

## ANGULAR DISTRIBUTION AND YIELD OF PROTONS FROM THE $^{10}\text{B}(d, p)^{11}\text{B}$ REACTION (II)

by C. H. PARIS, F. P. G. VALCKX and P. M. ENDT

Physisch Laboratorium der Rijksuniversiteit, Utrecht, Nederland

### Synopsis

In a previous paper<sup>1)</sup> (to be quoted as (I)) angular distribution measurements have been described of four proton groups from the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction at a deuteron energy of  $E_d = 0.31$  MeV. In the present investigation measurements were added at  $E_d = 0.20, 0.45$  and  $0.60$  MeV.

The differential cross section at  $\vartheta = 120^\circ$  has also been determined as a function of deuteron energy ( $E_d = 0.175 - 0.700$  MeV) by means of a proton scintillation spectrometer. The relative intensities of the four proton groups show irregularities at  $E_d = 0.21$  MeV corresponding to a new  $^{12}\text{C}$  resonance level at an excitation energy of 26.93 MeV.

Angular distributions have been analyzed into a stripping contribution and a contribution from compound nucleus formation. It is shown that the stripping contribution is large for at least two of the four proton groups down to the lowest deuteron energies. The values found by Butler analysis for the angular momentum transfer  $l_n$  are in agreement with known spins and parities.

§ 1. *Introduction.* In a previous paper<sup>1)</sup> measurements have been described of the angular distributions of four proton groups from the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction at a deuteron energy of 0.31 MeV.

Angular distribution measurements of the groundstate protons of this reaction have been reported by Redman<sup>2)</sup> at deuteron energies between 1 and 4 MeV, by Holt and Marsham<sup>3)</sup> at a deuteron energy of 8 MeV and by Burke, Risser and Phillips<sup>4)</sup> at deuteron energies of 1.06 and 1.43 MeV, while Pratt<sup>5)</sup> reported angular distribution measurements of four proton groups from the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction at a deuteron energy of 3.03 MeV.

In the present investigation the angular distribution measurements of four proton groups from the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction have been extended to four deuteron energies between 0.20 and 0.60 MeV. They have been supplemented by yield measurements at a fixed angle ( $\vartheta = 120^\circ$ ) in a still wider deuteron energy range ( $E_d = 0.175 - 0.700$  MeV).

In § 2 a description is given of the angular distribution measurements in which use was made of the nuclear emulsion technique. The yield measure-

ments with a thin crystal (NaI) scintillation spectrometer are given in § 3, and § 4 contains a discussion of the results obtained.

§ 2. *Angular distribution measurements.* The technique for angular distribution measurements of the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction using nuclear emulsions for proton detection has been given in reference 1.

Bombardments were performed at deuteron energies of 0.20, 0.31, 0.45 and 0.60 MeV. Effective deuteron energies are obtained from these figures by subtracting half the energy loss of deuterons in the target giving respectively 0.18, 0.29, 0.41 and 0.58 MeV.

The targets used for 0.31, 0.45 and 0.60 MeV bombardments consisted of layers of natural boron of  $65 \mu\text{gr}/\text{cm}^2$  to  $160 \mu\text{gr}/\text{cm}^2$  on a  $7 \mu$  aluminum backing. The target used for the 0.20 MeV bombardment was a layer of enriched  $^{10}\text{B}$  of  $80 \mu\text{gr}/\text{cm}^2$  on a  $6 \mu$  aluminum backing. This target was prepared by magnetic separation and was obtained from A. E. R. E., Harwell, England \*).

In Figs. 1, 2, 3 and 4 the measured angular distributions of respectively proton groups (0), (1), (2) and (3) leading to  $^{11}\text{B}$  states at 0, 2.14, 4.46 and 5.03 MeV are given in laboratory coordinates. They have been normalized such as to make the average differential cross section equal to unity. The curves drawn in these figures are those predicted by Butler's theory added to an isotropic contribution (see § 4). Table I gives the coefficients  $a_i$  of the measured angular distributions developed into a Legendre polynomial series of the form  $1 + \sum_{i=1} a_i P_i(\cos \theta)$  in center-of-mass coordinates. The curves representing these series constitute a best fit through the experimental points and have not been drawn in Figs. 1 through 4.

TABLE I

Coefficients of a Legendre polynomial series development of four proton groups from the $^{10}\text{B}(d, p)^{11}\text{B}$ reaction in c.m. coordinates						
$E_d$ in MeV	$E_x = 0 \text{ MeV}$			$E_x = 2.14 \text{ MeV}$		
	$a_1$	$a_2$	$a_3$	$a_1$	$a_2$	$a_3$
0.180	+0.35	—0.08	—0.02	—0.02	—0.06	0
0.290	+0.29	—0.10	—0.01	—0.05	—0.26	0
0.410	+0.17	—0.19	—0.03	—0.24	—0.20	0
0.585	+0.20	—0.08	—0.09	—0.17	—0.24	+0.10
$E_d$ in MeV	$E_x = 4.46 \text{ MeV}$			$E_x = 5.03 \text{ MeV}$		
	$a_1$	$a_2$	$a_3$	$a_1$	$a_2$	$a_3$
0.180	+0.72	+0.38	+0.07	—0.25	—0.18	—0.01
0.290	+0.80	+0.28	+0.02	—0.19	+0.07	0
0.410	+0.78	+0.27	—0.03	—0.17	+0.06	0
0.585	+0.68	+0.30	0	+0.06	+0.11	0

§ 3. *Yield measurements.* The yields of the four most energetic proton groups of the  $^{10}\text{B}(d, p)^{11}\text{B}$  reaction have also been measured as a function of

\*) We wish to thank Dr R. H. V. M. D a w t o n for the preparation of this target.

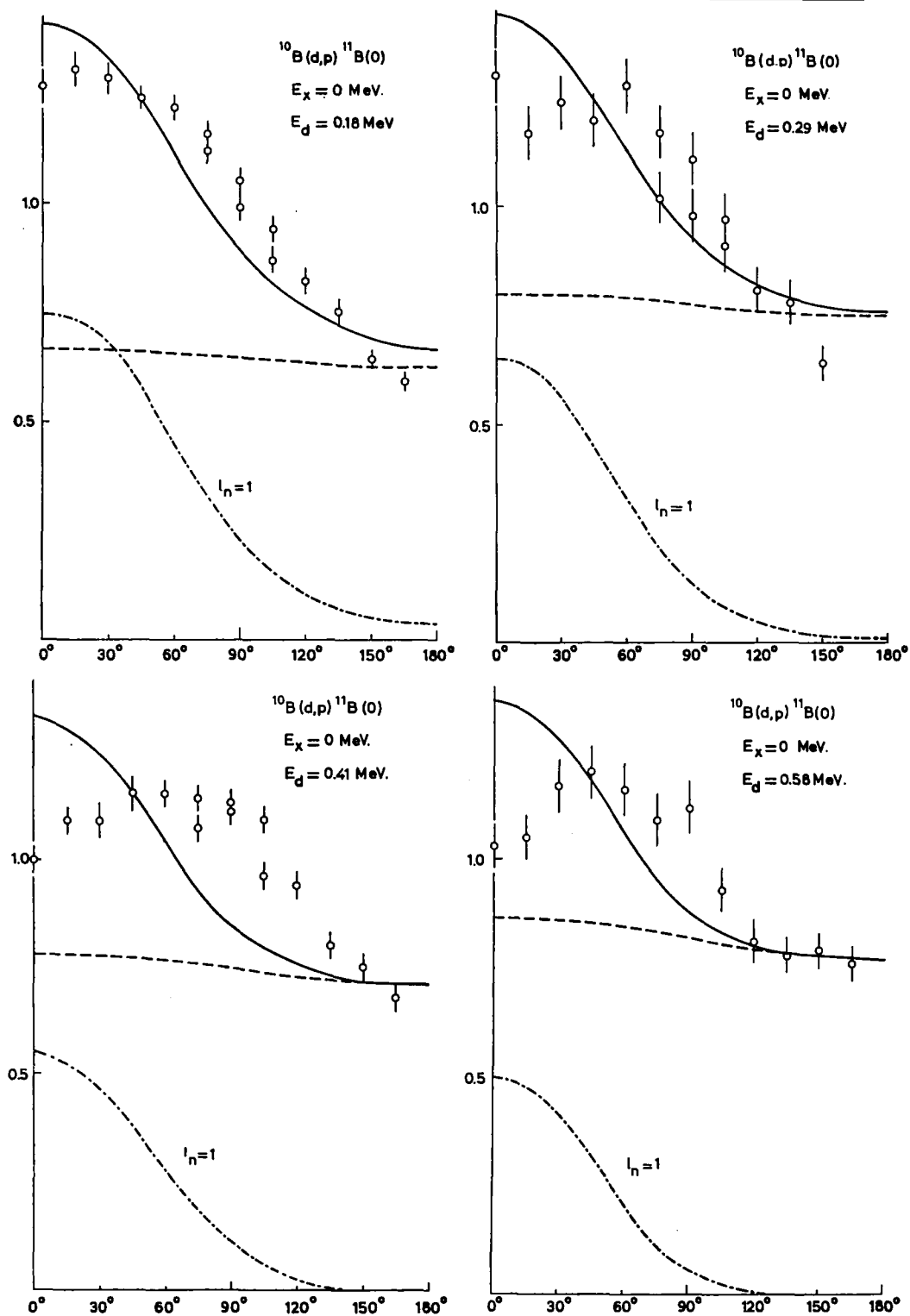
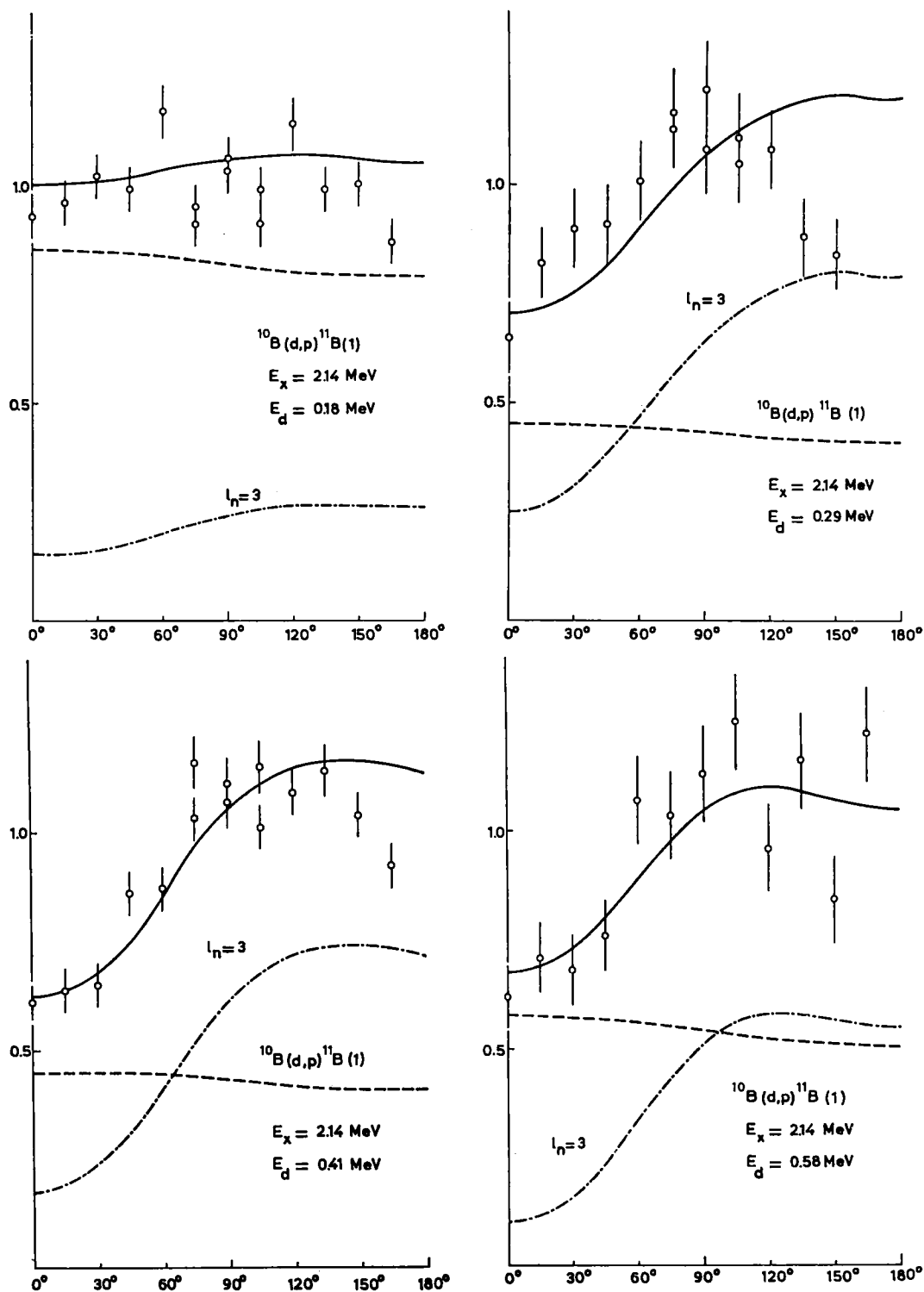
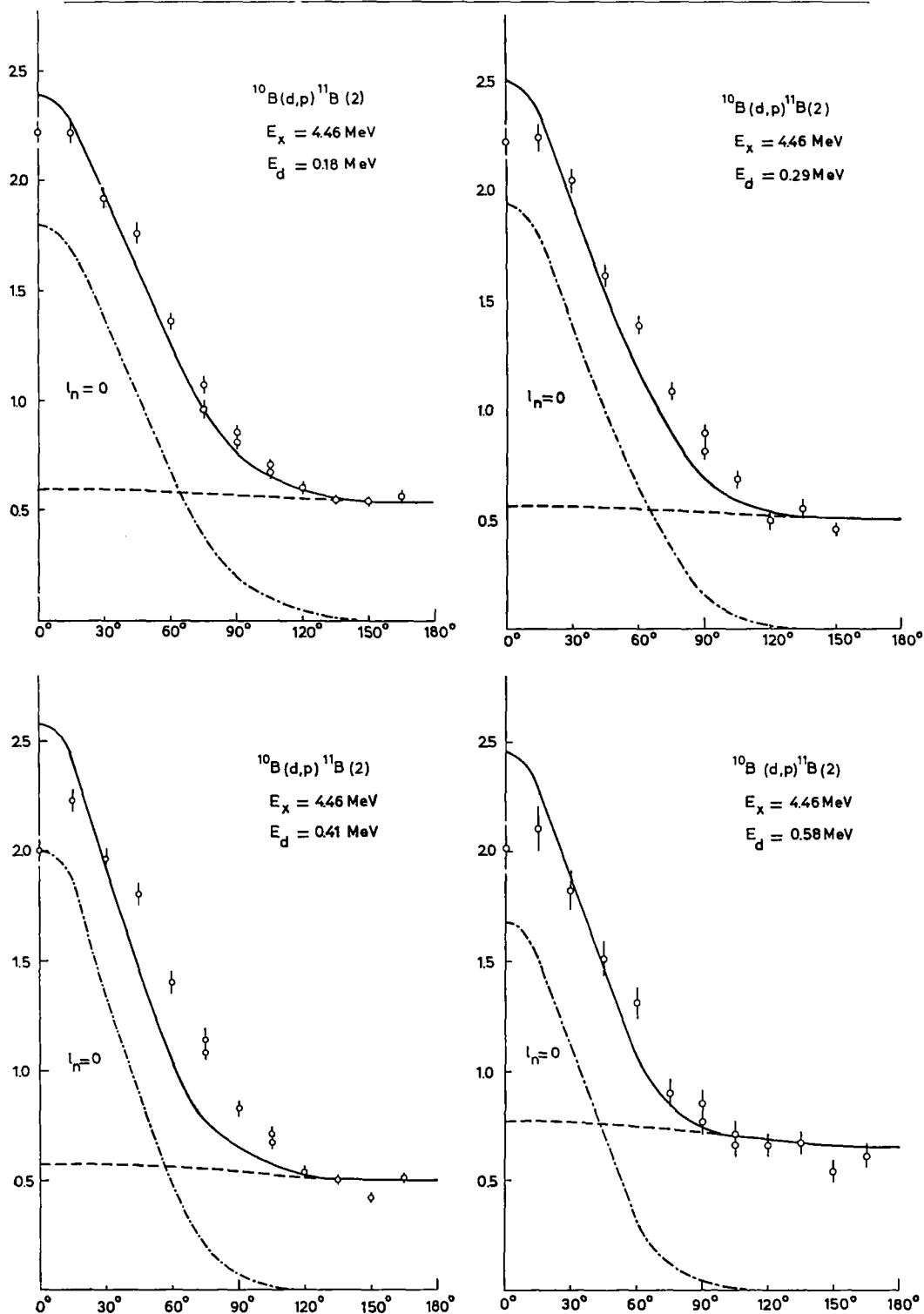


Fig. 1. Angular distributions of  $^{10}\text{B}(d,p)^{11}\text{B}(0)$  group (0) on arbitrary scale in laboratory coordinates. The full curve is the sum of a stripping contribution for  $l_n = 1$  (dot-dash curve) and an isotropic contribution for compound nucleus formation (dashed curve).

Fig. 2. Angular distributions of  $^{10}\text{B}(d, p)^{11}\text{B}$  group (1).


 Fig. 3. Angular distributions of  $^{10}\text{B}(d,p)^{11}\text{B}$  group (2).

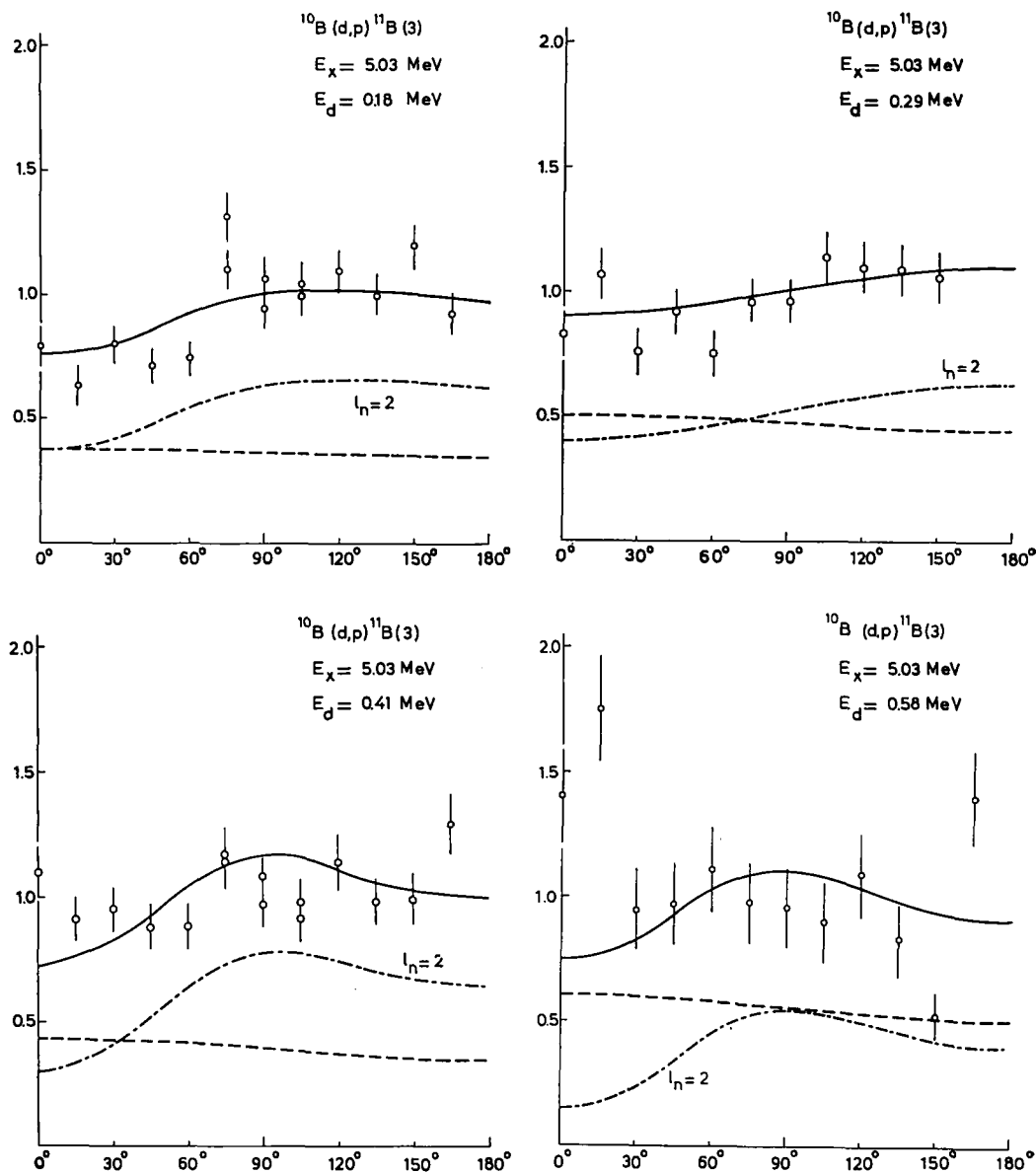


Fig. 4. Angular distributions of  $^{10}\text{B}(d, p)^{11}\text{B}$  group (3).

deuteron energy with a thin crystal (NaI) scintillation spectrometer<sup>6)</sup> detecting protons emitted at an angle of  $\vartheta = 120^\circ$  in respect to the deuteron beam. Aluminum absorbers to a total thickness of  $75 \mu$  were used between target (the enriched  $^{10}\text{B}$  target, see § 2) and crystal surface, in order to suppress low-energy protons from the  $\text{D}(d, p)\text{T}$  and  $^{12}\text{C}(d, p)^{13}\text{C}$  reactions and alpha particles. A pulse spectrum of the  $^{10}\text{B}(d, p)^{11}\text{B}$  proton groups showing the

resolution of the scintillation spectrometer has already been published <sup>6)</sup>. Such pulse spectra were taken at deuteron energy intervals of 100 keV. The positions of the pulse groups varied slowly with deuteron energy, due to:

- a) the dependency of  $E_p$  on  $E_d$ ;
- b) the influence of the stray field of the deuteron analyzing magnet on the multiplier tube.

At a given deuteron energy the pulses from the four proton groups were counted in succession by placing a 10 Volt discriminator channel in four suitably chosen positions. In this way the yields of the four groups were measured in the region from  $E_d = 175$  keV to  $E_d = 700$  keV at 25 keV intervals, except in the  $E_d = 200 - 250$  keV region where the intervals were narrowed to 12.5 keV. The yield of the groundstate group at  $E_d = 400$  keV was taken as a reference and was frequently remeasured. The target showed no sign of deteriorating during all of the measurements.

The yield measurements of proton group (3) had to be corrected for a small gamma-ray background. Its contribution could be measured by placing an extra 75  $\mu$  aluminum absorber before the crystal, thus suppressing groups (2) and (3).

The results of the yield measurements are given in Figs. 5 and 6. In Fig. 5 the sum of the differential cross sections of the four proton groups at  $\vartheta = 120^\circ$  is given, together with the sum of the total cross sections. The latter were obtained by integrating the differential cross sections over solid angle, making use of the angular distribution coefficients (Table I), which vary only slowly as a function of deuteron energy between  $E_d = 200$  and 600 keV. In Fig. 6 is plotted the ratio of the differential cross section at  $\vartheta = 120^\circ$  of each of the four proton groups to the sum of the groups. Deuteron energies are given as effective values (average energy of reacting deuterons) <sup>7)</sup>, which can be approximated at high deuteron energies by the bombarding energy minus half the deuteron energy loss in the target.

The absolute values of the cross sections (see Fig. 5) have been computed from the proton yield observed from the enriched  $^{10}\text{B}$  target. The  $^{10}\text{B}$  content of this target was assumed to be 100%. The most likely contaminant is  $^{11}\text{B}$ , but the  $^{11}\text{B}$  content could be shown to be smaller than 3% by comparing the neutron yield of the  $^{11}\text{B}(d, n)^{12}\text{C}$  reaction from this target and from an enriched  $^{11}\text{B}$  target <sup>8)</sup>. As a check the proton yield of the  $^{10}\text{B}(d, p)^{11}\text{B}$  ground-state group has also been measured from an "infinitely" thick borax target. Before using the borax the crystal water was driven out by heating to 250°C. The proton yield from such a thick target is proportional to

$$\int_0^{E_0} \left( -dx/dE \right) \sigma(E) dE$$

where  $E_0$  is the bombarding energy and  $(-dx/dE)$  is the deuteron energy loss per cm in the borax. The latter quantity has been computed from the  $dE/dx$  values for the atomic constituents B, O and Na, which were obtained (partly

by interpolation) from the measurements of Warsaw<sup>9)</sup> and of Reynolds, Dunbar, Wenzel and Whaling<sup>10)</sup>.

The differential cross sections of the  $^{10}\text{B}(d, p)^{11}\text{B}$  groundstate transition at  $\vartheta = 120^\circ$  and  $E_d = 400$  keV measured from the  $^{10}\text{B}$  enriched target and from the borax target agreed within 7%. The same good agreement was observed at  $E_d = 500$  keV.

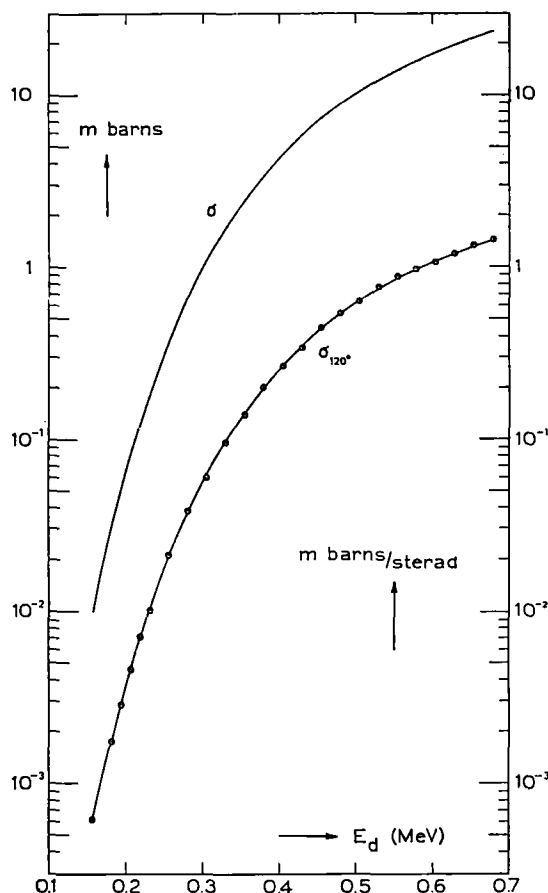


Fig. 5. Differential cross section at  $\vartheta = 120^\circ$  of the sum of four proton groups from  $^{10}\text{B}(d, p)^{11}\text{B}$  (lower curve), and total cross section of the sum of these four groups (upper curve). The deuteron energy was corrected for target thickness.

The error in the absolute cross section given in Fig. 5 is estimated as 10%. However, the error in the ratio of the yields of two proton groups at a given deuteron energy, or the error in the ratio of the yields of one proton group at two different deuteron energies, is smaller than 2%.

The absolute cross sections reported in reference 1 must be regarded as superseded by the present results. The former were obtained by bombardments of a natural boron target, but the boron metal used for this target



proved later to be far from pure, containing large amounts of magnesium and aluminum.

§ 4. *Discussion and conclusions.* Both stripping and compound nucleus formation may be expected to contribute to the differential cross section of  $(d, p)$  reactions at low energy.

To estimate the relative importance of these two mechanisms one has to make some sort of an assumption as to the angular distribution of the compound nucleus contribution. The simplest assumption is that this contribution is isotropic <sup>11</sup>). Of course this may be far from reality but it is good enough for an order of magnitude estimate.

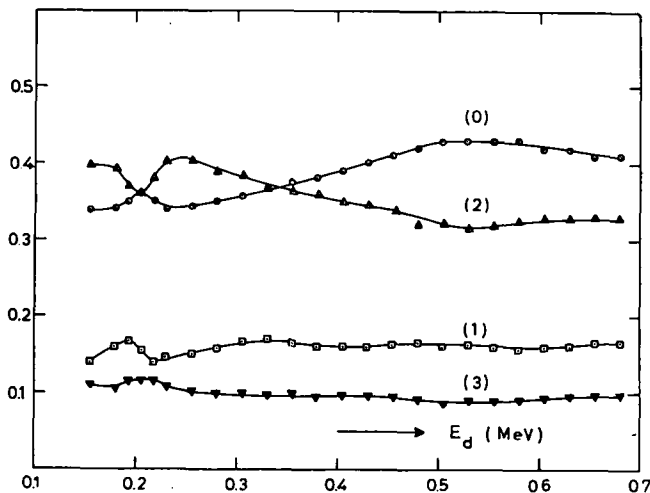


Fig. 6. Ratios of the differential cross sections at  $\theta = 120^\circ$  of the four  $^{10}\text{B}(d, p)^{11}\text{B}$  proton groups to the sum of the groups. The deuteron energy was corrected for target thickness.

To compute the angular distributions according to stripping theory the orbital momentum  $l_n$  of the captured neutron has to be known. From an investigation of the  $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$  reaction Jones and Wilkinson <sup>11</sup>) assigned the following spins and parities to the three lowest  $^{11}\text{B}$  excited states (taking the ground-state as  $J = \frac{3}{2}^-$ ):  $J = \frac{1}{2}^\pm$  ( $E_x = 2.14$  MeV),  $J = \frac{5}{2}^+$  ( $E_x = 4.46$  MeV) and  $J = \frac{1}{2}^\pm$  ( $E_x = 5.03$  MeV). This would agree with the single particle shell model, which predicts  $p_{3/2}$ ,  $p_{1/2}$ ,  $d_{5/2}$  and  $s_{1/2}$  for the four lowest  $^{11}\text{B}$  states. One then has to assign  $l_n = 1, 3, 0$  and  $2$  to the corresponding  $^{10}\text{B}(d, p)^{11}\text{B}$  proton groups, if for the  $^{10}\text{B}$  ground state is taken  $J = 3^+$ . Stripping angular distributions were computed for these  $l_n$  values using stripping theory in the form given by Bhatia e.a. <sup>12</sup>) and taking the  $^{10}\text{B}$  nuclear radius equal to  $5.8 \times 10^{-13}$  cm. This is in agreement with a radius of  $4.8 \times 10^{-13}$  cm found by Holt e.a. <sup>13</sup>) at  $E_d = 8$  MeV, if one

takes into account the fact that they made use of stripping theory in the form given by Butler<sup>13</sup>), which necessitates generally the use of a somewhat smaller nuclear radius.

The ratio of the stripping contribution to the compound nucleus contribution was finally chosen so as to obtain the best fit to the experimental angular distributions given in Figs. 1, 2, 3 and 4. From Figs. 5 and 6 it is then possible to compute total cross sections for stripping and for compound nucleus formation for the four  $^{10}\text{B}(d, p)^{11}\text{B}$  proton groups and for the four deuteron energies at which angular distributions were measured. These are collected in Table II.

TABLE II

Total cross section, and cross section for stripping and for compound nucleus formation of four $^{10}\text{B}(d, p)^{11}\text{B}$ groups at four deuteron energies					
Group number	$^{11}\text{B}$ excitation energy (MeV)	Total cross section (mb)	Stripping cross section (mb)	$l_n$	Compound nucleus cross section (mb)
$E_d = 180 \text{ keV}$					
(0)	0	$9.9 \times 10^{-3}$	$3.6 \times 10^{-3}$	1	$6.3 \times 10^{-3}$
(1)	2.14	$3.3 \times 10^{-3}$	$0.6 \times 10^{-3}$	3	$2.7 \times 10^{-3}$
(2)	4.46	$14.4 \times 10^{-3}$	$6.3 \times 10^{-3}$	0	$8.1 \times 10^{-3}$
(3)	5.03	$2.4 \times 10^{-3}$	$1.5 \times 10^{-3}$	2	$0.9 \times 10^{-3}$
$E_d = 290 \text{ keV}$					
(0)	0	$2.6 \times 10^{-1}$	$0.6 \times 10^{-1}$	1	$2.0 \times 10^{-1}$
(1)	2.14	$1.0 \times 10^{-1}$	$0.6 \times 10^{-1}$	3	$0.4 \times 10^{-1}$
(2)	4.46	$4.0 \times 10^{-1}$	$1.8 \times 10^{-1}$	0	$2.2 \times 10^{-1}$
(3)	5.03	$0.6 \times 10^{-1}$	$0.3 \times 10^{-1}$	2	$0.3 \times 10^{-1}$
$E_d = 410 \text{ keV}$					
(0)	0	1.5	0.4	1	1.1
(1)	2.14	0.5	0.3	3	0.2
(2)	4.46	2.4	1.1	0	1.3
(3)	5.03	0.4	0.2	2	0.2
$E_d = 585 \text{ keV}$					
(0)	0	6.4	1.2	1	5.2
(1)	2.14	1.8	0.9	3	0.9
(2)	4.46	7.1	2.5	0	4.6
(3)	5.03	1.3	0.6	2	0.7

On the whole one can say that the measured angular distributions and cross sections follow generally the features predicted by stripping theory. Stripping cross sections decrease with increasing  $l_n$ , as they should. An exception to this latter rule form the weak groups (1) ( $l_n = 3$ ) and (3) ( $l_n = 2$ ), whose intensity order does not follow the stripping prediction. Groups (2) ( $l_n = 0$ ) and (0) ( $l_n = 1$ ) show pronounced forward peaking, although the peaking is not quite strong enough. The intensity at about  $\vartheta = 90^\circ$  is too large, while it is too small at  $\vartheta = 0^\circ$ . Neither does the angular distribution of group (1) quite conform to the expected shape.

To explain the reversed intensity order of groups (1) and (3) one could make the assumption that the spin of the third  $^{11}\text{B}$  level (at  $E_x = 5.03 \text{ MeV}$ )

is not  $J = \frac{1}{2}^+$  but  $J = \frac{1}{2}^-$ . This would still be in agreement with the experiments of Jones and Wilkinson<sup>11)</sup>. It would entail  $l_n = 3$  both for group (3) and for group (1). Because the third  $^{11}\text{B}$  level would be a multiple excitation level, while the first is a single particle level, the intensity of group (3) might then well be smaller than that of group (1).

The relative intensities of the four proton groups seem to depend very little on deuteron energy (see Fig. 6) except for a region around  $E_d = 0.21$  MeV, where pronounced irregularities are found. They are certainly real and have been remeasured several times. They are best explained by assuming a resonance in the compound nucleus formation corresponding to a new  $^{12}\text{C}$  resonance level at an excitation energy of 26.93 MeV.

The present results can be compared to those of Pratt<sup>5)</sup> at  $E_d = 3.03$  MeV. Except for group (0), which is slightly peaked, he finds no peaking at all, and thus concludes that stripping is not important. The intensity order of his four proton groups, however, agrees with the stripping prediction. Angular distribution measurements of group (0) by Redman<sup>2)</sup>, by Holt and Marsham and by Burke, Risser and Phillips<sup>4)</sup> are in general agreement with stripping theory for  $l_n = 1$ .

The absolute values of differential cross sections can be compared to those of Burke, Risser and Phillips<sup>4)</sup>, who measured  $\sigma(90^\circ)$  and  $\sigma(135^\circ)$  from 0.5 to 1.85 MeV and  $\sigma(0^\circ)$  from 0.7 to 2.0 MeV for the ground state proton group. Their values between  $E_d = 0.5$  and 0.7 MeV are roughly 8 times as large as ours. We have no indication as to the origin of this discrepancy, and we can only say that the proton yields observed both with nuclear emulsions and with the scintillation spectrometer from different boron targets ( $^{10}\text{B}$  enriched boron metal, natural boron metal, borax, boric acid) are definitely incompatible with such high cross sections.

*Acknowledgements.* This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie", which was made possible by a subvention from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek".

The authors are indebted to Prof. J. M. W. Milatz for his interest in this investigation. They wish to thank H. M. Jongerius, A. L. Boers and Miss A. M. Hoogerduijn for their generous assistance.

Received 30-6-54.

## REFERENCES

- 1) Endt, Paris, Jongerius and Valckx, *Physica* **18** (1952) 423.
- 2) Redman, W. C., *Phys. Rev.* **79** (1950) 6.
- 3) Holt, J. R. and Marsham, T. N., *Proc. phys. Soc. A* **66** (1953) 1032.
- 4) Burke, Risser and Phillips, *Phys. Rev.* **93** (1954) 188.
- 5) Pratt, W. W., *Phys. Rev.* **93** (1954) 816.
- 6) Valckx, F. P. G. and Endt, P. M., *Physica* **19** (1953) 1140 (L).
- 7) De Jong, D., Thesis Utrecht 1953.
- 8) Paris, C. H. and Endt, P. M., *Physica* **20** (1954) 585.
- 9) Warshaw, S. D., *Phys. Rev.* **76** (1949) 1759.
- 10) Reynolds, Dunbar, Wenzel and Whaling, *Phys. Rev.* **92** (1953) 742.
- 11) Jones, G. A. and Wilkinson, D. H., *Phys. Rev.* **88** (1952) 420 (L).
- 12) Bhatia, Huang, Huby and News, *Phil. Mag.* **43** (1952) 485.
- 15) Butler, S. T., *Proc. roy. Soc. A* **208** (1951) 559.