SOME STUDIES OF NUCLEAR REACTIONS IN LIGHT NUCLEI

by

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Preface

In this thesis I have presented results on the experimental investigation of some nuclear reactions in light nuclei. All the experimental work was performed using the High Tension Generator of the Natural Philosophy Department of Glasgow University.

Part I contains a general survey of nuclear reactions in light nuclei, showing how the important properties of nuclear energy levels can be derived from the investigation of these reactions. The material for this section has been largely drawn from current literature.

In Part II I have reported the results obtained in the investigation of the reactions $^{27}Al(p,\gamma)^{28}Si$ and $^{26}Mg(p,\gamma)^{27}Al$. Assignments to the spins and parities of several excited states in ^{28}Si and ^{27}Al are made on the basis of these results. All of this work is original. The work on the reaction $^{27}Al(p,\gamma)^{28}Si$ was carried out in collaboration with Dr. J.G. Rutherglen, P.J. Grant and F.C. Flack, the author being primarily concerned in the experimental measurements. The reaction $^{26}Mg(p,\gamma)^{27}Al$ was

studied in collaboration with Dr. J.G. Rutherglen and Mr. K.A. Wallace, the author taking a full share of responsibility in both experimental and theoretical work.

Part III is concerned with the investigation of the reaction $^{10}B(d,p\gamma)^{11}B$. The proton angular distribution measurements are interpreted in terms of "stripping" and compound nucleus formation. Assignments are made to the spin and parity of excited states of ^{11}B. Although similar results of such measurements were published shortly after the close of these experiments, the interpretation of the results in this case is new. I should like to acknowledge the assistance of Mr. K.A. Wallace during the course of the experimental work of this section.

In Part IV I have concluded with a brief discussion of the importance of the results presented in this thesis, pointing out various improvements which could be made in experimental technique and theoretical interpretation, in order to increase the importance of studying nuclear reactions in light nuclei.

I should like to thank Professor P.I. Dee

for his sustained interest and encouragement during the course of this work. I should also like to thank Dr. J.G. Rutherglen, Dr. P.J. Grant, members of the H.T. Set research group, and technical staff for their interest and assistance during the course of this work. I wish to acknowledge the receipt of a D.S.I.R. maintainance grant during the past three years.

SOME STUDIES OF NUCLEAR REACTIONS IN LIGHT NUCLEI

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Part I. General Discussion of Nuclear Reactions

I.1. Classification of Nuclear Reactions

The principal problem confronting nuclear physics at the present time is the determination of the nature of the forces which act on nucleons inside the atomic nucleus. Although the fact that nuclei are composed of neutrons and protons has been known for many years, the nature of the forces required to hold these nucleons inside the compact structure of the nucleus has never been fully determined. As a result of this lack of knowledge, very little is known about the internal structure of nuclei, and although several models of nuclear structure have been proposed, they generally fail to explain one, or more, of the experimentally determined properties of nuclei.

The principal experimental method used in the study of nuclear structure has been the investigation of reaction products produced in the bombardment of nuclei with various nucleons, such as protons, neutrons, deuterons, alpha-particles etc. It is obviously impossible to give a comprehensive survey of all the various types of

nuclear reactions which have been investigated during the past few years, and hence emphasis has been given to reactions which are relevant to the succeeding experimental work.

Let us consider the following general type of nuclear reaction

$$a + X \longrightarrow Y + b \qquad (1)$$

or, in a more compact notation, X(a,b)Y. The notation means that particle "a" strikes nucleus X to produce nucleus Y and an outgoing particle "b". Particles "a" and "b" may be elementary particles (protons, neutrons), but they can also be nuclei (e.g. deuterons, alpha-particles, tritons, etc). It will be simpler to include radiative capture, i.e. when "b" is a gamma-ray quantum, in reactions of type (1), although it should be pointed out that in this case the general rule that the number of particles remains constant throughout the reaction does not hold if the γ -ray quantum is assumed to be a particle.

In general the main interest in nuclear reactions lies in the determination of the probability for the emission of "b" as a function of

the energy of "a", the energy of "b", and the probability for the emission of "b" as a function of the direction of emission.

If the mechanism of reaction (1) is studied more closely it leads to the concept of compound nucleus formation. In any nuclear reaction the actual nuclear process of the reaction does not start before the two initial particles "a" and X have come near enough to one another, within the range of nuclear forces. The nuclear process has ceased when the two products have separated by more than the range. During the time of interaction, a compound system is formed whose properties are decisive for the course of the nuclear reaction.

Thus equation (1) should really be written as

$$a + X \longrightarrow C \longrightarrow Y + b \qquad (2)$$

where C is a compound state, and the reaction considered as a two stage process: (a) formation of compound system C and (b) disintegration of C into the products of the reaction. Bohr has pointed out one valid assumption which can be made about any compound system, i.e. the two stages (a) and (b) can be treated as independent processes, so

that the mode of disintegration of C is independent of the way it has been formed and depends only on its specific quantum numbers.

A quantum mechanical treatment of this problem leads us to expect that the total energy of the nucleons in any compound system can only assume a set of discrete values, the "energy levels" of the nucleus. Thus the structure of the nucleus must be in many ways analogous to the structure of the atom, of which the nucleus forms the central core.

Thus it is possible to represent the reaction (2) by an energy level diagram as shown in Fig. I(1). In this diagram the energy is represented on the vertical scale and we plot the energy levels of the three systems a + X, C, and Y + b. The arrows represent transitions from one state to another, the vertical arrows represent γ-ray transitions, the diagonal arrows transitions in which a particle is emitted or absorbed.

For any compound system there exists a minimum excitation energy, W_{MIN}, below which the compound system can only de-excite itself by the emission of a γ-ray, but above which the compound state

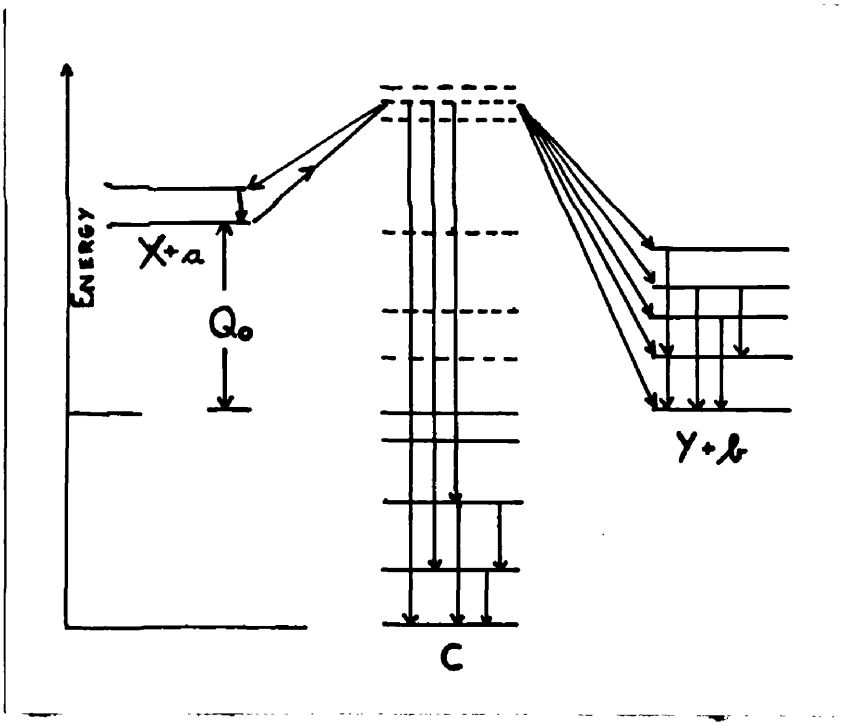


Fig. I(i). Energy level diagram for reaction X(a,b)Y.

can emit an elementary particle. Nuclear levels below this minimum energy are called "bound" levels, denoted by full horizontal lines in Fig. I(1), and levels above this energy are called "virtual" levels, and are denoted by dotted lines in Fig. I(1). It should be noted that quantitatively both these levels are similar and it is only as a matter of convenience that any distinction is made.

In reaction (2) the excitation energy of the compound state is given by $W_C = E_a + B_a$, where E_a is the kinetic energy of the incident particle and B_a is the binding energy of the nucleon "a" in the compound system, E_a is measured in the centre-of-mass system of the incident particle and target nucleus . The energy released in the reaction is usually denoted by Q and it is equal to the mass difference of the target and final nuclei expressed in energy units. In Fig. I(1) Q_o represents the energy released when particle "b" is emitted to the ground state of Y, similarly Q_1, Q_2 etc. represent the energy released when "b" is emitted to the first and second excited levels of Y respectively. Thus the total kinetic energy

available to the system Y + b is $E_a + Q_o$ (for the ground state transition) and in order to measure Q_o it is only necessary to measure the kinetic energy of the particle "b", since the geometry of the experiment and the principle of conservation of momentum define the division of energy between Y and b. Similarly we can measure Q_1 and Q_2 and hence determine the energy levels of the nucleus Y from the differences $Q_o - Q_1$, $Q_o - Q_2$ etc., which give the energy of the levels with respect to the ground state of Y. These measurements can be confirmed by measurement of the γ-ray spectra emitted from the excited states of Y, and in the above case we should expect to find a γ-ray of energy $Q_o - Q_1$, corresponding to a transition from the first excited state of Y to the ground state.

In the preceding paragraph we have considered the determination of the energy levels of nuclei formed by the emission of a particle from a compound nucleus. If, on the other hand, the compound nucleus C cannot decay by emission of a particle, then it must return to the ground state configuration by emission of gamma-radiation, and by studying

the probability of gamma-emission as a function of the energy of "a", i.e. measuring the excitation function for the reaction, it is possible to obtain information on the highly excited levels in the compound nucleus C. This is due to the fact that, provided the excitation energy of C is not too high and there exist discrete energy levels, only discrete values of the kinetic energy of the incident particle will give a total energy, $E_a + B_a$, equal to one of these discrete energy levels, and hence the excitation function will exhibit sharp maxima, or "resonance", corresponding to the formation of the compound nucleus C in one of these discrete states.

Further information on the energy levels of the compound nucleus C can be obtained from the study of the γ-ray spectra emitted in the subsequent de-excitation of C to the ground state. However, these spectra are generally very complex, and the subject will be treated in a later section.

So far we have considered the general case of nuclear reactions and how they are used in the determination of nuclear energy levels. No mention has been made of the other properties of these levels, and it will be left to a later section to

discuss these more fully.

The experimental work presented in this thesis has been concerned with two distinct types of nuclear reactions, and their importance with regard to the foregoing discussion will now be briefly discussed.

In the study of proton capture reactions we are dealing with a typical example of a reaction which proceeds by compound nucleus formation. Let us consider the following case

$$X(Z, A - Z) + p \longrightarrow Y(Z + 1, A - Z) + \gamma$$

i.e. bombardment of a nucleus X, consisting of Z protons and A - Z neutrons (A = atomic weight, Z = atomic number), by a proton, with the formation of a compound nucleus consisting of Z + 1 protons and A - Z neutrons and the subsequent emission of gamma-radiation from this nucleus.

As we have seen above, the compound nucleus Y is formed in a highly excited state, which decays to the ground state either directly or by cascade transitions through intermediate levels. It will be clearly seen that in all (p,γ) reactions it is not the bombarded nucleus which is being investigated,

but the nucleus with atomic weight and atomic number increased by unity, e.g. bombardment of ^{27}Al by protons gives information on the excited states of ^{28}Si.

In recent years the study of deuteron induced reactions has led to a new concept in the mechanism of nuclear reactions. It has been known for some time that deuteron reactions have a larger yield than corresponding reactions initiated with other charged particles. The new features of the deuteron reactions can be traced to the following facts: (a) the deuteron is a very loosely bound structure, its binding energy of 2.23 Mev being much lower than the average binding fraction; (b) its charge distribution is very "unsymmetric": the centre of mass and centre of charge do not coincide. The distance between the two centres is equal to the "radius" of the deuteron.

We shall consider only the (d,p) reaction, although similar considerations hold for the (d,n) reactions. If the deuteron forms a compound nucleus in the usual way then we have the reaction:

$$X(Z,\ A - Z) + d \rightarrow C(Z + 1,\ A - Z + 1) \rightarrow Y(Z, A - Z + 1) + \uparrow \quad (3)$$

In general the excitation curve for this reaction will not show any resonance maxima, as the excitation of the compound nucleus will be so large that no discrete energy levels will exist. Another feature of deuteron reactions proceding by compound nucleus formation is that the emission of either a proton or neutron, or both, is always energetically possible. Thus deuteron reactions, which proceed by compound nucleus formation adhere to scheme (2) and any gamma-radiation emitted comes from the excited states of Y.

Because of the special properties of the deuteron, compound nucleus formation is not the only process which can occur. The following processes occur with appreciable probability:

(a) The "electric" disintegration of the deuteron by the Coulomb field of the target nucleus.

(b) Formation of a compound nucleus by the absorption of only one constituent of the deuteron.

We shall consider only process (b). (a) is not important for light nuclei at low deuteron bombarding energies. The mechanism of process (b) is described as follows: Because of the finite size of the deuteron, it may happen that one

constituent comes into contact with the nuclear surface before the other one does. Since the nuclear interaction energies are much higher than the binding energy of the deuteron, the nucleon arriving first at the nuclear surface is quickly separated from its partner and forms a compound nucleus C^1. If the second nucleon hits the nuclear surface the compound nucleus C is formed as in case (3). If the second nucleon misses the nucleus, however, process (b) results:

$$X(Z, A - Z) + d \rightarrow C^1(Z, A - Z + 1) + p$$

which illustrates the case for a (d,p) reaction proceeding without passing through a compound nucleus. The fact that the Coulomb repulsion between the proton of the deuteron and the target nucleus tends to keep the proton away from the nucleus favours (d,p) reactions, as in this case the proton would not have to penetrate the Coulomb barrier in order to produce the reaction, as would be the case either in direct compound nucleus formation, or in (d,n) reactions proceeding by process (b). The process is called "stripping" at high energies and the "Oppenheimer-Phillips"

process at low energies. It will be discussed more fully in a later section.

I.2. Properties of Nuclear Energy Levels

During recent years the emphasis in the experimental investigation of nuclear energy levels has turned from the determination of the position of these levels to a determination of their characteristic properties. Three of the most important properties of a nuclear level are (a) the level width, (b) its angular momentum, and (c) its parity. These will be discussed separately, both from the point of view of theoretical interpretation and experimental determination

(a) Level Width

The width of a nuclear level C is normally defined by the equation

$$\Gamma^C = \frac{\hbar}{\tau^C}$$

where Γ^C is the level width, and τ^C is the mean lifetime of the level. Thus the level width expresses the probability for decay of the level per unit time.

In this case Γ^C refers to the total width of the level regardless of its mode of decay. The fact that most compound states can decay by one or more processes, or "channels", leads to the concept

of partial widths. Thus the total width of a level can be written as the summation of a number of partial widths corresponding to separate "channels" in the decay of the level, i.e.

$$\Gamma^{C} = \sum_{k} \Gamma_{k}^{C}$$

where Γ_{k}^{C} is the partial width of level C corresponding to its decay by channel k. The partial widths are proportional to the relative probabilities for the decay of the level by the appropriate channel.

Consideration of a particular type of reaction will illustrate how partial and total widths can be determined experimentally. In the case of resonance capture of a proton, where the compound state can only decay by emission of γ-ray, we have only two channels for the decay of the compound nucleus. These are (1) re-emission of the captured proton, and (2) emission of a γ-ray quantum. Thus the total width of the level is composed of two partial widths and

$$\Gamma = \Gamma_{p} + \Gamma_{\gamma} \text{ where } \Gamma_{p} \gg \Gamma_{\gamma}$$

It can be shown that the cross section, σ, for a reaction of the type X(p,γ)Y is given by the Breit-Wigner dispersion formula:

$$\sigma = \frac{\lambda^2}{2\pi} \cdot \omega \cdot \frac{\Gamma_p \cdot \Gamma_\gamma}{(E - E_r)^2 + \frac{1}{4}\Gamma^2}$$

where λ is the de Broglie wave-length of the bombarding particle p, E is the kinetic energy of p, E_r is the resonance energy, and ω is a factor which depends upon the angular momentum changes involved in the transition, and which is of the order of unity for small changes of angular momentum. If we integrate equation (1) over all values of E close to E_r for which σ is appreciably different from zero, we obtain the following expression for "Y" the thick target yield in disintegrations per incident particle.

$$Y = \frac{\hbar^2 \omega}{4 M E_r \epsilon} \cdot \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$

Here ϵ is the rate of loss of energy of the incident particle in the target material per disintegrable nucleus per cc., and λ^2 has been replaced by $\frac{h^2}{2ME_r}$, where M is the mass of the incident particle and h is Planck's constant.

Thus if $\Gamma_p \gg \Gamma_\gamma$, so that $\Gamma = \Gamma_p$ equation (2) reduces to

$$Y = \frac{\lambda^2 \omega}{4 M E_r \epsilon} \cdot \Gamma_\gamma \qquad (3)$$

so that a measurement of the thick target yield provides a method of measuring Γ_γ.

The total width Γ can be measured directly from the width of the thin target excitation curve, provided that it is greater than the experimental resolution. From these measurements Γ_p can be obtained from the relation

$$\Gamma = \Gamma_p + \Gamma_\gamma$$

Information on partial widths can be obtained from the analysis of high energy deuteron "stripping" reactions, but this is outside the scope of this survey.

(b) and (c) Angular Momentum and Parity

In this section we shall be concerned with the importance of the angular momentum and parity of nuclear levels on the course of nuclear reactions. No discussion upon the theoretical reasoning underlying these concepts will be made.

According to the principles of quantum mechanics

the orbital angular momentum of a system of particles can only assume integral values in units of $\frac{h}{2\pi}$. However, the individual nucleons which constitute the nucleus are known to have an intrinsic spin of $\frac{1}{2}(\frac{h}{2\pi})$. The total angular momentum J, of a nucleus in a given state, will be the vector sum of the orbital angular momentum and intrinsic spin of the individual nucleons, and can, therefore, assume integral or half-integral values, depending on whether the number of nucleons is even or odd. The parity of a state is introduced in a wave mechanical description of the state to define its symmetry properties. The parity is defined as being odd (-), or even (+), according to whether the wave function does, or does not, change its sign when the co-ordinates of the particles are interchanged.

In nuclear reactions involving only discrete levels of nuclei, which possess definite values of angular momentum and parity, it is the conservation rules of angular momentum and parity which largely control the course of the reaction. These rules can be stated as follows:-

(1) the total angular momentum of any system of particles must be conserved in a nuclear reaction.

(2) the parity of a system must remain unchanged during a reaction.

One result of these rules can be stated as follows:

If there is a transition between two states of differing parity then the angular momentum transfer in the transition must have an odd value, similarly if the two states have the same parity then the angular momentum transfer must be even. Thus in any transition between these two states the angular momentum transfer must always be even or odd, and no transition can occur involving both even and odd angular momenta. It should be stated that this applies only to transitions between states with definite values of angular momentum and parity.

Consideration of the "centrifugal barrier" surrounding a nucleus reduces the order of orbital angular momentum of any particle which plays an appreciable part in any nuclear reaction. Thus in the bombardment of light nuclei with charged

particles whose energy is $<$ 1 Mev only orbital angular momentum values of 0, 1 and 2 are considered to contribute appreciably to the reaction. This applies both to particles absorbed and emitted by the compound nucleus.

However, let us consider the general case of a reaction in which a particle with orbital angular momentum ℓ and spin s combines with a nucleus, with spin I, to form a compound nucleus in a level C. [ℓ, s and I are all in units of $\hbar$]. It is useful to introduce the vector sum, $\underline{S}$, of I and s. $\underline{S}$ is called the "channel spin", and for the case of a proton or neutron where $s = \frac{1}{2}$, $\underline{S} = I \pm \frac{1}{2}$. It is usual to consider the reaction as proceeding independently through either of the entrance channels $\underline{S} = I \pm \frac{1}{2}$. From the conservation of angular momentum we see that J, the spin of the compound level C, is limited to the following values

$$|\ell - \underline{S}| \leq J \leq |\ell + \underline{S}|$$

This compound level C can then decay by emission of a particle whose angular momentum and parity are limited by the spin of the level to which the transition takes place. Similarly if the level

decays by emission of a γ-ray quantum the multipolarity of the transition depends on the spins and parities of the two levels.

One of the most important experimental methods used in the determination of the spin and parity of nuclear energy levels is the measurement of the angular distribution of the products of a nuclear reaction. The term angular distribution implies a measurement of the probability for emission of a particle, or γ-ray, from a compound state as a function of angle, which is measured relative to some fixed direction.

It can be shown that the angular distribution depends on the following factors (1) $\underline{S}_1$, the incident channel spin, (2) ℓ_1, the orbital angular momentum of the captured nucleon, (3) J, the spin of the compound level, (4) ℓ_2, the orbital angular momentum of the emitted nucleon, and (5) $\underline{S}_2$ the emergent channel spin. In the case of γ-ray emission ℓ_2 is replaced by L, where 2L is the multipolarity of the γ-ray, and $\underline{S}_2$ is replaced by I_2, the spin of the final level.

There are three general features of angular distributions which apply to all nuclear reactions

involving discrete energy levels, provided both the target nucleus and incident particle are unpolarised:-

(1) As is clear on physical grounds, there will be axial symmetry about the direction of the incident beam.

(2) If, among the incoming partial waves, only those of angular momentum ℓ or below contribute appreciably to a reaction, the angular distribution of any single product particle cannot be more complicated that that of the incoming contributing partial wave. Indeed, the angular distribution of the outgoing particle will be a polynomial in $\cos\theta$, where θ is the polar angle of emission relative to the beam direction, of degree no higher than 2ℓ. This holds independently of the spin of any particles, or of the number which take part.

(3) If the distribution of the product particles contains any odd powers in $\cos\theta$, i.e. if it is not symmetrical with respect to the plane normal to the beam, then two (or more) intermediate states are involved with opposite parities. Thus an even polynomial in $\cos\theta$ is a

typical consequence of reactions involving a marked resonance.

A unique determination of the spin of a compound level normally requires additional information apart from the angular distribution measurements, and this will be illustrated more clearly in Part II of this thesis. The parity of a compound level is generally inferred from a knowledge of the parity of the target nucleus and the orbital angular momentum of the captured nucleon.

When the spin of the compound level has been determined an estimate of the spin of a particular excited level in the final nucleus can be obtained by measurement of the angular distribution of the reaction product leading to this level. This procedure will be illustrated in Part II.

Finally it should be noted that the above considerations do not apply to deuteron "stripping" reactions. A special theory has been developed which enables the spin and parity of levels excited in these reactions to be determined from angular distribution measurements of the proton or neutron, and this will be discussed in Part III.

I. 3. Detection of Products of Nuclear Reactions

(a) Gamma-rays

During recent years various experimental techniques have been developed to determine the energies and relative intensities of γ -radiation emitted in the disintegration of light nuclei.

In order to understand the basic principles underlying these techniques it is necessary to study the manner in which gamma-radiation is absorbed by matter. This process is a complex phenomenon, involving three processes of absorption:

(1) photo-electric absorption effect, prominent for low energy γ -rays, is still important up to γ -ray energies of 1 Mev.

(2) "Compton" absorption, in which recoil electrons and scattered quanta are produced. Predominant in the energy region 0.6 - 2.5 Mev (in lead).

(3) "pair production", in which the absorption is due to the formation of electron pairs and involves the transformation of part of the γ -ray energy into the mass of the electrons. It does not occur for energies less than $2\ m.c^2$, i.e. 1.01 Mev.

The three processes mentioned above involve different types of reduction in energy, (1) results in complete

absorption of the quantum, (2) produces partial transformation into β-ray energy and yields scattered quanta of degraded energies, and (3) results in the production of positrons which, on annihilation, produce photons of 0.51 Mev.

In all of the earlier techniques only one of the above processes was utilised in the measurement of γ-ray energy, e.g. the measurement of the maximum β-ray energy emitted in (2), by measuring its range and hence calculating E , or the measurement of the energy of the electron pairs using a magnetic pair spectrometer, or using the photo-electric absorption process in a proportional counter when measuring the energy of very low energy γ-rays. This limited the energy range over which these techniques could be efficiently utilised.

In γ-ray spectroscopy two factors must be considered in deciding the most efficient method of detection available. These are (a) high resolution efficiency of the γ-ray energy and (b) high efficiency for the detection of the γ-radiation over a wide energy range.

Most known methods do not satisfy condition (b), e.g. the proportional counter is only used in the

very low energy region; measurement of the range of the "Compton" electrons, while also not satisfying condition (a), is only applicable between energies of 1 - 3 Mev; and the magnetic pair spectrometer, while providing very high energy resolution, is only useful for energies > 2 Mev. and even then its efficiency is rather low.

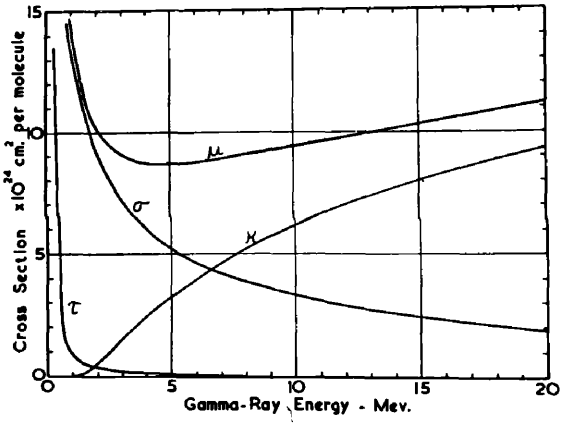
The development of the scintillation counter, with sodium iodide (thallium activated) as the scintillation phosphor, has provided a major advance in the field of γ-ray spectroscopy. In this technique all three modes of absorption are utilised, and so the counter has a reasonable detection efficiency over a wide range of γ-ray energy, and also provides good energy resolution.

As this is the method of detection used in the experimental work to be presented in this thesis, we will now discuss in detail the mechanism involved, and show the type of spectrum expected for a particular γ-ray energy.

It is convenient to divide the energy of γ-rays into three regions (a) low energy; up to 1 Mev., (b) intermediate energy; 1 - 5 Mev., (c) high energy; 5 - 20 Mev.

The cross sections for the interaction of γ-rays with sodium iodide are shown in Fig. I(ii). For low energies the photoelectric effect, τ, gives the major contribution to the total absorption cross section, μ, while for intermediate energies the Compton effect, σ, predominates, and for high energies the pair production process, K, predominates. Each interaction process releases electrons from the sodium iodide with a characteristic energy distribution, and the combination of crystal and photomultiplier produces a corresponding electrical pulse height distribution, which can be analysed by means of a differential pulse-height analyser or "kicksorter".

If only these primary interaction processes are considered then (1) the photoelectric effect gives a "line" spectrum corresponding to the full γ-ray energy, $h\nu$, (2) the Compton process gives a broad distribution with a sharp upper limit and (3) the pair production process gives a second line at $h\nu - 2m.c^2$. These theoretical distributions are broadened by the finite resolution of the apparatus resulting from the statistics of the light production and photomultiplier operation



Cross sections for the absorption of γ-rays in sodium iodide: τ—photoelectric, σ—Compton, κ—pair production, μ—total. The absorption coefficient in cm.$^{-1}$ equals 14.7 × 10^{21} times the molecular cross section.

Fig. I(ii). Cross-sections for interaction of γ-rays with NaI.

and from inhomogenieties of the crystal and photocathode.

However, the experimentally observed spectra differ considerably from those expected on the basis of the primary interaction process discussed above; the extent of the difference depends on the size of the crystal and the γ-ray energy. The principal differences can be accounted for by considering two secondary interactions which take place in the crystal:

(a) Scattered quanta following Compton events may be captured thus moving counts from theprimary Compton electron spectrum to higher energy regions of the spectrum.

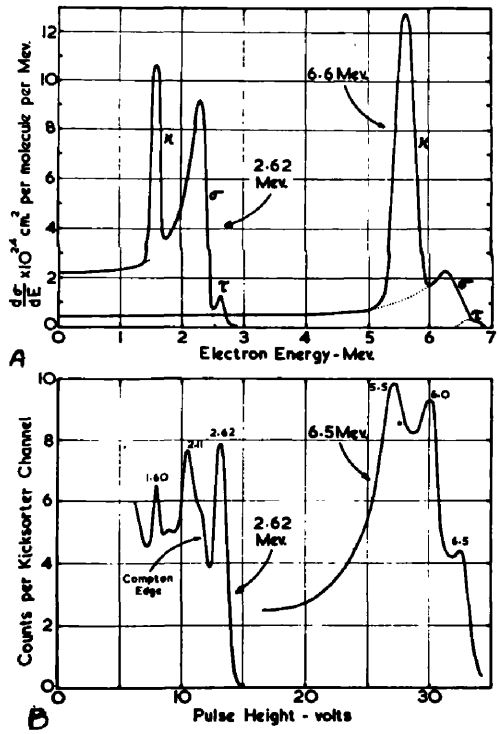
(b) Following pair production and the absorption of the kinetic energy $h\nu - 2\ m.c^2$ in the crystal the positron annihilates producing two 0.51 Mev γ-rays, one or both of which may be captured. If one is captured counts are shifted from the pair peak at $h\nu - 2\ m.c^2$ to a new peak at $h\nu - m.c^2$ and, if both are captured, counts are shifted from the pair peak to the full energy peak at $h\nu$. Thus pair production events may contribute to three different peaks in the

spectrum.

Fig. I(iii), due to Griffiths, gives a comparison between the theoretically predicted spectra for two γ -rays of energy 2.62 Mev. and 6.6 Mev., and the experimentally observed spectra using a sodium iodide crystal, $1\frac{3}{4}$" diameter and 2" long, similar to that used in the γ -ray measurement in this laboratory. Effects (a) and (b) are clearly evident in this graph.

From the above considerations it is obvious that γ-ray spectra, containing γ -rays whose energy is not widely different, will be very complex and difficult to analyse. In such cases it is essential to know the line shape spectra expected from monoenergetic γ-rays of the appropriate energy. These line-shapes are characteristic of each individual scintillation spectrometer, and must be determined experimentally. We have used the γ-radiation from the following nuclear reactions and radioisotopes to determine the line-shapes: $^{11}B(p,\gamma)^{12}C$ [4.43 and 11.8 Mev], $^{13}C(p,\gamma)^{14}N$ [8.06 Mev.], $^{19}F(p,\alpha\gamma)^{16}O$ [6.13 Mev], ^{24}Na [1.38 and 2.76 Mev], Th C'' [2.62 Mev] and ^{22}Na [0.51 and 1.28 Mev].

Fig. I(iv) shows the line-shapes for single



A Theoretical electron spectra following primary interactions of 2.62 and 6.6 Mev. γ-rays in sodium iodide.

B Experimental single crystal scintillation counter spectra for 2.62 and 6.5 Mev. γ-rays. Arbitrary vertical scales, representing the number of counts per kicksorter channel, are given on all curves showing experimental spectra as these curves are generally composites of several runs.

Fig. I(iii). Comparison of theoretical and experimental spectra from NaI [from Griffiths, Canadian Jour. of Physics].

high energy γ-rays normalised so that the peak corresponding to the escape of both annihilation quantum is at the same point. Fig. I(νa) shows the line-shape spectrum of a 2.62 Mev. γ-ray and Fig. I(νb) the line-shapes for 0.66 Mev, 1.28 Mev. and 1.38 Mev γ-rays normalised so that the total energy peak is at the same point.

By extrapolation from these results we can obtain the line-shapes corresponding to any desired γ-ray energy.

Intensities in a complex spectrum may be compared by measuring the areas under the separated single curves, but this is often difficult where several γ-rays, not widely differing in energy, are involved. It was found convenient to construct curves of the quantity A/PH where P is the pulse height for a given peak, H is the number of counts per unit pulse height interval at the peak, and A is the area under the curve. Fig. I(vi) shows this quantity plotted for the three peaks of electron energy E_γ, $E_\gamma - m.c^2$, $E_\gamma - 2\ m.c^2$, as a function of E_γ using the line-shapes shown in Figs. I(iv, v). Use of these curves enables the area under a curve to be determined from a knowledge of P and H only.

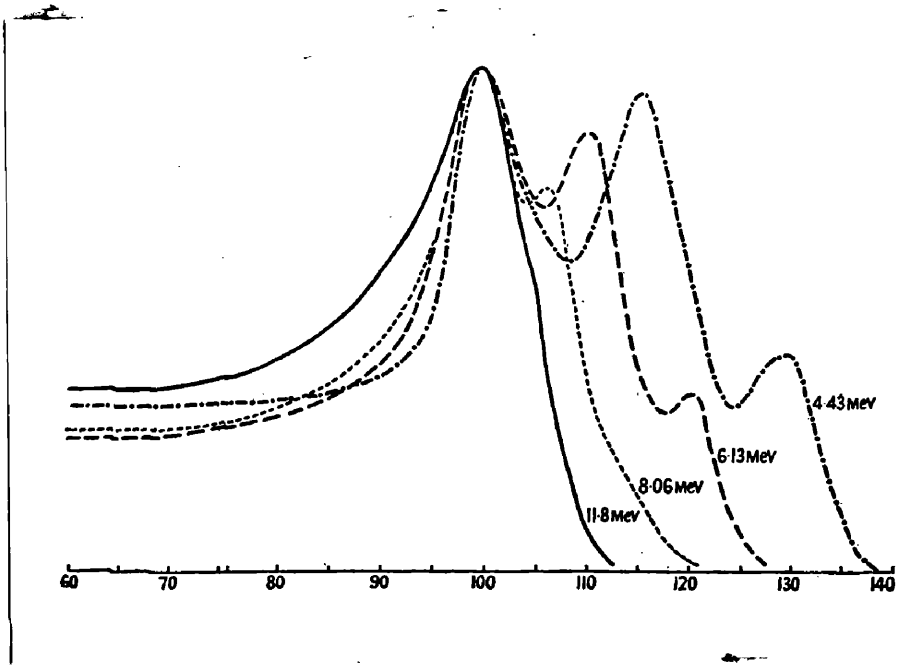


Fig. I(iv). High energy ϒ-ray line shapes using NaI scintillation spectrometer.

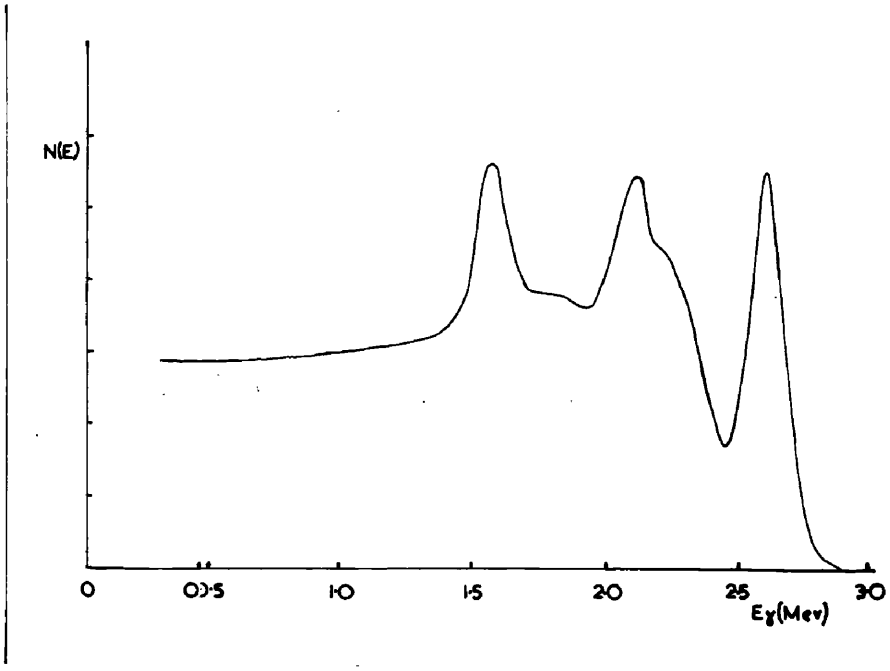


Fig. I(va). Line shape for 2.62 Mev ϒ-ray using NaI.

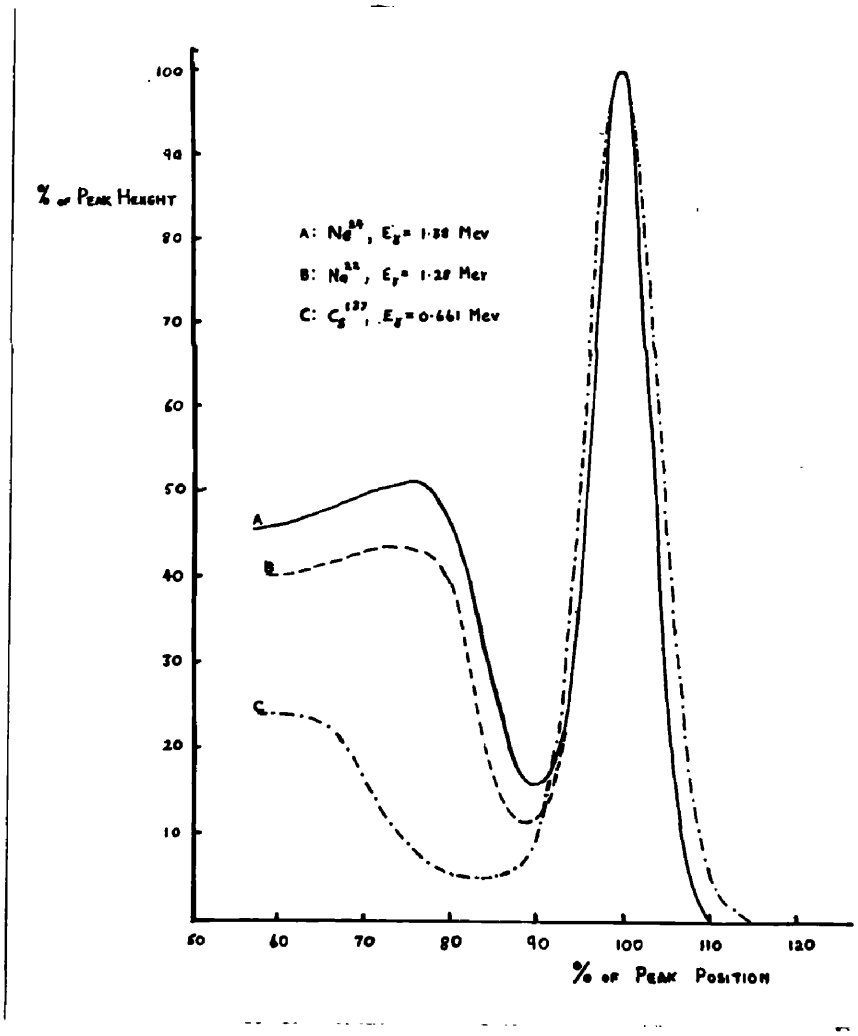


Fig. I(vb). Line shapes for 0.66, 1.28, and 1.38 Mev γ-rays using NaI.

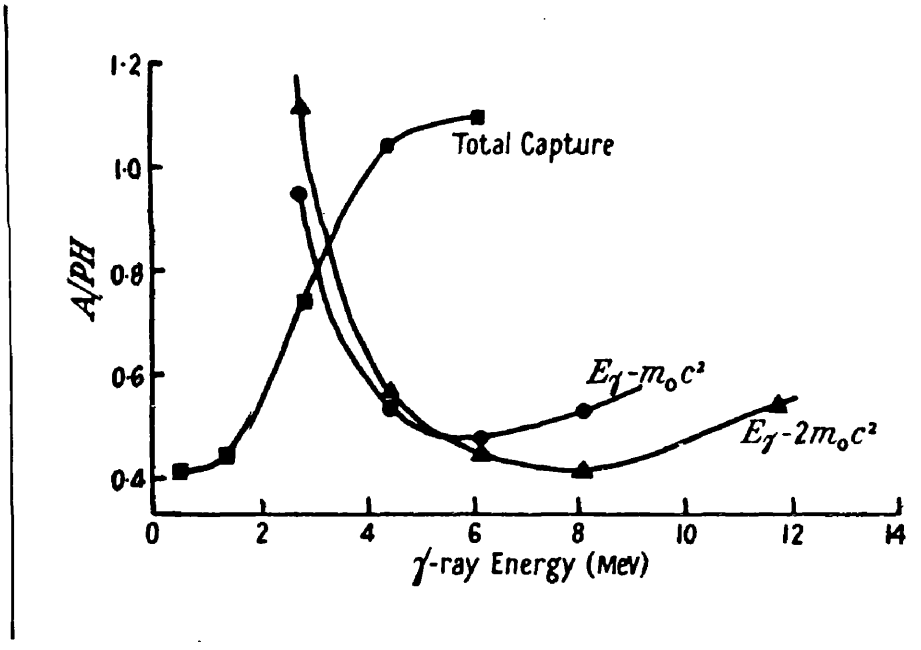


Fig. I(vi). Graph of $^{A}/_{PH}$ as a function of E_γ.

In this survey we have shown some of the limitations and advantages pertaining to the use of a sodium iodide scintillation spectrometer, a more detailed account of the analysis of complex γ-ray spectra will be given in Part II.

(b) Charged Particles

In this section we shall confine the discussion to the detection of protons. Similar considerations apply in the case of deuterons, α-particles etc.

The most widely used methods for detection and energy resolution of protons emitted in nuclear reactions are, (1) magnetic analysis (2) photographic plate method (3) proportional counters, and (4) scintillation counters.

The choice of detector in any particular experiment is governed by factors other than the degree of resolution desired, e.g. in determining the energy spectrum of protons from a reaction, magnetic analysis, with its very high energy resolution, has great advantages, but it is difficult to adapt this detector to measure the angular distribution of these protons, and the distribution measurements are usually made with

one of the methods (2), (3) or (4). In our experiments we desired to measure both angular distributions and angular correlations, which made photographic plates an unsuitable technique, and so we were left with a choice between (3) and (4).

Experience gained in the use of a sodium iodide scintillation spectrometer had shown that this technique was well adapted to the measurement of the angular distribution of the products of nuclear reactions. Experiments leading up to the final design of a proton spectrometer will be discussed in Part III.

The principal difficulty associated with the detection of a particular proton group emitted in a nuclear reaction, is the detection of the group in competition with any lower energy groups which may have a much higher intensity. In the case of scintillation counters this is avoided by inserting sufficient aluminium foil between the target and detecting phosphor to absorb all the undesired low energy particles.

The results obtained using a scintillation counter, with a "plastic" phosphor scintillator,

in measuring the proton spectrum emitted from the reaction $^{10}B(d,p)^{11}B$ have proved very satisfactory, as will be shown in Part III.

II. Study of (p,γ) reactions in light nuclei

(1) Introductory Survey

During recent years the study of (p,γ) reactions in light nuclei has made an important contribution to the determination of the position and properties of nuclear energy levels.

Measurement of the excitation functions over a wide range of proton energies has produced an extensive catalogue of resonance levels for practically all of the light nuclei in which such a reaction is energetically possible. For example, nearly 100 resonance levels are known to exist in ^{28}Si within the range of excitation 11.807 Mev to 15.555 Mev, corresponding to a range of bombarding proton energies of 226 Kev to 4.1 Mev; nearly 50 levels have been measured in ^{24}Mg in the range of excitation 0.8 Mev to 2.6 Mev. Reference to these, and all other known levels observed in (p,γ) reactions in light nuclei up to ^{41}Ca, can be found in the reviews by Ajzenberg and Lauritsen (1954) and Endt and Kluyver (1954).

Since the development of the sodium iodide scintillation spectrometer, facilitating the

analysis of complex γ-ray spectra, many γ-ray decay schemes have been determined. These measurements, apart from providing checks to the already known energy level schemes, provide information on the spins of the levels involved in the transitions, and on the process of the emission of electro-magnetic radiation from nuclei. This can be seen from the following considerations.

It has been shown that the absolute probability and multipole nature of the γ-transition from any state of a compound nucleus to a lower state, depends on the angular momenta and parities of the two states. If the transition is a 2L - pole one, the quantum carries away L units of angular momentum, and the parity of the radiation field is related to the multipolarity as indicated in the following scheme:

L	odd parity	even parity
1	electric dipole (E1)	magnetic dipole (M1)
2	magnetic quadrupole (M2)	electric quadrupole (E2)
3	electric octupole (E3)	magnetic octupole (M3)

The probability of a particular multipole

transition decreases with increasing order, therefore where conservation of angular momentum and parity permit a transition to have a mixed multipole nature, it will normally be the lowest multipole that predominates. However, electric radiation is more probable than magnetic, so that transitions of the type electric quadrupole - magnetic dipole may occur with equal probability. In practise it is usual to consider only the lowest multipolarity possible as playing an appreciable part in the transition.

From the above considerations it will be seen that the relative intensities of γ-rays emitted from various compound states, with differing J values and parities, to the same excited state of the nucleus can provide important information on the spin of this level, or, if the spin is known, provide a check on the theory of radiation transfer probabilities.

Apart from the measurement of γ-ray spectra, the most important experimental results from this type of reaction have been obtained from the measurement of γ-ray angular distributions. The

importance of these measurements in determining the spins of nuclear levels has been discussed in Part I.2(b), and at this point we will only point out the most marked features in the measured distributions expected from different types of reaction. These are:-

1. Whether isotropic or not.
2. If anisotropic, whether symmetrical about the plane normal to the incident beam.
3. Whether the distribution is energy dependent or not.

The various conditions affecting these are:

1. The distribution is always anisotropic unless the J value of the compound state is 0 or $\frac{1}{2}$, or the compound state is formed by absorption of a nucleon with orbital angular momentum zero.
2. If the two states involved in the transition have definite parities then the distribution will be symmetrical about the plane normal to the beam.
3. The distributions will be energy independent if there is only one level in the compound nucleus involved in the reaction.

The first accurate measurements of γ-ray

angular distributions were made by Devons and Hine (1949) who measured the distributions from the reactions $^{7}Li(p,\gamma)^{8}Be$, $^{9}Be(p,\gamma)^{10}B$, $^{12}C(p,\gamma)^{13}N$, $^{13}C(p,\gamma)^{14}N$ and $^{19}F(p,\alpha\gamma)^{16}O^{*}$. Since then many measurements of this type have been made, and the results have been listed in the review articles mentioned previously.

Recent developments in the field of (p,γ) reactions, include the measurement of the polarisation of the high energy components in the γ-ray spectra by observation of the photo-disintegration of deuterium in photographic plates. Measurements of this type have been carried out by Mr. I.S. Hughes in this laboratory on the reactions $^{27}Al(p,\gamma)^{28}Si$ and $^{26}Mg(p,\gamma)^{27}Al$. They are especially important in determining the parity change associated with a particular electro-magnetic transition.

II. 2. The Reaction $^{27}Al(p,\gamma)^{28}Si$

Introduction

In the region of proton energies below 800 Kev the reaction $^{27}Al(p,\gamma)^{28}Si$ has been investigated by Tangen (1946), Brostrum, Huus and Tangen (1947),

Rae, Rutherglen and Smith (1951), Hunt and Jones (1953), Rutherglen and Smith (1953) and Casson (1953).

Tangen measured the relative intensities of six resonances at E_p = 226, 294, 325, 404, 438 and 504 Kev. Brostrum et al measured accurately 29 resonances between 600 and 1380 Kev. Their energy calibration was accurate to 0.2% and they found that all the resonances had a width $<$ 1 Kev. Hunt and Jones re-examined the low energy region very accurately and found that their results agreed with those of Tangen. Rutherglen and Smith determined the excitation curve for the reaction, together with that of the competing reaction $^{27}Al(p,\alpha)^{24}Mg$, in the range of proton energies 400-750 Kev, and showed that, while all resonances produced γ-radiation, α-particle emission was forbidden at several of them.

In the present work we shall be concerned with the resonances at E_p = 404, 504, 630, 652 and 677 Kev.

Rutherglen and Smith, using a magnetic pair spectrometer, measured the γ-ray spectra emitted

in the thick target bombardment at E_p = 750 Kev. They observed three γ-rays 12.12 Mev, 10.46 Mev and 7.62 Mev corresponding to transitions to the ground state and first and second excited states ^{28}Si, respectively. Casson examined the thick target γ-ray spectra from resonances below 450 Kev by means of a sodium iodide scintillation spectrometer.

The energy level scheme of ^{28}Si has been determined by Peck (1949) using the reaction $^{27}Al(d,n)^{28}Si$.

Prior to the present work no measurements had been made of the γ-ray spectra from individual resonances or of the angular distribution of this γ-radiation.

II. 2. Reaction $^{27}Al(p,\gamma)^{28}Si$

(a) Measurement of γ-ray spectra

(i) Experimental Technique

The γ-ray spectra from this reaction were obtained at five resonances in the range of proton energy 400 - 700 Kev. using the Glasgow University High Tension Generator to accelerate the protons.

The γ-rays were detected by a sodium iodide crystal scintillation spectrometer. The sodium iodide crystal was about 1.3" cube, and was mounted on an E.M.I. 5311 photomultiplier tube. The crystal was cleaned, polished, and sealed into an airtight container, the space around the crystal being filled with magnesium oxide, which acted as a reflector. The whole operation was carried out in the dry atmosphere of a "dry box", as sodium iodide is very hygroscopic. Optical contact between the crystal and a quartz window in the airtight container was made using a thin film of silicone grease, which was found to have almost the same refractive index as the crystal and quartz. Similar contact was made between the window and photocathode of the multiplier. It should be noted that poor contact between these surfaces can produce appreciable loss in the final pulse size from the photomultiplier.

Pulses from the photomultiplier were fed by a cathode follower, of conventional design, into a pulse shaping delay line, through a linear amplifier, and hence into a five-channel pulse

height analyser. It should be noted that the crystal was mounted at 90^{o} to the direction of the incident proton beam.

The targets were prepared by evaporating pure aluminium on to a brass backing, and they were normally 15 Kev thick. The current of bombarding protons varied up to 70 μamp. Care had to be taken to keep the target clean as both carbon and fluorine were liable to appear as contaminants, producing background radiations from the reactions $^{19}F(p,\alpha)^{16}O^{*}\ (\gamma)^{16}O$ [6.13 Mev] and $^{13}C(p,\gamma)^{14}N$ [8.06 Mev].

The spectra were measured over two distinct regions (1) high energy 12 - 3 Mev (2) low energy 3 - 0.8 Mev. The low energy region was measured by increasing the E.H.T. supply to the photomultiplier, ensuring that the pulse height resolution over the two regions would be comparable.

To overcome the loss in pulse height resolution with decreasing input voltage to the pulse-height analyser, only a fixed range of input voltage was used, the spectra being measured

by varying the gain of the amplifier and normalising each run to one particular value of the amplifier gain. To allow for fluctuations in beam current, each run was taken for a fixed number of counts in a discriminator, ensuring that every run would be directly comparable.

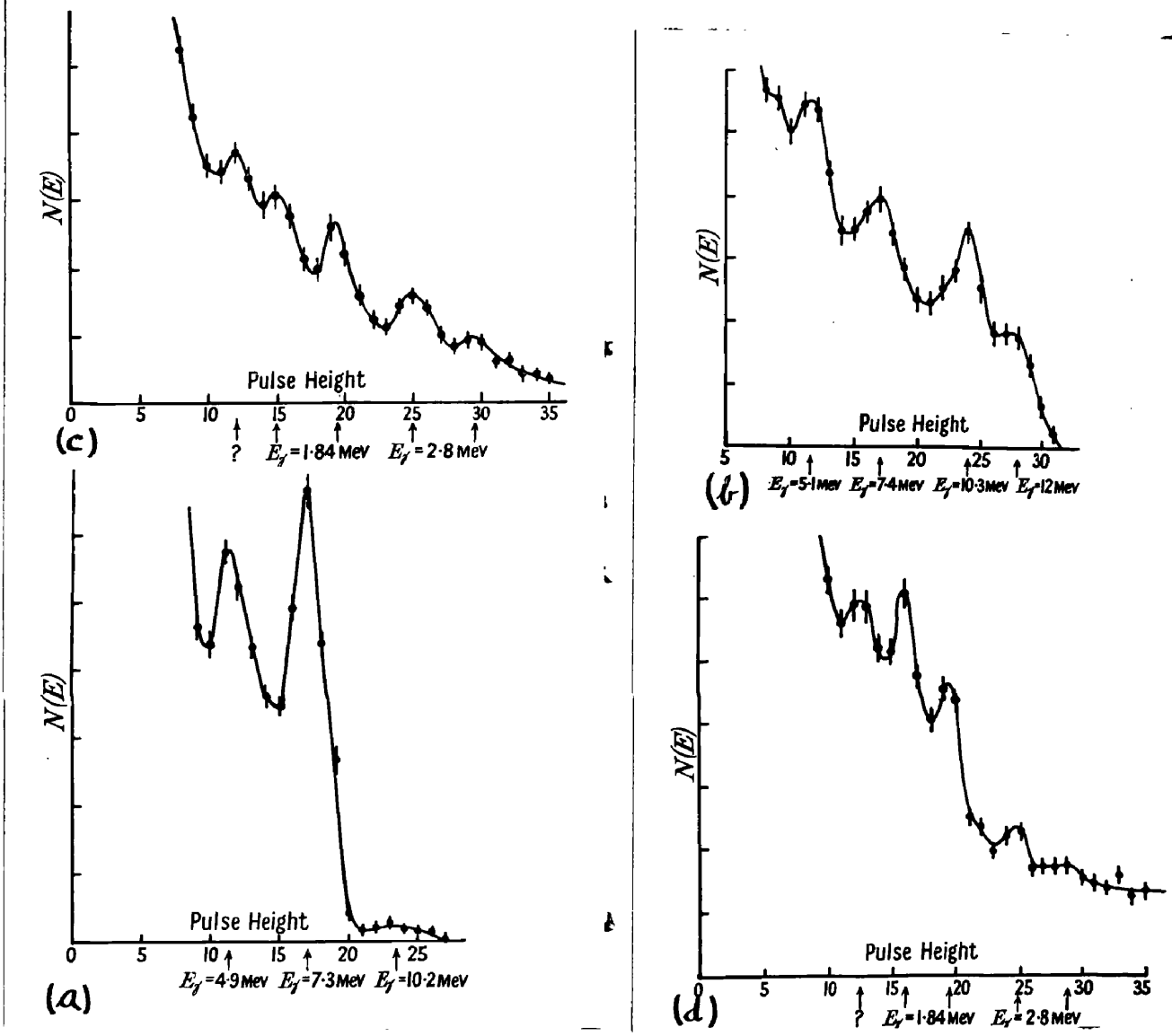
The crystal and multiplier system was calibrated in terms of pulse height against γ-ray energy using the 2.62 Mev γ-ray from ThC'' and γ-radiation from the following nuclear reactions $^{19}F(p,\alpha)^{16}O^{*}$ $(\gamma)^{16}O$ [6.13 Mev], $^{11}B(p,\gamma)^{12}C$ [4.45 and 11.8 Mev] and $^{13}C(p,\gamma)^{14}N$ [8.06 Mev]. From these calibration spectra a curve was constructed showing γ-ray energy plotted against pulse height at the peak, as for a crystal of the dimensions used only a single peak is produced for γ-ray energies $>$ 4 Mev. From this curve the energy of peaks in a complex spectra could be determined. The line shapes of these calibration γ-rays were used to estimate the line shapes of the various γ-rays found in the measured spectra, and these shapes then used to estimate the relative intensities of the various γ-ray components by estimating the relative areas under the curve.

(ii) Results

Gamma-ray spectra from the resonances at proton energies of 404, 503 and 630 Kev are shown in Fig. II 1. Figs. II 1(a,b,e) shows the high energy region down to about 3.5 Mev. Figs. II 1(c,d,f) were taken with the amplifier gain increased by a factor of four, and show the spectra in the energy range from 0.8 - 3.5 Mev. The high energy spectra at the 652 and 677 Kev resonances are similar to those at the 630 Kev resonance except that the 10.5 Mev gamma-ray is of slightly lower intensity, and the 652 Kev resonance shows a very weak ground-state transition.

More detailed examination of the spectra illustrated, in the region 2 - 4 Mev, has shown the presence at the 630 Kev resonance of two components, of energies 2.8 and 3.5 Mev. The energies and intensities are summarised in Table II(i). The energies of those γ-rays which are well resolved are accurate to within 3%. The intensities were estimated to be accurate within about 20%.

It will be seen that only the resonance at E_D = 503 Kev produces the 12 Mev ground-state



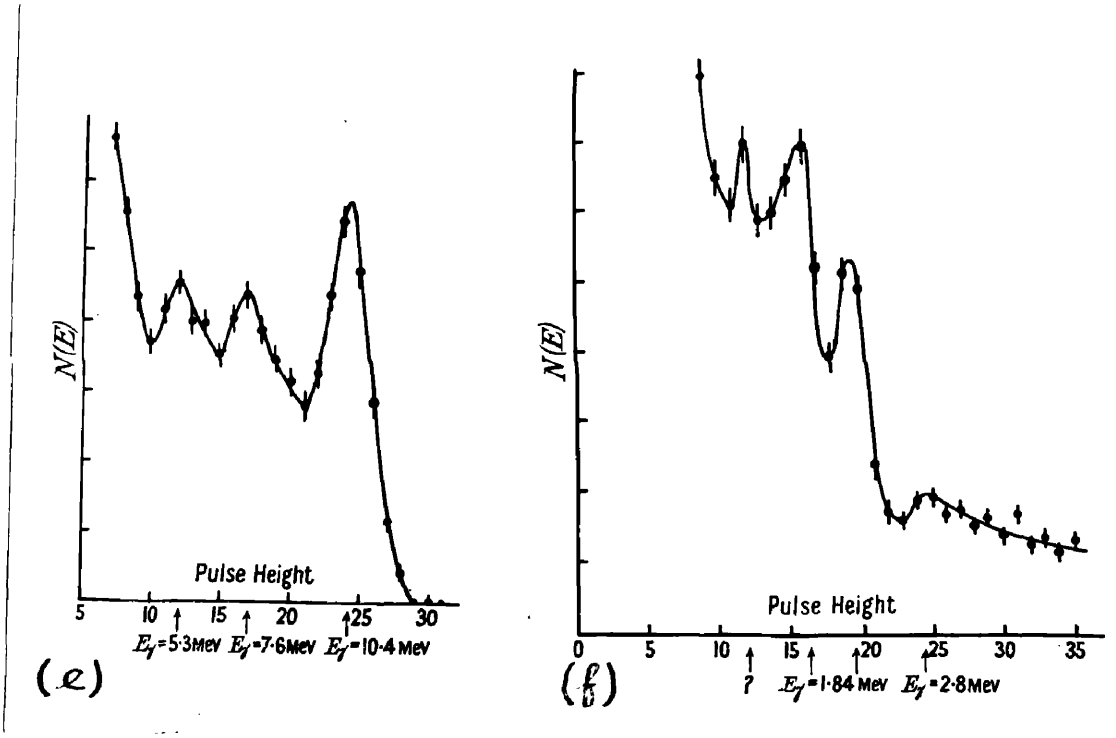
(a) High energy spectrum of γ-rays at E_p = 404 Kev.

(b) High energy spectrum of γ-rays at E_p = 503 Kev.

(c) Low energy spectrum of γ-rays at E_p = 404 Kev.

(d) Low energy spectrum of γ-rays at E_p = 503 Kev.

Fig. II(i): γ-Radiation from the reaction $^{27}Al(p,\gamma)^{28}Si$.



(e) High energy spectrum of γ-rays at E_p = 630 Kev.

(f) Low energy spectrum of γ-rays at E_p = 630 Kev.

Fig. II(i): γ-Radiation from the reaction $^{27}Al(p,\gamma)^{28}Si$.

Reson. energy	^{28}Si excit. energy	E_γ	Rel. int.	Interpretation
0·404	11·99	10·2	0·05	11·99 → 1·8
		7·3	1·0*	11·99 → 4·6 11·99 → 5·2
		5·1	0·35	11·99 → 7·1 7·1 → 1·8
		2·8	1·0	5·2 → 1·8 4·6 → 1·8
		1·84	1·0*	1·8 → 0
		1·13?		?
0·503	12·09	12·1	0·9	12·09 → 0
		10·3	1·0*	12·09 → 1·8
		7·3	0·54	12·09 → 4·6 12·09 → 5·2
		5·1	0·60	12·09 → 7·1 7·1 → 1·8
		2·8	0·3	5·2 → 1·8 4·6 → 1·8
		1·84	1·0*	1·8 → 0
		1·18?		?
0·630	12·21	10·4	1·0*	12·21 → 1·8
		7·6	0·21	12·21 → 4·6 12·21 → 5·2
		5·1,	0·10	12·21 → 7·1 7·1 → 1·8
		3·5 2·8	0·21	5·2 → 1·8 4·6 → 1·8
		1·84	1·0*	1·8 → 0
		1·13?		?
0·652	12·23	12·2	0·07	12·23 → 0
		10·4	1·0*	12·23 → 1·8
		7·5	0·74	12·23 → 4·6 12·23 → 5·2
		5·1	0·19	12·23 → 7·1 7·1 → 1·8
		Low energy region not measured		
0·677	12·25	10·4		12·25 → 1·8
		7·5		12·25 → 4·6 12·25 → 5·2
		Low energy region not measured		

* This figure was adopted as the standard of comparison for each spectrum. The intensity figures for different spectra are not directly comparable.

Table II(i). ^{27}Al(p,γ)^{28}Si.
(All energies in Mev.)

radiation with significant intensity, and it is estimated that its intensity is sufficient to account for all the radiation of energy 12.12 ± 0.10 Mev observed in the experiment of Rae et al. Thus a centre-of-mass bombarding energy of 490 Kev instead of 610 Kev should be used in evaluating the Q-value. The amended figure is Q = 11.63 ± 0.10 Mev.

This is in good agreement with that calculated from the nuclear masses given by Li(1952), Q = 11.59 ± 0.05 Mev, and that given by Feather (1953), Q = 11.56 ± 0.03 Mev. The Q-value used will be 11.60 Mev.

The γ-ray energies are consistent with the level scheme for ^{28}Si, deduced from the reaction ^{27}Al(d,n)^{28}Si and shown in Fig. II(ii).

(b) Measurement of γ-ray angular distributions

(i) Apparatus

For the determination of the angular distribution of the more prominent γ-ray components shown in the above spectra, the crystal and multiplier assembly used in these experiments was mounted on a movable arm which could rotate about the central axis of a cylindrical target chamber.

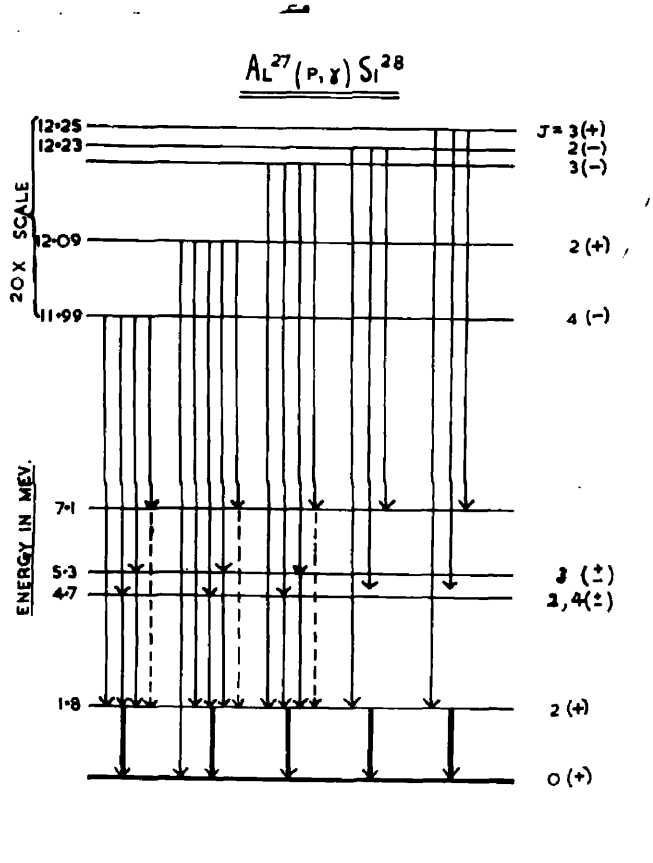


Fig. II(ii) Energy level diagram and decay scheme for ^{28}Si.

The distribution measurements were made in the plane containing the direction of the incident beam.

The proton beam incident on the target was accurately defined in direction by two molybdenum slits 1 mm. wide, separated by a distance of 15 cms. It was essential that the beam be accurately centred on the axis of rotation of the movable counter, any displacement of the beam producing an artificial anisotropy in the measured distribution.

Targets were prepared as before, except that in this case the backing used was 0.005" or 0.01" copper foil so that the γ-ray absorption in the backing could be neglected, except in the approximate direction of the plane of the target, where a copper "stiffener" produced a measurable absorption. This effect could be avoided by setting the plane of the target so that the absorption over the range of angles in which measurements were taken, was negligible. The target was water cooled to avoid evaporation of the aluminium by the proton beam overheating the copper foil.

The target chamber was insulated from the main H.T. set in order that it could be used as a Faraday cage to determine the total beam current falling on the target.

A slight anisotropy in the apparatus was found, and a correction factor determined by measuring the angular distribution of the 6.13 Mev γ-ray produced in the 340 Kev proton bombardment of ^{19}F. This radiation is known to be isotropic (Devons and Hine). The correction amounted to about 3% in the measured distribution.

(ii) Experimental procedure

The angular distributions were determined by setting the four channels of the pulse-height analyser to cover the peak of the γ-ray under observation, and recording the total number of counts in the four channels corresponding to a definite number of counts in a fixed monitor counter. This monitor counter also consisted of a sodium iodide crystal and photomultiplier, and was situated relative to the proton direction at an angle of $\theta = -90^{\circ}$.

Thus the number of counts in the movable counter for each angular position was independent

of any fluctuations in the proton beam current striking the target.

Every precaution was taken to ensure that the gain of the multiplier and other electronic apparatus did not vary during the course of the experiments. These precautions consisted of (a) checking the voltage on the photomultipliers regularly by measuring a small fraction of it with a vernier potentiometer, (b) keeping the mains supply to each amplifier constant by means of a Variac variable transformer on each mains input, (c) choosing the angular positions of the movable counter at random for short counting periods, the total distribution being taken as the aggregate of all these short runs. This eliminated any effect produced by residual drifts in the electronic apparatus.

The distributions were normally measured over a range of angles from $\theta = 20^{\circ}$ to $\theta = 100^{\circ}$ where θ is the angle the γ-ray detector made to the incident proton beam.

In order to obtain an accurate determination of the angular distribution of a specific γ-ray, it was necessary to know the line shape spectra

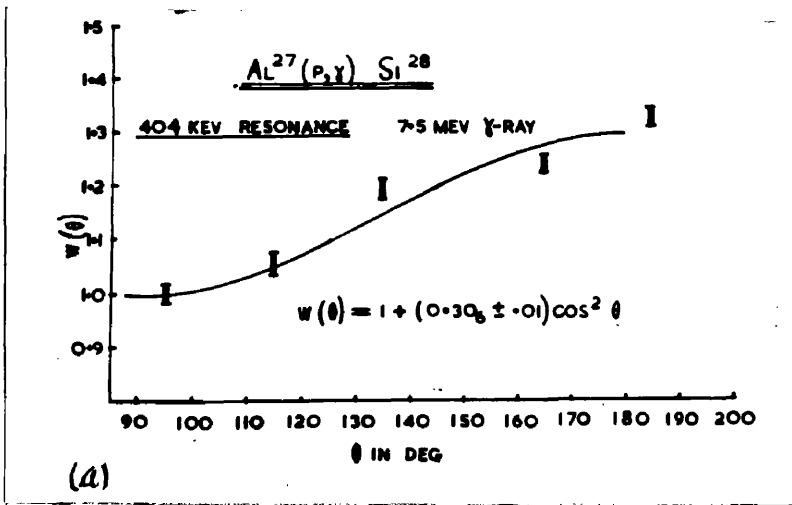
produced in the crystal by mono-energetic γ-rays of known energy, and this was done by determination of the spectra of the various calibration γ-rays mentioned previously. This procedure was especially important when considering a γ-ray other than the highest energy component in the spectrum, as the contribution of these higher energy γ-rays to the angular distribution of the lower energy ones, could seriously affect the distribution measured, since they generally have different angular distributions.

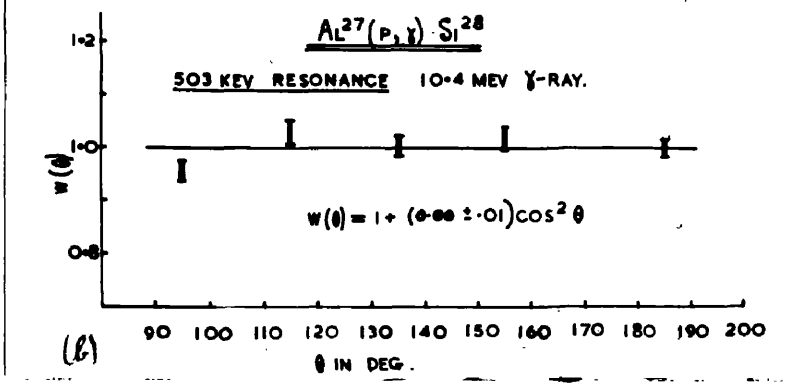
(iii) Results

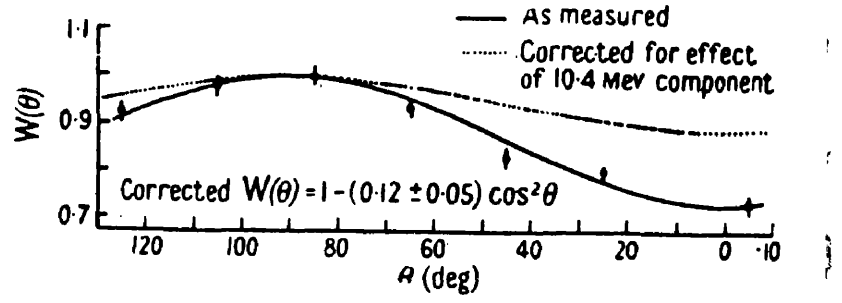
Angular distributions obtained at the various resonances are shown in Figs. II(iii, a, b, c, d, e, f). In each case the curve was fitted to the experimental points by the method of least squares, assuming that the distributions had the form

$$W(\theta) = 1 + A \cos^2 \theta$$

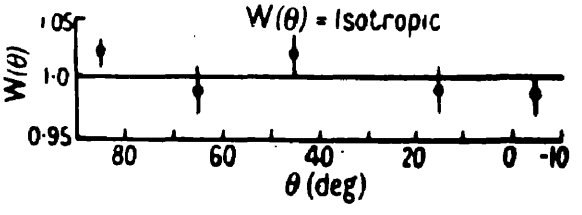
where θ is the angle between the incident proton direction and the direction of detection of the γ-ray. There appeared to be no evidence for higher orders of cos θ in any of the measured





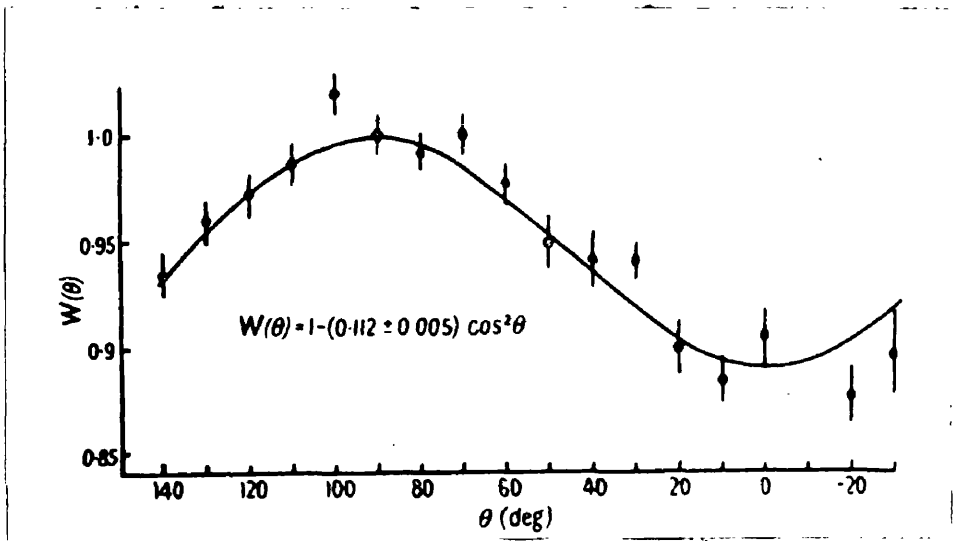


7·5 Mev γ-ray component at $E_p = 652$ kev.

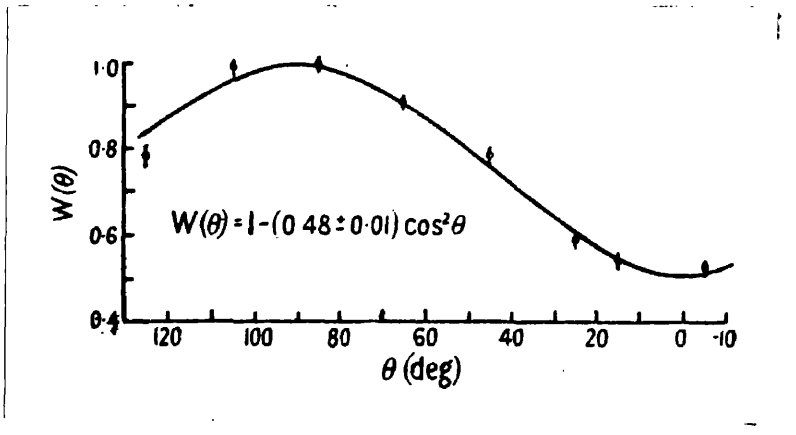


10·4 Mev γ-ray component at $E_p = 677$ kev.

Fig. II(iii). $^{27}Al(p,\gamma)^{28}Si$. Angular Distributions.



(e) 10.4 Mev γ-ray component at E_p = 630 Kev.



(f) 10.4 Mev γ-ray component at E_p = 652 Kev.

Fig. II(iii). $^{27}Al(p,\gamma)^{28}Si$. Angular Distributions.

distributions. The experimental points have been corrected for a slight instrumental anisotropy, as mentioned previously, but no correction has been applied for the finite solid angle of the detector, as this was less than 0.5%.

Table II(ii) summarises the results obtained, both as regards the emission of γ-radiation of a given energy from a particular resonance, and its angular distribution, if measured.

Also included are the results of Rutherglen and Smith on the emission of α-particles from these resonances.

(c) Interpretation

In this section we shall interpret the results presented in sections (a) and (b) in terms of the spins and parities of levels in ^{28}Si. As stated in the preface, this interpretation is primarily due to Drs. J.G. Rutherglen, P.J. Grant and F.C. Flack.

However, a brief discussion of the selection rules governing the emission of α-particles will help to clarify the reasoning in the later

Resonance (kev)	404	503	630	652	677
α	No	Yes	Yes	No	No
γ_{12}	No	Yes Isotropic	No	Very little	No
$\gamma_{10\cdot4}$	Very little	Yes Isotropic	Yes $1-0\cdot11\cos^2\theta$	Yes $1-0\cdot48\cos^2\theta$	Yes Isotropic
$\gamma_{7\cdot5}$	Yes $1+0\cdot31\cos^2\theta$	Yes	Yes $1+0\cdot10\cos^2\theta$	Yes $1-0\cdot12\cos^2\theta$	Yes
$\gamma_{1\cdot8}$	Yes	Yes	Yes $1+0\cdot13\cos^2\theta$	Yes	Yes

Table II(ii). $^{27}Al(p,\gamma)^{28}Si$.

discussion. Since the α-particle is known to have even parity, then a transition between two levels of the same parity can only occur by α-particle emission if the change in angular momentum is even. Similarly if the levels have different parity then ΔJ must be odd.

One general conclusion can be drawn from Table II(ii), namely, that there is no evidence that protons having an orbital angular momentum greater than unity take part in the reaction at any of the five resonances. The assumption of d-wave protons would not help to explain the results .

^{27}Al has a nuclear spin $J = \frac{5}{2}$ in its ground state and, assuming the shell model prediction to be correct, it is a state of even parity. With this assumption the possible states that can be formed by proton capture are as follows: s-wave, $\ell = 0$, $J = 2(+), 3(+)$; p-wave, $\ell = 1$, $J = 1(-), 2(-), 3(-)$ and $4(-)$. Of these, the $2(+)$, $1(-)$ and $3(-)$ states could emit α-particles to the ground state of ^{24}Mg, which has spin zero with even parity, while the others could not.

Rutherglen and Smith found no evidence of any other α-particle groups apart from that emitted to the ground state of ^{24}Mg . From this we may proceed to an assignment of spins and parities to all five resonance levels.

(1) 503 Kev resonance

This must produce a state J = 2(+) since it emits α-particles and emits γ-rays isotropically. The isotropic emission of γ-rays implies formation of the state by capture of s-wave protons.

(2) 677 Kev resonance

It is reasonable to assign J = 3(+) to this state since it emits γ-rays isotropically, but does not emit α-particles.

These two assignments are consistent with the fact that the 503 Kev resonance produces γ-radiation to the ground state of ^{28}Si [E2 transition, 2(+) $\rightarrow$ 0(+)] while the 677 Kev resonance does not [3(+) $\rightarrow$ 0(+) would be a M3 transition] . The other three resonances all have anisotropic γ-ray distributions, and cannot, therefore, be formed by s-wave proton capture. Of the four possible states which might be formed by capture

of p-wave protons, the 1(-) state does not appear to correspond to an experimentally observed level, since it should emit ground-state γ-radiation [1(-) $\longrightarrow$ 0(+) is an E1 transition].

(3) 630 Kev resonance

This must lead to a 3(-) state in ^{28}Si since it emits α-particles to ^{24}Mg. 1(-) is unlikely as shown above.

(4) 652 Kev resonance

Since this resonance does not emit α-particles it must have J = 2(-) or 4(-). The fact that a detectable ground-state transition occurs, limits the choice to J = 2(-), as the M4 transition 4(-) $\longrightarrow$ 0(+) would be very highly forbidden.

(5) 404 Kev resonance

This resonance must also have J = 2(-) or 4(-) and since its γ-ray spectrum is very different from that of the 652 Kev resonance, in particular showing no observable ground-state transition, and only a very weak transition to the first excited level at 1.8 Mev, we assign J = 4(-) to this resonance.

From the fact that the 404 Kev resonance

produces very little γ-radiation to the 1.8 Mev level in ^{28}Si we may say that this level cannot have $J > 2$ with even parity or $J > 1$ with odd parity. $J = 1$ seems unlikely, firstly from consideration of the β-decay of ^{28}Al in which the transition to the ground state of ^{28}Si is highly forbidden compared with the less energetic transition to the 1.8 Mev level, and secondly because a low-lying dipole level in an even-even nucleus has not hitherto been observed. It is also thought unlikely on theoretical grounds(Touschek 1950). We are left with the assignment $J = 2(+)$ to this level, which is consistent with all the experimental data on γ-ray intensities.

We shall now consider, in detail, the γ-ray angular distributions. The calculation of the theoretical distributions is a straightforward procedure, and recently comprehensive tables have been published which greatly simplify these calculations [Sharp et al (1953)]. We shall not discuss the calculations in detail, although the following point should be noted.

In calculating the transformation coefficients for the formation of the states J = 2(-) or J = 3(-) by adding a proton (spin $\frac{1}{2}$, $\ell = 1$) to ^{27}Al ($\frac{5}{2}$+) there are two possible "routes", by the addition of $\ell = 1$ to either "channel spin" S = 2, $(\frac{5}{2} - \frac{1}{2})$, or S = 3, $(\frac{5}{2} + \frac{1}{2})$. The two routes to a given J lead to different angular distributions, so that the theoretical distributions for these two states are not absolutely determined, but can be within certain limits. It has been pointed out by Christy (1953) that this indeterminacy is a consequence of lack of knowledge of the wave function describing the compound state, and could be removed by assuming, for example, either j-j or L-S coupling, between the incoming proton and the target nucleus.

If we define the channel-spin ratio

$$F = \frac{\text{number of states formed by S = 3}}{\text{number of states formed by S = 2}}$$

then the values of F required to fit the experimental data (J being known from other evidence) may give further information about the compound state. In the formation of the states J = 2(+), J = 3(+) and J = 4(-) there is no

uncertainty, only one "route" being possible.

<u>630 Kev resonance</u> [J = 3(-)] This resonance has a strong γ-ray component to the 1.8 Mev level. The theoretical distribution for a transition $3(-) \longrightarrow 2(+)$ is

$W(\theta) = 5F(17 + 9\cos^2\theta) + 4(28 - 9\cos^2\theta)$

giving the limiting distribution functions

$F = 0$, $W(\theta) \sim 1 - 0.32\cos^2\theta$; $F = \infty$, $W(\theta) \sim 1 + 0.53\cos^2\theta$

The experimental distribution is $W_{exp.}(\theta) \sim 1 - (0.112 \pm 0.01)\cos^2\theta$, which can be fitted by $F = 3/7$.

Using this value of F, the calculated distribution for the 1.8 Mev γ-ray transition [$2(+) \longrightarrow 0(+)$] which belongs to the same cascade, is $W(\theta) \sim 1 + 0.18\cos^2\theta$. This is in satisfactory agreement with the experimental distribution $W_{exp.}(\theta) \sim 1 + (0.13 \pm 0.05)\cos^2\theta$.

This resonance also produces γ-radiation to the levels at 4.6 and 5.2 Mev, which is unresolved, and has an angular distribution $W_{exp.}(\theta) \sim 1 + (0.10 \pm 0.05)\cos^2\theta$. This result may be explained by assigning J = 3 to one level of the doublet and J = 2 or 4 to the

other. The theoretical distributions, for dipole transitions and F = $^3/_7$ are

$3(-) \rightarrow 3(\pm)$ $\quad W(\theta) \sim 1 + 0.15 \cos^2\theta$

$3(-) \rightarrow 2(\pm)$ $\quad W(\theta) \sim 1 - 0.11 \cos^2\theta$

$3(-) \rightarrow 4(\pm)$ $\quad W(\theta) \sim 1 - 0.05 \cos^2\theta$

Combination in suitable proportions of the first of these with either of the others will readily explain the experimental result.

652 Kev resonance $[J = 2(-)]$

The γ-radiation leading to the 1.8 Mev level is markedly anisotropic; $W_{exp}(\theta) \sim 1 - (0.485 \pm 0.01) \cos^2\theta$. The theoretical distributions for the transition $2(-) \rightarrow 2(+)$, dipole, are

$F = 0$, $W(\theta) \sim 1 - 0.44 \cos^2\theta$; $F = \infty$ $W(\theta) \sim 1 + 0.16 \cos^2\theta$.

The distribution for F = 0 thus gives fair agreement with the experimental result, although the fit is not as good as might be expected. The difference, which is outside the experimental error, may be due to a small admixture of M2 radiation with the predominant E1 type.

Measurement of the polarisation of this γ-ray by Hughes and Grant (1954) has shown that

the predominant radiation is E1 type in agreement with the above considerations.

There appears to be radiation to both the 4.6 and 5.2 Mev levels from this resonance. The angular distribution of this radiation is

$$W_{exp}(\theta) \sim 1 - (0.12 \pm 0.05) \cos^2\theta$$

The theoretical angular distributions for F = 0 are

$2(-) \longrightarrow 3(\pm)$, dipole, $W(\theta) \sim 1 + 0.16 \cos^2\theta$

$2(-) \longrightarrow 2(\pm)$, dipole, $W(\theta) \sim 1 - 0.44 \cos^2\theta$

$2(-) \longrightarrow 4(\pm)$, dipole, $W(\theta) \sim 1 - 0.20 \cos^2\theta$

A suitable mixture of the first of these with either of the others may easily be made to fit the experimental result.

<u>404 Kev resonance</u> $[J = 4(-)]$

The angular distribution of the radiation to 4.6 and 5.2 Mev levels is $W_{exp} \sim 1 + (0.31 \pm 0.01) \cos^2\theta$. The calculated distributions are

$4(-) \rightarrow 3(\pm)$, dipole, $W(\theta) \sim 1 - 0.26 \cos^2\theta$

$4(-) \rightarrow 2(+)$, quadrupole, $W(\theta) \sim 1 + 0.49 \cos^2\theta$

$4(-) \rightarrow 4(\pm)$, dipole, $W(\theta) \sim 1 + 0.48 \cos^2\theta$

Once more a suitable mixture will explain the experimental result.

In conclusion Fig. II(ii) shows the proposed decay scheme for ^{28}Si with spin and parity assignments. It provides a good explanation of all the experimentally observed γ-ray intensities and angular distributions, but further evidence from $\gamma - \gamma$ correlation experiments is necessary before it can be regarded as definitely established. Such experiments might also serve to remove the uncertainties in spin and parity assignment to the 4.6 and 5.2 Mev levels. By consideration of the theoretical γ-ray transition probabilities, it is possible to derive spin and parity assignments to both of these levels, but in view of the uncertainty of the theory it is felt that this is of very doubtful value, and the correlation method seems the more promising.

Part II. 3. The reaction $^{26}Mg(p,\gamma)^{27}Al$

Introduction

This reaction has been studied in the range of proton energies 250 - 750 Kev. by Tangen (1946), Taylor et al (1952) and Hunt and Jones (1953).

Tangen, using natural magnesium, found seven resonances in the range of proton energies 250 - 500 Kev. Taylor et al, using a separated ^{26}Mg target, found four resonances in the range of proton energies 300 - 750 Kev and Hunt and Jones, using natural magnesium, found six resonances in the range 300 - 500 Kev. Using separated ^{26}Mg targets, we have found five resonances in the range of proton energies 250 - 750 Kev. These are at 290, 338, 454, 660, and 730 Kev, and correspond to those found by the other investigators.

The gamma-ray spectra from the 338 Kev resonances has been investigated by Casson (1953) and from the 454 Kev resonance by Kluyver et al (1953) and Russel et al (1952). Their results are very inconclusive, and they made no

measurements on the angular distribution of the γ-rays.

We have investigated the γ-ray spectra from all five measured resonances, as well as the angular distributions from the resonances at 290, 338, 454, and 660 Kev. On the basis of these measurements spin and parity assignments are made to some of the excited states of ^{27}Al.

(a) Measurement of γ-ray spectra

(i) Experimental procedure

The γ-ray spectra from this reaction were measured at five resonances in the range of proton energy 250 - 750 Kev, using the Glasgow University High Tension Generator to accelerate the protons.

The γ-rays were detected by a sodium iodide scintillation spectrometer. The sodium iodide crystal, $1\frac{3}{4}$" diameter and 2" long, was obtained, ready for use, from the Harshaw Chemical Company. The crystal was mounted on a DuMont 6292 photomultiplier, optical contact between the crystal and photocathode being

obtained by using a thin film of silicone grease.

Pulses from the photomultiplier were fed, after amplification, into a multi-channel pulse-height analyser or "kicksorter", similar to that designed by Hutchinson and Scarrott. The coincidence input to the kicksorter was used, and the kicksorter was triggered by a gating circuit operated by a discriminator on the output of the γ-ray amplifier. This arrangement prevented pulses smaller than the discriminating level reaching the kicksorter, and hence prevented any tendancy to overload the kicksorter. A 4 μsec. delay was inserted between the amplifier and kicksorter to ensure that the γ-ray pulses were coincident with the corresponding gate pulse.

The targets were separated ^{26}Mg, 15μ gms/cm^2 thick on a 0.02" copper backing, and were prepared by A.E.R.E., Harwell. The targets were heated to prevent the deposit of carbon which is normally deposited during the bombardment of any target by protons or deuterons, and which is thought to come from the oil in the diffusion pumps of the

main H.T. set vacuum system.

The spectra were measured over three energy regions:
(1) high energy 8 - 4 Mev (2) medium energy 4 - 2 Mev, (3) low energy 2 - 0.5 Mev. The transition between each region being obtained by varying the voltage applied to the photo-multiplier.

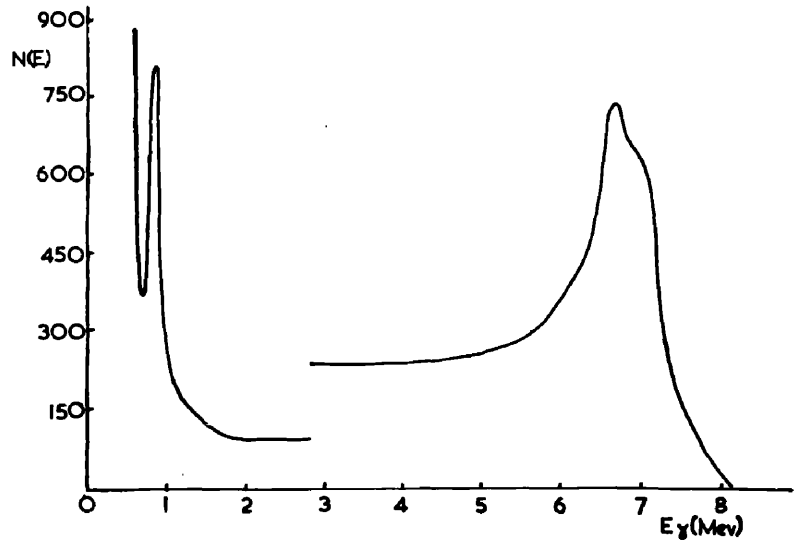
As the crystal used in these experiments had different dimensions from that used in studying the reaction $^{27}Al(p,\gamma)^{28}Si$, and as the electronic apparatus was entirely different, we had to calibrate the apparatus in terms of pulse height against γ-ray energy as described in Part II 2(a). In this case the mono-energetic γ-rays from the various nuclear reactions were used to provide accurate line shape spectra. This knowledge was especially important in assisting in the interpretation of the complex γ-ray spectra observed from this reaction. Energy calibration of the measured spectra was obtained using the 2.62 Mev γ-ray from ThC'' and the 1.28 Mev and 0.51 Mev γ-rays from ^{22}Na.

Each spectrum was analysed by successive subtraction, from the high energy region to the low energy region, of the known line shapes corresponding to the measured peak energies of the γ-rays. In this way we not only obtained information on the energy of the γ-rays present, but also on their relative intensity.

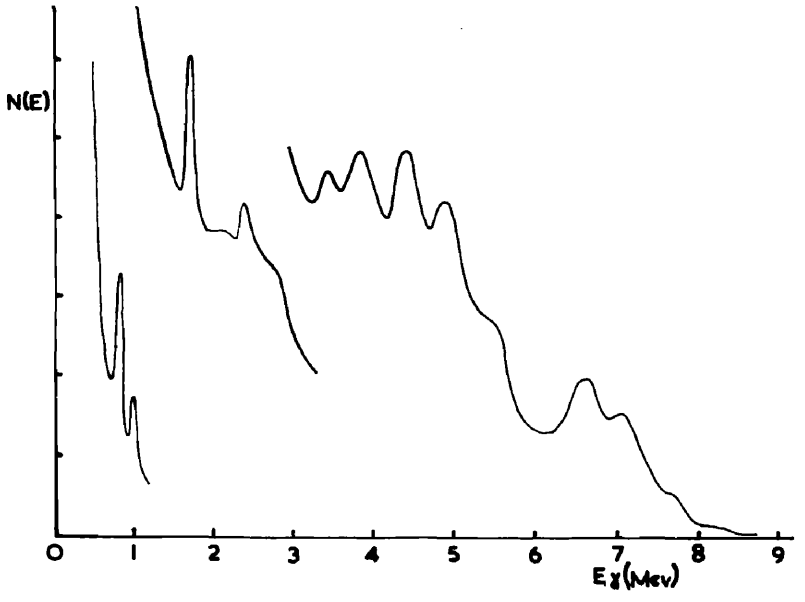
(ii) Results

Gamma-ray spectra from resonance levels in ^{27}Al at energies of 8.55, 8.59, 8.70, 8.90 and 8.96 Mev, corresponding to proton bombarding energies of 290, 338, 454, 660 and 730 Kev, are shown in Fig. II(iv, a,b,c,d,e). The statistical errors for each graph, except that for the 290 Kev resonance, are negligible. Only the line shape of the measured spectra are shown.

The energies and relative intensities of the more prominent γ-ray components at all five resonances are summarised in Table II(iii). The energy of the prominent γ-ray components in each spectra is accurate to 3%,

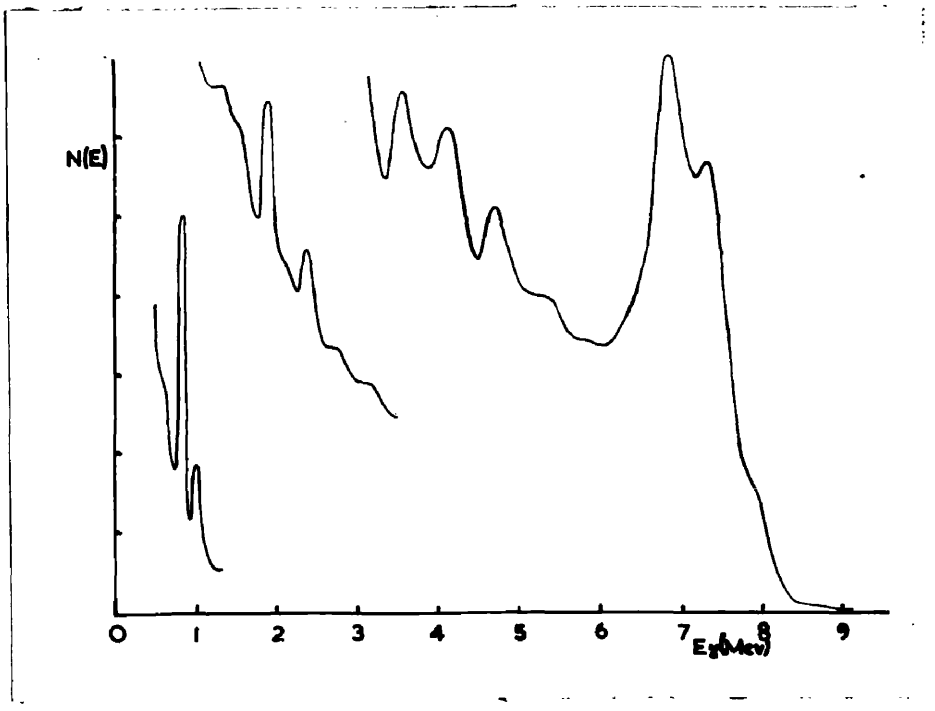


(a) E_p = 290 Kev.

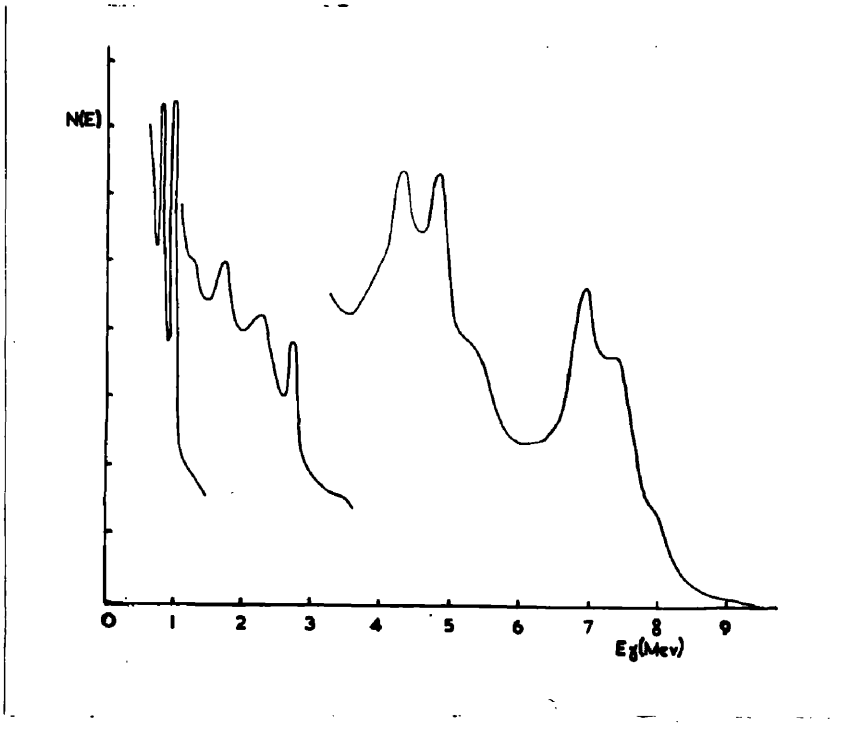


(b) E_p = 338 Kev.

Fig. II(iv). γ-ray spectra from the reaction $^{26}Mg(p,\gamma)^{27}Al$.

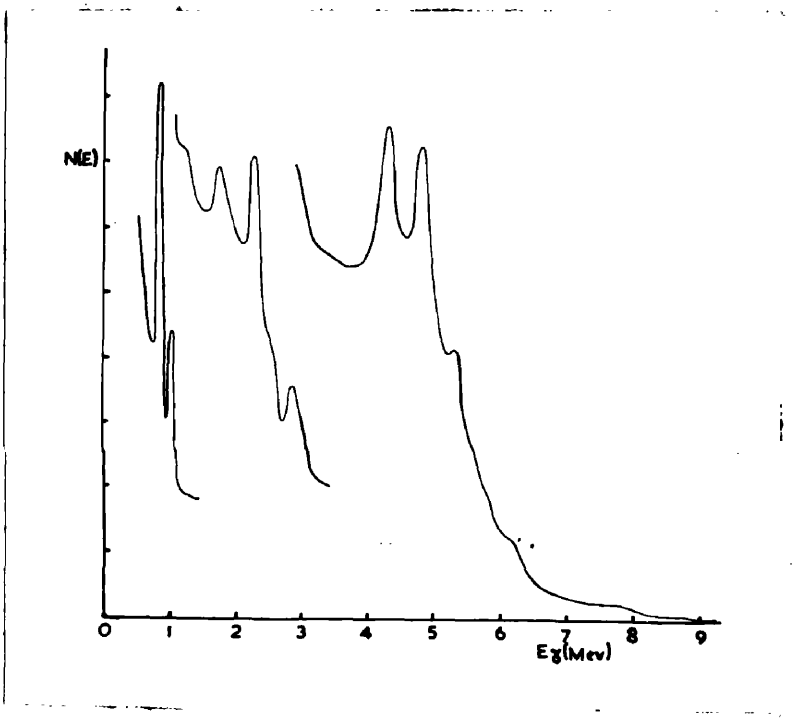


(c) E_p = 454 Kev.



(d) E_p = 660 Kev.

Fig. II(iv). γ-ray spectra from the reaction $^{26}Mg(p,\gamma)^{27}Al$.



(e) E_p = 730 Kev.

Fig. II(iv) γ-ray spectra from the reaction $^{26}Mg(p,\gamma)^{27}Al$.

Table II(iii)

$^{26}Mg(p,\gamma)^{27}Al$

(All energies in Mev.)

Resonance Energy	^{27}Al Excitation Energy	E_γ	Relative Intensity	Interpretation
0.290	8.55	7.7	1.0*	8.55 → 0.84
		0.84	1.0	0.84 → 0
0.338	8.59	8.6	0.12	8.59 → 0
		7.75, 7.6	1.0*	8.59 → 0.84, 1.01
		5.85, 5.62	1.1	8.59 → 2.75; 8.59 → 2.98, 3.00
		4.95	0.46	8.59 → 3.68
		2.98	0.61	3.00, 2.98 → 0
		2.75	0.40	2.75 → 0
				3.68 → 0.84, 1.01
		1.8	0.43	3.00, 2.98 → 0.84
		1.01	0.48	1.01 → 0
		0.84	0.71	0.84 → 0
0.454	8.70	8.70	0.02	8.7 → 0
		7.85	1.0*	8.7 → 0.84
		6.0	0.2	8.7 → 2.75
		1.05	0.25	1.01 → 0
		0.84	0.60	0.84 → 0

Table II(iii) (Contd.)

Resonance Energy	^{27}Al Excitation Energy	E_γ	Relative Intensity	Interpretation
0.660	8.90	9.0	0.13	8.90 → 0
		7.9	1.0*	8.90 → 1.01
		6.15	0.27	8.90 → 2.75
		5.3	0.82	8.90 → 3.68
		2.75	1.20	2.75 → 0
				3.68 → 0.84, 1.01
		1.01	1.15	1.01 → 0
		0.83	0.75	0.84 → 0
0.730	8.96	9.0	0.45	8.96 → 0
		8.1	1.0*	8.96 → 0.84, 1.01
		6.7	5.6	8.96 → 2.21
		5.35	26.2	8.96 → 3.68
		2.75	23.4	2.75 → 0
				3.68 → 0.84, 1.01
		2.3	10.2	2.21 → 0
		1.4	3.5	3.68 → 2.21
		1.02	11.2	1.01 → 0
		0.84	21.0	0.84 → 0

*This figure was adopted as the standard of comparison for each spectrum. The intensity figures for different spectra are not directly comparable.

and the relative intensities are accurate to ~25%.

As the Q-value for the reaction is 8.26 Mev. it will be seen that in all cases the transition to the ground state of ^{27}Al is weak.

It was not possible to resolve the γ-rays corresponding to transitions to the first two excited states of ^{27}Al [0.84 Mev and 1.01 Mev]. At the 290 Kev resonance, it is obvious that all the transitions proceed through the 0.84 Mev level, but in the other cases measurement of $\gamma-\gamma$ coincidence spectra was necessary in order to determine the relative intensities of the two transitions. The measurements and the results obtained will be described in a later section.

The 8.55 Mev level in ^{27}Al (E_p = 290 Kev) exhibits the unusual feature of decaying only by a single transition. This is perhaps due to the very low intensity of this resonance, and it is probable that the single transition is of E1 type.

We have tried to correlate the measured γ-rays to the known level scheme of ^{27}Al. The extreme

complexity of the γ-ray spectra, and the abundance of levels in ^{27}Al make such assignments rather tentative. The level scheme is that proposed by Browne et al (1954) from inelastic proton scattering experiments on ^{27}Al. Fig. II(v) shows the proposed decay scheme, containing only those transitions which have been definitely established. The dotted-transitions represent probable interpretations of some observed γ-rays.

(b) Measurement of γ-ray angular distributions

(i) Apparatus

The target chamber used to measure the γ-ray angular distributions from this reaction was similar to that used in studying the reaction $^{27}Al(p,\gamma)^{28}Si$.

The γ-ray spectrometer and electronic apparatus were the same as that used in the measurement of the γ-ray spectra.

The targets used were separated ^{26}Mg, 41 μgm/cm^2 thick on a 0.001" copper backing, prepared by A.E.R.E. Harwell.

(ii) Experimental procedure

The angular distribution measurements were

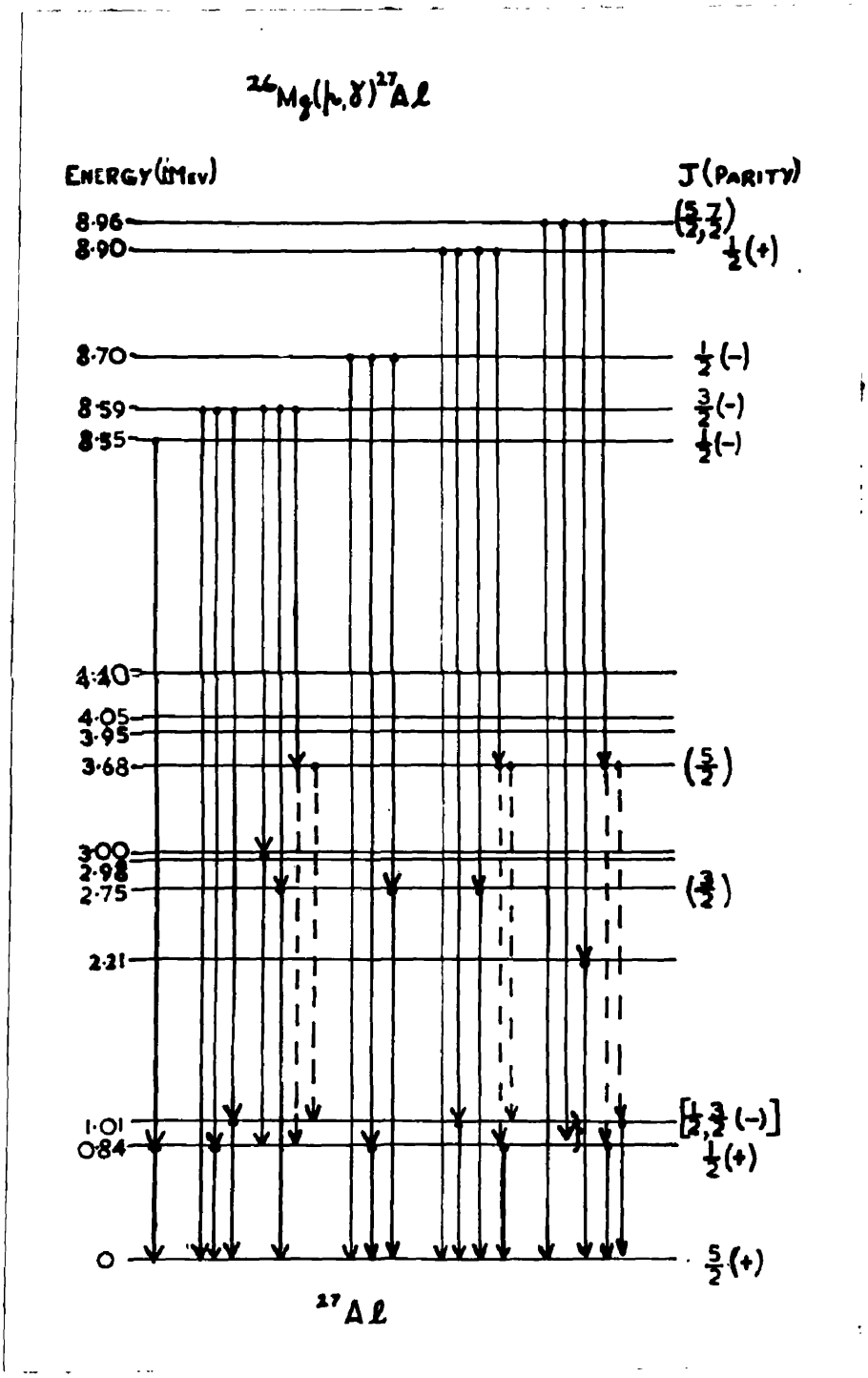


Fig. II(v). Energy level diagram and decay scheme for ^{27}Al.

confined to the high energy and low energy regions of the γ-ray spectra. No distribution measurements were made in the medium energy region.

At each resonance the distribution of all the high energy γ-rays was measured simultaneously by observing the spectrum at each angular position for a fixed number of counts in a monitor counter.

This monitor counter consisted of a similar sodium iodide scintillation spectrometer to that used in measuring the distributions, and it was set at an angle of $\theta = -90^{\circ}$ to the direction of the incident beam.

The distributions were measured over a range of angles from $\theta = 0^{\circ}$ to $\theta = 90^{\circ}$ at 30° intervals, where θ is the angle between the γ-ray detector and the direction of the incident beam.

The angular distributions were calculated by measurement of the area under the curve corresponding to each γ-ray component. In practice only the areas corresponding to fixed energy regions were calculated in each spectra for every angular position. This method required an accurate knowledge of the line-shapes for each

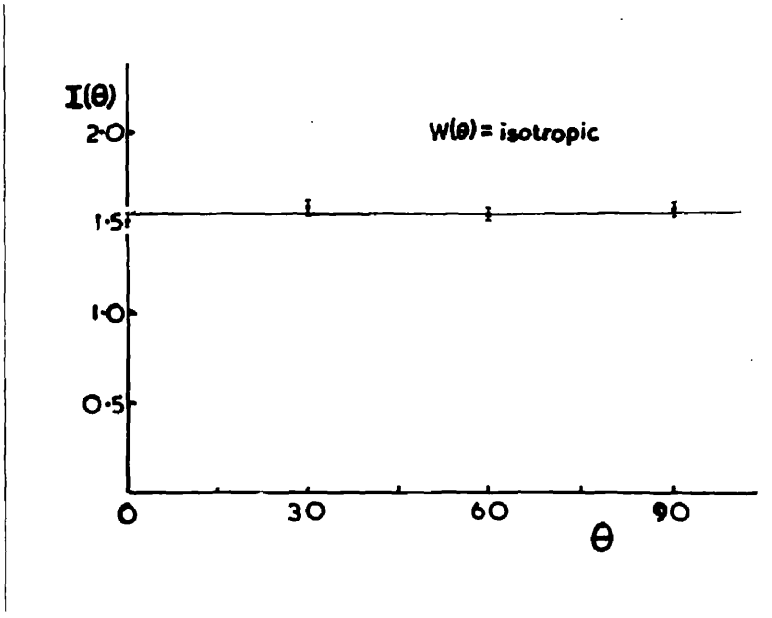
γ-ray in the spectrum, in order to allow for the contribution of high energy γ-rays in calculating the distribution of any γ-ray, other than the highest energy component.

It will be seen that this method of analysis requires careful energy calibration of the spectra.

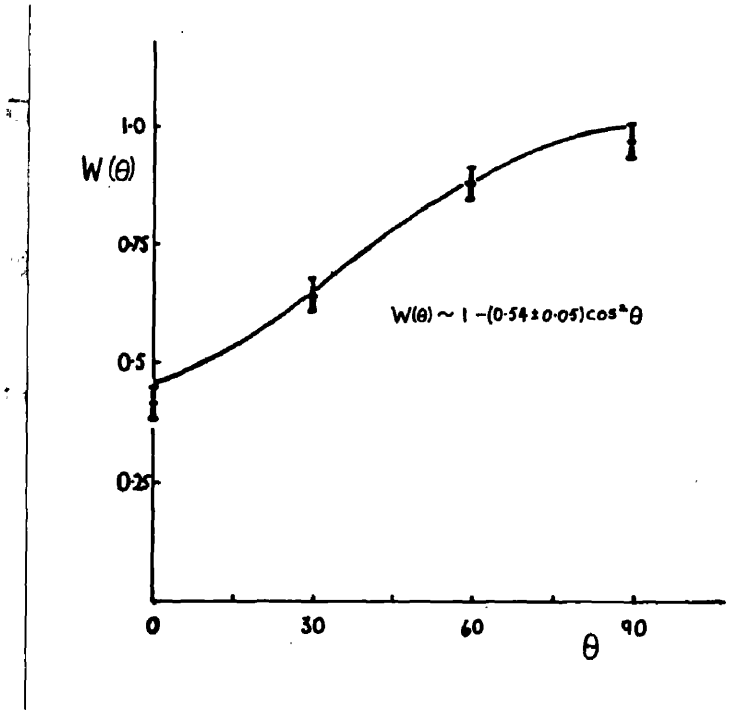
(iii) Results

Angular distribution measurements were made at four resonance levels in ^{27}Al; 855, 8.59, 8.70, 8.90 Mev, corresponding to proton energies of 290, 338, 454, and 660 Kev, respectively. Of these only the 8.59 Mev level gave anisotropic angular distributions. Fig. II(vi,a,b,c) shows the distributions obtained at E_p = 290, 338 and 454 Kev for the γ-radiation emitted to the first two excited states of ^{27}Al, and Fig. II(vii a,b) shows the angular distributions at E_p = 338 Kev, of the 0.84 and 1.01 Mev γ-rays emitted from these levels to the ground state. In each case the curve was fitted to the experimental points by the method of least squares, assuming that the distribution had the form

$$W(\theta) = 1 + a \cos^2\theta,$$

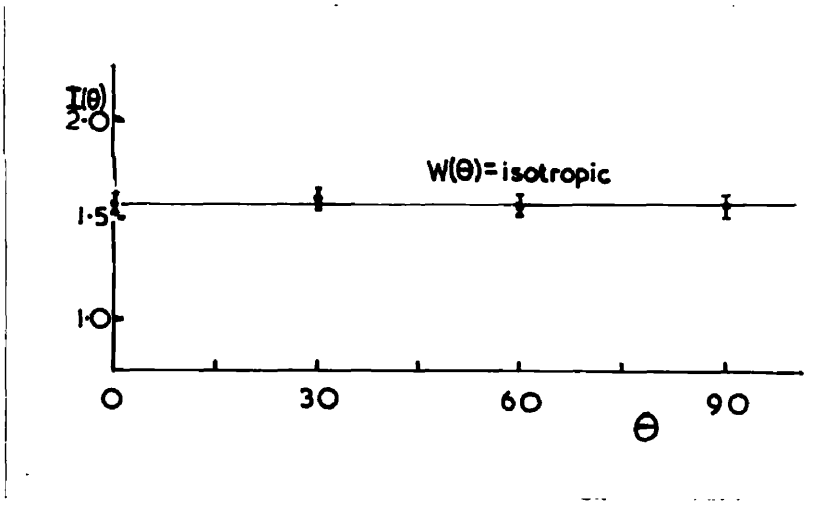


(a) 8 Mev ɣ-ray component at E_p = 290 Kev.



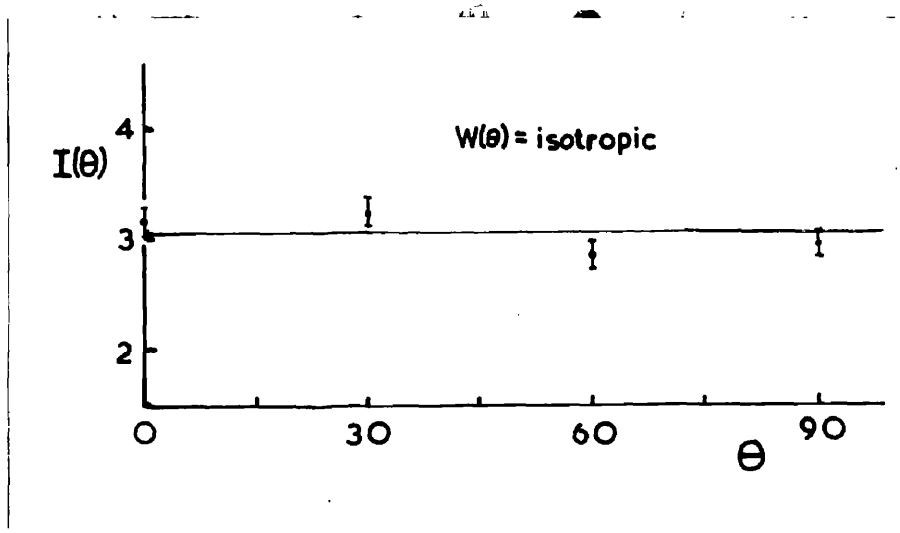
(b) 8 Mev ɣ-ray component at Ep = 338 Kev.

Fig. II(vi). $^{26}Mg(p,\gamma)^{27}Al$. Angular Distributions.

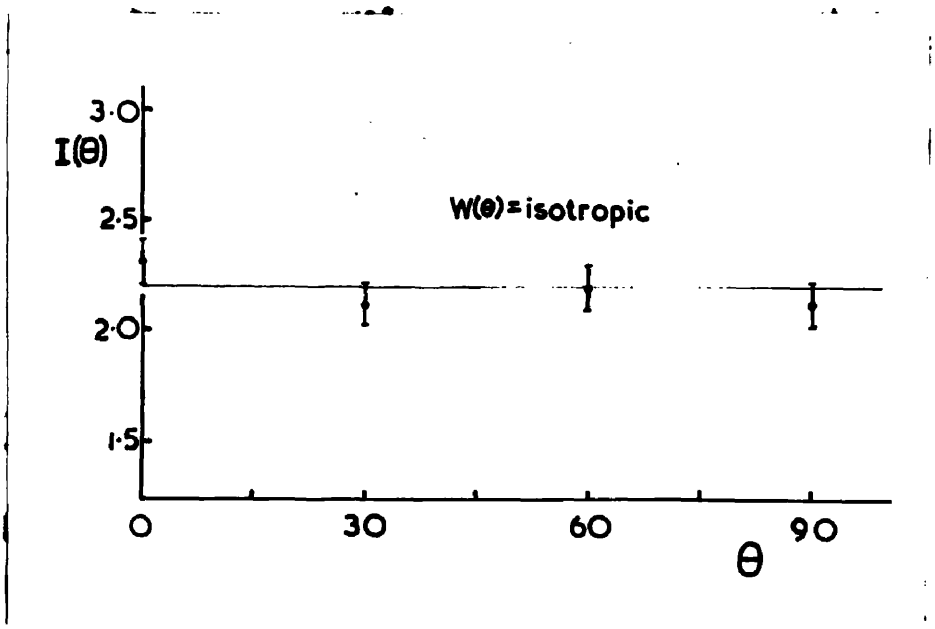


(c) 8 Mev γ-ray component at E_p = 454 Kev.

Fig. II(vi). $^{26}Mg(p,\gamma)^{27}Al$. Angular Distributions.



(a) 0.84 Mev ɣ-ray at E_p = 338 Kev.



(b) 1.01 Mev ɣ-ray at E_p = 338 Kev.

Fig. II(vii). $^{26}Mg(p,\gamma)^{27}Al$. Angular Distributions.

where θ is the angle between the incident proton direction, and the direction of detection of the γ-ray.

Table II(iv) summarises the results obtained, the distributions other than those shown being estimated from the measurement of $W(0)/W(\frac{\pi}{2})$.

(c) Measurement of γ-γ coincidence spectra and angular correlations

(i) Experimental procedure

The apparatus was similar to that used in the measurement of γ-ray angular distributions. The monitor counter, which remained fixed at $\theta = -90^{\circ}$, was used to detect only radiation emitted direct to the ground state or first two excited states of ^{27}Al, while the movable counter detected all radiation with energy $>$ 0.5 Mev.

Pulses from both counters were fed into a coincidence circuit, of conventional design, which supplied the gate pulse to "open" the kicksorter.

The low energy region (0.5 - 1.5 Mev) was examined to determine whether the cascade transition proceeded via the 0.84 Mev or the 1.01 Mev level.

The angular correlations were measured at two

Table II(iv)

Angular Distributions from the reaction $^{26}Mg(p,\gamma)^{27}Al$

(All energies in Mev)

Resonance Energy	0.290	0.338	0.454	0.660
^{27}Al Excitation Energy	8.55	8.59	8.70	8.90
E_γ (Distribution)	7.7 (Isotropic)	8.6 $1-(0.14 \pm 0.04)\cos^2\theta$	7.85 (Isotropic)	7.9 (Isotropic)
		7.75, 7.6 $1-(0.54 \pm 0.05)\cos^2\theta$		
		5.85 $1+(0.65 \pm 0.1)\cos^2\theta$		
		4.95 $1-(0.14 \pm 0.04)\cos^2\theta$		
		1.01 $1+(0.06 \pm 0.07)\cos^2\theta$		
		0.84 (Isotropic)		

angles only by moving the movable counter from $\theta = 0^{\circ}$ to $\theta = 90^{\circ}$. In this case the fixed counter was also used to monitor the reaction.

(ii) Results

Coincidence spectra were obtained at the resonances corresponding to proton energies of 338, 454 and 660 Kev. The results are summarised in Table II(v).

Table II(v)

Resonance level (Mev.)	Transition (Mev.)	Relative Intensity
8.55	8.55 → 0.84	1
8.59	8.59 → 0.84 8.59 → 1.01	1 $\leq$ 0.1
8.70	8.70 → 0.84	1
8.90	8.90 → 1.01	1

The results for the 8.55 Mev level were obtained by direct examination of the γ-ray spectrum from this level.

All the measured correlations were isotropic, within the statistical error of the measurements, irrespective of whether the cascade took place by the 0.84 or 1.01 Mev level. Table II(vi) summarises the results obtained:

Table II(vi)

Resonance level (Mev.)	Transition (Mev.)	W(θ)
8.59	8.59 → 0.84 → 0	$1 + (0.05 \pm 0.1)\cos^2\theta$
	8.59 → 1.01 → 0	$1 - (0.18 \pm 0.3)\cos^2\theta$
8.70	8.70 → 0.84 → 0	$1 + (0.02 \pm 0.06)\cos^2\theta$
8.90	8.90 → 1.01 → 0	$1 - (0.03 \pm 0.07)\cos^2\theta$

In this case θ is the angle between the two γ-ray detectors.

(d) Interpretation

In this section we shall attempt to interpret the results obtained in sections (a), (b) and (c), in terms of the spins and parities of levels in ^{27}Al. The fact that the angular distributions from three of the resonance levels are isotropic, and the extreme complexity of the γ-ray spectra, results in certain ambiguities in these assignments.

^{26}Mg has a nuclear spin and parity J = 0(+) in its ground state. Thus the possible states that can be formed by proton capture are as follows: s-wave, $\ell = 0$ $J = \frac{1}{2}(+)$; p-wave, $\ell = 1$ $J = \frac{1}{2}(-), \frac{3}{2}(-)$, d-wave, $\ell = 2$ $J = \frac{3}{2}(+), \frac{5}{2}(+)$. Of these $J = \frac{1}{2}(+)$ and $\frac{1}{2}(-)$ give isotropic angular distributions, while $J = \frac{3}{2}(-)$, $\frac{3}{2}(+)$ and $\frac{5}{2}(+)$ give anisotropic distributions.

In all cases there is only one possible "channel spin" corresponding to formation of a level with definite spin and parity.

290 Kev, 454 Kev, and 660 Kev Resonance levels

The excited states in ^{27}Al at energies of 8.55, 8.70 and 8.90 Mev, corresponding to proton energies of 290, 454 and 660 Kev, must have spin $\frac{1}{2}$ and $+^{ve}$ or $-^{ve}$ parity, since they emit γ-rays isotropically. Of these three levels only that at 8.90 Mev produces an appreciable amount of ground state radiation, and as the ground state of ^{27}Al is known to have nuclear spin $J = \frac{5}{2}(+)$, it is reasonable to assign $J = \frac{1}{2}(+)$ to the 8.90 Mev level $\left[\frac{1}{2}(+) \longrightarrow \frac{5}{2}(+);\ \text{E2 transition}\right]$ and $J = \frac{1}{2}(-)$ to the 8.55 and 8.70 Mev levels $\left[\frac{1}{2}(-) \longrightarrow \frac{5}{2}(+):\ \text{M2 transition, which is much less probable than an E2 transition}\right]$.

Consideration of the decay schemes for the 8.55, 8.70 and 8.90 Mev levels shows that, as far as transitions from these levels to the first two excited states of ^{27}Al are concerned, the 8.55 and 8.70 Mev levels decay only to the first excited state of ^{27}Al, while the 8.90 Mev level

decays only to the second excited state.

The fact that all three levels decay predominantly to one of the first two excited states instead of the ground state of ^{27}Al indicates that both the first and second excited states must have $J \leqslant \frac{3}{2}$. This was verified by measurement of the angular correlation between the γ-rays emitted from the 8.70 and 8.90 Mev levels to the first and second excited states of ^{27}Al respectively, and the subsequent γ-rays emitted from these levels to the ground state. The theoretical angular correlations for the following transitions are:

$$\tfrac{1}{2} \longrightarrow \tfrac{1}{2} \longrightarrow \tfrac{5}{2} \quad : \quad W(\theta) = \text{isotropic}$$

$$\tfrac{1}{2} \longrightarrow \tfrac{3}{2} \longrightarrow \tfrac{5}{2} \quad : \quad W(\theta) = 1 - 0.06 \cos^2\theta$$

$$\tfrac{1}{2} \longrightarrow \tfrac{5}{2} \longrightarrow \tfrac{5}{2} \quad : \quad W(\theta) = 1 + 0.39 \cos^2\theta$$

where θ is the angle between the direction of emission of the two γ-rays. The experimental correlation for the 8.70 Mev level is $W(\theta) = 1 + (0.02 \pm 0.06) \cos^2\theta$, and for the 8.90 Mev level is $W(\theta) = 1 - (0.03 \pm 0.07) \cos^2\theta$.

From these measurements alone we can only say that for the first two excited states of ^{27}Al,

$J = \frac{1}{2}$ or $\frac{3}{2}$.

Further consideration of the decay schemes from the three compound states at 8.55, 8.70 and 8.90 Mev shows that the first excited state of ^{27}Al has ($+^{ve}$) parity and the second excited state has ($-^{ve}$) parity. This can be justified by the fact that if both these states had the same parity then the transitions from any of the three compound states to both these lower excited states would be of the same type i.e. either E1 or M1 and we would expect the transition probabilities to be the same. Only if one transition was E1 type and the other M1 type would there be any difference in the transition probabilities. Thus the fact that both the 8.55 and 8.70 Mev levels, which have $J = \frac{1}{2}(-)$, decay only to the first excited state, and the 8.90 Mev level, which has $J = \frac{1}{2}(+)$ decays only to the second excited state leads to the above parity assignments, since this leads to the following transitions:

<u>8.55 Mev and 8.70 Mev levels</u>

$\frac{1}{2}(-) \longrightarrow \frac{1}{2}, \frac{3}{2}(+)$; E1 type - observed

$\frac{1}{2}(-) \longrightarrow \frac{1}{2}, \frac{3}{2}(-)$; M1 type - not observed

8.90 Mev level

$\frac{1}{2}(+) \longrightarrow \frac{1}{2}, \frac{3}{2}(-)$; E1 type - observed

$\frac{1}{2}(+) \longrightarrow \frac{1}{2}, \frac{3}{2}(+)$; M1 type - not observed

Thus we can make the assignments $J = \frac{1}{2}, \frac{3}{2}(+)$ to the first excited state of ^{27}Al and $J = \frac{1}{2}, \frac{3}{2}(-)$ to the second excited state.

338 Kev. Resonance level

The excited state in ^{27}Al at 8.59 Mev, corresponding to a proton energy of 338 Kev, must have $J = \frac{3}{2}(\pm)$ or $\frac{5}{2}(+)$ [neglecting f-wave capture of protons], since it produces anisotropic γ-ray angular distributions.

The experimental angular distribution for the ground state γ-ray is

$$W(\theta) \sim 1 - (0.14 \pm 0.04) \cos^2\theta$$

and the theoretical distribution for the transition $\frac{3}{2}(\pm) \longrightarrow \frac{5}{2}(+)$, assuming dipole radiation, is $W(\theta) = 1 - 0.14 \cos^2\theta$, in good agreement with the experimental distribution. This leads to the assignment $J = \frac{3}{2}(\pm)$ to the 8.59 Mev level.

It should be pointed out that it is impossible to discriminate between the angular distribution of γ-radiation emitted from a compound state which has been formed by p- or d-wave capture in a nucleus which has J = 0+. Thus from the angular

distribution measurements alone we cannot distinguish the parity of the compound state.

The angular distribution of the γ-radiation emitted to the first two excited states of ^{27}Al is

$$W(\theta) \sim 1 - (0.54 \pm 0.05) \cos^2\theta$$

and the theoretical distribution for the transition $\frac{3}{2}(\pm) \rightarrow \frac{1}{2}(\pm)$, assuming dipole radiation, is

$$W_{\frac{1}{2}}(\theta) = 5 - 3\cos^2\theta = 5\left[1 - 0.60\cos^2\theta\right]$$

and for the transition $\frac{3}{2}(\pm) \rightarrow \frac{3}{2}(\pm)$, assuming dipole radiation, is

$$W_{\frac{3}{2}}(\theta) = \frac{16}{5} + \frac{12}{5}\cos^2\theta = \frac{16}{5}\left[1 + 0.75\cos^2\theta\right]$$

As measurement of the coincidence spectrum between the high energy γ-rays and their associated cascade γ-rays showed that, at this particular resonance, the transition from the compound state to the second excited state of ^{27}Al was 10% of that to the first excited state, the measurement of this angular distribution leads to the assignment of $J = \frac{1}{2}(+)$ to the first excited state of ^{27}Al.

Although the theoretical angular distribution obtained by assuming a 10% admixture of the

transition $\frac{3}{2} \longrightarrow \frac{3}{2}$ on to the predominant $\frac{3}{2} \longrightarrow \frac{1}{2}$ transition is $W(\theta) = 1 - 0.51 \cos^2\theta$, this cannot be taken as definite evidence that the spin of the second excited state of ^{27}Al is $\frac{3}{2}$, due to the uncertainty in determining the relative intensities of the transitions and the rather large errors in the experimental angular distribution.

The spin of this level was further investigated by measurement of the angular distribution of the 1.01 Mev γ-ray emitted to the ground state. However, the theoretical distributions for the cascade transitions $\frac{3}{2} \longrightarrow \frac{1}{2} \longrightarrow \frac{5}{2}$ and $\frac{3}{2} \longrightarrow \frac{3}{2} \longrightarrow \frac{5}{2}$, in which the first radiation is not observed and the angular distribution of the second is measured, are $W(\theta)$ = isotropic and $W(\theta) = 1 - 0.03 \cos^2\theta$, respectively. The experimental distribution is $W(\theta) = 1 + (0.06 \pm 0.07) \cos^2\theta$. Although the theoretical distribution for a $\frac{3}{2} \longrightarrow \frac{3}{2} \longrightarrow \frac{5}{2}$ transition lies outside the error of the experimental distribution, this cannot be taken as definite evidence that the spin of the second excited state of ^{27}Al is $\frac{1}{2}(-)$.

The parity of the compound state was determined by measurement of the polarisation of the γ-rays emitted to the first two excited states of ^{27}Al. These measurements were performed by Mr. Hughes and Mr. Sinclair, [Hughes and Sinclair (1955)], in this department, using deuterium loaded photographic emulsions as the polarisation detector. Their results indicated that the predominant transition was E1 type, and as the predominant cascade proceeded through the first excited state which has $J = \frac{1}{2}(+)$, this leads to the assignment $J = \frac{3}{2}(-)$ to the 8.59 Mev compound level.

This assignment is in agreement with the fact that consideration of the angular momentum barrier, and low proton energy would make the probability of p-wave capture greater than d-wave capture.

We have also measured the angular distribution of the γ-rays emitted to the 2.75 Mev and 3.68 Mev levels in ^{27}Al at this resonance. These distributions were obtained by measurement of the ratio $W(0)/W(\frac{\pi}{2})$.

The experimental distribution for the 5.85 Mev γ-ray emitted to the 2.75 Mev level is

$$W(\theta) = 1 + (0.65 \pm 0.1) \cos^2\theta$$

in reasonable agreement with the theoretical distribution for the transition $\frac{3}{2} \longrightarrow \frac{3}{2}$, assuming dipole radiation, which is

$$W(\theta) = 1 + 0.75 \cos^2\theta$$

Thus the 2.75 Mev level has $J = \frac{3}{2}$.

The experimental distribution for the 4.95 Mev γ-ray emitted to the 3.68 Mev level is

$$W(\theta) = 1-(0.14 \pm 0.04) \cos^2\theta$$

in agreement with the theoretical distribution for the transition $\frac{3}{2} \longrightarrow \frac{5}{2}$, assuming dipole radiation, which is

$$W(\theta) = 1 - 0.14 \cos^2\theta.$$

Thus the 3.68 Mev level has $J = \frac{5}{2}$.

730 Kev Resonance

Owing to difficulties associated with operating the H.T. Set at this high voltage, we have been unable to make any angular distribution measurements at this particular resonance.

However, the marked difference between the γ-ray spectra observed at this resonance, and

that observed at any other resonance leads to the assignment of $J = \frac{5}{2}(\pm)$ or $\frac{7}{2}(-)$ to this level, which has an excitation energy of 8.96 Mev.

This assignment is in agreement with the fact that the most intense transition from this level takes place through the 3.68 Mev level, which has a J value of $\frac{5}{2}$, so that the emitted radiation is probably E1, whereas the transition to any lower state, except perhaps the ground state, would be M1, E2 or M2 type.

Although tentative assignments can be made on the basis of the relative intensities of the cascade γ-rays from this level, it is felt that only the measurement of the γ-ray angular distributions will lead to definite results. It is hoped that Mr. Wallace, in this department, will perform these measurements in the near future, as the H.T. Set has been reconstructed since the above experiments were performed.

Conclusion

The decay scheme for ^{27}Al showing the

spin and parity assignments derived from the above experiments is shown in Fig. II(v). The assignment to the first excited state $\left[J = \frac{1}{2}(+)\right]$ is in agreement with that derived from examination of the β-decay of ^{27}Mg by Daniel et al (1954), but the assignment to the second excited state does not agree with that derived by Daniel, who found $J = \frac{3}{2}(+)$ for this level.

Although we have not discriminated between $J = \frac{1}{2}$ or $\frac{3}{2}$ for this level, we are confident that the level has $(-^{ve})$ parity otherwise it proves impossible to provide an explanation for the observed decay scheme.

It should be possible, by careful measurement of the $\gamma - \gamma$ angular correlation, from the 8.90 Mev level, of the γ-ray emitted to the second excited state of ^{27}Al and the 1.01 Mev γ-ray emitted to the ground state, to discriminate between the alternative J values for this level.

III. Study of (d,p) reactions at low deuteron bombarding energies

1. General survey of deuteron stripping reactions.

The basic principles underlying the theory of deuteron stripping reactions have been presented in Part I(i) of this thesis. In this section we shall discuss more fully the theoretical interpretation of the experimental results, as well as giving a brief survey of these results for both high energy and low energy reactions.

The term "stripping" appears to have been coined by Serber (1947), who applied mathematically the general idea described in Part I(i), to the case of very fast projectiles in order to explain the production of fast neutrons observed when targets were bombarded with 190 Mev deuterons. However, as mentioned previously, the general idea had been put forward much earlier by Oppenheimer and Phillips (1935) to explain the emission of protons from targets bombarded with very slow deuterons.

Recently, Butler (1951) and Bhatia et al (1952) have developed theories of stripping

reactions, which show that the most important experimental factor in these reactions is the measurement of the angular distribution of the emitted nucleons. Both theories yield strikingly similar results, of which the following is a general outline.

The shape of the experimental distributions depends critically on the angular momentum ℓ of the captured nucleon. It also depends on the energies of the incident deuteron and the emergent nucleon. If we consider the reaction A(d,b)B, where b is either a neutron or proton, and B is left in a state B_1, then the angular momentum of the captured nucleon is limited by two selection rules:

(a) Addition by the vector sum rule of the spin J_A of the target, the orbital angular momentum ℓ of the captured nucleon, and its spin $\frac{1}{2}$, must be capable of yielding the spin J_{B_1} of the level B_1 i.e.

$$\text{MIN.} \left| \pm J_A \pm J_{B_1} \pm \tfrac{1}{2} \right| \leq \ell \leq J_A + J_{B_1} + \tfrac{1}{2}$$

or as limits of J_{B_1}

$$\text{MIN.} \left| \pm J_A \pm \ell \pm \tfrac{1}{2} \right| \leq J_{B_1} \leq J_A + \ell + \tfrac{1}{2}$$

(b) If the levels of A and B have the same parity, ℓ is even, if the parities are different, ℓ is odd.

For given levels A and B these selection rules frequently permit only one value of ℓ. In general, however, J_B is unknown, and is determined by comparison of the experimental distributions with those predicted theoretically for various values of ℓ. Knowledge of the correct ℓ value then fixes J_B within the limits given in (a). The particular dependence of the angular distribution on ℓ consists in the existence of a principal maximum at a fairly small angle to the direction of the deuteron beam, this angle increasing with ℓ. If $\ell = 0$, the maximum is usually at 0°, but otherwise at a finite angle. In most cases the experimental distributions permit a unique determination of ℓ, even where various ℓ values are permitted by the selection rules.

Both theories include an arbitrary parameter in the angular distribution formula for a given value of ℓ. This parameter is interpreted as the radius, R, of the target nucleus. However,

the theories disagree on the value of R required to produce the best fit to an experimental distribution even although they agree on the ℓ -value. From experimental evidence it is found that Butler's theory always produces a better fit with the experimental curve for one value of ℓ, than any other, if the value of R given by Gamow and Critchfield (1949), i.e., $R = (1.7 + 1.22\ A^{\frac{1}{3}}) \times 10^{-13}$ cm, is used. It is also found that the best fitting radius, using the formula of Bhatia et al., is, without exception, very nearly 1.0×10^{-13} cm. larger than that using Butler's.

Neither theory considers the Coulomb interaction between the deuteron and target nucleus. This produces doubts on the applicability of the two formula as the deuteron energy is reduced, on account of the increased Coulomb effect. However, recently Yoccoz (1954) and Grant (1954) have considered the problem of low energy deuteron stripping. Their conclusions can be summarised by three facts (1) the position of the principal maximum is shifted towards larger angles, (2) the distribution is broadened (3) the magnitude of the principal maximum is reduced.

By discussing the experimental results in this

field after summarising the theoretical interpretation we may give the impression that this was the order in which the discoveries were made. In actual practise the theories of Butler, and Bhatia et al were developed to explain the experimental results obtained by workers at Liverpool in bombarding various target nuclei with 8 Mev deuterons from the Liverpool cyclotron. A very good summary of all this early work, and also some more recent experiments, has been given by Huby (1953) and by Holt and Marsham (1953). Although the Liverpool group were largely responsible for all the early work, as well as much of the more recent, many reactions of the type (d,p) and (d,n) have been studied in numerous laboratories during the past few years, and it would obviously be impossible to give a comprehensive survey of them all. We shall confine the discussion to the important features arising from these experiments.

It is obvious from the nature of the experiments that the principal requirements of any technique designed to measure angular distributions from stripping reactions are (a) high energy resolution

(b) good angular resolution and (c) small intervals between angles of observation especially near the forward direction. Perhaps the most common method of particle detection used in these experiments is the photographic plate method. It is obviously well adapted to satisfy all the necessary conditions. Holt and Marsham, who have been responsible for much of the experimental work in this field, used a proportional counter telescope for the detection of protons, and their results are summarised in Proc. Phys. Soc. Vol. 66A.

One of the most important features of the majority of the experimental distributions is that it is necessary to subtract an isotropic background from the experimental points to provide a close fit to the theoretical curves. This background has been attributed to compound nucleus formation, and it will be discussed in greater detail in a later section.

Despite the fact that one or two distributions cannot be fully explained by the present theory, the experimental results have, in general, supplied a great deal of information, not only on the spins

and parities of the excited states of light nuclei, but also on other important properties of these levels, such as their "reduced widths" etc. It is an important feature of this type of reaction that a direct study of these levels is possible without the reaction proceding through an intermediate compound state.

In cases where there is some doubt as to the spin of an excited level it may be possible to resolve this difficulty by measurement of the angular correlation between the nucleon leading to this level and the γ-radiation emitted to the ground state or lower excited state. It has been shown theoretically (Satchler and Spiers (1952)) that this correlation is similar to the γ-ray angular distribution produced in the bombardment of the target nucleus by unpolarised particles, (similar to those absorbed in the stripping reaction) incident in the direction of the absorbed nucleon. In certain cases measurement of this correlation will lead to a unique determination of the spin of the excited state, and in other cases it will reduce the probable limits on the spin.

Recently attention in this field has turned to the measurement of the angular distributions produced in (d,p) and (d,n) reactions using low energy deuterons. Experiments using deuterons of energy 3 - 4 Mev, which is less than the limit to which the theories were deemed valid, have, in fact, shown that they still provide very good agreement with the experimental distributions e.g. Ajzenberg (1952) and Fulbright et al (1952) . However, at still lower energies the agreement becomes less certain, and, in general, a definite assumption about the nature of the "background" distribution due to compound nucleus formation has to be made before any conclusions can be drawn from the experimental distributions. The surprising feature of all these low energy distributions is that any form of agreement can be obtained, considering the fact that the Coulomb effect is completely ignored in both existing theories. For example Endt et al (1952) have measured the angular distributions obtained in the bombardment of ^{10}B, ^{12}C, and ^{14}N with low energy deuterons ($\leq$ 600 Kev) and have obtained remarkable agreement with theoretical

predictions, assuming an isotropic background due to compound nucleus formation. The results of other workers confirm this, although in some cases it is necessary to superimpose a stripping distribution on to an anisotropic component from compound nucleus formation in order to fit the experimental curves [Canavan (1952)]. It has generally been found that the l values predicted from low energy measurements agree with those predicted by the high energy experiments.

At present no adequate theory of these low energy reaction exists, however, perhaps the accumulation of sufficient experimental data will provide a basis on which to construct such a theory. The principal problems to be solved by such a theory include (a) determination of the interaction between a deuteron and target nucleus in the Coulomb field of the nucleus, (b) the effect of interference between stripping and compound nucleus processes, (c) the distribution of the compound nucleus component considering interference between broad overlapping levels in the compound nucleus. It is hoped that the present work

will eventually help to solve some of these topics.

III. 2. Study of reaction $^{10}B(d,p)^{11}B$

(a) Introduction.

There are seven proton groups with a Q-value > 1 Mev emitted from this reaction [Van Patter et al. (1951)]. We shall be concerned only with the three highest energy groups (denoted groups 0, 1 and 2). The reported Q-values for these groups are given in Table III(i).

Table III(i)

	Q(Mev.)	$^{11}B^*$
Group 0:	9.235 ± 0.011	0
Group 1:	7.097 ± 0.009	2.138
Group 2:	4.776 ± 0.008	4.459

These results are also due to Van Patter et al.

The angular distributions from this reaction have been measured at E_D = 7.7 Mev by Evans and Parkinson (1954), at E_D = 8 Mev by Holt and Marsham (1953), at E_D = 1.06 and 1.43 Mev by Burke et al (1954), at E_D = 300 Kev by Endt et al

(1952) and at E_D = 200 Kev, 450 Kev, 600 Kev by Paris et al (1954).

Analysis of these results by stripping theory gives general agreement on the ℓ value corresponding to group 0; $\ell_n = 1$. The results for the other groups which have been measured are not in such close agreement, e.g. Evans and Parkinson predict $\ell_n = 1$ for both group 1 and 2 contrary to the results of Paris et al who predict $\ell_n = 3$ and 0 respectively.

The present work, which covers the same energy range as that investigated by Paris et al, was completed before Paris's results became available to us. The results show essential agreement, although the higher statistical accuracy obtained by our technique considerably improves the agreement between theory and experiment. The results obtained for the distribution of group 0 were not in agreement with the predicted stripping theory assuming $\ell_n = 1$, and an isotropic background from compound nucleus formation. This will be discussed more fully later.

The angular correlations between groups 1 and

2 and their associated cascade γ-rays in the nucleus ^{11}B have been measured at E_D = 500 Kev. The results are in agreement with Thirion (1954) who measured the correlation at $\theta = 90^\circ$ and 180° only.

III 2(b) Development of apparatus

As most previous experiments on stripping reactions had been concerned solely in the measurement of the angular distribution of the emitted nucleon, and as these experiments principally used nuclear emulsions as a detector, they could not be adapted to the measurement of angular correlations between the emitted nucleon and its associated cascade γ-rays.

Therefore, as we wished to perform both types of measurements, it was necessary to devise a completely new technique enabling both distributions and correlations to be measured easily with the same apparatus.

Type 1.

The essential feature in the design was that both detectors i.e. the proton detector and the γ-ray detector, could rotate independently around

the fixed axis. In type I this was achieved by mounting the γ-ray counter on a rotating arm outside the target chamber, as in the previous γ-ray angular distribution experiments, and detecting the protons in a scintillator placed at the end of a specially designed perspex light guide which rotated inside the target chamber about the same axis as the γ-ray detector. A diagram of the target chamber (not showing the γ-ray detector) is shown in Fig. III(i).

Perhaps the most unusual feature of the design was the use of the perspex light guide. In most previous experiments using a light guide for the transmission of light from a phosphor to a photomultiplier, the only requirement of the light guide was that any light emitted by the phosphor be registered as a pulse by the photomultiplier, irrespective of the energy dissipated in the phosphor. In the present apparatus the light guide had to transmit the light without seriously affecting the pulse height spectrum from the phosphor.

As will be seen from Fig. III(i) the light

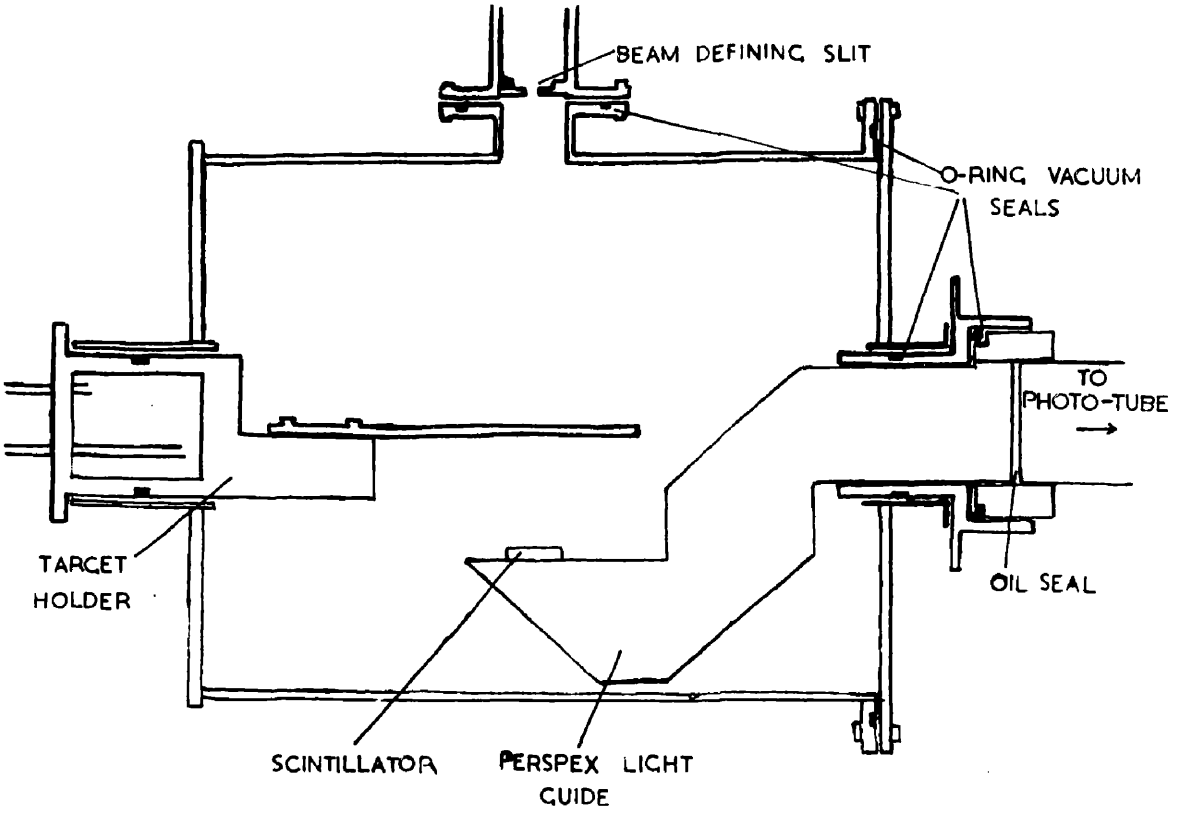


Fig. III(i) Type 1 of distribution apparatus.

guide had to have two right-angled bends, and in the initial models this was achieved by joining three straight pieces of perspex rod by two right-angled prisms. This method of construction proved unsatisfactory for two reasons, (1) it was difficult to produce joints which were of a uniform nature, and (2) the loss in intensity due to reflection of the light at each interface seriously affected the pulse-height resolution. In the final model of the apparatus the light guide was constructed by machining it from a solid piece of perspex. This design proved fairly satisfactory, as we shall show later.

In order that the light guide could rotate freely while the photomultiplier remained fixed, a rotating oil seal was used as shown in Fig. III(i). This was normally filled with paraffin oil which proved to be the most convenient substance, both from the point of view of light transmission properties, and for ease in handling.

A great deal of research was carried out on the problem of finding the most suitable phosphor for detecting the protons inside the vacuum. The

main requirements for this phosphor were:

a) good pulse height resolution (a resolution of 10% full width at half maximum peak height was required using the light guide),

b) long term stability of scintillating efficiency,

c) low vapour pressure to enable it to be used inside the vacuum of the H.T. set,

d) low efficiency for detection of γ -rays, beta-rays and other background radiations.

Of these (a) is the most important condition.

Previous work on phosphors had shown that with regard to condition (a) sodium iodide (thallium activated) was the most convenient phosphor. It also satisfied conditions (c) and (d) provided it was used in the form of a very thin crystal. However, as this substance is very hygroscopic it must be maintained in a dry atmosphere, and this necessitates considerable precautions in the preparation of the crystal if it is to satisfy condition (b). Initial experiments on the use of this phosphor proved unsuccessful, primarily because moisture managed to reach the crystal before it could be

properly mounted.

We were thus forced to try some other phosphors which, although not as efficient scintillators as NaI would be easier to work with. First of all zinc sulphide was used. The main difficulty with this phosphor is that it can only be obtained in the form of a micro-crystalline powder which is opaque to its own emitted radiation. This means that the phosphor can only be used efficiently in the form of very thin layers, and the micro-crystalline structure means that the pulse-height resolution is very poor. Although we managed to obtain very thin uniform layers of the phosphor, the results obtained from these did not justify any further attempts to develop it in a form useful for our apparatus.

The next phosphor tried was anthracene. As the commercial crystals available to us were too thick for our purpose, a series of experiments were carried out on the preparation of thin anthracene crystals from hot satured solutions of anthracene and amyl acetate. The amyl acetate was first purified by repeated distillation. Anthracene

was then dissolved in this amyl acetate, which had been heated to about 120°C, until a saturated solution was obtained. This solution was then allowed to cool very slowly over a period of several hours, and the anthracene crystallised out of the solution in the form of thin uniform crystals. The opacity and uniformity of the crystals depend largely on the purity of the amyl acetate and anthracene.

The dimensions of the crystals varied greatly, the best being 1 cm. x ½ cm. x ½ mm.

The pulse height spectrum obtained from these crystals using a P_0 α-source showed an improvement on the results obtained from zinc sulphide, but the resolution obtained did not offer any hope of using this phosphor in the proton spectrometer.

While this work was in progress Endt et al (1953) reported a suitable method of packaging thin sodium iodide crystals for use in heavy particle spectrometry.

In this method the crystal is cleaned and polished in a dry box and sealed in a specially designed container, which is then completely

evaculated. The design of the container is shown in Fig. III(ii). The cleaning and polishing of the crystals was the important part of the operation. After experimenting unsuccessfully with various organic solvents, we finally decided to clean and polish the crystals by rubbing with fine emery paper and polishing with carborundum powder. This method proved quite satisfactory.

Optical contact between the crystal and quartz window is obtained by cementing them together with a layer of silicone grease.

The protons enter through the aluminium foil window which, in our case, was 0.001" thick. Unfortunately this thickness of aluminium foild did not allow P_0 α-particles to penetrate to the crystal without an appreciable straggle in their energy, so that a direct comparison of the relative merits of sodium iodide and the two previously used phosphors was not possible.

However, measurement of the pulse height spectrum obtained from the annihilation quantum emitted from a ^{22}Na source, with and without the light guide, showed that the resolution decreased

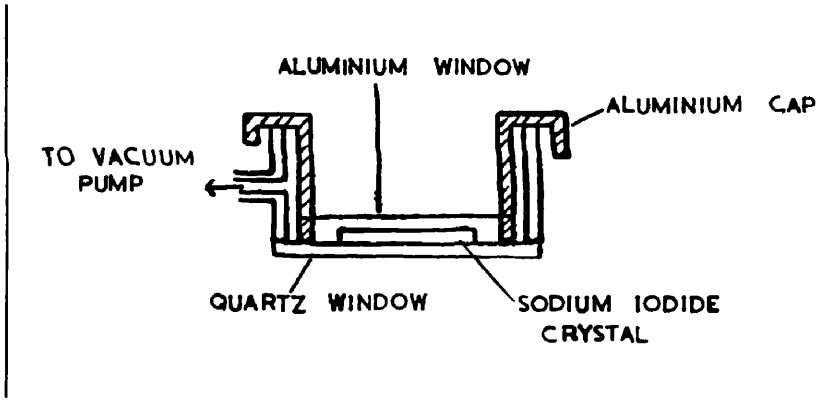


Fig. III(ii) Holder for NaI crystal.

from 18% without the light guide to 40% with it. As Endt et al had reported 4% peaks for the proton groups emitted in the reaction $^{10}B(d,p)^{11}B$ when the crystal was placed straight on to the photo-cathode of the multiplier, it was expected that 10% resolution could be obtained using the light guide in conjunction with the sodium iodide phosphor for detection of protons.

Thus sodium iodide should satisfy all the conditions of a suitable phosphor.

However, after this model of the target chamber had been used for the measurement of the angular distribution of the two highest energy proton groups from the reaction $^{10}B(d,p)^{11}B$ at various deuteron bombarding energies, a serious defect in the design was discovered, which necessitated complete redesign of the apparatus.

It was found that the end plate of the chamber which held the light guide, and which could be removed in order to mount the crystal, tended to buckle under the strain of supporting the weight of the target chamber. In order to replace it the light guide had to be removed by cutting it close

to the second right angled joint. When the apparatus was re-assembled it was found that the light guide had been distorted to such an extent that it was no longer practical to use it. Thus we had to decide whether to construct a new light guide or completely redesign the apparatus. The fact that we chose to redesign the apparatus was due to the following reasons:

1) the results obtained with the first model were not as satisfactory as had been at first expected, in particular it proved impossible to resolve the third proton group produced in the reaction $^{10}B(d,p)^{11}B$ so that this severely limited the usefulness of the apparatus.

2) we had by that time acquired a supply of plastic phosphors, and initial experiments had shown this to be ideal for our purpose, principally because of its low sensitivity for γ -radiation, and also because it could easily be obtained in any shape or thickness desired.

3) provided the plastic phosphor was mounted directly on to the photo-cathode of the multiplier, the pulse height resolution for the 9 Mev proton

group from the reaction $^{10}B(d,p)^{11}B$ was 10%, and the three highest energy proton groups were clearly resolved.

4) we had available new photomultipliers, DuMont 6292 type, whose improved performance more than offset the loss in scintillating efficiency due to the replacement of sodium iodide by the plastic phosphor.

Type 2.

The new design of target chamber retained the essential features of type 1 except that in this case the protons were detected by a phosphor situated outside the chamber instead of inside the vacuum system. The same target chamber was used, modified as shown in Fig. III(iii). The light guide was no longer used, and the protons emerged from the target chamber by thin Dural windows situated round the circumference of the chamber as shown. The windows were $\frac{3}{8}$" diameter, 0.001" thick and were equally spaced at 15° intervals over an angular range of 0° to 135° with respect to the incident deuteron direction. The deuteron beam was collimated on to the target by two slits, $\frac{1}{16}$" wide and separated by a distance of 4".

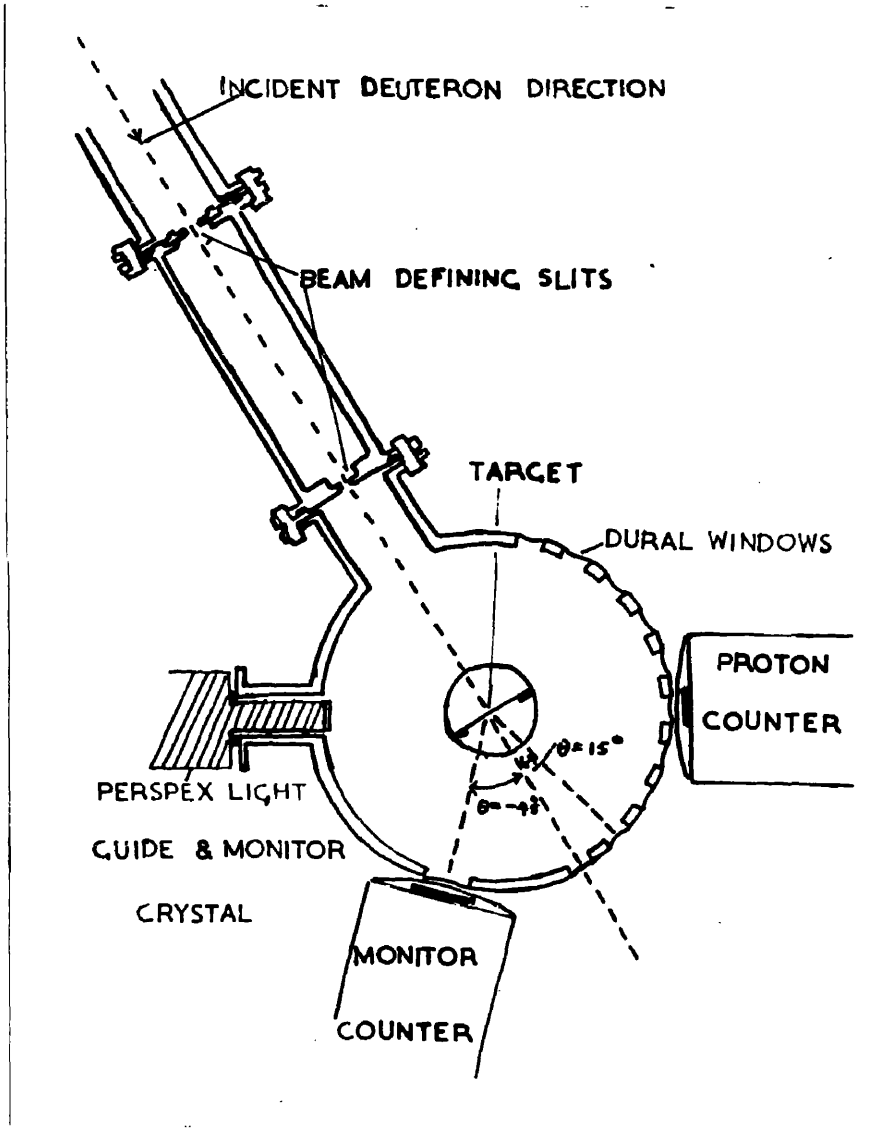


Fig. III(iii) Type 2 of distribution apparatus.

The target holder could be rotated relative to the incident beam direction and was easily removed to facilitate changing of targets. The target was water cooled to avoid overheating.

The two ports at $\theta = -45^{\circ}$ and $\theta = -120^{\circ}$ were used to provide a means of monitoring the reactions, and also measuring the excitation function at $\theta = 120^{\circ}$. Their importance will be discussed later.

As in the case of the apparatus used to measure the γ-ray angular distributions, the entire target chamber was insulated from the main H.T. set in order to provide a Faraday cage to measure the total beam current falling on the target.

As we have mentioned, the protons were detected, after passing through the thin Dural windows, by a plastic phosphor scintillator mounted straight on to the photo-cathode of a DuMont 6292 photomultiplier. The size of the scintillator was chosen such that it was larger than one of the emission ports, but not large enough to overlap two of them, thus ensuring that only protons from one angular position were detected during any particular run. The thickness

of the scintillator was chosen such that it would just stop the highest energy protons emitted in the reaction, thus reducing the effect of background radiations such as neutrons and γ-rays.

Optical contact between the scintillator and photo-cathode was maintained by a film of silicone grease and the scintillator was covered by two layers of aluminium foil 0.005" thick to produce a light-tight system.

Rotation of the proton spectrometer was provided by mounting it on an arm, attached to two-ball-races, coaxial with the central axis of the target chamber. The angular position of the spectrometer was determined by a circular ring, external to the main target and coaxial with the axis of the target, to which the rotating arm could be attached in known angular positions.

For the angular correlation measurements the proton spectrometer was replaced by a sodium iodide γ-ray spectrometer similar to that used in the study of the γ-radiation from the reaction $^{26}Mg(p,\gamma)^{27}Al$

In this case the proton spectrometer was held in a fixed position at $\theta = -45^{\circ}$ to the incident

beam direction and used not only for the detection of the protons in the correlation, but also to monitor the reaction.

No account of the electronic apparatus will be given at this stage, this being left till the more detailed discussion of angular distributions and correlations.

III 2(c) Measurement of proton angular distributions

(1) Experimental procedure

Initial measurements of the angular distributions of group 0 and 1 were made using type 1 of the target chamber. As the experimental procedure adopted was similar for both models of the apparatus, and as all the results to be presented were obtained using type 2, we shall not discuss the experiments on type 1 in any detail.

The two principal difficulties associated with type 1 were:

(a) The proton pulse height resolution was insufficient to enable resolution of the three highest energy proton groups, and even groups 0 and 1 were difficult to resolve when the protons were detected

through the target backing. A typical proton spectrum is shown in Fig. III(iv). The large rise in intensity towards lower energy is due to neutrons and γ-rays, as can be shown by interposing sufficient aluminium foil between the crystal and target to absorb all the charged particles. The shape of this spectrum is sketched in Fig. III(iv).

(b) The monitoring of the reaction by means of a sodium iodide scintillation spectrometer proved unsuccessful. We had hoped to bias the counter so that only pulses corresponding to detection of a γ-ray from the reaction $^{10}B(d,p\gamma)^{11}B$ were recorded. However, it was found that the background radiations from the slits, both neutrons and γ-rays, were so intense that they rendered the monitor unreliable. This defect was remedied in type 2 by monitoring the reaction by means of protons emitted from the reaction. This method has proved very satisfactory.

We shall now discuss, in detail, the technique adopted using type 2 of the apparatus.

The targets used were of separated ^{10}B prepared by A.E.R.E., Harwell, and were normally 10μgms/cm^2 thick, on either 0.001" aluminium or 0.001" copper

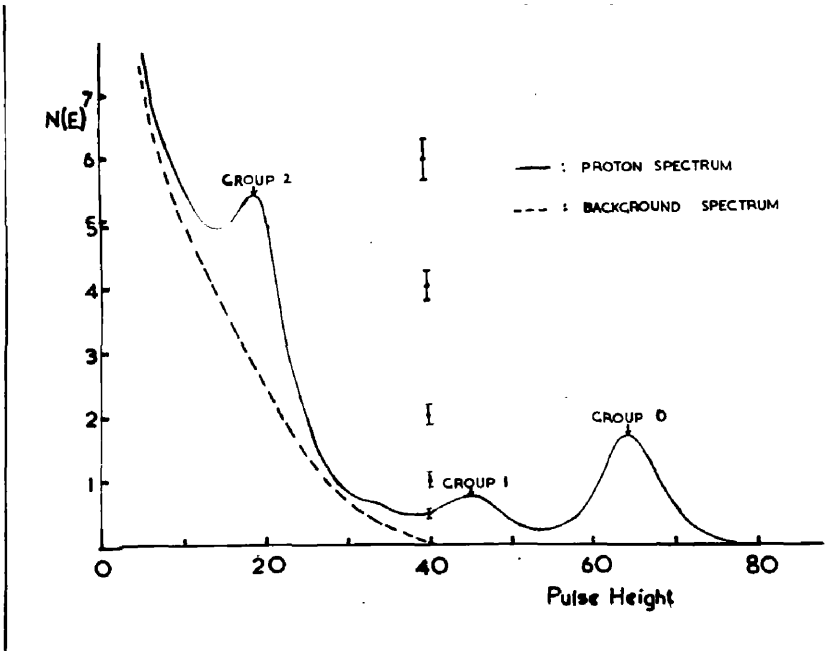


Fig. III(iv) Proton spectrum from reaction $^{10}B(d,p)^{11}B$ using type 1 of apparatus.

backings. The reaction is so intense that the beam current was reduced to less than 1 μamp, although even then some difficulty was encountered due to overheating of the thin backings.

As mentioned previously the protons were detected, after passing through the thin Dural windows, by a scintillation spectrometer consisting of a plastic phosphor and photomultiplier (DuMont 6292). Pulses from the photomultiplier were fed by a cathode follower to a linear amplifier, and hence through a 4 μ sec delay line to the coincidence input of a Hutchinson Scarrott multi-channel pulse-height analyser. The kicksorter was triggered by a gating circuit which was operated by a discriminator on the output of the linear amplifier. The coincidence input to the kicksorter was used to prevent pulses smaller than those required to trigger the gate circuit reaching the kicksorter, and so enabled much faster counting rates to be used in the high energy region. The total counting rate was normally about 100 counts/sec. and, as the kicksorter had a dead time of 0.25 msec., this meant that the maximum loss in counts was 2.5%. No correction was made for

variations in this loss. The 4μ sec. delay was used to ensure that the proton pulses arriving at the kicksorter were coincident with the corresponding gate pulse, which was delayed by about 2μ sec. and lasted for 4μ sec.

A typical proton spectrum is shown in Fig. III(v). In comparison with Fig. III(iv) it will be seen that groups 0 and 1 are well separated and that group 2 is reasonably well resolved, although once again the rising background under the peak from this group is due to neutrons and gamma-rays.

The angular distributions were measured in two distinct sections. Initially the plane of the target was set vertical and the distribution measured from $\theta = 0^{\circ}$ to 45° and from $\theta = 105^{\circ}$ to 135°, thus avoiding excessive absorption of the protons in the target backing. The plane of the target was then rotated to be at an angle of about 30° to the beam direction, and the distribution measured from $\theta = 45^{\circ}$ to 90°. The two 45° positions were used to normalise the total distribution. In both cases the angular positions were chosen in a random order to reduce the effect of variations in the monitoring

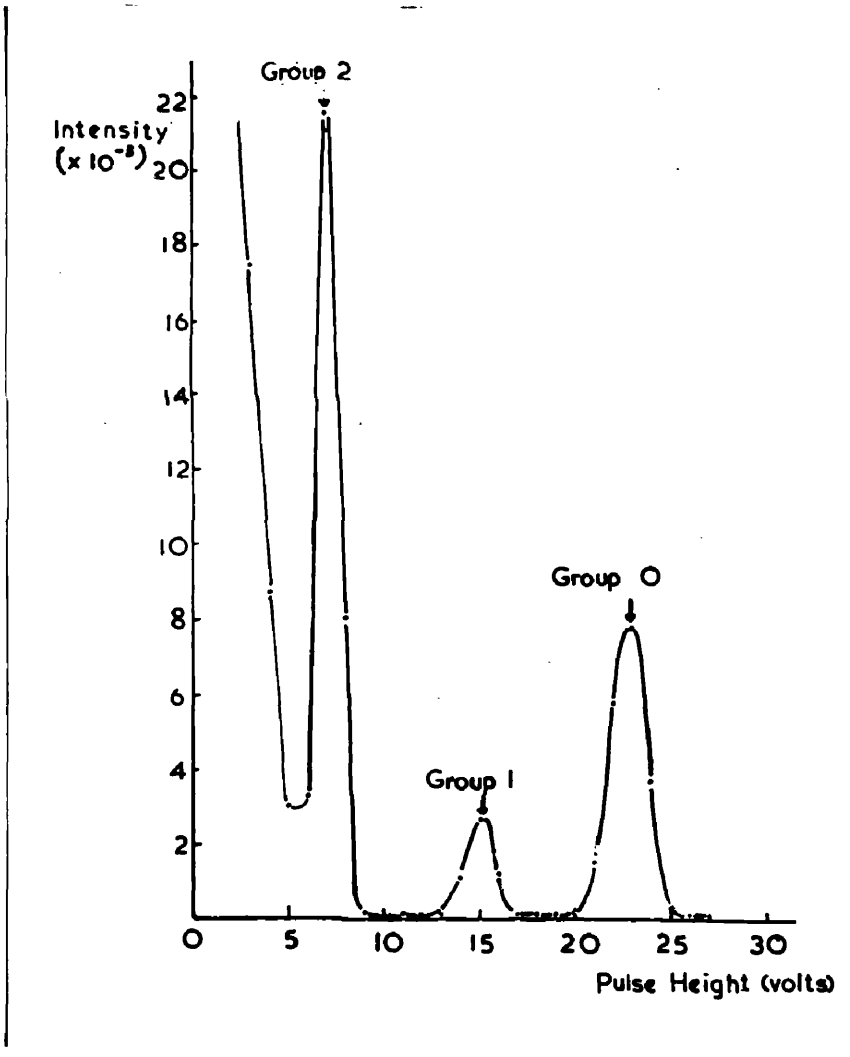


Fig. III(v) Proton spectrum from reaction $^{10}B(d,p)^{11}B$ using type 2 of apparatus.

system.

The reaction was monitored using a plastic phosphor scintillation spectrometer similar to that used in the movable counter. Pulses from the monitor counter were fed by a cathode follower to a linear amplifier, and hence through a discriminator to a scaler. The scaler operated a timing unit which could stop the kicksorter after a fixed number of counts had been recorded. The bias level of the discriminator was set to correspond to the valley between the peaks from groups 1 and 2, thus minimising the effect due to any drift in the bias level.

The angular distributions of groups 0 and 1 were measured simultaneously by observing the proton spectrum at each angular position for a constant number of counts in the monitor counter set at $\theta = -45^{\circ}$ as shown in Fig. III(iii). The distributions for group 2 were obtained by increasing the gain of the amplifier and repeating the above procedure. In this case an accurate estimate of the background in each angular position was obtained by repeating the observation with an aluminium foil, sufficiently thick to absorb all the charged particles emitted

in the reaction, between the target and the phosphor. This background spectrum was obtained immediately after the observation of the proton spectrum to ensure that any variation with time could be neglected.

The experimental angular distributions were calculated by measuring the total area under each peak in the spectrum, after subtraction of the appropriate background spectrum. For groups 0 and 1 the error introduced in fixing the limits in pulse height over which the area was to be calculated was negligible compared to the statistical error. In the case of group 2 a 3% error in the total count was introduced to allow for this uncertainty. The principal error present in the calculation of the experimental distributions lay in the uncertainty with regard to the isotropy of the apparatus, which could be due to (a) variation in the distance from the target to the detector, and (b) variation in the size of the ports for emission of protons. Effect (a) was measured by means of the angular distribution of the isotropic 6.1 Mev gamma-ray from the reaction $^{19}F(p,\alpha\gamma)^{16}O$

at E_p = 340 Kev [Devons and Hine (1949)] , using a sodium iodide scintillation spectrometer in place of the proton spectrometer. The effect was found to be negligible.

Experimentally the error introduced by (b) was more difficult to assess than that due to (a). Although it was felt that the areas of the emission ports were constant to within 1% it was obviously desirable to obtain experimental verification of this. Apart from direct measurement of the port diameters with a travelling microscope, which would only be a satisfactory method provided great care was taken to ensure that each port was examined under identical conditions, the only satisfactory method appeared to be the measurement of the angular distribution of some known isotropic radiation. As this radiation must only pass through the Dural windows, and not the walls of the target chamber, we were reduced to using either (a)protons or α -particles from a nuclear reaction or (b) low energy β-rays from a radio-active source. No known proton groups are isotropic and no α-particle group with sufficient energy to reach the crystal is known

to be isotropic, thus we were forced to try (b).

A source of RaE, which emits 1 Mev β-rays, deposited on a 0.001" nickel foil was used. These β-rays did not penetrate the wall of the target chamber, and when detected by a very thin piece of plastic phosphor gave a peak in the pulse height spectrum. However, measurements of the angular distribution of these β-rays did not produce an isotropic distribution. Instead the distribution had a shape which could be attributed to backscattering of the β-rays in the source backing. We were thus forced to abandon this method, as this fault will be present in all such experiments unless the source is prepared on a very thin backing, in which case it is very difficult to define the source size, a necessary feature in any satisfactory method.

The error was finally estimated by plotting the summation of all the experimental distributions, and fitting a smooth curve to the resultant points. This method is justified on the basis that, apart from statistical fluctuations, every separate distribution should be a smooth curve, and hence

summation of all the distributions, while reducing the statistical variation on each point, will not effect any systematic error due to the apparatus. It was found that no point was more than 2% from this curve. Thus it was decided to allow a 2% error on each of the experimental points for group 0 and 1 and a 5% error (including the 3% error already mentioned) corresponding to group 2.

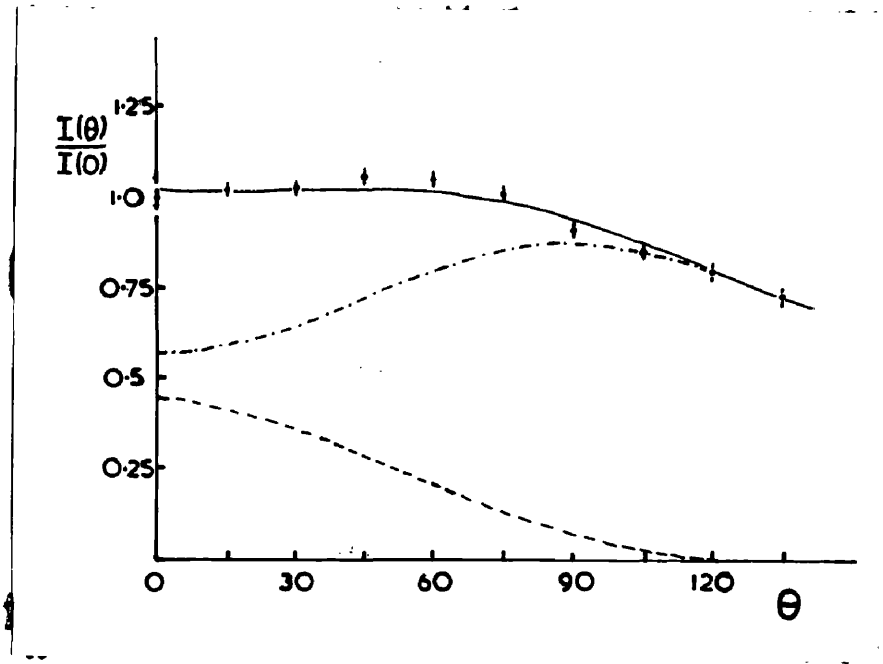
The statistical error on each point for all the distributions was generally less than 1%.

(ii) Results

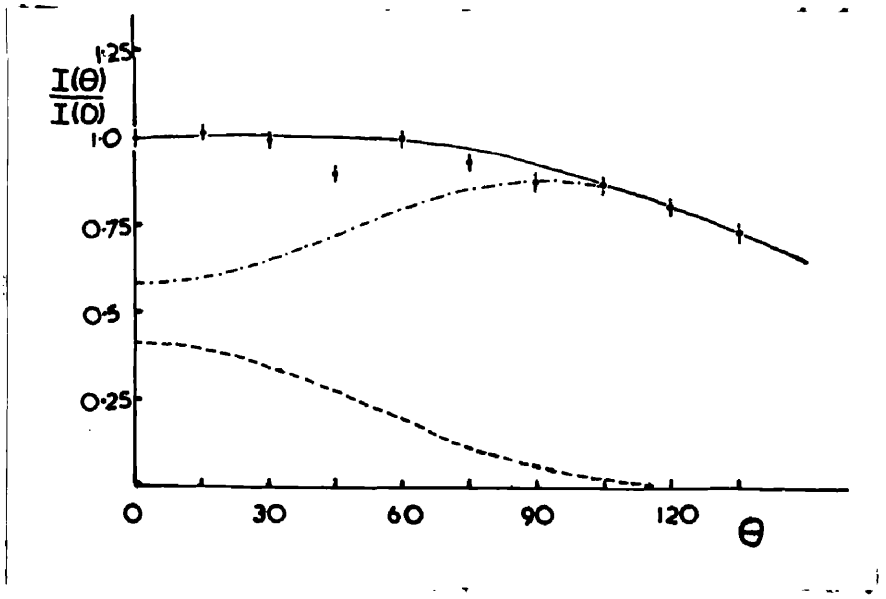
Angular distributions for groups 0 and 1 were measured at bombarding energies of 350, 500, 575 and 675 Kev and for group 2 at 500, 575 and 675 Kev. Figs. III[(vi), (vii) and (viii)] show the results for groups 0, 1 and 2 respectively.

For comparison Fig. III(ix) shows the distributions obtained with type 1 of the apparatus for group 0 at bombarding energies of 400, 500 and 600 Kev.

At this stage it should be pointed out that these initial results largely determined the



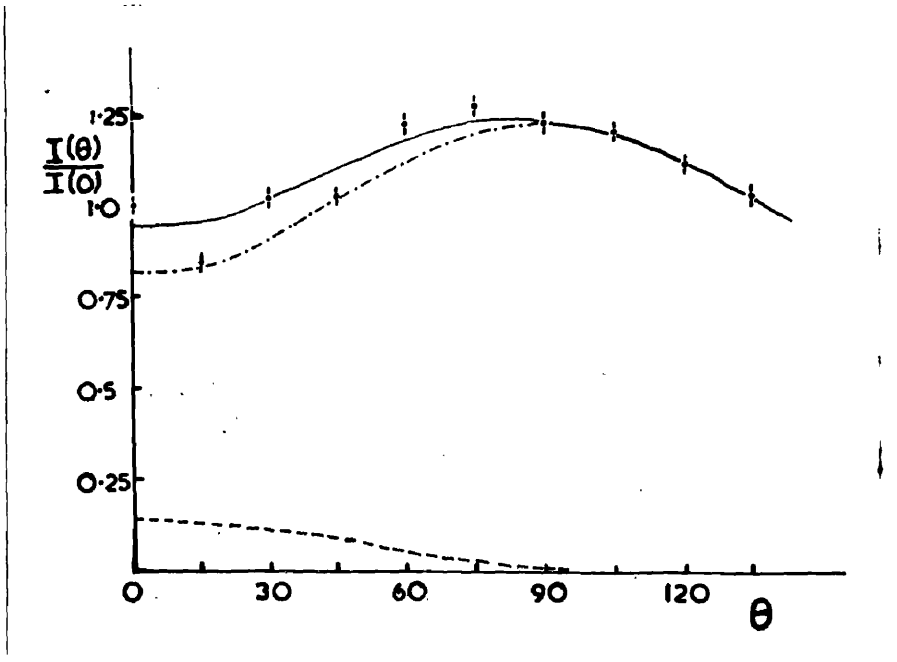
(a) E_D = 350 Kev.



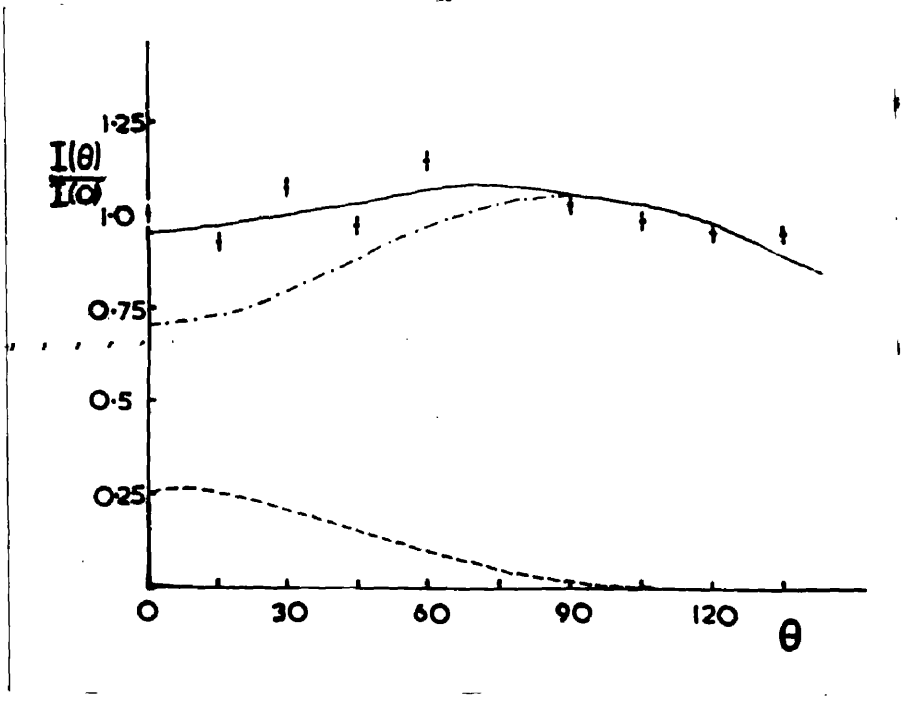
(b) E_D = 500 Kev.

Fig. III(vi). Angular distributions for proton group 0 from reaction $^{10}B(d,p)^{11}B$.

Dot-dash curve represents compound nucleus distribution given by $W(\theta) \sim 1 - 0.25\ P_2(\cos\theta)$. Dashed curve represents stripping distribution given by theory of Bhatia et al, with $R = 5.8 \times 10^{-13}$ cms. for the radius of ^{10}B, and $l_n = 1$. Full curve represents the summation of stripping and compound nucleus distributions.

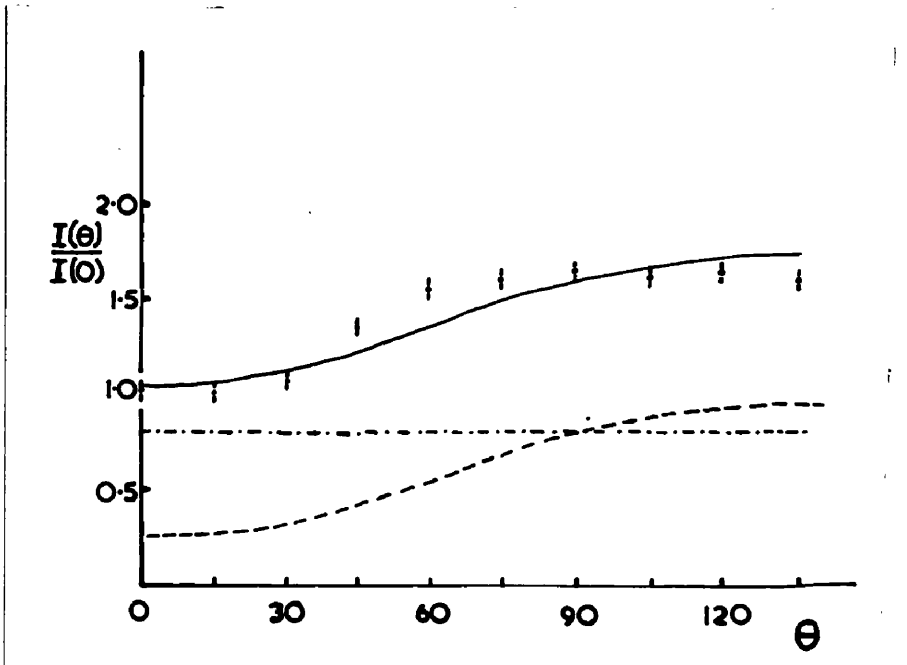


(c) E_D = 575 Kev.

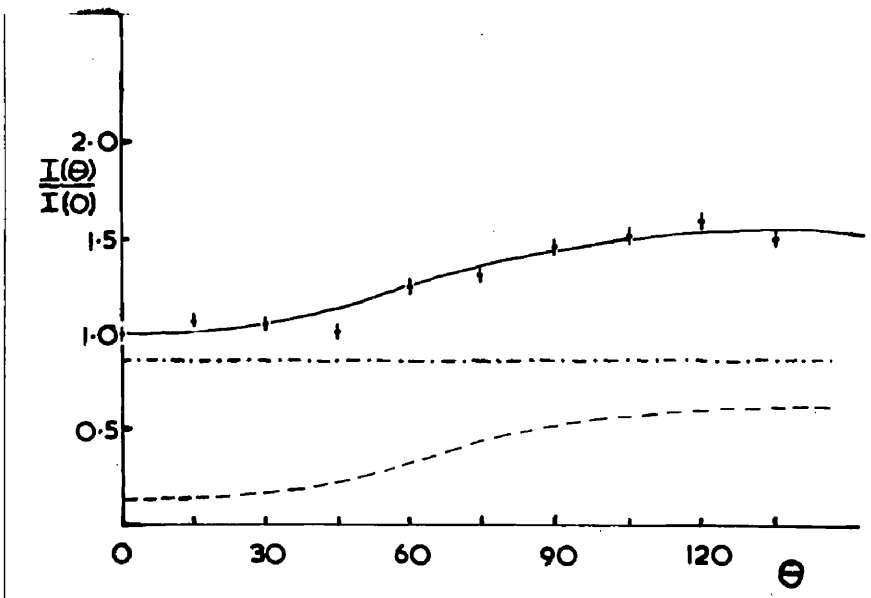


(d) E_D = 675 Kev.

Fig. III(vi). Angular distributions for proton group 0 from reaction $^{10}B(d,p)^{11}B$.



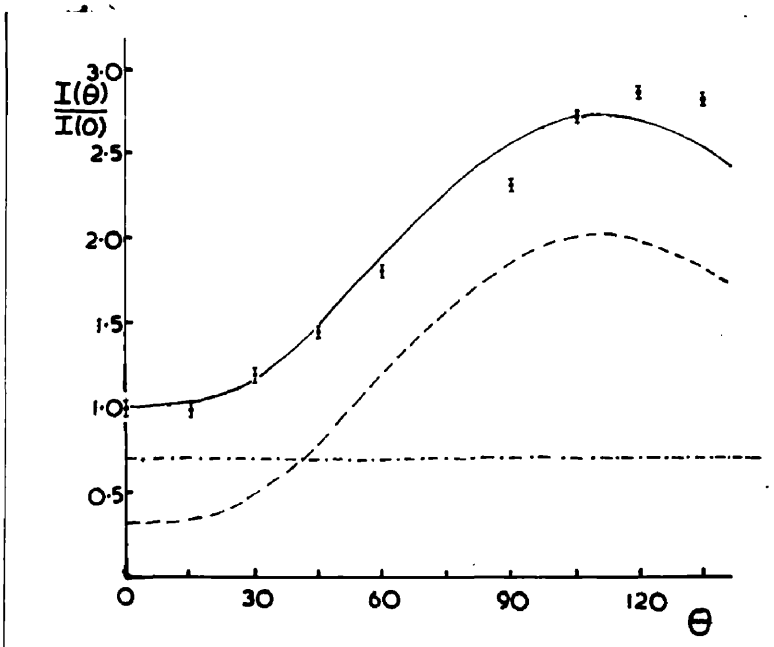
(a) E_D = 350 Kev.



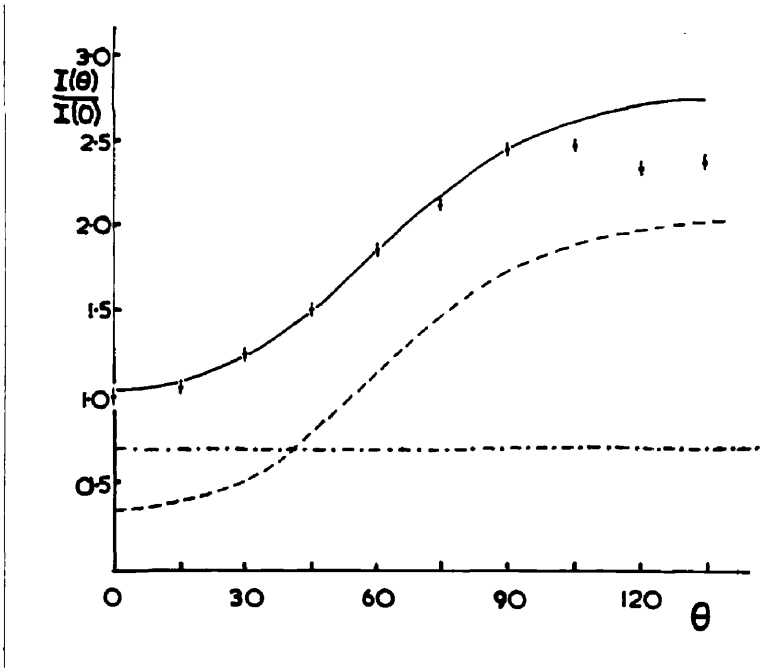
(b) E_D = 500 Kev.

Fig. III(vii). Angular distributions for proton group 1 from reaction $^{10}B(d,p)^{11}B$.

Dot-dash curve represents compound nucleus distribution given by $W(\theta)$ = isotropic. Dashed curve represents stripping distribution given by theory of Bhatia et al., with R = 5.8 x 10^{-13} cms. for the radius of ^{10}B, and ℓ_n = 3. Full curve represents the summation of stripping and compound nucleus distributions.

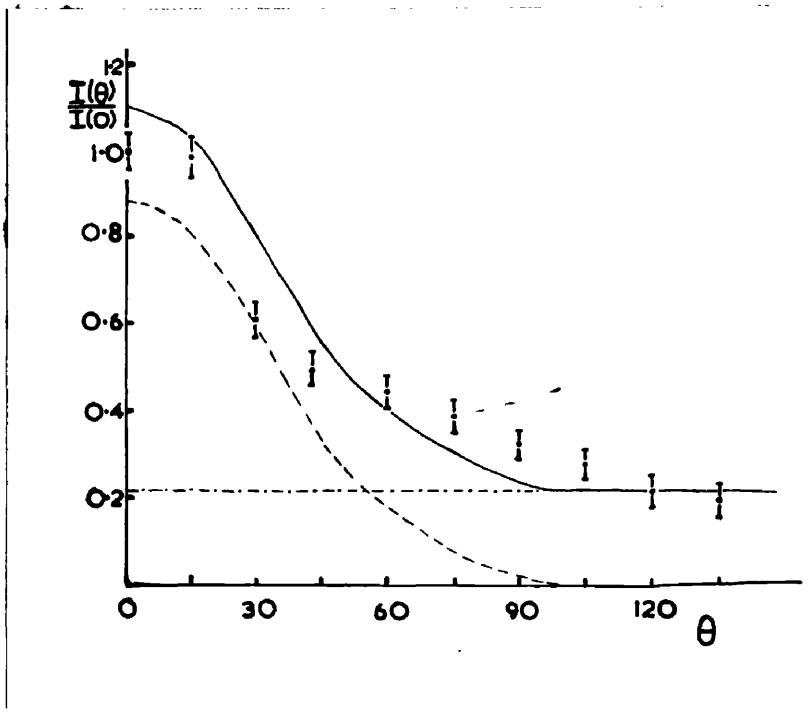


(c) E_D = 575 Kev.

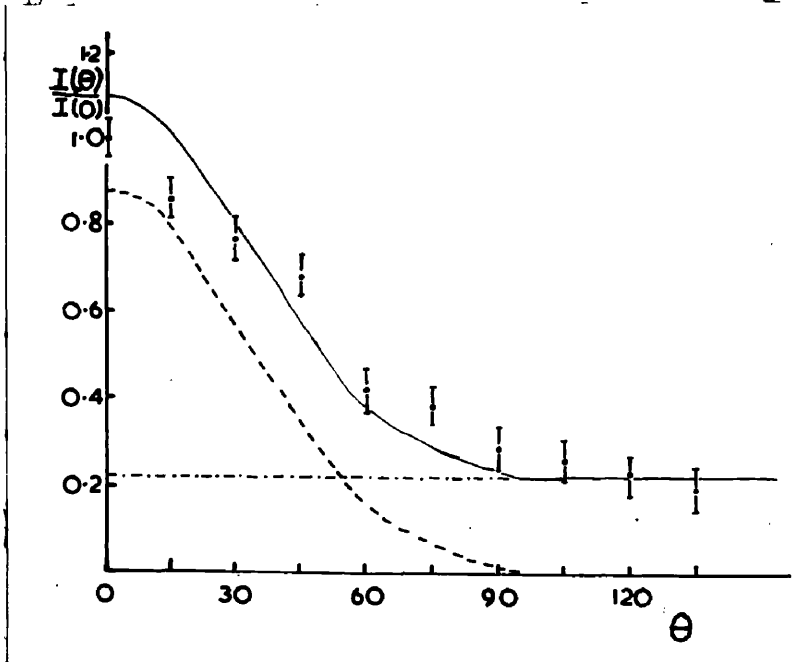


(d) E_D = 675 Kev.

Fig. III(vii). Angular distributions for proton group 1 from reaction $^{10}B(d,p)^{11}B$.



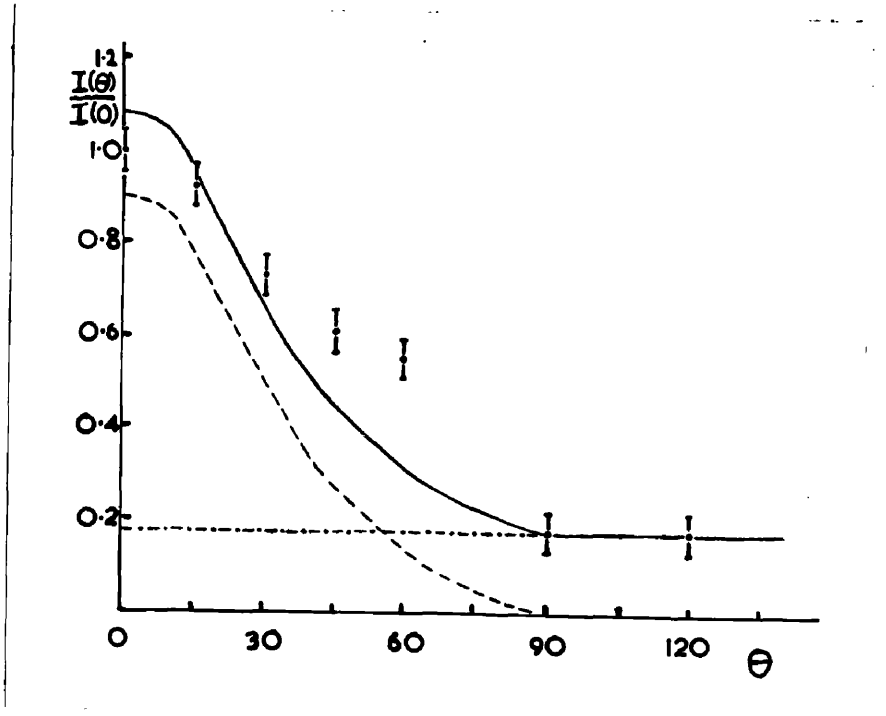
(a) E_D = 500 Kev.



(b) E_D = 575 Kev.

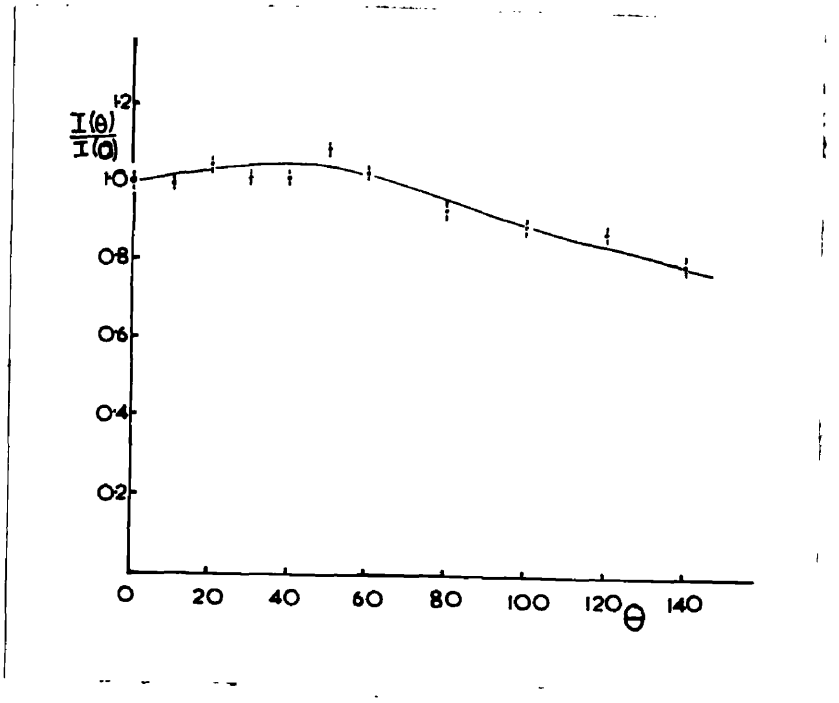
Fig. III(viii). Angular distributions for proton group 2 from reaction $^{10}B(d,p)^{11}B$.

Dot-dash curve represents compound nucleus distribution given by $W(\theta)$ = isotropic. Dashed curve represents stripping distribution given by theory of Bhatia et al, with $R = 5.8 \times 10^{-13}$ cm. for the radius of ^{10}B, and $\ell_n = 0$. Full curve represents summation of stripping and compound nucleus distributions.



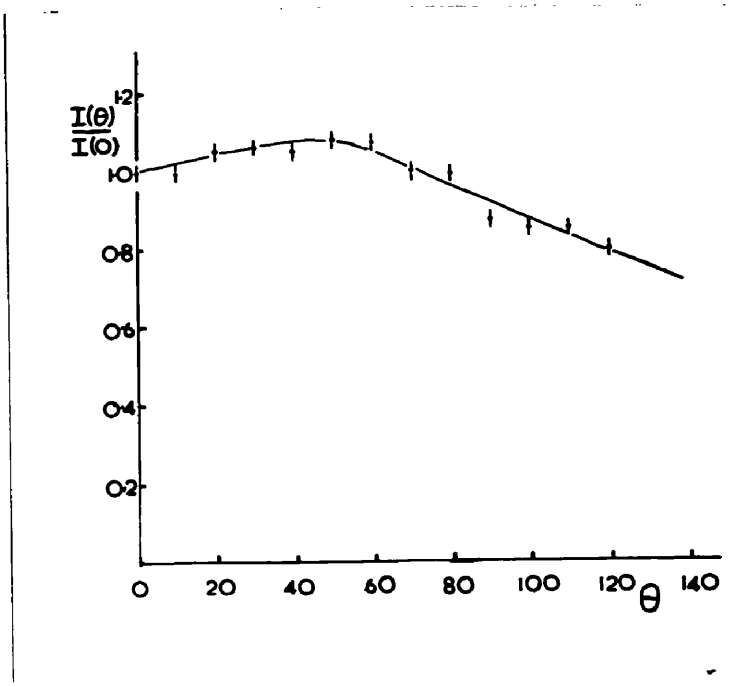
(c) E_D = 675 Kev.

Fig. III(viii). Angular distributions for proton group 2 from reaction $^{10}B(d,p)^{11}B$.

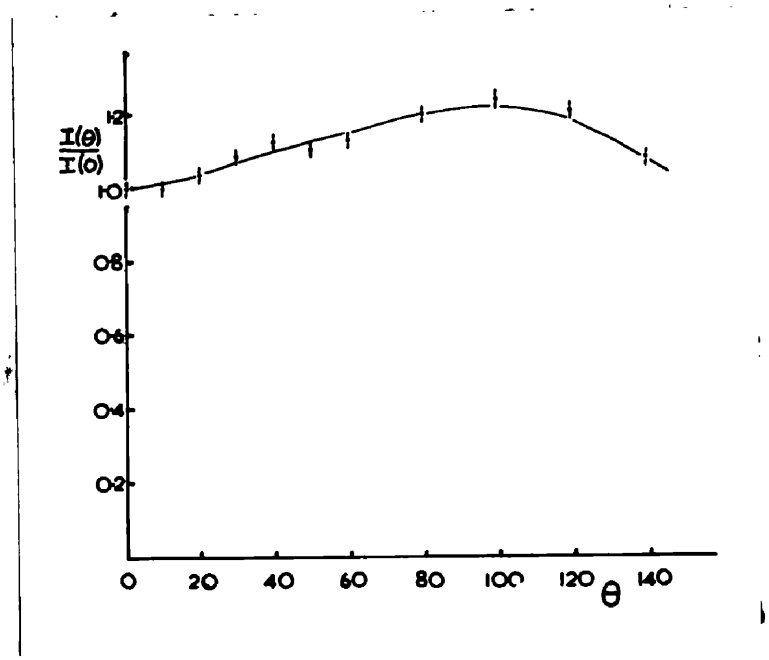


(a) E_D = 400 Kev.

Fig. III(ix). Angular distributions of proton group 0 from the reaction $^{10}B(d,p)^{11}B$ using type 1 of the angular distribution apparatus.



(b) E_D = 500 Kev.



(c) E_D = 600 Kev.

Fig. III(ix). Angular distributions of proton group 0 from the reaction $^{10}B(d,p)^{11}B$ using type 1 of the angular distribution apparatus.

course of the later experiments. Examination of Fig. III(ix) shows that the shape of the distribution varies markedly between 500 Kev and 600 Kev. At 600 Kev there are definite signs of symmetry about $\theta = 90^{o}$ not present at 400 and 500 Kev. Measurement of the excitation function at $\theta = 120^{o}$ of the reaction leading to the ground state of ^{11}B showed a definite discontinuity in the region of $E_D = 575$ Kev. The excitation function was checked many times and always exhibited this discontinuity. As the intensity of any stripping component in the distribution is zero at $\theta = 120^{o}$ then it is a reasonable assumption that this discontinuity is due in some way to compound nucleus formation. Thus we were first led to suspect the existence of a broad resonance level in the compound nucleus corresponding to a bombarding energy of $\sim$575 Kev. We have provided further verification for this assumption by careful measurement and analysis of the distributions over a range of bombarding energies from 350 Kev to 675 Kev. Other experimental evidence will be described and discussed

in a later section.

All the measured distributions have been corrected for variation in solid angle in centre of mass system, but no correction has been made for variation in centre of mass angle with respect to the laboratory system, as such variation was negligible.

The distributions have been plotted as a function $I(\theta)/I(0)$ against angle. This is only a matter of convenience, as there was no direct calibration between distributions at different energies.

III 2(d) Measurement of (d,pγ) angular correlations

(i) Introduction

Theoretically the measurement of the (d,pγ) angular correlation in this, or any other, reaction is of interest for two particular reasons:

(a) it may establish the spin of an excited state in cases where the interpretation of the stripping angular distribution leads to an uncertainty in this value

(b) it provides an estimate of the relative importance of the two competing processes, stripping

and compound nucleus formation, due to the variation in the theoretical predictions from the two theories.

In the case of the present reaction, Thirion (1954) has measured the correlations between proton groups 1 and 2 and their respective cascade γ-rays in ^{11}B. He only made measurements for two angular positions of the proton and γ-ray detectors, i.e. $\theta = 90^{o}$ and $\theta = 180^{o}$. As his results were published before the importance of this type of measurement was fully realised, it was felt that a more accurate measurement of the correlations may provide additional information of type (b). Apart from this, the angular distribution measurements, at low deuteron energies, [Paris et al, present work] for group 2 were so much at variance with those obtained at higher bombarding energies by Evans and Parkinson, that we hoped to resolve some of this difficulty by measurement of the correlation.

(ii) Experimental Procedure

The target chamber was the same as that used for the measurement of the proton angular distributions.

The γ-rays were detected by a sodium iodide crystal, $1\frac{3}{4}$" diameter and 2" long, mounted on a DuMont 6292 photomultiplier. This replaced the rotating proton spectrometer used in the angular distribution experiments. The protons were detected in a plastic phosphor scintillation spectrometer set at $\theta = -45^{\circ}$ to the direction of the incident beam, as shown in Fig. III(iii).

The targets used consisted of separated ^{10}B, prepared by A.E.R.E., Harwell, 15 μgms/cm^2 thick, on a 0.005" copper backing.

A block diagram of the electronic apparatus is shown in Fig. III(x). The coincidence circuit was of conventional design, and had a resolving time of 0.25 μsec. A variable delay (> twice the resolving time) in one side of the coincidence circuit allowed a direct measurement of the random coincidence spectrum to be made. The slow triple coincidence unit was used to provide a gating pulse for the kicksorter, and also to reduce the number of random coincidences. All the electronic equipment was available in the laboratory with the exception of the triple coincidence unit, which was built and

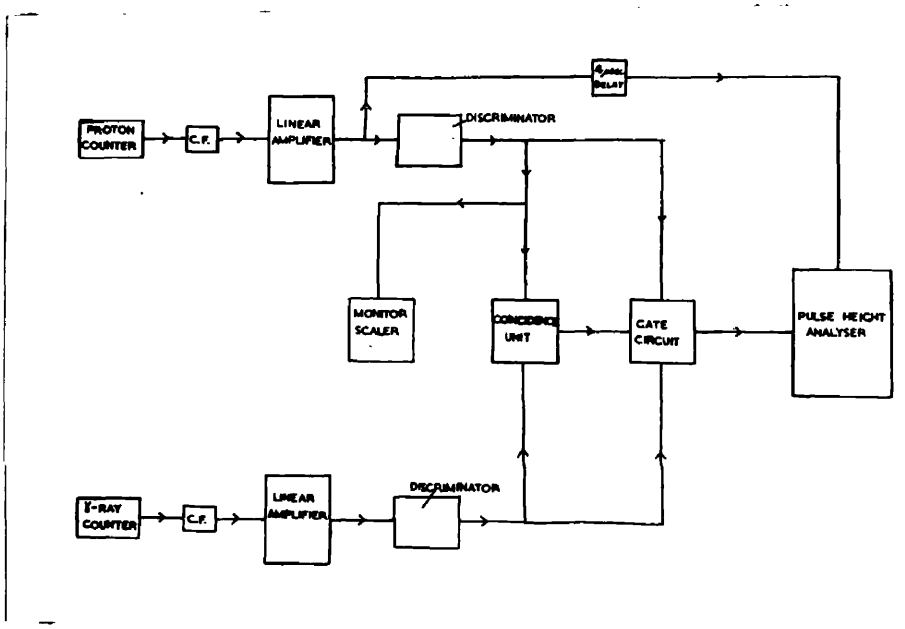


Fig. III(x). Block diagram of electronic apparatus used in angular correlation experiments.

tested by the author.

Previous experiments (Curling et al and Landon), studying the p - γ coincidence spectra had shown that the first two excited states of ^{11}B decay direct to the ground state. Thus proton group 1 is in coincidence with a 2.14 Mev γ-ray and group 2 with a 4.46 Mev γ-ray. As we had no reliable single-channel analyser available, all the γ-ray pulses corresponding to an energy $\geq$ 0.5 Mev were fed into one side of the coincidence unit, and all the proton pulses from groups 0, 1 and 2 into the other side.

Owing to the complex nature of the γ-ray spectrum, it was decided to use the proton spectrum in the measurement of the correlations. This method had two principal advantages:

(a) the single peaks from each proton group made the measurement of the intensity at each angular position relatively simple,

(b) the intensity of group 0 at each position relative to the intensities of group 1 and 2 gave a direct measurement of the random coincidence rate corresponding to each group, provided the

random coincidence spectrum was accurately known.

Before measuring the correlations the random coincidence spectrum was measured accurately at two angular positions to ensure that it was independent of the angular position of the γ-ray counter. This method of measuring the random coincidence rate tends to produce similar fluctuations in two correlations measured simultaneously, due to statistical variation in the number of random coincidences in group 0 and to variations in the monitoring system.

Both correlations were measured simultaneously at E_D = 500 Kev. The angular position of the γ-ray detector was varied from $\theta = 0^\circ$ to $\theta = 120^\circ$ in 30° intervals, and the proton coincidence spectrum taken at each position for 10^6 counts in the proton counter, which was used as a monitor. The intensity of groups 1 and 2 at each angular position was corrected for random coincidences as described above.

The isotropy of the apparatus was estimated from the angular distribution of 6.1 Mev γ-ray from the reaction $^{19}F(p,\alpha\gamma)^{16}O$ at E_p = 340 Kev.

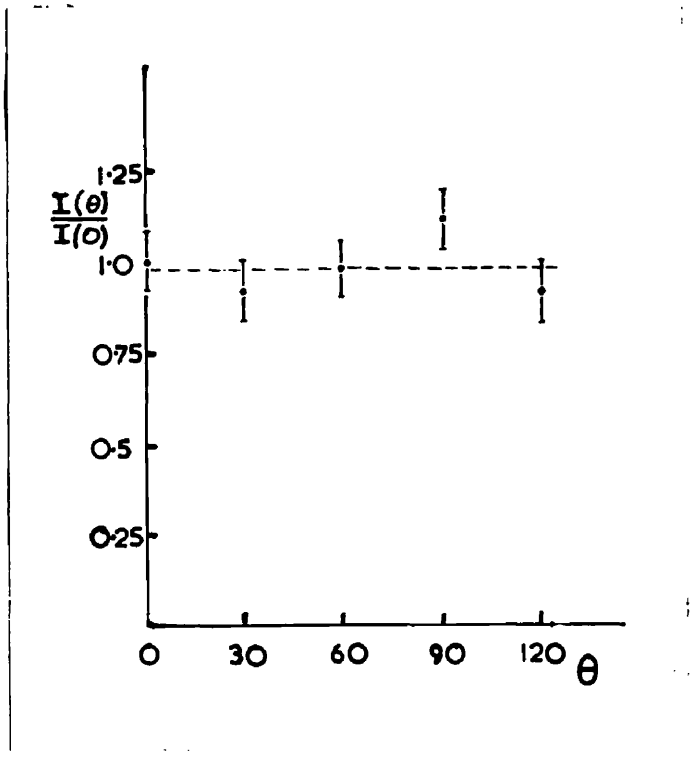
This radiation is known to be isotropic [Devons and Hine (1949)]. The correction was found to be negligible. No correction was made for the variation in absorption of the γ -rays in the target backing or for the finite solid angle of the detectors, as both of these factors were negligible in comparison with the statistical errors in the correlations.

(iii) Results

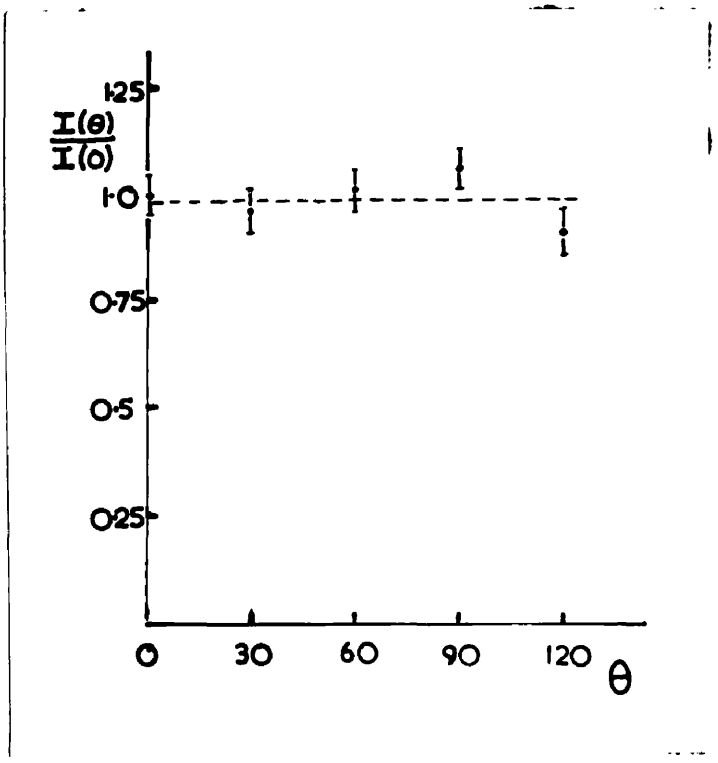
The measured correlations are shown in Fig. III (xi). In this case θ is the angle between the incident deuteron direction and the γ -ray counter. Both correlations are isotropic. This is in agreement with Thirion.

The interpretation of these results in terms of the spins of the first two excited states of ^{11}B will be discussed in the next section. The fact that the correlations were isotropic precluded any further measurements at different bombarding energies or at different angular positions for proton detection, as both correlation will be isotropic irrespective of the experimental conditions.

III 2(e) Interpretation/



(a) Group 1 – 2.14 Mev. γ-ray; W(θ) = isotropic.



(b) Group 2 – 4.46 Mev γ-ray; W(θ) = isotropic.

Fig. III(xi). Angular correlations from the reaction $^{10}B(d,p\gamma)^{11}B$ at E_D = 500 Kev.

III 2(e) Interpretation

(i) Group 0

The spins and parities of the ground states of ^{10}B and ^{11}B are known to be 3(+) and $\frac{3}{2}$(-) respectively. Thus stripping theory will allow a minimum ℓ-value of 1 for the orbital angular momentum of the captured neutron in the reaction $^{10}B(d,p)^{11}B$ leading to the ground state of ^{11}B. Experimentally this has been verified at high bombarding energies by many workers.

However, the results of Paris et al., at low bombarding energies do not appear to justify the assumption that the addition of an isotropic background, due to compound nucleus formation, to the stripping distribution for an ℓ-value of 1, will produce a close fit to the experimental points, especially in comparison with his results for groups 1, 2 and 3 from this reaction. This can be seen from Fig. III(xii) showing the distributions obtained by Paris at E_D = 580 Kev for groups 0 and 2. The present results will show that the assumption of an anisotropic distribution, symmetric about $\theta = 90^o$, due to

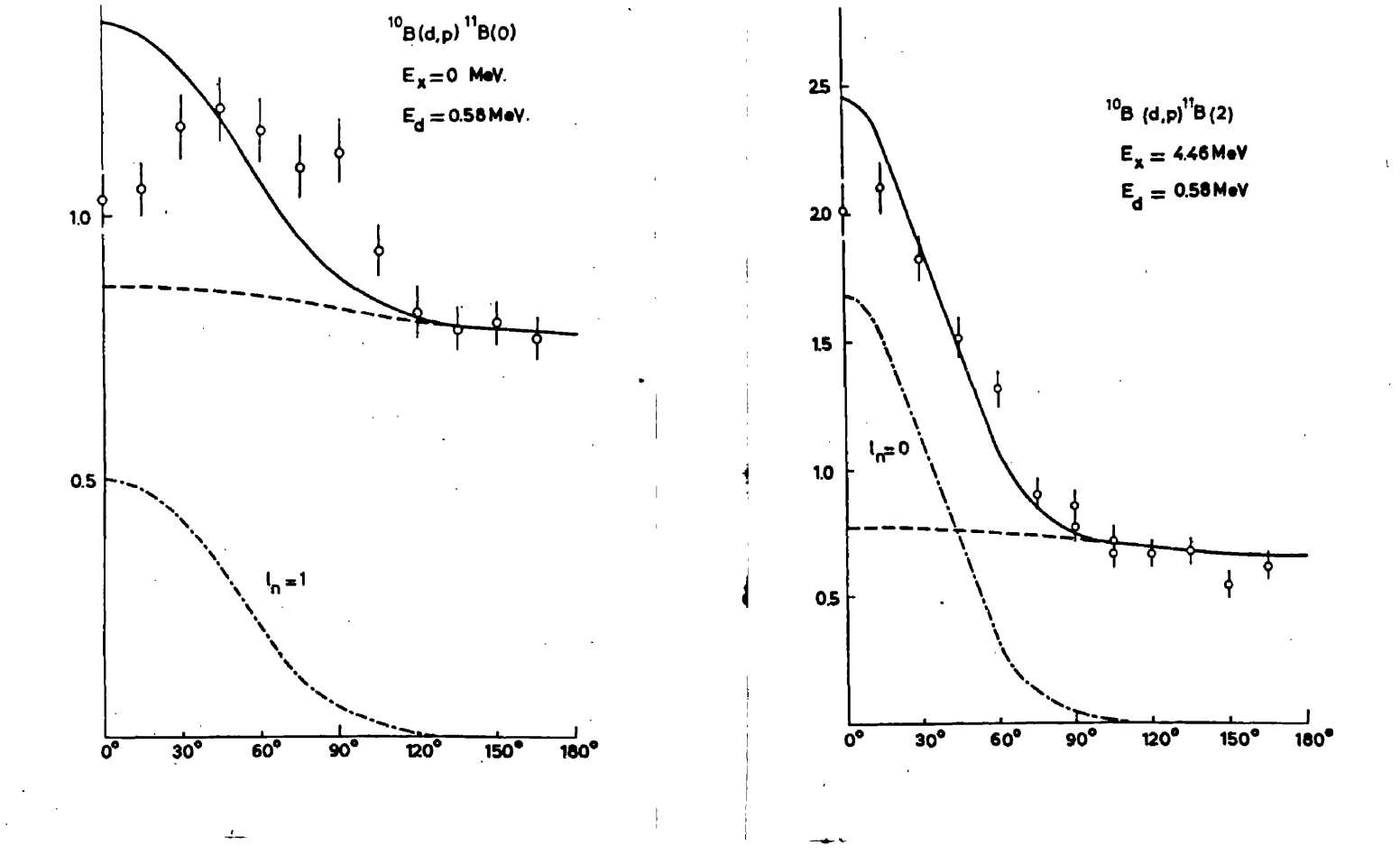


Fig. III(xii). Angular distributions for proton groups 0 and 2 from reaction $^{10}B(d,p)^{11}B$ obtained by Paris et al at E_D = 580 Kev. Stripping distribution calculation from theory of Bhatia et al, with R = 5.8 x 10^{-13} cm. for the radius of ^{10}B, and ℓ_n = 1 and 0 for groups 0 and 2 respectively.

compound nucleus formation leads to good agreement between theory and experiment over the range of deuteron energies investigated.

Theoretically an anisotropic background in this type of reaction could arise from one or more of three processes. These are (1) interference between stripping and compound nucleus formation, (2) interference between overlapping levels in the compound nucleus, and (3) single level formation in the compound nucleus. Of these only (3) will produce a distribution which is symmetric about $\theta = 90^{\circ}$, unless the interfering levels have the same parity, and as this is the only assumption about the nature of the background which has been required to fit the present experimental results, processes (1) and (2) have been neglected in the present case, although it is realised that these effects may be present.

Examination of the experimental curves shown in Fig. III(vi) shows that the distribution at $E_D = 575$ Kev exhibits a symmetry about $\theta = 90^{\circ}$. This is not evident in the distributions at $E_D = 350$ and 500 Kev., and only slightly in evidence

at E_D = 675 Kev.

It is also evident from Fig. III(vi) that none of the experimental distributions can be fitted by the theoretical stripping curve on the assumption of an isotropic "background" due to compound nucleus formation, and the distribution at E_D = 575 Kev suggests that this "background" is anisotropic, but symmetric about $\theta = 90^\circ$.

It should be noted that the use of the next allowed ℓ -value in the stripping calculations does not produce as good results as does the assumption $\ell_n = 1$.

By making three definite assumptions we have managed to produce close agreement between theory and experiment. These assumptions were:-

(1) the experimental distributions were compounded of two separate distributions from stripping and compound nucleus reactions, and these are assumed incoherent.

(2) the theoretical stripping distributions were calculated from the theory of Bhatia et al for an angular momentum ℓ -value of 1 and using the value $R = 5.8 \times 10^{-13}$ cms. for the radius of ^{10}B.

(3) the component from compound nucleus formation was anisotropic, but symmetric about $\theta = 90^{\circ}$.

Using these assumptions we have analysed the distribution at E_D = 575 Kev in the following way. From the fact that the stripping intensities at $\theta = 105^{\circ}$, 120° and 135° can be assumed negligible or zero, and using (3) above, we obtained estimates of the stripping intensities at $\theta = 45^{\circ}$, 60° and 75° from the differences $I_{45^{\circ}} - I_{135^{\circ}}$, $I_{60^{\circ}} - I_{120^{\circ}}$, $I_{75^{\circ}} - I_{135^{\circ}}$ respectively. Thus we obtained a mean value for the stripping intensity at $\theta = 0^{\circ}$, since we knew the shape of the stripping distribution accurately. We were then able to subtract from the experimental points a stripping component whose intensity at $\theta = 0^{\circ}$ corresponded to this mean value.

After subtracting this stripping component, the remaining points can be fitted by a curve of the form $W(\theta) = A\left[1 - 0.25\ P_2(\cos\theta)\right]$. If it is further assumed that the anisotropic component of the compound nucleus distribution is due to a single broad level in the compound nucleus ^{12}C,

then each of the experimental distributions should posses a component of the form $A^1 \left[1 - 0.25\ P_2(\cos\theta)\right]$, the value of A^1 varying with bombarding energy.

To verify this each of the experimental distributions was analysed in a similar manner to that described above. After subtracting the stripping component and analysing the remaining distribution in terms of Legendre polynomials, it was found that all the distributions had the form

$$W(\theta) = 1 \pm (0.02 \pm 0.01) P_1(\cos\theta) - (0.25 \pm 0.05) P_2(\cos\theta) - (0.01 \pm 0.01) P_3(\cos\theta)$$

Allowing for the uncertainties associated with the method of analysis, these results gave striking confirmation that each experimental distribution possessed a component of the form $W(\theta) = A^1 \left[1 - 0.25\ P_2(\cos\theta)\right]$.

In Fig. III(vi) the dot-dash curve represents the compound nucleus distribution, given by $W_c(\theta) = A \left[1 - 0.25\ P_2(\cos\theta)\right]$ and the dashed curve represents the stripping distribution, which was also expanded in a series of Legendre polynomials. It will be seen that the agreement

with the experimental distributions is remarkably close over the range of deuteron energies investigated.

The relative yields of the two processes at each bombarding energy were calculated by integration of the Legendre polynomial expansions over 4π solid angle. A graph showing $\frac{\text{Yield (compound nucleus)}}{\text{Yield (stripping)}}$, plotted against E_D, is shown in Fig. III(xiiia). The yields at 400 Kev and 600 Kev were calculated from the distributions measured with type 1 of the distribution apparatus at E_D = 400, 500, and 600 Kev. The result for 500 Kev agreed with the later value . In the absence of resonance effects in the compound nucleus formation, one would expect this function to exhibit a smooth curve. However, as will be seen from Fig. III (xiii a) there is an abrupt discontinuity at E_D = 575 Kev., although the existence of a maximum value of the function at this particular energy cannot be taken as definitely established due to the rather large errors introduced by the method of analysis, and to the fact that, owing to

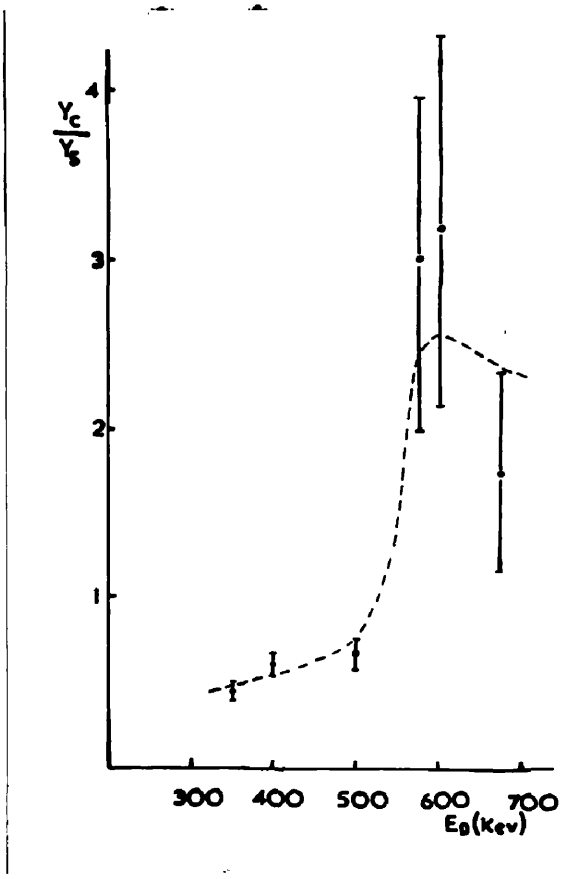


Fig. III(xiii) (a). $\frac{\text{Yield (compound nucleus)}}{\text{Yield (stripping)}}$ for group O, as a function of E_D.

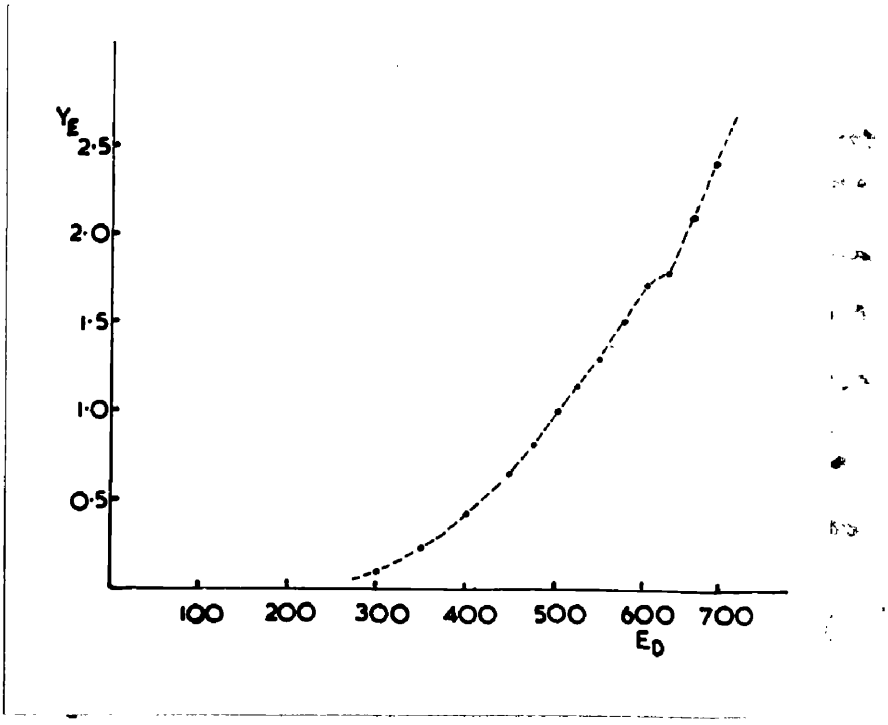


Fig. III(xiii) (b) Excitation function, at $\theta = 120^\circ$, for group O.

limitations in the H.T. set, we were not able to continue the measurements beyond E_D = 675 Kev. The presence of this discontinuity in the yield function, and the fact that the anisotropy in all the compound nucleus distributions is the same, pointed to the existence of a broad resonance level in the compound nucleus ^{12}C.

This was further investigated by measurement of the excitation function, at $\theta = 120^\circ$, for the reaction leading to the ground state of ^{11}B. These measurements were performed using the proton emission port at $\theta = 120^\circ$, as shown in Fig. III(iii), the target chamber was used as a Faraday cage. The yield of group 0 was measured at each energy value for the same deuteron current, as measured by a current integrator, incident on the target. The yield was measured from E_D = 300 Kev to E_D = 675 Kev in 25 Kev intervals. The measurements were repeated on several occasions using clean pieces of target on each occasion. The mean value of the excitation function is shown in Fig. III(xiii b). The slight discontinuity at E_D = 600 Kev is real, being observed every time

in the course of the separate experiments. This result offers further evidence for the existence of a compound level.

A further check on the two previous measurements was made by examining the ratio $\frac{I_{\theta = 120^\circ}}{I_{\theta = 0^\circ}}$ as a function of E_D, and this is shown in Fig. III(xiii c). As most of the yield at $\theta = 120^\circ$ is expected to arise from compound nucleus formation while the yield at $\theta = 0^\circ$ arises from both processes, this measurement should provide additional information on the behaviour of the compound nucleus reaction as a function of energy. If there is no resonance effect, the yield from compound nucleus should be a slowly increasing function of E_D, as should the yield from a stripping reaction. Thus in the absence of resonance the ratio $\frac{I_{\theta = 120^\circ}}{I_{\theta = 0}}$ should be reasonably constant when measured as a function of E_D.

The ratio was measured by placing two independent plastic phosphor scintillation spectrometers at $\theta = 0^\circ$ and $0 = 120^\circ$, and measuring

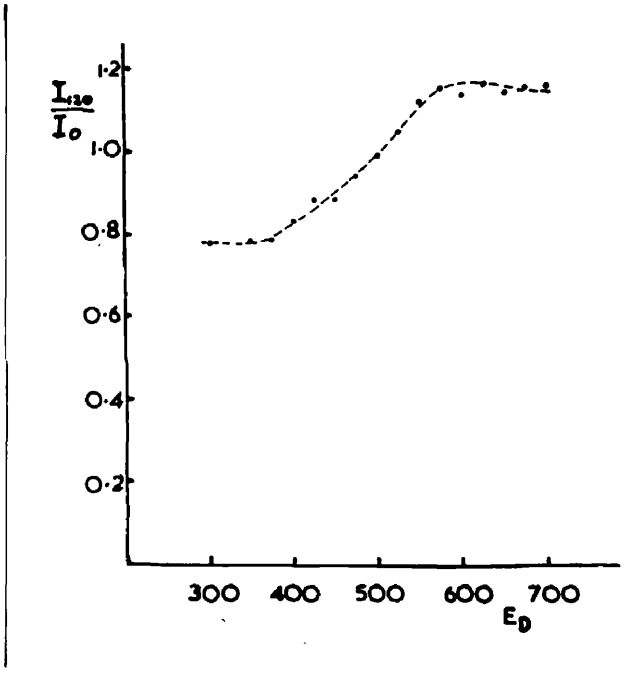


Fig. III(xiii) (c). $\frac{I_\theta = 120^\circ}{I_\theta = 0}$, for group O, as a function of E_D.

the number of counts in one at each particular energy corresponding the a fixed number of counts in the other. The results were then independent of fluctuations in beam intensity or variations in the position in which the beam strikes the target, factors which may have effected the ordinary excitation function measurements.

It will be seen that the ratio exhibits a definite discontinuity in the neighbourhood of E_D = 575 Kev, in agreement with the two previous measurements, and providing further evidence for the existence of a compound level.

In view of the preceding experimental results, the existence of a compound level in ^{12}C, corresponding to an excitation energy of $\sim$ 25.7 Mev, appears to be well established. No previous report of such a level has been made. It appears unlikely that this level corresponds to the reported levels at 25.36 Mev [Paris et al and 26.0 Mev [Burke et al.]

A theoretical analysis of the compound nucleus reaction has been made in order to investigate the possible values of the spin and

parity of this level, on the assumption that it decays to the ground state of ^{11}B by emitting a proton group with an angular distribution given by $W(\theta) \sim [1 - 0.25\ P_2(\cos\theta)]$.

The fact that the proton distribution is anisotropic forbids the formation of this state by capture of s-wave deuterons. D-wave capture appears unlikely on account of the low deuteron energy, and so we have assumed that the state is formed by capture of p-wave deuterons. Vector addition of the spin $I_1[3(+)]$ of the target nucleus ^{10}B and the intrinsic spin 1 of the deuteron gives the values 4, 3 or 2 for the incoming channel spin, S_1, in this reaction. These values of S_1 lead to the following values of J, the spin of the compound state: $S_1 = 4$, $J = 5, 4, 3$; $S_1 = 3$, $J = 4, 3, 2$; $S_1 = 2$; $J = 3, 2, 1$. All negative parity.

Since the parity of the ground state of ^{11}B is odd, the orbital angular momentum of the emitted proton must be even. As before S-wave emission is forbidden, and hence the compound state must decay by emission of d-wave protons.

Since the "outgoing channel spin" S_2, given by the vector addition of the spin $I_2 \left[\frac{3}{2}(-)\right]$ of the ground state of ^{11}B and the intrinsic spin, $\frac{1}{2}$, of the proton, has the values 2 and 1, this eliminates $J = 5$ as a possible value. Consideration of the relative intensities of proton groups 0, 1 and 2 shows that these are consistent with the assignments of 2, 4 and 1 to the angular momentum of the emitted protons respectively. It will be shown later that consideration of the angular distribution and correlation measurements for groups 1 and 2 leads to assignments of $\frac{1}{2}(-)$ and $\frac{5}{2}$ or $\frac{7}{2}(+)$ for the spins and parities of the first and second excited states in ^{11}B. Thus the angular momentum values for the emitted protons will only be consistent with a high J value for the compound state. In fact $J = 4$ appears to be the most probable assignment, and in this case we only have one variable parameter F, the incoming channel spin ratio. By choosing $F = \frac{4}{5}$ we can fit the experimental distribution.

However $J = 3(-)$ and $J = 2(-)$ cannot be

ruled out, although in these cases we have two variable parameters, the incoming and outgoing channel spin ratios, present in the calculations, and hence suitable adjustment of these will provide any desired distribution.

Irrespective of the J value chosen for the compound state, there exist variable parameters which can be adjusted to give isotropic distributions for groups 1 and 2, and hence the compound nucleus componenets in both of these distributions have been assumed isotropic.

We have looked unsuccessfully for any γ-rays emitted from this level to the ground state or first excited state of ^{12}C. This was done using a sodium iodide scintillation spectrometer biased to record only pulses $>$ 15 Mev., in order to eliminate any background from neutron capture in the crystal. The negative result is consistent with the level having a high J-value and small γ-ray partial width.

(ii) Group 1

It will be seen from Fig. III(vii) that in this case the assumption of an isotropic background

due to compound nucleus formation produces a reasonable fit to the experimental distributions by the addition of a stripping component calculated from the theory of Bhatia et al, assuming $\ell_n = 3$ for the angular momentum of the captured neutron and $R = 5.8 \times 10^{-13}$ cms. for the radius of ^{10}B. The assumption of an isotropic background has been justified in the preceding section.

From the observed ℓ_n value of the stripping component, the angular momentum and parity of the first excited state in ^{11}B is found to be $\frac{1}{2} \leqslant J \leqslant \frac{13}{2}$, negative parity, assuming the ground state of ^{10}B to be 3+.

Measurement of the angular correlation between this proton group and the corresponding cascade γ-ray from the 2.14 Mev level in ^{11}B, leads to a more definite assignment of the J value of this state.

As has been previously mentioned, it has been shown that, in a stripping reaction, a (d, pγ) correlation can be treated theoretically as an (n,γ) angular distribution, with the

direction of the captured neutron as an axis of symmetry. The angular momentum of the captured neutron used in the theoretical calculations is obtained from the experimental angular distributions. Thus, according to stripping theory, there are only two cases, apart from fortuitous mixing of variable parameters, in which an isotropic correlation will be obtained. These are: (a) the J value of the intermediate state is $\frac{1}{2}$ or 0 and (b) the angular momentum of the captured neutron is 0.

According to compound nucleus theory, condition (a) will also produce an isotropic correlation, although this is not necessarily true for (b).

Thus in view of the isotropy of the measured correlation, and the fact that the ℓ_n value corresponding to group 1 is not zero, we can assign the values $\frac{1}{2}(-)$ to the spin and parity of the first excited state in ^{11}B. This is in agreement with the shell model predictions [Lane (1953)].

The discrepancy between the low energy

results for this group [Paris et al, present work] and those obtained at higher bombarding energies [Evans and Parkinson (1954)] is difficult to understand. We only wish to point out that, (a) the choice of $\ell_n = 1$ for the angular momentum of the captured neutron gives a stripping distribution which shows a pronounced forward peak, no evidence of this has been found in the experimental distributions, which are remarkably constant over the range of energy investigated, (b) if $\ell_n = 1$ then J cannot be $\frac{1}{2}$, and the expected correlation would not be isotropic, in disagreement with the experimental result.

(iii) Group 2.

In this case, as will be seen from Fig. III(viii), the experimental distributions can be fitted by assuming an isotropic compound nucleus component plus a stripping component calculated from the theory of Bhatia et al., assuming $\ell_n = 0$ for the angular momentum of the captured neutron, and $R = 5.8 \times 10^{-13}$ cm. for the radius of ^{10}B. This gives $J = \frac{5}{2}$ or $\frac{7}{2}$, positive parity, for the second excited state of ^{11}B.

In this case the isotropy of the measured correlation, between group 2 and the 4.46 Mev. γ-ray emitted to the ground state of ^{11}B, does help to differentiate between the two possible values, since the isotropy is due to the absorption of an s-wave neutron.

It should be noted that if the ℓ_n value of the captured neutron is 1, as predicted by Evans and Parkinson, then the correlation expected from a stripping reaction would be

$W(\phi) \sim 1 - (0.2 \pm 0.05) \cos^2 \phi$ where ϕ is the angle between the direction of the captured neutron and the emitted γ-ray.

No evidence was found for such a correlation.

Part IV. Conclusion

During recent years there has been a gradual accumulation of spin and parity assignments to the energy levels of light nuclei. It is only by the knowledge of these properties that we can hope to construct a reliable model of nuclear structure. The problem is analogous to the case of atomic structure. In this case it was only by using the earlier empirical determinations of the energy levels in the hydrogen atom that Bohr was able to advance his theory of atomic structure. It is to be hoped that similar success will be obtained in the case of nuclear structure, even although the problem is very much more complex.

The present experimental investigations have enabled spin and parity assignments to be made to some excited states in the nuclei ^{11}B, ^{27}Al and ^{28}Si.

The interpretation of the results obtained from the study of the (p,γ) reactions is more conclusive than that obtained from the (d,p) reaction. This is due to the indeterminacy of

the theory associated with low energy deuteron reactions, and the fact that the theory of (p,γ) reactions has been well established by previous experiments.

There are still several features of the study of (p,γ) reactions in which increased accuracy in the experimental measurements would considerably increase the importance of this type of reaction. For example, if the energy resolution of the γ-ray detector could be improved, without any subsequent loss in detection efficiency, it would be possible to make more accurate estimates of the relative intensities of γ-ray transitions between nuclear levels of known spin and parity, and this would lead to an increase in knowledge of the electro-magnetic radiation transfer probabilities from the energy levels of light nuclei. Another important feature of (p,γ) reactions which, up to present, has not been fully utilised, is the measurement of $\gamma - \gamma$ angular correlations. Such measurements will usually remove any uncertainties in the spin and parity assignments derived from the measurement of γ-ray angular distributions.

However, these measurements will only become a practical consideration when the energy resolution of the γ-ray detector has been improved to enable measurements to be made on the $\gamma - \gamma$ correlations of γ-rays which cascade through the third, fourth or fifth etc. excited states of nuclei. At present such experiments are generally confined to γ-rays which cascade through the first two excited states.

It appears that this increase in energy resolution will only be achieved by the use of a detector which produces a single peak, in the pulse height distribution, corresponding to a mono-energetic γ-ray, in contrast to the triple peaks produced by a sodium iodide single crystal spectrometer. Even the use of double-or triple-crystal scintillation spectrometers does not provide the answer, due to the large drop in detection efficiency associated with these types of spectrometers.

In the study of low energy deuteron reactions, the interpretation of the experimental results is seriously hindered by the lack of an adequate

theoretical treatment of this type of reaction. Although several attempts have been made to extend the current "stripping" theories of deuteron reactions to the case of low energy reactions, these have so far proved unsuccessful. The principal problems which such a theory must answer are: (a) determination of the deuteron wave function in the Coulomb field of the target nucleus, (b) the coherence or incoherence of stripping and compound nucleus reactions, and (c) the effect of interference between levels in the compound nucleus on the angular distribution of the nucleons emitted in this type of reaction.

It is hoped that the present experimental results on the angular distribution of proton groups emitted from the reaction $^{10}B(d,p)^{11}B$, will provide the type of information useful in the construction of such a theory. In particular, the interpretation of the compound nucleus distribution associated with group 0 is interesting, in that it does not adhere to the usual assumption of an isotropic distribution from this type of reaction during deuteron bombardment. However,

we feel that the experimental evidence in support of our interpretation is very strong, and we hope that these results will lead to careful examination of the results from other low energy deuteron reactions.

References

Ajzenberg, F., 1952, Phys. Rev. 88, 298.

Ajzenberg, F., and Lauritsen, T., 1955, Rev. Mod. Phys., 27, 1, 77.

Bhatia, A.B., Huang, K., Huby, R., and Newns, H.C., 1952 Phil. Mag., 43, 485.

Browne, C.P., Zimmerman, S.F., and Buechner, W.W., 1954, Phys. Rev. 96, 725.

Brostrum, K.J. Huus, T., and Tangen, R., 1947, Phys. Rev., 55, 27.

Burke, W.H., Risser, J.R., and Phillips, G.C., 1954, Phys. Rev., 93, 188.

Butler, S.T., 1951, Proc. Roy. Soc. (London), A208, 559.

Canavan, F.L., 1952, Phys. Rev. 87, 136.

Casson, H., 1953, Phys. Rev. 89, 809.

Christy, R.F., 1953, Phys. Rev., 89, 839.

Curling, C.D., and Newton, J.O., 1950, Nature, 166, 339.

Daniel, H., and Bothe, W., 1954, Z. Naturf., 9A, 402.

Devons, S., and Hine, M.G.N., 1949, Proc. Roy. Soc., A199, 56.

Endt, P.M. Paris, C.H., Jongerius, H.M., and Valckx, F.P.G., 1952 Physica, 18, 423.

Endt, P.M., and Valckx, F.P.G. 1953, Physica, 19, 1140.

Endt, P.M., and Kluyver, J.C. 1954, Rev. Mod. Phys, 26, 1, 95.

Evans, N.T.S., and Parkinson, W.C., 1954, Proc. Phys. Soc. A67, 684.

Feather, N., 1953, Advances in Physics (Phil. Mag. Suppl.), 2, 141.

Fulbright, H.W., Bruner, J.A. Bromley, D.A., and Goldman, L.M., 1952, Phys. Rev., 88. 700.

Grant, I.P., 1954, Proc. Phys. Soc., A67, 981.

Griffiths, G.M., 1955, Canadian Jour. of Physics, 33, 209.

Holt, J.R., and Marsham, T.N., 1953, Proc. Phys. Soc., A66, 1032.

Huby, R., 1953, Progress in Nuclear Physics, Vol. 3.

Hughes, I.S., and Grant,P.J., 1954, Proc. Phys. Soc., A67, 481.

Hughes, I.S., and Sinclair, D., 1955, Private Communication.

Hunt, S.E., and Jones, W.M., 1953, Phys. Rev. 89, 1283.

Hutchinson, G.W., and Scarrott, G.G., 1951, Phil. Mag., 42, 792.

Kluyver, J.C., and Verploegh, G., 1954, Physica, 20, 178.

Landon, H.H., 1951, Phys. Rev., 83, 1081.

Li, C.W., 1952, Phys. Rev., 88, 1038.

Oppenheimer, J.R., and Phillips, M., 1935, Phys. Rev., 48, 500.

Paris, C.H., Valckx, F.P.G., and Endt, P.M., 1954, Physica, 20,573.

Peck, R.A., 1949, Phys. Rev., 76, 1279.

Pratt, W.W., 1954, Phys. Rev., 93, 816.

Rae, E.R., Rutherglen, J.G., and Smith, R.D., 1951, Proc. Phys. Soc., A64, 906.

Redman, W.C., 1950, Phys. Rev. 79, 6.

Russel, L.N., Taylor, W.E., and Cooper, J.N., 1952, Phys. Rev. 86, 819.

Rutherglen, J.G., and Smith, R.D. 1953, Proc. Phys. Soc., A66, 800.

Satchler, G.R. and Spiers, J.A., 1952, Proc. Phys. Soc., A65, 980.

Satchler, G.R., 1953, Proc. Phys. Soc., A66, 1081.

Serber, R., 1947, Phys. Rev. 72, 1114.

Sharp, W.T., Kennedy, J.M., Sears, B.J., and Hoyle, M.G., 1953, Tables of Coefficients for Angular Distribution Analysis.

Tangen, R., 1946, K. Norske Vidensk. Selsk. Skr., No. 1.

Taylor, W.E., Russell, L.N., Cooper, J.N., and Harris, J.C., 1952, Phys. Rev. 86, 630.

Thirion, J., 1953, Annales de Physiques, 8, 489.

Touschek, B.F., 1950, Phil. Mag., 41, 849.

Van Patter, D.M., Buechner, W.W., and Sperduto, A., 1951, Phys. Rev. 82, 248.

Yoccoz, J., 1954, Proc. Phys. Soc. A67, 813.