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ANGULAR DISTRIBUTIONS OF FOUR PROTON GROUPS FROM THE $B^{10}(d, p)B^{11}$ REACTION

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Synopsis

Angular distributions have been measured of four proton groups from the $B^{10}(d, p)B^{11}$ reaction corresponding to transitions to the groundstate (group (0)) and the three lowest excited states of B^{11} (groups (1), (2) and (3)). A thin target of natural boron was bombarded with 310 keV deuterons and protons were detected by nuclear emulsions placed at 15° intervals round the target. Protons of different groups were distinguished by their range in the emulsion. Angular distributions of groups (0) and (2) are peaked in the forward direction while those of groups (1) and (3) are more nearly isotropic. By integration over solid angle total cross-sections were determined. They amount to 48 microbarn for group (0), 18 microbarn for group (1), 76 microbarn for group (2) and 11 microbarn for group (3).

§ 1. *Introduction.* Many proton groups are known to result from the $B^{10}(d, p)B^{11}$ reaction. Of eleven of these groups reaction energies have been measured accurately by Van Patter e.a. [1]). Angular distributions of the groundstate protons have been measured by Redman [2]) at deuteron energies between 1 MeV and 4 MeV.

The low atomic number of boron makes it probable that these measurements of angular distributions may be extended to appreciably lower energies. The high energy release of the reaction, $Q = 9.23$ MeV, should make it possible to obtain angular distributions not only of groundstate protons but also of protons leaving the final nucleus in excited states. It should be possible to use natural boron targets for this purpose because ranges of $B^{11} + d$ reaction products can be expected to be much smaller than those of at least several $B^{10}(d, p)B^{11}$ proton groups.

§ 2. *Experimental procedure.* The experimental procedure for the measurement of angular distributions has been described in detail in previous papers [3] [4] [5]. Deuterons are accelerated by a cascade generator and analyzed by magnetic deflection over 30°. They are collimated by a slit of 1.5 mm width and hit the target placed directly behind the slit. Protons resulting from a nuclear reaction in the target are detected by photographic emulsions placed at 15° intervals round the target at an average distance of 60 mm.

Targets were prepared by evaporating in vacuum natural boron metal from tantalum boatshaped strips onto 7 μ aluminium backings. The target used in these experiments had a thickness of 82 $\pm$ 5 μgram/cm^2 as was determined by weighing. At a deuteron energy of 310 keV this corresponds to a deuteron energy loss in the target of 40 keV. The effective deuteron energy (average energy of reacting deuterons) obtained by subtracting half the target thickness in keV from the bombarding energy then amounts to 290 keV.

This target was bombarded by 7.30 milliCoulomb of 310 keV deuterons. The figure given for the total charge collected on the target was measured by a current integrator [4] and then corrected for the contribution of H_2^+ ions to the mass two beam. The H_2^+ ions result from contamination with normal hydrogen of the deuterium gas admitted to the ion source. This correction was made possible by measurement of the intensities of the mass three and mass four beams consisting resp. of HD^+ and D_2^+ ions. In previous experiments [3] where normal hydrogen had been admitted to the ion source it had been found that the mass three beam contains no H_3^+ ions. If it is now assumed that the gas mixture of D_2, HD and H_2 admitted to the ion source was in statistical equilibrium, then the following relation can easily be proven for the corresponding beam intensities:

$$(HD^+)^2 = 4(H_2^+)(D_2^+).$$

This relation allows to calculate the H_2^+ contribution to the mass two beam from the intensities of the mass three and mass four beams. The deuterium gas used here was rather impure, the (atomic) deuterium concentration being only 74%. The mass two beam consisted for 66% of D^+ ions.

Protons were detected in Ilford C2 emulsions of 200 μ thickness. In Fig. 1 a range analysis is presented of 1127 particles leaving the target in the forward direction. Five different proton groups of very different intensities can clearly be distinguished. The four groups with longest range marked (0), (1), (2) and (3) all originate from the $B^{10}(d, p)B^{11}$ reaction and correspond to the following reaction energies [1]: 9.23 MeV, 7.09 MeV, 4.77 MeV and 4.20 MeV. The fifth group marked D consists of protons of the reaction $D(d, p)T$, one of the usual contaminant groups. Some

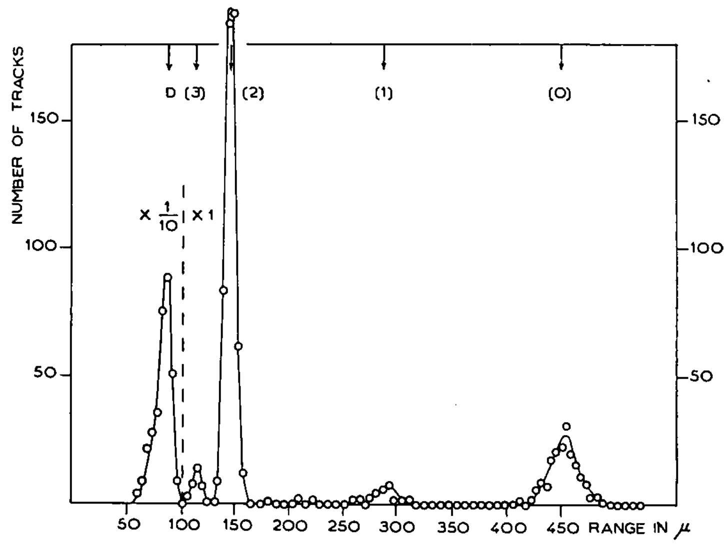

Fig. 1. Range analysis of 1127 tracks of protons leaving the target in the forward direction. Groups (0), (1), (2) and (3) originate from the reaction $B^{10}(d, p)B^{11}$, group D from the reaction $D(d, p)T$. Arrows indicate calculated ranges. The area scanned for tracks shorter than 100 μ was 10 times smaller than that for longer tracks.

tracks with a range around 220 μ are from protons from the $C^{13}(d, p)C^{14}$ reaction, the C^{13} being part (1.1%) from the natural carbon contamination on the target. This group can be disregarded as the range is well different from the ranges of the $B^{10}(d, p)B^{11}$ groups and the intensity very low. Many groups are present with ranges shorter than 50 μ but resolution was insufficient to separate these. The arrows indicated in Fig. 1 correspond to ranges calculated for the five groups mentioned above from the known Q-values and the range-energy relation valid for the emulsion. The agreement between experimental and calculated ranges is good.

Angular distributions were counted for the four $B^{10}(d, p)B^{11}$ groups mentioned above by scanning an area of 35 mm^2 of each plate with a total microscope magnification of 200 X. These distributions were then transformed into the center of mass system. Finally differential cross-sections were computed by dividing the number of protons emitted per steradian by the number of target B^{10} atoms per cm^2 and by the number of deuterons hitting the target during the exposure. These differential cross-sections are plotted in Fig. 2 and 3 in microbarns/steradian. The statistical errors of the experimental points have been indicated by vertical lines.

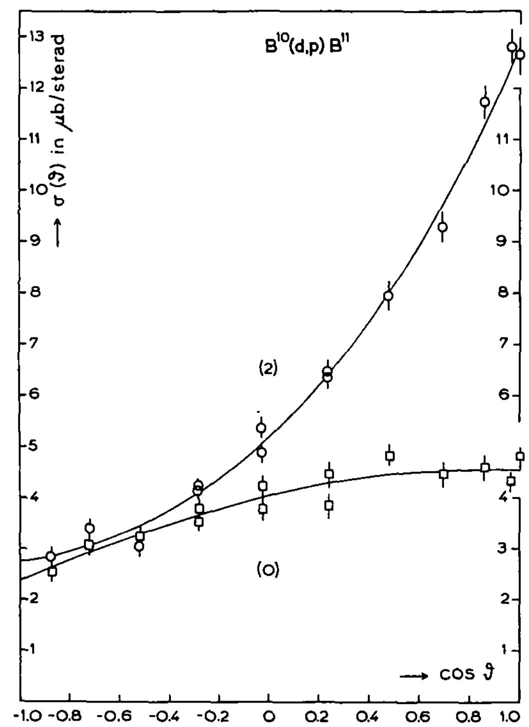

Fig. 2. Differential cross-sections (in center of mass system) of proton groups (0) and (2) from the reaction $B^{10}(d, p)B^{11}$. Full drawn curves have been plotted according to the expressions:
$\sigma(\vartheta) = 3.85(1 + 0.29\ P_1 - 0.10\ P_2 - 0.01\ P_3)$ μb/sterad (for group (0)) and $\sigma(\vartheta) = 6.03(1 + 0.80\ P_1 + 0.29\ P_2 + 0.03\ P_3)$ μb/sterad (for group (2)).

A total number of 20,558 proton tracks has been counted distributed over the four groups according to the respective total cross-sections (see Table I).

TABLE I

Total cross-section and first three coefficients in a Legendre polynomial series development of angular distributions of four proton groups from the reaction $B^{10}(d, p)B^{11}$ at $E_d = 310$ keV.

Group	σ_t in microbarns	b_1	b_2	b_3
(0)	48.3 ± 0.7	+0.29 ± 0.02	—0.10 ± 0.03	—0.01 ± 0.04
(1)	18.4 ± 0.4	—0.05 ± 0.04	—0.26 ± 0.05	0.00 ± 0.06
(2)	76.0 ± 0.7	+0.80 ± 0.02	+0.29 ± 0.02	+0.03 ± 0.03
(3)	10.9 ± 0.3	—0.19 ± 0.05	0.00 ± 0.06	+0.07 ± 0.07

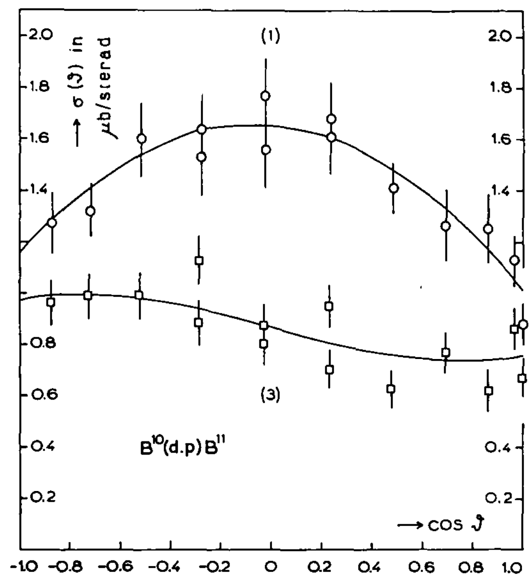

Fig. 3. Differential cross-sections (in center of mass system) of proton groups (1) and (3) from the reaction $B^{10}(d, p)B^{11}$. Full drawn curves have been plotted according to the expressions:
$\sigma(\vartheta) = 1.46(1 - 0.05\,P_1 - 0.26\,P_2)$ μb/sterad (for group (1)) and
$\sigma(\vartheta) = 0.87(1 - 0.19\,P_1 + 0.07\,P_3)$ μb/sterad (for group (3)).

§ 3. *Discussion of results.* The differential cross-sections thus obtained can be represented as a Legendre polynomial series:

$$\sigma(\vartheta) = \frac{\sigma_t}{4\pi}\{1 + \sum_{i=1}^{\infty} b_i P_i(\cos\vartheta)\},$$

where σ_t is the total cross-section. Total cross-sections and the first three coëfficients b_i were obtained from the differential cross-sections by numerical integration [4] [5]. They are assembled in Table I. Higher coëfficients than the third proved to be negligible.

The numerical constants given in Table I have been used in plotting the full drawn curves in Figs. 2 and 3. The statistical errors indicated in Table I have been computed from expressions given by Endt [6]. Besides the statistical error the total cross-sections contain a systematic error (alike for the four proton groups) of about 20% arising from errors in the weighing of the target, in the calibration of the current integrator and from uncertainties in the composition of the mass two beam. Also the errors in total cross-section and coëfficients b_i of proton group (3) may be somewhat larger than the statistical errors indicated in Table I because it was difficult to count the tracks belonging to protons of the group (3) in the presence of groups (2) and D (see Fig. 1) which had an average range differing only by 25% from that of group (3) and which were 16 viz. 100 times more intensive than group (3).

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