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ANGULAR DISTRIBUTIONS OF FOUR NEUTRON GROUPS FROM THE $^{10}B(d, n)^{11}C$ REACTION

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Synopsis

Measurements are described of the angular distributions of the four most energetic neutron groups from the $^{10}B(d, n)^{11}C$ reaction at a deuteron energy of 0.6 MeV. Neutrons were detected by their recoil protons in nuclear emulsions. The angular distributions have been analyzed in terms of a stripping contribution and an, assumedly isotropic, contribution from compound nucleus formation. From Butler analysis $l_p = 1$ is found for the stripping contribution of the neutron group leading to the ^{11}C ground state, and $l_p = 0$ for the group leading to the second excited state. This is in agreement with previous results obtained from the mirror reaction $^{10}B(d, p)^{11}B$ and with predictions from the nuclear shell model. Stripping contributions of the other two neutron groups are very small.

§ 1. *Introduction.* In a previous paper ¹) angular distribution and yield measurements have been described of four proton groups from the $^{10}B(d, p)^{11}B$ reaction. It seemed interesting to supplement these measurements with an investigation of the $^{10}B(d, n)^{11}C$ reaction. This latter reaction leads to ^{11}C, which is the mirror nucleus of ^{11}B. For this reason we may expect that angular distributions and yields of corresponding neutron and proton groups are very nearly identical.

The nucleus ^{11}C has excited states at 1.85, 4.23 and 4.77 MeV ²) ³). All these levels and the ^{11}C ground state should be reached from the $^{10}B(d, n)^{11}C$ reaction at $E_d = 0.6$ MeV, as the ground-state Q-value amounts to 6.472 MeV ²). Angular distribution measurements of all neutrons from the $^{10}B(d, n)^{11}C$ reaction detected by an energy insensitive "long" counter at $E_d = 0.71$, 1.06 and 1.43 MeV have been reported by Burke e.a. ⁴).

In § 2 a description will be given of the experimental procedure used for detection of neutrons by means of the nuclear emulsion method. The results of the measurements are presented in § 3 and discussed in § 4.

§ 2. *Experimental procedure.* Neutrons were detected and their energy was measured by means of their recoil protons in nuclear emulsions placed at 15° intervals around the target. The aluminum plate holder was very much the same as the one used for (d, p) angular distribution measurements [5]) with the following alterations:

a) the surface of the emulsion was put parallel to the direction of the incoming neutrons;

b) to reduce the background of neutrons resulting from bombardment of the slit system defining the deuteron beam, the slit to target distance was enlarged from 25 mm to 195 mm;

c) the average distance of target to emulsions was enlarged from 60 mm to 100 mm to reduce the uncertainty in the position of the target spot due to its finite extension and its possible eccentricity.

To prevent charged particles from reaching the emulsion an aluminum shield of 1 mm thickness was mounted between target and emulsions.

Of the proton recoil tracks found in the exposed and processed nuclear emulsions the following quantities were actually measured:

a) the projection of the track on the surface of the emulsion;

b) the "dip" of the track as measured by its component perpendicular to the surface of the emulsion;

c) the angle between the direction of the incident neutron and the direction of the projection defined under *a*).

From elementary geometrical considerations (taking into account the shrink of the emulsion by development) the actual range of the proton recoil can be found and the angle ϑ between neutron and proton direction. The proton energy E_p can be found from the range-energy relation and finally the neutron energy from the expression:

$$E_n = E_p/\cos^2 \vartheta.$$

These computations were much simplified by the use of suitable nomograms, in which the "corrected range" (the range of protons from head-on collisions) was used as an intermediate quantity. Only proton tracks were accepted of which the dip angle was smaller than 7.5° (in the unprocessed emulsion), and in which the azimuth angle, defined under *c*), was smaller than 15°.

For larger dip and azimuth angles the error in E_n, due to the errors in the measurements of the proton track parameters, rises rapidly.

The target consisted of a 80 μg/cm^2 ^{10}B layer on a 6 μ aluminum backing. It was prepared by electromagnetic separation by Dr R. H. V. M. Dawton at the Atomic Energy Research Establishment, Harwell, England. The ^{11}B content was too low (2.5 ± 1.5%) to interfere with the present measurements as was found from separate ^{11}B enriched target bombardments. The same was found for ^{13}C by bombarding an enriched ^{13}C target. The contaminants ^{12}C and ^{16}O, usually present on every target, do not interfere because the Q-values of their (d, n) reactions are very low.

The ^{10}B target was bombarded by a 1 μA current of 600 keV deuterons during 20 hours. The effective deuteron energy obtained by subtracting half the deuteron energy loss in the target amounted to 576 keV.

§ 3. *Experimental results.* In Fig. 1 the energy spectrum of neutrons leaving the target in the forward direction ($\vartheta = 0°$) is shown, in which the "corrected range" (see § 2) is used as a measure of neutron energy. A certain amount of background was present at ranges below 100 μ, and has been subtracted in Fig. 1. It is caused by D(d, n) ^{3}He neutrons from the slit system defining the deuteron beam, as could be certified by bombardments of a blank aluminum target. This background is most serious in emulsions placed in the forward direction ($\vartheta = 0° — 45°$), although these emulsions have the greatest distances to the slit system, because then the neutrons from the target and from the slit system reach the emulsion from almost the same direction, which makes their recoil protons indistinguishable.

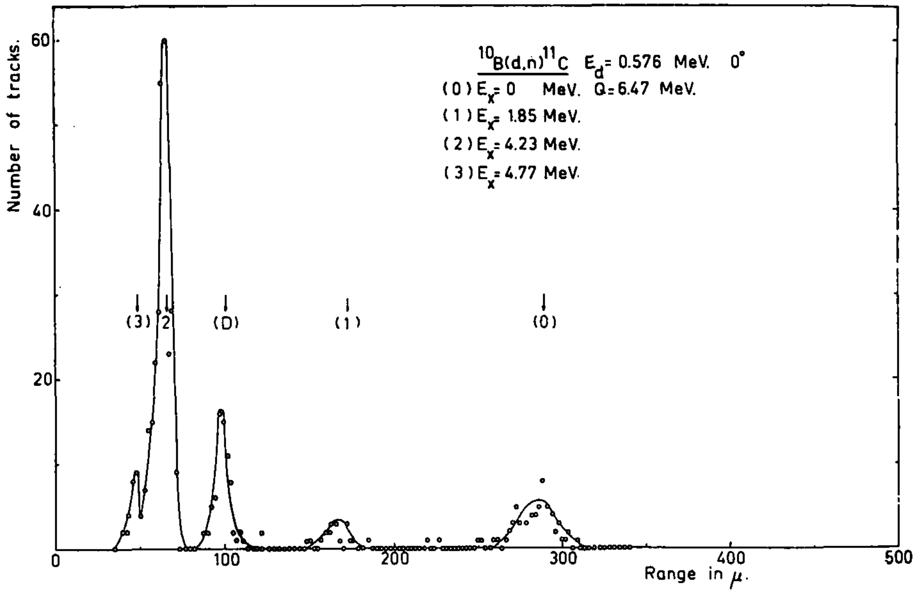

Fig. 1. Energy spectrum of neutrons emitted at $\vartheta = 0°$ from a ^{10}B target bombarded by 0.58 MeV deuterons. The number of counted tracks is plotted as a function of "the corrected range" of recoil protons i.e. the range of protons with the full neutron energy. The neutron group marked (D), results from the D(d, n) ^{3}He reaction, the groups marked (0), (1), (2) and (3) from the ^{10}B(d, n)^{11}C reaction. The total number of tracks counted for Fig. 1 amounted to 416.

In emulsions placed at $\vartheta = 60°$ and larger angles the recoil protons directed radially away from the target, and originating from D(d, n)^{3}He neutrons from the slit system, have such a low energy, that they can not be mixed up with the four ^{10}B(d, n)^{11}C groups which were counted.

Four different neutron groups can be seen in Fig. 1. The group at a range of about 100 μ is due to D(d, n)^{3}He neutrons from the target. The four other neutron groups marked (0), (1), (2) and (3) originate in the ^{10}B(d, n)^{11}C reaction. They correspond to transitions to the ^{11}C ground-state and to the three lowest excited states. Background has already been subtracted.

Differential cross sections of the three most energetic ^{10}B(d, n)^{11}C groups are given in Figs. 2, 3 and 4. For the conversion of counted number of tracks into differential cross sections one has to take into account the escape probability of proton tracks from the emulsion [6]) and the neutron proton elastic scattering cross section [7]). The statistics of the neutron group leading to the ^{11}C third excited state were too poor to allow the drawing of conclusions regarding its angular distribution. For this low-intensity and low-energy group the background correction was especially serious.

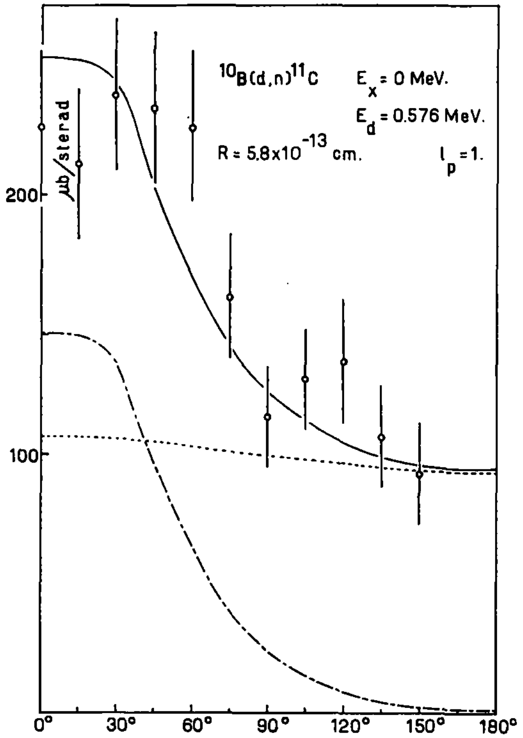

Fig. 2. Differential cross section of the ground-state neutron group from the reaction ^{10}B(d, n)^{11}C at E_d = 0.58 MeV plotted in the laboratory system. The cross section (full drawn curve) is analyzed as a sum of a stripping contribution for l_p = 1 (dotdash curve) and an isotropic compound nucleus contribution (dashed curve).

§ 4. *Discussion and conclusions.* To compute stripping angular distributions for the ^{10}B(d, n)^{11}C reaction leading to the ^{11}C states at E_x = 0, 1.85, 4.23 and 4.77 MeV one may safely assume that the proton angular momentum transfers l_p for this reaction are the same as the neutron angular momentum transfers l_n for the mirror reaction ^{10}B(d, n)^{11}B leading to the ^{11}B states at E_x = 0, 2.14, 4.46 and 5.03 MeV, i.e. respectively l_p = 1, 3, 0 and 2 [1]). Stripping angular distributions for these l_p values were computed for the three most energetic neutron groups, using stripping theory in the form given by Bhatia e.a. [8]). The ^{10}B nuclear radius was taken equal to 5.8 × 10^{-13} cm, the same value as was found to fit the $^{10}\mathrm{B}(d, p)^{11}\mathrm{B}$ angular distributions [1]).

The experimental differential cross sections given in Figs. 2, 3 and 4 were now analyzed into a stripping contribution and a contribution for compound nucleus formation which was assumed to be isotropic in the center of mass system [9]) [1]). It is seen that in this way a reasonable agreement can be obtained between calculated and measured angular distributions. The agreement is worst for the neutron group leading to the ^{11}C first excited state (Fig. 3), especially at the larger angles, but the discrepancy in this case might well be explained by the relatively poor statistics.

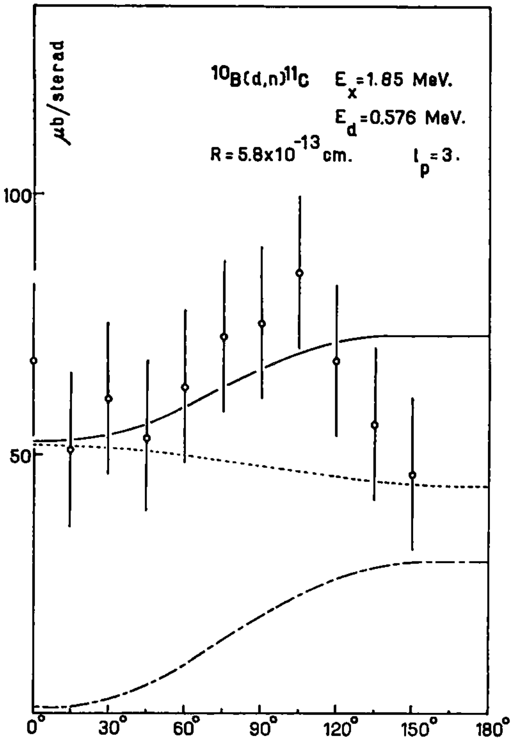

Fig. 3. Differential cross section at E_d = 0.58 MeV of the $^{10}\mathrm{B}(d, p)^{11}\mathrm{C}$ neutron group leading to the ^{11}C level at E_x = 1.85 MeV. The stripping contribution (dot-dash curve) has been drawn for l_p = 3.

In Table I are collected the total number of tracks counted for each neutron group, the total cross section, and the contributions to the total cross section from stripping and compound nucleus formation. Also the l_p-value used in the calculation of the stripping part has been indicated.

The stripping contributions show apparently a monotonic decrease with increasing l_p-values, as is predicted by theory. Only group (3) shows an exception to this rule. Its stripping contribution is smaller than can be accounted for.

The angular distributions and relative intensities of the neutron groups from the ^{10}B(d, n)^{11}C reaction agree very well with those of the proton groups from the mirror reaction ^{10}B(d, p)^{11}B [1]). Even the inverted intensity order of groups (1) and (3) is found in both reactions. For a possible explanation of this effect see reference 1. Also the absolute values of the total cross sections are nearly the same for the two reactions. Actually the sum of the total cross sections of the four groups at E_d = 0.58 MeV is 2.9 times larger for the (d, p) as for the (d,n) reaction. This is outside the experimental error which is only 10% for the (d, p) total cross section but might be up to a factor of two for the (d, n) reaction. However, a smaller cross section for the (d,n) reaction might well be explained by Coulomb repulsion, which makes it more difficult for the proton than for the neutron to enter the nucleus after deuteron break-up outside the nucleus.

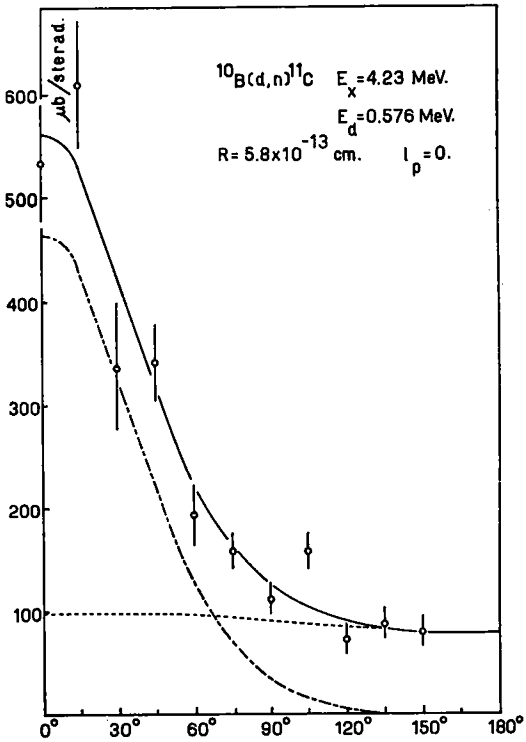

Fig. 4. Differential cross section at E_d = 0.58 MeV of the ^{10}B(d, n)^{11}C neutron group leading to the ^{11}C level at E_x=4.23 MeV. The stripping contribution (dot-dash curve) has been drawn for l_p = 0.

TABLE I

Contributions of stripping and compound nucleus formation to the total cross section of the $^{10}B(d, n)\,^{11}C$ reaction at $E_d = 0.58$ MeV leading to the four lowest ^{11}C states

Group	^{11}C excitation energy (MeV)	Counted number of tracks	Total cross section (mb)	Stripping cross section (mb)	l_p	Compound nucleus cross section (mb)
(0)	0	485	2.0	0.7	1	1.3
(1)	1.85	234	0.8	0.2	3	0.6
(2)	4.23	1406	2.2	1.1	0	1.1
(3)	4.77	463	0.7	0.1	2	0.6

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