EXPERIMENTAL STUDIES OF $^{10}\text{Be}(d,ny)^{11}\text{Be}$

by

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We accept this thesis as conforming to
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EXPERIMENTAL STUDIES OF $^{11}B^{10}(d,n\gamma)^{11}C$

ABSTRACT

An experimental study of the low lying excited states of $^{11}C$ has been made using the $^{10}B^{10}(d,n\gamma)^{11}C$ reaction at a deuteron bombarding energy of 0.8 Mev. Measurements were made of the $n-\gamma$ angular correlations of the ground state gamma transitions from the 6.49 Mev and 4.32 Mev levels and of the gamma ray branching ratios of the 6.49, 4.81 and 4.32 Mev levels. The apparatus used for the measurements was a combination of a NaI(Tl) gamma ray spectrometer and an improved fast neutron time-of-flight spectrometer developed by the author.

Theoretical analysis of the $n-\gamma$ angular correlations showed that the 6.49 Mev and the 4.32 Mev levels are formed by the capture of $P_{3/2}$ protons. This restricts the $J^\pi$ values of these levels to $(\frac{5}{2}^-)$ or $(\frac{7}{2}^-)$. The parities of the states observed in this experiment are all known to be negative from the high energy stripping data of Cerineo and Maslin et al. A comparison of the experimental branching ratios with the theoretical branching ratios predicted by the intermediate coupling shell model is consistent with the following spin and parity assignments in $^{11}C$:

- ground state $(\frac{3}{2}^-)$, 2.00 Mev $(\frac{1}{2}^-)$, 4.32 Mev $(\frac{5}{2}^-)$, 4.81 Mev $(\frac{3}{2}^-)$ and 6.49 Mev $(\frac{7}{2}^-)$. These assignments are in agreement with the recent results of Freeman and Braben et al.

The correspondence of these levels with those in $^{11}B$ is consistent with the hypothesis of the charge symmetry of nuclear forces. The experimental results agree in some cases and disagree in others with the intermediate coupling shell model calculations of Kurath.

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ABSTRACT

An experimental study of the low lying excited states of C\textsuperscript{11} has been made using the B\textsuperscript{10}(d,n\gamma)C\textsuperscript{11} reaction at a deuteron bombarding energy of 0.8 Mev. Measurements were made of the n-\gamma angular correlations of the ground state gamma transitions from the 6.49 and 4.32 Mev levels, and of the gamma ray branching ratios of the 6.49, 4.81 and 4.32 Mev levels. The apparatus used for the measurements was a combination of a NaI(Tl) gamma ray spectrometer and an improved fast neutron time-of-flight spectrometer, developed by the author.

Theoretical analysis of the n-\gamma angular correlations showed that the 6.49 Mev and 4.32 Mev levels are formed by the capture of p\textsubscript{3/2} protons. This restricts the J^\pi values of these levels to (5/2)^- or (7/2)^-. The parities of the states observed in this experiment are all known to be negative from the high energy stripping data of Cerineo and Maslin et al. A comparison of the experimental branching ratios with the theoretical branching ratios predicted by the intermediate coupling shell model is consistent with the following spin and parity assignments in C\textsuperscript{11}:
g.s. (3/2)^-, 2.00 Mev (1/2)^-, 4.32 Mev (5/2)^-, 4.81 Mev (3/2*)^- and 6.49 Mev (7/2)^-. These assignments are in agreement with other recent results.

The correspondence of these levels in C\textsuperscript{11} with those of B\textsuperscript{11} is consistent with the hypothesis of the charge independence of nuclear forces. The experimental results agree in some cases and disagree in others with the intermediate coupling shell model calculations of Kurath.
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INTRODUCTION

Nuclear spectroscopy encompasses all experimental methods of obtaining information about nuclear energy states which arise as the eigenstates of a nuclear Hamiltonian $H$. A nuclear energy state may be described by certain parameters, of which the most important are excitation energy $E$, magnetic moment $\mu$, parity $\pi$, total angular momentum $J$ and iso-spin $T$. The probabilities for various modes of decay of the state are also partially determined by the above parameters. If the exact nuclear Hamiltonian were known, it might be possible to use the standard methods for dealing with the many body problems to calculate the values of these parameters.

However, since the nuclear Hamiltonian is not understood in detail, the theoretical method of computing the above parameters proceeds by using nuclear models. A nuclear model is a set of theoretical approximations which replace the real nuclear system by a simplified system which can be handled mathematically. The extent of the agreement between the predictions of such a theory and the results of experiments is a measure of the success of that particular model.

The progress of nuclear theory has led gradually to the incorporation of some aspects of what is believed to be the fundamental nucleon-nucleon interaction into the structure of various nuclear models; and it seems possible that this process can be continued with resulting improvements in our understanding of the fundamental interaction, and in the accuracy of the
models. No single nuclear model can be expected to represent all the properties of the nucleus, which is an extremely complex many body quantum system. The Shell Model (Mayer and Jensen 1955, Feenberg 1955), for example, has had its main use in explaining the magnetic moments of the ground states, and parities and total angular momenta of the ground states and low lying excited states of light nuclei, especially of nuclei with closed shells or with one particle missing from, or added to, a closed shell. The compound nucleus theory and the statistical theory (Blatt and Weisskopf 1952), on the other hand, are mainly concerned with describing highly excited states of nuclei.

The study of nuclear reactions is a direct method of determining those nuclear parameters mentioned above. If the reaction is found to proceed by the stripping mechanism, which is the case for the reaction studied in this thesis, the measurement of angular distributions of the resulting neutrons and/or protons definitely fixes the parity of the nuclear states involved (Butler 1951). This measurement is, however, less useful in determining the spins, since it allows the assignment of restricted sets of J values rather than unique J values. If, however, the residual nucleus is left in an excited state, further information for identifying the spin of this excited state may be obtained from the angular correlation between the stripped particle and the subsequent gamma radiation de-exciting the state, and/or from the relative gamma de-excitation probabilities to the ground state and the intermediate excited states. The exploitation of these methods to study the spins of the low lying excited states of C\(^{11}\) forms one major part of this thesis.

These states of C\(^{11}\) are of particular interest for the following reasons.
First, the hypothesis of charge symmetry of nuclear forces predicts that the level structure of pairs of mirror nuclei should be identical, except for coulomb effects. Theoretical analysis of the energy shifts of mirror excited states of, for example, the \(^{13}\text{C}-^{13}\text{N}\) mirror pair has met with success only in a qualitative manner (Ehrman 1951, Thomas 1952) because the magnitude of the energy shift is critically dependent on the nuclear radius which in turn varies with the excitation energy in an unknown manner. Therefore it is of considerable interest to experimentalists to establish the relationship between the corresponding levels of mirror nuclei as precisely as possible.

Now the stripping reaction can be used to form a mirror pair if the target nucleus has an equal number of neutrons and protons, since a \((d,p\gamma)\) reaction adds a neutron to the target nucleus, whereas the competing \((d,n\gamma)\) reaction adds a proton. Experimentally the former reaction has been studied more extensively and with more accuracy than the latter, because the experimental techniques associated with charged particle detection are more straightforward than those for neutrons and gamma rays. The level structure of the nuclei produced by the latter reaction are, therefore, known less accurately than those of the mirror partners. A case in point is the \(^{11}\text{C}-^{11}\text{B}\) mirror pair. In this case, \(^{11}\text{B}\) produced by the reaction \(^{10}\text{B}(d,p\gamma)\) has been studied more thoroughly (Hinds and Middleton 1962, and references therein) than \(^{11}\text{C}\) produced by the \(^{10}\text{B}(d,n\gamma)\) reaction (McDonell et al 1960, Freeman 1962, Braben et al 1962).

A second reason for the interest in \(^{11}\text{C}\) is that it is one of those nuclei in the \(^{1}\text{p}\) shell which has been studied theoretically (Kurath 1956-57), to the point where further information is required, both to test the theoretical
predictions, and to provide stimulus to the theoreticians to improve their models and extend the calculations. The intermediate-coupling individual particle shell model calculations of Kurath predict, among other things, the transition probabilities of the various gamma-ray decay modes of the excited states of $C^{11}$. The comparison of measured relative gamma transition probabilities with Kurath's calculations (a) leads to a more critical evaluation of the relevance of the theory he used and (b) is a guide, of uncertain value, to the assignment of spins to the states involved.

The work to be described consists of the measurement (a) of relative gamma de-excitation probabilities and their comparison with the intermediate coupling model predictions (b) of n-$\gamma$ angular correlation patterns, and their interpretation using the results of the quantum theory of angular momentum.

The interpretation of n-$\gamma$ angular correlations becomes difficult if there is a contribution both from the ordinary stripping and heavy particle stripping mechanisms. Interference effects between these two reaction modes may give quite a different angular correlation from the relatively simple form expected from one of the mechanisms alone (Edwards 1959). The interpretation of the experimental correlations may be further complicated by contributions from compound nucleus formation. From another point of view, an experimental study of n-$\gamma$ or p-$\gamma$ angular correlations might be useful in studying the relative amplitudes of the various types of reaction mechanisms involved in the reaction.

The results of the measurements made by the author show that the $\mathcal{J}$ values of the ground state and first, second, third and fifth excited states of $C^{11}$ are
6.49 Mev \( (7/2)^- \)
4.81 Mev \( (3/2)^- \)
4.32 Mev \( (5/2)^- \)
2.00 Mev \( (1/2)^- \)
g.s. \( (3/2)^- \)

It should be mentioned here that, besides the work performed by the author during the past three years on the \( ^{10}\text{B}(d,n)^{11}\text{C} \) reaction, others have also published quite similar results in the past few months on the same reaction (Freeman 1962, Braben et al 1962). This is an indication of the large number of workers in the field of interest of the problem, and also of the rather poor communication between laboratories working in the same field. It is, however, useful that several different and independent investigations should be performed, since the results and conclusions thereby become more satisfactorily established.

A major technical effort was required to perform this experiment. The author was personally responsible for the development of the apparatus from the state as described by Neilson and James (1955) and Hardy (1957), and for constructing the entire apparatus described except for the Dynatron Amplifier and the Pulse Height Analysers, which were standard commercial components. The arrangement of the electronic system, more particularly the use of the Delayed Time Sorter (see chap. III E), is quite novel. The author made the system work, calibrated it, and performed all the experimental measurements described.

The experimental apparatus and technique is described in some detail in Part I of the thesis, with particular emphasis on those parts which are new in this laboratory, namely the use of the NaI(Tl) gamma ray spectrometer as
one component (giving zero time pulse) of the associated particle Time-of-Flight Spectrometer, and the simple method of \(n\bar{f}\) pulse shape discrimination. The results of the \(B^{10}(d,n\bar{f})C^{11}\) measurements, and their interpretation, are given in part II.
PART ONE

EXPERIMENTAL METHODS

AND

APPARATUS
CHAPTER I

EXPERIMENTAL METHODS

A. INTRODUCTION

The apparatus described in this thesis was designed for the study of \((d,n\gamma)\) reactions. It can be used either for the study of gamma ray spectra in coincidence with neutrons or for the study of neutron time-of-flight spectra in coincidence with associated gamma rays. For the sake of clarity, particular reference is made to the \(^{10}\text{B}(d,n)^{11}\text{C}\) reaction which may be considered typical. Some of the measurements made on that reaction are, therefore, summarized here in tabular and graphical form and will be used as examples in the description of the experimental apparatus and method. A detailed study of the results is presented in part II of the thesis.

The measurements required a combination of a neutron spectrometer and a gamma ray spectrometer. The neutron energy spectrum was measured by the time-of-flight technique utilizing the associated particle method (in this case the associated gamma ray), in which the neutron velocity is determined from its time of flight over a known distance. The gamma ray spectrometer was a NaI(Tl) scintillation spectrometer.

The time-of-flight spectrometer functions as follows: The gamma ray spectrometer, placed as close to the target as physically possible, detects the gamma ray at time \(t_\gamma\). The neutron counter, at a distance 'd' from the target, detects the associated neutron at time \(t_n\). Then, assuming that the gamma ray takes a negligible amount of time to travel from the target to the
detector, that is, $t_R - t^* \ll t_n - t_R$ (where $t_R$ is the time at which the reaction took place), the flight time $T$ of the neutron is $T = t_n - t^*$. This approximation is valid if the gamma ray flight paths are $\ll 5$ cm. $T$ was measured electronically in a way to be described below. The non-relativistic energy of the neutron is $E_n = \frac{1}{2} M_n \left( \frac{d}{t_n - t_R} \right)^2$. From this it follows that the time-of-flight of neutrons of energy $E_n$ is given by $T(E_n) = \frac{72.3}{\sqrt{E_n}}$ n sec, where $d$ is the length of the flight path in meters and $E_n$ is measured in Mev. For neutrons of energy 1 Mev, for example, the flight time is 72.3 n sec/meter.

The energies of the gamma rays were measured with the NaI(Tl) spectrometer, which produced voltage pulses related to the energy of the gamma rays. The voltage pulses were analysed with a 256 channel pulse height analyser.*

B. GENERAL DESCRIPTION OF EXPERIMENTAL METHODS

(i) Target and Beam

The nuclear reaction studied was produced by bombarding $B^{10}$ targets with a deuteron beam obtained from the 3 Mev Van de Graaff Generator at the University of British Columbia. The beam energy was stabilised by using a corona stabiliser (Auld 1961) in conjunction with the conventional slit arrangement.

The target and beam system is fully described in part II, chap. VII.

(ii) The Measurement of $T$

The block diagram of the conventional apparatus needed for the time-of-flight spectrometer is shown in fig. I.1. The gamma spectrometer upon detection of a gamma ray produces a time pulse $V(T_\gamma)$ and a pulse $V(E_\gamma)$ whose amplitude is related to the gamma ray energy. Similarly, the neutron detector upon detection of a neutron produces the time pulse $V(T_n)$ and a

* Nuclear Data Model 101
Fig. I.1. Block diagram of the time-of flight spectrometer
pulse \( V(E_n) \) whose amplitude is related to the neutron energy. The time pulses from both the detectors are fed into the time sorter (TS). The TS characteristics are such that its output \( V(TS) \) is given by

\[
V(TS) = \delta_+\left\{ k \left[ T_s - (|T_n - T_\gamma|) \right] \right\}
\]

where \( \delta_+(x) = 1 \) for \( x > 0 \), \( \delta_+(x) = 0 \) for \( x \leq 0 \), and \( k \) is a constant of proportionality which was determined experimentally (see chapt. V). \( T_s \) is the length of the shaped time pulse (see chapt. III, D) at the input to the time sorter and \( T_n \) and \( T_\gamma \) are the times when the time pulses from the neutron counter and the gamma counter respectively arrive at \( J_\perp \) (see fig. III. 2), the input to the time sorter.

The pulse height analysers (PHA) analyse \( V(E_\gamma) \), \( V(E_n) \) and \( V(TS) \) pulses and reject those whose amplitudes lie in unwanted voltage regions. The selection of voltage pulses in this manner improves the (effect/background) ratio by reducing the number of pulses at the input of the triple coincidence unit. The output of the triple coincidence unit indicates the occurrence of an \( n-\gamma \) coincidence; it opens the gate and allows the multichannel pulse height analyser (MCPHA) to analyse either the \( V(TS) \) pulse (for the study of the neutron time-of-flight spectrum) or the \( V(E_\gamma) \) pulse (for the study of the gamma ray spectrum).

(iii) Neutron Angular Distribution Measurements

The measurements were required to find the angle of minimum neutron yield. For the measurement of the angular distribution of a particular neutron group, the gamma counter was placed at \( \theta_\gamma = 90^\circ \) with respect to the deuteron beam. The \( V(E_\gamma) \) PHA was set to accept as much as possible of
the spectrum corresponding to the $J$ line associated with the neutron group under study. The $V(E_n)\text{PHA}$ was set to accept those pulses corresponding to the required neutron group. It also, of course, accepts those pulses corresponding to higher energy neutrons and gamma rays that fall within this voltage region (these pulses contributed only to the random and prompt backgrounds). The $V(TS)\text{PHA}$ was set to accept the neutron time-of-flight peak corresponding to the group under study and a section on both sides of the peak to allow corrections to be made for random background. The neutron angular distribution was then obtained as the $Q_n$ dependence of the number of triple coincidence counts per unit charge incident on the target. This was obtained either by feeding the triple coincidence output to the scaler or by recording the $V(TS)$ spectrum in the MCPHA. A typical time-of-flight spectrum, of the neutrons leading to the 6.49 Mev level in $^{11}C$, for $Q_n = 30^\circ$, is shown in fig. I.2. The deuteron bombarding energy was 1.3 Mev. The $V(E\gamma)\text{PHA}$ was set to accept the 5-6.5 Mev region of the gamma spectrum and the $V(E_n)\text{PHA}$ was set to accept pulses from just above noise level up to the maximum energy given up by one of the neutrons to the neutron detector ($\approx 1.2$ Mev). The corresponding angular distribution of this neutron group is shown in fig. I.3.

In the above discussion it was assumed that the gamma ray distributions themselves are isotropic. But even if the gamma ray angular distribution is anisotropic, the above assumption does not introduce a significant error in the neutron angular distribution, since the gamma ray angular distribution is, in general, much less anisotropic than the neutron angular distribution (typically the neutron count rate varied with angle to an extent at least five times greater than the gamma count rate). Hence the
Fig. I.3. Angular distribution of neutrons

\[ \text{B}^{10}(d, n \gamma)\text{C}^{11} \]

\[ E_d = 1.3 \text{ Mev} \]
\[ E_x = 6.49 \text{ Mev} \]

Fig. I.2. Time-of-flight spectrum of neutrons

\[ \text{B}^{10}(d, n \gamma)\text{C}^{11} \]

\[ E_d = 1.3 \text{ Mev} \]
\[ E_x = 6.49 \text{ Mev} \]
\[ \theta_n = 30^\circ \]
above approximation is valid for studies of the gross features of the neutron angular distributions as, for example, in finding the angle of maximum neutron yield.

(iv) \( n-\gamma \) Angular Correlation Measurements

The study of \( n-\gamma \) angular correlations consisted of determining the angular distribution of gamma rays detected in coincidence with a particular neutron group, as a function of \( Q_y \), where \( Q_y \) was measured from the direction of the recoil nucleus. By placing the neutron counter approximately at the peak of the corresponding neutron angular distribution, the stripping process was well favoured over any competing compound nucleus reactions, since these are not expected to yield a strongly peaked neutron angular distribution.

The \( V(E_\gamma), V(E_\gamma) \) and \( V(TS) \) pulse height analyser settings were the same as those used in neutron angular distribution measurements. The \( n-\gamma \) angular correlation was obtained by determining the \( Q_y \) dependence of the triple coincidence counts, normalized to the same number of counts in the neutron counter.

As an example, the \( n-\gamma \) angular correlation for the 6.49 Mev level of \( ^{11}\text{C} \) at \( E_d = 800 \) kev is shown in fig. I.4.

(v) Relative Gamma-Ray Transition Probabilities

The experimentally-determined energy level diagram of \( ^{11}\text{C} \) (Ajzenberg-Lauritsen 1962) is given in fig. I.5. The Q-value of the \( ^{10}\text{B}(d,n\gamma)^{11}\text{C} \) reaction is 6.466 Mev (above reference). Therefore, states up to an excitation of 6.5 Mev are excited even at moderate (\( \approx 1 \) Mev) deuteron bombarding energies. The various gamma rays and neutron groups of interest are labeled in fig. I.5.

In order to study the gamma spectrum arising from the de-excitation of
Relative Counts

Fig. I.4. n-γ angular correlation

\[ B^{10}(d,n\gamma)C^{11} (6.49 \text{ Mev}) \]  \[ E_d = 0.8 \text{ Mev} \].

Fig. I.5. Level diagram of excited states of C^{11}.
a particular level the gamma spectrum was measured in coincidence with the neutrons populating this level. The neutron counter was placed at the peak of the angular distribution of the associated neutron group so that the maximum coincidence count rate was obtained for a fixed reaction rate. The $E(\gamma)$PHA was set to accept all pulses well above the noise level of the gamma ray spectrometer and up to the maximum pulse height produced by the gamma ray in question. The $V(TS)$PHA was set to accept only the time-of-flight peak of the neutron group populating that level. The gamma ray spectrum was accumulated in the MCPHA which was gated by the triple coincidence output.

Correction for background counts was made by recording the gamma ray spectrum in coincidence with the $V(TS)$PHA pulses when $V(TS)$PHA had been set to accept only "background" pulses. The gamma ray spectrum was then analysed for the relative intensities of the various gamma rays by subtracting known spectrum shapes of standard gamma rays from the composite coincidence gamma spectrum (the "spectrum stripping" technique). The results of such an analysis are described in part II chap. IX.
CHAPTER II

THE FAST NEUTRON TIME-OF-FLIGHT SPECTROMETER

A. GENERAL DESCRIPTION

The arrangement of the electronic system described briefly in chap. I does not discriminate between genuine n-γ coincidences and random coincidences which introduce unwanted background counts. Much of this random coincidence background was removed by using a delayed time sorter (DTS) and a pulse shape discriminator (PSD).

The block diagram of the system incorporating the DTS and the PSD is shown in fig. II.1. Here we shall elaborate to show how the various functions of the complete system are carried out by the components used. A detailed description of the components themselves follows in chap. III.

There are two differences between figs. I.1 and II.1
(a) fig. I.1 V(TS)PHA → fig. II.1 DTS + Disc 2 + Disc 1
(b) the addition of PSD and its associated equipment.

The functions of the two new elements introduced in the time-of-flight system are described next.

As has been mentioned in chap. I, the TS response is given by

\[ V(TS) = \delta_k \left\{ k \left[ T_S - \left( |T_n - T_\gamma| \right) \right] \right\} \]

The DTS eliminates those coincidences occurring with -ve\((T_n - T_\gamma)\), that is coincidences occurring with unphysical values of \((T_n - T_\gamma)\).
Fig. II.1. Block diagram of the time-of-flight spectrometer using the delayed time sorter and the pulse shape discriminator.
corresponding to the neutron time pulse arriving at the TS earlier than the zero time pulse from the gamma counter. By suitable adjustment of delay D_{ll} and/or Disc 2 (see chap. III.E), the DTS can also be used to reject some V(TS) pulses with positive \((T_n - T^*_n)\), when this is necessary. The DTS described here differs from the negative time eliminator (NTE) described in literature (Neilson et al 1959) in the sense that the latter has been used to eliminate V(TS) pulses with \(-ve(T_n - T^*_n)\) only. The various regions of rejection of DTS are shown in fig. II.2.

The DTS + Disc 2, therefore, functions as the upper level discriminator of V(TS)PHA of fig. I.1 and, in addition, removes V(TS) pulses with negative \((T_n - T^*_n)\). Disc 1 is the lower level discriminator of V(TS)PHA of fig. I.1. All the measurements on \(^{10}\text{B}(d,n\gamma)^{11}\text{C}\) reaction mentioned in chap. I were obtained by utilizing the complete electronic system described in this chapter.

The PSD differentiates between neutron and gamma pulses in the neutron detector and, therefore, allows the elimination of those chance coincidences which arise when a gamma ray is detected in the gamma spectrometer and another gamma ray is detected in the neutron detector. The PSD that utilizes NE 213 liquid scintillator as the neutron detector is described in chap. III.F.

B. SCALE FACTORS

The physical dimensions of the detector-target system chosen were a compromise between the following factors.

(i) The Neutron Detector

The neutron detector was 2" diameter by 2" long. The thickness was
Fig. II.2. Performance of the delayed time sorter and of discriminators 1 and 2.
chosen as a compromise between the detection efficiency (that requires large thickness) and the time resolution desired (that needs small thickness). A thick crystal makes the time resolution worse as the neutron takes a finite time to travel through the detector thickness. The detector diameter was partly fixed by the diameter of the photomultiplier used (RCA 7264) and partly by the angular resolution needed for neutron angular distribution measurements.

The distance 'd' of the neutron counter from the target was mainly governed by the energy resolution needed in the experiment. Consistent with the above requirement, the distance 'd' was otherwise kept small to obtain maximum coincidence rates. The distance 'd' was about 25 cm for the study of the n_5 neutron group and about 90 cm to enable the n_2 and n_3 neutron groups to be resolved.

(ii) The Gamma Ray Spectrometer

The gamma ray spectrometer was 1.8" diameter by 1" thick NAI(Tl) crystal. As is described in detail in chap. III.A., this size was considered optimum for the interpretation of the spectrum in the energy region of interest in this experiment. Since the detection efficiency \( \eta = 1-e^{-\mu x} \) is not directly proportional to volume, the thickness of the crystal was kept small to reduce the neutron induced activity in the crystal, which is a volume effect.

The diameter of the crystal was governed partly by the diameter of the photomultiplier and partly by the angular resolution needed in the n-\( \gamma \) angular correlations when the \( \gamma \)-counter was placed at a distance of about 10 cm from the target.

(iii) The Target Assembly

For good stability of the beam current and beam energy the minimum
current strength was found to be about 0.5 $\mu$amp. The target thickness of 100 $\mu$gm/cm$^2$ to 200 $\mu$gm/cm$^2$ was found quite adequate to give reasonable coincidence count rates.
CHAPTER III

DETAILED DESCRIPTION OF INDIVIDUAL UNITS

A. THE GAMMA RAY SPECTROMETER

The gamma ray spectrometer consisted of a cylindrical NaI(Tl) crystal, 1.8" in diameter by 1.0" long, optically coupled to an RCA 7264 photomultiplier. Though from the time resolution point of view, NaI(Tl) has the disadvantage of a relatively long light output decay time (\( T = 250 \text{ nsec} \)), it gives better energy selection, larger pulse height, and has higher efficiency as compared with organic phosphors. In fact an adequate time resolution can be achieved with NaI(Tl) as discussed in appendix III.

The size of the crystal used was mainly governed by the ease in the interpretation of the gamma ray spectrum. In a crystal having dimensions, say 3" diameter by 3" long, each gamma ray in the energy range 2-10 Mev gives rise to three equally predominant peaks; photo peak \( V(E_\gamma ) = KE_\gamma \), (pair + 1) peak \( V(E_\gamma') = K(E_\gamma' - m_0c^2) \), and pair peak \( V(E_\gamma') = K(E_\gamma' - 2m_0c^2) \). The interpretation of a spectrum having several closely spaced gamma rays, therefore, becomes quite difficult. In a smaller crystal, say 2" diameter by 1" long, the pair peak predominates in the energy region of interest in this experiment and the interpretation of the spectrum is simplified.

Also, as has already been mentioned in chap. II.B, neutron capture by \(^{127}\text{I}\) in the crystal results in the prompt emission of gamma rays in the
energy range 4–6 Mev followed by 2 Mev beta decay or 1.6 Mev beta decay and a 0.4 Mev gamma ray. Such an activity in the crystal increases the random background and is less for a smaller crystal.

B. THE NEUTRON COUNTER

NE 213 liquid scintillator, enclosed in a glass cell, 2" diameter by 2" long, and optically coupled to an RCA 7264 photomultiplier, was used as a neutron detector. It has the following properties:

(a) it allows pulse shape discrimination, and so facilitates the reduction of random coincidences due to gamma rays detected in the neutron counter
(b) it has a light output 78% that of anthracene
(c) it has a fluorescence decay time of $2.8 \times 10^{-9}$ sec, and
(d) it has a larger hydrogeneous content than plastic scintillators and is, therefore, more efficient for neutron detection.

Plastic scintillators have the advantage of ruggedness and ease of handling and machining. Plastic NE 150, which also allows pulse shape discrimination, was tried and found to work well over a limited period of time. However it lost its $n-\gamma$ discrimination properties about two months after its preparation, and so was discontinued as the neutron detector in favour of the NE 213 liquid scintillator mentioned above, which showed no sign of deterioration over a period of six months.

C. THE PHOTOMULTIPLIER TUBES

The RCA 7264 multiplier photo tube is a fourteen stage tube and has a rated current gain of $1.25 \times 10^7$ at a voltage of 2000 volts and a spherical photo cathode which assures very good collection by dynode No. 1, of
electrons from all parts of the useful photocathode area. In addition, the specifications for the tube quote a maximum transit time spread of one nsec for electrons simultaneously released within a circle of 1.5" diameter centred on the tube face.

The spherical surface, however, poses coupling problems. The scintillators were coupled to the photomultipliers with lucite light guides. The concave faces of the lucite light guides were machined to fit the spherical surface of the tubes.

Dow Corning* QC-2-0057 optical grease was used as a coupling agent.

D. TIMING ELECTRONICS

(i) General Description

The timing electronics consists of two limiter circuits and a time sorter (TS), which is comprised of a pulse shaping network, a diode current switch and a current integrator.

Upon detection of a gamma ray, the limiter circuit in the gamma channel produces a time pulse \( V(T_\gamma) \), which is shaped by the pulse shaping network. Similarly, upon detection of the associated neutron, a time pulse \( V(T_n) \) is produced by the limiter circuit in the neutron channel. These two time pulses operate the TS which in turn produces a voltage pulse \( V(TS) \), whose amplitude is related to the arrival times of \( V(T_\gamma) \) and \( V(T_n) \) pulses. The TS must be calibrated (see chap. V) before it can be used for absolute flight time measurements.

(ii) The Limiter Circuit (Fig. III.1)

Figure III.1 is the diagram of the limiter circuit. The limiter tube is a sharp cut off pentode which produces a step pulse at the anode with a

* Dow Corning Corporation, Midland, Michigan, USA.
Earlier dynodes not decoupled

Fig. III.1. D3a Pentode limiter circuit.
rise time of about 2 nsec when the grid is driven negative by a pulse from the photomultiplier anode. The amplitude of the step pulse at the anode of the limiter tube is 2.5 volts, which is necessary to get a 1.0 volt pulse at the diode current switch in the TS, the 1.0 volt pulse being required for the correct operation of the current switch.

The circuit as originally designed by Jones (1959) used the high gain, high current 404A (Western Electric) pentode. The circuit was modified (Prescott 1959) to use the less costly El80F (Phillips) tube, which was ultimately replaced by a D3a (Siemens) tube which had the highest gain bandwidth product of vacuum tubes conveniently available at the time (Gain bandwidth product $B \times G = \frac{1}{\pi} \frac{gm}{c}$, where $gm$ is the transconductance (in mho's) of the tube and $c$ is the sum of the grid to ground and plate to ground capacitances). For the D3a tube $\frac{gm}{c} = 3.9$ m amps/V/MF, while the corresponding figures for 404A and El80F are 1.3 and 1.7 m amp/V/MF respectively.

The amplitude of the limiter output pulse is independent of count rates up to 20,000 cts/sec.

(a) D.C. operation of the limiter circuit

Since the operation of the current switch in the time sorter is critically dependent on the amplitude of the limiter output pulse (chap. III.D (iv), the object of the D.C. current arrangements is to stabilize to the maximum degree the limiter pulse shape against changes in tube characteristics, power supply voltages and count rates. This is done by forcing the screen current and grid current to attain constant values in the time interval between pulses. The grid is connected to the screen through a 120 K resistor $R_1$. The screen is connected through the diode $D_1$
to the 60 volts supply and through a 50 K resistor $R_2$ to the 250 volts line. The grid and screen voltages adjust themselves to be compatible with the currents passing through ($i_{sc} = 4 \text{ m amps, } ig = 0.5 \text{ m amps}$), thus ensuring that the resultant plate current is well defined and constant.

Connecting the grid supply resistor to the screen also provides some negative feedback which further assists in stabilising the plate current. If the screen current tends to decrease (indicating reduced tube conduction and decreased plate current), then the screen voltage rises increasing the grid current, and therefore the grid voltage, the increased $V_g$ leads to an increase in the total tube conduction. The plate current change, which would have otherwise occurred, is greatly reduced.

The 60 volts screen supply is adjusted to be a few volts ($\approx 5 \text{ volts}$) more positive than the screen itself. The diode $D_1$ therefore remains cut off in the quiescent state. Monitoring points were supplied to adjust the reverse voltage across the diode $D_1$.

(b) Pulsed operation

The limiter tube is completely cut off with a negative voltage pulse of about 0.7 volts from the photomultiplier anode (A 662 kev gamma ray from a $^{137}$Cs source produces a 200 volt pulse at the photomultiplier anode at E.H.T. = 2000 volts). The resulting positive voltage pulse $V_p$ of amplitude 2.5 volts at the anode of the limiter tube is fed to the 417A cathode follower acting as a cable driver. Because the cathode follower gain is less than unity, and due to the attenuating effects of the 75Ω matching resistances, the amplitude of the output pulse $V(T)$ from the cathode follower is 1 volt, which is sufficient to operate the TS or the DTS. With a limiter tube A.C. plate load of about 150Ω and assuming the plate
capacitance plus the stray capacitance to ground to be \( \approx 10 \) pf, the rise time of the pulse \( V_p \), when the grid is driven by a -ve voltage step function, is estimated to be \( 150 \times 10 \times 10^{-12} = 1.5 \) nsec. With the tube cut off, the screen voltage rises up to the 60 volt supply voltage and is clamped at that value by the diode \( D_1 \). The \( i_g \) current through \( R_1 \) discharges the grid/ground capacitance \( C_1 \) that had been charged negatively by the current pulse from the photomultiplier anode. Since \( i_g \) is approximately constant, the grid voltage recovers to its original value (\( \approx 0.5 \) volts), linearly rather than exponentially. The linear rise is preferable from the point of view of count rate insensitivity. Thus a wave form of the type shown in fig. III.1 is produced at the limiter grid.

When the grid has recovered, the tube starts conducting again. The diode \( D_1 \) turns off as the screen current rises. The screen voltage drops from 60 V to its normal value of \( \approx 55 \) volts with a time constant of \( R_2 C_2 = 50 \times 10^3 \times 20 \times 10^{-12} = 1 \) \( \mu \)sec. Thus the count rate effects are kept to a minimum. A further source of count rate shifts, the coupling condenser between the photomultiplier anode and the grid of the limiter tube, was removed by operating the photomultiplier at a negative H.T., so that the anode of the photomultiplier could be directly connected to the grid of the limiter tube.

Monitoring points were supplied to measure the standing plate current.

(iii) Pulse Shaping Network

The pulse shaping network, \( Z_s \), consists of a fixed length of RG58A/U delay line shorted at one end. The cable has a characteristic impedance \( Z \) of 50 ohms and a capacity \( C \) of 29.5 \( \mu \)F/ft specified by the manufacturer.

A characteristic impedance of 50 ohms is required for the delay cable \( Z_s \).
in order to match the impedances between this line and the two effectively parallel 100 \ \Omega \ lines \ Z_1 \ and \ Z_2 \ (see \ fig. \ III.2) \ from \ the \ two \ limiters.

The cables from the individual limiters are, however, mismatched at the junction J_1, the impedance seen by each at this point being the parallel combination of Z_o and the other 100 \ \Omega \ line, that is \ \frac{50 \times 100}{50 + 100} = 33 \ \Omega .

This produces a reflection ratio of \ \frac{100 - 33}{100 + 33} = 0.5, for pulses incident on J_1 from either of the limiter lines, which means that only half of the limiter pulse actually reaches the diode switch S_1. The lines Z_1 and Z_2 are sufficiently well matched at their driven ends that multiple reflections in the limiter cables are not a problem.

(iv) **Time Sorter**

(a) **General description**

The time sorter consists of a pulse shaping network (Z_o, Z_1 and Z_2 at J_1), a diode current switch D_1 and D_2, and a Miller current integrator as shown in fig. III.2. It has the following characteristics, determined by the methods described in chap. V.

1. An intrinsic electronic resolution time (defined as full width at half maximum height (FWHM) of the V(TS) spectrum obtained by electronically generated standard pulses driving the limiters) of less than 0.1 nsec.

2. A time resolution (FWHM) of 1.50 ± 0.05 nsec when both the neutron detector and the gamma detector were responding to 0.51 Mev annihilation radiation from a Na^{22} source. This time resolution was obtained when certain amplitude restrictions were placed on the V(E_y) and V(E_n) pulses, as described in chap. V.

3. A time/voltage calibration in the range 5-45 nsec which is a linear function of \ T_n - T_y \ ie \ V(TS) = \sum k \left[ T_o - (|T_n - T_y|) \right]. \ The \ proportionality \ constant, \ k , \ was \ found \ to \ be \ constant \ to \ within \ 1\% \ over \ the \ course \ of \ a \ day.
Fig. III.2. Circuit diagram of the time sorter.
(b) **Operation of the time sorter**

The operation of the time sorter can briefly be described as follows:

1. Upon detection of a gamma ray at time \( t_\gamma \), the gamma limiter output cathode follower produces a voltage pulse \( V(T_\gamma) \) of amplitude \( V_0 = 1 \text{V} \) which rises in a time \( T \approx 2 \text{nsec} \) and after remaining at 1 volt for about 2 \( \mu \text{sec} \) recovers to zero linearly in about 0.1\( \mu \text{sec} \) (fig. III.3a). \( V(T_\gamma) \) reaches \( J_\perp \) at time \( T_\gamma = t_\gamma + t_c \gamma \) where \( t_c \gamma \) is the delay in the interconnecting cable.

2. The pulse shaping network shapes this voltage pulse into a rectangle of \( \frac{1}{2} \) of the amplitude \( V(T_\gamma) \) and a fixed length in time of \( T_s \) (fig. III.3b).

3. The neutron detector upon detection of a neutron at time \( t_n \) produces a voltage pulse \( V(T_n) \) from the neutron limiter, of the same characteristics as that produced by the gamma limiter, which is also shaped to the same fixed length \( T_s \) (fig. III.3c) and reaches \( J_\perp \) at time \( T_n = t_n + t_c n \) where \( t_c n \) is the delay in the interconnecting cables. In this discussion, unless otherwise specified, \( t_c \gamma = t_c n \). If \( V(T_n) \) occurs within a time interval \( T_s \) of \( V(T_\gamma) \), a linear superposition of the two pulses occurs at the input to the diode switch. The diode switch is so biased that it is operated only by the overlap portion of the two pulses (fig. III.3d).

4. During the time of overlap of the two pulses, the constant current \( I_s \) (which in the quiescent state flows to ground through \( D_1 \)) is switched to flow through \( D_2 \) to the input of the Miller current integrator. This fixed current is then integrated in the capacitor \( C_m \) and a pulse of the form shown in fig. III.3e is obtained at the output of the time sorter. The amplitude of the output pulse is given by

\[
V(TS) = k \left[ T_s - |T_n - T_\gamma| \right]
\]
Fig. III.3. Time sorter pulse wave forms.
where \( k \) is a constant of proportionality and can be determined experimentally (chap. V).

Approximately

\[
V(TS) = \frac{\Delta I_s}{C_m} \left[ T_s - |(T_n - T_f)| \right] \left( \frac{Z_o}{Z_{in}} \right)^{1/2}
\]

where \( Z_{in} \) and \( Z_o \) are the input and output impedances of the pulse transformer TR1. For example \( V(TS) \) is approximately =0.5V for \( T_n = T_f \), \( T_s = 50 \) nsec, \( I_s = 1.25 \) m amps and \( C_m = 43 \) pf.

(c) Time to pulse height conversion - detailed description

The D.C. characteristics of the diode current switch utilising IN23C diodes are shown in fig. III.4. The D.C. output current \( I \), that is that current flowing through diode \( D_2 \) into the integrator, is plotted as a function of \( (V_{D1} - V_{bias}) \) where \( V_{D1} \) is the voltage applied at \( J_1 \) to the cathode of \( D_1 \) and \( V_{bias} \) is the bias voltage at the cathode of \( D_2 \). As is seen from the diagram a pulse at \( J_1 \) of amplitude greater than 0.5 volts would be sufficient to switch the output from zero to full current, provided that the pulse switching characteristic of the system are identical to the D.C. characteristics (this is not true for very short pulses because of inductance capacity and hole storage effects).

With perfect diodes a bias of \( V_{bias} = V_p \) would be required to prevent a pulse of amplitude \( V_p \) at \( J_1 \) from operating the current switch. Since the diodes are not perfect (i.e. there is \( \approx 50\% \) output for \( V_{bias} = 0 \)) sufficient bias must be applied to prevent formation of an output pulse when single pulses are incident on \( J_1 \). This value is found to be about 0.2V greater than the incident pulse, i.e. \( V_p + 0.2V \) amplitude. Then in order that
Fig. III.4. D.C. response of the diode current switch using 1N23C diodes.

Ideal characteristics for perfect diodes
an input pulse $V_p$ should not produce any output, $V_{bias} \geq 0.2V + V_p$. If $V_{bias}$ is set equal to $0.2 + V_p$, there will be no output for a single pulse $V_p$ at $J_1$, since the voltage applied across the current switch then is equal to $-0.2V$.

However during the overlap portion of the two pulses $V(T_y)$ and $V(T_n)$ which occur within time $T_s$ of each other, the voltage applied across the switch is

\[
(V_{D1} - V_{bias}) = (2V_p - 0.2V - V_p) = V_p - 0.2V
\]

From fig. III.4, if $V_p = 0.5$ volts, $(V_p - 0.2)$ volts is just sufficient to drive the current switch to full output (obviously bigger pulses than $V_p = 0.5$ volts would allow larger biases and larger switching margins of safety).

Pulse $V(T_y)$ and $V(T_n)$ of amplitude 0.5 volts should, therefore, produce satisfactory switching with a bias of about 0.7 volts.

Experimentally, the pulsed operation is slightly different from the one obtained under D.C. conditions (for example a voltage pulse of amplitude slightly greater than 0.5 volts is needed to operate the TS properly).

The bias is so adjusted as to give minimum time resolution (FWHM) as defined previously.

The output of the circuit as a function of pulse time overlap is shown in fig. III.5. The limiters were driven electronically by the same source (EPIC 200 Mercury Pulse Generator), while a relative delay was introduced into one limiter with respect to the other by means of a
Fig. III.5. Time sorter output $V(TS)$ as a function of $(T_n - T\gamma)$.
continuously variable delay inserted in the line connecting the pulser with that limiter. The non-linear response in the region A (of complete and near complete overlap) is ascribed to hole storage and minority carrier conduction effects in the diodes (Jones 1959).

E. THE DELAYED TIME SORTER (DTS)

The DTS is used to eliminate those chance coincidences in which \( V(T_n) \) precedes \( V(T_T) \), that is where \( T_n < T_T \), and also to veto some pulses for which \( T_T \leq T_n \).

The circuit components, and their basic operation, in the DTS are the same as those of the TS; the only difference being in the relative sequence of time delays. This difference is produced by introducing an extra delay in the \( V(T_n) \) pulse reaching the DTS; and hence the name. Figure 6a,b gives the sequence of pulses in TS and DTS.

(a) The elimination of all \( T_n < T_T \) (Region IV, fig. III.6c)

It will be recalled that the output of the TS is given by (chap.I.B.)

\[
V(TS) = \delta_+ \left\{ k \left[ T_s - (T_n - T_T) \right] \right\} \quad (1)
\]

The DTS is driven by the same \( V(T_n) \) and \( V(T_T) \) pulses, but the \( V(T_n) \) pulse is delayed an extra amount \( T_D \) in going to the DTS diode switch. The output of the DTS is, therefore, given by

\[
V(DTS) = \delta_+ \left\{ k \left[ T_s - (T_D + T_n - T_T) \right] \right\} \quad (2)
\]

\( V(DTS) \) triggers Disc 2, whose output is given by
Fig. III.6a,b. Time sorter and delayed time sorter pulse wave forms

Fig. III.6c. Performance of the DTS, disc 2 and disc 1.
\[ V(\text{Disc 2}) = \frac{-X}{|V(\text{DTS}) - V_2|} \delta_+ \left[ \frac{V(\text{DTS}) - V_2}{V(\text{DTS})} \right] \]  

(3)

i.e.

\[ V(\text{Disc 2}) = -X \quad \text{if} \quad V(\text{DTS}) > V_2 \]

(4)

\[ = 0 \quad \text{if} \quad V(\text{DTS}) < V_2 \]

where \( V_2 \) is the discrimination level of Disc 2 and \( X \approx 2 \) volts. Usually \( V_2 \ll V(\text{DTS}) \), so that

\[ V(\text{Disc 2}) = \frac{-X}{|V(\text{DTS})|} \delta_+ \left[ V(\text{DTS}) \right] \]  

(5)

However it is occasionally convenient to use larger values of \( V_2 \), see sec. (c) below.

If \( T_D \) is chosen equal to \( T_g \), the DTS circuit functions as the Negative Time Eliminator as described by Neilson, Dawson and Johonson (1959). With this choice of \( T_D \), from equation (2)

\[
V(\text{DTS}) \text{ is zero for } T_n > T_g \\
V(\text{DTS}) \text{ is +ve for } T_n < T_g
\]

and using approximation of eq. (5), \( V(\text{Disc 2}) \) is then produced for all \( T_n < T_g \). \( V(\text{Disc 2}) \) is used as a veto pulse to eliminate \( V(\text{TS}) \) pulses with \( (T_n - T_g) \) negative.
(b) Eliminating \( T_n = T_\gamma \)

Prompt \( \gamma-\gamma \) coincidences, where a gamma ray is detected by both the neutron and gamma detectors, give rise to time pulses such that \( T_n = T_\gamma \). These events can be eliminated by making \( T_D = (T_S - T_R) \) where \( 2T_R \) is the full width at zero amplitude of the time resolution function. Then the DTS output is

\[
V(DTS) = \delta_+ \left\{ k \left[ T_S - (|T_D + T_n - T_\gamma|) \right] \right\} \\
= \delta_+ \left[ k (T_S - T_D) \right] \text{ since } T_n = T_\gamma \\
= \delta_+ [k (T_R)] \quad (6)
\]

The resulting non-zero \( V(DTS) \) for \( T_n = T_\gamma \) produces a veto pulse from Disc 2. Because of the finite size of \( T_R \), positive time overlap interval lying from \( (T_n - T_\gamma) = 0 \) to \( (T_n - T_\gamma) = T_R \) is lost. This, however, does not matter, since physically interesting events almost never occur in this time interval.

(c) Elimination of some positive time overlap pulses (Reg.III, fig.III.6c)

Extending the argument of the previous section, it can be seen that by further decreasing the value of \( T_D \), successively larger sections of the positive overlap time interval can be vetoed by the DTS. Thus a particular time interval, for example an interval containing a single neutron group can now be selected from a complex time-of-flight spectrum. The lower energy neutrons with smaller time overlaps lying in region I, fig. III.6c, are vetoed by Disc 1. The higher energy neutrons lying in region III are
eliminated by the DTS and Disc 2 as explained below.

Pulses with \( +ve \ (T_n - T_f) \) lying in region III will be vetoed if

\[
V(DTS) = \delta_+ \left\{ k \left[ T_s - ( |T_n + T_D - T_f| ) \right] \right\} > V_2 \quad (7)
\]

This inequality can be satisfied for any given \( T_n = T_n^0 \) (that is for any given neutron energy) by suitably choosing either \( T_D \) or \( V_2 \) or both in combination. Thus all neutrons of energy greater than those giving pulses at \( T_n^0 \) are vetoed by the DTS.

The overall performance of the TS and the DTS is shown in fig. III.6c. \( V(DTS) \) is always maximum for \( -(T_n - T_f) = T_D \). The output of the TS, after action of veto driven by DTS, is

\[
V(TS) = \delta(DTS) \delta_+ \left\{ k \left[ T_s - ( |T_n - T_f| ) \right] \right\} \quad (8)
\]

where

\[
\delta(DTS) \equiv 1 \quad \text{if} \quad V(DTS) \leq V_2
\]

\[
\equiv 0 \quad \text{if} \quad V(DTS) > V_2 \quad (9)
\]

F. PULSE SHAPE DISCRIMINATION - General Description and Results

In fast neutron spectroscopy with the time-of-flight technique, one of the principal practical aims is to obtain a sufficiently high ratio of true events to background counts. The background radiation incident on the neutron detector consists chiefly of neutrons scattered from the floor or produced elsewhere than at the target (for example in the magnet box), and
the gamma rays from the target. In the neutron counter shield itself (see chap. IV), which typically consists of a mixture of paraffin wax and lithium carbonate, many of the background neutrons are converted into gamma rays by capture and inelastic scattering events. Because the organic phosphors used as neutron detectors exhibit a dependence of the intensity of the emitted light on the ionisation density of the ionising particle (Birks 1951), the pulse height due to a gamma ray is at least a factor of two bigger than the pulse height due to a neutron of the same energy. Hence many of these gamma rays producing pulses whose amplitudes are greater than those produced by the neutrons being studied can be eliminated by utilizing a pulse height selector on the $V(E_n)$ pulse. But since the detection of gamma rays in organic phosphors occurs mainly through Compton effect, a relatively large fraction of the gamma rays produce voltage pulses in the same amplitude range as the neutron pulses of interest. However it has been found possible, by examining the shape of the photomultiplier pulse, to distinguish between scintillations produced by electrons and those of heavy ionising particles. In this way it is possible to reject a large fraction of the unwanted gamma ray pulses without reducing neutron detection efficiency.

This technique of pulse shape discrimination in organic scintillation crystals was first suggested by F. D. Brooks (1956). It is based on the fact that the organic phosphors have a slow (200-400 nsec) scintillation component whose intensity depends on the nature of the exciting particle (C. T. Wright 1956). It was found by Owen (1958) that for pulses having the same peak height, the slow component was about twice as intense for proton excitation as for electron excitation. The fast component was found to be independent of the nature of the exciting particle. Recently developed organic
scintillators (Brooks et al 1960) which exhibit these characteristics have, therefore, become a valuable tool in Nuclear Spectroscopy.

Many circuits have since been put forward to distinguish between different exciting particles. Some of these have been discussed in a survey article by R. B. Owens (1962). In the method proposed by Owen himself, the photomultiplier is driven into saturation and so the anode pulse cannot be used for other purposes (e.g. to drive a fast coincidence unit).

In the method proposed by Brooks, two voltage pulses are obtained from the photomultiplier; the first from a dynode connected to a high resistance $R_2$ and the second from the anode connected to a resistance $R_1$ and a capacitor $C_1$ through a diode. The integration time constant $R_1C_1$ of the anode pulse is determined by the requirements of the pulse shape discrimination circuit and so is not free to be chosen to meet other requirements. Circuits designed by Neilson et al (1959) and Batchelor et al (1960) require two photomultipliers to view the same phosphor, a procedure which, in addition to being costly, limits the speed of the fast channel by reducing the light input to a single photomultiplier by a factor of two.

The circuit used in the work described in this thesis is similar in design to that of Rethmere et al (1961) and has the following characteristics.

(1) It utilizes only one photomultiplier and does not require a special (e.g. high speed) type of photomultiplier. It has successfully worked with a 2" diameter RCA 7264 photomultiplier coupled to a 2" diameter by 2" long NE213 liquid scintillator.

(2) The photomultiplier is operated linearly with only a single dynode signal being required for the operation of the circuit (unlike the circuit by L. J. De Vries and F. Udo 1961, which requires two dynode signals).
The anode signal can be used to drive any other circuit (the timing circuit in this case).

(3) It is very simple in design and consists of only nine active elements. No fast circuitry is required.

(4) The circuit utilizes the same principle, though not the same technique, as developed by Alexander and Goulding (1961).

The block diagram of the system is shown in fig. III.7. Positive pulses from the eleventh dynode of an RCA 7264 photomultiplier, after amplification, are shaped by an HH2500 shorted delay line (2t = 3μsec). The time constants at the dynatron amplifier are so adjusted that the shaped pulses have as little negative overshoot as possible if the pulses from the phototube are produced by neutrons. The required time constants were experimentally determined by using neutrons from the D(d,n) reaction. Under these conditions, the shaped pulse will cross zero and produce a negative overshoot for pulses with a smaller fraction of the long lived component, i.e. gamma rays in organic phosphors. The pulse shape discrimination circuit triggers on this negative overshoot producing an output pulse of -10 volts amplitude and 6 μsec duration which is used for anticoincidence purposes.

The following results were obtained utilizing this circuit. When 90.0 ± 0.5% of the 2.9 MeV neutrons from the D(d,n) reaction were counted by the system, 98.3 ± 0.5% of the pulses from a RaTh Source and 95.8 ± 0.2% of the gamma rays from a Co^{60} source above 400 kev (above channel 20 in figs. 8 to 10) were rejected by pulse shape discrimination (all percentages quoted are relative to count rates obtained when the PSD was not used). The results are shown in fig. III.8,9 and 10. Figure 8a is the ungated spectrum of the 2.9 MeV neutrons while fig. 8b gives the same spectrum when
Fig. III.7. Block diagram of the pulse shape discriminator assembly.
Fig. III.8. Performance of the pulse shape discriminator using 2.9 Mev d-d neutrons.

(a) Neutron spectrum (ungated)
(b) Neutron spectrum (gated from n- $\gamma$ PSD)
Fig. III.9. Performance of the pulse shape discriminator using gamma rays from RaTh source.

(a) RaTh (ungated)
(b) RaTh (gated from n-γ PSD)
Fig. III.10. Performance of the pulse shape discriminator using gamma rays from Co$^{60}$ source.

(a) Co$^{60}$ (ungated)
(b) Co$^{60}$ (gated from n-γ PSD)
gated by the pulse from the n - \( \gamma \) discriminator. Similarly fig. 9a and 10a illustrate the ungated spectra and 9b and 10b show the gated spectra of pulses from a Rath source and a Co\(^{60} \) source respectively.

For the purpose of comparison, the results obtained by Alexander (1961) are quoted here. With the PSD set to reject 99.5\% of the gamma ray pulses from a Rath source above approximately 400 kev, 65\% of the 2.5 Mev neutrons detected by the counter (as determined by the 400 kev amplitude discriminator) from the \( D(d,n) \) reaction and 75\% of the 14 Mev neutrons from \( T(d,n) \) were counted. NE 212 liquid scintillator, 2" in diameter by 4" long, was used as the neutron detector.

(ii) Operation of the Circuit

Figure III.11 is the circuit diagram of the PSD. The input pulses are shaped by the shorted line L, then differentiated by a small time constant, \( R_1 C_1 \), so that virtually all the pulses produce a negative overshoot at the base of the saturated transistor \( T_1 \), cutting it off, and so producing positive pulses of constant amplitude at the collector of \( T_1 \). The positive pulses trigger the univibrator consisting of \( T_2 \) and \( T_3 \) thus initiating a pulse at the base of \( T_4 \). The amplitude of this pulse can be varied from 0-5 volts with the 10 K variable resistor \( R_2 \).

In the lower part of the circuit, the diode \( D_5 \) transmits only the negative overshoot of the shaped pulse. After amplification and inversion by \( T_6 \), it then appears at the base of \( T_5 \) in time coincidence with the pulse from the univibrator. The emitters of \( T_4 \) and \( T_5 \) follow the positive part of the pulse at the base of \( T_5 \) for a time determined by the length of the univibrator pulse at the base of \( T_4 \). After integration by \( T_7 \), this pulse is then used to trigger the univibrator consisting of transistors \( T_8 \) and \( T_9 \).
Fig. III.11. Circuit diagram of the pulse shape discriminator.

$T_1, T_5, T_7, T_8$ and $T_9 = 2N167$

$T_6, T_2$ and $T_3 = 2N450$

$T_4 = 2N465$
producing an output pulse at the collector of \( T_9 \) which is used to drive the anticoincidence gate in fig. II.1. The variable 2K resistor, \( R_3 \), is used to adjust the trigger level of the univibrator and the condenser \( C_1 \) determines the length of the output pulse.

The discrimination level is very sensitive to changes in the D.C. voltage supply which should, therefore, be stable to better than 0.5%. The circuit is otherwise quite reliable and gives reproducible results over long periods of time.

G. **DISCRIMINATORS 1 AND 2**

The circuit diagram (McCollom 1959) of the discriminators (Disc 1 and Disc 2) is shown in fig. III.12. Here the basic Kandiah (1954) circuit is adapted to rapid response. Separate cathode resistors are used to stabilize each tube. The diode \( D_1 \) is used as the discriminating element.

The circuit operates with negative input pulses. A negative input pulse reduces the current in \( V_1 \) and consequently the clamping current in \( D_1 \). At the triggering threshold the impedance of \( D_1 \) becomes great enough for a loop gain of unity. \( D_2 \) limits the excursion of the grid of \( V_2 \). The feedback loop is completed by the 0.002 \( \mu F \) condenser that couples the rise of the cathode of \( V_2 \) to the cathode of \( V_1 \).

The output pulse width is determined by the time required for the cathode of \( V_1 \) to drop to its initial value, that is \( T = \frac{CV}{i_c} \), where \( C \) is the coupling capacitor, 0.002 \( \mu F \), \( V \) is the 4 volt signal at the grid of \( V_2 \) and also at the cathode of \( V_2 \) by the cathode follower action, and \( i_c \) is the cathode current of \( V_1 \), that is 8.5 m amps. Therefore \( T = \frac{2 \times 10^{-9} \times 4}{8.5 \times 10^{-3}} \sim 1 \mu\text{sec.} \)
Fig. III.12. Circuit diagram of discriminators 1 and 2.
Reliable operation with a threshold of 20 to 100 m volts was obtained using a 1N100 for $D_1$. The threshold was determined by the potentiometer which regulated the current through $D_1$ between 100 $\mu$amps and 300 $\mu$amps. The stability in discrimination threshold was better than 1% over the course of a day.

For Disc 1, the output was taken from the plate of $V_1$. A cathode follower was used as a cable driver and to isolate the discriminator circuit from the coincidence unit. The output pulse was +2 volts in amplitude. For Disc 2, the pulse width was increased to 2 $\mu$sec by doubling the coupling capacitor. The output pulse amplitude was -2 volts, and the output was taken from the plate of $V_2$. A cathode follower was used as a cable driver.

H. THE SLOW COINCIDENCE/ANTICOINCIDENCE UNIT

Figure III.13 is the circuit diagram of the slow coincidence/anti-coincidence unit utilizing standard diode circuitry. A total standing current $i_s$ of about 2 m amps flows through the diodes $D_1$, $D_2$ and $D_3$. Coincident pulses at the inputs I, II and III cut off the standing current and the voltage at the base of $T_3$ rises to 2 volts, which is the amplitude of $TS$ (Disc 1), the minimum of the 3 inputs. $T_3$ is an emitter follower whose output pulse is amplified to actuate the pulse height selector which is biased to give a standard shaped output pulse in response to a 3 fold coincidence.

If there is an anticoincidence pulse at input IV, $i_s$ passes to ground through $D_4$ and $T_2$. There is then no rise in voltage at the point A and the output pulse does not occur. Transistors $T_1$ and $T_2$ allow proper matching of

* Millman and Taub 1956, p.398
All diodes 1N96
All resistors 1/2 watt, 20%

Fig. III.13. Circuit diagram of the triple coincidence/anticoincidence unit.
the HH 2500 delay lines that are used to delay the signals at inputs III and IV.
CHAPTER IV

BACKGROUND SHIELDING

In a neutron time-of-flight spectrum the background, consisting chiefly of random coincidences, usually has a flat time dependence, and the sharp neutron peaks can therefore be distinguished to a certain extent (fig. IV.1). Nevertheless, since the subtraction of background lying under the neutron peaks increases the error in the resulting neutron count rates, the background must be kept to a minimum. Therefore, since the random coincidence count rate is directly proportional to the squared instantaneous value of the total count rate in the detectors, it is essential to shield the detectors to keep down the count rate due to background radiation. Figure IV.2 shows the cross-sectional view of the neutron counter shielding using tapered hole collimation. The neutron counter was shielded against gamma rays by surrounding it with lead, and against neutrons by placing it inside a hydrogenous shield.

Hydrogeneous materials, like paraffin wax, are used to thermalize neutrons as they are by far the most effective because of large energy loss per collision. Production of 2.22 Mev gamma rays from thermal neutron capture by hydrogen in the shielding was reduced by loading the paraffin wax with lithium carbonate in which the thermal neutrons are removed by the reaction \( \text{Li}^6(n,\alpha)\text{H}^3 \). Lithium carbonate is preferable to boron loading since 480 kev gamma rays are produced by thermal neutron capture in the latter.
Fig. IV.1. Time-of-flight spectrum of neutrons from Be\(^9\)(d,n\(\gamma\))B\(^{10}\).

\(E_d = 800\) Kev, \(\theta_n = 60^\circ\).
Neutron counter at 50 cm.

Fig. IV.2. Neutron counter shielding.
A 50% mixture by weight of lithium carbonate and paraffin wax was tried. A mixture richer in lithium carbonate than the present one was considered undesirable since it would decrease the density of hydrogen and neutron shielding would be less efficient per unit thickness.

Shielding with lithium hydride bonded together by paraffin should be very nearly the ideal hydrogeneous shielding (Langsdorf Jr. 1961) for all cases in which capture gamma rays are troublesome. But this method was not employed since lithium hydride was not locally available and was also more costly.

Neutrons scattered out of the scintillator itself may reflect back into the scintillator from the shielding around it. This undesirable effect was reduced by making the lead shield large enough to leave a cavity around the scintillator.

The gamma counter was shielded by a 1" thick lead casing. Since it was placed quite near the target, wax shielding from neutrons was quite impracticable.
CHAPTER V

CALIBRATION AND OPERATION OF THE EQUIPMENT

A. CALIBRATION OF THE TIME SORTER

The time-to-pulse height conversion factor of the time sorter was measured by driving both detectors simultaneously with the annihilation radiation from a Na$^{22}$ source and by inserting known time delays in the system. The required time delay was obtained either by inserting extra measured cable lengths between one limiter and the time sorter or by suitably placing the Na$^{22}$ source so as to produce various relative delays between $T_n$ and $T_\gamma$. The latter method is more reliable for time resolution measurements and is useful for time calibrations over small time ranges (1-5 nsec), but is not feasible for the time calibration of the circuit over the whole (50 nsec) range; the counters in that case would have to be moved about 10 meters apart and the coincidence count rate would be prohibitively small. The complete time calibration curve was, therefore, obtained by inserting measured cable lengths; small intervals of the time calibration curve (and also time resolution measurements) were done by the gamma ray method.

The Na$^{22}$ source was placed on the line joining the two counters, which were placed about 20 inches apart. The time pulses $V(T_\gamma)$ and $V(T_n)$ from the two counters were fed to the time sorter. The $E(\gamma)$PHA was set to accept only the photopeak from the 0.51 Mev annihilation radiation while
the E(n)PHA was set to accept only the peak of the compton distribution (see fig. V.1). Time sorter output curves were obtained on the 256 channel N.D. Analyser for various cable lengths inserted between the neutron limiter and the time sorter (fig. V.2). The time sorter output amplitude was defined as the channel number corresponding to the centroid of the TS spectrum. In this way a calibration curve as shown in fig.V.3 was obtained. The response is linear up to at least 40 nsec and the slope is 2.5 channels/nsec.

B. MEASUREMENT OF THE VELOCITY OF PULSES IN TELCON AS48M CABLE

The two counters were placed about a meter apart. A strong 50 μc Na^{22} source was placed on the line joining them at a distance of about 30 cm from the gamma counter and a time sorter output curve was obtained on the kick-sorter. The Na^{22} source was then moved 45 cm away from the gamma counter thus adding a relative delay of 3 nsec to the already existing delay between the neutron and gamma detector pulses (velocity of gamma rays in air assumed to be 3 x 10^8 meters/sec) and another V(TS) spectrum obtained on the kick-sorter. This time delay was compared with the time delay obtained when fixed lengths of AS48M cable were inserted between the gamma detector and the time sorter. In this way a value of (2.55 ± 2%) x 10^8 meters/sec for the velocity of voltage pulses with nsec rise times in AS48M cable was obtained; a value in good agreement with that of Jones (1959) - (2.48 ± 0.05) x 10^8 meters/sec and with the value 2.50 x 10^8 meters/sec obtained by the author by measuring the resonant frequencies of open and closed-end lines.

Type N, 75 ohm impedance, Amphenol connectors were used throughout the fast pulse portion of the circuitry.
Fig. V.1. The $V(E_n)\text{PHA}$ and the $V(E\gamma)\text{PHA}$ settings for time resolution measurements using annihilation radiation from a Na$^{22}$ source.
Fig. V.2. $\gamma$-ray time-of-flight resolution curves.
Channel number corresponding to centroid of TS spectrum

Relative delay between $V(T_{n})$ and $V(T_{Y})$

Slope
2.5 channels/nsec

Fig. V.3. Time sorter calibration curve.
C. COUNT RATE EFFECTS

The count rate effect on the V(TS) spectrum is shown in fig. V.4. The measurements were made by placing the counters about 30 cm apart with a Na$^{22}$ source placed halfway between them. The solid circles represent the V(TS) spectrum obtained with a weak source (2 $\mu$C) and the open circles represent the V(TS) spectrum with a strong source (50 $\mu$C). The respective count rates in the Na I(Tl) counter were 1000 cts/sec and 20,000 cts/sec. These count rates were measured by setting the lower level discriminator of the E($\gamma$)PHA just above the noise level and by counting all the pulses above this level. There was no significant change either in the slope of the TS output curve or in the position of the centroid of the curve.

D. TIME RESOLUTION OF THE EQUIPMENT

For the time resolution measurements the time/pulse height calibration was first established by the gamma ray method (sec V.A). The E($\gamma$)PHA and the E(n)PHA were set as shown in fig. V.1. The measurements were made with a weak source (2 $\mu$C) and collimated beams of gamma rays (produced by Pb collimators with a 1 cm diameter hole) were allowed to hit the centres of the detectors. The following results were obtained.

(1) A time resolution of $1.95 \pm 0.05 \times 10^{-9}$ sec using NaI(Tl) crystals 1" long by 1" diameter on one photomultiplier and 1" long by 1.8" diameter on the other.

(2) A time resolution of $1.50 \pm 0.05 \times 10^{-9}$ sec using a NaI(Tl) crystal (1" diameter by 1" long) on one photomultiplier tube and a plastic NE 102 scintillator (1.5" diameter by 1" long) on the other tube.

(3) An electronic time resolution of less than $0.1 \times 10^{-9}$ sec when the
Legend:
- High count rate (20,000 cts/sec)
- Low count rate (1,000 cts/sec)

Fig. V.4. Time-of-flight spectrum of gamma rays showing count rate effects.
grids of both the limiters were driven by $>10$ volt negative pulses from an Epic 200 Mercury Generator, rather than by photomultiplier anode pulses.

(4) A time resolution of $0.3 \times 10^{-9}$ sec, when both the limiters were driven by the same pulse from a photomultiplier viewing a plastic scintillator detecting gamma radiation from a Na$^{22}$ source. The degradation of time resolution compared with (3) is due to a combination of the following effects.

(a) The "walk" of the pulse (the "walk" is the variation in the time required to cut off the limiter tube after the arrival of the photomultiplier anode pulse. This effect is illustrated in fig. V.5 and is caused by the differences in the amplitudes of the anode pulses). Although both limiters are driven by the same pulse, when 'walk' is combined with

(b) slight differences between the $V_g/i_p$ curves of the limiter tubes, the result is to produce pulses of slightly different rise times in the two limiters.

Fig. V.5. The "walk" of the anode pulse.
A time resolution of $0.56 \times 10^{-9}$ sec, when both the limiters were driven by the same pulse from the NaI(Tl) counter. The increase in the time resolution compared with (4) is believed to be due to longer decay time (250 nsec) of scintillations in NaI(Tl) crystal than in plastic NE 102 ($T = 3.5$ nsec).

**E. OVERALL STABILITY OF THE EQUIPMENT**

The stability of the whole system was tested by two independent methods. Firstly two sets of time calibrations, taken four days apart, were plotted on the same graph. It was found that, within the experimental error, the slope of the calibration curve remained the same. Secondly, two time-of-flight spectra of neutrons leading to the 6.5 Mev level in $^{11}$C were taken twenty four hours apart (fig. V.6). The peaks of the time-of-flight curves were found to fall in the same channel. The stability of the whole system was, therefore, considered quite satisfactory for the experimental measurements to be described in this thesis.

All equipment, whose stability in any way affected the accuracy of the electronic system, was operated from highly stabilized power supplies. These are listed below.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Power Supply</th>
<th>Stability of Power Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Photomultipliers</td>
<td>Northeast Scientific Corporation</td>
<td>0.01% per hour, 0.1% per day</td>
</tr>
<tr>
<td>(2) H.T. and heater supplies for Limiter, TS and DTS circuits</td>
<td>Lambda Model 28</td>
<td>better than 1% from no load to full load and line voltage variations of $\pm$ 10%.</td>
</tr>
<tr>
<td>(3) Transistorized equipment (PSD)</td>
<td>Hewlett Packard Model 721 A</td>
<td>better than 0.3% from no load to full load and line voltage variations of $\pm$ 10%.</td>
</tr>
</tbody>
</table>
Fig. V.6. Neutron time-of-flight spectra from $^{10}\text{B} (d,n \gamma)^{11}\text{C} \gamma_{6.49 \text{ MeV}}$, taken 24 hours apart.
PART TWO

EXPERIMENTAL STUDIES

OF

$\text{B}^{10}(d, n \gamma')\text{C}^{11}$
CHAPTER VI

THE $^6$B$_{10}$(d,n$^\gamma$)$^6$C$_{11}$ REACTION

A. INTRODUCTION AND PREVIOUS WORK

Because of their relatively simple structure, nuclei with unfilled lp shell configurations lying between He$^4$ and O$^{16}$ have been the subject of considerable theoretical and experimental interest. Among these nuclei, the mirror nuclei $^6$B$_{11}$ and $^6$C$_{11}$ are important because they are in the middle of the lp shell. However the spins and parities of the levels of $^6$C$_{11}$, which are experimentally difficult to measure, had until recently remained quite uncertain, while the situation in $^6$B$_{11}$ was somewhat clearer (Hinds and Middleton 1962, and references therein).

The experimentally measured energy level scheme for $^6$C$_{11}$ up to an excitation of 6.5 Mev (Ajzenberg-Lauritsen 1962) is shown in fig. VI.1. On the assumption that these states arise mainly from excitations within the lp shell, the intermediate coupling shell model predicts (Kurath 1956) the ordering of these levels to be $(3/2)^-,(1/2)^-,(7/2)^-,(5/2)^-\text{ and } (3/2^*)^-$. Some freedom in ordering is available depending upon the values of the intermediate coupling parameter $a/K$ and the radial integral parameter $L/K$. The theoretical level scheme for $a/K = 6, L/K = 6.8$ and $K = 0.9$ Mev is also shown in fig. VI.1.

For deuteron bombarding energies of greater than 7 Mev (for which Butler's theory is a good approximation), the angular distribution of
Fig. VI.1. Energy level diagram of $^{11}$C.

Fig. VI.2. $J^\pi$ assignments to the excited states of $^{11}$C
(after McDonell et al 1960).
neutrons leading the ground state, and first, second, third and fifth excited states can be well fitted with Butler's curves having $\ell_p = 1$ (Cerineo 1956, Maslin et al 1956). As the ground state of $^{10}\text{B}$ is known to be $3^+$, the assignment of $\ell_p = 1$ from the stripping patterns determines the parity of the corresponding states in $^{11}\text{C}$ as $-ve$, consistent with the independent particle shell model predictions. The $\ell_p = 1$ assignments also restrict the $J$ values of these levels to be $3/2 \leq J \leq 9/2$, which are also consistent with the shell model predictions, except for the first excited state whose predicted value of $(1/2)^-$ can be reconciled with the stripping results only if some spin-flip mechanism operating during the reaction is postulated (Wilkinson 1957).

The measurement of the relative intensities of the possible gamma ray transitions between these levels helps to select one of the few alternatives provided by stripping angular distributions. The results of McDonell et al (1960) derived from the relative gamma ray intensity measurements using the $^{10}\text{B}(d,n\gamma)\text{C}^{11}$ reaction are summarized in fig. VI.2.

More recent measurements of Braben et al (1960) and those of Freeman (1962) are in agreement with the intermediate coupling model predictions and will be discussed in more detail in chap. X. There is very close agreement between the results of Freeman and those described in this thesis.

B. $n-\gamma$ ANGULAR CORRELATIONS - GENERAL FEATURES

It has been suggested (Satchler and Spiers 1952, Biedenharn et al 1952, Gallahar and Cheston 1952, and Satchler 1953) that studies of the angular distribution of gamma rays in coincidence with outgoing neutrons in $(d,n\gamma)$ reactions might be more decisive than relative intensity measurements in
determining the spins of the excited states and the multipolarity of the emitted radiation. The reason for the word "might" lies in the difficulty of formulating a precise theoretical description of the reaction mechanism.

For example, if plane waves are used to describe the incoming and outgoing particles in the A(d,nγ)B reaction, the product nucleus B is expected to be formed by the capture of the proton incident along the direction defined by the momentum transfer vector \( \mathbf{k}_p = \mathbf{k}_d' - \mathbf{k}_n \); here \( \mathbf{k}_p, \mathbf{k}_d \) and \( \mathbf{k}_n \) are the wave vectors of the captured proton, the incident deuteron and the outgoing neutron. The reaction is therefore similar to a \((p, \gamma)\) reaction and the orbital angular momentum \( \ell \) of the captured proton is always perpendicular to \( \mathbf{k}_p \), which is also the direction of the recoiling nucleus, and equally distributed around it. Then (provided the neutron counter is kept in a fixed direction so that \( \mathbf{k}_p \) is always defined and the gamma rays are measured in coincidence with the neutrons) the angular distribution of any resulting gamma rays should have \( \mathbf{k}_p \) as the axis of symmetry and depend only on \( \ell \) and the angular momentum of the states involved. Explicitly the gamma ray distribution should have

(i) the direction of \( \mathbf{k}_p \) as its symmetry axis

(ii) symmetry in the plane perpendicular to this axis

(iii) an unique angular distribution in the d-n plane for a given set of spin values of the excited and ground states, and

(iv) an angular distribution independent of deuteron bombarding energy.

This simple picture is however modified by taking into account the refraction, reflection and absorption of deuteron or neutron waves and by using distorted waves for the deuteron and the outgoing neutron (Tobocman and Kalos 1955, Newns and Refai 1958). Thus, such effects as screening of
some of the neutrons by the nucleus may be introduced (fig. VI.3). For protons captured in region (i), the neutrons emitted and observed at A, are screened by the nucleus. This screening phenomenon, crudely speaking, favours one "side" of the nucleus as a source of neutrons emitted in a given direction (Newns 1953, Butler et al 1958). Therefore $\vec{l}_p$ becomes preferentially aligned parallel or antiparallel to $\vec{K}_d \times \vec{K}_n$. This polarization of the capture process allows the emergent particle to be polarized. The direction of polarization depends on the value of the total angular momentum $j$ of the proton as it is captured by the nucleus. It is found that if only one value of $j$ and $l$ contribute to the reaction, then the outgoing particles are partially polarized in the direction of $\vec{K}_d \times \vec{K}_n$ if only $j = l - \frac{1}{2}$ is permitted, and in the opposite direction is only $j = l + \frac{1}{2}$ is permitted. For $l = 0$ the polarization is zero (Newns 1953).

Thus, the degree of anisotropy of the $n-\gamma$ correlation is changed and some azimuthal and left-right asymmetry about the $K_p$ axis is introduced. In particular for $l_p = 1$ captures the effect is to rotate the gamma ray symmetry axis away from $K_p$, while for higher $l_p$ there is, in general, no axis of symmetry for the gamma rays (Satchler and Tobocman 1960). However, the reaction plane containing $K_d$ and $K_n$ always remains a plane of symmetry for the gamma rays, that is, up down symmetry is preserved (Huby, Refai and Satchler 1958).

In a more complete description of the reaction, however, contributions from heavy particle stripping (Owens and Madansky 1957) and possible compound nucleus formation must be taken into account. In the former case, the $^{10}B$ nucleus breaks up into a neutron and a $^{9}Be$ core. The core is captured by the deuteron to form $^{11}C^*$, and the neutron is the outgoing
Fig. VI.3. Nuclear screening effects.
particle. In the latter case the deuteron is captured by the target nucleus to form Cl\textsuperscript{12*} which then ejects a neutron leaving Cl\textsuperscript{11} in an excited state. Since the direction of momentum transfer vector is different for the three processes the correlation symmetry axis may vary as a function of both the outgoing neutron direction and the bombarding deuteron energy due to the variation of the relative contributions from the various reaction modes (Edwards 1959).

Thus an experimental study of n-\gamma and p-\gamma angular correlations may be sensitive to deviations from the simple stripping process. If better agreement is obtained with the experimental results by the use of distorted waves than by the simple theory, this will be very important in showing what distortion is in fact produced by the nucleus and in throwing light on the reaction mechanisms. Out of the few correlations measured so far, the results of Allen et al (1956) on the (p,\gamma) correlations in Si\textsuperscript{28}(d,p\gamma)Si\textsuperscript{29*} (1.28 Mev) at a deuteron bombarding energy of about 9 Mev show the predicted symmetry about the axis of the recoil nucleus. These data also show an anisotropy in the plane perpendicular to the axis of the recoil nucleus.

Similar results were also reported by Taylor (1959) on the Be\textsuperscript{9}(d,n\gamma)Be\textsuperscript{10} (3.37 Mev) correlations who found the symmetry axis along the predicted recoil nuclear axis and isotropy to 6\% in the plane perpendicular to the recoil axis.

Cox and Williamson (1957) studied the (p,\gamma) correlations in Be\textsuperscript{10}(d,p\gamma)Be\textsuperscript{11} (4.46 Mev and 6.76 Mev). The correlations for the 4.46 Mev were found to be isotropic to \pm 5\% while the correlations for the 6.76 Mev level showed some anisotropy above 3 Mev bombarding energy.
C. GAMMA RAY TRANSITION PROBABILITIES

To calculate theoretically numerical values of relative transition probabilities that may be compared to experiment, it is necessary to adopt a model of the nucleus. The single particle model in its simplest form (that is, that a single particle is responsible for the transition and that this particle moves in a velocity independent central potential) lends itself to easy calculations (Blatt and Weisskopf 1952). However, as might be expected due to the crudity of the model, the single particle transition probabilities, called Weisskopf units, are unreliable by orders of magnitude. Wilkinson (1960) has made a statistical analysis of the agreement by the Weisskopf predictions of transition probabilities and the measured values. He concluded that, for E1, M1 and E2 transitions in light nuclei, the comparison of Weisskopf units and measured values was completely unreliable as a tool in the determination of gamma ray multipolarities and nuclear J values.

Of the more sophisticated models, the individual particle model in the intermediate coupling representation, as developed by Kurath (1956) for the lp shell nuclei makes more precise predictions about the electromagnetic transition probabilities (Kurath 1957) between those states predicted by the model. There is no critical review, at least to the author's knowledge, of the accuracy with which it predicts the transition probabilities of transitions where the multipole character has already been unequivocally established by other means: gamma-gamma angular correlations, particle-gamma angular correlations, internal pair or internal conversion measurements. Kurath (1957) has himself remarked "The predictions of this intermediate coupling model do not give a satisfactory picture of the
experimental evidence concerning gamma transitions in the lp 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".

The model, however, seems to have had a considerable degree of success in predicting the ordering of the excited states of some nuclei in the lp shell. We shall take the work of Kurath as being the best model available and attempt to assign spins and multipolarities by comparing the branching ratios predicted by it with our experimental results.

The assignments resulting from such a comparison must, of course, be treated with considerable caution. The true function of the thesis is to present the experimental results in the hope that their availability may stimulate further work by the theoreticians, who with the new data, may be able to further improve the model and to describe this nuclear mass region.
CHAPTER VII

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in fig. VII.1a,b. Deuterons from the University of British Columbia Van de Graaff Generator were analyzed by a 90° bending magnet and were refocussed by means of an electrostatic lens on to a target placed at the centre of the target chamber at a distance of about 15 feet from the bending magnet. The beam energy was known to better than 0.30% and was stabilized with a corona stabilizer using the conventional slit arrangement (Auld 1961).

The target chamber (fig. VII.2) was made from a 2" diameter brass cylinder with a metallic target holder to conduct away the heat. The relative positions of the target, the axis of rotation of the gamma counter and the vertical axis of the target chamber were determined to better than 0.1 mm by triangulation using a Wild T2 Theodolite. The targets used were 100 $\mu$gm/cm$^2$ and 200 $\mu$gm/cm$^2$ separated B$^{10}$ targets (99% B$^{10}$) deposited on 0.0005" thick gold backing and were supplied by A.E.R.E., Harwell, England.

A pivoted arm for rotating the gamma detector in the (d,n) plane was centred under the target chamber. The distance from the target to the front face of the gamma detector (for n-$\gamma$ angular correlation measurements) was 10.0 ± 0.1 cm corresponding to a solid angle of 0.16 ster. The distance from the target to the front face of the neutron counter was 25.0 ± 0.1 cm so that the neutron detector subtended a linear angle of 6° at the target.
Fig. VII.1. The experimental layout.
Fig. VII.2. The target chamber.
The neutron counter could also be rotated about a vertical axis passing through the target. The angular positions of the neutron counter and the gamma counter could be determined to better than half a degree.

The beam current was monitored with a beam current meter and the current was integrated in an Eldorado Electronica Type Cl-110 Current Integrator. For the neutron angular distribution measurements, the coincidence counts were normalized to the same number of counts in the gamma counter. For the n-γ angular correlations, the coincidence counts were normalized to the same number of counts in the neutron counter. The reaction rate as measured by the neutron and gamma monitor count rates, was maintained constant, to avoid second order effects in background corrections.

The PHA windows in both the neutron and gamma energy channels were adjusted to select the appropriate energy interval of the radiations detected, rejecting unwanted pulses from outside these energy intervals. Since the neutrons in organic phosphors give a continuous pulse amplitude spectrum from zero pulse height to a maximum determined by the energy of the neutrons, the lower bias in $E(n)_{\text{PHA}}$, which is necessary to cut out photomultiplier noise pulses, also cuts out a fraction of the useful neutron pulses. In order to determine the relative detection efficiency of the neutron spectrometer as a function of this bias, it was necessary to know the pulse height versus energy calibration of the neutron spectrometer. The required calibration was obtained by using gamma rays of known energies, and by determining the relative response of the scintillator to neutrons and gamma rays, using $D(d,n)$ neutrons. No correction was necessary for the change in detection efficiency caused by the kinematical change in neutron energy as $Q_n$ was varied (for neutron angular distribution measurements),
since the accuracy of these measurements did not affect the significance of the results on n- γ correlations or gamma/gamma transition probability ratios.

Similarly the pulse height versus energy calibration of the gamma ray spectrometer was obtained by using Na$^{22}$ and RaTh sources and nuclear reaction gamma rays from $^{11}\text{B}(p,γ)^{12}\text{C}$ and $^{19}\text{F}(p,αγ)^{16}\text{O}$, which give 4.43 and 6.14 Mev gamma rays respectively. In this way the whole region up to 6.14 Mev was covered. These points, together with the points identified from the $^{11}\text{C}$ spectrum, gave a pulse height versus energy relation that was linear within the experimental error. This calibration measurement also showed that the gain of the whole system was count rate independent, as the calibration points were obtained under different count rates. The various count rates are given in table VII.1.

<table>
<thead>
<tr>
<th>Source</th>
<th>$E_γ$ (Mev)</th>
<th>Count Rate (Sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$^{22}$</td>
<td>1.28</td>
<td>500</td>
</tr>
<tr>
<td>RaTh</td>
<td>1.60</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>2.62</td>
<td></td>
</tr>
<tr>
<td>$^{11}\text{B}(p,γ)^{12}\text{C}$</td>
<td>4.43</td>
<td>1000</td>
</tr>
<tr>
<td>$^{19}\text{F}(p,αγ)^{16}\text{O}$</td>
<td>6.14</td>
<td>1500</td>
</tr>
<tr>
<td>$^{10}\text{B}(d,nγ)^{11}\text{C}$</td>
<td>6.50</td>
<td>10000</td>
</tr>
</tbody>
</table>

TABLE VII.1

VARIOUS COUNT RATES ENCOUNTERED IN THE PULSE HEIGHT/ENERGY CALIBRATION
CHAPTER VIII

EXPERIMENTAL RESULTS

In this chapter, the raw results of angular correlations and relative intensity measurements are presented. They are reduced to standard forms in chap. IX and then compared with theory and discussed in chap. X.

A. ANGULAR DISTRIBUTIONS OF NEUTRONS

For general statement of the method used, see chap. VII.

(i) 6.49 Mev Level

Figure VIII.1a shows the angular distribution of neutrons populating the 6.49 Mev level. The measurements were made at 1.3 Mev deuteron bombarding energy. The gamma ray counter was placed at 90° with respect to the deuteron beam and about 4.0 cm away from the target. The E(γ)PHA was set to accept the 5-6.5 Mev energy interval. The E(n)PHA was set to accept all pulses well above the noise level of the neutron spectrometer up to the level corresponding to the maximum pulse height of neutrons. Counts were accumulated for about 15 minutes at each point which was sufficient to give adequate statistical accuracy. The neutron time-of-flight spectra obtained during this measurement are shown in fig. VIII.2. The vertical coordinates of the points in fig. VIII.1a are proportional to the areas under the corresponding neutron time-of-flight spectrum corrected for background counts. Correction was also applied for the
Fig. VIII.1. Angular distribution of neutrons for $^{10}\text{B}(d,n)^{11}\text{C}$ at $6.49$ Mev
Fig. VIII.2. Time-of-flight spectra of neutron from $^7\text{Li}(d,n)^{11}\text{B}$ at $E_d = 1.3$ Mev.
dependence of the relative efficiency of the neutron spectrometer on the lower bias of the E(n)PHA due to the kinematical change in neutron energy as $Q_n$ was varied.

Similar angular distribution curves for $E_d = 1.1, 0.8$ and $0.5$ Mev are shown in fig. VIII.1b,c and d respectively. The object of these angular distribution measurements was to find the angle of maximum yield of the neutrons and to choose a suitable deuteron bombarding energy for the $n-\gamma$ angular correlation measurements. Above $0.8$ Mev, the neutron angular distributions show peaking in the forward direction which is typical of stripping angular distributions. It was therefore assumed that at $E_d \geq 0.8$ Mev, the reaction proceeds by the stripping mechanism. A deuteron bombarding energy of $0.8$ Mev was chosen, as the random background increased substantially above $1.0$ Mev deuteron bombarding energy because of increased background radiation from the Van de Graaff Generator and de-excitation radiation from C¹¹ and B¹¹ as the higher energy levels were being populated.

(ii) 4.32 and 4.81 Mev Levels

Figures VIII.3a,b show the angular distributions of the neutron groups $n_2$ and $n_3$ at $E_d = 800$ kev; $n_2$ leading to the excited state at $4.32$ Mev and $n_3$ leading to the excited state at $4.81$ Mev. The $E(\gamma)$PHA was adjusted to accept a 1-5 Mev energy interval. The E(n)PHA was set to accept pulses due to neutrons of approximate energy 0.5 to 3 Mev.

The ordinates are equal to the number of counts under the neutron T.O.F. peaks, corrected for random background. The object of the angular distribution measurement was to find the relative intensity of the $n_2, n_3$ neutron groups as a function of $Q_n$, to allow the optimizing of the subsequent $n-\gamma$ angular correlation measurements. It was found that the $n_2$ neutron group
Fig. VIII.3. Angular distribution of neutrons for $^{10}$B$(d,n)^{11}$C. Neutron counter at 90 cm.

(b) $E_X = 4.81$ Mev

$E_d = 0.8$ Mev
was about three times more intense in the forward direction than the \( n_3 \) neutrons. The two groups are of roughly equal intensity at \( \theta_n \simeq 130^\circ \).

B. \( n-\gamma \) ANGULAR CORRELATIONS

For a general statement of the method used, see chap. VII.

The \( n-\gamma \) angular correlations were measured only for 6.49 Mev and 4.32 Mev levels because of count rate limitations. The neutron angular distributions described in the previous section exhibited sufficiently strong angular dependence that it seemed reasonable to proceed with the \( n-\gamma \) angular correlations. It is assumed that there is a large contribution from the deuteron stripping mechanism involved in the reaction even at this \( E_d \), although the neutron angular distributions do not seem amenable to any simple quantitative explanation based, say, on Butler's theory. In this section, therefore, it will be assumed that the gamma ray angular distribution symmetry axis, if one exists, lies along the direction \( \vec{K}_p = \vec{K}_d - \vec{K}_n \).

Of course it is not necessary to make any assumption of this nature in order to perform the measurements, but this assumption is a guide in the selection of the gamma counter angle sequence with respect to the assumed axis of symmetry.

(i) 6.49 Mev Level

The measurements were made at \( E_d = 0.8 \) Mev. The neutron counter was placed at \( \theta_n = 30^\circ \) which was approximately the angle of maximum neutron yield. With the neutron counter in this position, the recoil nucleus axis \( \vec{K}_p \) is along 39\(^\circ\) on the opposite side of the beam. The target holder was mounted in a vertical plane making an angle of 30\(^\circ\) with the incoming deuteron beam (see fig. VIII.4).
Fig. VIII.4. Diagram showing beam-target-detector geometry.

With this geometry, the gamma ray spectrometer could be rotated around the target from $15^\circ$ to $105^\circ$ with respect to the recoil nucleus axis without being obscured by the target backing. The gamma ray spectrometer was placed with its front face at a distance of $10.0 \pm 0.1$ cm from the target. This distance was maintained constant to $0.1\%$ accuracy.

The $E(\gamma)$PHA was adjusted to accept the 5-6.5 Mev energy interval. The $E(n)$PHA was set to accept pulses well above the noise level up to a maximum due to neutrons of maximum energy. The angular correlation is then equivalent to the $\theta_\gamma$ dependence of the suitably normalized counts under the T.O.F. peaks produced by the neutrons populating the 6.49 Mev level. This statement is justified in the next paragraph.

If the angular distribution of the neutron group $n_5$ with respect to the direction of the wave vector $\vec{k}_d$ is given by some function $F(\theta_n)$, then
the \((n, \gamma)\) coincidence count rate is proportional to \(F(\theta_n) G(\theta_\gamma)\) where \(G(\theta_\gamma)\) is the \(n-\gamma\) angular correlation function. Under the conditions chosen, \(F(\theta_n)\) has a constant value as the direction of the neutron counter is kept fixed. The measured \(\theta_\gamma\) dependence of the coincidence count rate would, therefore, be equivalent to the neutron-gamma angular correlation. Any possible effects due to the polarization of the outgoing neutrons (Newns 1953) have been neglected and it is assumed that \(G(\theta_\gamma)\) is independent of \(\theta_n\). This assumption is justified if \(\theta_\gamma\) is measured with respect to the recoil nucleus axis.

The T.O.F. spectra were corrected for the random coincidence background by subtracting from the neutron T.O.F. peak the number of counts obtained by extrapolating within the peak the approximately flat background outside the peak.

Two types of measurements were made which differed from each other in the normalization procedure used. In the first type of measurement, in which the normalization was to the same number of counts in the neutron counter, neutron T.O.F. spectra were recorded with \(\theta_\gamma\) successively = 15\(^\circ\)(A), 30\(^\circ\)(B), 45\(^\circ\)(C), 60\(^\circ\)(D), 75\(^\circ\)(E), 90\(^\circ\)(F) and 105\(^\circ\)(G). The gamma counter was rotated first in the sequence ABCDEFGGFEDCBA and then in the sequence GFEDCBAAABCDEFG, to average any drifts in the system as far as possible. Counts were accumulated for about 7.5 minutes at each position which, as can be seen above, was repeated four times during the above sequences, thus giving a total time of about half an hour for each point. The T.O.F. spectra obtained are shown in fig. VIII.5 and the corresponding angular correlation in fig. VIII.6.

In the second type of measurement, the counts per unit charge at the
Fig. VIII.5. Time-of-flight spectra of neutrons from $^{10}\text{B}(d,n)^{11}\text{C}$ as functions of $\theta$. 

$\theta = 15^\circ$

$\theta = 30^\circ$

$\theta = 45^\circ$

$\theta = 60^\circ$
Fig. VIII.5. (Continued)
Fig. VIII.6. n-γ angular correlation from $^1_0(d,n\gamma)^{11}(6.49$ Mev) normalized to counts per unit charge in the neutron counter.
\Theta \chi = 90^\circ \text{ point were taken as the normalizing factor. The angular correlation was taken as the counts/unit charge at other values of } \Theta \chi \text{ measured as a ratio to the counts per unit charge at the normalizing point. The gamma counter was set successively in the sequence ABABAB ----- , then CBCBCB ----- etc.}

The counter was placed at any one position for about two minutes only. This rapid alteration of the gamma counter between the normalizing position and the other angles means that all but very rapid drifts in the electronics or target and beam system were averaged out. A total time of about 35 minutes for each point gave adequate statistics. The pairs of T.O.F. spectra are shown in fig. VIII.7 and the angular correlation in fig. VIII.8. Note that this measurement statistically is completely independent of the preceding one; none of the results from the first type of measurement have been used in the second result.

Greater weight is given to the results of the second type of measurement because of averaging-out effects due to rapid alteration of the gamma counter position as mentioned above. The result of this n-\gamma angular correlation used in the discussion of the results in chap. X is, therefore, that obtained by the second method.

(ii) 4.32 MeV Level

The neutron counter was placed at a distance of 35 cm from the target at an angle of 20^\circ with respect to the deuteron beam. At 800 kev bombarding energy, the neutrons populating the 4.32 Mev level in C^{11} and with \Theta_n = 20^\circ are associated with recoil nuclei with \vec{k}_{\text{recoil}} in the 121^\circ direction on the opposite side of the beam axis as shown in fig. VIII.9. The gamma spectrometer was placed at a distance of 10 cm from the target.
Fig. VIII.7. Time-of-flight spectra from $^7\text{Li}(d,n\gamma)^{11}\text{B}$ as functions of $\theta_\gamma$. 

Counts per channel

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<thead>
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<th>Channel</th>
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<tr>
<td>10</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>150</td>
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<tr>
<td>50</td>
<td>250</td>
<td>250</td>
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</tbody>
</table>

Counts per channel

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\theta_\gamma = 105^\circ$</th>
<th>$\theta_\gamma = 90^\circ$</th>
</tr>
</thead>
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<tr>
<td>20</td>
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<td>30</td>
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</tr>
<tr>
<td>50</td>
<td>250</td>
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</tr>
</tbody>
</table>
Fig. VIII.7. (continued)
Fig. VIII.8. n-γ angular correlation from $^{10}\text{B}(d,n\gamma)^{11}\text{C}$ (6.49 Mev) normalized to counts per unit charge at $\theta_\gamma = 90^\circ$. 
The $E(\gamma)\text{PHA}$ was adjusted to accept pulses in the 3-4.5 Mev energy interval. The $E(n)\text{PHA}$ was adjusted to accept all pulses in the 0.5-3 Mev energy region. The discriminators on the T.O.F. spectrum were adjusted to accept a section of the background region on both sides of the T.O.F. line. Time-of-flight spectra were taken with $\Theta_\gamma = -15^\circ(A'), 0^\circ(B'), 15^\circ(C'), 30^\circ(D'), 45^\circ(E')$ and $60^\circ(F')$. The counter was placed at each point for about 5 minutes in the $A'B'C'D'E'F'F'E'D'C'B'A'$ sequence to reduce errors due to changes in reaction rates or electronic gain shifts. The coincidence counts were normalized to the same number of counts in the neutron counter. Seven sets of measurements (four with the above sequence and three with the sequence $F'E'D'C'B'A'A'B'C'D'E'F'$) corresponding to a total time of about 65 minutes at each point gave adequate statistics. The resulting time-of-flight spectra are shown in fig. VIII.10. The total

![Diagram showing beam-target-detector geometry.](image)

Fig. VIII.9. Diagram showing beam-target-detector geometry.
Fig. VIII.10. Time-of-flight spectra of neutrons from $^9$Be$(d,n\gamma)^{11}$ as a function of $\theta_\gamma$. 

Counts per channel

Channel

$\theta_\gamma = 60^\circ$

$\theta_\gamma = 45^\circ$

$\theta_\gamma = 30^\circ$

$\theta_\gamma = 15^\circ$

$\theta_\gamma = 0^\circ$

$\theta_\gamma = -15^\circ$
Fig. VIII.11. \( n - \gamma \) angular correlations from \( B^{10}(d,n\gamma)C^{11} \) (4.32 Mev) normalized to counts per unit charge in the neutron counter.
number of counts between channel 20 and 35 (both inclusive) are plotted as a function of $\theta_{\gamma}$ in fig. VIII.11.

C. COINCIDENCE GAMMA-RAY SPECTRA

(i) 6.5 Mev Level; gamma spectrum measured in coincidence with $n_5$ neutrons

The spectrum of gamma rays in coincidence with the neutron group populating the 6.49 Mev level is shown in fig. VIII.12. The gamma counter was placed at a distance of 4 cm from the target at 90° to the deuteron beam. The neutron counter was at a distance of 25 cm from the target and was placed at an angle of 30° on the opposite side of the d beam. The discriminators 1 and 2 were adjusted to accept the T.O.F. peak only (see fig. VIII.13). The spectrum due to random background pulses (dotted line in fig. VIII.12) which was needed for background corrections, was obtained separately by adding an extra delay of 18 nsec to $V(T\gamma)$ which moved the neutron peak out of the time-of-flight window and moved in the random background. The coincident gamma spectrum of fig. VIII.12 was plotted after making corrections for random background.

![Counts per channel vs Channel](attachment:image.png)

**Fig. VIII.13.** Time-of-flight window of $n_5$ neutrons
Counts per channel

Fig. VIII.12. Gamma spectrum in coincidence with $n_5$ neutrons.
The gamma spectrum shows evidence that in addition to the predominant ground state transition of 6.49 Mev, there are two gamma rays of approximate energies 2.2 Mev and 4.3 Mev. It is believed that they are due to the decay of the 6.5 level via the second excited state at 4.32 Mev producing the cascade (2.17 Mev, 4.32 Mev). The accuracy of the gamma ray energy measurements is sufficient to rule out the possibility that these two gamma rays might arise by some other cascade transition, for example through the first excited state giving the cascade gammas (2.00, 4.49 Mev). The relative intensities of the peaks at 4.3, 3.8 and 3.3 Mev are consistent with those which would be produced by gamma rays of \( \gamma = 4.3 \) Mev in this size of NaI(Tl) crystal, the peaks being of energy \( E\gamma = m_0c^2 \), and \( E\gamma = 2 m_0c^2 \).

There is no evidence in favour of a cascade via the third excited state at 4.81 Mev. The predominant modes of decay from the state at 6.49 Mev are, therefore, (a) direct to ground state, and (b) a cascade via the second excited state at 4.32 Mev. The precise analysis of this gamma spectrum in terms of relative intensities of the two decay modes is performed in chap. IX. An upper limit of 2% can be put for the decay of the 6.49 Mev level through either the 4.81 Mev level or the 2.00 Mev level.

(ii) 4.81 Mev Level; gamma spectrum measured in coincidence with \( n_3 \) neutrons

The T.O.F. spectra of the neutron groups \( n_2 \) (populating the level at 4.32 Mev) and \( n_3 \) (populating the level at 4.81 Mev), for various values of \( Q_n \) are shown in fig. VIII.14. The spectra were taken at a deuteron bombarding energy of 800 kev and with the neutron counter placed at 90 cm from the target. The spectra show that the group \( n_3 \) is stronger at backward angles. Therefore in order to obtain the spectrum of gamma rays
Fig. VIII.14. Time-of-flight spectra of $n_2$ and $n_3$ neutrons. Neutron counter at 90 cm.
in coincidence with group \( n_3 \), the neutron counter was placed at an angle of 120° with respect to the beam. The neutron counter was, however, moved closer to the target, to a distance 30 cm, to increase the coincidence count rates.

With the neutron counter at this distance, it was not possible to completely resolve the two neutron groups; the \( n_2 \), \( n_3 \) neutron time-of-flight spectrum at 30 cm is given in fig. VIII.15. The T.O.F. window was, therefore, set to accept the left half of the composite time-of-flight peak. In this way, the ratio of \( n_3/n_2 \) neutrons accepted by the T.O.F. window was \( \approx 3/1 \), this being the ratio of the areas in the T.O.F. window under the curves due to \( n_3 \) and \( n_2 \) neutrons. The gamma spectrum in coincidence with pulses in this T.O.F. window is shown in fig. VIII.16.

The spectrum is mainly that of four gamma rays of approximate energies \( E_{\gamma_3} = 4.8 \text{ Mev} \), \( E_{\gamma_6} = 2.8 \text{ Mev} \), \( E_{\gamma_1} = 2.0 \text{ Mev} \) and \( E_{\gamma_2} = 4.3 \text{ Mev} \). The first three result from the decay of the 4.8 Mev level by (a) a direct ground state transition, \( E_{\gamma_3} = 4.8 \text{ Mev} \), (b) a cascade through the first excited state \( E_{\gamma_6} = 2.8 \text{ Mev} \), \( E_{\gamma_1} = 2.00 \text{ Mev} \). The gamma ray \( E_{\gamma_2} = 4.3 \text{ Mev} \) is that produced by the decay of the second excited state which is populated by the \( n_2 \) neutron group; the T.O.F. window specified above accepts about 1 \( n_2 \) neutron for every 3 \( n_3 \) neutrons. The relative intensity of the \( E_{\gamma_2} \) spectrum to the \( (E_{\gamma_1} + E_{\gamma_3} + E_{\gamma_6}) \) spectrum is consistent with this neutron ratio.

(iii) 4.32 Mev level; gamma spectrum in coincidence with \( n_2 \) neutron

The T.O.F. spectra of the \( n_2 \) and \( n_3 \) neutrons (fig. VIII.14) show that the higher energy neutron (\( n_2 \)) group is stronger in the forward direction. With the neutron counter at 20° with respect to the deuteron beam and with
Fig. VIII.15. Time-of-flight window for $n_3$ neutrons.
Fig. VIII.16. Gamma spectra in coincidence with time-of-flight window pulses of Fig. VIII.15.
the time-of-flight window suitably chosen, the gamma spectrum in coincidence with T.O.F. window pulses is predominantly due to the decay of 4.32 Mev level, the ratio of $n_2/n_3$ neutron counts in the T.O.F. window was estimated to be $\approx 5:1$.

The neutron counter was again placed 30 cm from the target for count rate reasons. The T.O.F. window was adjusted to accept only the right half of the unresolved time-of-flight peak due to $n_2$ and $n_3$ neutrons. The gamma spectrum in coincidence with these T.O.F. window pulses is shown in fig. VIII.17. There is no evidence for a cascade through the first excited state; from the statistics an upper limit of 2.5% can be placed on the intensity relative to the ground state transition of such a cascade.
Fig. VIII.17. Gamma spectrum in coincidence with n$_2$ neutrons.
CHAPTER IX

ANALYSIS OF RESULTS

In this section, the experimental results described in the previous chapter are reduced to standard forms which are then compared with the predictions of the theory in the next chapter.

A. n-γ Angular Correlations

If, in discussing the experimental results, it is assumed that the reaction mechanism is stripping, then the n-γ angular correlation measurements are essentially gamma angular distributions about the recoil axis. Such angular distributions following a deuteron stripping reaction have been treated both in terms of the channel spin of the capture process (Biedenharn, Boyer and Charpie 1958, Gallahar and Cheston 1952) and in terms of the total angular momentum \( j \) of the captured particle (Satchler and Spiers 1952). Equation (6) of Satchler and Spiers reduces, for an unique \( j \) value, to (Satchler 1953)

\[
W(\theta) = \sum \eta_{l_{\gamma}}(j j_{\gamma} j_{e}) \mathcal{P}_{l_{\gamma}}(l_{f} j_{e}) \mathcal{P}_{l_{\gamma}}(\cos \theta)
\]  

(1)

where \( W(\theta) \) is the angular distribution function and \( \theta \) is the angle between the emitted gamma ray and the direction of the recoiling product nucleus; \( j_{\gamma} = \) spin of initial nucleus, \( j_{e} = \) spin of excited state of the final
nucleus, \( J_f \) = spin of the final state, \( j \) = total angular momentum (1 ± \( \frac{1}{2} \)) of the captured nucleon and \( 2L \) = multipole order of the emitted gamma ray.

The usual limitations on \( \mathcal{V} \) apply (Biedenharn and Rose 1953), that is \( \mathcal{V}_{\text{max}} \) is less than or equal to the smallest value of \( 2j \) or \( 2L \) or \( 2J_e \) and takes only even values. The functions \( \eta_{\mathcal{V}} \) and \( F_{\mathcal{V}} \) are tabulated by Satchler (1953) and Beidenharn and Rose (1953) respectively. Formula (1) can be written in a more convenient form as

\[
W(\theta) = 1 + \sum_{\mathcal{V}} \eta_{\mathcal{V}} F_{\mathcal{V}} (\cos \theta)
\]

where \( \mathcal{V} = 2, 4, 6 \ldots \). We see that in particular the reactions involving \( s_{\frac{1}{2}} \) and \( p_{\frac{1}{2}} \) capture give \( W(\theta) = 1 \), that is, the n-\( \gamma \) angular correlation is isotropic.

An upper limit may be placed on \( \mathcal{V} \) from previous stripping pattern results; the angular distribution of neutrons from \( ^{10}\text{Be} (d,n)^{11}\text{Be} \) at \( E_d = 7 \text{ Mev} \) (Cerineo 1956, Maslin et al 1956), where the Butler theory is valid, are consistent with \( j \ll \frac{3}{2} \) for the captured proton. Therefore the maximum value of \( \mathcal{V} \) is \( \ll 3 \), and even, hence \( \mathcal{V}_{\text{max}} = 2 \). The angular distribution of gamma rays (about the recoil axis), reduces to

\[
W(\theta) = 1 + a_2 P_2 (\cos \theta)
\]

The experimental values of 'a_2' are calculated in the next two sections. In chap. X, the experimental angular correlations are compared graphically with theoretical curves with values of 'a_2' corresponding to various spin and multipolarity assignments.
(i) **6.49 Mev Level**

The least square fit (appendix I) to a curve of the form (3) of the experimental results of fig. VIII.6 gives

\[ W(\theta)_{6.49 \text{ Mev}} = 1 + (0.093 \pm 0.021) P_2(\cos \theta) \]  

(4)

Similarly a least square fit of the results of fig. VIII.8 to a curve of the form (3) gives

\[ W(\theta)_{6.49 \text{ Mev}} = 1 + (0.015 \pm 0.010) P_2(\cos \theta) \]  

(5)

However, as discussed in chap. VIII, greater weight is attached to equation IX.5 and the comparison with theoretical curves is discussed in chap. X.

(ii) **4.32 Mev Level**

The n-\(\gamma\) angular correlation for the 4.32 Mev level is shown in fig. VIII.11. When the data is fitted to a curve of form (3), the value of the coefficient 'a2' is given by

\[ W(\theta)_{4.32 \text{ Mev}} = 1 - (0.065 \pm 0.015) P_2(\cos \theta) \]  

(6)

The comparison with theoretical curves is given in chap. X.

B. **ANALYSIS OF COINCIDENT GAMMA SPECTRA**

(i) **6.49 Mev Level**

The spectrum of gamma rays in coincidence with the neutron group n5, obtained as described in chap. VIII, is shown in fig. VIII.12. As was
shown there, this spectrum is consistent with the assumption that the 6.49 Mev level decays predominantly (a) by direct ground state transition, $E(\gamma_5) = 6.49$ Mev, and (b) to second excited state, $E(\gamma_2) = 4.32$ Mev and $E(\gamma_7) = 2.17$ Mev.

In order to calculate the gamma branching ratio of this level, using the spectrum stripping technique, it is essential to know the shape of the spectrum of a gamma ray of energy about 6.5 Mev. The 6.14 Mev gamma ray produced in $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ was chosen as this calibration spectrum. The spectrum produced in the gamma ray spectrometer at the $E_p = 340$ kev resonance is shown in fig. IX.1. However, there was some degradation of energy resolution (called "smearing") of the gamma spectrum (fig. VIII.12) due to high count rates which probably produced some gain shifts. Therefore the calibration spectrum was also "smeared" to the same extent by continuously varying the side channel amplifier gain by about 7% while recording the calibration spectrum. The gain of the $V(E\gamma)$ amplifier was increased by the factor $(5.49/5.14)$ during the accumulation of the calibration spectrum, so that the $(E\gamma - 2m_o^2c^2)$ peak of the 6.14 Mev spectrum fell in the same channel as the $(E\gamma - 2m_o^2c^2)$ peak of the 6.49 Mev gamma rays. The calibration spectrum so obtained was normalized to the same $(E\gamma - 2m_o^2c^2)$ peak height as the coincidence spectrum (VIII.12) and then subtracted from it. The two spectra are shown in fig. IX.2.

The quantitative analysis of the spectrum was carried out as follows.

Let $N(6.49)$ be the number of 6.49 Mev gamma rays emitted from the target during the experimental running time $T$. Let $K(6.49)$ be the overall detection efficiency of the gamma ray spectrometer for the detection of 6.49 Mev gamma rays in coincidence with the T.O.F. window pulses, and let
Fig. IX.1. Spectrum of 6.14 Mev gamma rays from $^9\text{Fr}(p, \alpha \gamma)^{16}\text{O}$.
Fig. IX.2. Gamma spectrum in coincidence with $n_5$ neutrons showing contribution of ground state transition of 6.49 Mev level.
Let \( A_1 \) be the number of gamma rays actually detected during the time \( T \) (that is, \( A_1 \) is the area under the curve (fig. IX.2) due to 6.49 Mev gamma rays).

Similarly let \( N(4.32), K(4.32), A_2 \) and \( N(2.17), K(2.17), A_3 \) represent the corresponding numbers for the 4.32 and 2.17 Mev gamma rays.

\( K(E_\gamma) \) in the above discussion is the product of

1. the detection efficiency, corrected for \( E(\gamma)\)PHA window bias, of the Na(Tl) crystal for gamma rays of energy \( E_\gamma \),
2. the detection efficiency, corrected for \( E(n)\)PHA window bias, of the NE213 liquid scintillator for the neutrons leading to the 6.49 Mev level, and
3. coincidence efficiency of the time-of-flight spectrometer (usually considered to be \( \approx 1 \)).

Factors (ii) and (iii) remain constant during the measurement of gamma rays in coincidence with neutrons of one fixed energy. \( K(E_\gamma) \) was, therefore, taken simply as directly proportional to the bias dependent detection efficiency of the gamma ray spectrometer for gamma rays of energy \( E_\gamma \) and was obtained from (a) the curves provided by Mott and Sutton (1958) and (b) the experimentally determined fraction of the calibration gamma ray spectrum above the bias used in \( E(\gamma)\)PHA. The constant of proportionality in \( K(E_\gamma) \) does not enter into the calculation of branching ratios.

Since \( \gamma(4.32) \) and \( \gamma(2.17) \) are in cascade

\[
N(4.32) = N(2.17) \tag{1}
\]

Now from their definition

\[
A_1 = K(6.49) N(6.49) \tag{2}
\]
\[ A_2 = K(4.32) N(4.32) \]  

\[ A_3 = K(2.17) N(2.17) \]  

so

\[ A_3 + A_2 = N(4.32) \left[ K(4.32) + K(2.17) \right] \]  

From (5) and (2)

\[ \frac{N(6.49)}{N(4.32)} = \frac{A_1}{A_2 + A_3} \frac{K(4.32) + K(2.17)}{K(6.49)} \]  

Substituting numerical values

\[ A_1 = (178 \pm 10) \times 500 \]

\[ A_2 + A_3 = (66 \pm 10) \times 500 \]

\[ K(4.32) = 0.176 \]

\[ K(2.17) = 0.20 \]

\[ K(6.49) = 0.175 \]

we get

\[ \frac{N(6.49)}{N(4.32)} = 5.8 \pm 0.9 \]

The error quoted in the above ratio is mainly due to the uncertainty in the values of \( A_1, A_2 \) and \( A_3 \).

(ii) 4.81 Mev level

The spectrum of gamma rays in coincidence with n_3 neutron group is
shown in fig. VIII.16. Due to incomplete resolution of neutron groups n_2 and n_3 in the T.O.F. spectrum as discussed in the previous chapter, gamma radiation from the decay of the 4.32 Mev level is also present. The spectrum stripping technique was again used. From the experimental spectrum, the contribution of the 4.32 Mev gamma rays was first removed by subtracting a calibration spectrum whose relative area was proportional to the known (n_2/n_3) ratio in the T.O.F. window. The calibration spectrum used was that of the 4.43 Mev gamma rays from B^{11}(p,\gamma)C^{12}, measured in coincidence with the higher energy (\approx 12 Mev) gamma rays produced from the decay of the 16.6 Mev level via the 4.43 Mev first excited state. The spectrum of the 4.43 Mev gamma rays is shown in fig. IX.3. The gain of the E\gamma amplifier was reduced by the (3.43/3.32) factor during the accumulation of the calibration spectrum, so that the (E_{\gamma} - 2m_0c^2) peak for the 4.43 Mev gamma rays fell in the same channel as the (E_{\gamma} - 2m_0c^2) peak of the 4.32 Mev gamma rays. Figure IX.4 is the coincidence spectrum after the contribution of the 4.32 Mev gamma rays has been subtracted. This spectrum was again treated by the same type of spectrum stripping method to determine the intensity ratio of (\gamma_3/\gamma_6). The dotted line shows the estimated contribution of 4.81 Mev gamma rays. The calibration spectrum was again obtained from the 4.43 Mev gamma rays, this time increasing the E\gamma amplifier gain until the (E_{\gamma} - 2m_0c^2) peak of the 4.43 Mev calibration spectrum fell in the same channel as the 4.81 Mev pair peak of fig. VIII.16.

A numerical analysis of the spectrum similar to the one for the 6.49 Mev level was carried out.

Substituting numerical values of
Fig. IX.3. Spectrum of 4.43 Mev gamma rays from $^{11}(p, \gamma)^{12}$. 

Counts per channel

E(Mev)

Channel
Fig. IX.4. Gamma spectrum in coincidence with n_3 neutrons showing contribution of ground state transition of 4.81 Mev level.
A(4.81) = (36 \pm 6) \times 100

A(2.81) + A(2.00) = (20 \pm 6) \times 100

K(2.81) = 0.19

K(2.00) = 0.20

and K(4.81) = 0.175

in the equation

\[
\frac{N(4.81)}{N(2.81)} = \frac{A(4.81)}{A(2.81) + A(2.00)} \times \frac{K(2.81) + K(2.00)}{K(4.81)}
\]

we get

\[
\frac{N(4.81)}{N(2.81)} = 4.0 \pm 1.4
\]

This is the desired intensity ratio of \( \gamma_3/\gamma_6 \).

(iii) 4.32 Mev level

The gamma spectrum in coincidence with \( n_2 \) neutrons, that is, in coincidence with T.O.F. window pulses, with the time-of-flight window chosen as described in chap. VIIIC(iii), is shown in fig. VIII.17. If the 4.32 Mev level decayed via the first excited state at 2.00 Mev, each such cascade would give rise to two gamma rays in the two Mev region. From fig. VIII.17 an upper limit of 2.5% can be placed on the relative intensity of (cascade through first excited state/direct transition to ground state). This result was also obtained by spectrum stripping method, the upper limit referred to above corresponds to the residue, after a suitable calibration spectrum had been subtracted from fig. VIII.17.
C. **ANALYSIS OF THE T.O.F. SPECTRUM OF \( n_2, n_3 \) NEUTRONS**

From the analysis of the gamma spectrum in the previous section, it was found that the branching ratio for the 4.81 Mev level is

\[
\frac{4.81 \rightarrow \text{g.s.}}{4.81 \rightarrow 2.00} = 4.0 \pm 1.4
\]

The analysis of the T.O.F. spectrum of the associated neutrons provides another method of obtaining a measure of this branching ratio and serves as a check on that calculated from the coincident gamma spectrum.

The method is described below.

Two neutron T.O.F. spectra (fig. IX.5) were obtained and recorded in the kicksorter, the charge incident on the target being the same for both the spectra. For spectrum I, \( E(\gamma) \text{PHA} \) was adjusted to accept gamma pulses in the 1-5 Mev energy interval, while for spectrum II, the \( E(\gamma) \text{PHA} \) accepted energy interval 2.5 Mev → 5 Mev. The neutron counter was 30 cm from the target at an angle of 120° with the deuteron beam. The \( E(n) \text{PHA} \) was kept the same during both the runs and was set to accept pulses due to neutrons of energy between approximately 0.5 and 3.0 Mev. Figure I.5, in which the various neutrons and gamma rays are labeled, is reproduced here for ready reference as fig. IX.6.

The analysis of the time-of-flight spectra was carried out as follows.

Let \( N^I(n_3) \) and \( N^I(n_2) \) be the number of T.O.F. coincidences due to \( n_3 \) and \( n_2 \) neutrons respectively in spectrum I. Let \( N^{II}(n_3) \) and \( N^{II}(n_2) \) be the corresponding number of coincidences in spectrum II.

Then we can write

\[
N^I(n_3) = \alpha \left[ k^I(2.00) N(\gamma_1) + k^I(2.81) N(\gamma_6) + k^I(4.81) N(\gamma_3) \right] \tag{1}
\]
Fig. IX.5. Time-of-flight spectra of unresolved $n_2$ and $n_3$ neutrons from $B^{10}(d,n)C^{11}$ at $E_d = 800$ kev. $\theta_n = 120^\circ$. Neutron counter at 30 cm.

Fig. IX.6. Energy level diagram of $C^{11}$ and neutron groups from $B^{10}(d,n\gamma)C^{11}$. 
where $\alpha$ is a constant of proportionality, the $N(\gamma)'s$ and $K(\gamma)'s$ have already been defined in this chapter (see section B); the superscripts I and II denote the two $E(\gamma)$ PHA window settings specified above. Possible angular correlations between $\gamma_1$ and $\gamma_6$ have been ignored. Also

$$N^I(n_2) = \alpha K^I(4.32) N(\gamma_2)$$

(2)

while from the experimental results

$$N^I(n_3) + N^I(n_2) = 2723 \pm 52$$

(3)

Similarly, for the second window setting

$$N^{II}(n_3) = \alpha \left[ K^{II}(4.81) N(\gamma_3) + K^{II}(2.81) N(\gamma_6) \right]$$

(4)

$$N^{II}(n_2) = \alpha K^{II}(4.32) N(\gamma_2)$$

(5)

and

$$N^{II}(n_3) + N^{II}(n_2) = 1553 \pm 40$$

(6)

Also

$$N(\gamma_1) = N(\gamma_6)$$

(7)

since $\gamma_1$ and $\gamma_6$ are in cascade.

It was calculated from the T.O.F. spectrum at $\Theta_n = 120^\circ$ in fig. VIII.14 that
\[ N^\mathrm{I}(n_2) = 1.22 \, N^\mathrm{I}(n_3) \]  

Then since the contribution due to 2.81 Mev gamma rays in \( E(\gamma) \) PHA window for spectrum II is negligible as compared to the contribution due to 4.81 Mev gamma rays, equation (4) reduces to

\[ N^\mathrm{II}(n_3) = \alpha \, K^\mathrm{II}(4.81) \, N(\gamma_3) \]  

The remaining system of equations can be solved for \( N(\gamma_3) \) and \( N(\gamma_6) \). The calculations yield

\[ \frac{N(\gamma_3)}{N(\gamma_6)} = 2.7 \pm 1.3 \]  

From the analysis of the \( \gamma \)-ray spectrum of fig. IX.2 we have

\[ \frac{N(\gamma_3)}{N(\gamma_6)} = 4.0 \pm 1.4 \]  

The statistical accuracy of the results in equations (10) and (11) is almost the same and the error introduced by the approximation made in equation (9) is negligible. Taking the average from equations (10) and (11), therefore, gives

\[ \frac{N(\gamma_3)}{N(\gamma_6)} = 3.4 \pm 1.0 \]
These experimental branching ratios are in very good agreement with those of R. Freeman (1962) and Braben et al (1962). The n–γ angular correlations described in this thesis are, however, more conclusive than the ones reported by Freeman.

These results are discussed and compared with theory in the next chapter.
A. DISCUSSION OF RESULTS

In this section the results described in the previous chapters are compared with theory. The conclusions to be drawn from this comparison are discussed in section B.

Two distinct branches of nuclear theory are involved. The first, necessary for the discussion of the angular correlation results, is concerned with nuclear symmetry properties. The second, required to discuss the gamma ray branching ratios involves the consideration of nuclear wave functions in more detail.

(i) Angular Correlation Results

Arguments based on symmetry properties, because of their generality, are usually of considerable power. However in the present case, this power is to a certain extent diminished by our imprecise knowledge, first about the reaction mechanisms involved at low deuteron bombarding energies and second, about the details of the angular momentum couplings involved in the reaction. However, in the absence of clear evidence about the exact nature of the reaction mechanism, we proceed with the analysis of the angular correlation results using the simplest assumption available, namely that the reaction mechanism is pure Butler stripping.

The experimental ecorrelations from the previous chapter are

\[ W(\theta)_{6.49 \text{ Mev}} = 1 + (0.015 \pm 0.010) P_2(\cos \theta) \]
\[ W(\theta)_{4.32 \text{ MeV}} = 1 - (0.065 \pm 0.015) P_2(\cos \theta) \]

Theoretical values of the coefficient \(a_2\) were calculated (using the method described in chap. IX.A.) for the various possible spin and multipolarity assignments resulting from \(p_{3/2}\) and \(p_{1/2}\) capture of the incoming proton. These values are listed in table X.1. The resulting theoretical angular correlation functions, \(W(\theta)\), are shown in figs. X.1 and 2 along with experimental points.

TABLE X.1

<table>
<thead>
<tr>
<th>Capture process</th>
<th>(J_e) (excited State)</th>
<th>Multipolarity (Ground state transition)</th>
<th>Theoretical (a_2)</th>
<th>Experimental (a_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.49 Mev</td>
<td>4.32 Mev</td>
</tr>
<tr>
<td>(p_{3/2}) ((j=1 + \frac{1}{2}))</td>
<td>9/2</td>
<td>M3</td>
<td>+0.46</td>
<td>+0.015±0.01</td>
</tr>
<tr>
<td></td>
<td>7/2</td>
<td>E2</td>
<td>-0.10</td>
<td>-0.065±0.15</td>
</tr>
<tr>
<td></td>
<td>5/2</td>
<td>M1</td>
<td>+0.22</td>
<td>+0.086</td>
</tr>
<tr>
<td>(p_{1/2}) ((j=1 - \frac{1}{2}))</td>
<td>7/2</td>
<td>E2</td>
<td>0.00</td>
<td>+0.015±0.01</td>
</tr>
<tr>
<td></td>
<td>5/2</td>
<td>M1</td>
<td>0.00</td>
<td>-0.065±0.15</td>
</tr>
</tbody>
</table>

* The symbol * means the second lowest state in energy of the specified \(J\) and \(T\).
Fig. X.1. Theoretical n-γ angular correlations from $B^{10}(d,n\gamma)_{C^{11}}$ (6.49 Mev)
Fig. X.2. Theoretical n-γ angular correlations from $^{10}\text{B}(d,\gamma)^{11}\text{C}$ (4.32 Mev)
Assignments based on the visual inspection of fig. X.1, while intuitively more obvious, are, however, less conclusive than those based on the least square results of table X.1. These results show that 
\[ J^\Pi (6.49\text{ Mev}) = (5/2)^- \text{ or } (7/2)^- \text{ with } p_{3/2} \text{ capture of the incoming protons,} \]

since \( a_2 \) (experimental, 6.49 Mev) is clearly equal to 0.00 within the statistical accuracy. For the 4.32 Mev level, the most probable assignment is \( J^\Pi = (7/2)^- \) with \( p_{3/2} \) capture of the incoming proton followed closely by \( J^\Pi = (7/2)^- \text{ or } (5/2)^- \text{ with } p_{1/2} \) capture, since \( a_2 \) (experimental, 4.32 Mev) lies \( 2\frac{1}{2} \) standard deviations from \( a_2 \) (theoretical, \( J^\Pi = 7/2^- \), \( p_{3/2} \)) and 4 standard deviations from \( a_2 \) (theoretical, \( J^\Pi = 7/2^- \text{ or } 5/2^- \), \( p_{1/2} \)). But as will be seen in (ii) below, the branching ratio results are best satisfied with the assignment \( J^\Pi (4.32\text{ Mev}) = (5/2)^- \), which is one of the possible assignments (although not the most probable) arising from the n-\( \gamma \) correlations.

(ii) Branching Ratio Results

From the high energy stripping results of Cerineo (1956) and Maslin et al (1956) all states up to 6.5 Mev, except the fourth excited state at 6.34 Mev, are assigned odd parity. The very low reduced width of the fourth excited state observed by Hinds and Middleton (1961) in \( B^{10}(\text{He}^3,d)c^{11} \), is evidence that this state is probably not formed by stripping and has abnormal parity. It was not resolved in the present experiments and was assumed to be of such low yield as to be negligible. It will, therefore, not be discussed further here, except in section B(i) of this chapter.

On the basis of the intermediate coupling shell model, the branching ratios of the various levels for the mass 11 system have been calculated by Kurath (1957) as functions of \( a/K \) for \( L/K = 6.8 \). Here '\( a \)' is a measure of the strength of the spin-orbit force, \( L \) is the direct integral and \( K \) is the
exchange integral as defined by Inglis (1953). For nuclei in the lp shell, typical values are 'a' the order of 1 Mev and L the order of 6 to 10 Mev. The value of K depends on the range x of nuclear forces. If x is assumed to be greater than r, the nuclear radius, K = 0. In the other extreme, if x is assumed to be short compared to r, K \approx L/3. A typical value of L/K = 6 is considered to be valid for lp shell nuclei. The value of L/K taken in the branching ratio calculations of Kurath was in fact 6.8.

Numerical calculations of the branching ratios using the results of Kurath's theory and the experimentally assigned energies of the states are given in appendix II. These theoretical calculations are compared with the experimentally determined branching ratios in fig. X.3-6, where the theoretical branching ratios, for different spin and multipolarity assignments are plotted as functions of a/K.

In selecting the possible sets of J^π assignments, use was made of the present n-γ angular correlation results and the predictions of Kurath's theory. The assignment of (1/2)^+ to the first excited state is inconsistent with the simple interpretation of the stripping angular distributions. Similar inconsistency also exists in B^{11} and was first explained by Wilkinson (1957) who postulated that the reaction to this state takes place through spin-flip stripping, the interaction between the outgoing protons and the residual nucleus is supposed to flip the intrinsic spin of the proton and so transmit a further unit of angular momentum to the residual nucleus. It is assumed that a similar explanation is also applicable in C^{11}.

This comparison is repeated in table X.2 for the specific value of a/K = 5.5. The sensitivity of the branching ratios to the J^π assignments is evident from this table. This value of a/K was chosen for the following
Fig. X.3. Theoretical branching ratios of 6.49 Mev level for the ground state transition to the transition via the 4.32 Mev level.
Fig. X.4. Theoretical branching ratios of 6.49 Mev level for the ground state transition to the transition via the 4.81 Mev level.

\[ \frac{\Gamma(\gamma_5)}{\Gamma(\gamma_8)} \]
Fig. X.5. Theoretical branching ratios of 4.81 Mev level for the ground state transition to the transition via the 2.00 Mev level.

\[ \frac{\Gamma(\gamma_3)}{\Gamma(\gamma_6)} \]

(a) (b) (c)
7/2 5/2 3/2
3/2 1/2 1/2
3/2 3/2 3/2

\[ \gamma_6 \]
\[ \gamma_3 \]

Experimental

\[ a/K \]
1 2 3 4 5 6 7 8
Fig. X.6. Theoretical branching ratios of 4.32 Mev level for the ground state transition to the transition via the 2.00 Mev level.
TABLE X.2

Comparison of experimental and theoretical branching ratios for different spin assignments for the g.s. and the first, second, third and fifth excited states respectively, for the spin sequence

(a) \((3/2)^-, (1/2)^-, (5/2)^-, (3/2)^*\) and \((7/2)^-\)

(b) \((3/2)^-, (1/2)^-, (7/2)^-, (3/2)^*\) and \((5/2)^-\)

<table>
<thead>
<tr>
<th>Branching Mode</th>
<th>Branching Ratio</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6.49\text{ Mev} \rightarrow \text{g.s.})</td>
<td>6</td>
<td>800</td>
<td>5.8 (\pm) 0.9</td>
</tr>
<tr>
<td>(6.49\text{ Mev} \rightarrow 4.32\text{ Mev})</td>
<td>10</td>
<td>10</td>
<td>3.4 (\pm) 1.0</td>
</tr>
<tr>
<td>(4.81\text{ Mev} \rightarrow \text{g.s.})</td>
<td>1200</td>
<td>3 (\times) 10(^7) (\dagger)</td>
<td>(\geq 40)</td>
</tr>
<tr>
<td>(4.32\text{ Mev} \rightarrow \text{g.s.})</td>
<td>1000</td>
<td>12</td>
<td>(\geq 50)</td>
</tr>
<tr>
<td>(6.49\text{ Mev} \rightarrow \text{g.s.})</td>
<td>2 (\times) 10(^6) (\dagger)</td>
<td>150</td>
<td>(\geq 50)</td>
</tr>
</tbody>
</table>

* second lowest state in energy of the specified J and T.

\(\dagger\) transition ratio obtained by using Weisskopf units since Kurath did not consider M3 transitions in his work.
reasons: In fig. X.7 the various $a/K$ values associated with nuclei in the
1p shell are plotted against the mass number $A$. These values lie on a
reasonably well defined curve. The points shown on this graph, and the
errors on the points, were extracted by the present author from Kurath (1957).
The value of $a/K$ for $B^{11}$ is that of Hinds and Middleton (1962). The value
of $a/K = 5.5$ is consistent with the value predicted by interpolation on this
curve at the value of $A = 11$. There is considerable degree of internal con­
sistency in this choice as it does allow the assignment of $J^\pi$ values,
consistent with those available from the shell model, using theoretical
values of the branching ratios made available by the Kurath theory. For
this value of $a/K$, and $L/K = 0.8$, the closest agreement between the branch­
ing ratios calculated from Kurath's theory and the experimental results, is
obtained for the following spin and parity assignments of the states of $C^{11}$.

<table>
<thead>
<tr>
<th>State</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.49 Mev</td>
<td>$(7/2)^-$</td>
</tr>
<tr>
<td>4.81 Mev</td>
<td>$(3/2^*)^-$</td>
</tr>
<tr>
<td>4.32 Mev</td>
<td>$(5/2)^-$</td>
</tr>
<tr>
<td>2.00 Mev</td>
<td>$(1/2)^-$</td>
</tr>
<tr>
<td>g.s.</td>
<td>$(3/2)^-$</td>
</tr>
</tbody>
</table>

It should be noted that these assignments are not made completely
independently of the theory (Kurath's theory) which it is intended to test.
This is not wholly satisfactory. A more stringent test of the theory could
be made if the $J^\pi$ assignments were made in a completely non-cyclic fashion,
as is done in the spectroscopy of radioactive nuclei by assigning spins and
multipolarities through $\gamma-\gamma$ and $\beta-\gamma$ angular correlations and internal
Fig. X.7. Experimental values of $a/K$ as a function of $A$ in the $l$p shell nuclei (after Kurath 1956-57).
conversion coefficient measurements. An attempt to use analogous techniques to study the present reaction (using $\gamma - \gamma$ correlations, internal pair conversion coefficients and angular correlations) would be technically very difficult, but also would be very rewarding if it permitted completely unambiguous $J^\pi$ assignments.

In table X.3, the "Kurath" branching ratios, calculated using the above assignments, are compared with theoretical branching ratios predicted by the Weisskopf single particle model (Weisskopf Units)(Wilkinson 1960). As can be seen from this table, when the branching mode involves radiations of different multipolarities Kurath's theory gives reasonable agreement with experimental results while the Weisskopf units are in error by orders of magnitude. When the branching involves two radiations of the same multipolarity, an order of magnitude agreement is obtained with the experimental results either by using Kurath's theory or Weisskopf units. It is of course not possible to make any general statement about the comparative reliability of the two methods of computing branching ratios, based merely on the present measurements. Such general statements could be made only on the basis of a critical analysis of the statistical correlation between Kurath's predictions and a large number of experimental branching ratio measurements, similar to the analysis made by Wilkinson (1960) of the correlation between the Weisskopf units and experimental results.

B. CONCLUSIONS

In the introduction to this thesis, it was proposed that the results of the experiment should be of use in discussing three aspects of nuclear theory
TABLE X.3

The comparison of experimental branching ratios of levels in $^{11}$C with the theoretical branching ratio calculated using Kurath's theory and Weisskopf units.

$^{11}$C  $T = 1/2$ states

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Experimental</th>
<th>Theoretical (Kurath L/K=6.8, a/K=5.5)</th>
<th>Theoretical (Weisskopf units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.49$ Mev $\rightarrow$ g.s. (E2)</td>
<td>$5.8 \pm 0.9$</td>
<td>$6$</td>
<td>$0.13$</td>
</tr>
<tr>
<td>$6.49$ Mev $\rightarrow$ 4.32 Mev (M1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4.81$ Mev $\rightarrow$ g.s. (M1)</td>
<td>$3.4 \pm 1$</td>
<td>$10$</td>
<td>$5$</td>
</tr>
<tr>
<td>$4.81$ Mev $\rightarrow$ 2.00 Mev (M1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4.32$ Mev $\rightarrow$ g.s. (M1)</td>
<td>$\geq 40$</td>
<td>$1.20 \times 10^3$</td>
<td>$1.13 \times 10^4$</td>
</tr>
<tr>
<td>$4.32$ Mev $\rightarrow$ 2.00 Mev (E2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6.49$ Mev $\rightarrow$ g.s. (E2)</td>
<td>$\geq 50$</td>
<td>$10^3$</td>
<td>$0.8 \times 10^3$</td>
</tr>
<tr>
<td>$6.49$ Mev $\rightarrow$ 4.81 Mev (E2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(1) The charge independence of nuclear forces, through the correspondence of levels in mirror nuclei.

(2) The usefulness of the individual particle intermediate coupling (1p1c) shell model theory in the form developed by Kurath in the discussion of the low lying excited states of 1p shell nuclei, in particular, of $^{11}$C, (for brevity we shall call this theory "Kurath's theory").

(3) The type of reaction mechanism involved at low deuteron bombarding energy $E_d(\text{lab}) < Q$ of reaction.

From the experimental results described in this thesis, the following conclusions can be drawn regarding the above mentioned aspects of nuclear theory.

(i) **Charge Independence of Nuclear Forces**

The experimental information on the low lying excited states of $^{11}$C and the mirror nucleus $^{11}$B is summarized in fig. X.8. Column (1) lists the restricted sets of $J^\pi$ values deduced from the stripping angular distributions. Column (3) shows the diminished set of $J^\pi$ values obtained by the author from $n-\gamma$ angular correlation results and by assigning multipolarities to the de-excitation gamma rays by assuming the accuracy of Kurath's transition ratios. Column (2) shows the $J^\pi$ values as presently established for the corresponding levels in $^{11}$B (Hinds and Middleton 1962).

There are only two differences between the two spectra. (1) The energies of the excited levels in $^{11}$B are on the average about 5% higher than those in $^{11}$C. (2) The ordering of the levels in the 6.5 Mev doublet is inverted. This of course is not surprising, since only one member of the doublet is predicted by the Kurath theory. The other member was not observed in this experiment for reasons discussed at the beginning of X.A(ii).
Fig. X.8. Energy level scheme and decay modes of $C_{11}$ and $B_{11}$. Correspondence with predicted level scheme of Kurath is made.
Because of its non-shell model character its behaviour under the influence of coulomb perturbation is likely to be different from that of the other levels. The conclusion is, therefore, that the hypothesis of charge independence of nuclear forces is well substantiated by the detailed correspondence of the level structure of these two mirror nuclei as far as the de-excitation branching ratios and \( J^{\pi} \) values are concerned. The excited state energies are, of course, not exactly the same. The systematic increase in the energies of the \( B^{11} \) states over the \( C^{11} \) states can be attributed to coulomb perturbations. Since the coulomb perturbation depends on the nuclear radius, which is not a well defined quantity particularly for excited states, it is not possible to determine whether there are contributions to this shift due to charge dependent interactions of non-coulomb origin.

(ii) The Usefulness of Kurath's Theory in the Discussion of Low Lying States of \( C^{11} \)

Kurath's theory may be used to predict both the level structure of \( C^{11} \) and the branching ratios for the gamma decay modes of these levels.

Figures X.9 and X.10 are taken from Kurath (1956). The first figure shows the level structure of the mass eleven system as a function of \( a/K \) for \( L/K = 6.8 \), and the second shows the level structure of the mass eleven system as a function of \( L/K \) for \( a/K = 4.0 \). Fig. X.11, which is a repetition of Fig. X.3, shows a particular branching ratio as a function of \( a/K \) for two possible spin assignments and for a fixed value of \( L/K \). Fig. X.12 is a repetition of Fig. X.6, and it shows the dependence of \( a/K \) upon \( A \) in the \( 1p \) shell.

Two alternative procedures are now available to the experimenter
Fig. X.9. Level order curves for $A = 11$, $L/K = 6.8$ (after Kurath).

Fig. X.10. Level order curves for $A = 11$, $a/K = 4$ (after Kurath).

Fig. X.11. Theoretical branching ratios of 6.49 Mev level.

Fig. X.12. Experimental $a/K$ as a function of $A$ (Kurath 1956-57).
attempting to correlate his results with Kurath's theory. He may choose a value of $a/K$ (for the single value of $L/K$ provided by Kurath) which will fit the branching ratio results. As can be seen, in the present experiment, the value of $a/K = 5.5$ arrived at in this fashion is also consistent with the interpolation at $A = 11$ in Fig. X.12. But this value of $a/K$ does not give the correct level order (Fig. X.9) of the second, third and fifth excited states.

Alternatively, he may choose a value of $a/K$ and $L/K$ which will lead to agreement between the theoretical and experimental level scheme. If he does this he will find, as the inspection of Figs. X.9 and 10 show, that the resulting values of $a/K (< 4)$ and $L/K (< 5)$ differ considerably from the values arrived at by the first procedure.

The branching ratios in Fig. X.11 go to infinity at $a/K = 4.5$ as the levels concerned cross over in Fig. X.9. The presence of the infinity in the branching ratios has a strong influence on the value of $a/K$ which is chosen from the branching ratios. However, the crossover point in Fig. X.9 is a function of $L/K$ as can be seen from Fig. X.10. It is possible that the values of $a/K$ and $L/K$ which give better agreement with the experimental level scheme, might also give good agreement with the branching ratio results. The labour involved in extending Kurath's calculations of transition strengths to values of $L/K$ and $a/K$ not covered in his work is very formidable, so that the author has not attempted such an extension.

Summarizing, the evidence seems to indicate that Kurath's theory as applied to branching ratios is somewhat better than the Weisskopf single particle model but that the theory at present cannot be shown to deal very satisfactorily with the level ordering and the branching ratios simultaneously.
Further calculations of transition strengths as functions of $a/K$ for values of $L/K$ other than the one already performed would be very helpful in arriving at a definite conclusion regarding the validity of the intermediate coupling shell model theory of Kurath (1956).

(iii) **Reaction Mechanism**

Since both the n- $\gamma$ angular correlations were isotropic, it was not possible to deduce anything about the relationship between the predicted symmetry axis and the various momentum vectors available for defining spatial directions.
APPENDIX I

CURVE FITTING BY THE METHOD OF LEAST SQUARES

The data on n-\(\gamma\) angular correlations obtained experimentally in the study of stripping reactions is fitted to a curve of the form (Satchler 1953)

\[
W(\theta) = a_0 + \sum a_\gamma P_\gamma (\cos \theta)
\tag{1}
\]

where \(\gamma = 2, 4, \ldots\). The usual limitations on \(\gamma_{\text{max}}\) apply, that is \(\gamma_{\text{max}} \leq 2j\) or \(2L\) or \(2J\), whichever is the smallest, where \(j\) is the total angular momentum of the captured nucleon, \(2^L\) is the multipole order of the emitted radiation and \(J\) is the spin of the excited state of the residual nucleus. For the reaction, \(^{B^{10}}(d,n\gamma)^C^{11}\), described in this thesis, we have \(\gamma_{\text{max}} = 2\) and equation (1) reduces to

\[
W(\theta) = a_0 + a_2 P_2 (\cos \theta)
\tag{2}
\]

The unknown parameters \(a_0\) and \(a_2\) are obtained by the method of least squares, that is, by minimizing

\[
S(a_0,a_2) = \sum S_i(a_0,a_2) = \sum \left[ a_0 + a_2 P_2 (\cos \theta_i) - W(\theta_i) \right]^2
\tag{3}
\]

Here \(W(\theta_i)\) are normalized experimental coincidence count rates at angles \(\theta_i\).
If the function $S(a_0, a_2)$ is to have a minimum value, its partial derivative with respect to $a_0$ and $a_2$ must vanish, that is

$$\frac{dS}{da_0} = \sum_2 \left[ a_0 + a_2 P_2 (\cos \theta_1) - W(\theta_1) \right] = 0$$

and

$$\frac{dS}{da_2} = \sum_2 \left\{ \left[ a_0 + a_2 P_2 (\cos \theta_1) - W(\theta_1) \right] P_2 (\cos \theta_1) \right\}$$

$$= 0$$

The normal equations to be solved are, therefore

$$n a_0 + a_2 \sum P_2 (\cos \theta_1) = \sum W(\theta_1)$$

(6)

and

$$\sum P_2 (\cos \theta_1) a_0 + a_2 \sum P_2^2 (\cos \theta_1) = \sum W(\theta_1) P_2 (\cos \theta_1)$$

(7)

A minimum value of $S(a_0, a_2)$ is obtained when $a_0$ and $a_2$ are calculated from the above equations. Since the normal equations are axisymmetric, that is coefficient of $a_0$ is equal to the coefficient of $a_2$ in the normal equation for $a_0$, in the normal equation for $a_2$, we shall use the determinant method for the solution of these equations

$$\begin{vmatrix} n & \sum P_2 (\cos \theta_1) & a_0 & \sum W(\theta_1) \\ \sum P_2 (\cos \theta_1) & \sum P_2^2 (\cos \theta_1) & a_2 & \sum P_2 (\cos \theta_1) W(\theta_1) \end{vmatrix} = 0$$

(8)
Therefore

\[
\begin{bmatrix}
  a_0 \\
  a_2 \\
  \end{bmatrix} = \begin{vmatrix}
  \sum p^2_2(\cos \theta_i) & -1 \\
  \sum p_2^2(\cos \theta_i) & \sum p_2(\cos \theta_i) W(\theta_i) \\
  \end{vmatrix}^{-1}
\]

\[
\begin{vmatrix}
  \sum p_2(\cos \theta_i) W(\theta_i) \\
  \sum p_2(\cos \theta_i) W(\theta_i) \\
  \end{vmatrix}
\]

where the \(C_{jk}\)'s are the elements of the inverted matrix.

Therefore

\[
a_0 = C_{11} \sum W(\theta_i) + C_{12} \sum p_2(\cos \theta_i) W(\theta_i) = \chi_0
\]

and

\[
a_2 = C_{21} \sum W(\theta_i) + C_{22} \sum p_2(\cos \theta_i) W(\theta_i) = \chi_2
\]

where \(\chi_0\) and \(\chi_2\) are now the least square estimates of the coefficients \(a_0\) and \(a_2\).

The sum of squares of the residuals, \(S(a_0,a_2)\), is then calculated by substituting the least square values of \(a_0\) and \(a_2\) in equation (3).
The sample variance

\[ \sigma^2 = \frac{S(a_0, a_2)}{n-2} \] (12)

The weight of unknown parameters

The reciprocals of the weights of the parameters are found on the diagonal of the inverse matrix, that is, representing the weight by \( \omega \).

\[ \omega_{a_0} = \frac{1}{c_{11}} \] (13)

\[ \omega_{a_2} = \frac{1}{c_{22}} \] (14)

Since the weights are reciprocals of variance coefficients

\[ \sigma_{a_0}^2 = c_{11} \sigma^2 \] (15)

and

\[ \sigma_{a_2}^2 = c_{22} \sigma^2 \] (16)

Therefore, the coefficients \( a_0 \) and \( a_2 \) are given by

\[ a_0 = \hat{\alpha}_0 \pm \sigma_{a_0} \] (17)
Since the Legendre polynomials are not in themselves normalized, the distribution can validly be written

\[ W(\theta) = a_0 \left[ 1 + \frac{a_2}{a_0} P_2(\cos \theta) \right] \]

or

\[ G(\theta) = 1 + A_2 P_2(\cos \theta) \] (19)

where

\[ A_2 = \frac{a_2}{a_0} \]

The error in \( A_2 \) is calculated by the formula

\[ \frac{\sigma_{A_2}^2}{A_2^2} = \frac{\sigma_{a_0}^2}{a_0^2} + \frac{\sigma_{a_2}^2}{a_2^2} \] (20)

As is seen from equation (20) the relative error in \( A_2 \) is increased as compared to \( a_2 \). Since the theoretical value of the coefficient \( a_0 \) is generally unity, the experimental distribution is often reduced to the form (19) for comparison with theory.

Ref: Statistical Adjustment of Data by W. E. Deming. Wiley (1944)
APPENDIX II

GAMMA RAY TRANSITION PROBABILITIES IN $^{11}$C

The transition probability $\lambda$ is calculated in terms of the transition width $\Gamma$. They are related by $\frac{\Gamma}{\lambda} = \hbar$, or

$$\frac{\Gamma}{\lambda} = 6.58 \times 10^{-16}$$  \hspace{1cm} (1)

where $\Gamma$ is in ev and $\lambda$ in sec$^{-1}$.

The transition width for a magnetic dipole is defined by

$$\Gamma_{(M1)} = 2.76 \times 10^{-3} E^3 \Lambda_{(M1)}$$  \hspace{1cm} (2)

where $\Gamma$ is in ev, $E$ in Mev, and

$$\Lambda_{(M1)} = \frac{2J_f + 1}{2J_i + 1} \left| \frac{\langle J_f m | \mu \cdot | J_i m \rangle}{(J_i m 0 | J_f m)^2} \right|^2$$  \hspace{1cm} (3)

where $J_i$ is the spin of the initial state, $J_f$ is the spin of the final state and $\mu$ is the magnetic moment operator. The denominator is the square of the usual vector addition coefficient (Condon and Shortley 1935).

Similarly for $E2$ transitions

$$\Gamma_{(E2)} = 8.02 \times 10^{-6} E^5 \Lambda_{(E2)}$$  \hspace{1cm} (4)
where again \( \Gamma \) is in ev, \( E \) in Mev and

\[
\Lambda(E2) = \frac{2J_f + 1}{2J_i + 1} \left| \frac{\langle J_f m | Q/e | J_i m \rangle}{(J_i 2 m 0 | J_f m)²} \right|^2
\]

(5)

\( Q/e \) is the electric quadrupole operator summed over all protons.

The \( \Lambda \)'s, which are independent of the energy factor in \( \Gamma \) are called "transition strengths". The relevant transition strengths for M1 and E2 transitions, calculated by Kurath as functions of \( a/K \) for \( L/K = 6.8 \), are listed in tables I and II respectively for ready reference. The corresponding transition widths were calculated and are given in tables III and IV for M1 and E2 transitions respectively.

**TABLE I**

Transition strengths, \( \Lambda \), for M1 transitions as functions of the relative strength of spin orbit coupling, \( a/K \), for \( L/K = 6.8 \)

<table>
<thead>
<tr>
<th>( J_i \rightarrow J_f )</th>
<th>0.0</th>
<th>1.5</th>
<th>3.0</th>
<th>4.5</th>
<th>6.0</th>
<th>7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/2 ( \rightarrow ) 5/2</td>
<td>0.060</td>
<td>0.075</td>
<td>0.053</td>
<td>0.00</td>
<td>0.083</td>
<td>0.278</td>
</tr>
<tr>
<td>5/2 ( \rightarrow ) 3/2</td>
<td>0.90</td>
<td>0.05</td>
<td>0.97</td>
<td>1.54</td>
<td>1.69</td>
<td>1.76</td>
</tr>
<tr>
<td>( \rightarrow ) 3/2*</td>
<td>9.22</td>
<td>9.69</td>
<td>8.52</td>
<td>7.87</td>
<td>7.67</td>
<td>7.62</td>
</tr>
<tr>
<td>( \rightarrow ) 7/2</td>
<td>0.08</td>
<td>0.10</td>
<td>0.07</td>
<td>0.00</td>
<td>0.11</td>
<td>0.37</td>
</tr>
<tr>
<td>3/2* ( \rightarrow ) 3/2</td>
<td>0.36</td>
<td>1.46</td>
<td>4.59</td>
<td>5.51</td>
<td>5.63</td>
<td>5.57</td>
</tr>
<tr>
<td>( \rightarrow ) 1/2</td>
<td>0.00</td>
<td>1.14</td>
<td>2.75</td>
<td>3.02</td>
<td>2.82</td>
<td>2.68</td>
</tr>
</tbody>
</table>

* The state labelled with an asterisk refers to the second lowest state in energy of the specified \( J \) and \( T \).
TABLE II

Transition strengths, $\Lambda$, for E2 transitions as functions of the relative strength of spin orbit coupling, $a/K$, for $L/K = 6.8$.

$C^{11}$, $T = 1/2$ states

<table>
<thead>
<tr>
<th>$J_i \rightarrow J_f$</th>
<th>a/K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>7/2 $\rightarrow$ 3/2</td>
<td>0.175</td>
</tr>
<tr>
<td>$\rightarrow$ 3/2*</td>
<td>0.021</td>
</tr>
<tr>
<td>5/2 $\rightarrow$ 1/2</td>
<td>0.416</td>
</tr>
</tbody>
</table>

* The state labelled with an asterisk refers to the second lowest state in energy of the specified $J$ and $T$. 
TABLE III

Transition widths, $\Gamma$, in ev, for M1 transitions in $^{11}C$ as functions of the relative strength of the spin orbit coupling, $a/K$

$^{11}C$, $T = 1/2$ states

<table>
<thead>
<tr>
<th>E(Mev)</th>
<th>2.17 Mev</th>
<th>2.81 Mev</th>
<th>4.32 Mev</th>
<th>4.81 Mev</th>
<th>6.49 Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$J_i \rightarrow J_f$</td>
<td>$\Gamma$</td>
<td>$\Gamma$</td>
<td>$\Gamma$</td>
<td>$\Gamma$</td>
</tr>
<tr>
<td></td>
<td>7/2 $\rightarrow$ 5/2</td>
<td>5/2 $\rightarrow$ 7/2</td>
<td>3/2* $\rightarrow$ 1/2</td>
<td>5/2 $\rightarrow$ 3/2</td>
<td>5/2 $\rightarrow$ 3/2</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>1.69x10^-3</td>
<td>2.26x10^-3</td>
<td>0.00</td>
<td>0.200</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>2.11x10^-3</td>
<td>2.82x10^-3</td>
<td>6.98x10^-2</td>
<td>0.011</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>1.48x10^-3</td>
<td>1.97x10^-3</td>
<td>1.68x10^-1</td>
<td>0.216</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>1.85x10^-1</td>
<td>0.343</td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td>2.33x10^-3</td>
<td>3.10x10^-3</td>
<td>1.73x10^-1</td>
<td>0.376</td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td>7.83x10^-3</td>
<td>1.04x10^-2</td>
<td>1.64x10^-1</td>
<td>0.392</td>
</tr>
</tbody>
</table>

* The state labelled with an asterisk refers to the second lowest state in energy of the specified J and T.
TABLE IV

Transition widths, $\Gamma$, in ev, for E2 transitions in $^{\text{C}11}$ as functions of the relative strength of the spin orbit coupling, $a/K$.

$^{\text{C}11}$, $T = 1/2$ states

<table>
<thead>
<tr>
<th>$E$(Mev)</th>
<th>$J_i \rightarrow J_f$</th>
<th>2.32 Mev</th>
<th>2.81 Mev</th>
<th>4.32 Mev</th>
<th>4.81 Mev</th>
<th>6.49 Mev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5/2 $\rightarrow$ 1/2</td>
<td>7/2 $\rightarrow$ 3/2*</td>
<td>5/2 $\rightarrow$ 1/2</td>
<td>7/2 $\rightarrow$ 3/2</td>
<td>7/2 $\rightarrow$ 3/2</td>
<td>7/2 $\rightarrow$ 3/2</td>
</tr>
<tr>
<td>a/K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.24x10^{-4}</td>
<td>1.13x10^{-5}</td>
<td>2.95x10^{-5}</td>
<td>5.84x10^{-4}</td>
<td>2.11x10^{-3}</td>
<td>3.61x10^{-3}</td>
</tr>
<tr>
<td>1.5</td>
<td>2.78x10^{-4}</td>
<td>2.16x10^{-5}</td>
<td>5.62x10^{-5}</td>
<td>7.24x10^{-4}</td>
<td>2.17x10^{-3}</td>
<td>3.72x10^{-3}</td>
</tr>
<tr>
<td>3.0</td>
<td>2.97x10^{-4}</td>
<td>2.53x10^{-5}</td>
<td>6.60x10^{-5}</td>
<td>7.74x10^{-4}</td>
<td>2.02x10^{-3}</td>
<td>3.45x10^{-3}</td>
</tr>
<tr>
<td>4.5</td>
<td>3.01x10^{-4}</td>
<td>4.02x10^{-5}</td>
<td>1.05x10^{-4}</td>
<td>7.84x10^{-4}</td>
<td>1.45x10^{-3}</td>
<td>2.48x10^{-3}</td>
</tr>
<tr>
<td>6.0</td>
<td>2.98x10^{-4}</td>
<td>5.63x10^{-5}</td>
<td>1.47x10^{-4}</td>
<td>7.77x10^{-4}</td>
<td>9.4x10^{-3}</td>
<td>1.61x10^{-3}</td>
</tr>
<tr>
<td>7.5</td>
<td>2.93x10^{-4}</td>
<td>6.74x10^{-5}</td>
<td>1.76x10^{-4}</td>
<td>7.64x10^{-4}</td>
<td>6.0x10^{-3}</td>
<td>1.03x10^{-3}</td>
</tr>
</tbody>
</table>

* The state labelled with an asterisk refers to the second lowest state in energy of the specified $J$ and $T$. 
APPENDIX III

ULTIMATE RESOLVING TIME USING NaI(Tl) CRYSTALS

Assuming no transit time spread in the photomultiplier, the resolving time obtainable from a photomultiplier and a scintillator assembly is limited only by the fluctuation in time delay between the event in the scintillator and the ejection of the first 'n' photoelectrons from the photomultiplier photocathode, where the number 'n' is that required to actuate the coincidence unit and depends, therefore, on the sensitivity of the coincidence unit and the current gain of the photomultiplier. If the coincidence unit can be actuated by single photoelectron pulses (n = 1) and if the actual transit time spread is negligible as compared to the uncertainty in the time of ejection of the first photoelectron, it is not possible to improve upon the resolving time by refinements in the electronic circuitry of the coincidence unit.

Post and Schiff (1950) have shown that the mean time delay for the appearance of the nth photoelectron from the photocathode after the excitation of the phosphor by the radiation is

$$t = \frac{T}{R} n(1 + \frac{n + 1}{2R} + \ldots) \quad (1)$$

and the variance of the signal time, the time at which the anode pulse becomes large enough to cut off the limiter tube and produce a limiter pulse
(or signal pulse) is

\[ \sigma_t^2 = \frac{\tau^2}{R^2} \left[ 1 + \frac{n + 1}{R} + \ldots \right] \]  \hspace{1cm} (2)

where \( \tau \) is the decay time of the phosphor and \( R \) is the average total number of primary photoelectrons produced during the pulse. These equations were determined for \( n \ll R \).

In the experimental equipment described in this thesis, a NaI(Tl) crystal coupled to an RCA 7264 photomultiplier with a lucite light guide gave about 9.6\% energy resolution and a current gain of about \( 10^7 \) for pulses produced by 662 kev \( \gamma \)-rays from a Cs\(^{137} \) source. Due to the statistical nature of the light emission from the crystal and the multiplication process in the photomultiplier, the distribution of pulse heights in the full energy peak of monoenergetic gamma rays can be considered to be a Gaussian function (Prescott and Takhar 1962). With this consideration, the value of \( R \) can be calculated as follows:

For a Gaussian distribution

\[ \frac{\text{Full width at half maximum}}{m} = 2.345 \frac{\sigma}{m} \] \hspace{1cm} (3)

where \( \sigma \) is the standard deviation of the distribution and \( m \) is the mean pulse height.

For the situation under consideration, with 9.6\% energy resolution, we have
In the case of NaI(Tl) crystals, it was found (Prescott and Takhar 1962, eq. 4) that

\[ 0.096 = \frac{2.345}{R} \]  

(4)

where \( R \) is the average total number of primary photoelectrons produced during the pulse. It has been assumed here that all the photoelectrons emitted from the photocathode reach the first dynode (that is that \( R = N \) of Prescott and Takhar).

Substituting (5) in (4) we get

\[ 0.096 = 2.345 \sqrt{\frac{2}{R}} \]

or

\[ R = 2 \times \left( \frac{2.345}{0.096} \right)^2 \approx 1157 \text{ photoelectrons} \]  

(6)

This gives \( \frac{1157}{0.662} \approx 1746 \) photoelectrons/Mev for gamma rays. The number of photoelectrons in a pulse produced by the 0.51 Mev annihilation radiation from a Na\textsuperscript{22} source is, therefore, \( 1746 \times 0.51 \approx 890 \). Substituting this number in (2) we get, for the standard deviation of the signal time of a single photoelectron pulse,
\[ \sigma_{T_1}(n=1) = \frac{250 \times 10^{-9}}{890} \left( 1 + \frac{2}{890} + \cdots \right)^{\frac{1}{2}} \]

\[ = 0.28 \times 10^{-9} \text{ sec} \quad (7) \]

The total time uncertainty \( \sigma_T \), for single photoelectron pulses from the two detectors to operate the coincidence unit is

\[ \sigma_T = (\sigma_{T_1}^2 + \sigma_{T_1}^2)^{\frac{1}{2}} = \sqrt{2} \sigma_T = 0.4 \times 10^{-9} \text{ sec} \quad (8) \]

To compare these results with the experimental resolution time defined in terms of the full width at half maximum of the resolution curve, we shall have to multiply the above time uncertainty by 2.345 (see eq. 3). The theoretical minimum resolving time obtainable from NaI(Tl) gamma ray spectrometers driving a coincidence unit which operates on \( n = 1 \) pulses is therefore

\[ T_{\text{theor.}}(n=1) = 2.345 \sigma_T(n=1) = 0.95 \times 10^{-9} \text{ sec} \quad (10) \]

In this analysis the effect of the transit time spread in the photomultiplier itself has been neglected.

The effect of the transit time spread would be to increase the value of \( T_{\text{theor.}} \) and for a more sophisticated treatment of the problem including such effects, reference should be made to a paper by Gatti and Svelto (1959).
The experimental value of the time resolution

\[ T_{\text{expt.}} = (1.95 \pm 0.05) \times 10^{-9} \text{ sec} \]  \hspace{1cm} (10)

is a factor of about two larger than the minimum theoretical value. One reason for this is that \( n_{\text{expt}} \) is probably equal to 3 or 4, as will now be shown.

The RCA 7264 photomultiplier was found to have a current gain of \( \approx 10^7 \) at 2000 volts operating voltage. The sum of the photomultiplier anode capacitance and the D3a (limiter tube) grid capacitance to ground is \( \approx 10 \text{ pf} \); a single electron pulse would therefore give only \( \approx -0.2 \text{ volt} \) pulse at the anode which is not sufficient to cut off the limiter tube. (The grid swing found necessary to cut off the limiter tube completely was about 0.7 volts.) Therefore \( n = 3 \) or 4 is probably a more realistic figure and would give better agreement with the experimentally obtained resolving time.

Therefore further improvements in the time resolution require either the use of higher gain photomultipliers with very small total transit time spreads, or the employment of high intensity, short fluorescent decay time phosphors. A possible improvement of the latter type may be obtained in the following way. For the NaI(Tl) crystal, the decay time of the scintillations decreases from 250 nsec at room temperature (20°C) to about 120 nsec at 150°C while the luminescence intensity approximately remains the same (Starasev et al 1962). Thus an improvement in time resolution by a factor of two may be achieved by using the NaI(Tl) crystal at higher (>100°C) temperatures. The photomultiplier tube, of course, would have to be kept
cool to keep the dark current to a reasonable value.

Alternatively, Beghian (1958) has used cooled unactivated NaI crystals for the measurement of gamma ray spectra with a resolving time of $2.7 \times 10^{-9}$ sec for gamma ray energies of 120 Kev. At 77° K the unactivated crystal has a value of $\frac{\tau}{\sqrt{R}} = 0.045$ nsec Mev per photoelectron, a factor of three better than the activated crystal value of 0.125 (Neiler and Good 1960). The unactivated NaI crystals may, therefore, be used at low temperatures with some advantage over the activated ones.
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