoms and producing
D(d, n)He³ reactions. In connection with some measurements on the gamma-
ray yield from the D(p, γ)He³ reaction this effect was found to contribute a
considerable background (Griffiths and Warren 1955). Consequently we have
made a detailed experimental and theoretical study of the effect.

EXPERIMENTAL

The gamma-ray insensitive neutron counter used in these experiments has
been described previously (Griffiths et al. 1959). It consists of a block of lucite
sheets with thin layers of zinc sulphide powder sandwiched between them,
mounted on an RCA 6342 photomultiplier. A bias setting which made the
6-Mev gamma-ray sensitivity less than 10⁻⁹ of the neutron sensitivity was
used. The absolute efficiency for neutron detection varied with neutron
energy from 0.15% for 2-Mev neutrons to 0.3% for 4-Mev neutrons at this
bias. The pulse height spectrum was analyzed with a 100-channel Computing
Devices of Canada kicksorter.

The target chamber used is shown in Fig. 1. A gold-plated liquid air cooled
copper plate formed the target backing. This could be turned to face an inlet
hole through which heavy water vapor from the dispenser was admitted to
the target chamber. For thin targets, the constant volume dispenser was
evacuated, taps T₁ and T₂ were closed, and tap T₃ was opened to admit
the required pressure of water vapor as measured by the oil manometer. Then
tap T₃ was closed and T₁ was opened to admit the vapor slowly via the

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Contribution from the Physics Department, University of British Columbia, Vancouver,
B.C.

glass-wool diffuser to the target chamber. The target thickness as a function of dispenser pressure was calibrated by freezing the vapor on top of thin fluorine targets for various initial pressures in the dispenser and measuring the shift in the $^19\text{F}(p, \alpha, \gamma)^{16}\text{O}$ 340-kev resonance due to the energy loss of the protons in passing through the ice layers. From a knowledge of the stopping power of the protons in ice (Whaling 1958) the number of deuterium atoms per square centimeter on the target could then be calculated as a function of the manometer pressure (Fig. 1). When a thick target was required so that the incident protons would be stopped completely in the ice layer, taps $T_1$ and $T_3$ were opened for 2 minutes and then a measurement of the yield was made. The taps were opened for a further 2 minutes and a second yield measurement was made. When no increase in yield occurred for additional ice on the target, the target was judged to be "thick".

**RESULTS**

1. **Thick Target Yield and Excitation Function**

A thick heavy ice target was bombarded with protons of energies from 350 kev to 1.5 Mev and the neutron yield at zero degrees to the proton beam per millicoulomb of beam per steradian was obtained. Since the detection efficiency is a function of the neutron energy and since at any angle the neutron energies incident on the counter varied from approximately 2 Mev to 4 Mev, the mean neutron energy at 0° was estimated for each bombarding energy by assuming that on the average the deuterons were scattered at 45° to the proton beam direction and then by calculating the neutron energy in
the direction of the counter from the mechanics of the D(d, n)He³ reaction. The experimental excitation function, shown in Fig. 2, has been corrected for the change in efficiency due to the change in mean neutron energy. The theoretical neutron yield as a function of proton energy calculated on the basis of the secondary process is also shown in Fig. 2.

![Theoretical and experimental excitation functions.](image1)

**Fig. 2.** The theoretical and experimental thick target excitation functions.

2. Thick Target Angular Distribution

With the counter subtending a solid angle of 0.15 steradian at the target the thick target neutron yield was measured for a proton energy of 1.5 Mev.

![Thick target angular distribution.](image2)

**Fig. 3.** The thick target angular distribution for 1.5-Mev incident protons. Curve (a), experimental results—uncorrected; curve (b), theoretical result; curve (c), experimental results—corrected for change in neutron-detection efficiency with mean neutron energy.
at seven different angles. The neutron yield observed at each is shown by the lower curve in Fig. 3. Since, for each counter position, neutrons from deuterons, scattered with various energies and travelling in various directions in the target, may reach the counter a rough estimate of the mean neutron energy and thence the mean detection efficiency for each counter position was made. The correction for efficiency change results in the upper curve of Fig. 3. The theoretical curve is also shown in the figure. The increase in neutron yield towards backward angles after a minimum at 90° results from the corresponding increase in the D(d, n)He³ neutron yield at backward angles. In this case the effect is less pronounced than for a D(d, n)He³ experiment since it is averaged over the scattered deuteron directions and energies in the target.

3. Pulse Height Spectrum

The pulse height spectrum from the fast-neutron counter produced by bombarding a thick heavy ice target with 1.5-Mev protons is shown in Fig. 4.

![Pulse Height Spectrum](image)

**Fig. 4.** The differential pulse height spectra from the neutron detector for 4-Mev and 2-Mev monoenergetic neutrons and for the neutrons from a heavy ice target bombarded with protons of 1.5-Mev energy.

For comparison the spectra produced by monoenergetic neutrons of 2-Mev and 4-Mev energy from the D(d, n)He³ reaction are also shown. It is apparent that the neutrons from the ice target are comparable in energy to those from the D(d, n)He³ reaction.

4. Thin Target Yield and Angular Distribution

A thin target containing 24X10¹⁸ deuterium atoms per square centimeter, approximately 70 kev thick for 1.5-Mev protons, was bombarded by 1.5-Mev protons and the neutron yield was measured as a function of angle. The
the change of efficiency with neutron energy was applied to the curve. The theoretical curve is also shown. The two curves show good agreement in shape and the factor of about two between the absolute values may be partly accounted for by the fact that in the theory for the thin target it was assumed, for the sake of simplicity, that all the deuterons scattered in the ice layer started out at the front face of the layer which gives an overestimate of the neutron yield.

5. Effect of D₂O Concentration

If the neutron production from heavy ice targets is due to primary processes one would expect the neutron yield to depend linearly on the deuterium concentration in the target, whereas if the yield is due to secondary processes, as suggested here, one would expect the neutron yield to depend on the square of the deuterium concentration. This was checked by measuring the zero-degree neutron yield for 1.5-Mev protons using thick targets with various concentrations of heavy water in ordinary water. The results are shown in Fig. 6. The 6-Mev gamma-ray yield from the D(\(p, \gamma\))He\(^3\) reaction is directly proportional to the deuterium concentration as expected since it arises from a direct interaction of the incident protons with the target nuclei. However, it is clear that the neutron yield increases as the square of the
concentration. This leaves no doubt about the secondary nature of the neutron production.

THEORETICAL ANALYSIS

Calculations have been made of the yield, excitation function, and angular distribution of neutrons from thick and thin targets of heavy ice bombarded with protons on the assumption that they are produced by scattered deuterons colliding with other deuterons in the target and producing D(d, n)He³ reactions.

In the case of a thick target the calculations involved the following steps. The target was divided into six layers perpendicular to the proton beam direction as shown in Fig. 7(a), so that each layer has approximately one sixth of the incident proton energy of 1.5 Mev dissipated in it and in each layer the protons were considered to have a constant energy equal to the mean proton energy in the layer. The data of Sherr et al. (1947) and Taschek (1942) on proton-deuteron scattering were used to calculate the energy and the angular distribution of the deuterons from each layer. The scattered deuterons from each layer were divided into overlapping cones, Fig. 7(b), symmetrical about the proton beam direction, with angular limits for each cone such that the difference in the deuteron energies at the outside and the inside of the cone was equal for all cones. It was assumed that all deuterons entering a cone have an energy equal to the mean energy of the deuterons entering the cone. Further, assuming Rutherford scattering and using the analytical expression for the energy and angular dependence of the proton-deuteron scattering cross section the number of deuterons scattered into each cone was obtained by analytical integration between the angular limits of the cone. To allow for the fact that the scattering does not follow the Rutherford formula for all energies and angles due to some nuclear interaction, the results from the Rutherford formula were multiplied by the ratio of the measured cross section to the Rutherford cross section. This ratio was interpolated for
the required energies from the results of Sherr et al. (1947) and Taschek (1942). Each cone was subdivided into 12 “tubes”, Fig. 7(b), each tube containing 1/12 of the deuterons in the cone. All deuterons in each tube were assumed to travel down the center of the tube. For each tube the angle between this direction and the line joining the target to the detector was obtained geometrically. These angles were computed for the counter at 0°, 45°, 90°, and 135° with respect to the incident beam direction. Finally each tube was divided into “sections” along its length such that the energy loss of the deuterons in traversing each section was approximately equal to the difference between the deuteron energies at the outside and the inside of the particular cone. In all there were 672 sections. The stopping power data for heavy ice of Wenzel and Whaling (1952) was used to compute the thickness and hence the number of target deuterons in each section of the target. The yield and angular distribution of D(d, n)He³ neutrons has been expressed by Hunter and Richards (1949) in terms of Legendre polynomials which were used to provide the relevant neutron yields from each section in the direction of the counter for four counter positions at 0°, 45°, 90°, and 135°. The total neutron yield from the thick target in the counter direction can be obtained by summing over all sections of each tube, over all tubes of each cone, over all cones of each layer, and over all layers.
Table I gives typical neutron yield data at 0° for each of the six layers with the energy of the protons in each layer.

**TABLE I**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Proton energy, kev</th>
<th>0° neutron yield per steradian per millicoulomb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1500 to 1322</td>
<td>3.25×10^6</td>
</tr>
<tr>
<td>B</td>
<td>1322 to 900</td>
<td>7.02×10^6</td>
</tr>
<tr>
<td>C</td>
<td>900 to 563</td>
<td>1.55×10^6</td>
</tr>
<tr>
<td>D</td>
<td>563 to 338</td>
<td>1.08×10^6</td>
</tr>
<tr>
<td>E</td>
<td>338 to 113</td>
<td>1.08×10^6</td>
</tr>
<tr>
<td>F</td>
<td>113 to 0</td>
<td>Neglected</td>
</tr>
</tbody>
</table>

From this table the thick target yield of neutrons as a function of energy can easily be obtained by adding the zero-degree contribution from the bottom of the table to the layer which has an incident proton energy equal to the particular energy at which the total yield is required. The theoretical results are plotted in Figs. 2, 3, and 5 along with the experimental results. In principle the calculations for the thin target yield and angular distribution function were the same as for the thick target calculations except that only one target layer was considered; however, since a large fraction of the higher-energy scattered deuterons escape from the thin target layer the yield from the low-energy scattered deuterons was considered in greater detail than for the thick target calculation.

The over-all agreement between theory and experiment leaves no doubt as to the secondary process responsible for the neutron production.

**ACKNOWLEDGMENT**

One of us (P.P.S.) wishes to thank the National Research Council of Canada for an award of a Studentship.

**REFERENCES**

FIG. 17 THERMAL LEAK
APPENDIX I

Thermal Leak.

A thermal valve of the type shown in Fig. 17 was installed in the helium gas bottle. The functioning of the valve depends on the differential thermal expansion of dissimilar metals. The brass body of the leak expands more than the mild steel rod when heat is applied, thus decreasing the pressure on the ball which in turn lets helium gas through the body and out through the copper tube to the manifold.

The ball seat and the copper tube were hard soldered in place in the main brass body of the leak and the body was then cleaned with warm dilute nitric acid. The ball and steel rod were placed in position and the brass screw was screwed in as far as it would go. The leak was then clamped in a vise so that the end with the screw was tilting downwards in order to avoid solder running into the main body of the leak via the screw threads. A little tenacity flux was applied to the screw and the end was then slowly tightened until it just touched the steel rod and the leak was allowed to cool. Two coils, made of 9 inches of nichrome wire (2.67 ohms per foot), of 8 turns each were then wound over a thin layer of asbestos placed around the brass body (see Fig. 17). One end of both coils was attached to the body of the leak. Power to both the coils was obtained from two 6.3 volt, 400 cycle heater trans-
formers. The primary of one transformer was connected to the mains through a 100 ohm resistor while the other coil was connected to the mains via a variac which could be manually operated from the control board by means of selsyn motors and a nylon cord running from the bottom of the machine to the top. About 15 watts were dissipated in the first coil while another 15 watts were available for the 2nd coil from the variac.

The main advantages of this leak lie in its simplicity of design, its small size and fast response. The helium leak was mounted inside the helium storage bottle to avoid any air leaks and to provide the leak with an environment having a reasonably long thermal time constant. This was necessary since these leaks were quite sensitive to ambient temperature fluctuations.

The general performance of this leak was quite satisfactory over a period of several months running on helium. There was very little if any helium leak through the valve when shut off. It is interesting to note that the valve required less power and was rather more sensitive to temperature fluctuations and supply voltage fluctuations than similar valves operated with hydrogen gas. This difference may be explained by the different heat conductivities of the gases. The response time of the valve was satisfactorily short; changes in oscillator loading
corresponding to changes in leak rate were noted a few seconds after adjustment of the heater power. It took about 1 minute to open the leak at full power when starting cold.
APPENDIX II

Angular Distribution Functions.

A. The angular distribution functions, expressed in the form

\[ W(\theta) = 1 + A_2 \cos^2 \theta + A_4 \cos^4 \theta \]  

were calculated using the method outlined by Wilkinson (1954) and tables of coefficients by Biedenharn and Rose (1953) and those of Sharp et al. (1953). A nucleus of spin \( J \), may absorb an \( \alpha \)-particle carrying in an angular momentum \( l_1 \), to form a state of spin \( J \) which then goes to the final state of spin \( J_2 \) by the emission of a \( 2^{12} \)-pole radiation. This two stage sequence can be expressed as

\[ J_1 (l_1) J (l_2) J_2 \]  

For a "pure" transition, involving a radiation of single multipolarity and parity, the angular distribution is of the form

\[ W(\theta) = \sum_{\mu} \xi_{\mu} K_{\mu} P_{\mu}(l_1 J_1 J) P_{\mu}(l_2 J_2 J) \]  

where, \( K_{\mu} = 2^{l_1} (l_1 + 1)/2^{l_2} (l_2 + 1) - \mu(\mu + 1) \) is the "particle factor", \( P_{\mu} \) is the Legendre polynomial of order \( \mu \) and the values of \( P_{\mu} \) are listed by Biedenharn and Rose (1953).

For a "Mixed" transition, containing 1 part of \( 2^{12} \)-pole radiation to \( \alpha^2 \) parts of \( 2^{12} \)-pole the sequence can be
expressed as

\[ J_1 \ (l_1) \ J \ (l_2) \ J_2 \]

Only cases where \( l_2 = l_2 + 1 \) were considered, for these the angular distribution function is

\[
W(\theta) = \sum_{\mu} P_\mu B_\mu (l_1 J_1 J) \left\{ P_\mu (l_2 J_2 J) + \alpha^2 P_\mu (l_2 J_2 J) + 2\alpha (-1)^{J - J_2 - 1} \left[ (2J + 1) (2l_2 + 1) (2l_2' + 1) \right]^{1/2} G_\mu (l_2 l_2' J_2 J) \right\} 
\]

Equation 4 simply contains the correlations obtained for pure \( 2^{l_2} \)-pole and pure \( 2^{l_2'} \)-pole radiations, weighted according to their relative intensities, and an interference term characterized by \( G \). The \( G \)'s are given in the Biedenharn and Rose (1953) compilation.

If the spin of the compound state, of spin \( J \), proceeds to the final state, of spin \( J_3 \), through an intermediate state, of spin \( J_2 \), with the emission of two gamma rays of multipolarity \( 2^{l_2} \) and \( 2^{l_3} \) then the sequence of this three stage process can be written as

\[ J_1 \ (l_1) \ J \ (l_2) \ J_2 \ (l_3) \ J_3 \]

The angular distribution function for the second \( \gamma \)-ray \( (l_3) \) can be written as
\[ W(\theta) = (-)^{L_1-J_1-J_2} \left( (2J + 1) (2J_2 + 1) \right)^{1/2} \sum_{\mu} \tilde{F}_{\mu} (l_2 J_3 J_2) W(J J_1 J_2; \mu_{l_2}) \]

The values for \( W \)'s are given in tables of Sharp et al.
An expression similar to (4) can be written for the "mixed" three stage transition.

For the present work the coefficients \( A_2 \) and \( A_4 \) were calculated, for two stage and three stage processes, for those cases where a compound state of \( B^{11} \) is formed by p-wave, d-wave or f-wave \( \alpha \)-particles and for the cases where dipole or quadrupole (Electric or Magnetic) \( \gamma \)-radiation is emitted. Since all the experimentally observed \( \gamma \)-rays are anisotropic in distribution, the formation of \( B^{11} \) compound states by s-wave particles is ruled out because it leads to isotropic distributions. The values of \( A_2 \) and \( A_4 \) calculated for the various cases of interest in this work are listed in the table below. The spin of the ground state of lithium is 3/2 and so \( J_1 = 3/2 \) for all cases.

(a) Two stage processes -- \( J_1 (l_1) J (l_2) J_2 \)

<table>
<thead>
<tr>
<th>( l_1 )</th>
<th>( J )</th>
<th>( l_2 )</th>
<th>( J_2 )</th>
<th>( A_2 )</th>
<th>( A_4 )</th>
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<td>3/2</td>
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<tr>
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<td>3/2</td>
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<td>5/2</td>
<td>+.125</td>
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</tr>
<tr>
<td>1/2</td>
<td>3/2</td>
<td>- .42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( l_1 )</td>
<td>J</td>
<td>( l_2 )</td>
<td>J</td>
<td>( l_2 )</td>
<td>( A_2 )</td>
</tr>
<tr>
<td>-------</td>
<td>-----</td>
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<td>-----</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>3/2</td>
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<td>7/2</td>
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<tr>
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<td>7/2</td>
<td>-.33</td>
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</tr>
<tr>
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<td>7/2</td>
<td>+.56</td>
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### Three stage processes

<table>
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<th>$A_2$</th>
<th>$A_4$</th>
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<td>5/2</td>
<td>-1.15</td>
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<td>3/2</td>
<td>-.56</td>
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(b) Three stage processes

<table>
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<th>Sequence</th>
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</thead>
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<tr>
<td>3/2 (1) 5/2 (1) 5/2 (1) 3/2</td>
<td>- .27</td>
<td></td>
</tr>
<tr>
<td>3/2 (1) 5/2 (1) 7/2 (2) 3/2</td>
<td>+ .6</td>
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</tr>
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<td>+ .39</td>
<td></td>
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<td></td>
</tr>
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<td>for $\alpha = .1$</td>
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<td></td>
</tr>
<tr>
<td>for $\alpha = .15$</td>
<td>- .06</td>
<td></td>
</tr>
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<td>+ 1.0</td>
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</tr>
<tr>
<td>3/2 (2) 7/2 (1) 5/2 (1/2) 3/2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>for $\alpha = .15$</td>
<td>- .09</td>
<td></td>
</tr>
<tr>
<td>3/2 (3) 3/2 (1) 3/2 (1) 3/2</td>
<td>+ .1</td>
<td></td>
</tr>
<tr>
<td>3/2 (3) 5/2 (1) 3/2 (1) 3/2</td>
<td>+ .29</td>
<td></td>
</tr>
<tr>
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<td>+ .31</td>
<td></td>
</tr>
<tr>
<td>3/2 (3) 7/2 (1) 5/2 (1) 3/2</td>
<td>- .30</td>
<td></td>
</tr>
</tbody>
</table>
\[
\begin{array}{cccc}
\text{Sequence} & & A_2 & A_4 \\
3/2 (3) 7/2 (1) 5/2 (\frac{1}{2}) 3/2 & &\text{for } \alpha = .15 & -.07 \\
3/2 (3) 7/2 (1) 7/2 (2) 3/2 & &+.4 &+.07 \\
\end{array}
\]

B. For the three resonances, various theoretical sequences which have values of angular distribution coefficients comparable with the experimental values of \(A_2\), for each of the \(\gamma\)-rays, are tabulated below.

(1) 960 Kev. Resonance.

(a) 9.28 Mev state.

(1) 9.28 Mev \(\gamma\)-ray

\[
3/2^- (1) 5/2^+ (1) 3/2^- \\
3/2^- (1) 3/2^+ (1) 3/2^- \\
\]

Experimental \(A_2 = -0.41 \pm .04\)

\(A_2 = -.37\) \(A_2 = -.41\)

(2) 4.82 Mev \(\gamma\)-ray

Experimental \(A_2 = +0.56 \pm .08\)

\[
3/2^- (1) 5/2^+ (1) 5/2^- \\
3/2^- (1) 3/2^+ (1) 3/2^- \\
\]

\(A_2 = +.56\) \(A_2 = -.42\)

This evidently rules out the second sequence. Hence the assignment \(5/2^+\) for the 9.28 Mev level.

(b) 6.76 Mev state.
(1) 2.52 Mev $\gamma$-ray

$3/2^- (1) 5/2^+ (1) 3/2$

$3/2 (1) 5/2^+ (1) 7/2$

Experimental $A_2 = -0.38 \pm 0.04$

$A_2 = -0.37$

$A_2 = -0.33$

(2) 6.76 Mev $\gamma$-ray

$3/2^- (1) 5/2^+ (1) 3/2 (1) 3/2^-$

$3/2^- (1) 5/2^+ (1) 7/2 (2) 3/2^-$

Experimental $A_2 = +0.7 \pm 0.1$

$A_2 = +0.4$

$A_2 = +0.6$

Here also the assignment $7/2$ for 6.76 Mev state is quite conclusive.

(c) 4.46 Mev state.

4.46 Mev $\gamma$-ray

$3/2 (1) 5/2 (1) 5/2 (1) 3/2$

$3/2 (1) 5/2 (1) 5/2 (1/2) 3/2$

Experimental $A_2 = -0.07 \pm 0.03$

$A_2 = -0.27$

$A_2 = -0.115$

$A_2 = -0.07$

for $\alpha = 0.14$

(ii) 820 Kev. Resonance.

(a) 9.19 Mev level.

4.73 Mev $\gamma$-ray

$3/2 (3) 7/2 (1) 5/2$

$3/2 (3) 3/2 (1) 5/2$

$3/2 (2) 7/2 (1) 5/2$

Experimental $A_2 = -0.26 \pm 0.04$

$A_2 = -0.29$

$A_2 = -0.115$

$A_2 = -0.38$

The last two sequences give values of $A_2$ far outside the experimental error and so are ruled out. Hence the assignment $7/2^+$ for the 9.19 Mev level.
(b) **6.76 Mev level.**

(1) **2.43 Mev γ-ray**

<table>
<thead>
<tr>
<th>State</th>
<th>Experimental $A_2$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2 (3) 7/2 (1)$</td>
<td>$+0.6 \pm 0.1$</td>
<td>$+0.57$</td>
</tr>
<tr>
<td>$3/2 (2) 7/2 (1)$</td>
<td>$+0.77$</td>
<td></td>
</tr>
</tbody>
</table>

(2) **6.76 Mev γ-ray**

<table>
<thead>
<tr>
<th>State</th>
<th>Experimental $A_2$</th>
<th>$A_2$</th>
<th>$A_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2 (3) 7/2 (1) 7/2 (2) 3/2$</td>
<td>$+0.37 \pm 0.04$</td>
<td>$+0.4$</td>
<td>$+0.07$</td>
</tr>
<tr>
<td>$3/2 (2) 7/2 (1) 7/2 (2) 3/2$</td>
<td>$+1.0$</td>
<td>$-0.4$</td>
<td></td>
</tr>
</tbody>
</table>

The assignment for the 6.76 Mev level, of $7/2$, is quite evident from these comparisons.

(c) **4.46 Mev state.**

<table>
<thead>
<tr>
<th>State</th>
<th>Experimental $A_2$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.46$ Mev $\gamma$-ray</td>
<td>$-0.07 \pm 0.02$</td>
<td>$-0.3$</td>
</tr>
<tr>
<td>$3/2 (3) 7/2 (1) 5/2 (1)$</td>
<td>$-0.3$</td>
<td></td>
</tr>
<tr>
<td>$3/2 (3) 7/2 (1) 5/2 \left( \frac{1}{2} \right)$</td>
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<td></td>
</tr>
<tr>
<td>for $\alpha_2 = 0.14$</td>
<td>$A_2 = 0.07$</td>
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</tr>
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</table>

(iii) **400 Kev. Resonance.**

(a) **8.92 Mev state.**

(1) **8.92 Mev γ-ray**

<table>
<thead>
<tr>
<th>State</th>
<th>Experimental $A_2$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2 (1) 5/2 (1)$</td>
<td>$-0.25 \pm 0.1$</td>
<td>$-0.37$</td>
</tr>
<tr>
<td>$3/2 (2) 5/2 (1)$</td>
<td>$-0.22$</td>
<td></td>
</tr>
<tr>
<td>$3/2 (3) 5/2 (1)$</td>
<td>$-0.3$</td>
<td></td>
</tr>
</tbody>
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APPENDIX III

Energy Loss of α-Particles in Lithium.

The energy loss of a charged particle of mass $M$, charge $Ze$, velocity $v$ and energy $E$ is given by

$$\frac{dE}{dx} = \frac{4\pi e^2 Z^2}{m v^2} NB$$  \hspace{1cm} (1)

where $m$ is the electron mass, $N$ is the number of stopping atoms per cubic centimeter and $B$ is called the "Stopping Number". Bloch (1933) has shown that for an ion velocity $v$, large compared to the velocity of the atomic electrons in the stopping material, $B$ approaches the form

$$B = Z \ln \left(\frac{2m v^2}{I_0 Z}\right)$$  \hspace{1cm} (2)

where $I_0$ is an empirical constant, a measure of the average excitation potential of the absorbing atoms, and $Z$ is the atomic number of the stopping material. One could calculate the energy loss for low energy α-particles in lithium by using the above expression. However, the results so obtained are not very accurate at low energies unless due account is taken of the changes in the effective $Z$ and $I_0$ which result from the electron capture and loss by the α-particles. Unfortunately, there is not sufficient experimental data to make these corrections accurately. However, if one knows the stopping power as a function of energy for one material, say air, one can find it for another material by obtaining from experiments the ratio of the stopping number for the two
materials at some energy. Bethe (1937) has shown that this ratio should be independent of energy. Thus we can write

\[ s = \frac{B_{Li}}{B_{Air}} = \text{constant} \]

where \( s \) is the "stopping power" relative to air for the target material. Thus

\[ \frac{dE}{dx} \text{ (Lithium)} = \frac{N_{Li}}{N_{Air}} \times s \times \frac{dE}{dx} \text{ (Air)} \]  

(3)

\( N_{Air} = 5.28 \times 10^{19} \) atoms per cubic centimeter.

\( N_{Li} = 4.64 \times 10^{22} \) atoms per cubic centimeter.

\( s = 0.52 \) for lithium - Average of Geiger's and Mano's values as quoted by Bethe (1937, p. 272).

The values of \( \frac{dE}{dx} \text{ (Air)} \) were taken from Bethe (1950).

The values calculated by equation (3) of \( \frac{dE}{dx} \) in lithium for \( \alpha \)-particles are:

<table>
<thead>
<tr>
<th>( E_\alpha )</th>
<th>( \frac{dE}{dx} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.400 Mev</td>
<td>1.04 \times 10^9 \text{ ev./cm.}</td>
</tr>
<tr>
<td>0.820 Mev</td>
<td>1.09 \times 10^9 \text{ ev./cm.}</td>
</tr>
<tr>
<td>0.960 Mev</td>
<td>1.11 \times 10^9 \text{ ev./cm.}</td>
</tr>
</tbody>
</table>

As a check on these values the procedure outlined by Whaling (1958) to determine the stopping cross section \( \xi_\alpha \) where \( \xi = -\frac{1}{N} \frac{dE}{dx} \) in units of ev.-cm\(^2\), in any material was
Fig. 18 Stopping power vs. α-particle energy
also used. He computed the ratio $\xi_\alpha/\xi_p$, for $\alpha$-particles and protons of the same velocity, from all the known experimental values. Assuming that the ratio $\xi_\alpha/\xi_p$ is a function of ion velocity alone, the experimental ratios for all stopping materials were averaged to obtain the average value of $\xi_\alpha/\xi_p$. Using these ratios, the stopping cross sections $\xi_\alpha$ in lithium, helium and hydrogen were estimated from the known value of $\xi_p$ in these materials and are plotted in Fig. 18 as a function of $\alpha$-particle energy. Experimental values (Weyl, 1953) of stopping cross section for low energy $\alpha$-particles in He and H in the energy range from 150 kev. to 400 kev. are also plotted. On the basis of the difference at low energies in the experimental curve and the curve obtained from the proton data, the shape of the lithium curve was modified from the shape obtained using the proton data so that it corresponded more closely to the shape of the experimental curves at low energies for H and He. The error in the values taken from the corrected lithium curve were estimated to be $\pm$ 10%. The probable error in Weyl's results is quoted to be $\pm$ 5%. Using the stopping cross section of $\alpha$-particles in lithium, $\xi_\alpha$, from Fig. 18, the values of $\frac{dE}{dx}$ were calculated to be

<table>
<thead>
<tr>
<th>$E_\alpha$ (Mev)</th>
<th>$\frac{dE}{dx}$ (ev./cm.)</th>
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</thead>
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<tr>
<td>0.400</td>
<td>$9.3 \times 10^9$</td>
</tr>
<tr>
<td>0.820</td>
<td>$1.02 \times 10^9$</td>
</tr>
<tr>
<td>0.960</td>
<td>$1.00 \times 10^9$</td>
</tr>
</tbody>
</table>
The two methods gave values of the stopping power within better than 10% of each other. The values obtained from the second method were used to find the absolute thick target yield described in chapter III.
APPENDIX IV

Efficiency of NaI Crystals.

Since scintillation counters are now so extensively used for $\gamma$-ray studies, accurate knowledge concerning their $\gamma$-ray detection efficiencies is very desirable. Many attempts to calculate the efficiencies of NaI crystals by monte-carlo methods have been made (Berger et al., 1956 and Miller et al., 1957). This method involves extensive computations requiring the use of electronic computers. It was decided to develop a semi-empirical method for calculating the efficiency of NaI crystals of any size or shape for $\gamma$-rays in the range 0.5 to 12 Mev and to check the method experimentally by determining the absolute efficiencies with known fluxes of $\gamma$-rays of several energies. In any experimental arrangement the distortion of the spectrum by scattering and geometrical details can cause effects of the order of 10% or more, consequently it is important to have some accurate experimental checks on the detection efficiency. Further, if these absolute efficiencies are available somewhat less elaborate theoretical calculations are very useful for making interpolations between the experimental points.

(1) Gamma Ray Absorption and Pulse Height Distribution.

Gamma rays interact with matter by three processes, Compton scattering, photoelectric absorption and, when $E_\gamma$ is greater than 1.02 Mev, by the pair production process. Below
0.3 Mev the photoelectric process predominates in NaI, above this to about 7 Mev the compton scattering accounts for the major part of the absorption and above this pair production becomes predominant. Each of these processes imparts a certain amount of the $\gamma$-ray energy to the electrons, released from the phosphor with an energy distribution characteristic of the process involved. The electron energy distribution is reproduced in the pulse height spectrum from the photomultiplier. Considering only the primary interactions, photoelectric effect results in a line spectrum corresponding to the full $\gamma$-ray energy, $E_\gamma$; the pair production process gives a second line corresponding to an energy release of $E_\gamma - 2mc^2$ in the phosphor; the compton scattered electrons have a broad distribution, with a cut-off at about $E_\gamma - 0.25$ Mev, which is given by:

$$\frac{d\delta}{dT} = \frac{\pi r_o^2}{mc^2} \frac{1}{\alpha^4} \left[ \frac{T_{\text{max}}^2}{(T-T_{\text{max}})^2} + 2\alpha^2 + \frac{\alpha(T_{\text{max}}^2 - 2T_{\text{max}})}{\alpha - T_{\text{max}}} \right]$$

(1)

where,

$$\frac{d\delta}{dT}$$ the number of compton electrons per target electron per Mev with energies between $T$ and $T + dT$.

$$T_{\text{max}} = \frac{2\alpha^2}{1+2\alpha},$$ the maximum energy of the compton electron in units of $mc^2$.

$$\alpha = \frac{E_\gamma}{mc^2}$$

$$mc^2 = 0.5108 \text{ Mev}$$

$$r_o = 2.818 \times 10^{-13} \text{ cm}.$$
The primary spectrum is broadened as a result of statistical fluctuations in the number of photoelectrons produced in the photomultiplier and by the non-uniformities in the light production and collection. Further, the spectrum shape is considerably modified by secondary absorption processes in the crystal and escape of electrons and secondary quanta from the walls of the crystal (Griffiths, 1955). To compute the pulse height distribution produced by γ-rays in NaI crystals, after taking all the above factors into account, would be a tedious process. However, one can do this effectively by a monte-carlo method. In practice, however, one is more interested in obtaining the γ-ray detection efficiency in terms of the number of counts above a given bias rather than in very detailed knowledge of the spectrum shape. The problem of determining the efficiency above a given bias is discussed below.

(ii) Gamma Ray Efficiency - Theoretical.

Let $N_0$ be the number of gamma rays of energy $E_γ$ which are incident on the face of a NaI crystal of length "L". The total number of γ-rays which interact in the crystal is given by

$$N_μ = N_0 (1 - e^{-μL}) = N_π + N_γ + N_σ,$$

where $μ$, $γ$, $σ$, and $π$ are the total, photoelectric, compton and pair production absorption coefficients in NaI respectively and $N_π$, $N_γ$ and $N_σ$ are the counts produced by the three interaction processes separately. In practice we count only the pulses above a definite bias, say $1/2 E_γ$. Obviously not all inter-
(a) Sections Of The Crystal

(b) Compton Electron Energy Distribution
actions will lead to sufficient energy release in the crystal to produce pulses greater than the bias chosen.

Consider the theoretical compton electron energy spectrum (Eq. 1, Fig. 19b) and designate the number of counts in the spectrum above the bias as $N_{\sigma 1}$ and that below it as $N_{\sigma 2}$, then the total number of counts in the compton distribution is $N_{\sigma} = N_{\sigma 1} + N_{\sigma 2}$. Due to the absorption of the secondary compton photons, some of the counts, below the selected bias, in the primary theoretical distribution will be shifted above. Let a fraction "K" of $N_{\sigma 2}$ be shifted up. Also due to the escape of electrons from the sides and the front end of the crystal and due to the loss of bremsstrahlung produced by the electrons of high energy, some counts from the upper end will be shifted down. Let the fraction of $N_{\sigma 1}$ which is shifted below be "m". The total number of counts expected above the bias due to the compton events only is

$$N_{\sigma 1}' = N_{\sigma 1} + KN_{\sigma 2} - mN_{\sigma 1}$$

since for a given bias

$$\frac{N_{\sigma 1}}{N_{\sigma}} = d = \text{constant, which can be calculated theoretically, and}$$

$$\frac{N_{\sigma 2}}{N_{\sigma}} = 1 - d,$$

we can write
\[ N_1 = dN_\sigma + K (1 - d) N_\sigma - mdN_\sigma \]
\[ = N_\sigma d \left[ 1 + K \left( \frac{1 - d}{d} \right) - m \right] \]
\[ = N_\sigma x b \]  

(2)

where
\[ b = d \left[ 1 + K \left( \frac{1 - d}{d} \right) - m \right] \]

Similarly a certain fraction 'a' of the total photoelectric events, \( N_\gamma \), and a fraction 'c' of the pair events, \( N_\pi \), will produce pulses above the counting bias. Therefore, the total number of counts, \( N_. \), expected above the bias is,

\[ N_. = N_\gamma + N_\sigma + N_\pi \]
\[ = aN_\gamma + bN_\sigma + cN_\pi \]
\[ = N_\mu \left[ \frac{a \gamma + b \sigma + c \pi}{\mu} \right] \]
\[ = N_0 \left( \frac{1 - e^{-\mu t}}{\mu} \right) \left[ a \gamma + b \sigma + c \pi \right] \]

(3)

The \( \gamma \)-ray detection efficiency above a certain bias, \( b \), is defined as

\[ \xi_b = \frac{N_.}{N_0} \left( \frac{1 - e^{-\mu t}}{\mu} \right) \left[ a \gamma + b \sigma + c \pi \right] \]

(4)

From equation (4) it is evident that by estimating \( a, b \) and \( c \) one can calculate the efficiency above a certain bias for a given crystal size using the theoretical values of \( \gamma, \sigma \) and \( \pi \).

The efficiencies have been calculated for a bias equal to half the \( \gamma \)-ray energy. This bias was chosen because
the $\gamma$-ray spectra are generally low and flat in this region and there is relatively little contribution above this bias due to photons scattered into the crystal from the shield and surroundings. Also for those cases where the pair production cross section is significant compared to the Compton cross section (above 2 Mev), this bias is below $E_\gamma - 2mc^2$, so that one does not have to consider the transfer of pulses among the three pair peaks due to the absorption of annihilation quanta. The efficiency for any other bias can be calculated empirically from the experimental $\gamma$-ray spectra with the following relation

$$\xi_b = \xi_{1/2} \times \frac{\text{counts above bias } b}{\text{counts above } 1/2E_\gamma \text{ bias}}$$

(5)

(iii) Procedure For Calculating 'a', 'b' and 'c'.

The following simplifying assumptions were made in the estimation of the fractions a, b and c. First, only primary and secondary absorption processes were considered so that if a Compton photon interacted in the crystal it was assumed to be absorbed completely. Second, the energy loss resulting from the escape of the bremsstrahlung radiations produced by the high energy electrons was neglected. This should be a reasonable approximation because 12 Mev electrons in NaI lose only about 25% of their energy in the form of bremsstrahlung quanta and most of these are soft and readily absorbed.
(1) **Correction to the Photoelectric Absorption Coefficient.**

At energies greater than about 1 Mev the photoelectric absorption coefficient, \( \tau \), is so small compared to the total absorption coefficient, \( \mu \), that for higher energies 'a' was assumed to be unity. For energies below 1 Mev, corrections due to the loss of photoelectrons from the walls and the front face of the crystal were made in the same manner as described below for the pair electrons.

(2) **Correction to the Pair Production Absorption Coefficient.**

A correction for the escape of pair electrons from the end and walls of the crystal was applied by rejecting all those events which occurred sufficiently close to the surfaces that the pair electrons escaped leaving an energy less than \( E_\gamma / 2 \) in the crystal. This correction amounted to 5\% of the total pair absorption for 6 Mev \( \gamma \)-rays in the 3.5 inch long by 2.5 inch diameter crystal. The stopping power for electrons in NaI, required for these calculations, was obtained from the formulae given by Heitler (1954).

(3) **Correction to the Compton Absorption Coefficient.**

The loss of compton electrons from the walls and the end was considered in the same fashion as for the pair electrons. This correction refers to the fraction m in equation (2) and was about 5\% for 6 Mev \( \gamma \)-rays.
The correction due to the absorption of secondary photons was calculated as follows. The crystal was divided into three concentric cylindrical rings, A, B and C, of equal cross sectional area and into 4 lengthwise sections, I, II, III and IV, of equal length. Fig. 19a shows these divisions in a plane section of the crystal. The part of the Compton electron energy distribution function, Fig. 19b, which is below the half energy bias was divided into four parts, D, E, F and G, such that the area in each part is the same. All the electrons in each part were considered to have an energy \( (T_D, T_E, T_F, T_G) \) equal to the average energy for the group. All the Compton photons corresponding to the Compton electrons in a part were considered to have an energy \( (E_D, E_E, E_F, E_G) \) equal to the difference between the incident photon energy and the average energy of the Compton electrons in that part. The angles at which these Compton photons are scattered are given by

\[
\cos \theta = \frac{1 + \alpha}{\alpha} - \frac{1}{\alpha} \frac{E_D}{E_D}
\]

where, \( \alpha = E_\gamma/\text{mc}^2 \) and \( E_D \) is the average Compton photon energy corresponding to part D.

To estimate the secondary interactions of the Compton photons in the crystal it was assumed that all the Compton interactions of the incident \( \gamma \)-rays in a particular subsection take place at the centre of the subsection. Since the incident photon, the Compton scattered photon and the
corresponding electron are in the same plane, from the knowledge of the scattering angles of the Compton photons, the path length, \( x \), of these photons in the crystal were geometrically obtained. For the central ring all the planes through the axis are the same, but for the outer two rings, the various planes making different angles with the vertical plane, \( ab \) (Fig. 19a), have different dimensions and contain a different distribution of path lengths. To take this effect into consideration, for the rings B and C, the path lengths in the planes at \( 0^\circ, 30^\circ, 60^\circ \) and \( 90^\circ \) to the vertical were calculated and an average path length was determined for each of the four average photon energies corresponding to the 4 parts of the Compton tail. Using the known total absorption coefficient, \( \mu \), for each of the average Compton photon energies, the fraction "\( k \)" of the photons from each part of the spectrum which further interact in the crystal was determined from the simple relation

\[
    k = (1 - e^{-\mu x})
\]

These fractions were calculated for each of the 12 subsections and then an average fraction (\( k_I, k_{II}, k_{III} \) and \( k_{IV} \)) was determined for each of the four sections (I, II, III and IV). These fractions were then normalized to the number of primary Compton interactions in each section, and a final fraction \( K \) of the Compton photons which further interacted in the crystal was determined. Thus knowing \( m, k \) and \( d \) the total fraction \( b \)
can be determined from the equation (2).

From the estimated values of 'a', 'b' and 'c', the known values of \( \tau, \sigma, \xi \) and \( \mu \) and the dimensions of the crystal, the efficiency of NaI crystals for counts above the half energy bias, \( \xi_{1/2} \), was determined using the equation (5).

(iv) Gamma Ray Efficiencies - Experimental.

The \( \gamma \)-ray efficiencies of the NaI crystal were experimentally determined at 0.51 Mev and 1.25 Mev by using Na\(^{22}\) and Co\(^{60}\) sources, which were calibrated independently as described below, and also at 6.14 Mev by using the reaction \( \text{F}^{19}(p, \alpha \gamma) \text{O}^{16} \). In the last case absolute calibration was obtained by the simultaneous counting of \( \alpha \)-particles by a proportional counter (see Larson, 1957) and \( \gamma \)-rays by the scintillation crystals. Relative efficiencies were determined at 4 Mev and 12 Mev by obtaining 4 Mev and 12 Mev \( \gamma \)-rays from the reaction \( \text{B}^{11}(p, \gamma) \text{C}^{12} \). To obtain the efficiency at 12 Mev, the flux of these \( \gamma \)-rays was determined by taking the efficiency at 4 Mev from the appropriate efficiency curve (Fig. 21) and assuming a one to one ratio of 4 to 12 Mev \( \gamma \)-rays from the above reaction.

(1) Calibration of Co\(^{60}\) Sources.

The absolute \( \gamma \)-ray flux from a weak Co\(^{60}\) source
(referred to as Co$^{60}$ #1) was determined by means of standard coincidence technique (Siegbahn, 1955) using a fast slow coincidence system (Jones, 58, 59). This system converts a time delay spectrum into a pulse amplitude spectrum with an intrinsic time resolution of $5 \times 10^{-11}$ sec. This "time-sorter" method possesses several advantages over the direct coincidence method in which the pulses from the two counters are fed into a coincidence circuit and the output pulses are recorded by a scaler. The most important advantage is that one obtains a complete pulse height spectrum in which the flat level on either side of the prompt peak corresponds to the counts due to random coincidences, observed simultaneously with the true coincidences as shown in Fig. 20. Therefore, one can make the random coincidence correction by interpolating the flat level under the peak. Also the measurements taken with this arrangement are less sensitive to gainshifts because one can see the effect of such changes in broadening of the peak and so can correct for such changes.

If $N$ is the number of disintegrations per sec. from the source placed between the two detectors, then the number of pulses produced in the two counters, $N_1$ and $N_2$, are

$$N_1 = 2N \xi_1 \omega_1 \quad \text{per sec.}$$
$$N_2 = 2N \xi_2 \omega_2 \quad \text{per sec.}$$

where $\xi_1$ and $\xi_2$ are the efficiencies of the two counters for detecting $\gamma$-rays and $\omega_1$ and $\omega_2$ are the solid angles subtended
by the counters at the source and the factor 2 accounts for the fact that there are two \( \gamma \)-rays of almost the same energy for each disintegration of Co\(^{60}\). Since both the \( \gamma \)-rays are so nearly the same in energy (1.333 and 1.173 MeV) it was assumed that the counter efficiencies were the same for both \( \gamma \)-rays. The coincidence counting rate, \( N_c \), is then given by

\[
N_c = 2 N (1 + \omega_1 \omega_2 F(\theta)) \text{ per sec.} \tag{7}
\]

where \( F(\theta) = B C (1 + A \cos^2 \theta) \), and B is the factor which takes into account the finite solid angle of the counters, \( (1 + A \cos^2 \theta) \) is the angular correlation function for the two \( \gamma \)-rays, and C is the normalizing constant such that

\[
\int C (1 + A \cos^2 \theta) \, d\omega = 1
\]

which gives

\[
C = \frac{1}{4\pi (1 + A/3)}
\]

From (6) and (7) we get

\[
N = \frac{N_1(\theta) N_2(\theta) B(\theta) C (1 + A \cos^2 \theta)}{2 N_c(\theta)} \tag{8}
\]

Equation (8) can be used to find \( N \) from the knowledge of the other factors. Measurements were taken with 90° and 180° between the counters in order to determine a value for the parameter A. From (8) we can write

\[
A = \frac{N_c(180) N_1(90) N_2(90) B(90)}{N_c(90) N_1(180) N_2(180) B(180)} - 1
\]
From 12 measurements made with angular separations of 90° and 180° between the counters an average value of \( A = 0.167 \pm 0.003 \) was determined. This agrees very well with the experimental value, \( A = -0.167 \pm 0.001 \) of Steffen (as reported by Siegbahn, 1955, p. 553) and with the theoretical value of \( A = 0.1667 \). A value 0.167 was used for \( A \) in the following work.

The counts observed by each detector, \( N_1 \) and \( N_2 \), were corrected for combined dead time of the side channels and the scaling units while the observed coincidence counts were corrected for losses in the fast and slow coincidence circuits. These corrections were always less than or equal to 0.5%. The counter solid angle correction factor \( B \) was evaluated by making a graphical average over the known angular correlation function for the two angular separations and amounted to a + 0.3% correction at 90° and a - 0.7% correction at 180°.

After having applied the various corrections to the observed quantities, the value of \( N \) was calculated using equation (8). The average of 12 measurements, each one involving about 40 million single channel counts and about 20 thousand coincident counts, gave a value of

\[
N = 876.9 \times 10^3 \text{ disintegrations per sec.}
\]

or a source strength of 0.0237 \( \pm \) 0.0006 mc on 22nd April, 1958.
The error stated is the root mean square error from the 12 separate runs. The strength obtained compares very well with the N.R.C. calibration of this source. This calibration was done by scintillation counter comparison of this source (Co\textsuperscript{60} #1) with a Co\textsuperscript{60} source of about 1 mc. (#3) which had been previously compared with the Canadian radium standard by ionization chamber measurements (N.R.C. certificate No C-121). These measurements indicated a strength for Co\textsuperscript{60} #1 of 0.041 ± 0.002 Mr/hr. at 1 meter on 25th April, 1956. Converting this to disintegration rate at 1.33 Mr/hr. at 1 meter for 1 mc of Co\textsuperscript{60} gives a source strength of 0.0308 ± 0.0015 mc. Correcting for the decay, the strength on 22nd April, 1958, becomes 0.0236 ± 0.0010 mc, which is in excellent agreement with the strength obtained above independently.

(2) Calibration of Na\textsuperscript{22} Source.

The flux of 0.51 Mev quanta from a Na\textsuperscript{22} source was determined by scintillation counter comparison with the Co\textsuperscript{60} #1 source. Since Na\textsuperscript{22} gives out 1.28 Mev \ensuremath{\gamma}-rays along with 0.51 Mev quanta, produced by the decay of the positrons in the holder, scintillation counter spectra covering an energy range of 0.2 Mev to 1.5 Mev were taken, under identical geometry, for a Na\textsuperscript{22} source and for the calibrated Co\textsuperscript{60} source. Since the mean energies of the \ensuremath{\gamma}-rays from the Co\textsuperscript{60} and the high energy \ensuremath{\gamma}-ray from Na\textsuperscript{22} are almost exactly the same, it was assumed that the efficiency of the NaI for these \ensuremath{\gamma}-rays is the same. By comparing the counts above the half energy bias
FIG. 21 EFFICIENCY CURVES

FOR 4.5 INCH CRYSTAL

FOR 3.5 INCH CRYSTAL

FOR 2 INCH CRYSTAL

Efficiency - %

Gamma-ray Energy - MEV

O O O Theo. Points

● ● ● Exp. Points
in the 1.28 Mev γ-ray spectrum from Na\textsuperscript{22} and from Co\textsuperscript{60}, the 
1.28 Mev γ-ray flux was determined. From the known decay 
scheme of Na\textsuperscript{22} (β+) Ne\textsuperscript{22} (90% β+ and 10% electron capture 
both to the 1.28 Mev state in Ne\textsuperscript{22} - Ajzenberg and Lauritsen, 
1959) and the fact that each positron produces two annihilation 
quanta, the flux of the 0.51 Mev γ-rays from the Na\textsuperscript{22} was 
determined absolutely.

The experimental efficiency, $\xi_{1/2}$, is defined as

$$\xi_{1/2} = \frac{4\pi r^2 N_s}{AN}$$

where $N_s$ is the number of counts observed above the half 
energy bias in a certain time $t$, $N$ is the number of γ-rays 
emitted by the source in the same time, $r$ is the distance 
from the source to the effective centre of the crystal and 
$A$ is the area of the front face of the NaI crystal. The 
effective centre is taken as that point in the crystal from 
which measurements of source to crystal distance are made in 
order to give an inverse square relation between counting 
rate and distance.

(V) RESULTS

The experimental and theoretical efficiencies at 
half energy bias for γ-ray energies in the range of 0.5 Mev 
to 12 Mev are shown in Fig. 21. The errors in the experimental 
points are also shown. The agreement between the theory and 
the experiments is quite good. Not only does the theory give 
the efficiency as a function of energy in good agreement with
the shape of the experimental curve but also the absolute values have agreed to better than 10% in all cases calculated. Consequently this fairly simple theoretical approach seems to be capable of predicting efficiencies absolutely to as good an accuracy as is required for most work and if experimental points are available to greater accuracy the theory should be useful for interpolating between them to an accuracy comparable to the accuracy of the experimental points.

SCINTILLATION COUNTER

BIBLIOGRAPHY

1959, Private Communication.
BIBLIOGRAPHY

1959 Nuclear Physics 11, 1.

Barnes, C.A., Carver, J.H., Stafford, G.H.

Bennett, W.E., Roys, P.A. and Toppel, B.J.

Bent, R.D., Bonner, J.W., McCrary, J.H., Rankin, W.A.


Bethe, H.A., Bacher, R.F. and Livingston, M.S.
1936 Rev Mod Phys 8, 82.
1937 Rev Mod Phys 9, 69.


Bloch, F. 1933 Zeitschrift Fuer Physik 81, 363.

Bloch, I., Hull, M.H., Jr., Broyles, A.A., Bouricius, W.G.,
Freeman, B.E. and Breit, G.
1951 Rev Mod Phys 23, 147.
Ferguson, A.J., Grove, H.E., Kuehner, J.A., Litherland, A.E.,
Kaye, G.W.C. and Laby, T.H. 1956 Longmans, Green and Co. Ltd.,
London, Tables of Physical and Chemical Constants,
         1957 Phys Rev 106, 975.
Mayer, M.G. and Jensen, J.H.D. 1955 Joyn Wiley and Sons Inc.,
         New York, Elementary Theory of Nuclear Shell
         Structure.
Metzger, F.R., Swann, C.P. and Rasmussen 1958 Phys Rev
         110, 906.
Meyer-Schutzmeister, L. and Hanna, S.S.
         Nuclear Data Card, 57-4-10-B11.
Moszkowski, S.A. 1955 XIII Chapter of Beta and Gamma-Ray
         Spectroscopy, Editor K. Siegbahn, North Holland
         Publishing Company, Amsterdam.
         Columbia.
Rasmussen, V.K., Metzger, F.R. and Swann, C.P.
Robertson, L.P. 1957 M.A. Thesis, University of British
         Columbia.
Graphs of Coulomb Functions.

Tables of Angular Distribution Functions.


Radiative Transitions in Light Elements II.

1956 Phil Mag 1, 127.

1957 Phys Rev 105, 666.