Angular Distributions in the $^{10}B(d, p)^{11}B$ Reaction

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Abstract. Angular distributions of six proton groups from the reaction $^{10}B(d, p)^{11}B$ were obtained using a scintillation counter spectrometer and an incident deuteron energy of 7·7 MeV. Distributions for the three longest range groups were also obtained at the additional deuteron energies of 6·2, 7·1 and 8·0 MeV. The results are largely compatible with the normal theory of deuteron stripping, and the five longest range proton groups appear to correspond to ingoing p-neutrons. The properties of the first excited state in ^{11}B are, however, in some doubt. Possible spin assignments for the lower levels of ^{11}B arising from excitation within the p-shell are considered and the corresponding relative values of the neutron capture probability are listed.

§ 1. Introduction

It is well known that the parities of the energy levels of a residual nucleus, together with some information about the spins, may be derived (Butler 1950) from a study of the stripping process for deuterons of energy about 10 MeV. This paper describes a study of the reaction $^{10}B(d, p)^{11}B$ using 7·7 MeV deuterons from the Cambridge University cyclotron in conjunction with a scintillation crystal spectrometer. Tentative assignments of spins and parities for a number of levels of ^{11}B were made by Jones and Wilkinson (1952) as a result of a study of the $^{7}Li(\alpha, \gamma)^{11}B$ reaction, but, as they pointed out, an independent determination of the parities, particularly as obtained from the stripping reaction, would be of considerable interest.

In addition to determining the parities of a number of the levels, a preliminary investigation was made of the part played in the reaction by processes other than simple stripping.

§ 2. Apparatus

2.1. *Target Chamber*

The deuteron beam was defined by two vertical slits, 2 mm and 5 mm wide respectively, placed 8 ft apart in the fringe field of the cyclotron magnet; these served to reduce the spread in energy of the beam. After passing through a focusing magnet, the beam was further collimated by a circular lead liner of 1 cm internal diameter located at the entrance of the target chamber (figure 1). The upper half of the chamber carried the proton detector and could be rotated, permitting measurements over a range $\pm 140°$ with respect to the incident deuteron beam. The protons entered the counter through an aperture of 1 cm diameter and an aluminium window 0·0006 in. thick. The elastically scattered deuterons were stopped in lead foil of just sufficient thickness placed inside the target chamber in front of the window.

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The targets were prepared by allowing a slurry of amorphous boron and water to dry on backing foils of gold 0·000 05 in. thick. Targets both of commercial boron (19% ^{10}B) and of enriched boron (95% ^{10}B)‡ were used. The relative intensities of the proton groups measured in each case served as a check on the identification of those groups due to the ^{10}B(d, p)^{11}B reaction. The targets were thin enough to have no significant effect on the resolution.

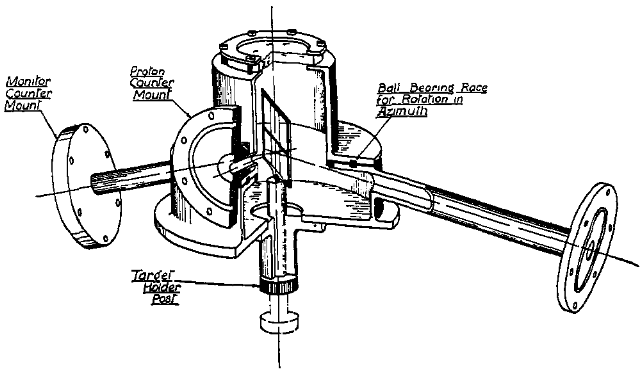

Figure 1. The scattering chamber.

The target could be displaced vertically so as to bring a similar foil without boron into the beam for background measurements. It could also be rotated about an axis perpendicular to the beam, although it was inclined at an angle of 20° for most measurements.

The deuteron beam was monitored by a second crystal counter which detected deuterons scattered elastically through an angle of 24° by the target nuclei. Their intensity was reduced to a suitable value by a lead stop 1 mm in diameter. The bottom and sides of the target chamber were lined with lead to stop the main deuteron beam and to reduce the background counting rate.

2.2. *The Crystal Counters*

The crystal was 1 cm in diameter and was approximately 0·040 in. thick so as to reduce the number of γ-rays detected. This thickness was sufficient to stop all protons with energies less than about 14 MeV. Proton groups of higher energy were first slowed down by aluminium foils placed in front of the crystal. The crystal itself was cleaved in a dry box and immediately sealed in an air-tight Perspex holder by an aluminium foil 0·0006 in. thick.

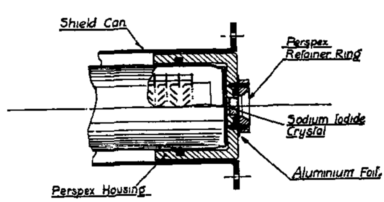

Figure 2. The NaI(Tl) crystal mounting.

The Perspex holder fitted over the end of the photomultiplier as shown in figure 2. An EMI 5311 photomultiplier was used because it gave the best energy

‡ We are indebted to the Atomic Energy Research Establishment, Harwell, for supplying us with the enriched ^{10}B.

resolution of the tubes available to us. Nine stages of electron multiplication were used, and the output taken from the ninth dynode in order to obtain positive pulses; the remaining dynodes were earthed.

A cathode follower, mounted at the base of the photomultiplier, and a matched coaxial cable fed the pulses into an amplifier with an integrating time constant of 0·2 μsec. The output pulses were displayed on a multi-channel kicksorter (Hutchinson and Scarrott 1951). The voltage supply of the photomultiplier was an electronically stabilized power pack. To reduce drift the counter was operated in the 'plateau' region, where the counting rate increases least rapidly with voltage. The plateau was located by plotting counting rate against counter voltage for γ-rays from a ^{134}Cs source. For the photomultiplier used the plateau occurred with 70 volts per stage, with four times this voltage between the photocathode and the first dynode. Under these conditions no noticeable drift occurred in the location of the proton groups.

The monitor counter consisted of a NaI(Tl) crystal cut to a thickness of approximately 0·05 in. and an RCA 5819 photomultiplier operating at 1120 v. The 5819 was used because of the change in counting rate with time of the EMI 5311 at high counting rates, due presumably to charge collecting on the dynode insulators. The output was taken from the tenth dynode and the pulses, after amplification, were recorded on a fast scaling unit.

§ 3. Experimental Details

3.1. *Limitations on Resolution*

The resolution of the experimental arrangement is determined mainly by five factors : (i) the energy spread in the incident beam, (ii) the finite and non-uniform thickness of the target and backing, (iii) the change in proton energy over the finite range of angles covered by the detector, (iv) range straggling in the absorbers between the target and detector, (v) the inherent energy resolution of the detector. The first four factors produce a spread in energy of the protons reaching the crystal and result in a spread in amplitude of the detector voltage pulses which may be considerably greater than that due to the detector alone. It is of interest, then, to assess the relative contribution of each to the overall resolution.

The deuteron beam from the cyclotron has a spread in energy of the order of 5% to 10%. Without additional magnetic focusing this may be reduced only at the expense of beam intensity. The use of slits in the fringe field of the cyclotron magnet reduced the spread to approximately 2%, which represented a reasonable compromise.

The energy spread due to target thickness is a result of the stripping reaction occurring at different depths in the target and is easily calculated from the rates of energy loss (Aron *et al.* 1949) of deuterons and protons in the target and backing material. By using thin targets this effect was made negligibly small without undue sacrifice of counting rate. Also, because the targets were thin, their lack of uniformity contributed a negligible amount to the energy spread. It is perhaps worth noting that in this respect the crystal spectrometer has a decided advantage over a proportional counter telescope in that the former records all the pulses in a proton group, whereas the latter is normally used to obtain a differential range curve. Thus for measurements of a given statistical accuracy to be taken in the same total time, the energy spread due to the incident beam and target thickness may be reduced considerably with the crystal spectrometer.

The problem of detector geometry has been treated for a special case by Livingston and Bethe (1937). Recently Beach (1952) has treated the more general case. His results indicate that for our arrangement the energy spread resulting from the finite solid angle is of the order of 0·1% and is thus negligible.

The effect of range straggling in the aluminium absorbers can be estimated from the straggling curve given by Bethe (1949). For example, in completely stopping 13 Mev protons the range straggling is about 1·7%. Since the protons are slowed down but not stopped in the aluminium, this value represents an upper limit.

The factors affecting the resolution of the combined crystal and photomultiplier have been treated by Garlick and Wright (1952). These are (i) the variation in intensity of successive light pulses reaching the photocathode due to imperfect crystals and to absorption and reflection in the crystal and optical system, (ii) variations due to the low photoelectric response and non-uniformity of the photocathode, and (iii) statistical fluctuations due to the finite number of photoelectrons produced per pulse. They have shown experimentally that the half-width of the output pulse does vary inversely as the square root of the number of photoelectrons per light pulse. Thus for a given crystal and optical system the inherent resolution of the detector varies inversely as the square root of the energy of the incident particle. Perhaps the greatest gain in counter resolution is to be made by improving the quality of the optical system and the photoelectron collection efficiency of the photomultiplier.

The important factors in the present measurements were energy spread of the deuteron beam, range straggling and detector resolution. Protons of 13 Mev expending their whole range in the crystal produced voltage pulses the half-width of which was 10%, due almost entirely to the detector. (Considerable improvement in this figure should be possible by improving the optical system and by having a larger selection of photomultipliers from which to choose.) Because of the non-linearity of the range–energy curves, and the fact that the resolution of the detector varies inversely as the square root of the energy of the incident particle, the effective resolution can be improved by slowing down the proton groups before they enter the crystal. Two factors have to be considered, namely the variation of the half-width of the voltage pulses due to a given proton group, and the change in the mean separation of two groups, as absorber is added.

The voltage spread ΔV of a given group of mean pulse height V will be a minimum when the slope of the $[(\Delta V)^2, V]$ curve of the detector is equal and opposite to the slope of the $[(\Delta V)^2, V]$ curve obtained from all the other factors combined. A semiquantitative estimate of the spread can be made by assuming a range–energy relationship of the form $R=kE^{n/2}$. A value of $n=3{\cdot}5$ gives a reasonable fit to the curve for protons in aluminium down to approximately 4 Mev. On the assumption that range straggling is gaussian, it can be shown that the spread in energy ΔE_{2s} for a proton group slowed down in aluminium to an energy E_2 from an initial energy E_1 is

$$\Delta E_{2s}=\frac{2}{n}\sqrt{\frac{2}{\pi}}\left\{[(S_1E_1)^2-(S_2E_2)^2+2(1-2/n)]\int_{R_2}^{R_1}\frac{S^2E^2}{R}\,dR\right\}^{1/2}$$

where S_1 and S_2 are the values of range straggling of protons of energy E_1 and E_2 (and range R_1 and R_2) stopped completely in aluminium. It also follows that the spread in energy ΔE_2 at an energy E_2 due to an initial spread ΔE_1 at E_1 is

$$\Delta E_2=\left(\frac{E_1}{E_2}\right)^{(n-2)/2}\Delta E_1.$$

The 2% spread in energy of the incident deuteron beam produced a spread ΔE_{1b} of the initial proton groups of almost 0·13 Mev which, after slowing down in foil to about 4 Mev, resulted in a value of $(\Delta E_{2b})^2$ approximately five times that due to range straggling. If ΔE_{2d} and E_2 are measured in Mev, then the spread due to the detector can be represented by $(\Delta E_{2d})^2 \simeq 0{\cdot}12\, E_2$. Thus the total energy spread $\Delta E_T \simeq [(\Delta E_{2b})^2 + (\Delta E_{2d})^2]^{1/2}$ was due mainly to the detector and to the non-homogeneity of the incident deuteron beam, and had a minimum of roughly 600 kev at about $E_2 = 4$ Mev.

The separation of two adjacent proton groups increases as absorber is added. As an example, a separation of 0·6 Mev between two groups near 13 Mev is increased to 1·5 Mev when the groups are slowed down to about 4 Mev. While it is possible to add just enough foil to stop the lower of the two groups completely, the high background counting rate due to γ-rays makes it impracticable to reduce the mean energy of the group under observation to less than about 4 Mev. This is not a serious drawback since the energy spread of the individual groups becomes rapidly worse below 4 Mev.

3.2. *Experimental Procedure*

Since it was observed that the widths of the proton groups remained very nearly constant for all angles of the proton counter up to 70°, the intensities of the groups at each angle were estimated from the heights of the peaks displayed on the kicksorter. As a check on this method the areas under the curves for each group were determined in several cases. Any errors due to possible secular changes in the apparatus were minimized by repeatedly covering a range of angles and combining the separately normalized angular distributions thus obtained. The monitor count was corrected for the different numbers of scattering centres in the background foil and the target foil. The correction factor was measured by alternating between the two foils a number of times while the cyclotron beam was held reasonably constant.

The differential cross sections and the angles of observation were converted to the centre-of-mass system. No corrections were made for the finite width of the deuteron beam or for the solid angle of the proton counter, as errors due to these were negligible compared with the statistical fluctuations in the counts. The proton counting rate was reduced below 100 per second to reduce kicksorter counting losses.

§ 4. Results

The proton spectrum obtained with an enriched ^{10}B target is shown in figures 3 and 4. In figure 3 the proton groups Q_0 and Q_1 are not resolved, since the former has not come to rest in the crystal. The addition of 60 mg cm^{-2} of aluminium foil in front of the crystal resulted in the spectrum shown in figure 4. With the apparatus employed it was not possible to resolve groups Q_4 and Q_5, or groups Q_8, Q_9 and Q_{10}.

The observed angular distributions for the groups Q_0, Q_1, Q_2, Q_3, $Q_{4,5}$ and $Q_{8,9,10}$ are shown in figures 5–10, together with the theoretical distributions calculated from the 'modified' Butler formula (Butler and Salpeter 1952) using $r_0 = 6{\cdot}0 \times 10^{-13}$ cm. (It might be noted that the use of the modified Butler formula requires essentially the same value of r_0 as the Huby formula (Bhatia *et al.* 1952).) The wave number of the neutrons was calculated from the value of $E_n = -(Q+\epsilon)$ rather than as given by Butler, since the modified form is not consistent with the original assumption of an infinitely heavy target nucleus.

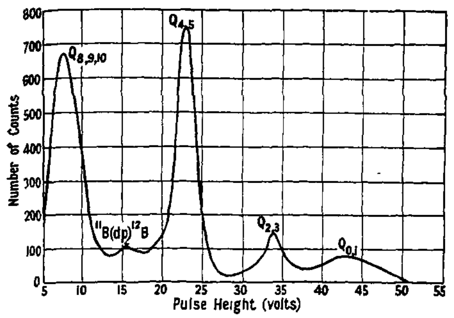

Figure 3. The proton spectrum obtained in the reaction ^{10}B(d, p)^{11}B. Proton groups Q_0 and Q_1 are not resolved; the proton group Q_0 does not come to rest in the crystal.

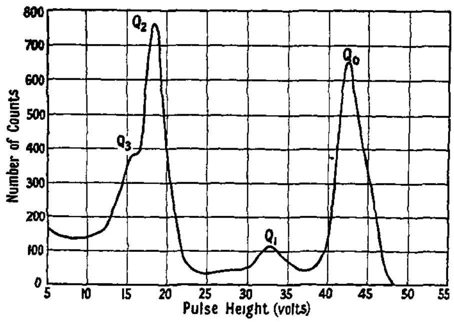

Figure 4. The proton spectrum obtained with 60 mg cm^{-2} of aluminium in front of the crystal. Proton groups Q_0 and Q_1 are both brought to rest in the crystal.

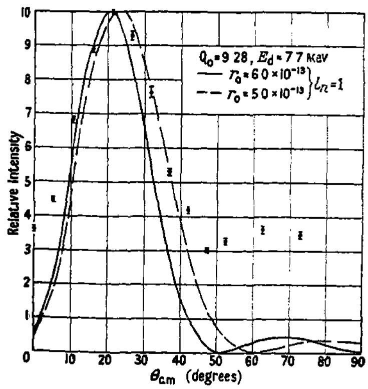

Figure 5. The angular distribution of protons in the centre-of-mass system for the ground state group Q_0 in the ^{10}B(d, p)^{11}B reaction.

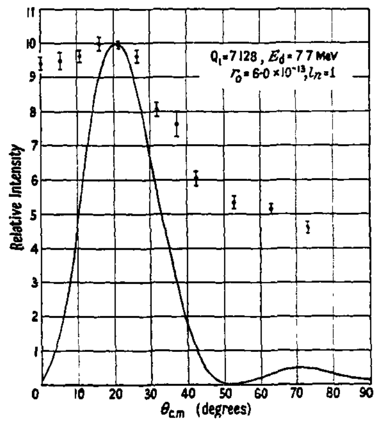

Figure 6. The angular distribution of proton group Q_1 in the ^{10}B(d, p)^{11}B reaction.

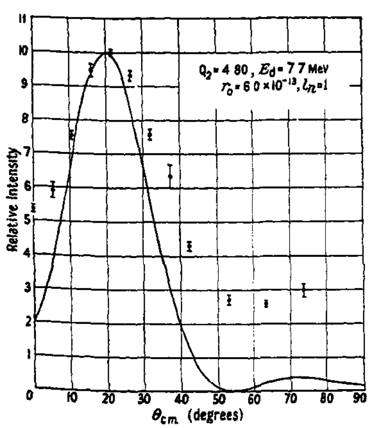

Figure 7. The angular distribution of proton group Q_2 in the ^{10}B(d, p)^{11}B reaction.

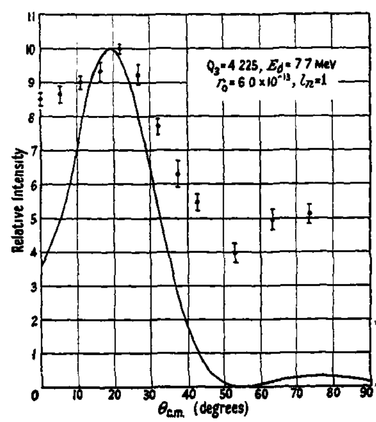

Figure 8. The angular distribution of proton group Q_3 in the ^{10}B(d, p)^{11}B reaction.

The data are summarized in the table. The measured levels are listed in column 1, with their respective excitation energies given in column 2. Column 3 lists the l-values assigned to the incoming neutron. For the unresolved levels the possibility of other l-values occurring can certainly not be excluded, nor should it be inferred that admixtures of $l_n = 3$ or $l_n = 5$ do not occur in the resolved levels.

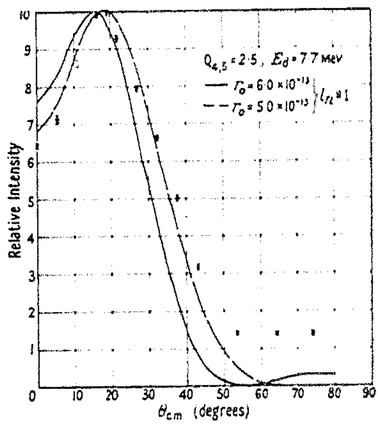

Figure 9. The angular distribution of proton groups Q_4 and Q_5 (unresolved) in the $^{10}B(d, p)^{11}B$ reaction.

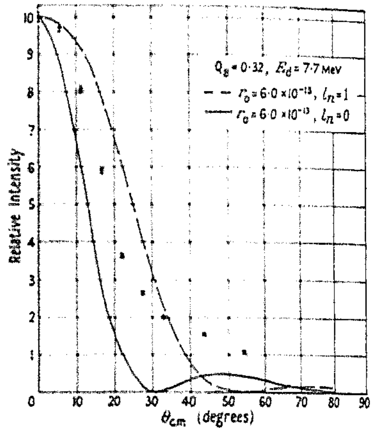

Figure 10. The angular distribution of proton groups Q_8, Q_9 and Q_{10} (unresolved) in the $^{10}B(d, p)^{11}B$ reaction.

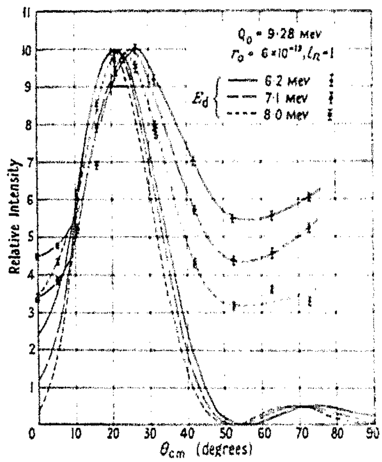

Figure 11. The angular distributions obtained for proton group Q_0 at deuteron bombarding energies of 6·2, 7·1 and 8·0 Mev.

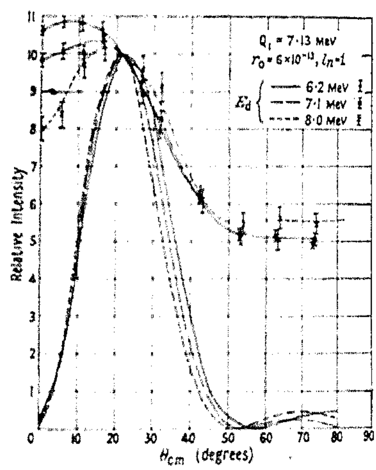

Figure 12. The angular distributions obtained for proton group Q_1 at deuteron bombarding energies of 6·2, 7·1 and 8·0 Mev.

In addition to these results there was evidence for a proton group, presumably Q_7, with an energy about 0·5 Mev less than the Q_8 group, which appeared to correspond to an ingoing neutron for which $l_n = 1$. It was not resolved sufficiently, however, for any accurate angular distribution to be obtained.

No evidence was found for proton groups between $Q_{4,5}$ and Q_7 corresponding to the 7·30 Mev (Van Patter *et al.* 1951) and 7·99 Mev (Elkind and Sperduto 1953) levels in ^{11}B. These levels are presumably very weak, the group corresponding to the 7·30 Mev level perhaps being lost in the tail of $Q_{4,5}$ and that corresponding to the 7·99 Mev level being masked by the ground state protons of the ^{11}B(d, p)^{12}B reaction.

Figures 11 to 13 show the angular distributions obtained for the groups Q_0, Q_1 and Q_2 at deuteron energies of 6·2, 7·1 and 8·0 Mev, together with the calculated distributions. Data taken at a deuteron energy of 6·7 Mev for the three groups are intermediate to the data of 6·2 and 7·1 Mev but, to avoid confusion, are not shown.

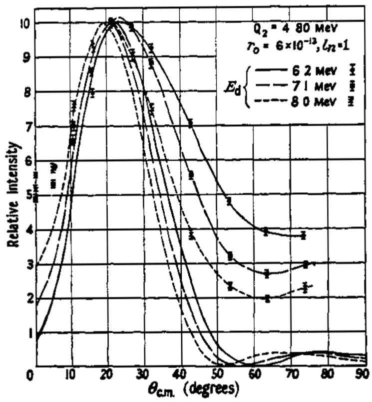

Figure 13. The angular distributions obtained for proton group Q_2 at deuteron bombarding energies of 6·2, 7·1 and 8·0 Mev.

§ 5. Discussion

In the table are listed the l-values associated with each level of ^{11}B for which a reliable measurement could be taken. The levels up to and including at least one member of the 6·8 Mev doublet appear to have not only odd parity but some contribution of $l_n = 1$. Since the spin of ^{10}B in the ground state is 3, the existence in the (d, p) reaction of an $l_n = 1$ component, no matter how small, restricts the spin j_f of

(1) Group	(2) Excitation (Mev)	(3) l_n-value	(4) Rel. int.	(5) Λ_{l_n}	(6) j_f (assumed)	$\frac{\Lambda_{l_n}}{2j_f+1}$	(7) j_f (assumed)	$\frac{\Lambda_{l_n}}{2j_f+1}$
Q_0	0	1	10·1	5·0	3/2	1·3	3/2	1·3
Q_1	2·14	1	2·3	0·9	1/2	0·45	7/2	0·12
Q_2	4·46	1	6·0	1·6	5/2	0·26	5/2	0·26
Q_3	5·03	1	2·23	0·5	3/2	0·13	3/2	0·13
$Q_{4,5}$	{6·76, 6·81}	1	35	5·7	7/2	—	1/2	—
$Q_{8,9,10}$	{8·93, 9·19, 9·28}	0–1 ?	126	—	—	—	—	—

that level to $3/2 \leqslant j_f \leqslant 9/2$. Our results, therefore, cannot be reconciled with the tentative assignments made by Jones and Wilkinson (1952) from their study of the ^{7}Li(α,γ)^{11}B reaction, in which they assign even parity to the second excited state and a spin 1/2 to the first excited state.

Odd parity is consistent with the shell model, provided these levels arise from excitation within the p-shell. The ground state configuration for ^{11}B is presumed to be $(p_{3/2})^7$, giving rise to a spin of 3/2. A possible configuration for the first few excited states is $(p_{3/2})^6(p_{1/2})^1$. On this assumption Inglis (1953) has shown that for the first excited state a spin 1/2 is to be expected on the basis of both pure j–j and intermediate coupling. Pure L–S coupling is unlikely since it would imply a spin 1/2 for the ground state with the 3/2 level lying close to it. With a value of about 5 for the intermediate coupling parameter a/K defined by Inglis the ordering of the first five levels is 3/2, 1/2, 5/2, 7/2, 3/2. Thus the difficulty persists of reconciling spin 1/2 for the first excited state with the interpretation of the data. It must be stressed that the character of the data for this state is unusual, and an assignment of $l_n = 1$ for the transition should be viewed with some doubt. Nevertheless it is difficult to believe that it contains no component less than $l_n = 2$.

A possible explanation is obtained by assuming ^{11}B to have the configuration $(p_{1/2})^4(p_{3/2})^3$. This implies an interchange of the ordering of the $p_{1/2}$ and $p_{3/2}$ sub-shells. In support of this questionable assumption it might be noted that Flowers (1952) in calculating the magnetic moment of the ^{11}B ground state, assuming j–j coupling between the nucleons, finds better agreement for the configuration $(p_{3/2})^5(p_{1/2})^2$ than for $(p_{3/2})^7$. Assuming a complete interchange to occur, the levels then arise from the coupling of three $p_{3/2}$ nucleons, for which the ordering as given by Inglis, and also as calculated by Edmonds and Flowers (1952) for a suitable range of force parameter, is 3/2, 7/2, 5/2, 3/2 and 1/2. This is not inconsistent with our results, since one member of the close doublet at 6·8 MeV could have a spin 1/2, implying an $l_n = 3$ transition, which might be so weak as to be masked by the other member of the doublet having $l_n = 1$.

Following the procedure of Holt and Marsham (1953), the relative intensities of the various proton groups were determined and the neutron capture probabilities Λ_{l_n} calculated, using the expression of Bhatia *et al.* (1952). These are listed in columns (4) and (5) respectively of the table. The intensities used in the calculations were those obtained from the peaks of the angular distributions. For proper comparison the values of Λ_{l_n} should be divided by the statistical weight factor $2j_f + 1$ where j_f is the spin of the final state. Since states of similar constitution are expected to have similar neutron capture probabilities, with the values for single particle states being somewhat larger than those formed by excitation within the configuration, one might expect the value of $\Lambda_{l_n}/(2j_f + 1)$ for the ground state to be significantly larger than for the excited states arising from the $(p_{1/2})^4(p_{3/2})^3$ or $(p_{3/2})^6(p_{1/2})^1$ configurations. Further, these states would be expected to have approximately the same values of $\Lambda_{l_n}/(2j_f + 1)$. Column (6) of the table lists the sequence of j_f values expected for j–j coupling in the $(p_{3/2})^6(p_{1/2})^1$ configuration, together with the resulting values of $\Lambda_{l_n}/(2j_f + 1)$. Column (7) gives the corresponding quantities for the $(p_{1/2})^4(p_{3/2})^3$ configuration. While the results bear out the above remarks, there seems to be little to choose between the two configurations, although the scatter is less for $(p_{1/2})^4(p_{3/2})^3$. Little can be said about the $Q_{4,5}$ doublet since the relative contributions from the two levels are unknown, but it appears that one may be a single particle state.

The assumption of the $(p_{1/2})^4(p_{3/2})^3$ configuration still leads to difficulties when applied to the results of Jones and Wilkinson (1952). In the light of the parity determinations by the stripping reaction, their data can be interpreted,† though less

† Private communication. We are indebted to Drs. Wilkinson and Jones for many enlightening discussions.

well, as giving 5/2 – for the 4·46 MeV level, and 3/2 – for the 6·81 MeV level. However, the near absence of γ-transitions to the 2·14 MeV level still requires them to assign it a spin of 1/2 or 9/2 or higher. The values 1/2 or greater than 9/2 would be at variance with our admittedly questionable conclusion that $l_n = 1$ for this level. The value 9/2 is consistent with $l_n = 1$, but would be excluded by the Pauli principle if this level represents an excitation within the p-shell. In support of the assignment of spin 1/2 to the first excited state, Thirion (1951) finds a (pγ) coincidence ratio of unity between 90° and 180° in the (d, pγ) reaction. One hesitates to place too much weight on these results, however, since the measurements were made at a deuteron energy of 790 kev, and the statistics are about 8%.

A striking feature of the data is the deviation from the theoretical angular distributions. The variation with deuteron energy, especially for the 2·14 MeV level, is rather unexpected and may suggest some kind of interference effect. It is significant that the variation cannot be accounted for by the assumption of an isotropic 'background' due to compound nucleus formation. However, it is reasonable to believe that a more complete theory of (d, p) reactions, particularly one in which the interaction of the proton and nucleus is included, will give rise to interference terms.† The introduction of potential scattering of the proton by the nucleus (Horowitz and Messiah 1953) does not seem adequate to explain all these anomalies. It is possible that coulomb scattering may help to account for the relatively large cross section at high angles (Grant, private communication).

The variation with energy indicates that some uncertainty exists in the interpretation of stripping data. The angular distribution of Q_1 at 6·2 MeV would hardly be interpreted as an $l_n = 1$ transition as is suggested by the data at 8·0 MeV. A mixture of $l = 0$ and 2 does not improve the fit. While it is probable that such a variation is rare, it will be of interest to look for other cases. Transitions for which $l_n = 1$ are particularly suited for study since the angular distributions at small angles cannot contain $l_n = 0$ components and are not likely to be influenced by mixtures of higher l-values. Distributions for which the cross section at large angles is an appreciable fraction of the peak cross section can be expected to show the greatest energy dependence.

In the light of these results, any quantitative attempt to arrive at the purity of the nuclear states on the basis of admixtures of l-values (Bethe and Butler 1952, Parkinson *et al.* 1952) will have little significance until the effect is better understood.

The measurements are being extended, particularly to larger angles. The results will be reported in the future.

Acknowledgments

To the members of the technical staff of the Cavendish cyclotron, in particular Messrs. Morley and Turner, who were most helpful throughout the course of this work, we express our appreciation.

† Interference may occur between the normal stripping amplitude and an 'exchange' amplitude, in which the proton in the deuteron exchanges with a proton in the nucleus. This possibility was pointed out to us by Dr. A. P. French. A preliminary analysis carried out by him indicates that such an effect can account for many of the observed deviations of stripping data from the theoretical distributions. While such a treatment can only be considered as a crude approximation to the true situation, it does indeed produce better agreement with experiments.

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