SOME REACTIONS OF PROTONS AND DEUTERONS WITH LIGHT NUCLEI.

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PREFACE.

This thesis describes the experiments which the author performed between October 1953 and September 1956 in the Department of Natural Philosophy at the University of Glasgow. The original field of study was an investigation of the energy level systems of certain light nuclei by observing the nuclear reactions in which these nuclei were produced by bombarding other nuclei with protons or deuterons. In the case of the experiments in which deuterons were used, there was later a change of emphasis from the use of these reactions as a tool for investigating nuclear structure to the analysis of the mechanisms of the reactions themselves.

These two facets of the subject are described in Part I where a general survey is given of the theoretical background to the study of these reactions. This section also includes a discussion of the various techniques that have been used by other research workers in their investigations of nuclear reactions. The material for this survey has been drawn from current literature on the various subjects.

Part II contains the results of the investigation of the $^{26}Mg(p,\gamma)^{27}Al$ reaction which was chosen to illustrate the mode of interaction of protons. The protons were accelerated in the High Tension Generator at Glasgow University and the γ-rays were detected by a scintillation spectrometer. This work is all original. The first measurements of the γ-ray spectra and angular distributions were carried out in collaboration with Dr. J. G. Rutherglen and Dr. W. M. Deuchars. However, all the results, which are actually quoted in this thesis, were obtained by the author in a series of more accurate measurements. In the course of this work observations were made of the angular correlations between γ-rays in cascade as well as of the angular distributions, etc., of individual γ-rays. Thus the author took the major part in all the experimental work and was entirely responsible for the analysis of the results. This section of the thesis concludes with a discussion of the information about the spins and parities of the levels in ^{27}Al, that was obtained, and of the relevance of current ideas on nuclear structure to the results.

In part III is described the work that was carried out on the $^{10}B(d,p)^{11}B$ reaction and the $^{24}Mg(d,p)^{25}Mg$ reaction which were chosen to illustrate the interaction of deuterons with light nuclei. The angular distributions of the protons and the angular correlations between the protons and subsequent γ-rays were measured with scintillation counters and have been analysed in various ways. Although Paris et alia (1954) published angular distributions for the protons from the $^{10}B(d,p)^{11}B$ reaction at a late stage in these measurements, our detection technique was quite different from their technique and our measurements were more accurate. Our analysis of the results also differs from that which was used by Paris. Most of the results for the $^{10}B(d,p)^{11}B$ reaction were obtained in collaboration with Dr. W. M. Deuchars who was responsible for the original analysis of the angular distributions in terms of components from stripping and from compound nucleus formation. The crucial measurements were repeated by the author with the assistance of Mr. R. S. Storey who also assisted in the study of the $^{24}Mg(d,p)^{25}Mg$ reaction. The analysis of this reaction in terms of a modified stripping theory was suggested by Dr. A. H. de Borde and was carried out by the author.

In part IV there is a brief discussion of the importance of the results, which are presented in this thesis, and of experiments which could be carried out to investigate further details of these reactions.

ACKNOWLEDGMENTS.

I should like to thank Professor P. I. Dee for his sustained interest and encouragement during the course of this work and for this opportunity to work in his department. My thanks are also due to Dr. A. H. de Borde, Dr. P. J. Grant, Dr. J. G. Rutherglen and Dr. J. Varma for many helpful discussions and to Dr. W. M. Deuchars and Mr. R. S. Storey for their invaluable co-operation.

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Finally I wish to acknowledge with gratitude the receipt of a D.S.I.R. maintenance allowance during the three years that I spent on this work.

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LIST OF DIAGRAMS AND TABLES.

PART I. A SURVEY OF NUCLEAR REACTIONS INVOLVING PROTONS AND DEUTERONS.

I. 1 INTRODUCTION.

Ever since the famous experiments on the scattering of α-particles, in which Lord Rutherford showed that atoms consist of small, heavy nuclei surrounded by a number of light electrons, physicists have been engrossed in the study of the properties of the atomic nucleus. Many different methods have been used to evaluate these properties, and one of the most powerful has been the study of the transformations that result from the interaction of two nuclei. The target nuclei in these experiments have generally had an atomic number of less than twenty, so that the analysis of the results of the experiments would not be obscured by effects arising from a large number of nucleons being involved in the reaction. For the same reason the bombarding nucleus has usually been that of hydrogen, or deuterium. The hydrogen nucleus is the lightest of all the nuclei and consists of a single, positively charged, particle called a proton. In contrast the nucleus of deuterium is called a deuteron and is made up of a proton and a neutron, which is an uncharged particle with the same mass as a proton. All other nuclei are made up of numbers of neutrons and protons tightly bound together by forces which act between neutrons and protons as well as between like particles.

It is found that the deuteron has a very loosely bound structure with an average distance between its constituent neutron and proton of $2 \cdot 18 \times 10^{-13}$ cms.. This is to be contrasted with the range of the nuclear force between the two particles which is only $1 \cdot 7 \times 10^{-13}$ cms. Thus one would expect that the main difference between the modes of interaction of the deuteron and the proton would be explicable in terms of the two particle nature of the former. This has been shown to be true when the energy of the bombarding nucleus is greater than a few Mev. At lower energies, however, a considerable complication is caused by the fact that the absorption of a deuteron releases about 14 Mev. while the absorption of a proton only releases about 8 Mev.

Experiments by other research workers have shown that, for light nuclei and low proton energies, the proton can be considered to be absorbed to form a compound nucleus which then decays into the product nucleus plus the emerging particle. On the other hand in experiments with light nuclei and large deuteron energies the deuteron is broken up by some direct interaction between its constituent neutron or proton and the target nucleus before a compound nucleus can be formed.

I. 2 REACTIONS PRODUCED BY PROTONS.

(a) Theory.

One of the most striking facts that has emerged from the study of nuclear interactions is that the energy and angular momentum of the nucleus are quantised. It has been shown that only discrete values of the total energy of the nucleons in a nucleus are observed, and that for any given energy state of the nucleus the total angular momentum has a value that is an integral multiple of $\frac{1}{2}\hbar$. "$\hbar$" is Planck's constant divided by 2π. This angular momentum is called the spin of the state. Other properties of these nuclear energy states have been observed, viz. that the mode of de-excitation is a property of the state and not of the mode of excitation, and that the parity of the state is unique. The parity is a measure of the symmetry of the wave function of the system and is defined as being plus if the wave function does not change sign on inversion of the axes, and minus if the wave function changes sign.

The probability of de-excitation of an energy level by a particular mode is inversely proportional to the lifetime that the state would have if that mode was the only one available for de-excitation. Moreover, the Uncertainty Principle gives a relationship between the uncertainty in the energy of a given state and its lifetime, viz. $\Delta E \cdot \Delta t = \hbar$. Thus a partial width Γ of the energy can be associated with each mode of decay such that the probability of decay by that mode is proportional to the partial width. Then the sum of the partial widths will be the total width, or uncertainty, in the energy of the level. It is found that with few exceptions the total widths of energy levels increase as the energy increases. As the density of energy levels also increases with increasing energy, there is a region of low energy for each nucleus in which the energy levels are discrete, and above this is a region in which the energy levels overlap to form a continuum.

When the binding energy of the last nucleon in a nucleus is X Mev., the states with energies below X Mev. will only be able to lose their energy by emitting a γ-ray whereas the states with energies above X Mev. can lose their energy by emitting a nucleon, or group of nucleons, or a γ-ray. Although both types of energy state are essentially the same it is convenient to call the former, "bound states", and the latter, "virtual states". For most nuclei the energy of dissociation of the least bound nucleon is less than the energy of the lowest level in the continuum of overlapping energy levels. Thus most nuclei have a number of discrete, virtual levels.

Many experiments have shown that protons, whose energies are low, interact with light nuclei to form virtual states of the nuclei whose atomic number and

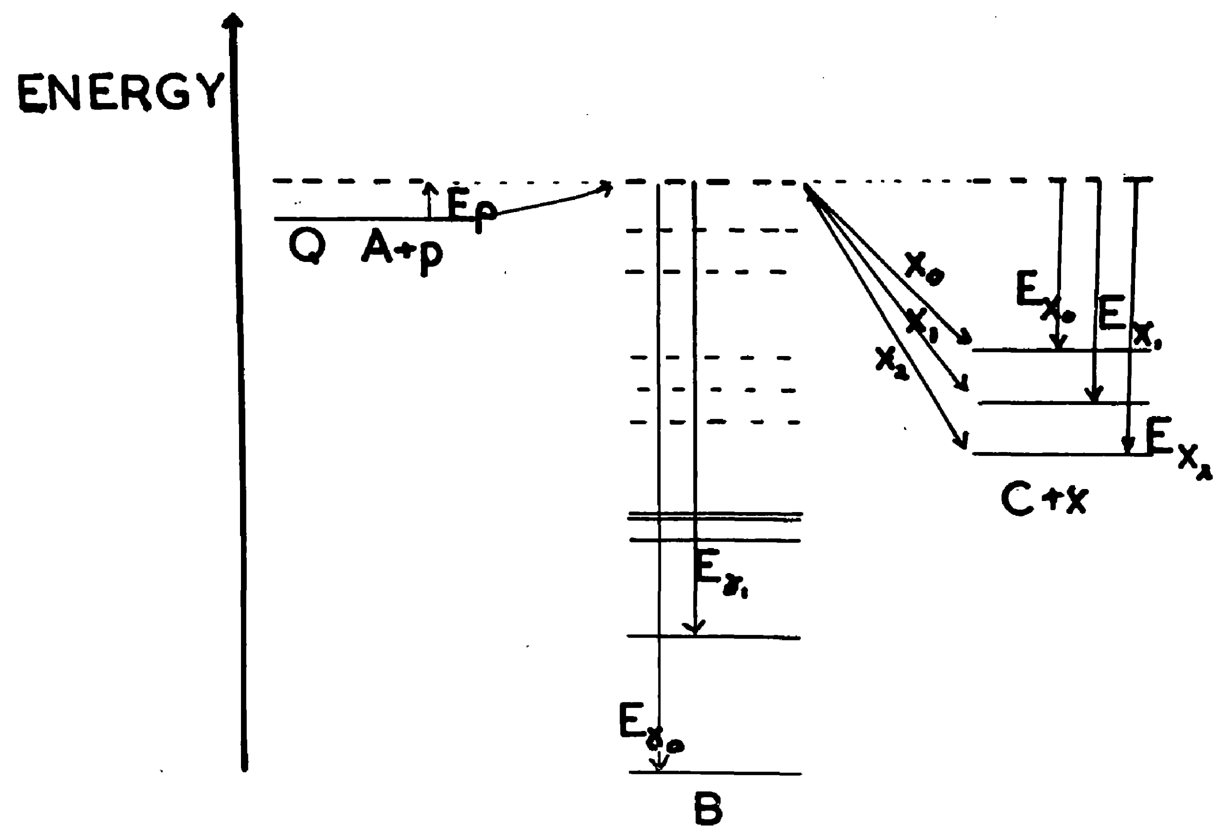


Fig. I.1. An energy level diagram for the reactions $A(p,\gamma)B$ and $A(px)C$.

weight are both one unit greater than those of the target nuclei. The virtual states, which are formed in this way, de-excite by emitting nucleons or γ-rays. The whole reaction may be described schematically as follows:-

$$
{}^{A}_{z}A + {}^{1}_{1}p \longrightarrow {}^{A+1}_{z+1}B^{*} \begin{cases} \longrightarrow {}^{A}_{z}A + {}^{1}_{1}p \\ \longrightarrow {}^{A+1-x}_{z+1-y}C + {}^{x}_{y}X \\ \longrightarrow {}^{A+1}_{z+1}B + \gamma \end{cases}
$$

Such a reaction can also be portrayed by an energy level diagram like the one that is shown in fig. I.1. This can be interpreted as meaning that a proton with kinetic energy E_p will be absorbed by the nucleus A to form a virtual state with energy E_{γ_0} in nucleus B, which is called, "the compound nucleus". This level has excess energy and so is unstable. The energy may be lost by emitting a proton with energy E_p^1 and leaving the nucleus A with an energy E_A such that $E_p = E_p^1 + E_A$, in which case the original proton is said to have been scattered by nucleus A. Alternatively the energy may be lost by the emission of a γ-ray with energy E_{γ_0}, or a series of γ-rays whose energies total to E_{γ_0}. In this case one has a (p,γ) reaction. Finally the state may emit a particle x to form a nucleus C. Such a reaction is called a (p,x) reaction.

If the Q of the (p,γ) reaction is defined as the energy difference between a system that consists of a stationary proton situated at an infinite distance from the nucleus A, and another system in which nucleus B is in its ground state, then $E_{\gamma_0} = Q + \frac{M_A}{M_B} E_p$ where M_A and M_B are the masses of nuclei A and B. In general $M_A \doteqdot M_B$ to make $E_{\gamma_0} = Q + E_p$ as is shown in fig I.1.

In most (p,γ) reactions one finds that Γ_p (the partial width for emission of the proton) is very much greater than Γ_γ (the sum of the partial widths for the emission of γ-rays). If Γ_x is zero, as is usually the case when $E_p < 1$ Mev., then Γ_p is very nearly the total width of the level.

Breit and Wigner (1936) derived a formula for the variation with energy of the cross-section for reactions in which a compound nucleus is formed. This formula is known as a dispersion formula and has the following form in the region where E_p is near E_R:-

$$\sigma_{(E_p)} = \frac{\lambda^2 \omega \Gamma_p \Gamma_\gamma}{2\pi[(E_p - E_R)^2 + \frac{1}{4}\Gamma^2]}$$

where

λ is the de Broglie wave length of the proton

ω is a factor involving the change in angular momentum.

This cross-section will have a maximum value at $E_p = E_R$. This maximum in the excitation function is called a resonance and E_R is the resonance energy.

When this cross-section is integrated over values of E_p near E_R one obtains the thick target yield "Y". For reactions where $\Gamma_p \doteq \Gamma$ one obtains the following value:-

$$Y = \frac{h^2 \omega \Gamma_\gamma}{4 M E_R \varepsilon}$$

where

ε is the energy loss per target nucleus in material A for a proton with energy E_R

M is the reduced mass of the proton viz. $M = \frac{M_A \cdot M_p}{M_A + M_p}$

Y is the yield in γ's per proton.

Thus the excitation curve for a (p,γ) reaction that proceeds through a compound nucleus should show resonances. The widths of the resonances are measures of the probability of decay of the level, and the thick target yield gives a measure of the partial width for γ-emission of the level.

It can be shown that the γ-rays resulting from a (p,γ) reaction have angular distributions with respect to the direction of the beam of protons which are functions of the nuclear parameters involved. The main parameters are the spins of the energy states, the multipoles that are present in the γ-radiation, and the angular momentum of the proton with respect to the target nucleus at the time of impact. Since angular momentum and parity must be conserved in the reaction only certain values of the parameters are allowed. The following selection rules form a summary of the position:-

(i) $S + \ell \geqslant j_R \geqslant |S - \ell|$

where $\vec{S}$ is the vector sum of the spins of the proton and target nucleus i.e. $S = j_I \pm \frac{1}{2}$

$\vec{\ell}$ is the angular momentum carried in by the proton

$\vec{j}_R$ is the spin of the resonance level.

(ii) $j_R + L \geqslant j_F \geqslant |j_R - L|$

where $\vec{j}_F$ is the spin of the final state and $\vec{L}$ is the angular momentum carried off by the γ-ray.

(iii) $\pi_I \pi_R = (-1)^{\ell}$

where π_I and π_R are the parities of the initial and resonance states

(iv) $\pi_R \pi_F = (-1)^L$ for Electric transitions

$\pi_R \pi_F = (-1)^{L+1}$ for Magnetic transitions

where π_F is the parity of the final state.

Transitions are said to be Electric when the electric vector is in the plane of the proton direction, and Magnetic when the two are at right angles.

For any given combination of j_I, j_R, j_F, π_I, π_R, π_F these selection rules will usually permit more than one value for each of S, ℓ and L. In practice it is found that as

ℓ increases the probability for the absorption of the proton decreases due to momentum barrier effects. Since rule (iii) makes two units the minimum difference between possible values of ℓ, only the lowest possible value need be considered.

Similarly, only the lowest permitted value of L needs to be considered since the probability of decay by the emission of a γ-ray with multipole order L is roughly proportional to $\left(\frac{2\pi R}{\lambda}\right)^{2(L-1)}$ for Electric transitions and $\left(\frac{R}{\lambda}\right)^{2L}$ for Magnetic transitions where R is the radius of the nucleus and λ is the wavelength of the γ-ray ($\lambda = \frac{h}{E}$). However, $E_{2(L+1)}$ transitions may compete with M_{2L} transitions.

As one would expect the angular distributions are symmetrical about the direction of the incident proton, and they may be analysed in terms of Legendre polynomials of the angle between the directions of the γ-rays and the protons. The exact forms of the angular distributions for cases where all the levels are discrete have been tabulated by Sharpe et alia (1953), who have shown that the permitted orders of the Legendre polynomials are given by:-

$$\max\left(\ell-\ell^1,\ L-L^1,\ j_R-j_R^1\right) \leqslant k \leqslant \min\left(\ell+\ell^1,\ L+L^1,\ j_R+j_R^1\right)$$

where the dash signifies the values for competing transitions.

The parities of the levels do not appear explicitly in the expressions for the angular distributions of the γ-rays. Thus it is impossible to distinguish between Electric and Magnetic transitions by measuring the distributions of the transitions. Some device, which is sensitive to the polarisation itself must be used to distinguish between the two cases.

No knowledge of the nature of the forces between nucleons is necessary to predict the resonant nature of the excitation curve for (p,γ) reactions or the angular distributions of the γ-rays. These can be deduced from the fact that the nucleons must obey the laws of Quantum Mechanics. However, the energies and spins of the excited states of nuclei, or the exact relative intensities of the different multipole orders of γ-radiation present in a transition, can only be obtained from a detailed theoretical study of the system using the correct form for the interaction between the nucleons. So far no theoretical treatment has predicted these quantities correctly. The shell model of the nucleus which identifies the nuclear energy levels with those of a set of nucleons in a spherical potential well has had some success in predicting the spins of the ground states of nuclei. By applying the Pauli exclusion principle to limit the number of nucleons with a given energy, and by filling the energy levels of single nucleon in the spherical well potential from the bottom, this treatment produces a result similar to the "Fermi sea" of electrons in a metal. The excited states of the nucleus are visualized as being states in which the most energetic nucleon is raised to one of the higher levels. For this reason levels which fit such a picture are called single particle levels.

A modification of this treatment, in which the coupling between this single nucleon and the rest of the nucleus is allowed to have spin-dependent terms, and the core is allowed to undergo distortions such as vibrations or rotations, has had some success in predicting the properties of the energy levels of nuclei with $A > 20$. The main result of such a treatment is that it predicts the existence of additional approximate quantum numbers which describe the amounts of these distortions that are present. These quantum numbers, if they have any meaning, should have selection rules which govern the permitted changes in them for electromagnetic transitions between the energy levels. Thus the measurement of the intensities of the γ-rays that correspond to transitions between levels, whose other parameters are known, should show whether these new selection rules are needed. An example of this treatment has been given by the theoretical predictions of Alaga et alia (1955) for ^{25}Al. and the experimental studies of Varma (1956).

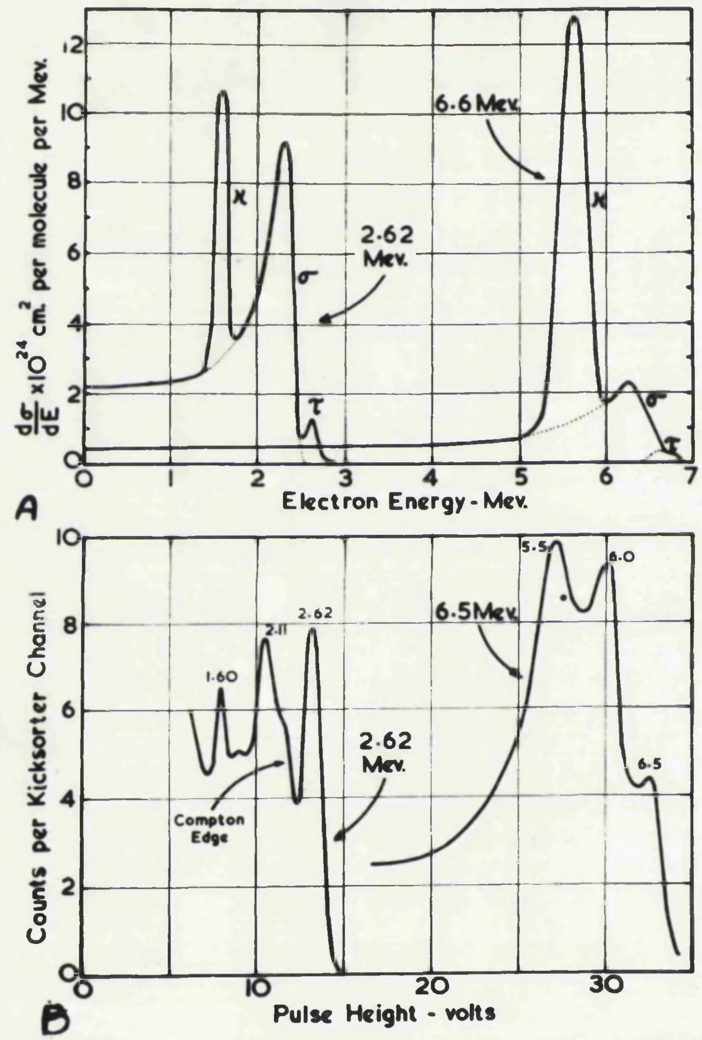
(b) Experimental Techniques.

In the experimental study of (p,γ) reactions there are six measurements that can be made, viz. the energies of the resonances in the excitation curve: the widths of the resonance levels: the partial widths of the levels for γ-ray emission: the energies of the γ-rays which are produced: the angular distributions of the γ-rays; and finally the polarisation of the γ-rays. It is usual to find that a particular technique is only suitable for measuring a few of these quantities with any high degree of precision. For this reason people have tended to concentrate on measurements of a particular type.

The excitation functions of (p,γ) reactions have been measured by a number of workers e.g. Tangen (1946). The essential feature of this type of measurement is that the energy of the protons must be known and controllable to within small limits (say $\doteqdot$ 0·1 Kev.) This is achieved by producing a very homogenious beam of protons in an accelerator and then passing it through a system of narrow slits in a carefully calibrated magnetic field. Since a magnetic field causes the protons to travel in the circles given by radius $\rho = \frac{p}{He}$, where p is the linear momentum, H the magnetic field, and e the charge on the proton, only protons with the correct momentum will pass through the system of slits. The proton beam is then allowed to strike a target inside a Faraday cage so that the total charge carried by the proton beam may be measured. The number of protons that strike the target can be deduced from this measurement of the charge. The γ-rays produced in the target by the beam are detected by a Geiger counter or some similar detecting device, and the variation with proton energy of the ratio of γ-rays produced to protons incident is noted.

The measurement of the thick target yields and the energies of the γ-rays does not require such careful control of the energy of the beam of protons unless the resonances are very close together. As the normal separation of energy levels in this region of a nucleus is $\geqslant$ 10 Kev. an accuracy of 1 Kev. is sufficient. Often a maximum accuracy of $\pm$ 5 Kev. will not be a severe handicap. Of greater importance is some means of measuring the γ-ray energy to the required degree of accuracy. Several techniques have been used for this purpose, but only two have had any reasonable degree of success. The first is the scintillation counter in which the γ-rays are allowed to pass through a material like $NaI_{(Th)}$. Some of the γ-rays interact with the electrons in the material and transfer energy to these electrons. The electrons in turn lose the energy to the rest of the substance which then radiates the energy as visible light onto the cathode of a photomultiplier. There a pulse of photo-electrons is produced which is multiplied by acceleration onto a series of secondary emission electrodes. The electrical pulse from the photo-multiplier is proportional to the energy of the electron, which was released in the NaI $_{(Th)}$, and can be measured by electrical means.

There are three types of interaction between γ-rays and electrons each of which produces a different distribution of energy among the electrons. The γ-ray may eject an electron from an atom by the photo-electric effect so that the electron is given almost all the energy of the γ-ray. The small difference between the energies of the γ-ray and the electron is the binding energy of the electron in its atomic orbit. Another type of interaction can take place between a free, or very loosely bound, electron and the γ-ray. This process is called Compton scattering and may be visualized as an elastic collision between the photon and the electron. In such a collision the energy that is transferred will depend on the angle that the electron recoil direction makes with the direction of the incident γ-ray. The energy varies between $\frac{2\ E_{\gamma}^{2}}{m_o c^2 + 2E_{\gamma}}$ when the electron goes forward, and zero when the electron goes at right angles to the γ-ray direction. The remaining energy is released in the form of a γ-ray in the direction that allows the conservation of linear momentum. The third type of interaction is



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.2. A comparison of the theoretical and experimental spectra from γ-rays in $NaI_{(Th)}$ by Griffiths (1955).

that in which the γ-ray produces an electron-positron pair and transfers all its energy to them. The kinetic energies of the pair will only total $E_\gamma - 2m_oc^2$ because of the rest mass energy that is required to produce them.

The final energy distribution in the electrons that have interacted with a γ-ray will depend on the energy of the γ-ray since the cross-sections of all three processes vary with energy. Fig. I.2 shows these energy distributions for γ-rays of 2·6 Mev. and 6·6 Mev. Since the cross-section for the pair production process is zero for energies below $2m_oc^2$ (i.e. 1·1 Mev) low energy γ-rays only produce photo-electric peaks and Compton recoil spectra.

As fig I.2 demonstrates, the pulse height spectra obtained from an actual crystal do not agree exactly with these theoretical predictions. The differences are easy to explain, however, in terms of the finite size of the crystal. Some of the electrons will escape from the sides of the crystal and so will lose part of their energy in non-scintillating material. This will have the effect of broadening out the peaks in a spectrum and smoothing out the high energy region of the Compton continuum. Another effect becomes apparent at energies where pair production is important. The simple treatment given above suggests that a single peak corresponding to an energy of $E_\gamma - 2m_oc^2$ should be all that is produced by pair formation. The extra energy ($2m_oc^2$) is released in the form of two 0·505 Mev. γ-rays when the positron annihilates. If one of these γ-rays is stopped in the crystal by interaction with an electron the total energy release is $E_\gamma - m_o c^2$, and if the two 0·505 Mev. γ-rays are both stopped the energy pulse in the crystal has a value of E_γ Mev. Thus pair production produces three peaks at E_γ, $E_\gamma - m_o c^2$ and $E_\gamma - 2m_o c^2$ respectively. Similarly the Compton scattered γ-ray may be stopped in this crystal so that the total energy released is $\doteq E_\gamma$.

It is clear that the pulse height spectrum produced by mono-energetic γ-rays is complicated if the energy of the γ-rays is greater than 1 Mev. This makes the analysis of a spectrum, which has been produced by γ-rays of several different energies, rather difficult. To some extent this difficulty can be reduced by measuring the shapes of the spectra produced by γ-rays whose energies are known. The energies of the unknown γ-rays can then be deduced from the positions of the peaks that they produce. The shapes of the spectra that are produced by such γ-rays can then be deduced by interpolation between the shapes of the spectra produced by known γ-rays of similar energies. Results have been reported recently of some measurements that have been made with crystals of NaI 5 inches long and 5 inches in diameter. Suitable collimation of the γ-rays going into these crystals produces spectra which have only one peak for each energy of γ-ray. This is a vast improvement, and makes experiments which were extremely difficult become fairly easy.

Because the crystal and photomultiplier can be moved freely from one position to another the scintillation counter is very useful for measuring the angular distributions of γ-rays. No great difficulty is experienced in measuring the rates of coincidences between cascade γ-rays with scintillation counters, because the pulses from the counters can be made extremely short, i.e. $< 1\ \mu$ sec. This allows the measurement of the angular correlations between successive γ-rays.

It is possible to measure the energies and intensities of γ-rays by another technique. This uses a thin foil to convert the γ-ray energy into the kinetic energy of an electron by providing a material in which the γ-ray can interact with an electron by photo-electric effect, pair production, or Compton effect. The energy of the electron is then measured by finding its radius of curvature in a magnetic field. If the electron is produced by the ejection of a photo-electron from an atom then its energy is independent of the angle of projection. However, the energy of an electron that has undergone a Compton collision with a γ-ray varies with the angle between the electron and γ-ray so that only those electrons which come out in a specified direction (usually forwards) are observed in this case. Since the distribution of the energy between the electron and positron produced by pair formation can vary, the energies of both particles must be measured. This requires a coincidence arrangement as well as a magnetic spectrometer. Thus it is clear that a magnetic spectrometer will usually only measure a very few γ-ray energies at a time, i.e. it has a low efficiency. Its main advantage, however, is that its energy resolution can be $\doteqdot$ 1 part in 10^4 as against the 1 part in 10^2 of the best scintillation counters. Because the magnet is large and heavy magnetic spectrometers are rarely used to measure angular distributions.

Although the Compton effect is sensitive to the polarisation of the γ-ray no successful measurements of γ-ray polarisations have been reported in which this technique was used. A better method is to study the photo-disintegration of Deuterium. The protons produced in this reaction have a tendency to come off in the plane containing the Electric vector. Hughes and Grant (1954) have loaded photographic emulsions with heavy water (D_2O) and have studied the tracks left by the protons in the emulsions. The energy resolution that can be obtained with this technique is comparable with that of the scintillation spectrometer, but the efficiency for the detection of γ-rays is extremely low. As the cross-section for the photo-disintegration of Deuterium has a threshold at 2·23 Mev. only the polarisation of high energy γ-rays can be measured in this way.

I. 3 REACTIONS PRODUCED BY DEUTERONS.

(a) Theory.

As has already been stated the deuteron has a very loosely bound structure and spends a large fraction of time with the constituent neutron and proton outside the range of the nuclear forces between them. Moreover, the binding energy of the deuteron is only 2·23 Mev. as compared with the binding energies of $\doteqdot$ 8 Mev. per nucleon in heavy nuclei. It is not surprising, therefore, that the deuteron appears to break up before interacting with a nucleus so that only one of its constituent particles actually interacts with the nucleus.

This idea was put forward by Oppenheimer and Phillips (1935) and Bethe (1935) to explain the fact that deuterons with low energies appeared to have usually large cross-sections for interacting with light nuclei. In 1950 some workers at Liverpool University found that, when targets were bombarded with deuterons with 8 Mev. energy, protons were released with very anisotropic angular distributions. These results were explained by the theory produced by Butler (1951) in which the neutrons of the deuterons were considered to be stripped off by interaction with the target nucleus. The interaction was visualized as taking place at the surface of the target nucleus. This made the process of fitting together the wavefunction of an incident beam of deuterons and the wavefunctions of the captured neutrons plus the emerging protons at this boundary seem reasonable. The theoretical angular distributions produced by this treatment contained two parameters which were the radius of this spherical surface, viz. R, and the angular momentum in units of $\hbar$ of the captured neutron, viz. ℓ.

A quite different approach by Bhatia et alia (1952) used the Born approximation to treat the problem. This produced angular distributions, which were very similar in form to those described by Butler, containing two parameters that corresponded to R and ℓ. It has been shown that both treatments are fundamentally the same, so a full discussion of one will cover the essential details of the other. The angular distributions, which are obtained by using Bhatia's treatment, are more easily interpreted in physical terms, so this treatment is more suitable to describe.

According to Bhatia the cross-section for a (d,p) reaction is:-

$$\sigma_{\theta} = \Pi_{(K_b)} \sum_{\ell_n} P_{\ell_n} \; L_{\ell_n}(kR)$$

where K_b is the wave number of the proton in the deuteron

k is the wave number of the captured neutron

$\ell_n \hbar$ is the angular momentum of the captured neutron

R is the radius of the target nucleus.

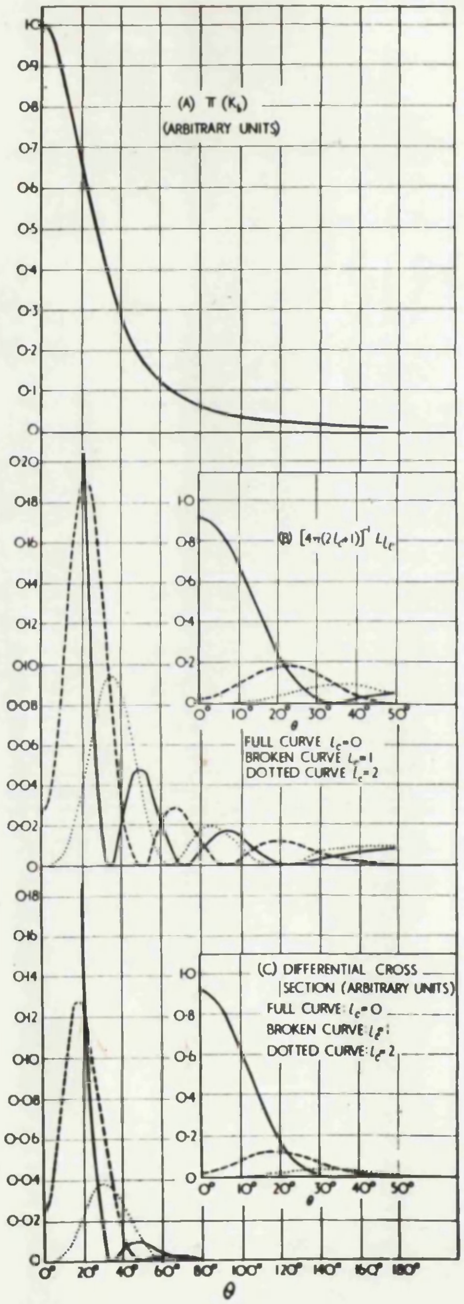


Fig. I.3. The variation with angle of $\Pi_{(K_b)}$, L_{l_n} and σ as calculated for E_D = 6·9 Mev, E_p = 10·8 Mev. by Huby (1953). The insets show the same curves on a smaller scale.

The first term in this expression for σ is the probability of finding the proton in the deuteron with the correct wave-number. This term is dependent on the angle at which the proton finally emerges. $P_{\ell n}$ is the probability that a neutron, which strikes the target nucleus with the correct energy and angular momentum, will be absorbed. This probability is independent of the angle between the proton direction and the deuteron direction. Finally, $L_{\ell n}$ (kR) is a kinetic factor which gives the probability of the neutron having the correct momentum and angular momentum at the surface of the target nucleus. L is an oscillating function of Θ with the analytical form of a Bessel function. Fig. I.3 shows the shapes of $\Pi_{(K_b)}$, L_{1n}(kR), and σ as functions of Θ for different values of ℓn. The target nucleus is presumed to give a value for R of $7\cdot0 \times 10^{-13}$ cms while $E_D = 6\cdot9$ Mev. and $E_p = 10\cdot8$ Mev. respectively.

From the form of the expression for σ it is clear that the cross-section increases smoothly as the energy of the deuteron increases and that there are no resonances in the excitation function.

In (d,p) reactions, as in all other nuclear reactions, angular momentum and parity have to be conserved and so the following expressions must be true:-

minimum of $|J_A \pm J_B \pm \tfrac{1}{2}| \leqslant \ell_n \leqslant J_A + J_B + \tfrac{1}{2}$

and $\Pi_A \; \Pi_B = (-1)^{\ell_n}$

	Good Fit	Good Fit with Isotropic Background	Poor Fit	No Fit
Independently Confirmed	33	12	9	2
Unconfirmed	21	8	12	10

Table I.1. An analysis of reactions produced by deuterons with >3 Mev. energy showing the agreement between the angular distributions, as calculated from the theories of Bhatia and Butler, and the experimental observations.

where J_A, Π_A, J_B, Π_B are the spins and parities of the initial and final states respectively.

If the spin and parity of the initial level are known and ℓ_n has been deduced from the shape of the angular distribution, one can evaluate Π_B and put limits on the possible values of J_B. The importance of such measurements lies in the fact that the final states are bound states of the product nucleus. Thus stripping reactions provide the only direct means of measuring their spins and parities since other reactions involve higher virtual levels in the nucleus or in a compound nucleus.

Both Bhatia's and Butler's treatments of stripping reactions neglect the effects of the Coulomb barrier, and so they should only be expected to give an accurate description when the deuteron has more than $\doteq$ 3 Mev. of energy. Table I.1 shows an analysis of the experiments, which had been reported up to the end of 1955, using deuterons in the region of energies between 3 Mev. and 20 Mev. This table was compiled by examining the experimental angular distribution curves. Those curves for which the theoretical distributions fitted the experimental points within small errors were called "good". Those in which the errors were large or the fit was not nearly so good were called "poor". A number of cases gave good agreement between theory and experiment when an isotropic component was subtracted from the results of the latter, and these cases are grouped together. Finally there was a group of results for which no theoretical curves gave agreement with the experimental points. For the sake of comparison the cases where both the spin and parity of the final level were known from other experiments, and so only one value of ℓ_n was allowed, have been grouped together.

From this table one can conclude that the theory is a reasonable description of the basic features of the process that is involved in (d,p) reactions. The fairly large percentage of cases, in which an isotropic component must be subtracted from the experimental angular distributions, suggests that some features of the interaction are not covered by these theories. This is confirmed by the small, but not insignificant, number of cases where the theory does not describe the experimental results at all. A closer examination of the problem shows that two assumptions were made in the theory and that either of these assumptions may be invalid for particular cases. It is assumed that no other mode of interaction competes to an appreciable extent, and that the Coulomb barrier has no effect on the angular distributions.

The fact that protons and alpha particles are absorbed to form compound nuclei suggests that some (d,p) reactions may involve the formation of a compound nucleus. Those (d,p) reactions, which do proceed via a single level in a compound nucleus, will produce a proton angular distribution which is symmetrical about the direction at 90° to the deuteron beam. As the absorption of a deuteron produces a level at $\sim$ 16 Mev. in the compound nucleus and as there may be considerable overlapping of levels in this energy region, the net angular distribution may be isotropic. If stripping and compound nucleus formation are incoherent their angular distributions will add arithmetically. However, if they are coherent, interference terms will appear in the angular distributions and these may be expected to have a form like $\sqrt{S_{(\theta)}\, C_{(\theta)}}$ where $S_{(\theta)}$ and $C_{(\theta)}$ are the undisturbed distributions from stripping and compound nucleus formation. No reliable theoretical estimates have been made of the relative values of the stripping and compound nucleus cross-sections. At low deuteron energies the (d,p) reactions should have $\sigma_{\text{stripping}} \gg \sigma_{\text{compound nucleus}}$ while the (d,n) reactions should have $\sigma_{\text{stripping}} \leq \sigma_{\text{compound nucleus}}$ according to Bethe (1935) and (1937).

The effect that the Coulomb barrier will have on the angular distributions is still a matter of dispute. A paper by Grant (1955) showed that the only effects were to broaden the peaks and to shift them to slightly higher angles. On the other hand Tobocman (1955) suggested that large distortions could be produced in the angular distributions by the scattering of the incident deuteron and the emergent proton by the Coulomb barrier. Unfortunately the angular distributions produced by this treatment of the problem require the use of a computer for their numerical evaluation. Two other papers by Ter-Martirosyan (1955) and Biedenharn et alia (1957) tend to confirm that, where the height of the Coulomb barrier is large compared to the energy of deuteron, major distortions are produced in the angular distributions of the protons.

De Borde (1955) suggested a treatment of the problem, which may prove of value. Since the S-Wave deuterons can be considered to approach closest to the nucleus the effect of the barrier on them will be more pronounced than the effects on deuterons with higher angular momenta. If the effects on the latter are ignored then the Coulomb barrier will produce an S-Wave phase shift. This alters the cross-section as follows;-

$\sigma_{(\theta)}$ was equal to $I^2_{(\theta)}$ but now

$$\sigma_{(\theta)} = (I_{(\theta)} + Ae^{-i\delta})^2 = I^2_{(\theta)} + (2\ A \sin\delta) \times I_{(\theta)} + A^2$$

The calculation of the constants A and δ for any particular (d,p) reaction is laborious and involves assumptions about various nuclear parameters, e.g. P_{l_n} in the formula for $I^2_{(\theta)}$, which may well be quite wrong. However, the values of δ that correspond to any particular channel spin for the incoming deuteron will be the same for all groups of protons coming from nuclei of a particular isotope. If the spin of the target nucleus is zero only one value of

the channel spin is involved and so only one value of δ.
Thus by studying the angular distributions of protons coming from (d,p) reactions in nuclei with zero spin one should be able to tell whether this particular approximation is justifiable.

It is interesting to calculate the distortion that an S-Wave phase shift will produce. The turning points in a plot of σ against θ are given by $2I_{(\theta)}I^{1}_{(\theta)} = 0$, and it can be shown that $I_{(\theta)} = 0$ gives minima while $I^{1}_{(\theta)} = 0$ gives maxima. On the new formula the turning values are given by $2I^{1}_{(\theta)}\,(I_{(\theta)} + A\sin\delta) = 0$, i.e. the positions of the maxima are unaltered but minima are shifted. Moreover, the minimum value is increased from zero to $A^2(1-\sin^2\delta)$.

One important feature of the stripping process appears when one measures the angular distributions of the γ-rays by which the bound states de-excite. It has been shown by Satchelor et alia (1952) that these distributions are symmetrical about the direction in which the neutron is absorbed, i.e. $K_d - K_p$. Moreover they have the form which one would expect for the corresponding (n,γ) reaction. As the directions of the neutrons and protons are related, this determines the shape of the (p,γ) angular correlation. According to the compound nucleus theory, on the other hand, the angular correlations should be symmetrical about the direction of the deuteron beam. Thus one can tell which of the two processes is the more important by measuring the position of the axis of symmetry in the angular correlation.

(b) Experimental Techniques.

When deuterons interact with nuclei they cause the emission of protons, alpha-particles, neutrons and γ-rays. Both of the charged particles can be detected by the same means, while the γ-rays may be detected by any of the means described in section 1.2(b). As the detection of neutrons is a very specialised subject, which is not relevant to experiments, which are described in this thesis, it will not be discussed here. Thus only the proton spectrometers will be described.

The proton spectrometer with the best resolution is the magnetic spectrometer. In this instrument the protons are passed through a uniform magnetic field and their radii of curvature in the field are measured. As the radius of a particular proton's orbit is proportional to its momentum this device acts an energy analyser. It is possible to separate proton groups, whose energies differ by 1 part in 10^3 or less, with this spectrometer. In the past year or two magnetic spectrometers have been built, which can rotate round the target and measure angular distributions. The solid angle of acceptance is usually small, however, so that the angular correlations between protons and their cascade γ-rays are difficult to measure.

The photographic plate is widely used as a detector for protons. In these plates the tracks left by the protons, which slow down in the emulsion, are revealed by their property of blackening the emulsion as they lose their energy. A number of these plates can be placed at a series of angles to the deuteron beam and, as they are all exposed simultaneously, all difficulties of normalising the counting rates at different angles are avoided. The energy resolution obtainable with this spectrometer varies with energy but is usually ~ 5% with ~ 5 Mev. protons. The main disadvantage of this technique is the long time required to measure the tracks with a high powered microscope.

While proportional counters can be adapted to detect both neutrons and γ-rays they are mainly used in the study of charged particles. When so used they can be made relatively insensitive to neutrons and γ-rays. As the proportional counter is usually used outside the target chamber two gas-tight windows are needed to let the protons out of the target chamber and into the proportional counter. The energy that is lost in penetrating these windows gives a lower limit to the energy of particle that can be detected by this means. This energy can be as small as 1 Mev. if the windows are made of Mylar or Mica. The energy resolution of a proportional counter can be made to be ~ 4% for 5 Mev. protons. Thus it is better than the photographic plate but not as good as the magnetic spectrometer. There are two disadvantages inherent in a proportional counter. First it gives out a slow pulse and this severely limits its use in coincidence studies. The ratio of chance coincidences to real coincidences is directly proportional to the length of the pulse produced by each of the spectrometers used to detect the radiations. Secondly the fact that a proportional counter contains gas makes the length of the track of an 8 Mev. proton about 4 ft. Thus a counter which detected protons of all energies from 0 up to 8 Mev. would be very bulky. This difficulty can be overcome by inserting foils in the region between the counter and the target to reduce the range in the counter of the high energy protons. To measure the low energy protons one then needs an anti-coincidence arrangement of two counters. The final arrangement again becomes bulky and needs a certain amount of additional electronic equipment.

One of the most convenient means of detecting protons and measuring their energy is the scintillation counter. Because the scintillators are made of solid material the range of an 8 Mev. proton will only be $\sim 0{\cdot}1$ cms. Like the proportional counter a scintillation counter is most easily used outside the target chamber, but the whole energy range from 1 Mev. to 8 Mev. can be studied simultaneously by a device which is only as large as the photomultiplier.

The other advantage of the scintillation spectrometers is that the pulses are very short, indeed they are usually $< 0{\cdot}1$ μsec, so that they can be used in coincidence work. Various scintillators can be used although as will be described later CsI and plastic scintillator (i.e. solid organic) are best.

I. 4 SELECTION OF THE REACTIONS TO BE STUDIED.

At the time when the experiments that form the subject of this thesis were started the (p,γ) reactions in very light nuclei had already been widely studied e.g. by Devons and Hine (1949). These experiments had shown that the general properties of the reactions were well described by the type of phenomonological theory outlined in I.2. The extension of these results to nuclei of higher atomic number by Rutherglen et alia (1954) etc. was also nearing completion. These later experiments revealed that the transition probabilities did not vary with the multipole order of the γ-rays in the way that one would expect for transitions between single particle levels. As tentative ideas of additional quantum numbers and selection rules were being discussed it was important to obtain additional experimental information. One of the nuclei most suitable for investigation was ^{26}Mg where the Q-value for the reaction was known to be ~ 8 Mev. From these measurements we hoped to identify the spins and parities of the levels of ^{27}Al and to see whether additional selection rules were needed to explain the γ-ray intensities.

At the same time it was felt that independent confirmation of the spins and parities that had been assigned to various levels in light nuclei would be useful. The simplest way of obtaining this information was to study the (d,p) reactions which led to the formation of the levels in question, or to the formation of the corresponding levels in the mirror nuclei. Since the measurement of the angular distribution of a group of protons allows one to determine the parity of the level uniquely, but only allows limits to be put on the spins, some additional type of experiment was needed. The obvious one was a measurement of the angular correlation between the protons, which were emitted when the level was formed, and the γ-rays that were emitted when the level decayed.

It soon became obvious, however, that the mechanism of the (d,p) reactions had not been fully described by the theories then in existence. In particular the problems of the effects of the competing compound-nucleus-type reactions and the effects of the Coulomb barrier required investigation. With the energies of deuterons that were available each of these effects could be expected to be large. Subsequent experiments at higher energies as summarised in table I.1 have confirmed the importance of this investigation.

The first requirement of a suitable reaction was that the Q-value should be high and that the number of low-lying levels in the final nucleus should be small. Thus the first nucleus studied was ^{10}B which has the highest Q-value, yet observed, for its (d,p) reaction. Later the importance of the examination of target nuclei with ground state spin zero led to the study of the $^{24}Mg(d,p)^{25}Mg$ reaction which has a Q-value of 5·1 Mev.

TABLE II. 1 The resonance levels in the $^{26}Mg(p,\gamma)^{27}Al$ Reaction.

	Author			
Date	1954 to 1956			
Target Material	^{26}Mg			
Energy Region Examined	200 Kev. to 730 Kev.			
Measurement	Resonance Energy	Full Width (Γ)	Thick Target Yield	Partial Width ($\omega \Gamma_\gamma$)
Results	293 ± 1 Kev.	<1 Kev.	$5{\cdot}6\times10^{-11}$ γ's/Proton	$0{\cdot}03 \pm 0{\cdot}03$ e.v.
	338 ± 1 Kev.	$<1{\cdot}8$ Kev.	$28{\cdot}8\times10^{-10}$ γ's/Proton	$1{\cdot}5 \pm 0{\cdot}1$ e.v.
	454 ± 1 Kev.	$<1{\cdot}5$ Kev.	$68{\cdot}0\times10^{-10}$ γ's/Proton	$4{\cdot}2 \pm 0{\cdot}4$ e.v.
	659 ± 1 Kev.	$<4{\cdot}0$ Kev.	$24{\cdot}7\times10^{-10}$ γ's/Proton	$1{\cdot}7 \pm 0{\cdot}2$ e.v.
	726 ± 1 Kev.	$<2{\cdot}5$ Kev.	$15{\cdot}8\times10^{-10}$ γ's/Proton	$0{\cdot}85 \pm 0{\cdot}1$ e.v.

TABLE II. 1 The resonance levels in the $^{26}Mg(p,\gamma)^{27}Al$ Reaction.

	Tangen	Taylor et alia		Hunt et alia		Kluyver et alia
Date	1946	1952	1954	1952	1955	1954
Target Material	Nat Mg.	^{26}Mg.	^{26}Mg.	Nat Mg.	^{26}Mg.	^{26}Mg.
Energy Region Examined	250 Kev. to 500 Kev.	300 Kev. to 750 Kev.	300 Kev. to 750 Kev.	300 Kev. to 500 Kev.	300 Kev. to 500 Kev.	250 Kev. to 500 Kev.
Measurement	Resonance Energies	Resonance Energies	Resonance Energies	Resonance Energies	Resonance Energies	Resonance Energies
Results	290 ± 3 Kev.					300 Kev.
	314 ± 3 Kev.			$314 \cdot 8 \pm 0 \cdot 5$ Kev.		
	$336 \pm 1 \cdot 5$ Kev.	339 ± 10 Kev.	343 Kev.	$338 \cdot 5 \pm 0 \cdot 5$ Kev.	$338 \cdot 5 \pm 0 \cdot 5$ Kev.	340 Kev.
	338 ± 4 Kev.			$389 \cdot 4 \pm 0 \cdot 5$ Kev.		
	430 ± 4 Kev.			$436 \cdot 5 \pm 0 \cdot 4$ Kev.		
	451 ± 2 Kev.	449 ± 10 Kev.	450 Kev.	$454 \cdot 2 \pm 0 \cdot 3$ Kev.	$454 \cdot 2 \pm 0 \cdot 3$ Kev.	458 Kev.
	494 ± 5 Kev.			$484 \cdot 0 \pm 1 \cdot 0$ Kev.		
		660 ± 10 Kev.	662 Kev.			
		726 ± 10 Kev.	720 Kev.			

PART II. THE REACTION $^{26}Mg(p, \ )^{27}Al$.

II.1 INTRODUCTION.

Tangen (1946) was the first to report values of the resonance energies in the excitation curve of the $^{26}Mg(p,\gamma)^{27}Al$ reaction. He bombarded targets of natural Magnesium with protons with energies in the range 250 Kev. to 500 Kev. and he found the resonances which are detailed in Table II.1. Since he had no means available to determine the energies of the γ-rays produced at each resonance, he distinguished between the reactions in the isotopes ^{24}Mg and ^{25}Mg and the reactions in ^{26}Mg by the presence of positrons from ^{25}Al and ^{26}Al in the former. Table II.1 suggests that the weakness of the positron activity at some resonances led him to ascribe these resonances to the wrong reaction.

In 1952 Hunt et alia reported a repetition of the work of Tangen in the range of proton energies between 300 Kev. and 500 Kev. using much better energy resolution on the protons. Unfortunately no attempt was made to check the correctness of Tangen's assignment of the resonances to the reactions in the various isotopes. Also in 1952 came the first report of some studies of the reactions obtained when targets of isotopically pure ^{26}Mg were bombarded with protons in the energy range 300 Kev. to 750 Kev. These studies were carried out by

Taylor et alia (1952) and their results disagreed with those of Tangen and Hunt.

In the year that our examination of the reaction commenced, viz. 1954, some other results were reported of measurements of the resonances in this reaction. First Taylor et alia (1954) reported improved measurements of the resonance energies in a paper that was read to the American Physical Society. Unfortunately the abstract of the paper does not quote the probable errors in the measurements. In a description of the reaction $^{25}Mg(p,\gamma)^{26}Al$ Kluyver et alia (1954) gave values for three of the resonance energies for the reaction $^{26}Mg(p,\gamma)^{27}Al$, but the paper does not quote the accuracy of the measurements. Later Hunt et alia (1955) corrected the results of their earlier experiments by reporting measurements which had been made with a target of isotopically pure ^{26}Mg. The results of all these measurements are given in table II.1 along with the author's results for similar measurements.

None of these papers gives details of the γ-ray spectra that were obtained at the various resonances. There is no doubt that this is due to the methods of γ-ray detection, e.g. Geiger counters, that were used in these experiments and to the complexity of the γ-ray spectra.

Some measurements have been made by other workers.

659 Kev.	Isotropic	8·90 Mev.	8·90 ± 0·1 Mev.	8 ± 1
			8·05 ± 0·1 Mev.	8 ± 1
			7·90 ± 0·1 Mev.	100 ± 4*
			6·10 ± 0·1 Mev.	$^{19}F(p,\alpha,\gamma)^{16}O$
			5·20 ± 0·1 Mev.	89 ± 8
			3·60 ± 0·1 Mev.	29 ± 4
			2·80 ± 0·05 Mev.	54 ± 5
			1·00 ± 0·01 Mev.	100 ± 4
			0·85 ± 0·01 Mev.	66 ± 4
726 Kev.	Anisotropic	8·96 Mev.	9·0 ± 0·1 Mev.	45 ± 4 at 90°
			8·1 ± 0·1 Mev.	100 ± 9* "
			6·7 ± 0·1 Mev.	560 ± 50 "
			5·35 ± 0·1 Mev.	2620 ± 250 "
			3·70 ± 0·1 Mev.	870 ± 61 "
			2·75 ± 0·05 Mev.	1740 ± 150 "
			2·20 ± 0·03 Mev.	1020 ± 100 "
			1·40 ± 0·02 Mev.	350 ± 40 "
			1·00 ± 0·01 Mev.	1120 ± 100 "
			0·85 ± 0·01 Mev.	2100 ± 200 "

* This figure was adopted as the standard of comparison for γ-rays at a resonance. The relative intensities of the different resonances can be obtained from the cross-sections which are given in table II. 1.

TABLE II. 3 The energies and intensities of the γ-rays from the five resonances in the $^{26}Mg(p,\gamma)^{27}Al$ reaction.

Resonance			γ-rays	
Energy	Angular Nature	Excitation in ^{27}Al.	Energy	Intensity
293 Kev.	Isotropic	8·55 Mev.	8·55±0·1 Mev.	10± 1
			7·75±0·1 Mev.	100± 1*
			0·85±0·01 Mev.	100± 1
338 Kev.	Anisotropic	8·59 Mev.	8·60±0·1 Mev.	8± 1
			7·75±0·1 Mev.	100± 2*
			7·60±0·1 Mev.	32± 2
			6·15±0·1 Mev.	$^{19}F(p,\alpha\gamma)^{16}O$
			5·85±0·1 Mev.	56± 3
			5·60±0·1 Mev.	68± 3
			5·00±0·1 Mev.	101± 3
			3·60±0·05 Mev.	48± 2
			3·00±0·05 Mev.	57± 3
			2·80±0·05 Mev.	65± 3
			2·75±0·05 Mev.	20± 3
			2·25±0·03 Mev.	9± 3
			1·75±0·03 Mev.	35± 3
			1·00±0·01 Mev.	61± 5
			0·85±0·01 Mev.	150± 5
454 Kev.	Isotropic	8·70 Mev.	7·85±0·1 Mev.	100± 2*
			7·70±0·1 Mev.	10± 1
			5·95±0·1 Mev.	10± 1
			4·55±0·1 Mev.	16± 1
			3·95±0·1 Mev.	11± 1
			2·95±0·1 Mev.	3± 1
			2·70±0·1 Mev.	3± 1
			2·35±0·05 Mev.	$^{12}C(p,\gamma)^{13}N$
			1·75±0·03 Mev.	6± 1
			1·00±0·01 Mev.	22± 1
			0·85±0·01 Mev.	98± 1

TABLE II. 2 The energies of the γ-rays from some resonances in $^{26}Mg(p,\gamma)^{27}Al$.

Resonance	Casson 1953	Smith et alia 1954	Kluyver et alia 1954
338 Kev.	5·8 Mev 2·8 Mev.		
454 Kev.		5·9 Mev. 2·8 Mev. 0·8 Mev.	8·70 ± 0·20 Mev. 7·86 ± 0·20 Mev. 6·54 ± 0·20 Mev. 5·74 ± 0·15 Mev. 4·58 ± 0·15 Mev. 4·10 ± 0·15 Mev. 2·80 ± 0·10 Mev. 2·28 ± 0·10 Mev. 0·81 ± 0·05 Mev.
660 Kev.		8·5 Mev. 6·2 Mev. 2·8 Mev. 1·0 Mev. 0·8 Mev.	

Neither Casson nor Smith quote the probable errors of their measurements.

Casson (1953) identified γ-rays of 5·8 Mev. and 2·8 Mev. at the 338 Kev. resonance using a scintillation counter. Several γ-rays from the resonances at 454 Kev. and 660 Kev. were reported by Smith et alia (1954) in a paper to the American Physical Society. The abstract did not give details of the measurements. Kluyver et alia (1954)(b) reported a series of γ-rays from the 454 Kev. resonance. These measurements were made with a scintillation spectrometer and no attempt was made to estimate the intensities of the individual γ-rays. Table II.2 gives a complete summary of the results, while our experimental measurements are given in table II.3.

Since our work was completed the report of the Amsterdam Conference (1956) shows that Endt et alia have made measurements of the intensities and angular distributions of the γ-rays from all the resonances described in this thesis. While their results agree with most of ours it is not possible to comment on the discrepancies until a further report is published of their work. For comparison purposes figs. II. 8 (a) and (b) show the level diagrams for ^{27}Al, which are obtained from our results and Endt's respectively.

II. 2 EXPERIMENTAL PROCEDURE.

(a) The Measurement of the Excitation Curves.

The γ-ray spectrometer, which was used in these experiments, was a cylindrical crystal of $NaI_{(Th)}$, i.e. Sodium Iodide activated with Thallium, 2 inches long and $1\frac{3}{4}$ inches in diameter. The crystal had been packed in an air tight aluminium can with a glass window by the Harshaw Chemical Company and it was used in conjunction with a Du Mont 6292 photomultiplier. The pulses from the photomultiplier were fed by a cathode follower through an amplifier onto a pulse height analyser of the type designed by Hutchinson and Scarrott (1951).

The spectrometer was calibrated in the high energy region with the following γ-rays:- 8·0 Mev. from $^{13}C(p,\gamma)^{14}N$; 6·13 Mev. from $^{19}F(p,\alpha,\gamma)^{16}O$; 4·43 Mev. from $^{11}B(p,\gamma)^{12}C$ and 2·62 Mev. from ThC^{11}. In the low energy region the standard γ-rays, which were used, were the 1·28 Mev. from ^{22}Na; the 0·667 Mev. from ^{137}Cs and the 0·501 Mev. from the decay of the positron from ^{22}Na.

The protons were accelerated to the required energy by our High Tension Generator. They were passed through a magnetic field and slit system before being allowed to strike a target of 15 μ gms/cm^2 of ^{26}Mg on a backing of 0·010 inches of Copper which had been prepared at A.E.R.E. Harwell. The voltage scale of the accelerator was carefully calibrated against the well-known resonance at

340·4 Kev. in the reaction $^{19}F(p,\alpha,\gamma)^{16}O$ and checked at the 550 Kev. resonance in the reaction $^{13}C(p,\gamma)^{14}N$.

The pulses from the amplifier were fed to two discriminators as well as to the pulse height analyser. The bias voltages of these discriminators were adjusted to the levels at which only pulses, that corresponded to γ-rays of more than 6 Mev. and 0·5 Mev. respectively, were counted. The outputs of the two discriminators were then fed to two scalers.

The total number of counts, which were registered by each of these scalers when 2×10^3 micro-coulombs of charge were carried into the target chamber by the protons, were measured as functions of energy. The measurements were made at 5 Kev. intervals between 200 Kev. and 730 Kev. and then repeated at 1 Kev. intervals in regions where large fluxes of γ-rays were observed. The charge carried by the protons was measured by insulating the target chamber to form a Faraday cage and then allowing the charge, which had accumulated, to leak to earth through an electrometer. These measurements gave the thick target excitation curve in which the resonances appeared as flat-topped peaks. The difference between the number of counts registered by the lower discriminator at the top of the peak and just before the peak gave a measure of the thick target yield. This was corrected later to take into account the number of γ-ray pulses in the region below 0·5 Mev. and the fact that some γ-rays come from excited states below the resonance level. Corrections were also made for the efficiency of the spectrometer and the solid angle subtended by the crystal. The main error in these measurements of the thick target yields was caused by the probable error in the measurement of the current of protons that was incident on the target. It was estimated that this, plus the effects of Carbon films on the surface of the target, and instrumental errors, would amount to errors of about 5% to 10%.

By taking the differences between successive measurements made at 1 Kev. intervals the thin target or differential excitation curve was obtained. This gave the positions and widths of the resonances to within $\pm$ 1 Kev. Corrections were made to the widths of the resonances for the effects of the spread in the energy of the proton beam. This was estimated by comparing the observed width of the 340·4 Kev. resonance in $^{19}F(p,\alpha,\gamma)^{16}O$ with the correct width of 2·9 Kev. As this energy spread was = $\sim$1·5 Kev. it was felt that measurements with a thin target would not add to the information which had been obtained in this way.

The results of these experiments are given in table II.1, in which $\omega\Gamma_\gamma$ is given because of the doubt about the correct values to use for "ω". These values are expected to be approximately unity.

(b) <u>The Measurement of the Intensities and Angular Distributions of the γ-rays.</u>

Because the measurement of the angular distributions involved the measurement of the relative intensities of the different γ-rays at various angles, no separate measurements were made of the intensities of the γ-rays. The intensities that are quoted in table II.3 are the intensities which were obtained by integrating over the complete angular distributions.

Two crystals of $NaI_{(Th)}$, each of which was 2 inches long and $1\frac{3}{4}$ inches in diameter, were used in the measurement of the angular distributions of the γ-rays. The first crystal was held fixed at 90° to the direction of the beam of protons. The pulses from the photomultiplier were fed by a cathode follower to an amplifier. The output pulses from this amplifier were fed into a discriminator, whose bias level had been adjusted to reject pulses from γ-rays below 3 Mev. A timing unit was fed with the pulses, which were passed by the discriminator, and it was arranged that all the scalers etc. were stopped when this timing unit had received a preset number of counts (2×10^{6}).

Meanwhile the second crystal and its photomultiplier were held in a bracket which could rotate on ball-races round the axis of the target. The plane of rotation contained the direction of the beam of protons and a scale, which showed the angle relative to this direction, was

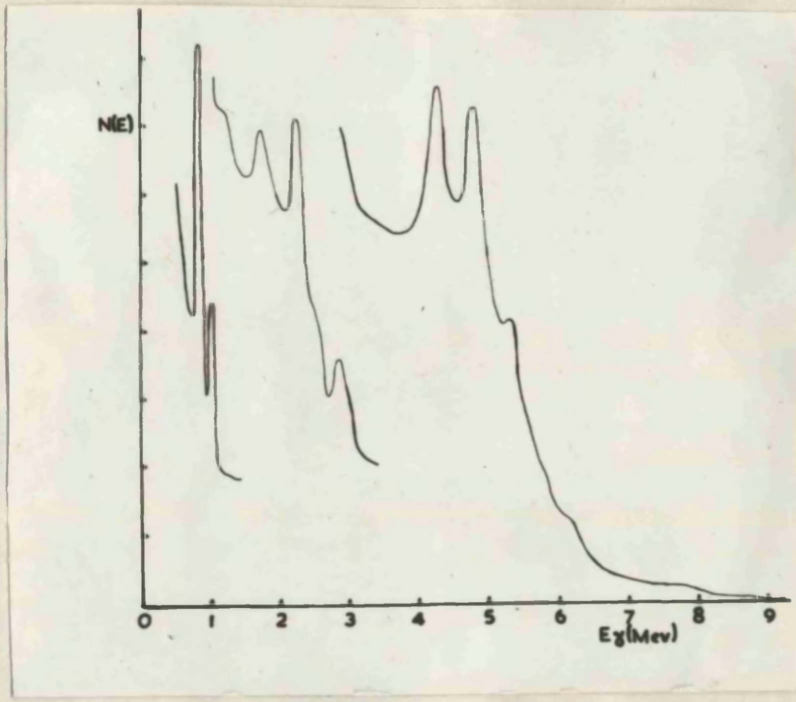
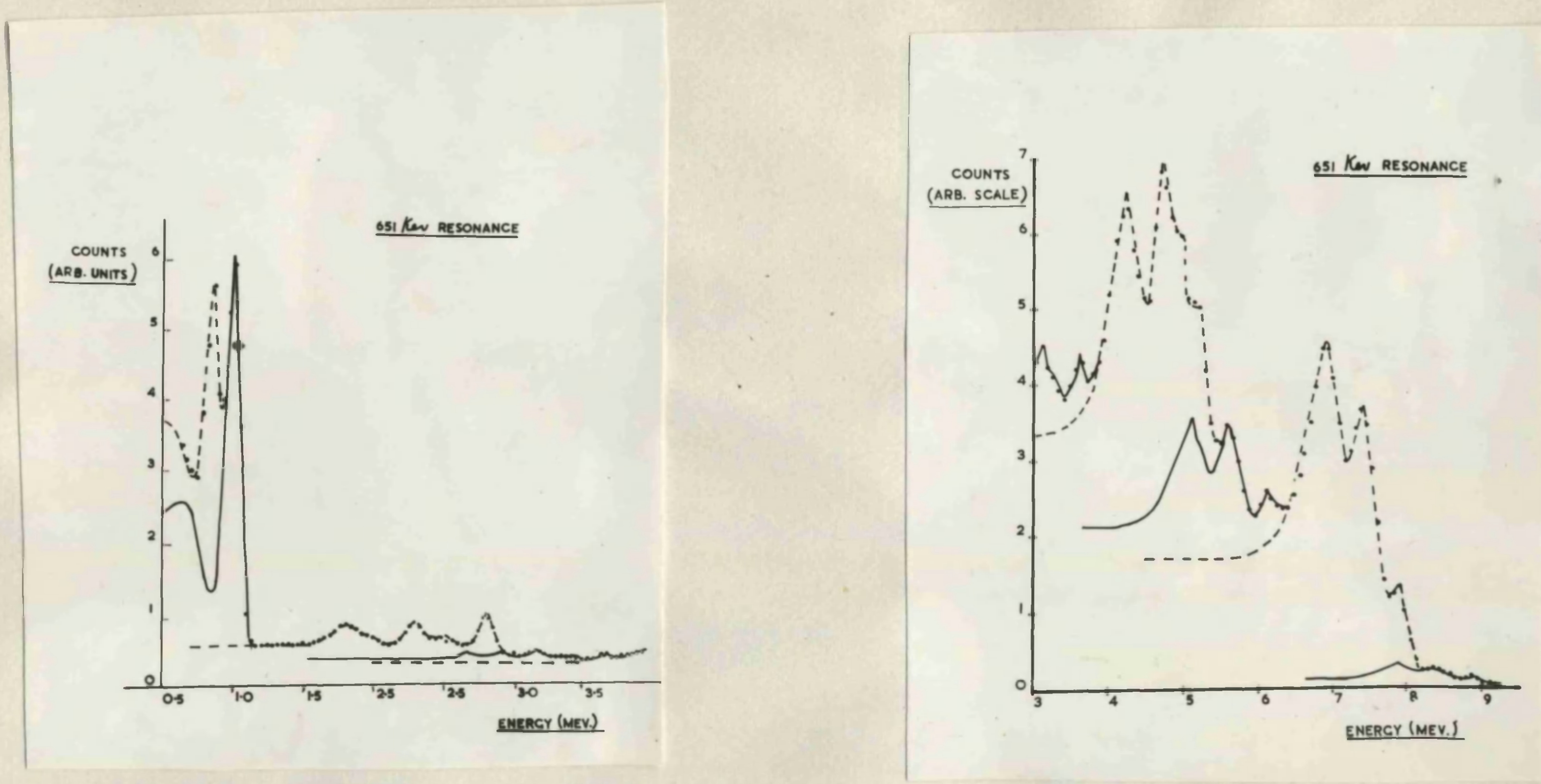


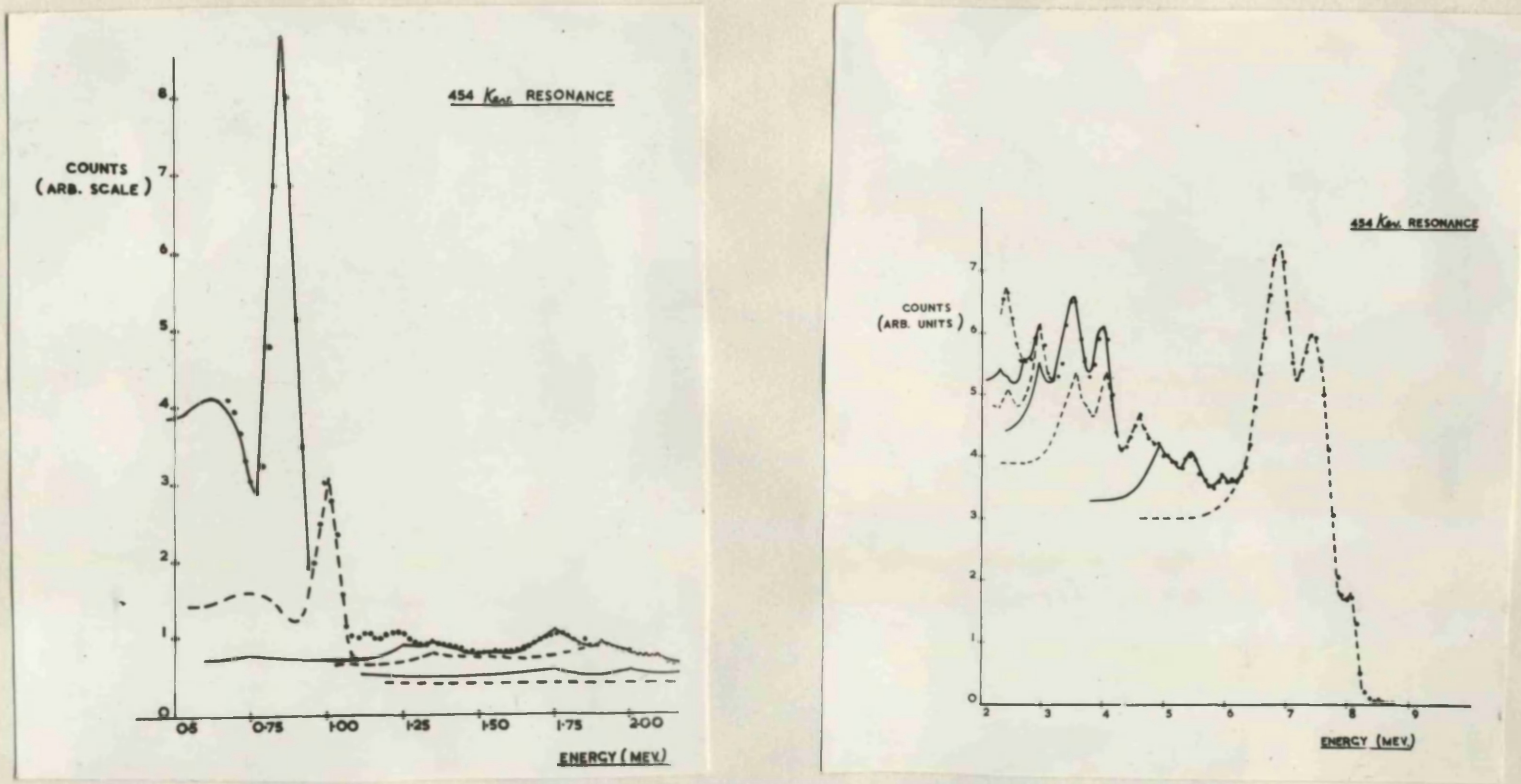
Fig. II. 5. The energy spectrum of the γ-rays from the 726 Kev.resonance. On the scale used the deviations of the points from the smooth curve are negligible and the statistical errors are $<$ 1%.



(a) (b)

Fig. II.4 (a) The energy spectra of the low energy γ-rays at the 659 Kev.Resonance and (b) the high energy γ-rays (90^{o} position).

The statistical errors in the points are = 1% for both spectra

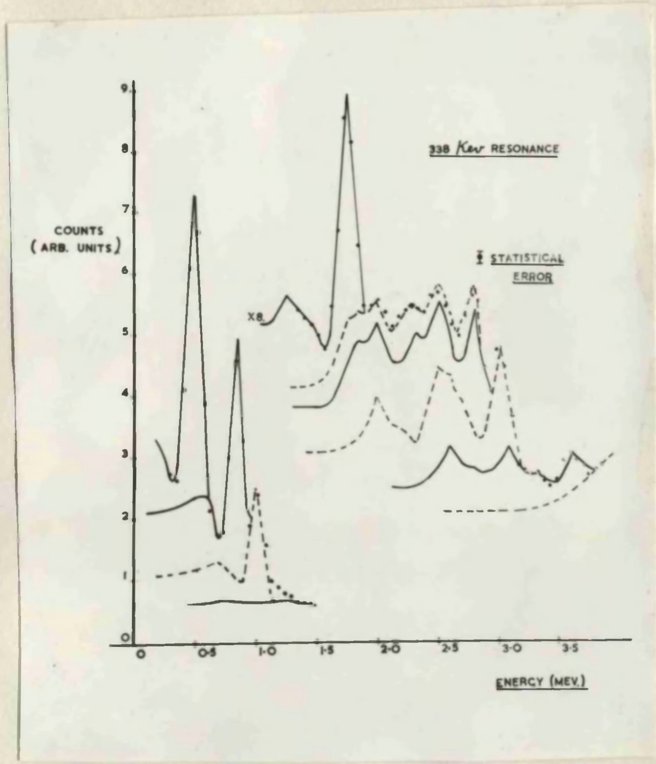


(a) (b)

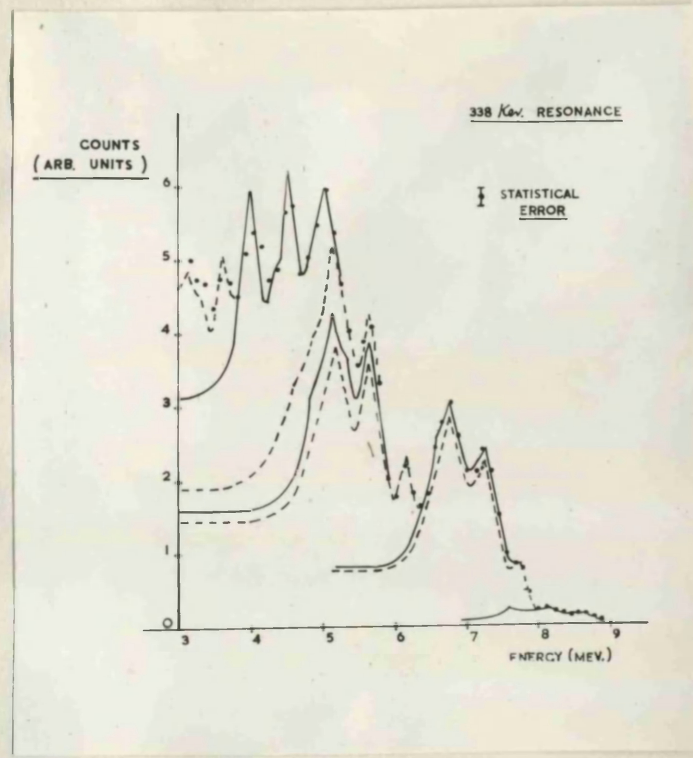
Fig. II. 3 (a) the low energy γ-rays at the 454 Kev. resonance, and

(b) the high energy γ-rays (90° position).

The statistical errors in the points are = 1% for both spectra.

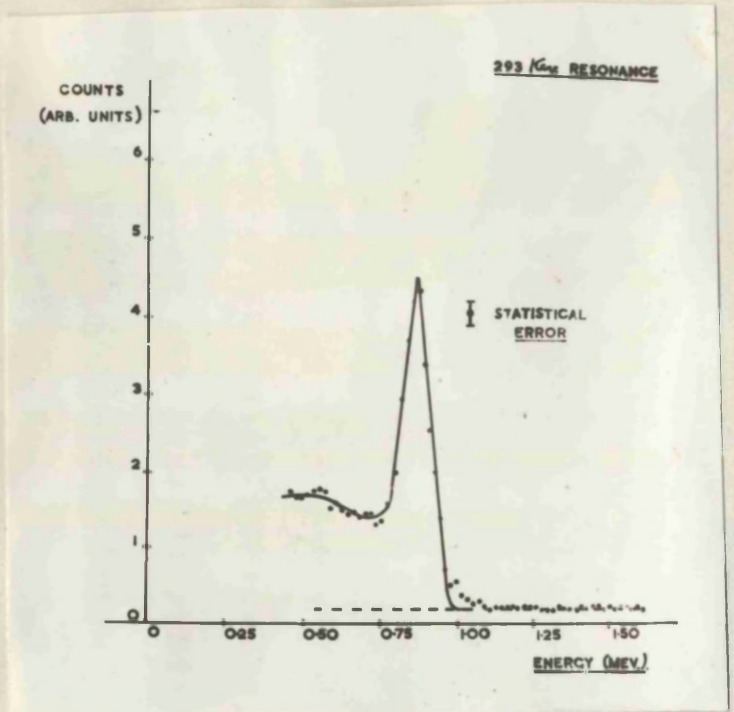


(a)

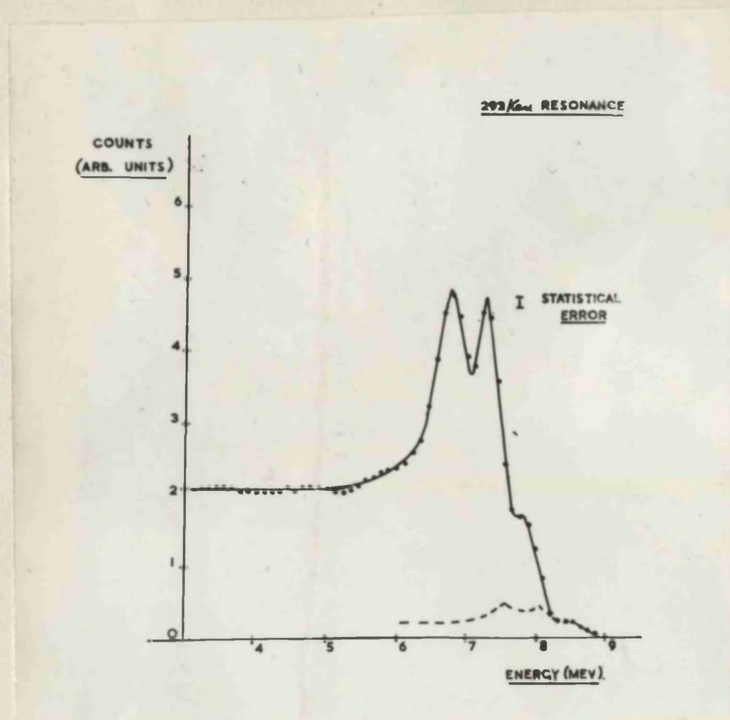


(b)

Fig. II.2. (a) The low energy γ-rays at the 338 Kev. resonance, and (b) the high energy γ-rays. (90° Position).



(a)



(b)

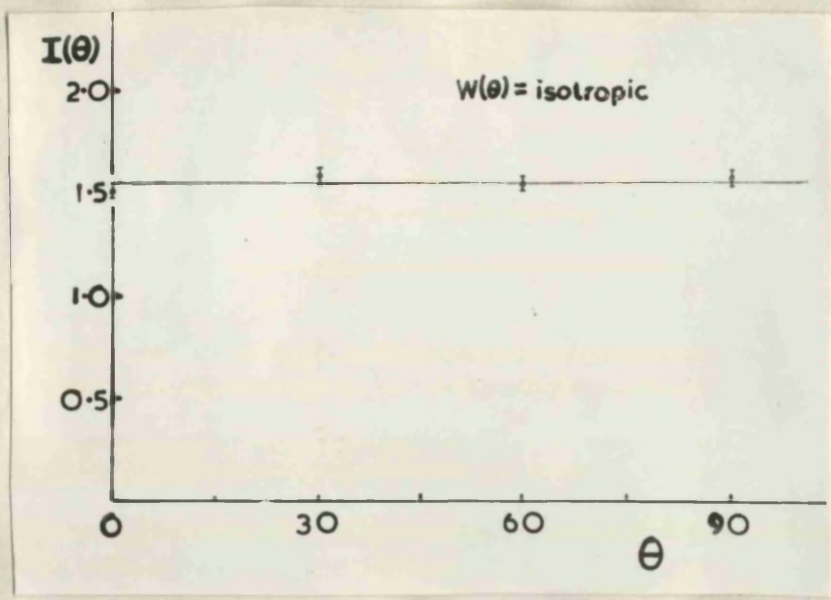
Fig. II.1 (a). The low energy γ-rays at the 293 Kev. Resonance, and (b). the high energy γ-rays.

provided such that the bracket could be clamped to the scale at the desired position. With the bracket, and hence the crystal, at 0° to the direction of the proton beam the energy spectrum of the γ-rays was measured. The pulses from the photomultiplier were amplified and then they were measured by the pulse height analyser. As the range of γ-ray energies was large the pulse height spectrum was obtained in two parts, viz. below 2·5 Mev. and above 2·5 Mev. Since the pulse height analyser was stopped by the timing unit, which was fed from the stationary crystal, these two measurements were automatically normalised.

For each resonance in the excitation curve γ-ray energy spectra were obtained at 0°, 30°, 60°, 90° both for the protons with energies E_R + 2 Kev. and those with energy E_R - 10 Kev. Since the targets were 15 μgms/cms^2 thick (i.e. $\sim$ 5 Kev. thick) the first spectrum of each pair gave the value at the resonance plus background and the second gave the background spectrum. The difference between the two was assumed to be a measure of the spectrum of the γ-rays from the resonance. These difference spectra for the 90° position at each resonance are shown in figs. II. 1(a) --- 4(b). The measurements at 726 Kev. could not be made accurately (i.e. with small statistical errors) due to this being approximately the upper voltage limit of the accelerator. However, an earlier measurement of the spectrum obtained at this resonance is shown in fig. II.5, and the angular distributions of the main γ-rays are given in table II.4.

The energy scales of the 90° spectra were calibrated in absolute terms by measuring the spectra of the standard γ-rays (listed on Page 36) at this angle. The energies of the γ-rays in the $^{26}Mg(p,\gamma)^{27}Al$ spectra were deduced from the positions of the peaks. The shape of the spectrum for each of these γ-rays was deduced from the shapes of neighbouring standard γ-rays. The intensities of the ^{26}Mg γ-rays were then found by calculating the values of the sums of these shapes which would add up to give the observed spectra. The values obtained by this procedure are illustrated in figs. II.1 to 4 where the proportions of the total spectra to be allocated to separate γ-rays are shown by the various types of line shapes.

The energy scales at other angles were only fitted on the ^{22}Na peaks in the low energy region and the $^{19}F(p,\alpha,\gamma)^{16}O$ in the high energy region. The same procedure for analysing the spectra as were used at 90°, were used here. Because the pulse height analyser was controlled by the timing unit attached to the stationary counter all the spectra at different angles were already normalised. The spectra at E_R + 2 Kev. and E_R - 10 Kev. were normalised by making the total proton charge collected by the target chamber the same in the two cases. This had



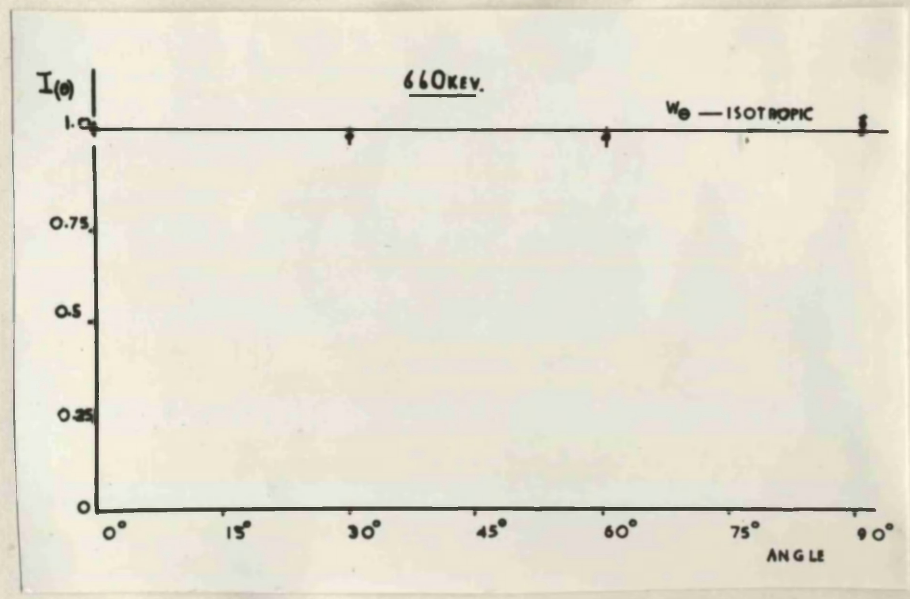
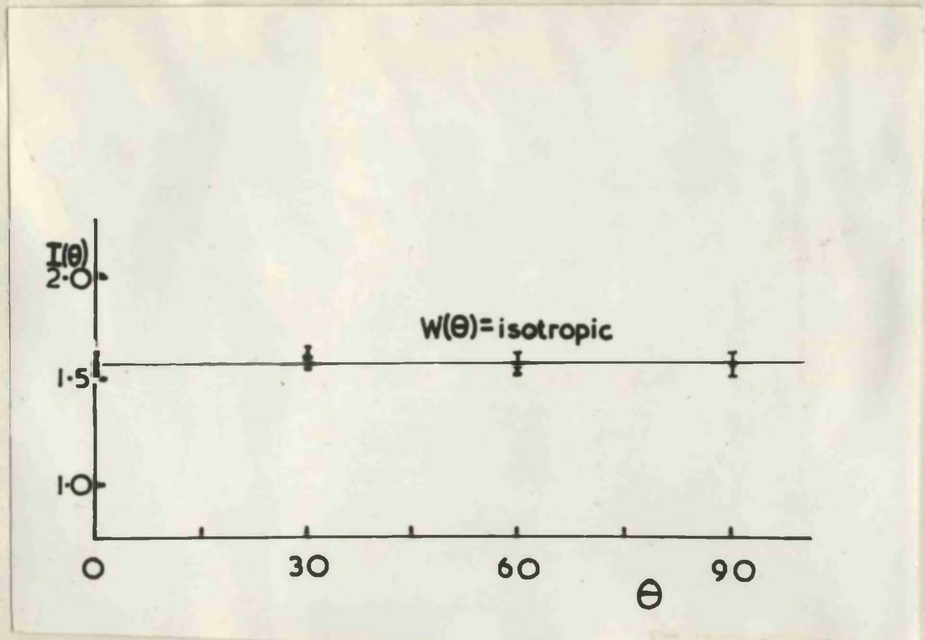


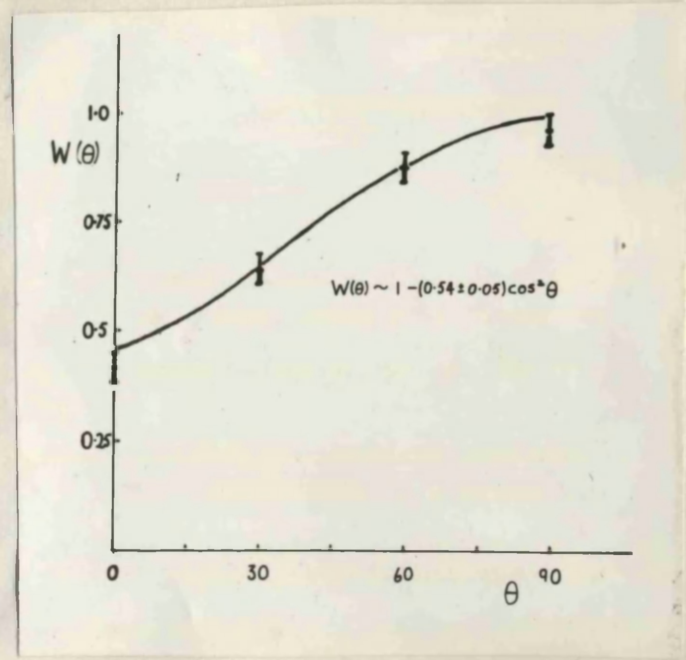
Fig. II. 6.

(c) The angular distribution of the sum of the 7·85 Mev. and the 7·70 Mev. γ-rays from the 454 Kev. resonance.

(d) The angular distribution of the sum of the 8·90 Mev., and 8·05 Mev., and the 7·90 Mev. γ-rays from the 659 Kev. resonance.



(a)



(b)

Fig. II. 6.

(a) The angular distribution of the sum of the 8·55 Mev. and 7·75 Mev. γ-rays from the 293 Kev. resonance in $^{26}Mg(p,\gamma)^{27}Al$.

(b) The angular distribution of the sum of the 7·75 Mev. γ-ray and the 7·60 Mev. γ-ray from the 338 Kev. resonance.

The errors shown are the statistical errors due to the finite numbers of counts that were observed at each position.

TABLE II. 4 The angular distributions of γ-rays from the $^{26}Mg(p,\gamma)^{27}Al$ reaction.

Resonance	γ-ray Energy	Angular Distribution	Theoretical Distribution	Mixture of Multipoles	Spins of Levels
338 Kev.	8·60 Mev.	$P_o - (0{\cdot}20 \pm 0{\cdot}12)P_2$	$P_o - 0{\cdot}10P_2$	E_1	$\frac{3}{2}(-)$ $\frac{5}{2}(+)$
	7·75 Mev.	$P_o - (0{\cdot}47 \pm 0{\cdot}05)P_2$	$P_o - 0{\cdot}50P_2$	E_1	$\frac{3}{2}(-)$ $\frac{1}{2}(+)$
	7·60 Mev.	$P_o + (0{\cdot}34 \pm 0{\cdot}23)P_2$	$P_o + 0{\cdot}40P_2$	E_1	$\frac{3}{2}(-)$ $\frac{3}{2}(+)$
	6·15 Mev.	$P_o + (0{\cdot}04 \pm 0{\cdot}20)P_2$	P_o		$^{19}F(p,\alpha,\gamma)^{16}O$
	5·85 Mev.	$P_o + (0{\cdot}45 \pm 0{\cdot}34)P_2$	$P_o + 0{\cdot}40P_2$	E_1	$\frac{3}{2}(-)$ $\frac{3}{2}(+)$
	5·60 Mev.	$P_o + (0{\cdot}55 \pm 0{\cdot}20)P_2$	$P_o + 0{\cdot}40P_2$	E_1	$\frac{3}{2}(-)$ $\frac{3}{2}(+)$
	5·00 Mev.	$P_o - (0{\cdot}40 \pm 0{\cdot}15)P_2$	$P_o - 0{\cdot}50P_2$	E_1	$\frac{3}{2}(-)$ $\frac{1}{2}(+)$
	3·60 Mev.	$P_o + (0{\cdot}03 \pm 0{\cdot}18)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{5}{2}(+)$
	3·00 Mev.	$P_o + (0{\cdot}08 \pm 0{\cdot}12)P_2$	$P_o + 0{\cdot}06P_2$	$M_1 + 0{\cdot}4\ E_2$	$\frac{3}{2}(+)$ $\frac{5}{2}(+)$
	2·80 Mev.	$P_o - (0{\cdot}10 \pm 0{\cdot}14)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{1}{2}(+)$
	2·75 Mev.	$P_o + (0{\cdot}38 \pm 0{\cdot}25)P_2$	$P_o + 0{\cdot}11P_2$	$M_1 + 2{\cdot}6\ E_2$	$\frac{3}{2}(+)$ $\frac{5}{2}(+)$
	2·20 Mev.	$P_o + (1{\cdot}00 \pm 0{\cdot}23)P_2$			?
	1·75 Mev.	$P_o - (0{\cdot}20 \pm 0{\cdot}08)P_2$	$P_o - 0{\cdot}12P_2$	$M + E_2$	$\frac{3}{2}(+)$ $\frac{3}{2}(+)$
	1·00 Mev.	$P_o + (0{\cdot}18 \pm 0{\cdot}05)P_2$	$P_o + 0{\cdot}08P_2$	$M + 0{\cdot}8\ E_2$	$\frac{3}{2}(+)$ $\frac{5}{2}(+)$
	0·85 Mev.	$P_o + (0{\cdot}03 \pm 0{\cdot}03)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{5}{2}(+)$
730 Kev.	5·35 Mev.	$P_o - (0{\cdot}35 \pm 0{\cdot}05)P_2$	$P_o - 0{\cdot}50P_2$		$\frac{3}{2}(+)$ $\frac{1}{2}(+)$
	3·70 Mev.	$P_o - (0{\cdot}09 \pm 0{\cdot}10)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{5}{2}(+)$
	2·75 Mev.	$P_o + (0{\cdot}08 \pm 0{\cdot}10)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{1}{2}(+)$
	2·21 Mev.	$P_o - (0{\cdot}20 \pm 0{\cdot}10)P_2$			?
	1·01 Mev.	$P_o - (0{\cdot}16 \pm 0{\cdot}10)P_2$			?
	0·85 Mev.	$P_o + (0{\cdot}02 \pm 0{\cdot}05)P_2$	P_o		$\frac{1}{2}(+)$ $\frac{5}{2}(+)$

been measured in the same way as before by making the target chamber a Faraday cage. Although this second method of normalising spectra is rather prone to error the small value of the background everywhere except at the 454 Kev. resonance made this unimportant.

The intensity of a particular γ-ray in a particular spectrum was measured by integrating the area under the curve of its line shape, when the latter had the magnitude required for the fitting procedure. Due allowance was made for the variation with energy of the efficiency of the crystal. The angular distributions were calculated from the intensities by the method of least squares and had the form $A + B \cos^2\theta + C \cos^4\theta$. Those which had significant values of B (no distributions had significant values of C) were then transformed into the form $E(P_o + F\ P_2)$ where P_o and P_2 are Legendre Polynomials in order to compare them with the theoretical predictions. The angular distributions at the 293 Kev., 454 Kev. and 659 Kev. resonances were found to be isotropic, while at the 338 Kev. and 726 Kev. resonances the angular distributions had the values given in table II.4. Some typical distributions are shown in fig. II. 6(a) --- (d).

Although the energy scale of the spectrometer was calibrated absolutely by comparison with standard γ-rays, the energies of the observed γ-rays were subject to error due to the finite width of the channels of the pulse height analyser and the widths of the peaks themselves. The errors to be ascribed to these sources are shown in table II.3. Similarly the intensities, which are quoted for the various γ-rays, can be in error because of uncertainties about the true shapes and because of statistical errors in the observations. The latter were the larger in most cases since many of the γ-rays were similar in energy to standard γ-rays. Table II.3 quotes the probable errors to be expected in the various intensities. The errors quoted in table II.4 for the angular distributions are deduced from the statistical treatment of the errors in the intensities at the various angles and are not the deviations obtained from the fitting of the distributions by the method of least squares. A A correction was made to the angular distributions to allow for the finite value of the solid angle subtended at the target by the crystal. This amounted to a 10% increase in the coefficient of $P_2(\cos\theta)$.

The angular distribution of the 6·13 Mev. γ-ray from the $^{19}F(p,\alpha,\gamma)^{16}O$ reaction, which is known to be isotropic, was measured and found to be less than 1% anisotropic. This showed that the apparatus did not have any significant anisotropy and confirmed the calculation which had shown that the differential absorption with angle of the γ-rays in the target backing was unimportant. The target had been kept at 135° to the direction of the beam

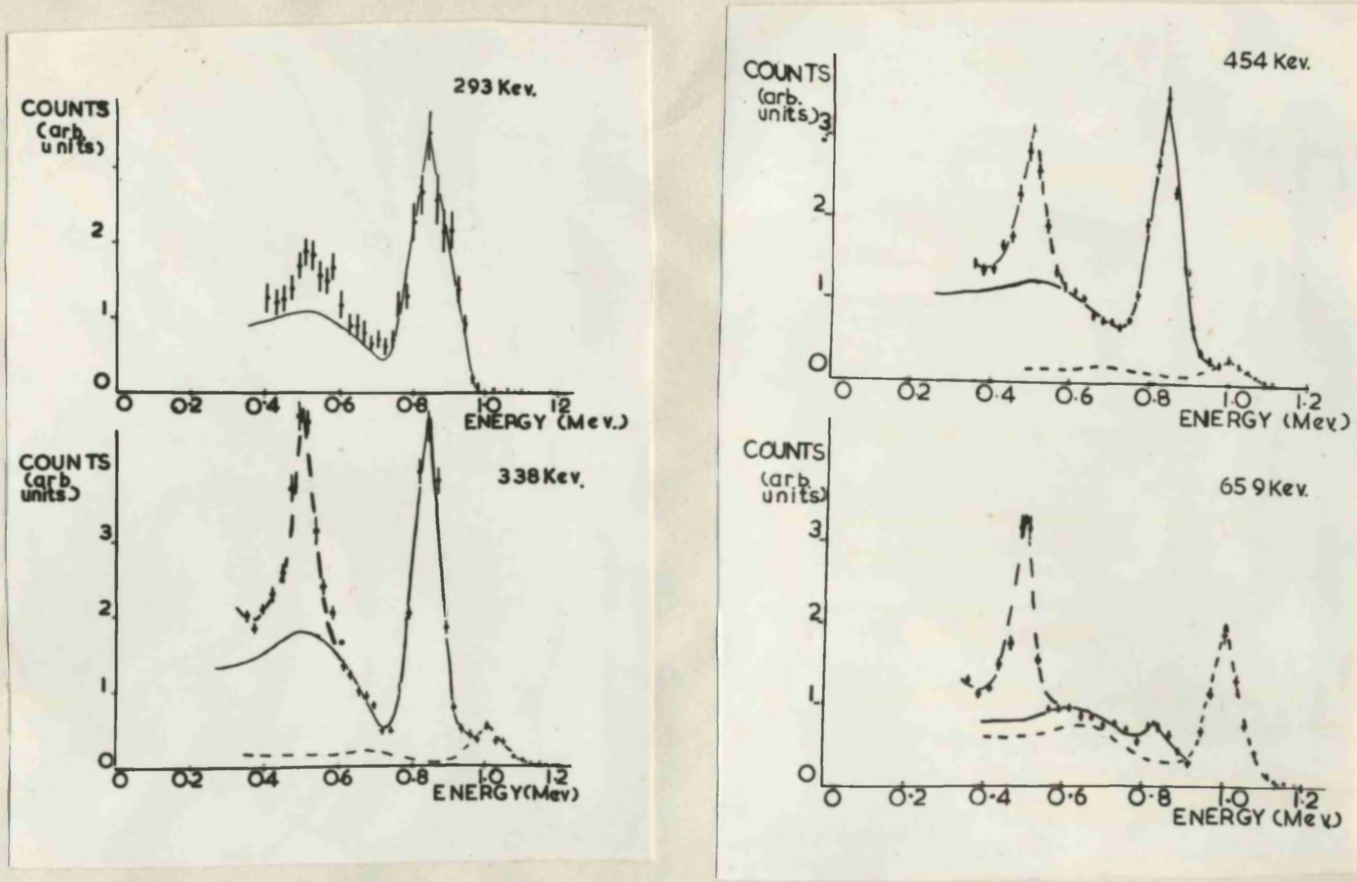


Fig. II. 7. The pulse height spectra of the γ-rays at the various resonances, which are in coincidence with γ-rays of between 6·2 Mev. and 8·2 Mev. The errors shown are statistical.

of protons in order to minimise this effect.

A search was made for the 0·17 Mev. γ-ray which would come from the transition between the 1·01 Mev. level and the 0·84 level. No trace of this γ-ray was found at any of the resonances. This result is in agreement with the results of Lyon et alia (1956) of the γ-radiation following the β^--decay of ^{27}Mg.

(c) <u>The Measurement of the γ - γ Angular Correlations.</u>

The same two crystals were used in the measurement of the angular correlations as had been used for the measurement of the angular distributions. In this case the pulses from the stationary crystal, which was held at 90° to the direction of the beam of protons, were amplified and then they were fed to a single channel analyser. This had the property of selecting those pulses which had heights within a narrow region and so corresponded to γ-rays of a selected energy. The height and width of the channel could be varied continuously so that any part of the γ-ray spectrum could be chosen. The pulses from the second crystal, which was held in the movable bracket, were amplified and then they were fed to the pulse-height analyser and a discriminator. The pulses from the two amplifiers were also fed to a coincidence circuit with a resolving time of 0·25 μ secs. The outputs of the single channel analyser, the discriminator and this coincidence unit were fed into a triple coincidence unit with a resolving time of 3 μ secs.

and also to the timing unit and two scalers, respectively. The output of the triple coincidence unit was used to gate the pulse height analyser. In this way the pulse height analyser displayed the energy spectrum of the γ-rays detected in the movable crystal, which were in coincidence with a selected group of the γ-rays detected by the stationary crystal.

At each resonance except the 726 Kev. resonance, at which no measurements were made, the correlations between the high energy γ-rays of approximately 8 Mev. and the 0·84 Mev. and 1·01 Mev. γ-rays were observed. The single channel analyser was adjusted so that it detected pulses corresponding to γ-rays in the region between ≈ 6·2 Mev. and ≈ 8·2 Mev. The gain of the second amplifier was adjusted till the range of energies displayed on the pulse height analyser was 0·2 Mev. to 1·5 Mev. and the discrimination was set to reject pulses below ≈ 0·3 Mev. The timing unit was set so that it stopped the scalers and the pulse height analyser when a selected number of counts had been registered by the single channel analyser. This number varied from resonance to resonance due to the variation in yields. It was 10^6 for the 454 Kev. resonance and 4×10^4 for the 293 Kev. resonance. The low energy spectra were obtained at 90°, 60°, 45°, 30°, 0° to the direction of the beam of protons and they were analysed as before. The variation of the coincidence rates with

TABLE II. 5 The angular correlations between γ-rays in the $^{26}Mg(p,\gamma)^{27}Al$ reaction

Resonance	γ-rays	Angular Correlation	Theoretical Correlation	Mixture of Multipoles First γ-ray	Mixture of Multipoles Second γ-ray	Spins of Levels
293 Kev.	7·75 Mev. and 0·85 Mev.	$P_o+(0\cdot07\pm0\cdot08)P_2$	P_o			$\frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{5}{2}$
338 Kev.	7·75 Mev. and 0·85 Mev.	$P_o+(0\cdot002\pm0\cdot04)P_2$	P_o	E_1		$\frac{3}{2} \rightarrow \frac{1}{2} \rightarrow \frac{5}{2}$
	7·60 Mev. and 1·01 Mev.	$P_o+(0\cdot14\pm0\cdot07)P_2$	$P_o+0\cdot18\ P_2$	E_1	$M_1+0\cdot8\ E_2$	$\frac{3}{2} \rightarrow \frac{3}{2} \rightarrow \frac{5}{2}$
454 Kev.	7·85 Mev. and 0·85 Mev.	$P_o-(0\cdot008\pm0\cdot02)P_2$	P_o			$\frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{5}{2}$
	7·70 Mev. and 1·01 Mev.	$P_o-(0\cdot06\pm0\cdot10)P_2$	$P_o-0\cdot11\ P_2$	E_1	$M_1+0\cdot8\ E_2$	$\frac{1}{2} \rightarrow \frac{3}{2} \rightarrow \frac{5}{2}$
659 Kev.	7·90 Mev. and 1·01 Mev.	$P_o-(0\cdot21\pm0\cdot10)P_2$	$P_o-0\cdot21\ P_2$	$M_1+0\cdot16\ E_2$	$M_1+0\cdot8\ E_2$	$\frac{1}{2} \rightarrow \frac{3}{2} \rightarrow \frac{5}{2}$
	5·20 Mev. and 3·6 Mev. 2·8 Mev.	$P_o-(0\cdot12\pm0\cdot20)P_2$	P_o			$\frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{5}{2}$ $\frac{1}{2} \rightarrow \frac{1}{2} \rightarrow \frac{1}{2}$

angle, i.e. the correlations, were estimated for the 1·01 Mev. γ-rays and the 0·84 Mev. γ-rays at the 338 Kev. and 454 Kev. resonances. Similar measurements for the 0·84 Mev. γ-ray at the 293 Kev. resonance and the 1·01 Mev. γ-ray at the 659 Kev. resonance were made, but the 1·01 Mev. γ-ray in the former case and the 0·84 Mev. γ-ray in the latter case were not studied because of their low intensities. Fig. II.7 shows the coincidence spectra for the 90° position and table II.5 gives the values of the correlations.

Because the measurement of the angular distribution of the 7·60 Mev. γ-ray at the 338 Kev. resonance was obscured by that of the 7·75 Mev. γ-ray the angular correlations of the 1·01 Mev. γ-ray were considered to be the only sure means of establishing the spin of the 1·01 Mev. state. However, even the results of the angular correlations were ambiguous due to the mixing of multipoles in the radiations. To resolve this difficulty the "inverse correlation" was measured for the cascade of γ-rays through this level. By this is meant the correlation in which the low energy γ-ray is detected in the stationary counter and measured by the pulse height analyser, while the high energy γ-ray is detected in the movable one and measured by the single channel analyser. The angular correlation measured in this way is the product of the angular distribution of the high energy γ-ray and the true angular

TABLE II. 6 The inverse correlations on γ-rays from the 338 Kev. resonance from the $^{26}Mg(p,\gamma)^{27}Al$ reaction.

γ-rays	Angular Correlation	Theoretical Correlation	Spins of Levels
7·75 Mev. and 0·85 Mev.	$P_0 - (0{\cdot}48 \pm 0{\cdot}02)P_2$	$P_0 - 0{\cdot}50\ P_2$	$\frac{3}{2} \rightarrow \frac{1}{2} \rightarrow \frac{5}{2}$
7·60 Mev. and 1·01 Mev.	$P_0 + (0{\cdot}30 \pm 0{\cdot}06)P_2$	$P_0 + 0{\cdot}40\ P_2$	$\frac{3}{2} \rightarrow \frac{3}{2} \rightarrow \frac{5}{2}$

correlation (provided this is nearly isotropic). As the correlation is isotropic for the 0·84 Mev. γ-ray the inverse correlation should give exactly the angular distribution of the 7·75 Mev. γ-ray. Similarly the correlation of the 1·01 Mev. γ-ray should give the angular distribution of the 7·60 Mev. γ-ray to within 14%. The big advantage of this measurement is the ease with which the 1·01 Mev. and 0·84 Mev. γ-rays can be distinguished. The results of the measurement are given in table II.6 and they confirm the values of the angular distributions.

Although other correlations were measured only the results for the correlation at the 660 Kev. resonance between the 5·20 Mev. γ-ray and the 3·60 Mev. γ-ray plus the 2·80 Mev. γ-ray are given in table II.5. It was found that the counting rates in all the other cases were too low to make the results statistically significant. Moreover, the complications arising from the tails of the spectra of the γ-rays with higher energy made the analysis virtually impossible. However, coincidence measurements were made which showed that the 1·75 Mev. γ-ray was in coincidence with the 1·01 Mev. γ-ray at the 454 Kev. resonance and that the 2·80 Mev. γ-ray was in coincidence with the 0·84 Mev. γ-ray at the 659 Kev. resonance.

In all the correlation measurements the number of chance coincidences was taken to be the product of the numbers of counts in the discriminator and single channel analysers multiplied by the resolving time of the fast coincidence unit and divided by the time of observation. The shape of the spectrum of chance coincidence was taken to be that of the γ-ray spectrum as observed by the movable crystal. The isotropy of the apparatus had been checked for the angular distribution measurements and had been found to be satisfactory.

The correlations were obtained from the measurements at the various angles by fitting a function of the form $A(P_o + B P_2)$, where P_o and P_2 are Legendre polynomials, by the method of least squares. The coefficients of P_2 were increased by 20% to compensate for the effect of the finite solid angles subtended at the target by the crystals. The main errors were those, which were due to the statistical variations in the number of counts, so these are the only errors quoted.

II. 3 INTERPRETATION OF RESULTS.

Before considering the results of the experiments performed by the author on the $^{26}Mg(p,\gamma)^{27}Al$ reaction, it is helpful to review the information about the energy levels of ^{27}Al that has been obtained from other sources. At the time of writing the most accurate values, that have been obtained for the energies of the levels of ^{27}Al, are those given by the measurements of Browne et alia (1954) on the energies of protons that had been inelastically scattered by ^{27}Al. These values of the energies of the levels will be used throughout the following discussion.

The spin of the ground state of ^{27}Al should be $\frac{5}{2}$ and the parity positive according to the shell model of the nucleus and these values were confirmed by the measurements of Daniel et alia (1954) on the β^--decay of ^{27}Mg. These measurements on $^{27}Mg(\beta^-)^{27}Al$ also showed that the first and second excited states at 0·84 Mev. and 1·01 Mev. respectively had positive parity and spins of $\frac{1}{2}$ or $\frac{3}{2}$.

The only other information available on the levels of ^{27}Al is the result of some studies on deuterons which had been scattered inelastically by ^{27}Al. The angular distributions of these deuterons were measured by Hinds et alia (1956), but troubles with backgrounds from other reactions confined the measurements to deuterons leaving ^{27}Al in states above 2·0 Mev.. The results show that the levels at 2·75 Mev. and 3·00 Mev. have positive parity and spins between $\frac{1}{2}$ and $\frac{3}{2}$ or $\frac{7}{2}$ and $\frac{11}{2}$. The results for the 2·21 Mev. level cannot be given an unambiguous interpretation. Since the theory, on which the analysis of these experiments was based, is known to be invalid in other similar cases according to Middleton (1957), these results must be treated with caution.

^{26}Mg is an even even nucleus with twelve protons and fourteen neutrons. This makes it almost certain that the spin of the ground state is 0 and the parity positive. Thus any value of the angular momentum, with which the proton is captured, will give not more than two values for the spin of the resonance level, viz. $\ell \pm \frac{1}{2}$. Moreover, the parity of the resonance level will be given uniquely by $\Pi = (-1)^{\ell}$. Of the various spin states that could be formed by the capture of a proton those which are $\frac{1}{2}(+)$ and $\frac{1}{2}(-)$ in character, will give isotropic angular distributions. On the other hand levels with other spins will give anisotropic angular distributions for all pure dipole transitions and most mixed- multipole transitions.

More information about the spins of the low lying levels can be obtained from the analysis of an anisotropic resonance than from the study of an isotropic one. Therefore the results, which were obtained at the 338 Kev. resonance, will be considered first.

(a) <u>338 Kev. Resonance.</u>

The mean value for the energy of the proton which forms this level is 338·5 Kev. and this value lies within the errors of all the results for which these are quoted. Table II.4 shows the angular distributions of the high energy γ-rays, which were observed at this resonance, and compares each of them with one of the angular distributions to be expected for the dipole transitions from a $\frac{3}{2}$ level to a $\frac{1}{2}$, $\frac{3}{2}$ or $\frac{5}{2}$ level. In each case the experimental result can be fitted by one of the theoretical angular distributions to within the probable error of the former. Hughes et alia (1956) have shown that the 7·75 Mev. γ-ray, which goes to the 0·84 Mev. level, is E_1 in nature. They obtained this result by examining the protons that were produced by the photo-disintegration of Deuterium by this γ-ray with the technique described on page 18. The 0·84 Mev. level is known to have positive parity and we have shown that it has spin $\frac{1}{2}$. Thus the resonance level must be the $\frac{3}{2}(-)$ level which is formed by the absorption of a p-wave proton.

Since the γ-ray width of the level is reasonably large and one of the γ-rays with the higher energies is known to be E_1 it is reasonable to assume that all the γ-rays coming from the resonance level are E_1, and that all the levels filled directly from the resonance level have positive parity.

The γ-ray corresponding to the transition to the ground state has the correct angular distribution for an E_1 transition between a $\frac{3}{2}(-)$ level and a $\frac{5}{2}(+)$ level. However, the intensity relative to that of the γ-ray, which leaves ^{27}Al in its first excited state at 0·84 Mev., is much smaller than one would expect on the simple Weisskopf formula. This suggests that the transition is partially forbidden by the selection rule of one of those approximate quantum numbers mentioned on page 11.

As described above the angular distribution of the 7·75 Mev. γ-ray, which leaves ^{27}Al in its first excited state at 0·84 Mev., shows that the level is $\frac{1}{2}(+)$. This value for the spin of the level is confirmed by the isotropic angular distribution of the 0·84 Mev. γ-ray, and the isotropic angular correlation of the cascade through the level. The inverse correlation, which is given in table II.6, agrees within its experimental error with the angular distribution of the high energy γ-ray, as one would expect for a cascade through a $\frac{1}{2}$ level.

The studies of coincidences between the γ-rays above 6·2 Mev. and those below 1·5 Mev. are illustrated in fig. II.7. They show that the second excited state at 1·01 Mev. is fed directly from the resonance level. Using this knowledge it is possible to estimate the angular distribution of the 7·6 Mev. γ-ray, which feeds the level, despite the presence of the much stronger 7·75 Mev. γ-ray. To confirm this angular distribution the inverse correlation was measured and this is quoted in table II.6. These measurements show that the spin of the 1·01 Mev. level is $\frac{3}{2}$, and the β^--decay of ^{27}Mg shows that the parity is positive. One would expect that a $\frac{3}{2}(+)$ level at 1·01 Mev. would decay by a mixture of M_1 and E_2 transitions to the ground state rather than by a similar mixture to the 0·84 Mev. level. The factor by which the first transition is more likely than the second, is ≈ 100 and this explains the failure to observe the 0·17 Mev. γ-ray. The normal angular correlation measurements on the cascade coming directly from the resonance level through this level are given in table II.5 and they suggest that the multipoles, which are present in the 1·01 Mev. γ-ray, are in the ratio of 0·80 E_2 : 1 M_1 and that they are in phase. The fact that the angular distribution of the 1·01 Mev. level does not fit this result may be due to the effects of the other cascades which fill this level e.g. through the 2·75 Mev. level.

Our experiments do not allow us to say whether or not the 2·21 Mev. level is fed by a transition from the resonance level. This is due to the energy of the primary γ-ray in such a cascade being 6·4 Mev. which is very close to the 6·13 Mev. energy of the γ-ray from $^{19}F(p,\alpha,\gamma)^{16}O$. It is common experience that Fluorine is present in most materials as a trace element, and even when the target is originally uncontaminated the Fluorine content builds up due to some sort of surface layer being formed. As the cross-section for the reaction in Fluorine is very high and the resonance energy of 340·4 Kev. is very close to the energy of this particular resonance in $^{26}Mg(p,\gamma)^{27}Al$ the Fluorine γ-ray was expected to be present. That some at least of the

γ -ray called 6·15 Mev. in table II.4 comes from the Fluorine reaction was shown by the observation that the relative intensity of this γ-ray varied from target to target and increased with time for each target. Moreover similar intensities of this γ-ray could be obtained by bombarding the copper of the target backing where the surface contaminations should be similar to those on the targets. The isotropic angular distribution of this γ -ray is consistent with its being the γ-ray from Fluorine, but one cannot rule out the possibility that the 6·4 Mev. γ-ray is present. The measurements of coincidences between the γ-rays from 6 Mev. to 6·5 Mev. and those above 0·5 Mev. showed very little trace of a 2·21 Mev. γ-ray and none of either a 1·20 Mev. γ-ray or a 1·37 Mev. γ-ray. Even the traces of a γ-ray of about 2 Mev. were not really statistically significant. It seems unlikely, therefore, that the 2·21 Mev. level is fed from the resonance level. No explanation is offered for the presence of a 2·25 Mev. γ-ray with its markedly anisotropic angular distribution, particularly since its intensity at 90° appears to be zero as is shown in fig. II. 2(b).

The 5·85 Mev. γ-ray which leaves ^{27}Al in the level at 2·75 Mev. has an angular distribution which is consistent with the level having spin $\frac{3}{2}$. If the γ-ray is E_1, as seems to be likely, the parity is positive in agreement with the result of Hinds et alia on the reaction $^{27}Al(d,d^1)^{27}Al^*$. The coincidence studies at the 454 Kev. resonance showed that this level decays to the ground state and the state at 1·01 Mev. From the angular distributions in table II.4 the 1·75 Mev. γ-ray appears to be a mixture of E_2 with M_1 of equal intensities and in phase, while the 2·75 Mev. γ-ray is a mixture of E_2 with M_1 with a ratio of 2·6 and in phase.

One or both of the levels at 3 Mev. is filled by the γ-ray of 5·6 Mev. coming from the resonance level. The angular distribution of this γ-ray suggests that the level at 3 Mev. has spin $\frac{3}{2}$, and once again we are entitled to assume that the transition is an E_1 one making the parity positive. Coincidence measurements for the cascades through this level were complicated by the presence of many other γ-rays, which gave pulses in the region near 5·6 Mev. and at the same time were in coincidence with low energy γ-rays. All that could be established was that the level at 3 Mev. decays to the ground state, but the possibility that the 2·25 Mev. γ-ray corresponds to a transition from the level at 3 Mev. to the level at 0·84 Mev. could neither be confirmed nor denied. The 3 Mev. γ-ray described in table II. 4 must be this ground state transition, and the angular distribution suggests that the ratio of E_2 to M_1 is 0·40 and that the two multipole radiations are in phase.

The only other level, which is filled to an appreciable extent by a transition coming directly from the resonance level, is the level at 3·66 Mev.. The γ-ray of 5·0 Mev. which fills this level has the angular distribution that corresponds to the transition from a $\frac{3}{2}$ level to a $\frac{1}{2}$ level. This value for the spin is in agreement with the observed isotropic angular distributions of the 3·6 Mev. and 2·8 Mev. γ-rays by which this level decays. Coincidence studies at the 659 Kev. resonance show that this level decays to the $\frac{1}{2}(+)$ level at 0·84 Mev. as well as to the $\frac{5}{2}(+)$ ground state. If the parity of the 3·66 Mev. level is positive, as we believe, then these two γ-rays would be M_1 and E_2 respectively. On the other hand, if the parity were negative the two γ-rays would have to be E_1 and M_2, so that the intensity of the ground state transition should be about one thousand times smaller than it is.

(b) <u>293 Kev. Resonance.</u>

This is a most unusual resonance in that it appears to decay by no more than two γ-rays. The first goes to the ground state and the second to the first excited state at 0·84 Mev.. The angular distribution of the sum of the high energy γ-rays is isotropic and is shown in fig. II.6. The angular correlation of the cascade through the 0·84 Mev. level is also isotropic. These facts suggest that this resonance level has spin $\frac{1}{2}$. If the parity were negative the ground state transition should be M_2 and so be very much weaker than the first excited state transition which would be E_1. In contrast a positive parity for the resonance level would give an E_2 transition to the ground state and an M_1 transition to the 0·84 Mev. level. These two transitions should have comparable intensities. Thus it is reasonable that the resonance level is the $\frac{1}{2}(+)$ state formed by the capture of s-wave protons. The reason why the resonance is so weak and does not decay to any other levels must be associated with the complex nature of the resonance level and suggests the presence of the extra selection rules mentioned before.

(c) The 454 Kev. Resonance.

The weighted mean value of the various measured values of the energy of the protons which form this level is 454·4 Kev.. The isotropic nature of this resonance is demonstrated by the angular distribution of the 7·85 Mev. γ-ray which is shown in fig. II.6. Thus the spin of the resonance level is clearly $\frac{1}{2}$, and by the absence of the ground state transition in contrast to the situation at the 293 Kev. resonance the parity would seem to be negative. One can account for the greater intensity of the γ-rays coming from this resonance in comparison to those from the 338 Kev. resonance by noting that, although both levels are formed by p-wave protons and decay by E_1 γ-rays, the probability of a proton penetrating the Coulomb barrier increases as the energy of the proton increases.

Since only the ground state, out of all the low-lying levels which are filled by direct transitions from the 338 Kev. resonance, has a spin greater than $\frac{3}{2}$, one would expect that this would be the only level which is filled directly from the 338 Kev. resonance level and not from the 454 Kev. resonance level. However, in practice only the four high energy γ-rays given in table II. 3 were observed. The differences between the γ-rays which are present in the two cases, must be due to the operation of additional selection rules.

The angular correlation of the cascade through the 0·84 Mev. level is isotropic as is expected for an intermediate state with a spin of $\frac{1}{2}$. The errors on the value quoted in table II. 5 for the correlation of the cascade through the 1·01 Mev. level are large because of the poor statistics. However, the result is consistent with the value of $\frac{3}{2}$ for the spin of the intermediate level and a ratio of E_2 to M_1 in the 1·01 Mev. γ-ray of + 0·8. This agrees with the result for the 338 Kev. resonance.

The other high energy γ-rays go to the 2·75 Mev. level and the 3·95 Mev. level, respectively. The coincidence measurements show that the 2·75 Mev. level decays to both the 1·01 Mev. level and the ground state. Unfortunately, because of the slow counting rates it did not prove possible to measure the angular correlations accurately enough to make the results meaningful. With the cascades through the 3·95 Mev. level it was not possible to do more than show that the 3·95 Mev. and 4·55 Mev. γ-rays were in coincidence. However, it seems reasonable to believe that the 2·95 Mev. γ-ray represents a transition from this level to the 1·01 Mev. level and that the spin of the 3·95 Mev. level is $\frac{3}{2}$ like that of the 2·75 Mev. level.

The γ-ray of 2·35 Mev., which is observed at this resonance, is thought to be mainly due to the broad resonance at 435 Kev. in the $C^{12}(p,\gamma)^{13}N$ reaction. Measurements of the γ-rays from the bombardment of the back of the target showed a similar intensity of γ-rays of this energy. Moreover, the spectrum obtained with 440 Kev. protons consisted entirely of this γ-ray. The carbon was thought to be present on the target as a result of the deposition of oil from the vapour of the oil diffusion pumps. This vapour was known to be carried onto targets by the beam of protons.

(d) <u>659 Kev. Resonance.</u>

The agreement is reasonable between our value for the energy of the protons which form this level and that of Taylor et alia (1952) and (1954). The mean value which is 660 Kev. is probably correct to within 1 Kev.. This resonance gives isotropic γ-rays e.g. the 7·9 Mev. γ-ray shown in fig. II. 6, which shows that it has spin $\frac{1}{2}$. The presence of a ground state transition suggests that the level has positive parity and is formed by s-wave protons. The γ-rays from such a level to levels with spins $\frac{1}{2}$, or $\frac{3}{2}$, or $\frac{5}{2}$ and positive parity will be M_1 or E_2, or a mixture of the two. The intensity of the γ-rays from this level is much greater than the intensity at the similar level at 293 Kev. Part of this can be explained by the increase in the barrier penetration by the protons, but the great dissimilarity in γ-ray spectra suggests that there is some other underlying reason.

The energy spectrum of the γ-rays, which are observed at this resonance, is very different from that observed at the 293 Kev. resonance. For instance the γ-ray going to the 0·84 Mev. level is comparatively weak here whereas the 7·9 Mev. γ-ray going to the 1·01 Mev. level is very strong. Similarly the 5·20 Mev. γ-ray, which goes to the 3·66 Mev. level at this resonance, has no counterpart at the 293 Kev. resonance.

The γ-ray of 6·1 Mev., which is observed here, is almost certainly due to the resonance in $^{19}F(p,\alpha,\gamma)^{16}O$ at 669 Kev.. This was confirmed by observing the spectrum of γ-rays obtained when the target was bombarded with 670 Kev. protons. The only possible level that could be filled by this γ-ray, if it was part of the $^{26}Mg(p,\gamma)^{27}Al$ spectrum is the level at 2·75 Mev. This level is known to decay by a 1·75 Mev. γ-ray (see 454 Kev. resonance) and no trace of such a γ-ray was observed.

The angular correlation of the cascade through the 1·01 Mev. level was measured. The value obtained was consistent with the assignment of the values of $\frac{3}{2}$ to the spin of the 1·01 Mev. level and of + 0·8 to the ratio of E_2 to M_1 for the 1·01 Mev. γ-ray provided the ratio of E_2 to M_1 in the 7·9 Mev. γ-ray is 0·16 and the multipoles are in phase. This condition is reasonable.

The coincidence measurements, which show that the 2·8 Mev. γ-ray is in cascade with the 0·84 Mev. γ-ray, confirm that the 3·66 Mev. level decays to the 0·84 Mev. level as well as to the ground state. Because of the low counting rates the angular correlation was measured for the 5·2 Mev. γ-ray and the sum of the 3·6 Mev. and 2·8 Mev. γ-rays. The isotropy of this correlation lends weight to the assignment of $\frac{1}{2}(+)$ to the spin and parity of the 3·66 Mev. level.

(e) <u>726 Kev. Resonance.</u>

Due to the smallness of the amount of information that we managed to collect about this level one cannot deduce much about its properties. Since one would expect the increase in the probability for capture of a proton

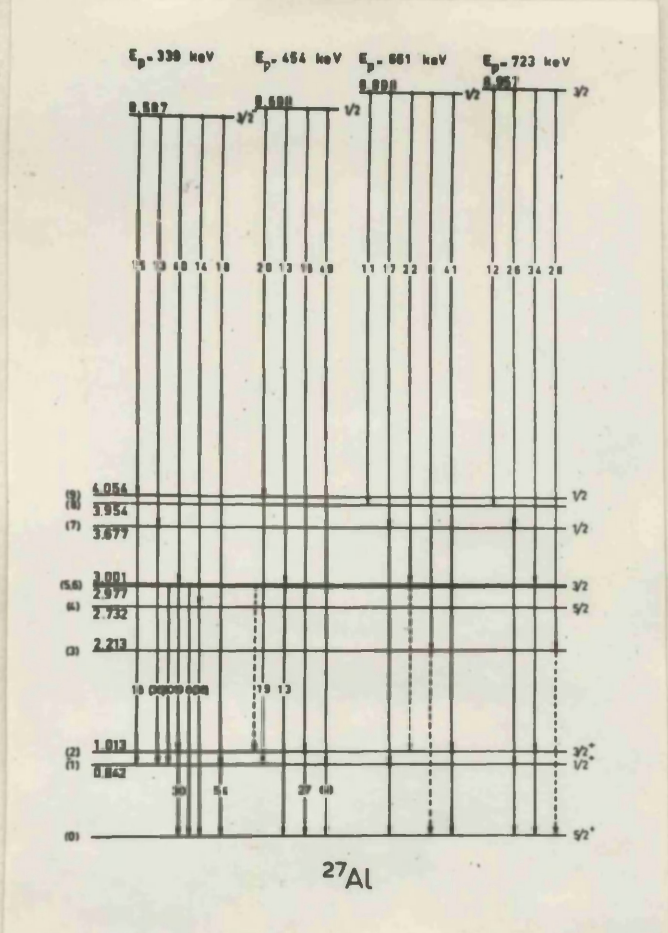


Fig. II. 8 (b) A similar energy level diagram propo

by Endt (1956).

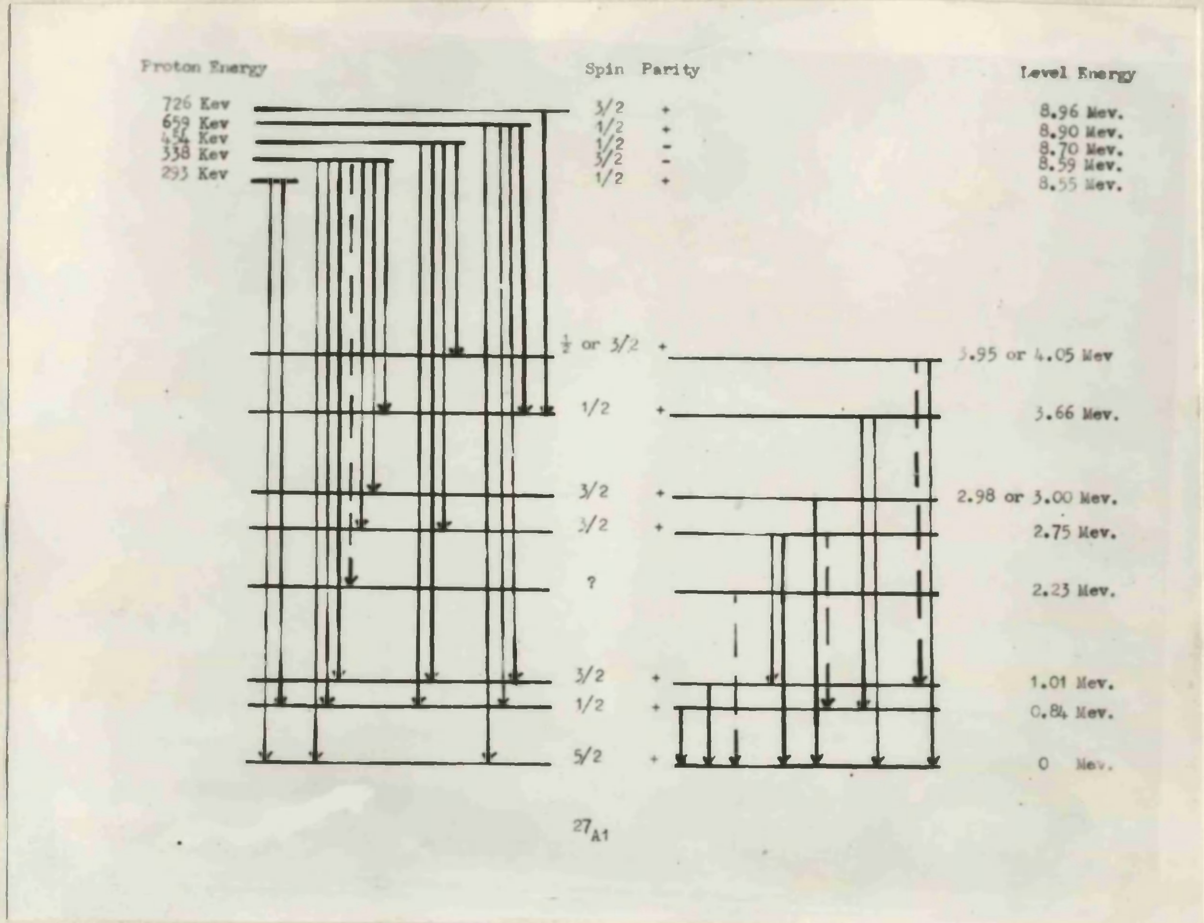


Fig. II. 8 (a) The energy level scheme for ^{27}Al proposed by the author to explain the results of his measurements on the $^{26}Mg(p,\gamma)^{27}Al$ reaction.

with energy to make this resonance the strongest, the fact that it is weaker than the 338 Kev. resonance suggests that it is formed by the capture of a d-wave proton. The strength of the transition to the $\frac{1}{2}(+)$ level at 3·66 Mev. in comparison to the other transitions to $\frac{3}{2}(+)$ levels suggests that the resonance level cannot have spin greater than $\frac{3}{2}$. It seems likely that the level is in fact the $\frac{3}{2}(+)$ state formed by the capture of a d-wave proton.

The angular distribution of the 5·35 Mev. γ-ray does not have the form which one would expect for a pure dipole transition from a $\frac{3}{2}$ level to a $\frac{1}{2}$ level. This may be due to the mixing of E_2 with the M_1. The distribution is anisotropic enough to make one confident that the level does not have spin $\frac{1}{2}$. It is unfortunate that more information could not be obtained about this resonance because the presence of a 6·7 Mev. γ-ray plus a 2·21 Mev. γ-ray suggests that the level at 2·21 Mev. is fed directly from the resonance level.

(f) Conclusions.

The results of this analysis of our measurements on the $^{26}Mg(p,\gamma)^{27}Al$ reaction can be summarised by the energy level diagram for ^{27}Al shown in fig. II. 8. Here the well established γ-rays are shown as full vertical lines while the doubtful γ-rays are shown as broken lines. The 2·25 Mev. γ-ray has been shown as being the transition from the 2·21 Mev. level to ground, although it may well be the transition from a level at 3·00 Mev. to the 0·84 Mev. level.

The most surprising feature of this diagram is the absence of many transitions which one would expect to be present in large amounts e.g. the E_1 transition from the 454 Kev. resonance to the 3·66 Mev. level. The most likely explanation is that the energy levels of ^{27}Al should be grouped according to some additional quantum number apart from spin and parity. The selection rules for this quantum number would then explain the absence of transitions which are favoured by the present selection rules.

TABLE III. 1 Q-values for the Reaction $^{10}B(d,p)^{11}B$

Group	Van Patter et alia 1951	Paris et alia 1954	Author 1953-56
	Q-values	Cross-sections* (total) milli-barns	Cross-sections* (milli-barns per steradion)
P_0	9·235 ± 0·011 Mev.	2·0	0·3 ± 0·03
P_1	7·097 ± 0·009 Mev.	0·8	0·096 ± 0·01
P_2	4·776 ± 0·008 Mev.	2·2	0·33 ± 0·03
P_3	4·201 ± 0·008 Mev.	0·7	0·083 ± 0·01

+ At E_D = 580 Kev.

* At 65° for E_D = 600 Kev.

PART III. THE (d,p) REACTIONS WITH ^{10}B AND ^{26}Mg.

III.1 INTRODUCTION TO THE REACTION $^{10}B(d,p)^{11}B$.

Although there are seven proton groups with Q values over 1 Mev. produced in this reaction only the four groups with the highest energies were studied. The Q values of the four most energetic groups, as measured by Van Patter et alia (1951) are given in table III. 1.

The first measurements of the angular distributions of the proton groups were reported by Endt et alia (1952). These measurements were carried out using deuterons of 300 Kev. to produce the reaction and photographic techniques for the detection of the protons. The results were rather inconclusive. Later Holt et alia (1953) used 8 Mev. deuterons to initiate the reaction and they detected the protons with a proportional counter telescope. The values of l_n and R for the P_o proton group, which was the only group that Holt studied, are shown in table III. 2.

In the period since our work at Glasgow commenced in 1953 several other studies of this reaction have been reported. First Evans et alia (1954) used a scintillation counter to detect the protons and measure their angular distributions. The energy of the deuterons used by Evans was 7·7 Mev.. This work was followed by a report by Paris et alia (1954), who had collaborated with Endt in

TABLE III. 2 The values of ℓ_n and R for the $^{10}B(d,p)^{11}B$ reaction.

Group	Holt et alia 1953		Evans et alia 1954		Paris et alia 1954		Deuchars and Wallace 1953-55.		Wallace and Storey 1956	
	ℓ_n	R_{Bhatia}	ℓ_n	R_{Bhatia}	ℓ_n	R_{Bhatia}	ℓ_n	R_{Bhatia}	ℓ_n	R_{Bhatia}
P_o	1	$5\cdot8\times10^{-13}$ cms.	1	$6\cdot0\times10^{-13}$ cms.	1	$5\cdot8\times10^{-13}$ cms.	1	$5\cdot8\times10^{-13}$ cms	1	$5\cdot8\times10^{-13}$ cms
P_1			1		3		3		3	
P_2			1		0		0		1	
P_3			1		1				1	

the earlier measurements. These later results described an extension of Endt's measurements to cover the range between 200 Kev. and 600 Kev. Angular distributions were measured at 200 Kev., 450 Kev., and 600 Kev. These experiments were performed with the same photographic technique for the detection of the protons that was used by Endt. The statistical errors on the individual points are fairly large as can be seen in figs. III. 5(a) and III. 5 (b). The values for ℓ_n and R used by Evans and Paris to interpret their results in terms of the stripping theory are given in table III. 2 along with our values.

Finally Marion et alia (1956) have reported a comprehensive study of the reaction in the region of deuteron energies between 0·9 Mev. and 3·0 Mev. These experiments show that "stripping" does not become the major mode of interaction until the higher energies are reached. No detailed analysis of these results in terms of mixtures of compound nucleus and stripping has been attempted.

Up till now no complete description of the angular correlations between these protons and the γ-rays, which follow them, has been published. Thirion (1954) showed that for the P_1 and P_2 groups of protons the ratios of $\frac{I_{\perp\ell}}{I_{\parallel\ell}}$ were $1{\cdot}05 \pm 0{\cdot}05$ and $0{\cdot}95 \pm 0{\cdot}05$ respectively when the deuterons have 500 Kev. energy. Gorodetsky et alia (1956) claimed that the correlation between the P_1 proton group and the 2·14 Mev. γ-ray was isotropic to within $\pm$

3·5% for deuterons of 1,200 Kev.

Other workers who have reported results for the $^{10}B(d,p)^{11}B$ reaction include Redman (1950), Burke (1954), Pratt (1954), Thompson (1954) whose results are in agreement with one or other of those already described.

III.2 DESCRIPTION OF APPARATUS.

(a) General Principles.

The measurements, which had been made on (d,p) reactions prior to the commencement of our studies, were concerned only with the study of the angular distributions of the protons. These angular distributions were measured with photographic plates or a proportional counter telescope as the detector for the protons. As it was intended to include studies of the angular correlations between the protons and their cascade γ-rays amongst our measurements, neither of these techniques was considered suitable.

A number of experiments on (p,γ) reactions, similar to that described in Part II, had shown that the scintillation counter was well suited to the detection of γ-rays. Moreover, coincidence techniques with these counters were known to have been developed to a stage where angular correlations could be studied. In view of this situation it was decided that a target chamber and its ancillary equipment should be constructed in which both the protons and the γ-rays would be detected by

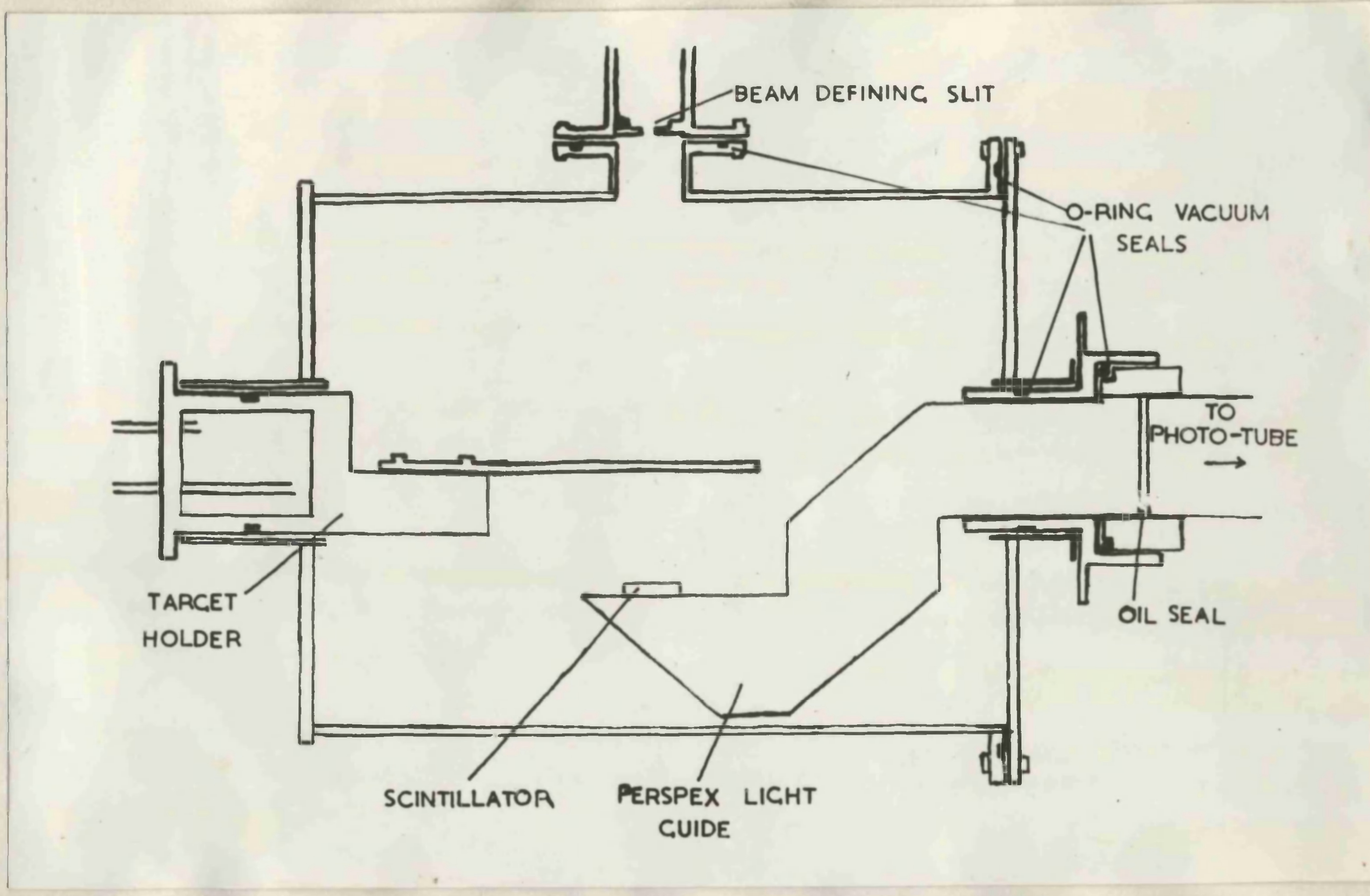


Fig. III. 1 The first target chamber, showing the detector for the protons.

scintillation counters. It was arranged that the angular distributions of the protons and the angular correlations between protons and γ-rays could both be measured without any major alteration to the apparatus.

(b) First Arrangement.

Fig III. 1 shows the general arrangement of the first target chamber that was constructed. The scintillator, which detected the γ-rays, is not shown because it was mounted on an external arm that could rotate around the axis of the target on a pair of ball-races. The plane of this rotation also contained the direction of the deuteron beam and a scale was provided so that the arm could be held at any required angle to this direction. As the figure shows, the other scintillator, which was used to detect the protons, was mounted on a movable light guide. This light guide could rotate around the axis of the target carrying the scintillator round in the plane that contained the γ-ray detector. Four features of this arrangement required careful investigation before it was constructed.

The light guide itself presented the first problem. At first a series of perspex cylinders and prisms were joined together with perspex cement. Experience showed that small bubbles appeared round the edges of the joints. These bubbles absorbed light and so worsened the energy resolution of the spectrometer by a large factor. In order to overcome this a light guide was machined from a solid piece of perspex, and it was found that this arrangement was satisfactory.

At the place where the light guide emerged from the target chamber an optical joint was required between the movable guide and the stationary guide which was attached to the photomultiplier. Originally the gap was left with air in it, but this allowed multiple reflections at the two air-perspex interfaces and these caused a loss of energy resolution. Several liquids were tried in the gap. Some, like Silicone oil, were so viscous that bubbles formed whenever the movable guide was rotated. Water, amongst others, had an index of refraction which did not match that of perspex. The problem was solved by using a syringe to inject liquid paraffin through a very fine hole into the gap. The hole was then sealed to leave an air-free liquid contact between the faces.

The third problem to arise was the choice of scintillator to use for detecting the protons. It was important that the scintillator should have the following four characteristics:-

(i) A large light output for a given energy loss in the scintillator. Since the ultimate energy resolution was determined by the statistical error in the number of electrons liberated from the photocathode, and some light was bound to be lost in passing through the light guide, the intensity of the light given out by the scintillator was vital.

(ii) Long term scintillation efficiency under bombardment with protons, neutrons and γ-rays.

(iii) A low vapour pressure to allow it to be used in the vacuum of the High Tension Generator.

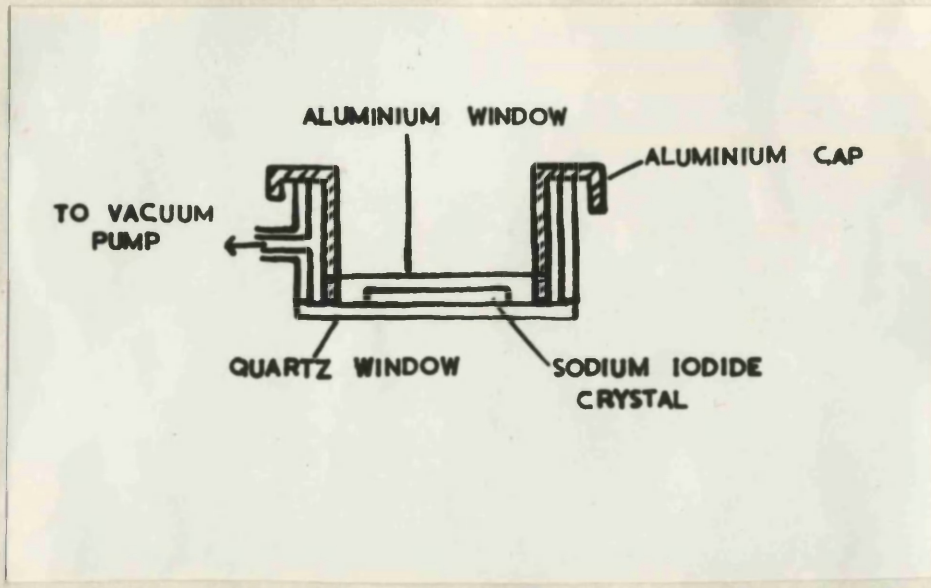
(iv) A low response to neutrons and γ-rays in order that the spectrum of the protons would not be swamped by the background.

Zinc Sulphide was the scintillator which best fitted these criteria. Unfortunately this material could only be obtained in the form of a microcrystalline powder. This powder was opaque to the light radiated within it. Thus, even though the initial light output was high, the spread in light intensity from mono-energetic particles was considerable. With the most uniform layer, that could be deposited by evaporating the alcohol from a suspension containing Zinc Sulphide, the energy resolution for 5 Mev. α-particles was about 50%. Here energy resolution is defined as the ratio of the full width of a peak at half the maximum height, to the peak energy.

The next scintillator that was examined was $NaI_{(Th)}$, i.e. sodium iodide which has been activated with thalium. This material suffered from the drawback of being hygroscopic, which meant that it had to be handled in a dry-box or in vacuo. The initial attempts to use this scintillator involved covering it with thin foils of Aluminium or evaporating an aluminium layer onto the surface. None of these attempts was successful.

Anthracene crystals were known to be about half as efficient in terms of light output as $NaI_{(Th)}$ so the possibility of using Anthracene was explored. The anthracene crystals then available from commercial sources were 1 cm. cubes and were all rather cloudy. As anthracene is difficult to cut or work because it cracks very easily, an attempt was made to grow crystals from solution. Very pure anthracene was dissolved in various organic solvents, which had been specially purified, to form saturated solutions at about 100°C. These solutions were allowed to cool very slowly in a thermally insulated system. Using amyl acetate as the solvent thin crystals of various sizes were grown. The largest was about 1 cm x 5 mm. x 0·5 mm. The light output of this crystal under bombardment with α-particles from a Polonium source was as large as was expected, but the energy resolution was disappointing. Part of the width of the peak was thought to be due to straggle in the source, but most of it was blamed on irregularities on the surface of the crystal.

At this stage a report by Endt et alia (1953) showed that it was possible to mount thin $NaI_{(Th)}$ crystals in a container that was suitable for use inside our vacuum



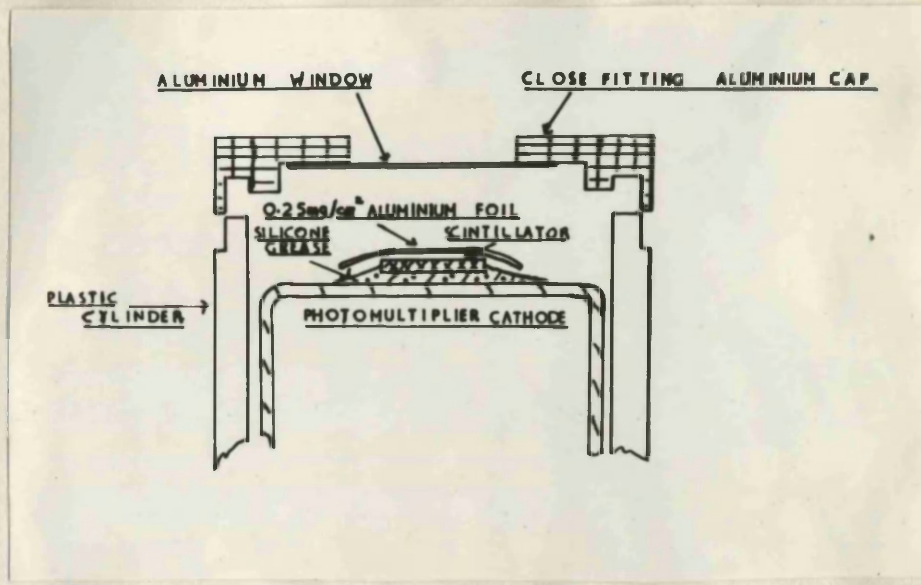


Fig. III. 2

(a) The mounting for thin $NaI_{(Th)}$ crystals designed by Endt (1953).

(b) The mounting for CsI crystals and plastic scintillator used by the author. The thickness of the layer of Silicone grease has been magnified for the purposes of illustration.

system. A diagrammatic representation of this container is shown in fig. III. 2(a). The crystal was cleaned and polished in a dry-box using fine emery paper and carborundum powder. Meanwhile a glass cylinder, with a tube attached to it for evacuating the container, was prepared and then was sealed onto a quartz window with araldite. An aluminium cap with a window of 0·001" thick aluminium foil was also constructed and then the whole container was fitted together inside the dry-box. The optical contact between the crystal and the quartz window was made of Silicone grease, while the final seal between the glass cylinder and the aluminium cap was of cold-setting araldite. When the araldite had set the container was evacuated through the glass tube, which was melted to seal off the container. A small piece of metallic sodium was placed in beside the crystal during the preparation of the container to protect the crystal from the fumes coming off from the araldite.

The whole apparatus was used successfully for several months and fig. III. 4(a) shows a typical energy spectrum of the products of the $^{10}B(d,p)^{11}B$ reaction. The peaks from the 9·0 Mev. and 7·0 Mev. protons can be seen clearly, while the 4·5 Mev. peak is almost obscured by a steeply rising background.

The fourth major problem, that was solved in connection with this apparatus, was the choice of the monitor for the reaction. At first it was intended that the γ-ray counter should be the monitor in the measurements of the proton angular distributions. It was found, however, that the γ-ray detector registered a large number of counts due to the background of neutrons from the accelerator. Since this number was comparable to the number of γ-rays coming from the target, and it was not proportional to the number of (d,p) reactions taking place in the target, another monitor was required. A short piece of straight light guide was inserted at -120° to the direction of the beam of deuterons. By attaching a crystal, mounted as described above, to the inner end of the guide and a photomultiplier to the outer it was possible to monitor the measurements on protons coming from the target.

After a period of use a leak developed in the side of the target chamber holding the light guide. In order to repair this leak the light guide had to be cut into two parts. After the leak was repaired the parts of the light guide were rejoined with perspex cement. This joint developed bubbles round its edge as had happened with the joints in the original guide. This mishap forced the choice between having a new light guide constructed and altering the form of the apparatus. Two factors influenced the decision in favour of the second alternative. The first was the fact that, as fig. III. 4(a) shows, the

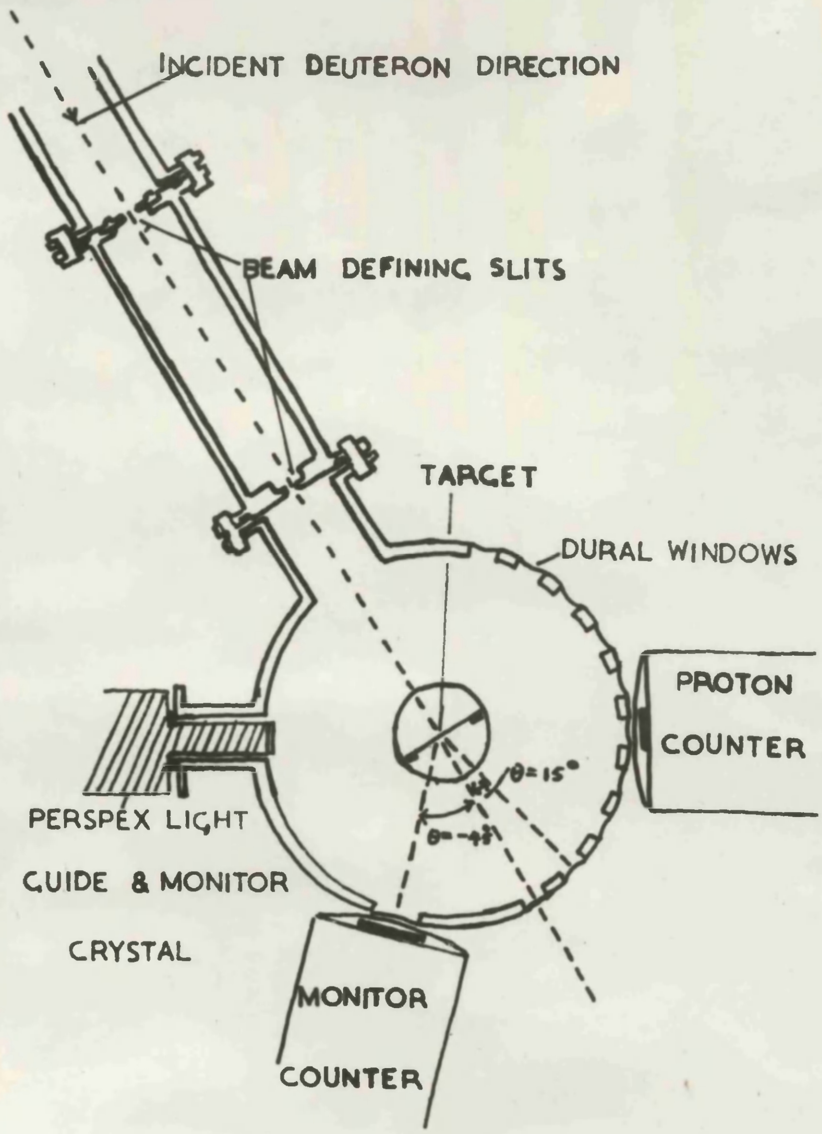


Fig. III. 3 The second target assembly.

third group of protons was swamped by the background of pulses from γ-rays and neutrons. It was suspected that the perspex was acting as a rather inefficient scintillator which produced large numbers of small pulses from the protons that received energy from collisions with neutrons. These small pulses would tend to pile up to form a background and would also worsen the resolution of the peaks. The other reason for the decision was that plastic scintillator had become available. This was believed to offer scope for use in a spectrometer for protons when placed directly on the cathode of a photomultiplier, although its light output was too small to allow its use with the light guide.

(c) Second Arrangement.

It was found that the resolution of the peaks in the energy spectrum of protons coming from the $^{10}B(d,p)^{11}B$ reaction was better for the spectrum from plastic scintillator on the short, straight light guide than that obtained for the spectrum from $NaI_{(Th)}$ on the rotating guide. A further improvement was obtained when the plastic scintillator was mounted on the cathode of the photomultiplier and the protons were detected after they had emerged through a 0·001" thick Aluminium window in the side of the target chamber. This observation led to the assembly of the new spectrometer, which is shown in fig. III. 3. The main change was that the light guide was removed and

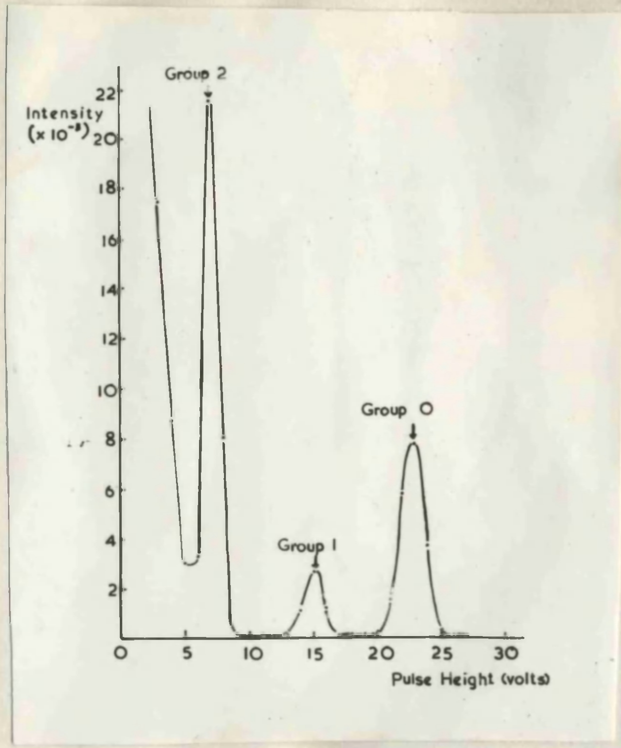
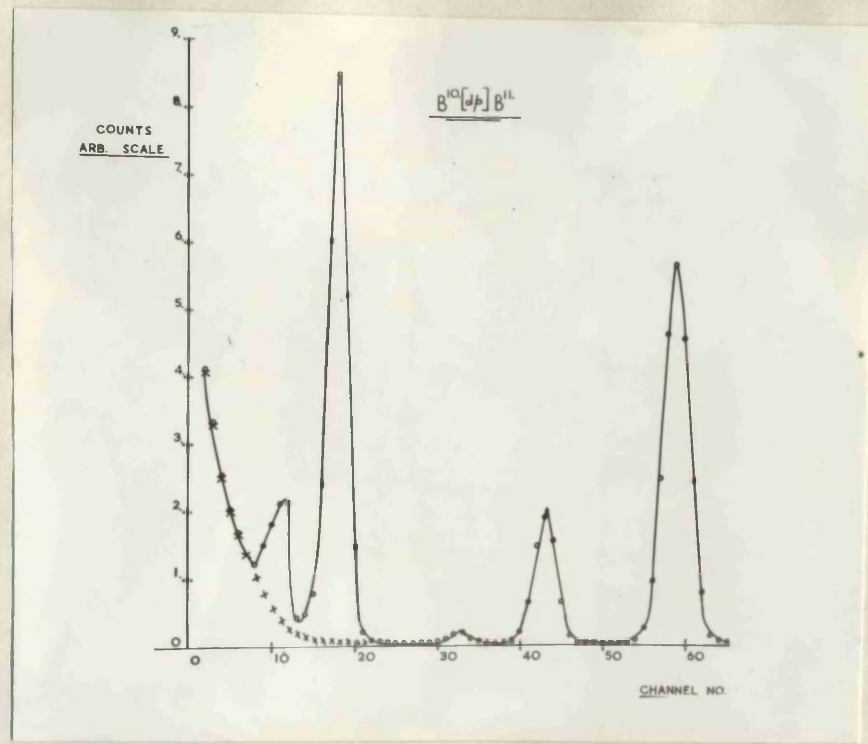


Fig. III. 4(b)

The energy spectrum of protons from the $^{10}B(d,p)^{11}B$ reaction as measured by the second target assembly using plastic scintillator.



(c) The energy spectrum of protons from the $^{10}B(d,p)^{11}B$ reaction as measured by the third type of target assembly using a CsI crystal. The crosses represent the intensity of the background.

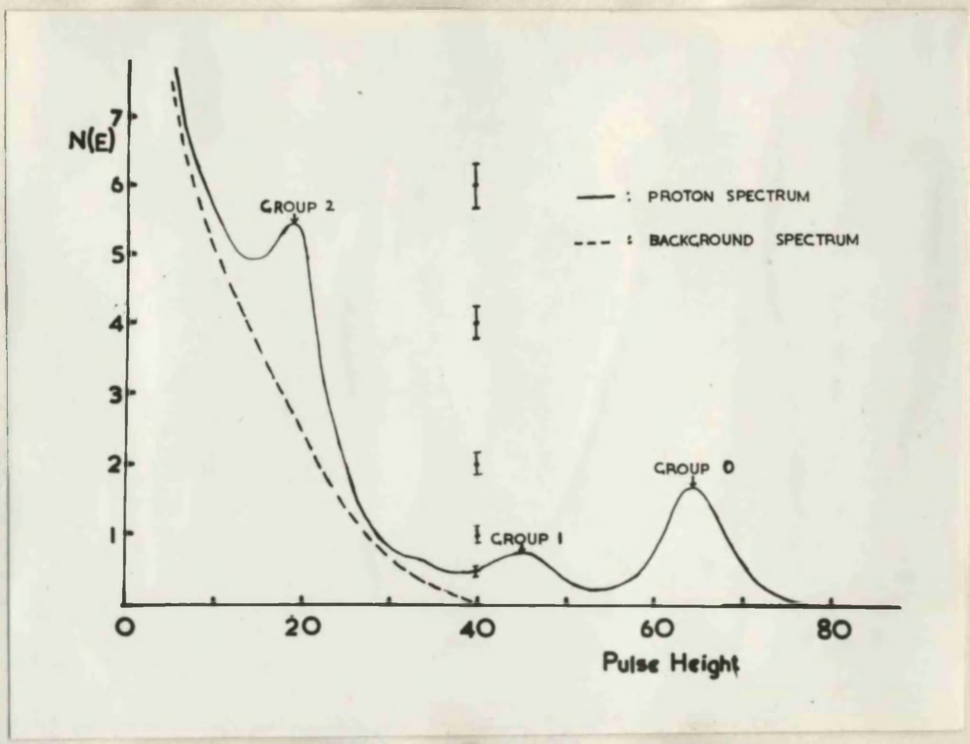


Fig. III. 4(a) The energy spectrum of protons from the $^{10}B(d,p)^{11}B$ reaction as measured by the first target assembly using a crystal of $NaI_{(Th)}$.

a series of $\frac{3}{8}$" diameter holes were drilled at 15° intervals, from 0° and 150° to the direction of the beam of deuterons, around the circumference in the plane of the beam. The holes were covered by a 7 mg./cm^2 thick aluminium foil which was sealed onto the chamber with sealing wax. A $\frac{1}{2}$" diameter hole was drilled at − 45° to the direction of the beam in order to provide an alternative monitor in place of the straight light guide at − 120°.

The thin pieces of plastic scintillator, which formed the proton detectors, were molded by compressing pieces of plastic scintillator at 150°C and 7 atmospheres pressure between flat plates down to the thickness of the aluminium spacers. The thickness was arranged to be slightly greater than the range of the 9 Mev. proton group. A layer of Silicone grease provided optical contact between the scintillator and the photocathode while a foil of 0·001" of aluminium provided a light tight cover for the detector. Fig III. 4(b) shows a typical example of the energy spectra that were obtained for the protons from $^{10}B(d,p)^{11}B$ with this spectrometer. By comparing this figure with III. 4(a) one can see the improvement that was obtained by using this new technique.

During the series of experiments performed by Dr. Deuchars and the author it became clear that the $\frac{3}{8}$" holes varied in size by about ± 2%. Another drawback about the arrangement was that the energy of the least energetic protons, which could be observed, was governed by their loss of energy in the aluminium windows of the target chamber and counter. In addition it became clear that the requirements of good angular resolution for the angular distributions and high counting rates for the angular correlations could not be reconciled successfully.

To solve these difficulties the author had two new target chambers constructed for the second series of experiments, which were carried out with the assistance of Mr. Storey. As there are no changes in principle between the design of these new target chambers and that of the model described above, no diagrams are shown for them. The first one had a radius of 3" and a set of $\frac{1}{4}$" wide slits running from + 155° to + 45°, and + 20° to − 60°, and − 80° to − 100°. The other was only $\frac{3}{4}$" in radius and had a $\frac{1}{8}$" wide slit from + 15° to − 90°. Both sets of slits were covered with Mylar foils 1·7 mg/cms^2 thick which were attached to the brass chambers by a layer of 3 M. cement. This cement was found to provide sufficient adhesion to maintain a vacuum without becoming brittle, or cracking when the Mylar film curved under the difference in pressure. In spite of the thinness of these windows they were subjected to repeated changes in pressure without apparent deterioration. The widths of the slits were tested along their lengths and were found to be constant to within 1%. Although these two target chambers had different radii they could fit into the same stand and so were easily interchangeable. Each was provided with a movable arm which could rotate around the axis of the target on a pair of ball-races. As the scale, which measured the position of the arm, was on the stand great care was taken to make sure that the axis of rotation of the arm coincided with the centre of the circular scale.

In an attempt to obtain better energy resolution the plastic scintillator was replaced by CsI. This scintillator, which has only become available recently, does not give much more than 50% of the light output of NaI but it has the great advantage of being stable in moist air. This contrasts with the hygroscopic nature of $NaI_{(Th)}$. The type of mounting shown in fig III. 2(b) was used. The thickness of the Silicone grease layer between the crystal and the photocathode has been greatly exaggerated for pictorial reasons. By keeping the coverings for the crystal down to 0·25 mg/cm^2 of aluminium as a reflector plus 0·75 mg/cm^2 of aluminium as a light tight window the least energetic proton that could be detected after penetrating the Mylar window and the aluminium was about 1·5 Mev.

Since the slits in the target chambers only defined the direction of the protons in one plane the crystal was covered with an aluminium disc $\frac{3}{4}$" in radius, 1/16" thick with a $\frac{1}{8}$" wide slit. The two slits were made perpendicular to each other by rotating the photomultiplier and its cover. Fig. III. 4(c) shows that this arrangement produced an energy spectrum for the protons which was so much better than had been obtained in any of the previous measurements that another group of protons could be seen.

III.3 EXPERIMENTAL PROCEDURE.

(a) Angular Distributions.

The actual method of making measurements was not affected by the variations in the apparatus. Thus it is unnecessary to describe more than one set of measurements in detail. Because the series of measurements, that was made with the second set of apparatus,,was the most extensive this will be described.

The targets consisted of 10 μgms/cm^2 of separated ^{10}B on a backing of 0·001" of aluminium and had been obtained from A.E.R.E. Harwell. The thinness of this backing made it necessary to restrict the beam to a current of about 1 μ amp. However, this was not a serious restriction because, as table III. 1 shows, the cross-sections were high. With this target the angular distribution of the three most energetic groups of protons were measured for an energy of the deuterons of 500 Kev.

The piece of plastic scintillator, which formed the monitor counter, was fixed in position outside the hole at -45^{o} and the pulses from the photomultiplier were fed by a cathode follower into a linear amplifier and thence into a discriminator. A level between groups P_1 and P_2 was chosen for the bias of this discriminator and the pulses from the top two groups were fed into the timing unit. This unit was adjusted in such a way that it stopped all the scalers and the pulse height analyser, when 10^5 counts had been registered by the timing unit. The other piece of plastic scintillator had been specially prepared so that its thickness just exceeded the range of the P_o protons and it was wide enough to cover one hole, but not two. This scintillator was attached to the photomultiplier in the rotating arm and was presented to the various holes in turn. The pulses from the photomultiplier were fed via a cathode follower and linear amplifier to the pulse amplitude analyser which was of the type designed by Hutchinson and Scarrott (1951). Three observations were made at each hole. First the gain of the amplifier was adjusted so that peaks P_o and P_1 were observed on the display of the analyser. The intensities of the two groups of protons were then measured at each angular position for a fixed number of counts in the monitor counter. Then the gain of the amplifier was increased to bring the P_2 group into the centre of the display and a spectrum was obtained for the time required to register 10^5 monitor counts. Finally a piece of aluminium $\frac{1}{16}^{\text{Th}}$ inch thick was interposed between the counter and the window and a spectrum was measured. Since this third observation gave the size and shape of the background due to neutrons and γ-rays, the difference between the second and third observations gave the intensity of the P_2 group.

Since each intensity measurement was made for the same number of counts in the monitor they were all directly comparable, and the angular distributions could be obtained from the observed intensities at the various angles. Several sources of error were recognised as being present and they were corrected for whenever possible. The numbers of counts in each group at each angle were larger than 10^4 making the statistical errors less than 1%. The finite dead-time of the pulse height analyser was 0·25 milleseconds and the counting rate was 100 counts per second, so that about 2·5% of the counts were lost. It was felt that variations in this loss could be neglected, so the correction for this effect became irrelevant. It was found that the intensity of the background was mainly caused by neutrons from the slits. The intensity of these was not really proportional to the number of counts in the monitor so an additional error was introduced into the measurement of the P_2 group. As the background formed about 20% of the counts in the region of the peak, an error of 3% was allowed for the errors in estimating the value of this background.

The main source of error lay in the variation from isotropy in the apparatus itself. The centre of the target was shown by direct measurement to be on the axis of the cylindrical surface of the chamber. Then a measurement of the well known isotropic angular distribution of the 6·13 Mev. γ-rays from the $^{19}F(p,\alpha,\gamma)^{16}O$ reaction, with a NaI crystal mounted on a photomultiplier in the rotating arm, showed that the centre of the target lay on the axis of rotation of the arm. However, the possible variations in the size of the holes formed a source of error whose magnitude it was difficult to estimate. The first method, that was tried, consisted of replacing the target by a source of RaE which emitted low energy β^--particles. Unfortunately, the back-scattering in the material of the backing for the source was so large that it produced a considerable anisotropy by itself. The measurement of the hole sizes by observing each hole in turn through a low powered microscope was tried next. The errors in this procedure were found to be larger than the differences to be expected in the holes. Finally a composite curve was made up from all the angular distributions so that the statistical errors on the individual points became negligible. From the variations of these points from a smooth curve it was estimated that the variation in the size of the holes was less than 2%. To account for all the errors the individual points in the angular distributions for the P_o and P_1 groups were allowed a 2% probable error, while the points on the P_2 angular distribution were allowed a 5% probable error.

Before measuring the angular distributions at other bombarding energies it was decided to measure the excitation curve at 0° for the P_o group. In order to do this the movable counter was placed outside the hole at 0° and the pulses were fed from the amplifier to a discriminator instead of to the pulse amplitude analyser. The bias of this discriminator was set at the level where only the pulses from the P_o group were accepted and fed into the succeeding scaler. The target chamber was constructed in such a way that it was electrically insulated from both the stand and the system of collimating slits to form a Faraday cage. This arrangement made it possible to measure the total charge carried onto the target which was large enough to ensure that it intercepted all the deuterons which passed through the slits. From this measure of charge one could determine the number of deuterons in the beam. The actual value of the charge was obtained by integrating the current which fed through a lead going from the target chamber to earth. The excitation curve was a graph of the variation with energy of the deuterons of the ratio of the numbers of protons and deuterons. The ratio was measured at 5 Kev. intervals from 300 Kev. to 700 Kev. and fig. III. 7 shows the smooth curve that was obtained and, for comparison, the actual points at 25 Kev. intervals. Because there was an irregularity at about 575 Kev. this region was studied several times and the shape of the curve in this region was established with great accuracy.

As a check on this excitation curve the ratio of the intensities at 0° and 120° was measured as a function of energy by setting the two counters at these holes. The results of this measurement are shown in fig. III. 8(a) and once again a singularity can be seen at 575 Kev.

In view of these features the angular distributions of the P_o and P_1 groups were measured at values of the energy of the deuterons of 350 Kev., 575 Kev., 675 Kev.. The angular distribution of the P_2 group was only measured for the values of E_D of 575 Kev. and 675 Kev.

When the third target chamber with its Mylar window was prepared the angular distributions at E_D = 575 Kev. and 650 Kev. were measured for the P_o, P_1, P_2 and P_3 groups of protons. These values of the bombarding energy were chosen because of their importance in the analysis of the whole experiment in terms of a resonance at 575 Kev. The measurements with this new target chamber were performed in the way described above for those which were made with the earlier target chamber. In this case, however, the errors due to anisotropy in the apparatus were much smaller. The width of the slit did not vary by 1%, while checks with a NaI crystal on the isotropic γ-rays from the $^{19}F(p,\alpha,\gamma)^{16}O$ reaction showed that the axes of the cylindrical wall of the target chamber and the rotation of the arm were the same as the axis of the target. These checks were made by first measuring the angular distribution when the crystal touched the target chamber and then measuring it when the crystal was held in the movable arm. Any differences between the various axes would have shown up as assymmetries in the angular distributions. As the numbers of counts in each peak at each angle was greater than 10^5 the only probable error that it was necessary to quote on the points of the angular distributions was the 1% due to variations in the width of the slit. The only exceptions to this were the points on the curves for the P_3 group where the background introduced a 10% uncertainty.

One additional error did appear with this apparatus, which could have been present in previous measurements although it was not detected. This was the difference between the zero on the scale for the moving arm and the direction of the beam of deuterons. This difference was measured by allowing the beam to burn a hole in a piece of paper backed with copper when the paper was in the target holder. As the heating due to the beam was localized this hole measured the position on the target of the point of impact of the beam. The slit system and target chamber were detached from the accelerator and the copper was removed from behind the paper. By shining a parallel beam of light through the slits and the hole onto the cover of the counter, which was held in the rotatable arm, the difference between the zero on the angular scale and the direction of the beam was found. The average correction amounted to about $2{\cdot}5^{\circ}$, but as the angular distributions were measured in three sections, viz. 0° to $-\ 45^{\circ}$, $+\ 45^{\circ}$ to $+\ 105^{\circ}$, $+\ 90^{\circ}$ to $+\ 145^{\circ}$ the signs and magnitudes of the corrections varied from section to section.

The angular distributions that resulted from these measurements are shown in figs. III. 6: III. 9: III. 12: and III. 13 for groups P_0, P_1, P_2, P_3 respectively.

(b) Angular Correlations.

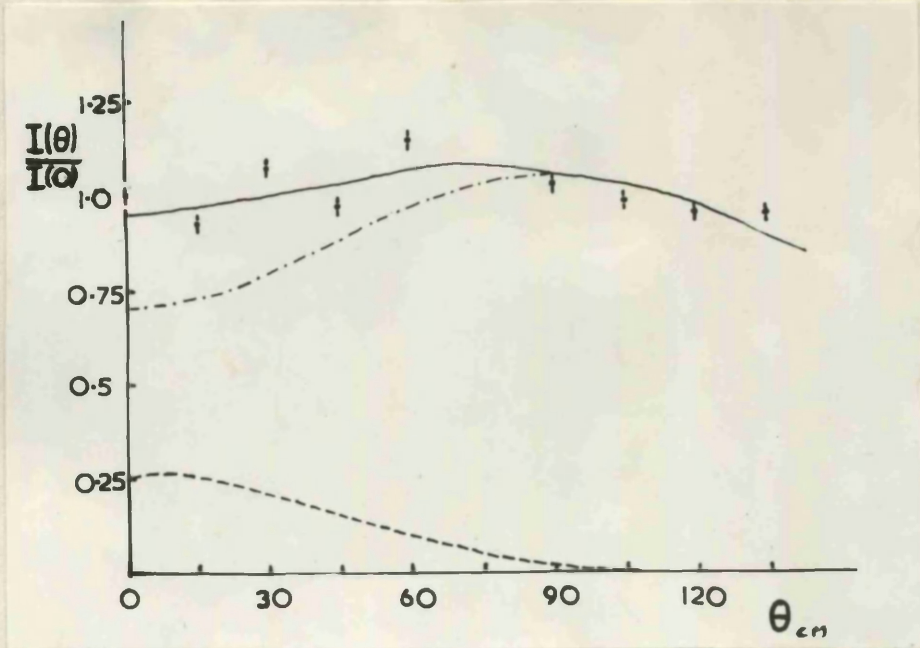
No measurements of angular correlations were made with the first target chamber. With the second target chamber, however, the correlations between the P_1 and P_2 protons coming out at $-\ 45^{\circ}$ to the direction of a beam of deuterons with 500 Kev. energy, and the $2{\cdot}14$ Mev. and the $4{\cdot}46$ Mev. γ-rays, respectively, were measured. A beam of 10 μamps of deuterons was allowed to hit a target of 15 μ gm./cm^2 of ^{10}B on a backing of 0·005" of copper, which was obtained from A.E.R.E. Harwell. The target was set at – 30° to the direction of the beam so that the protons came out of the front of the target. The protons were detected by a piece of plastic scintillator whose thickness was just bigger than the range of the p_o group of protons. The plastic was mounted by a layer of Silicone grease onto a Du Mont 6292 photomultiplier, which was held firmly outside the hole at – 45°. The γ-rays were detected by a cylinder of $NaI_{(Th)}$ 2 inches long and 1¾ inches in diameter. This crystal was mounted on another Du Mont 6292 photomultiplier which was carried round the target chamber in the movable arm. The pulses from each photomultiplier were fed through a linear amplifier into a discriminator. The bias levels of these discriminators were adjusted so that the γ-rays above 0·5 Mev. and the protons above 3·5 Mev. were counted. The outputs of the two discriminators were fed into the inputs of a coincidence unit with a resolving time of 1 μ sec. The output of the coincidence unit operated the gate of the pulse height analyser, which was displaying the pulses from the amplifier on the proton side. The output of the discriminator on the γ-ray side was also fed to a scaler and the output of the discriminator on the proton side was fed to the timing unit, which automatically controlled the scaler and the pulse amplitude analyser. The actual measurements consisted of observing the spectrum of these protons, which were in coincidence with γ-rays, that was obtained in the time that it took for 10^6 counts to be registered by the timing unit. These observations were made for five positions of the γ-ray counter viz. $0°$, $30°$, $60°$, $90°$, $120°$ to the direction of the beam of deuterons.

Previous measurements by Jones et alia (1952) had shown that the 2·14 Mev. level and the 4·46 Mev. and 5·03 Mev. levels all decay by γ-rays going directly to the ground state. Thus one γ-ray, and only one, followed the liberation of each proton and it was immaterial whether the spectrum of the γ-rays or of the protons is observed. There were considerable experimental advantages, however, to be gained from using the spectrum of the protons. First it was much easier to identify two groups of protons with energies of 7·1 Mev. and 4·8 Mev. than two groups of γ-rays with energies of 2·1 Mev. and 4·5 Mev. because of the simple nature of the spectrum of protons. Of greater importance was the fact that it allowed an easy and accurate measurement of the relative numbers of real and random coincidences. These random coincidences were caused by the finite resolving time of the coincidence unit and their rate of production was given by $C = N_1 N_2 \tau$

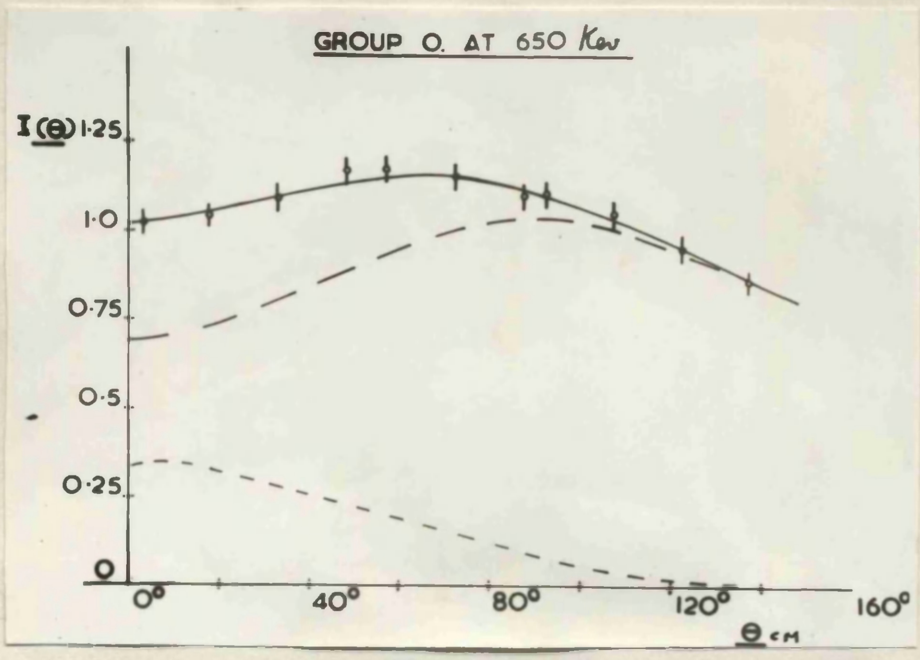
where N_1 and N_2 were the counting rates of the two counters and τ was the resolving time. Since both N_1 and N_2 are proportional to the current of deuterons, the number of random coincidences varies with the square of any fluctuations in the beam and so the total number of such coincidences is a difficult thing to measure. However, the number of random coincidences with the P_o group of protons will be proportional to the number with any other group. The constants of proportionality being the relative numbers of each group of protons that are detected. Moreover there are no γ-rays in coincidence with the P_o group, so all the coincidences, in which the proton lies in the P_o group, must be random. The constants of proportionality were found by making all the coincidences random by putting a delay of 5 μ sec. between the amplifier on the γ-ray side and the coincidence unit. The numbers of coincidences that had been observed for the five positions of the γ-ray counter were then corrected for the presence of random coincidences. Because the main error in each measurement arose from the uncertainty in this subtraction due to the statistical error in the measurement of the P_o group, the two angular correlations appeared to fluctuate together, as can be seen in fig. III. 10(a). This fluctuation is less than the quoted probable errors which are purely statistical as the apparatus was known to be isotropic from the previous experiments. The errors amounted to 7% for the P_1 group and 5% for the more intense P_2 group.

A second series of angular correlation measurements were made using the fourth target chamber. In these measurements the correlation of the P_3 group was measured as well as those of the P_1 and P_2 group, and the energy of the deuterons was increased from 500 Kev. to 600 Kev. This new target chamber was only $\frac{1}{4}$" in radius and it had a slit $\frac{1}{2}$" wide stretching from + 15° to – 90°. The slit was covered with a Mylar foil 1·7 mg/cm^2 thick. This target chamber allowed the solid angles of acceptance of the two counters to be much bigger and hence increased the ratio of real coincidences to random coincidences.

The CsI crystal, which detected the protons, was fixed at 65° to the direction of the beam of deuterons and the NaI crystal was mounted in the rotatable arm to detect the γ-rays. This time the coincidence unit had a resolving time of 0·25 μ sec. and the pulses from the coincidence unit were used to open an external gate instead of the gate on the pulse amplitude analyser. Observations were made of the spectrum of the protons which were in coincidence with γ-rays above 0·5 Mev. for positions of the γ-ray counter at 15° intervals between + 10° and + 145° to the direction of the beam of deuterons. The numbers of random coincidences were estimated as before,

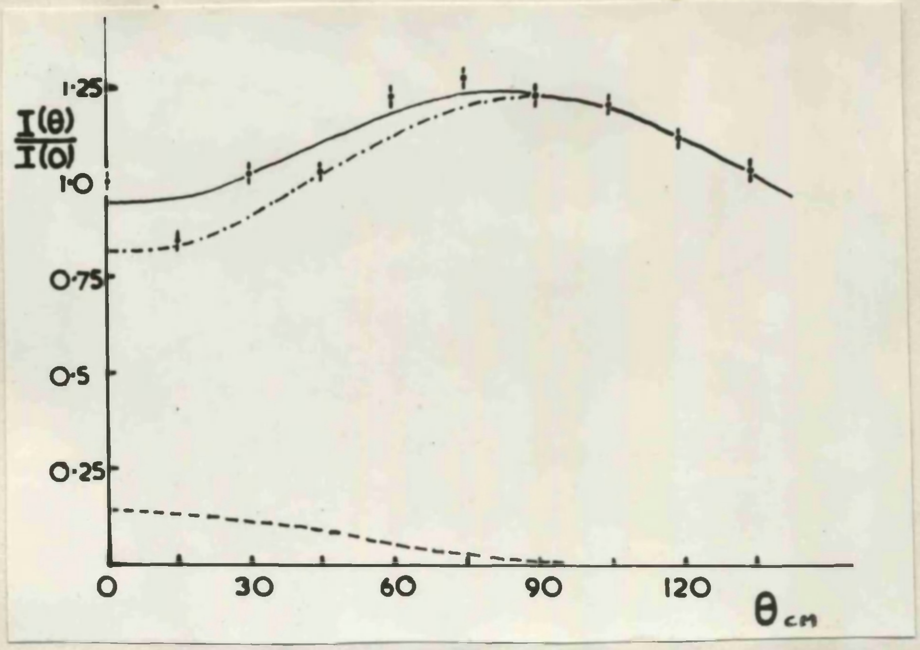


(e) At E_D = 675 Kev. (2nd target assembly)

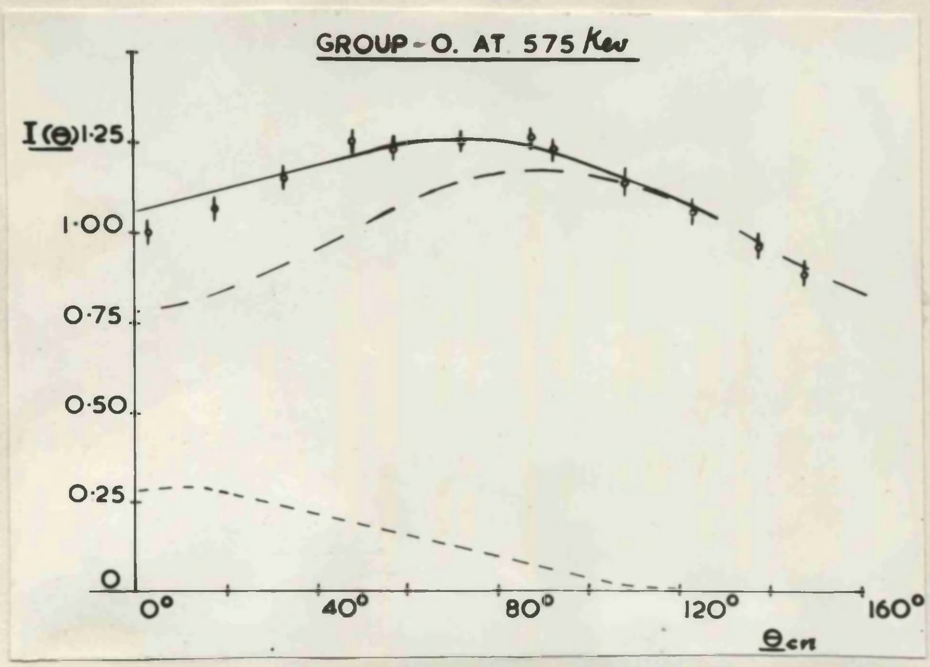


(f) At E_D = 650 Kev. using the third target assembly.

Fig. III. 6 The angular distributions of the P_o group of protons from the $^{10}B(d,p)^{11}B$ reaction.

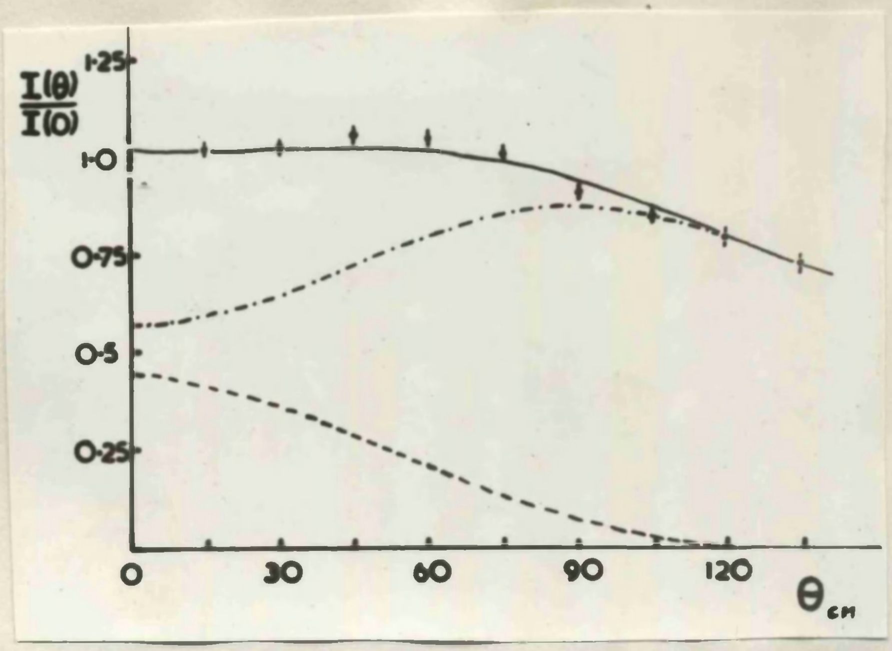


(c) at E_D = 575 Kev. (2nd target assembly).

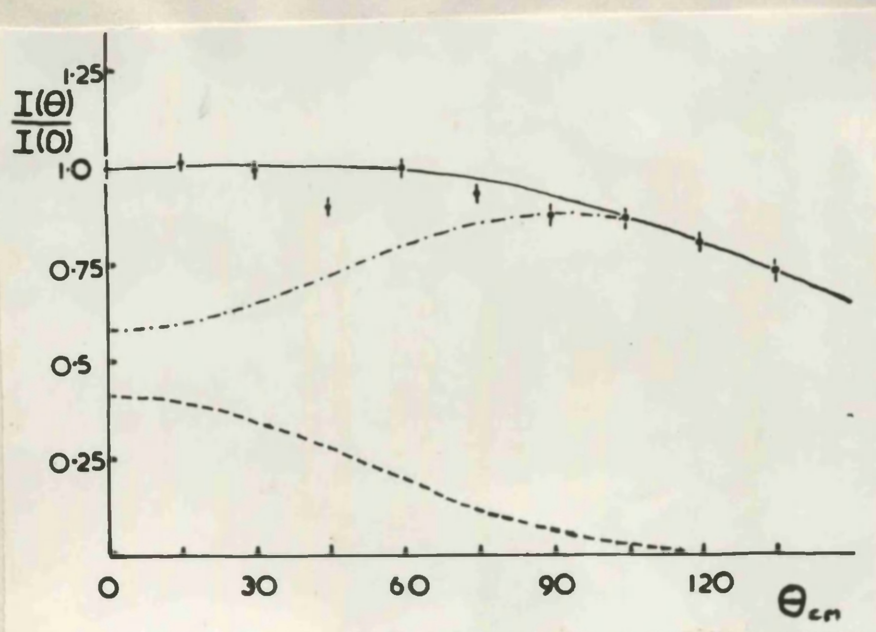


(d) Repeat at E_D = 575 Kev. using the third target assembly

Fig. III. 6 The angular distributions of the P_o group of protons from the $^{10}B(d,p)^{11}B$ reaction.



(a) at E_D = 350 Kev. (2nd target assembly)



(b) at E_D = 500 Kev. (2nd target assembly)

Fig. III. 6 The angular distributions of the P_o group of protons from the $^{10}B(d,p)^{11}B$ reaction. The dot-dash curve represents the component due to the formation of a compound nucleus and has the form $W_\theta = P_o - 0\cdot25\ P_2$. The dashed cur represents the stripping component for $\ell_n = 1$ and R = $5\cdot8 \times 10^{-13}$ cms. according to the treatment of Bhatia et al.

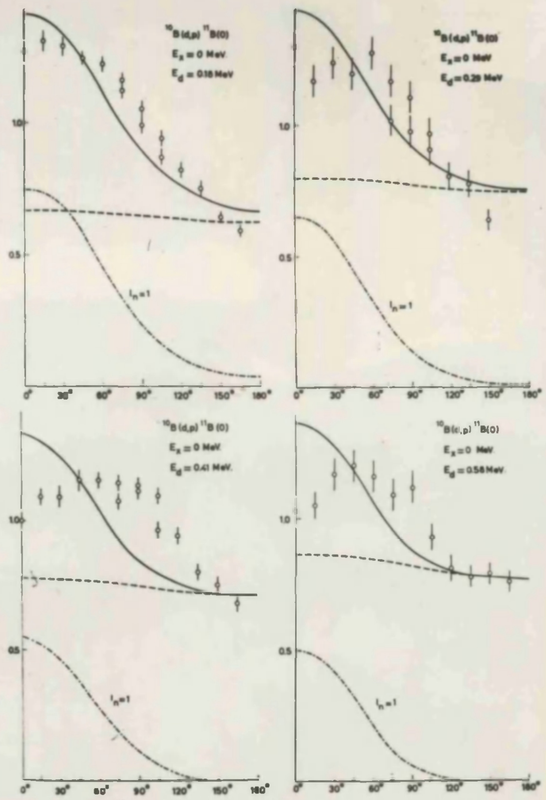


Fig. 1. Angular distributions of $^{10}B(d, p)^{11}B$ group (0) on arbitrary scale in laboratory coordinates. The full curve is the sum of a stripping contribution for $l_n = 1$ (dot-dash curve) and an isotropic contribution for compound nucleus formation (dashed curve).

Fig. III. 5 The results of Paris (1954)

and the isotropy of the γ-ray detection system was checked against the $^{19}F(p,\alpha,\gamma)^{16}O$ reaction. The main errors in the measurements were statistical and the probable errors were 3%; 2% and 3% for the P_1, P_2, P_3 groups respectively. The experimental results are shown in fig. III. 10(b) and the analysis is given in table III. 3. In this analysis a correction of 15% was made to the coefficients of P_2 to allow for the finite solid angles subtended by the two detectors.

III.4 RESULTS AND INTERPRETATION.

The results of these experiments are most logically treated by considering the proton groups one at a time starting with group 0.

(a) Group 0.

The spins of the ground states of ^{10}B and ^{11}B are known to be 3(+) and $\frac{3}{2}$(-), respectively. Thus the minimum value, and hence the most likely value, of the angular momentum of the neutron at the moment of capture is 1 according to stripping theory. The results of Holt (1953) and Evans (1954) suggest that this is the only value of ℓ_n which contributes to the reaction. Although Paris et alia (1954) interpreted their experimental results as showing that the reaction proceeds via stripping with $\ell_n = 1$ even at low energies of the deuterons, fig. III. 5 shows that the experimental results only agree with theory in a qualitative manner.

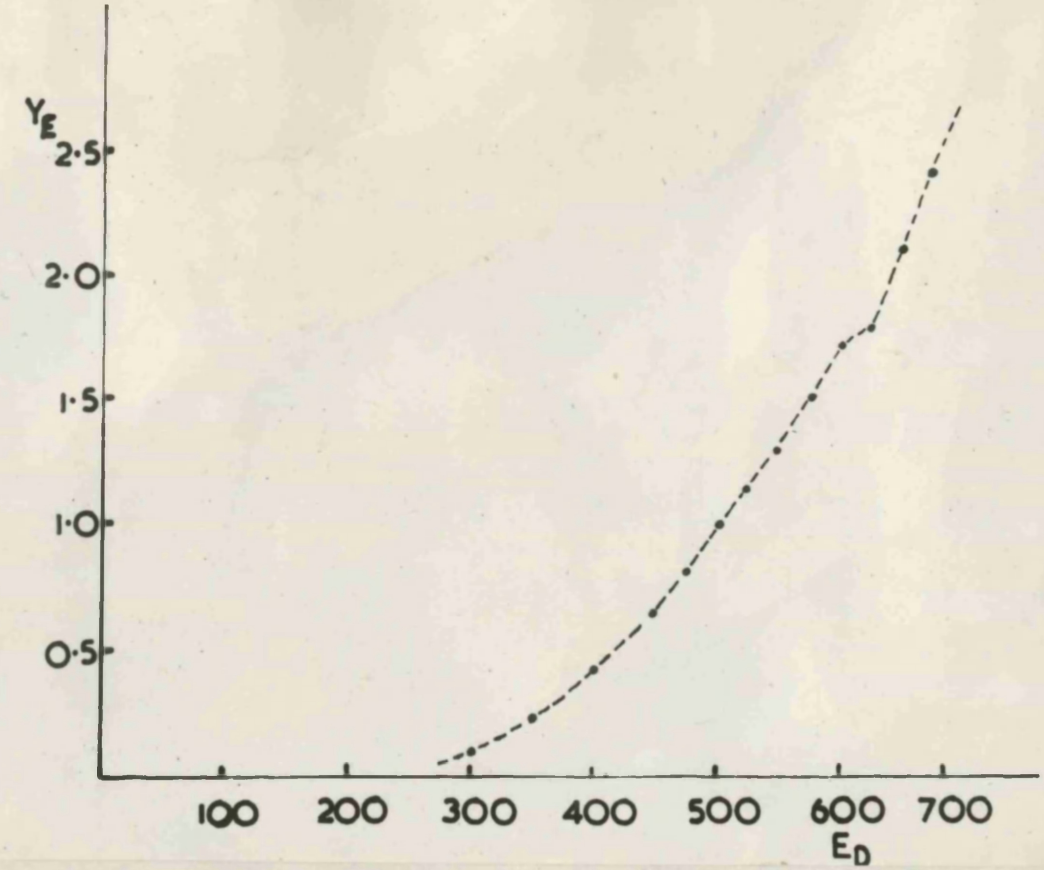
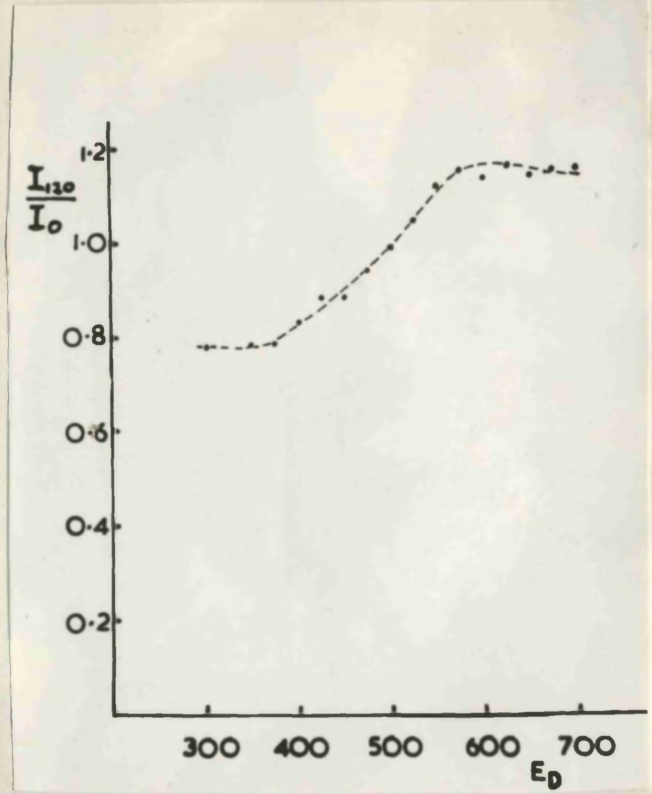


Fig. III. 7 The excitation curve for the P_0 group of protons from the $^{10}B(d,p)^{11}B$ reaction.

The presence of a change of slope at 575 Kev. in both the excitation curve in fig. III. 7 and the curve of $\frac{I_{120}}{I_o}$ in fig. III. 8(a) suggests that there may be a resonance in a compound nucleus reaction at this energy. The angular distribution of the P_o group of protons for this value of E_D is almost symmetrical about 90^o. This is suggested by the original measurement, which is shown in fig. III. 6(c), and is confirmed in fig. III. 6(d), which shows the later measurement. It is possible to analyse this angular distribution into two components, one with the form of a stripping distribution and the other with the form $A\ P_o + B\ P_2$ where P_o and P_2 are Legendre polynomials. When the stripping distribution has the form calculated from the theory of Bhatia using $\ell_n = 1$ and $R = 5{\cdot}8 \times 10^{13}$ cms., one finds that the other component has the form $A\ (P_o - (0{\cdot}25 \pm 0{\cdot}05)\ P_2)$.

If the angular distributions for this group of protons, that were obtained with other values of the energy of the deuterons, are analysed in this manner one finds that they appear to consist of different ratios of the same two components. No other values of R, ℓ_n, or the coefficient of P_2 make a consistent interpretation of the results possible. The various parts of fig. III. 6 show the experimental points and the two components with their sum for each angular distribution. When the intensities of the two components are integrated over the full 4π solid angle



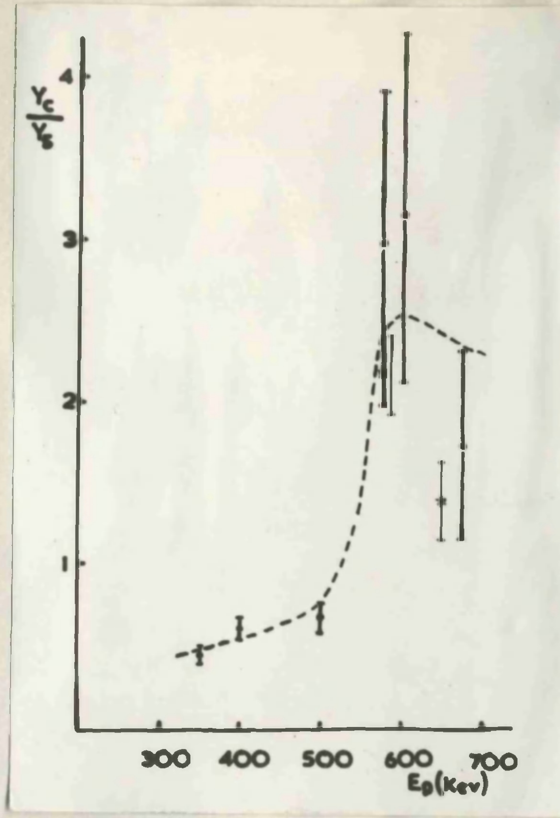


Fig. III. 8

(a) The variation with the energy of the deuterons of the ratio $\frac{\text{Intensity at } 120^\circ}{\text{Intensity at } 0^\circ}$ for the P_o protons from the $^{10}B(d,p)^{11}B$ reaction.

(b) The variation with the energy of the deuterons of the ratio

$$\frac{\text{Yield from the Compound Nucleus Reaction}}{\text{Yield from the Stripping Reaction}}$$

for the same P_o group of protons. The dots represent the earlier measurements of Deuchars and Wallace. The crosses represent the later measurements of Wallace and Storey.

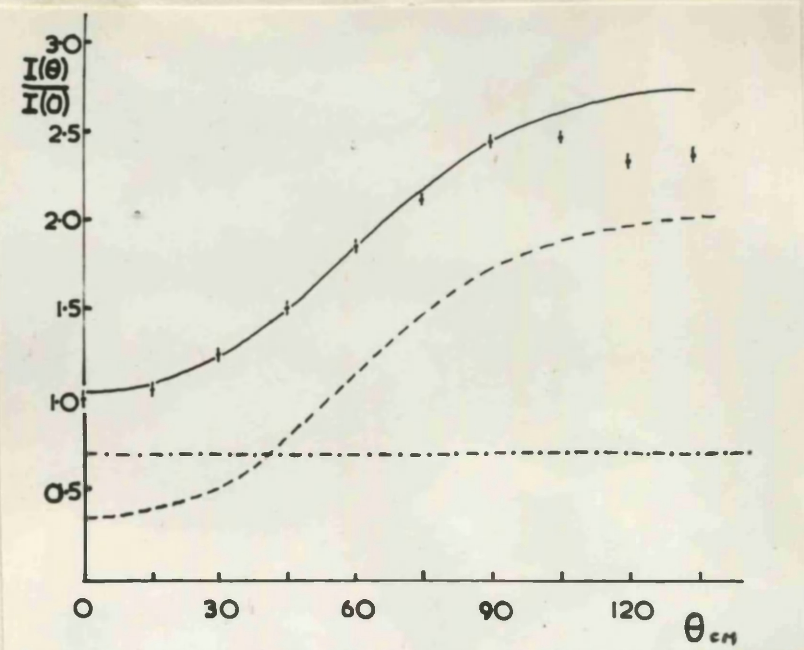
their ratio varies with energy as shown in fig. III. 8. The results are included of some measurements, which were made at 400 Kev. and 600 Kev. with the original apparatus, and they show reasonable agreement with the later results. The experiments, which used the second type of apparatus, seemed to show that the ratio of the compound nucleus reaction to the stripping reaction had a maximum at 575 Kev. However, the errors were too large to make this definite. In the light of the results, which were obtained later with the third type of apparatus, this conclusion now seems quite definite.

Since the stripping component has a pronounced forward maximum and virtually zero intensity at 120°, the curve in fig. III. 8 of the variation with energy of $\frac{I_{120^\circ}}{I_{0^\circ}}$ would be expected to show a pronounced change in region near 575 Kev., as it does in fact.

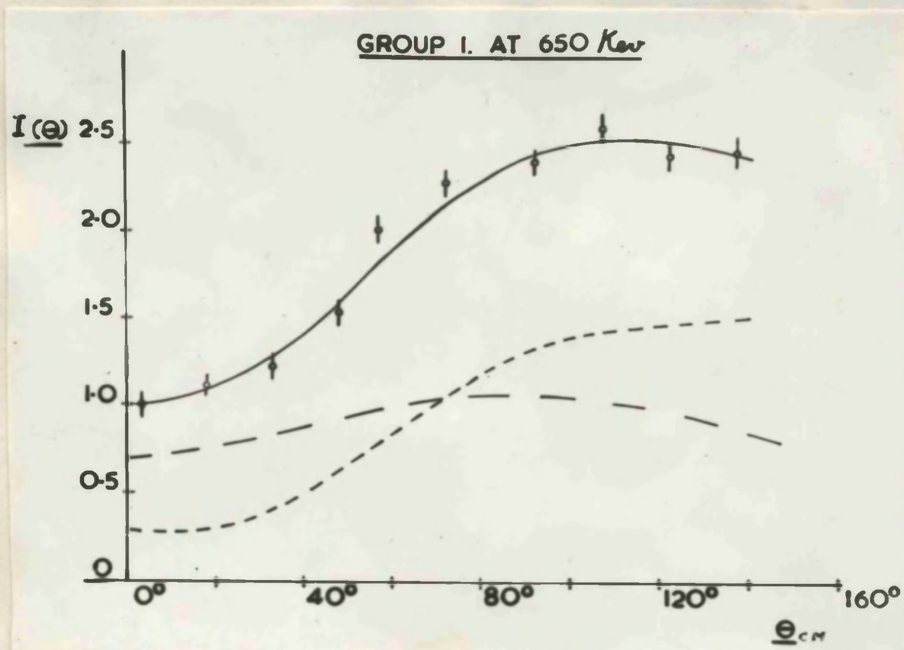
When protons are emitted by the decay of a single level in a compound nucleus they have an angular distribution that is symmetrical about the direction at 90° to the direction of the radiation which formed the level. Moreover, the intensity with which the level is formed, and hence protons are emitted, should show a resonance at some value of the energy of the bombarding particle. In contrast to this is the situation in which the protons are produced by a stripping mechanism. Here the angular distributions have a forward maximum whose position varies with the energy of the incoming particle, and the excitation function increases steadily with the energy of the bombarding particle.

It seems reasonable to believe, therefore, that the observed angular distributions and excitation function show that the P_0 group of protons are produced by two contrasting modes of interaction of the ^{10}B nuclei with the incident deuterons. The less important of these at the values of E_D being considered is stripping. The other is the formation of a broad level at 25·7 Mev. in ^{12}C by deuterons with a resonance energy of 575 Kev. The anisotropic angular distribution of the protons coming from this resonance shows that neither the deuterons nor the protons can be s-wave and the level cannot have spin zero. Because the cross-section for this reaction is fairly high, as is shown by table III, 1, it seems likely that the level is formed by p-wave deuterons and hence has spin 1, 2, 3, or 4 and negative parity. The lowest partial wave of protons that can come from the level must then be d-wave since the ground state of ^{11}B has negative parity. A search for a γ-ray going from this level to the ground state, or one of the low lying states, of ^{12}C was fruitless showing that the spin of the resonance level is probably 3 or 4.

It may be wrong to think of this level as being discrete in the manner of most bound states since the

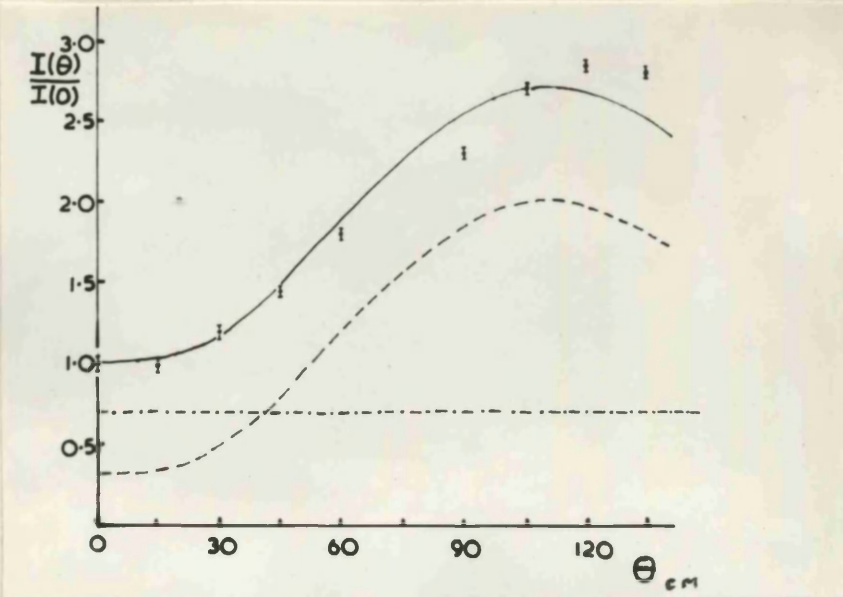


(e) At E_D = 675 Kev.using the second target assembly

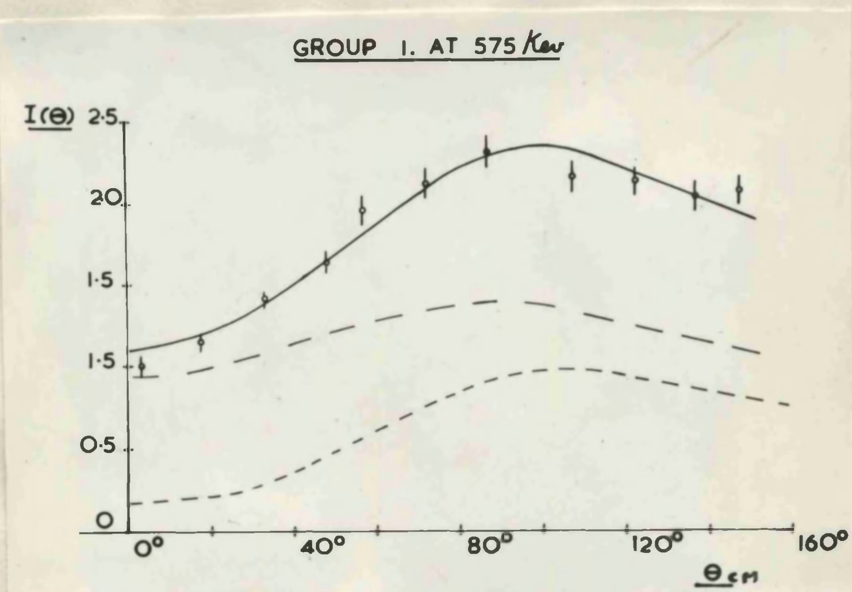


(f) At E_D = 650 Kev.using the third target assembly.

Fig. III. 9 The angular distributions of the P_1 group of protons from the $^{10}B(d,p)^{11}B$ reaction.

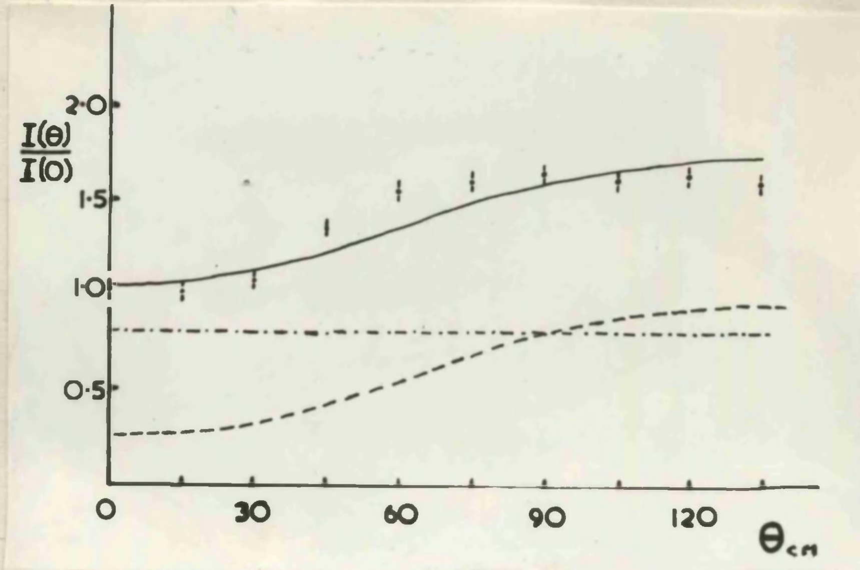


(c) At E_D = 575 Kev. using the second target assembly

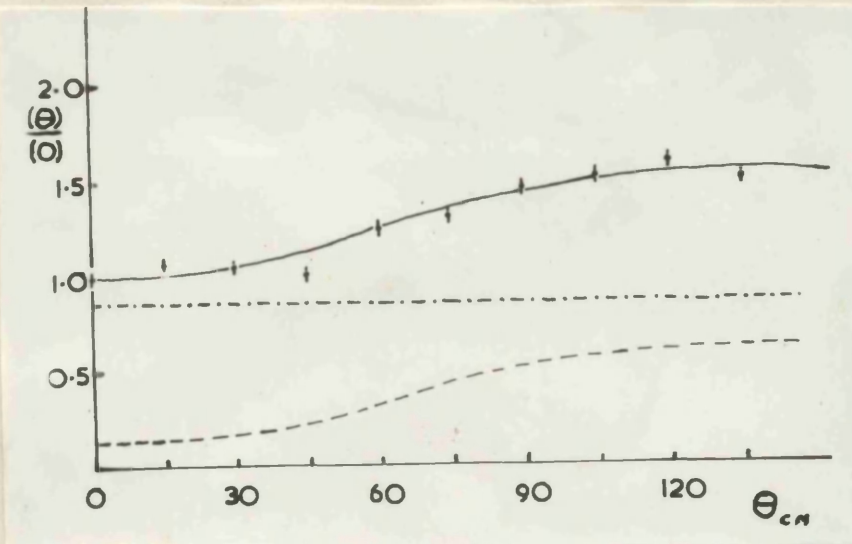


(d) At E_D = 575 Kev. using the third target assembly.

Fig. III. 9 The angular distributions of the P_1 group of protons from the $^{10}B(d,p)^{11}B$ reaction.



(a) At E_D = 350 Kev. using the second target assembly.



(b) At E_D = 500 Kev. using the second target assembly.

Fig. III. 9 The angular distributions of the P_1 group of protons from the $^{10}B(d,p)^{11}B$ reaction. The dashed curve represents the stripping component as calculated from the Bhatia formula using $\ell_n = 3$ and $R = 5{\cdot}8 \times 10^{-13}$ cms. The dot-dash curve is the component due to the formation of a compound nucleus. It is given as isotropic in the early curves, and has the form $P_0 - 0{\cdot}25\ P_2$ in the later ones.

level density and widths must be large at an excitation of 25·7 Mev.. A more likely description of the situation is that the other levels in this region of energies have spins and parities which make their formation by the capture of a deuteron unlikely, e.g. a 0(–) level could only be formed by deuterons with angular momentum 3.

(b) Group 1.

Table III. 2 shows that there is considerable disagreement about the value of angular momentum of the neutron which is captured to form this level. The angular distributions, which are shown in fig. III. 9, give qualitative agreement with the stripping curves as calculated by the treatment due to Bhatia when the value of ℓ_n is 3 and the value of R is $5{\cdot}8 \times 10^{-13}$ cms. If an isotropic background is subtracted the agreement is better, and if a background of the form $P_0 - 0{\cdot}28\ P_2$ is subtracted, as in fig. III. 9(d) and (f), the agreement is extremely good.

Figs. III. 10(a) and (b) show that the angular correlations for the 2·14 Mev. γ-ray and this proton group are isotropic within very small limits at two values of E_D, viz. 500 Kev. and 600 Kev. This would suggest that the spin of the 2·14 Mev. level is $\frac{1}{2}$.

In direct conflict with this interpretation of the results are the experiments of Evans et alia (1954) and

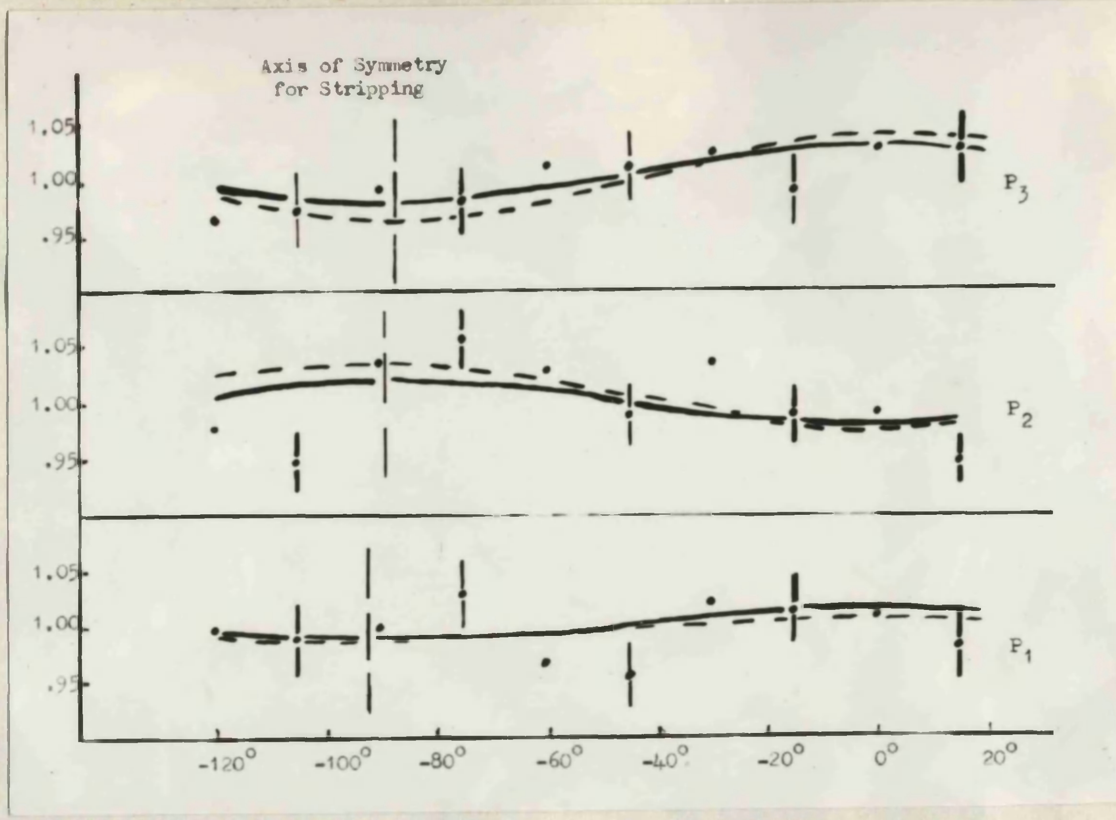
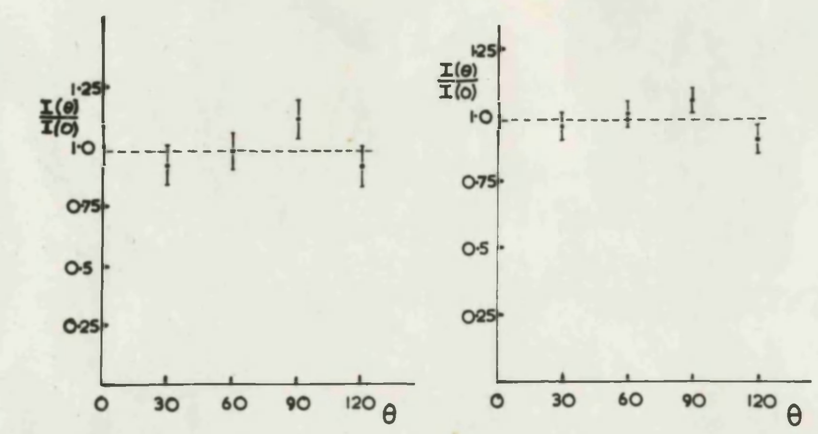


Fig. III. 10(b) The angular correlations at E_D = 600 Kev. The angles θ are measured between the directions of the beam of deuterons and the γ-rays. The proton counter was at 65° to the direction of the beam of deuterons. Two interpretations of the curves are illustrated, viz the dashed curve uses the axes of symmetry, that are postulated by the stripping theory, while the smooth curve uses the axes of symmetry that are proposed on the compound nucleus theory.



(i) P_1 proton and 2·14 Mev. γ-rays

(ii) P_2 protons and 4·46 Mev. γ-rays

Fig. III. 10(a) The angular correlations at E_D = 500 Kev. between protons(at 45° to the direction of the beam of deuterons)and γ-rays. The angle θ is measured between the directions of the γ-rays and deuterons.

Maslin et alia (1956). Evans measured the angular distribution of the protons from the $^{10}B(d,p)^{11}B$ reaction when the deuteron energy was 7·7 Mev.. He found that $l_n = 1$ gave the greatest agreement between stripping theory and the experimental results, although the agreement was not as good as one would have expected. However, Maslin et alia have measured the angular distribution of the corresponding group of neutrons from the $^{10}B(d,n)^{11}C$ reaction using 8 Mev. deuterons. The results of this measurement shows excellent agreement with the theoretical shape for the stripping distribution where $l_p = 1$. As ^{11}C and ^{11}B are mirror nuclei it is most unlikely that the properties of their levels are very different. Thus one must conclude that for large values of E_D the value of l_n should be 1.

In the intermediate energy region i.e. 0·9 Mev. $\leqslant E_D \leqslant$ 3·0 Mev. Marion et alia found that if there was any stripping the value of l_n was greater than 2.

There does not seem to be any doubt, however, that the γ-ray, by which the 2·14 Mev. level decays to the ground state, has an isotropic nature. The measurements of Thirion and Gorodetsky confirm that the (p,γ) correlation is isotropic for the $^{10}B(d,p)^{11}B$ reaction. Moreover, Blair et alia (1955) have shown that the 2·14 Mev. γ-ray has an isotropic angular distribution when it is formed by the $^{11}B(p,p^{1},\gamma)^{11}B$ reaction.

TABLE III. 3 The (p,γ) angular correlations in $^{10}B(d,p)^{11}B$

Proton Group	γ-ray	Angular Correlation+ θ.w.r.t. stripping axes	Angular Correlation* θ.w.r.t. deuteron direction
P_1	2·14 Mev.	$P_o-(0{\cdot}008\pm0{\cdot}03)P_2$	$P_o+(0{\cdot}016\pm0{\cdot}03)P_2$
P_2	4·46 Mev.	$P_o+(0{\cdot}035\pm0{\cdot}02)P_2$	$P_o-(0{\cdot}024\pm0{\cdot}02)P_2$
P_3	5·03 Mev.	$P_o-(0{\cdot}050\pm0{\cdot}03)P_2$	$P_o+(0{\cdot}034\pm0{\cdot}03)P_2$

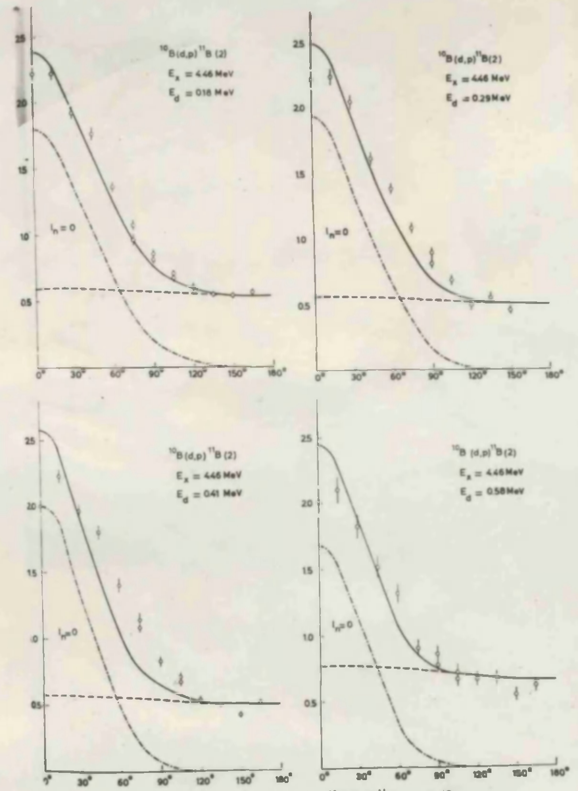
\+ ie experimental correlation when analysed as a pure stripping reaction

* ie experimental correlation when analysed as a pure compound nucleus reaction.

The errors, which are quoted, are statistical.

One is forced to the conclusion that either the level has spin $\frac{1}{2}$, which would mean that $\ell_n = 3$ and the results of Evans and Maslin have been misinterpreted, or that this isotropy is coincidental. If the neutrons, which form ^{11}B in this level have $\ell_n = 1$ then the spin may be $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ but the parity must be minus. A level which is $\frac{3}{2}^{(-)}$, $\frac{5}{2}^{(-)}$, or $\frac{9}{2}^{(-)}$ would decay to the $\frac{3}{2}^{(-)}$ ground state of ^{11}B by a mixed multipole transition. If this mixing was in the correct ratio the coefficients of P_2 would cancel leaving an isotropic distribution e.g. if the spin is $\frac{3}{2}$ the ratio of E_2 to M_1 would be $-\frac{1}{\sqrt{15}}$ which is quite a reasonable value. No measurement on the 2·14 Mev. γ-ray itself could distinguish between this accidental isotropy and the alternative case in which the level has spin $\frac{1}{2}$. Since the measurements on the protons, which leave the nucleus in this state, are in conflict one cannot hope to decide the question by a study of the $^{10}B(d,p)^{11}B$ reaction. The alternative seems to be to study either the $^{10}B(n,\gamma)^{11}B$ reaction or the $^{7}Li(\alpha,\gamma)^{11}B$ reaction. Jones et alia (1952) have studied the latter reaction, but their results were ambiguous.

If subsequent experiments show that the 2·14 Mev. level in ^{10}B does not have spin $\frac{1}{2}$, then the angular distributions, which are shown in fig. III. 9, demonstrate that stripping plays no part in the reaction at these low energies of the deuterons.



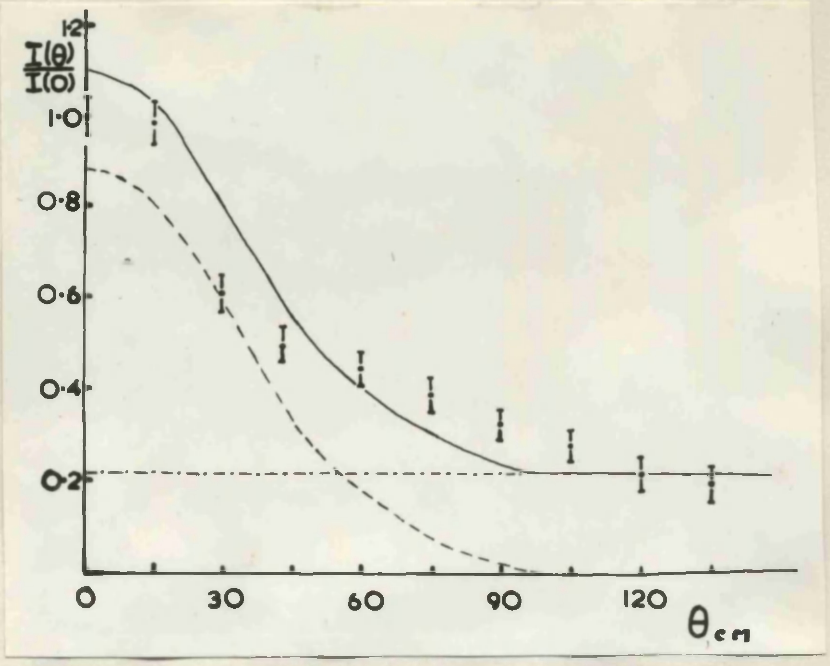
Angular distributions of $^{10}B(d, p)^{11}B$ group (2).

Fig. III. 11. The angular distributions as measured by Paris (1954).

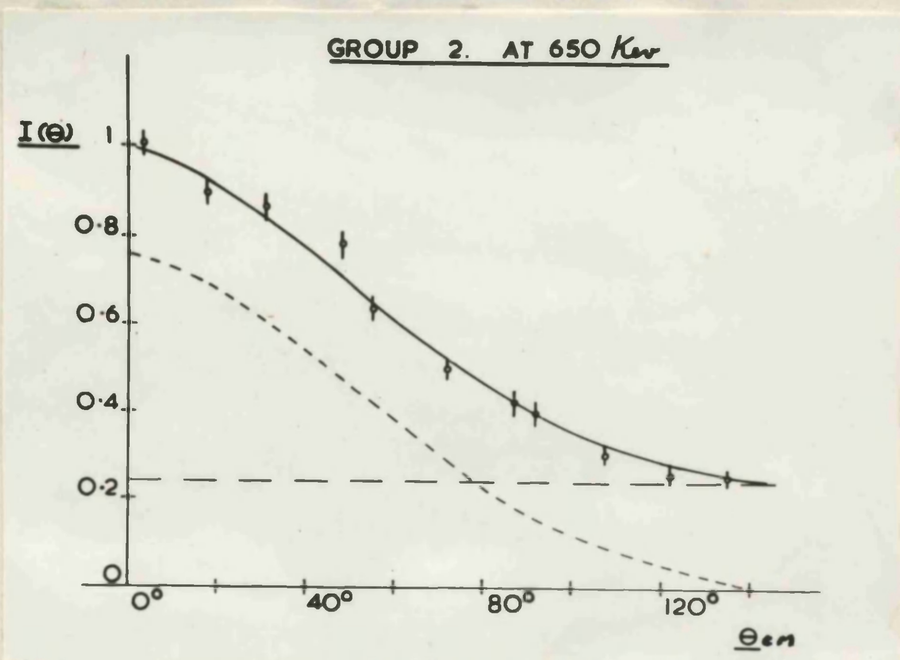
(c) Group 2.

Evans et alia found that when ^{10}B was bombarded with deuterons of 7·7 Mev. the protons, which leave ^{11}B in the level at 4·46 Mev., had the angular distribution corresponding to a value of 1 for ℓ_n. Similarly, Maslin et alia found that $\ell_p = 1$ gave the correct angular distribution for the corresponding group of neutrons from the $^{10}B(d,n)^{11}C$ reaction when $E_D = 8$ Mev. At lower values of E_D Paris et alia found that their results suggested that $\ell_n = 0$. The measurement of the angular correlation between the protons and the γ-rays by Thirion would appear to substantiate this latter view, as an isotropic correlation corresponds to a value of $\frac{1}{2}$ for the spin of the level, or a value of 0 for ℓ_n. However, as fig. III. 11 shows, the agreement between the experimental results of Paris and the theoretical curves is qualitative rather than quantitative. One should also remember that the errors in Thirion's measurements are rather large.

Both $\ell_n = 1$ and $\ell_n = 0$ give maxima at 0^o in the angular distributions for values of $E_D = 600$ Kev. and $R = 5{\cdot}8 \times 10^{-13}$ cms according to the theory of Bhatia. However, the maximum is much more pronounced for the case where $\ell_n = 0$. When the angular distributions, which are shown in fig. III. 12(a) and (c), were analysed the pronounced nature of the forward maximum suggested that

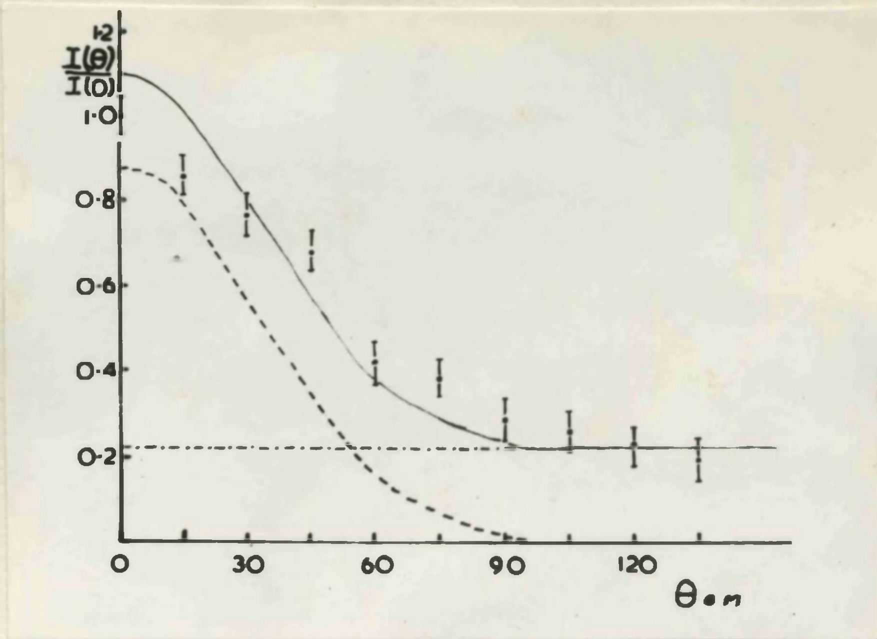


(c) At E_D = 675 Kev. using the second target assembly.

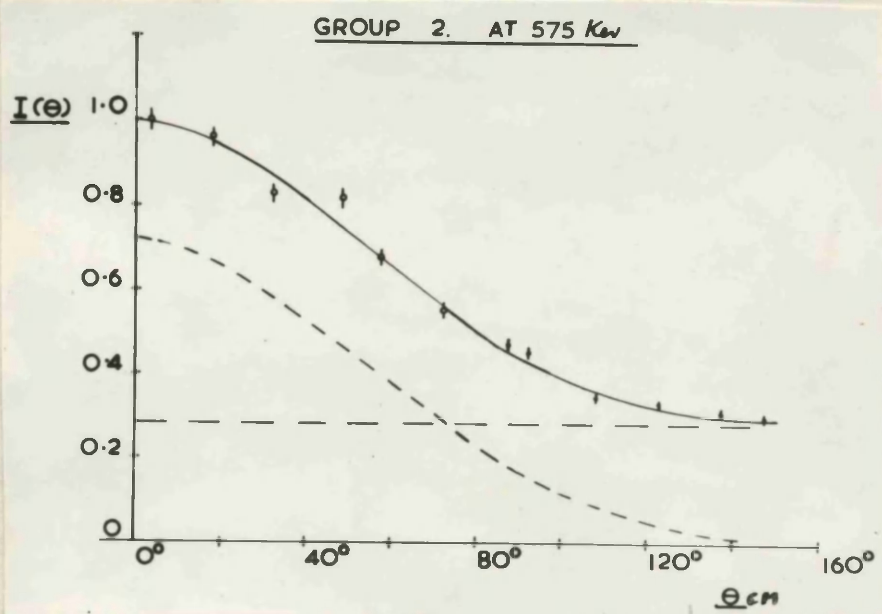


(d) At E_D = 650 Kev. using the third target assembly.

Fig. III. 12 The angular distributions of the P_2 group of protons from the $^{10}B(d,p)^{11}B$ reaction.



(a) At E_D = 575 Kev.using the second target assembly.



(b) At E_D = 575 Kev.using the third target assembly.

Fig. III. 12 The angular distributions of the P_2 group of protons from the $^{10}B(d,p)^{11}B$ reaction. The dashed curves represent the stripping component as calculated by the method of Bhatia using R = 5·8 and ℓ_n = 0 for the old curves, and ℓ_n = 1 for the new curves. The backgrounds are assumed to be isotropic in all the cases considered.

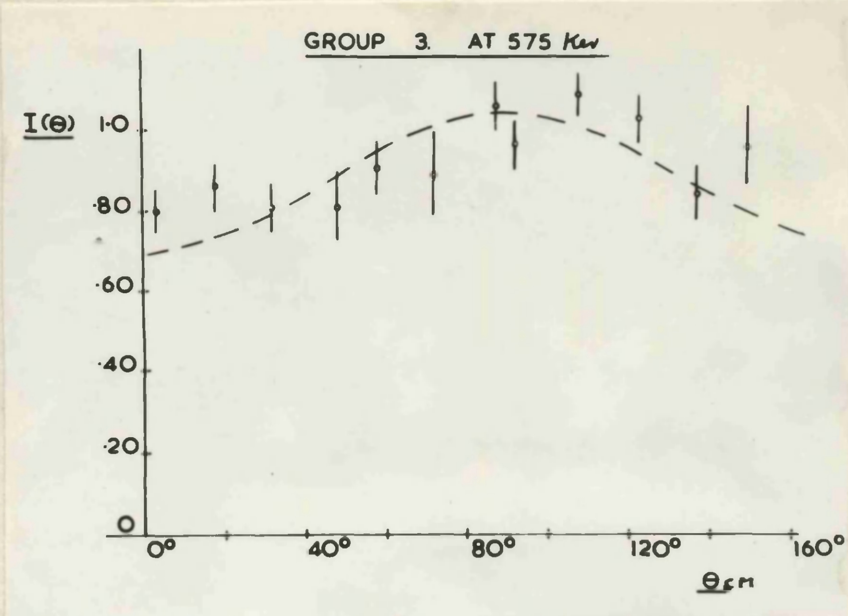
$\ell_n = 0$. The measurement of the angular correlation to give the isotropic shape shown in fig. III. 10(a) suggested that this interpretation was correct. The deviations of the points, on both the angular distribution graphs and the angular correlation graphs, from the smooth curves were ascribed to the large errors.

When the angular distributions, which are shown in fig. III. 11(b) and (d), were measured it was found that the deviations from the smooth curve of an $\ell_n = 0$ stripping shape plus an isotropic background were greater than the errors on the points. No adjustments of the background into the form $A\,P_o + B\,P_2$ would give better agreement because the points between 40^o and 90^o seemed to be significantly higher than they were expected to be from the theory. However, when the curves for $\ell_n = 1$ were tried, immediate agreement was obtained in each case between the experimental points and a curve made up from an isotropic component plus a stripping component. By comparing the points in the graphs in fig. III. 11 and fig. III. 12(a) and (c) with the curves for $\ell_n = 0$, one can see that the same region, viz. 40^o to 90^o, shows the experimental points as too large. This means that the sum of an isotropic background plus an $\ell_n = 1$ stripping curve would fit the points in these graphs as well.

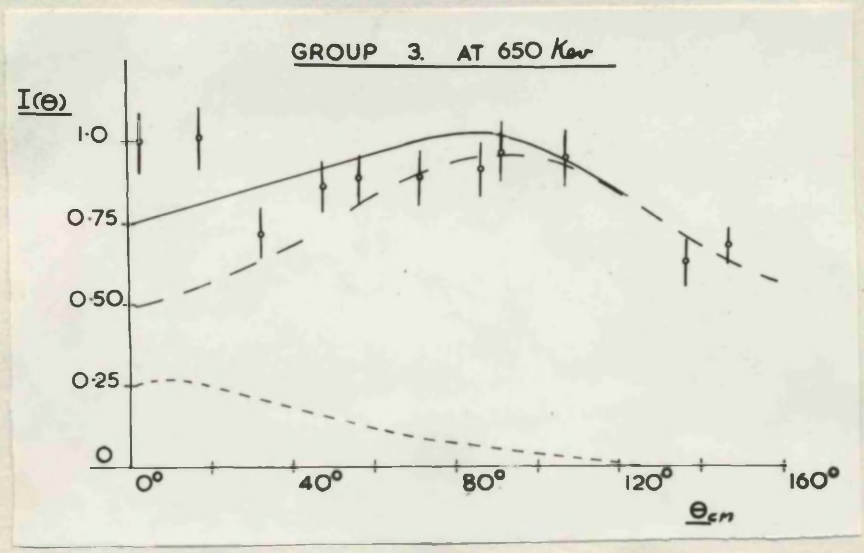
The results of the second measurement of the angular correlation between this group of protons and the 4·46 Mev.

γ-ray are shown in fig. III. 10(b). Although the errors on the points are about the same size as the deviations from the mean value there does seem to be a suggestion of a systematic anisotropy. By analysing the distributions by the method of least squares one can show that it has the form $A\,P_0 + 0{\cdot}035 \pm 0{\cdot}03\,P_2$ where P_0 and P_2 are Legendre polynomials of the angle between the direction of the γ-ray and the direction of the recoil nucleus (i.e. the captured neutron). A similar value is obtained for the angular correlation of the γ-rays with the protons themselves, which is the relevant measurement if one assumes that the reaction proceeds via a compound nucleus. As the anisotropy is very small one cannot use these measurements of the correlation to distinguish between the importance of the competing processes.

However, if one assumes that only stripping is important, then the correlation should have the shape appropriate to the case where $J_I = 3(+)$; $\ell_n = 1$; $J_F = \frac{3}{2}(-)$ and the parity of the intermediate state is minus. There are four possible values of the spin of the intermediate level, viz. $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, $\frac{9}{2}$ but Jones et alia (1952) showed that it was a $\frac{5}{2}(-)$ level in their studies of the $Li^7(\alpha,\gamma)^{11}B$ reaction. A $\frac{5}{2}(-)$ level would decay to the ground state by a mixture of E_2 and M_1. The ratio would have to be $0{\cdot}1$ E_2 to M_1, if the ratio



(a) At E_D = 575 Kev. using the third target assembly



(b) At E_D = 650 Kev. using the third target assembly

Fig III. 13 The angular distributions of the P_3 group of protons from the $^{10}B(d,p)^{11}B$ reaction. The curve with the small dashes has the stripping distribution for $\ell_n = 1$ and $R = 5{\cdot}8 \times 10^{-13}$ cms. The curve with the large dashes is the compound nucleus component with the form $P_o - 0{\cdot}27\ P_2$. The large errors are caused by the subtraction of the large background which can be seen in fig. III. 4(c).

of the intensities of the $\frac{7}{2}$ and the $\frac{5}{2}$ channel spins is $\frac{3}{2}$. These values for the mixing ratios of multipoles and channel spins are perfectly reasonable.

While one could in theory analyse the angular correlation taking into account the mixing of stripping reactions and compound nucleus reactions the actual values involve so many arbitrary parameters that no useful information can be gained from the calculation.

It seems reasonable to believe that the isotropic component in the angular distributions represents reactions which proceed via a compound nucleus. This background is so small that any anisotropy of the form $P_o - A\,P_2$ would fit the observations, where $-0{\cdot}1 < A < +0{\cdot}1$. Thus no explanation for the isotropic nature of these backgrounds, as compared to the ones for the P_o group, is necessary.

(d) Group 3.

The measurements of the angular distributions for this group of protons have only been made for values of E_D of 575 Kev. and 650 Kev.. The errors on these measurements are so large that one cannot analyse the angular distributions systematically. From the similarity between the results for this group and the P_o group, however, it seems clear that $\ell_n = 1$ in this case. The angular correlation between the proton group and the subsequent 5·03 Mev. γ-ray seems to be anisotropic according to fig. III. 10(b) and table III. 3. As no information is available about the spin and parity of the 5·03 Mev. level from other sources, and the results of the angular correlation would fit values of $\frac{3}{2}$, $\frac{5}{2}$, $\frac{9}{2}$ for the spin, all that can be stated is that the level has negative parity and spin $> \frac{1}{2}$.

(e) General.

As a result of these measurements on the reaction $^{10}B(d,p)^{11}B$ several points have become clear. At energies of less than 700 Kev. for the deuterons there are two competing processes. The first is the formation of a broad level at an excitation of 25·7 Mev. in ^{12}C by the absorption of a deuteron with 575 Kev. energy. This level then emits a proton to leave ^{11}B in one of its low lying excited states.

The second process is a stripping reaction in which one of the low lying levels of ^{11}B is formed by the absorption of a neutron. The angular momenta of the neutrons, which form the ground state and the levels at 4·46 Mev. and 5·03 Mev., are all 1 in units of $\hbar$. Then the two excited states decay by mixtures of E_2 and M_1 radiation to the ground state. In the cases of the stripping reactions, which form ^{11}B in its ground state and its level at 4·46 Mev., the theory of Bhatia provides curves which fit the stripping component provided $R = 5{\cdot}8 \times 10^{-13}$ cms. This value of R is the same as that used at higher energies of the deuterons.

TABLE III. 4 The $^{24}Mg(d,p)^{25}Mg$ Reaction.

Group	Endt et alia 1953	Holt et alia 1953		Author 1956			
	Q-values	ℓ_n	R_{Bhatia}	ℓ_n	R_{Bhatia}	Phase Angle δ	Cross-section* milli-barns per steradian
P_o	5·10 Mev.	2	$\doteq 5{\cdot}5 \times 10^{-13}$ cms	2	$6{\cdot}7 \times 10^{-13}$ cms	+ 78°	$2{\cdot}4 \times 10^{-4}$
P_1	4·52 Mev.	0	$= 7{\cdot}4 \times 10^{-13}$ cms	0	$6{\cdot}7 \times 10^{-13}$ cms	− 52°	$8{\cdot}0 \times 10^{-4}$
P_2	4·12 Mev.	2	$= 5{\cdot}5 \times 10^{-13}$ cms	2	$9{\cdot}5 \times 10^{-13}$ cms	0°	$6{\cdot}0 \times 10^{-4}$

* measured with E_D = 600 Kev. and with the proton counter at 65° to the direction of the beam of deuterons.

In the case of the reaction, which forms ^{11}B in its first excited state, the results of these experiments confirm those of Paris et alia and Marion et alia, but conflict seriously with those of Evans and Maslin. It is not possible to say which interpretation is the more reliable.

III.5 INTRODUCTION TO THE REACTION $Mg^{24}(d,p)^{25}Mg$.

The Q values for the reactions, which produce the three most energetic groups of protons from the bombardment of ^{24}Mg with deuterons, were measured by Endt et alia (1952)$_{(b)}$ to be 5·10 Mev., 4·52 Mev. and 4·12 Mev. respectively. Only one series of measurements have been made of the angular distributions of these groups of protons. Using deuterons with 8·2 Mev. energy Holt et alia (1953) bombarded a target of natural Magnesium and they found that they had obtained stripping curves for the values of ℓ_n of 2, 0 and 2. For the two most energetic groups of protons the angular distributions only fitted the theoretical shapes near the peaks. The differences, that occurred elsewhere, were believed to be due to a small isotropic background from the competing compound nucleus reactions. In the case of the third group the experimental points at small angles had fairly large errors due to the strong forward maximum of the 4·52 Mev. group overlapping this group. Moreover the most energetic group from the reaction $^{26}Mg(d,p)^{27}Mg$

could not be separated at all from this group. The fact that the experimental curve seemed to be compounded of a part with $\ell_n = 0$ and another with $\ell_n = 2$ was explained by ascribing the former to the group from the reaction in ^{26}Mg which was known to give this shape. On this basis the value of $\ell_n = 2$ was given to the third group from the reaction with ^{24}Mg. Holt states that the value of R was $5{\cdot}3 \times 10^{-13}$ cms. when the theory of Butler was used. In order to obtain the same values of ℓ_n from Bhatia's formula one required values of R of $7{\cdot}4 \times 10^{-13}$ cms. and $5{\cdot}5 \times 10^{-13}$ cms depending on whether $\ell_n = 0$ or 2.

The values of the spins and parities of the corresponding levels in ^{25}Al have been obtained by various studies of the reaction $^{24}Mg(p,\gamma)^{25}Al$, e.g. Varma et alia (1956), and are $\frac{5}{2}(+)$, $\frac{1}{2}(+)$, $\frac{3}{2}(+)$. If ^{25}Mg has a similar level scheme, as one would expect for a mirror nucleus, the ℓ_n values for the angular distributions of the three most energetic groups of protons should be 2, 0, 2.

III.6 EXPERIMENTAL METHOD.

The set of apparatus, which was used in the third series of measurements on the $^{10}B(d,p)^{11}B$ reaction, was used in this experiment. The direction of the protons was defined by the $\frac{1}{4}$" slit in the wall of the target chamber and they emerged through a $1{\cdot}7$ mg/cm^2 Mylar window. The protons then passed through another $\frac{1}{4}$" slit in a piece of

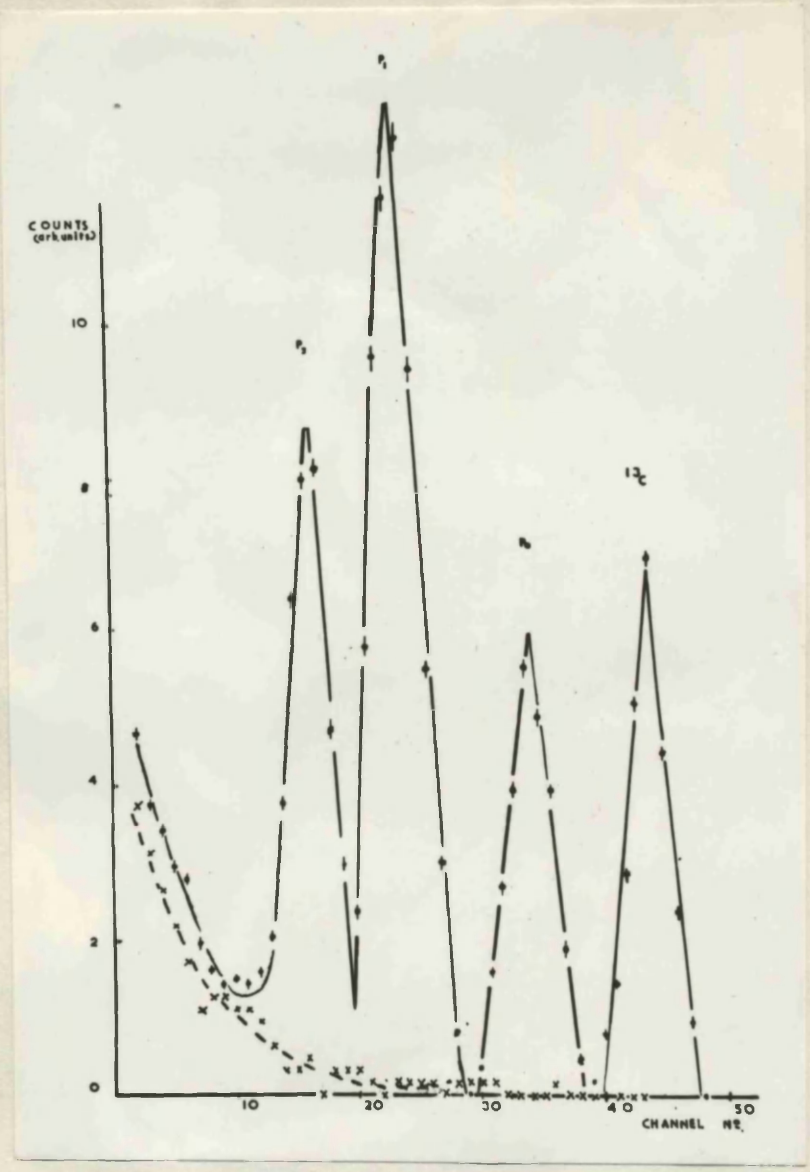


Fig III. 14. The energy spectrum of the protons from the $^{24}Mg(d,p)^{25}Mg$ reaction.

$\frac{1}{8}$" thick aluminium which was held onto the counter in such a way that the two slits were perpendicular. The counter consisted of a CsI crystal and photomultiplier arranged as shown in fig. III. 2(b), and fig. III. 14 shows an example of the energy spectra of the protons from the $^{24}Mg(d,p)^{25}Mg$ reaction. The counter was held in the movable arm which could be clamped at any angle to the direction of the beam of deuterons.

As fig. III. 14 shows, a strong peak of protons from the $^{13}C(d,p)^{14}C$ reaction was observed as well as the peaks from the $^{24}Mg(d,p)^{25}Mg$ reaction. In the lower region of the spectrum, which is not shown, very strong peaks from the $^{12}C(d,p)^{13}C$ reaction and the $^{2}D(d,p)^{3}T$ reaction could be seen as well. These three contaminations, viz. ^{13}C, ^{12}C, ^{2}D, came from the materials carried onto the target by the beam, or deposited from the vapours in the vacuum system of the High Tension Generator. By comparing the cross-sections for the $^{10}B(d,p)^{11}B$ reaction and the $^{24}Mg(d,p)^{25}Mg$ reaction, which are given in tables III. 1 and III. 4 respectively, one can see how small a percentage of the weight of the target these contaminations formed if the cross-section for $^{13}C(d,p)^{14}C$ is of the same order as the $^{10}B(d,p)^{11}B$ cross-sections.

The excitation function at 90° for the sum of the intensities of all three groups of protons from the $^{24}Mg(d,p)^{25}Mg$ reaction was measured first. The target

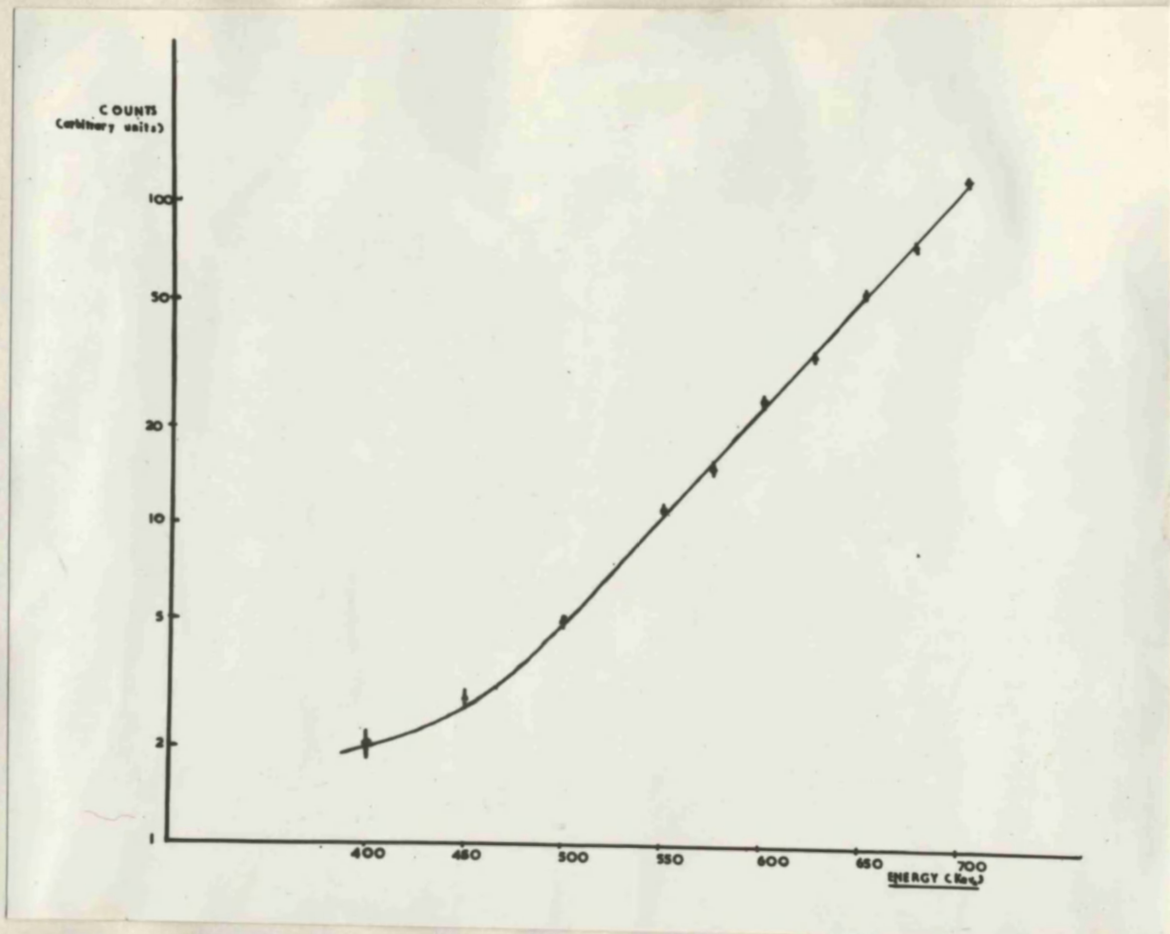


Fig. III. 15 The excitation function for the sum of the three groups of protons, i.e. $P_o + P_1 + P_2$, from the $^{24}Mg(d,p)^{25}Mg$ reaction.

chamber was insulated to form a Faraday cage and the charge, which was brought into it by the beam, was allowed to leak to earth through a current integrator. The pulses from the photomultiplier were fed by a cathode follower via a linear amplifier into two discriminators. These two discriminators were biased in such a way that the lower one only passed pulses from the P_2 peak and the region above it, while the upper discriminator only passed pulses from the region above the P_0 peak. By feeding the outputs of the two discriminators into two scalers, and then noting the difference between the numbers of counts that were registered by the scalers one can find the number of protons from the reaction in ^{24}Mg. The targets used in these measurements consisted of 50 μ gms/cm^2 of ^{24}Mg on 0·01" of copper and were obtained from A.E.R.E. Harwell. The excitation curve for the reaction, i.e. the plot of the numbers of counts per deuteron against the energy of the deuteron, was measured in 25 Kev. steps from 400 Kev. to 700 Kev. and is shown in fig. III. 15. As can be seen it has the form of a smooth exponential rise between 450 Kev. and 700 Kev. The actual values of the cross-sections at E_D = 600 Kev. were measured by displaying the spectrum on the pulse height analyser and integrating the numbers of counts in the separate peaks. The results of this measurement are given in table III. 4 and they provide an absolute value

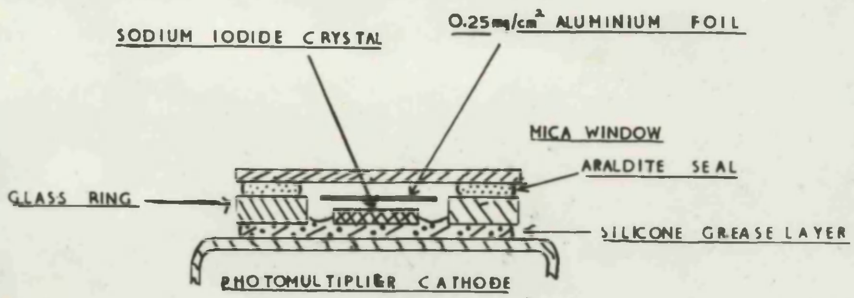


Fig. III. 16 A mounting for thin $NaI_{(Th)}$ crystals. The thicknesses of the Silicone grease layer and the araldite seal have been exaggerated to simplify the drawing.

for the scale of fig. III. 15.

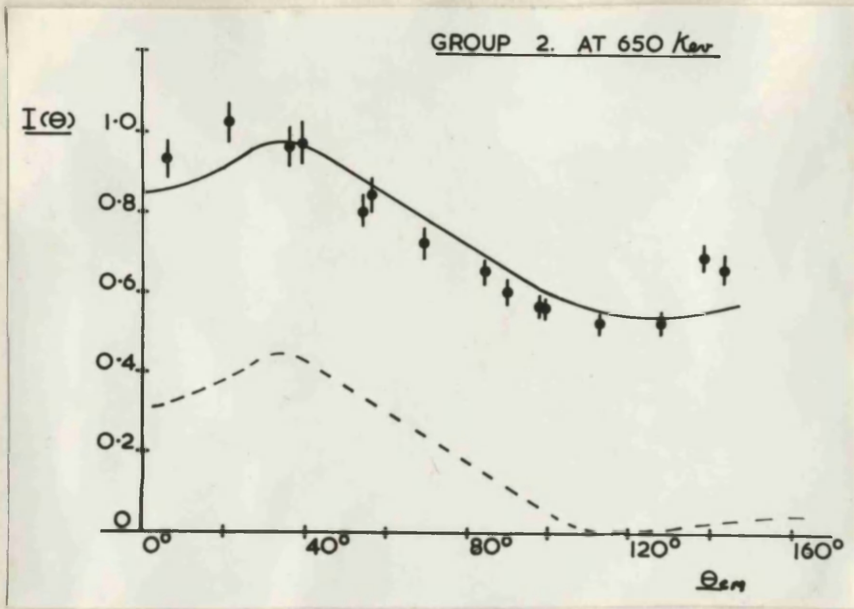
The steepness of the slope of the excitation curve meant that it was only possible to measure the angular distributions at a value of 650 Kev. for the energy of the deuterons. Below that value the yield was too low and at much above it the accelerator became unstable.

The angular distributions were measured in three parts because the target backing was almost as thick as the range of the protons. This thickness of target backing was chosen because the low yield of the reaction made it desirable to use large beam currents where possible. The three regions that were studied were 150° to 90°; 105° to 45°; -60° to 0°. For the first two the 50 μ gm/cm^2 targets of separated ^{24}Mg were used. For the third set of measurements a target of 100 μ gms/cm^2 of natural magnesium on 0·0005" copper was used and the beam currents were kept to a minimum, i.e. $< 10\,\mu$ amps. The monitor counter consisted of a NaI crystal mounted as shown in fig. III. 16 and it was placed at 90°; 150°; 60° in turn for the three groups of measurements. The pulses from this counter were amplified and then fed into a single channel analyser, which only recorded those pulses in the region of the three peaks from ^{24}Mg. The output of the single channel analyser was fed into the timing unit to control the time of counting at each angle. The resolution of this NaI$_{(Th)}$ detector was as good as that of the CsI detector, but it tended to deteriorate at about three weeks after the crystal was mounted.

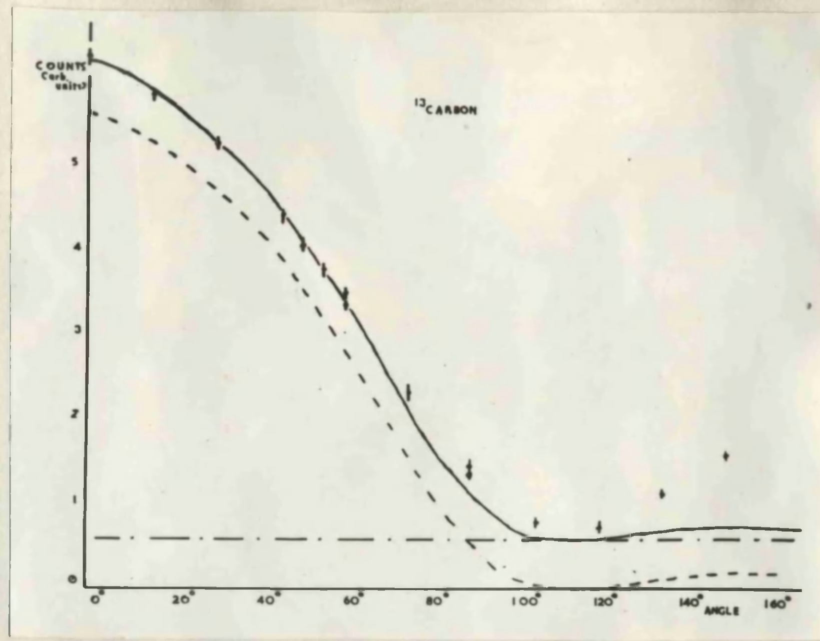
The output pulses from the CsI counter were amplified and then displayed on the pulse height analyser. It was found that a group of α-particles appeared to be present among the groups of protons, when the particles were observed as they came from the front of the target. A foil of 0·001" aluminium was placed between the crystal and the targets for the angles at which these α- particles were seen. This foil reduced the energy of the α-particles much more than it reduced the energies of the protons so that the former were removed from the part of the spectrum being studied.

The intensities of all the groups of protons were measured at 15° intervals from 0° to 150° and the three parts of each angular distribution were fitted together by using the values at the overlaps between the parts. Before the three parts were fitted, however, the zero degree position of the scale was compared to the direction of the beam of deuterons by the method already described for the $^{10}B(d,p)^{11}B$ reaction.

The main errors in the measurements were statistical and they were caused by the low counting rates that resulted from the low cross-sections. The P_o group was unaffected by the use of different targets, but the shapes

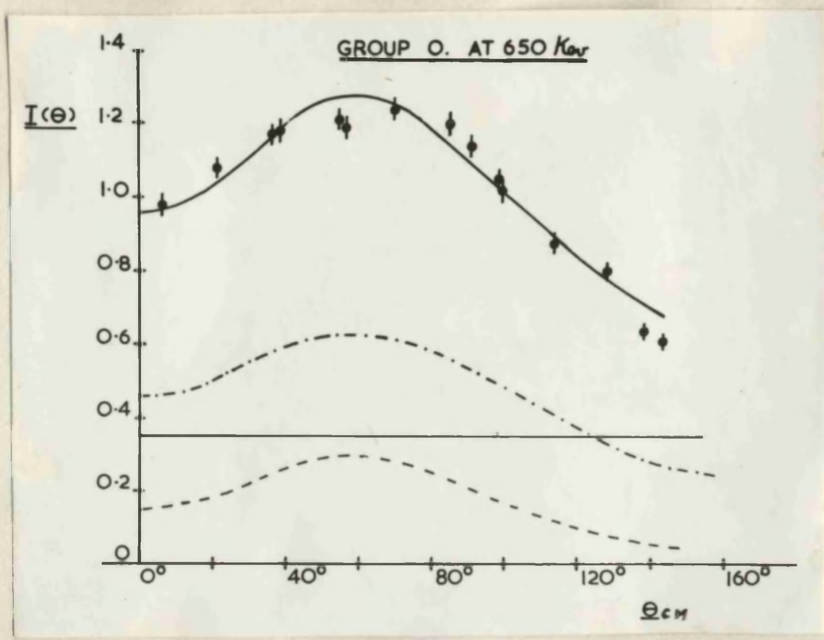


(c) P_2 Group.

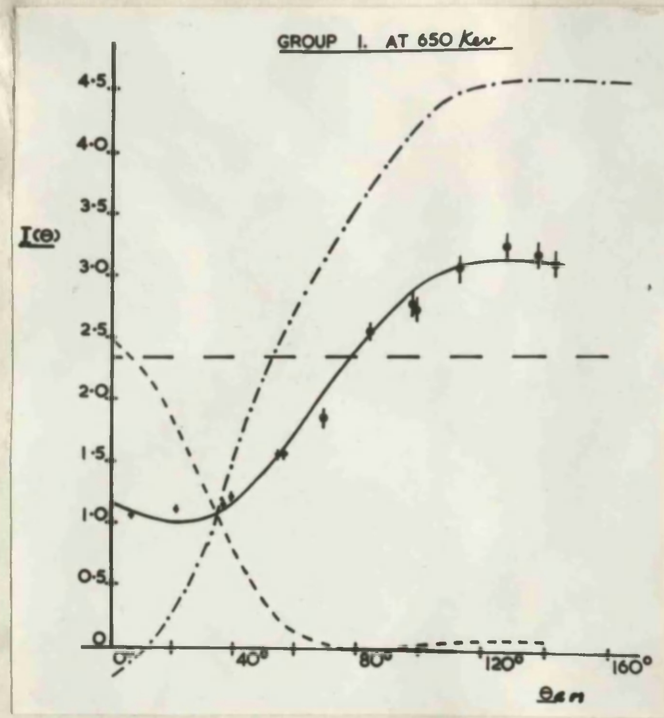


(d) $^{13}C(d,p)^{12}C$ angular distribution with $\ell_n = 1$ and $R = 5 \cdot 2 \times 10^{-13}$ cms.

Fig. III. 17 The angular distributions of the protons from the $^{24}Mg(d,p)^{25}Mg$ reaction. The dashed curve shows the stripping component as calculated from the theory of Bhatia using the values of ℓ_n and R shown in table III. 4



(a) P_o Group



(b) P_1 Group

Fig. III. 17 The angular distributions of the protons from the $^{24}Mg(d,p)^{25}Mg$ reaction. The dashed curve shows the stripping distribution as calculated from the theory of Bhatia using the values of ℓ_n and R given in table III.4.

of the angular distributions of the P_1 and P_2 groups may be in error in the region below 45^{o} due to the presence of protons from the other isotopes of magnesium. The errors from this source are unlikely to be greater than 5% and should in fact be very small, say $\sim 1\%$, as none of the angular distributions vary rapidly near 0^{o}. The errors in the points on the P_2 curve are larger near 0^{o} because the group of protons from the $^{2}D(d,p)^{3}T$ reaction overlap with the P_2 group at these angles. The effect of the small background, which can be seen below the P_2 and P_1 peaks in fig. III. 14 was estimated by making measurements with 0·050" aluminium between the target and the crystal. The shapes of the angular distributions of the three groups from ^{24}Mg and the one group from ^{13}C are shown in fig. III. 17. The shape for the ^{13}C group was also obtained by a measurement on a target of natural carbon (soot) and the two measurements agreed reasonably well. This makes one more confident about the results for the protons in the groups from the $^{24}Mg(d,p)^{25}Mg$ reaction.

III.7 RESULTS AND ANALYSIS.

The fig. III. 15 shows that the excitation function for this reaction increases smoothly with energy as would be expected if the stripping process predominates in this reaction. When one considers that the increased difficulty of penetrating the Coulomb barrier has reduced the cross-section by a factor of about one thousand in going from the $^{10}B(d,p)^{11}B$ reaction to the $^{24}Mg(d,p)^{25}Mg$ reaction it is reasonable that the cross-section for the formation of a compound nucleus should be reduced more than the cross-section for stripping. This conclusion follows from the fact that the deuterons have to penetrate further through the barrier in order to form a compound nucleus than they have to penetrate in order to be stripped. Moreover, the factor, by which the (d,n) compound nucleus reaction is more likely than the (d,p) compound nucleus reaction, has also become larger because of the effect of the increased Coulomb barrier on the probability for the emission of a proton.

For this reason the angular distributions of the various groups of protons have been analysed as if the only perturbations to the simple stripping theory that could be present, were those which could be ascribed to the Coulomb barrier.

(a) Group 0.

The angular distribution, which was obtained for this group of protons, is shown in fig. III. 17(a) where the experimental points have been plotted and their probable errors have been indicated. The smooth curve through the points has been analysed into three components. The first was the angular distribution which was calculated by the method due to Bhatia for the stripping reaction with $\ell_n = 2$ and $R = 6\cdot 7 \times 10^{-13}$ cms. The shape of this component is shown by a line of dashes. The second component, which is indicated by a line of dots and dashes, represents a positive multiple of the square root of this stripping distribution. The third component has the form of an isotropic distribution.

When the three components are associated into the form $W(\theta) = F^2_{(\theta)} + 2\ A\ \sin\delta \times F_{(\theta)} + A^2$, where $F^2_{(\theta)}$ is the unperturbed stripping distribution, one finds that δ has the value $+ 78^{\circ}$. Since $F^2_{(\theta)}$ is not known in absolute terms the value of A has no real significance.

There are no values of R which make it possible to fit the experimental points by $F^2_{(\theta)}$ alone, or by a combination of the form $F^2_{(\theta)} + A^2$. Thus it seems reasonable that some form of interference occurs between the process, which forms the isotropic component, and the stripping process.

(b) Group 1.

The various points on the angular distribution of this group of protons are shown in fig. III. 17(b) and the probable errors on the points are indicated. When the shape of the angular distribution of protons from the stripping reaction, where $\ell_n = 0$ and $R = 6\cdot 7 \times 10^{-13}$ cms., is calculated by the method of Bhatia the result is the curve which is shown by the line of dashes. Clearly this would not fit the experimental points in any combination of the form $W(\theta) = F^2_{(\theta)} + A^2$. If $F_{(\theta)}$ is calculated and is multiplied by a negative number one obtains a curve of the form which is indicated by the line of dots and dashes. In the case shown, however, $B\,F_{(\theta)} + 3{\cdot}5$ is plotted instead of $B\,F_{(\theta)}$ in order to show all the curves on one diagram. Once again the experimental points seem to fit a curve of the form $W(\theta) = F^2_{(\theta)} + 2A \sin\delta \, F_{(\theta)} + A^2$, but in this case $\delta = -52^\circ$ instead of $+78^\circ$.

The fact that the values of δ are different for the P_0 and P_1 groups of protons must mean that the actual situation is more complicated than was allowed for in the treatment of the problem by de Borde. According to this the values of δ should be identical since both groups of protons come from a reaction in which the target nucleus has spin zero.

(c) <u>Group 2.</u>

It is unfortunate that in this case the measurement of the intensities at angles of less than 45° was rendered inaccurate by the effects of the overlap between the peaks due to this group and the group of protons from the reaction $^2D(d,p)^3T$. This must make the analysis of the results somewhat suspect.

It appears that, if $\ell_n = 2$ as the other evidence suggests, $9{\cdot}5 \times 10^{-13}$ cms is the only value of R which gives reasonable agreement between theory and the experimental results. For these values of R and ℓ_n one finds that the experimental points have an angular distribution of the form $W_{(\theta)} = F^2_{(\theta)} + A^2$.

It is hard to see why the value of R should be different for this group of protons from the value of $6 \cdot 5 \times 10^{-13}$ cms which fits the other angular distributions. While Holt states that the value of R varies according to the value of ℓ_n, our results would seem to show that R can be different for two cases where ℓ_n has the same value, and be the same for two cases where ℓ_n has different values. If our result is the more accurate then the explanation for the variation of R could lie in the properties of the levels which are formed in the final nucleus. Varma (1956) has shown that the ground state and first excited state of ^{25}Al are single particle levels, while the second excited state has a more complicated structure. Unfortunately, the value of R depends to quite a large extent on the experimental results in the region 0° to 45°, which are rather suspect.

The value of $W_{(\theta)} = F^2_{(\theta)} + A^2$ for the shape of this angular distribution would indicate that $\delta = 0^{\circ}$ for this group of protons.

(d) <u>General.</u>

The measurement of the three most energetic groups of protons from the $^{24}Mg(d,p)^{25}Mg$ reaction was undertaken in order to test the validity of the various theories which try to analyse the effects of the Coulomb barrier on stripping reactions. The shape of the excitation curve suggests that the main mode of interaction between deuterons with low energies and ^{24}Mg is stripping. This means that those theories, which predict relatively small changes in the angular distributions, cannot explain the large changes that are found in these experiments.

Indeed the observed shapes are very different from those which are predicted by the theory of Bhatia et alia. There does seem to be a general tendency for the experimental angular distributions to have the form $W(\theta) = F^2_{(\theta)} + 2A \sin\delta \times F_{(\theta)} + A^2$ where A is a constant and $F^2_{(\theta)}$ is the angular distribution that is predicted by the stripping theory. Contrary to the theory put forward by de Borde the value of δ is different for the various groups of protons although the spin of the target nucleus is 0. Thus the perturbation by the Coulomb barrier must involve more than a simple scattering of the S-Wave deuterons.

PART IV. CONCLUSIONS.

In this first part of this thesis a number of problems were described and now it is necessary to see how far the experiments, which have been discussed in the second and third parts, have gone towards providing the answers.

The evidence from the $^{26}Mg(p,\gamma)^{27}Al$ reaction shows that the nucleus of ^{27}Al does not behave as if the energy levels were single particle in nature. It seems to be possible to identify pairs of levels for which the transition probabilities are much smaller than would be predicted by the Weisskopf formula. Thus one is tempted to group the levels into sets such that transitions between levels within a set are more probable than transitions between levels in different sets. However, a better approach is to say that the results provide experimental evidence with which to compare theoretical predictions based on a model of the nucleus that is different from the single particle model. One such model would be the "rotational state" model of Alaga et alia (1955) which has already provided an excellent description of ^{25}Al.

The evidence from these (p,γ) reactions provides a powerful tool for obtaining the information that will be necessary, if further progress is to be made towards a complete theory of the nucleus. Even among the light nuclei more work is required on the reactions in

^{28}Si., ^{32}S, ^{35}Cl, ^{37}Cl and many others. Because the results that have been obtained with 5 inch diameter $NaI_{(Th)}$ crystals are much more certain than those, which are obtained by other means, the author feels that techniques, which use these crystals, provide the greatest hope for advance in this field.

The $^{10}B(d,p)^{11}B$ reaction provides an example of the competition between stripping and compound nucleus formation in a case where the former is more important than the latter. There seems to be strong evidence that the compound nucleus is formed in a level at 25·7 Mev. in ^{12}C and that the angular distributions of protons, which come from the level, are symmetrical about the direction at right angles to the direction of the beam of deuterons. There is no evidence that the stripping and compound nucleus formation are coherent and the values for the parameters R and ℓ_n in the stripping reactions are in agreement with the values obtained at higher energies. The only case of disagreement occurs for the P_1 group, where the other evidence is conflicting.

In contrast to this experiment are the results of the study of the $^{24}Mg(d,p)^{25}Mg$ reaction. This seems to be a case where the effect of the Coulomb barrier provides the distortion to the simple stripping mechanism. The effect appears to be to introduce an isotropic term and an interference term into the angular distribution. This feature is not due to a scattering of the S-Wave deuterons, however, because the phase shift is different for each of the three groups of protons. No attempt has been made to apply this type of treatment to the results of the $^{10}B(d,p)^{11}B$ reaction because the stripping components are relatively less important in that case and the Coulomb barrier is smaller.

Clearly two studies of different nuclei are not sufficient evidence on which to put forward this interpretation of deuteron reactions. To enlarge the available evidence Mr. R. S. Storey at Glasgow is carrying out a further series of studies on ^{28}Si, ^{26}Mg, ^{20}Ne and possibly on other nuclei such as ^{6}Li. It would be of great interest if a parallel series of studies in the region E = 1 Mev. to 2 Mev. were carried out elsewhere. There seems every reason to hope that such a course of investigation would resolve the doubts about the interpretation of (d,p) reactions that is revealed in table I. 1, and would make these studies a sure means of measuring nuclear parameters.

ADDENDA

Since the main body of this thesis was written two papers have been published which have a direct bearing on this work.

In the first Van der Leun et alia (1956) have published a fuller account of the experiments on the $^{26}Mg(p,\gamma)^{27}Al$ reaction that were first described by Endt at the Amsterdam Conference (1956). This account shows that the γ-rays were detected by a scintillation spectrometer which used a $NaI_{(Th)}$ crystal 2 inches long and 1¼" in diameter. Thus their technique was very similar to ours except that they only made measurements at 0° and 90° instead of at a series of angles. Some of the discrepancies between the two sets of results can be explained. The first difference between the two results is that Van der Leun did not find a 6·15 Mev. γ-ray from $^{19}F(p,\alpha,\gamma)^{16}O$ at the 338 Kev. resonance. While it is possible that there was no ^{19}F on his target at the time when the measurements were made, a small contribution from this reaction would alter his distribution for the 5·8 Mev. γ-ray. Similarly a contribution from the resonance at 669 Kev. in the $^{19}F(p,\alpha,\gamma)^{16}O$ reaction, which we found and Van der Leun did not find, would explain our disagreement over the spectrum from the 659 Kev. resonance.

The other differences between the two results are harder to understand. It is almost inevitable, however, that errors in the measurement of the intensities of the γ-rays will result from the triple-peak nature of the spectra for the individual γ-ray. This will be particularly true in cases where several γ-rays of similar energies overlap. Thus only a measurement with a spectrometer, which gives single peaks e.g. a large 5" $NaI_{(Th)}$ crystal, will show whether the results of our measurements are more reliable than those of Van der Leun.

In the second paper Wilkinson (1957) showed that the γ-ray, by which the first excited state of ^{11}B decays, is M_1 in nature. This was demonstrated by a measurement of the lifetime of the state, when it was formed in the $^{11}B(p,p',\gamma)^{11}B$ reaction. He analysed the Doppler shift that was seen for the γ-ray when it was viewed from two different directions with respect to the beam of protons. Wilkinson went on to show that the 2·14 Mev. level must have spin $\frac{1}{2}$ as the γ-ray was emitted isotropically. From this he deduced that the appropriate group of protons in the $^{10}B(d,p)^{11}B$ reaction should have the angular distribution for $\ell_n = 3$. He explained the "apparent" value of 1, which was obtained by Evans (1954), by introducing the idea that the emergent proton can transfer angular momentum to the nucleus by a spin-flip mechanism. While the author would prefer to treat this latter concept with caution, the experimental result does reinforce the results that are contained in this thesis, and clears up the uncertainty about the 2·14 Mev. level in ^{11}B.

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