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LOW-ENERGY CROSS SECTIONS FOR $^{10}B(p, \alpha)^{7}Be$

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Abstract: Cross sections were determined for the $^{10}B(p, \alpha)^{7}Be$ reaction between 60 keV and 180 keV proton energies using an activation method as well as direct α-detection by a solid-state track detector. In the energy region investigated the influence of the 8.694 MeV state of ^{11}C on $S(E)$ has been observed. The cross section for the Gamow energy is given. The half-width of this level and the branching ratio $^{7}Be(\varepsilon)^{7}Li$ were found to be $\Gamma \approx 300$ keV and $R = 0.104 \pm 0.003$, respectively.

E | NUCLEAR REACTION $^{10}B(p, \alpha)$, $E = 60$–180 keV; measured $\sigma(E)$, branching ratio for $^{7}Be(\varepsilon)^{7}Li$; deduced $S(E)$, ^{11}C level Γ. Enriched target, NaI(Tl) and solid-state detectors.

1. Introduction

The investigations of nuclear reactions induced by low-energy charged particles are especially important from the point of view of nuclear astrophysics in addition to nuclear physics itself. Of particular interest to nuclear astrophysics is the region below 100 keV, since the mean energy of a thermonuclear reaction in the stars is around 10 keV. Measurements above 100 keV, however, render it possible to check cross-section formulae. Nuclear physics can use these results to investigate the level scheme of the intermediate nucleus as well as the reaction mechanism well below the Coulomb barrier.

The $^{10}B(p, \alpha)^{7}Be$ reaction is an important destructive process and may have considerable effect on the extremely low boron abundance in the universe. Owing to technical difficulties only one relative measurement has been done for this reaction cross section below 100 keV [ref. [1])].

The solid-state track detectors, because of their favourable detection efficiency, low background and long stability period, proved to be useful for the investigation of charged-particle reactions having small cross sections. The $^{10}B(p, \alpha)^{7}Be$ reaction can also be measured through the decay of ^{7}Be. The decay scheme can be seen in fig. 1. With knowledge of the branching ratio and by measuring the intensity of the 477.6 keV γ-line one can determine the number of ^{7}Be nuclei produced and the value of the cross section.

By detecting the reaction α-particles and γ-rays from electron capture, the branching ratio R can also be determined.

To measure cross sections for energies $E_p < 100$ keV and for a bombarding intensity of ≈ 10 μA only direct α-detection can be applied owing to the low activity. The above cross section was measured in the energy range $100 < E_p < 180$ keV by the activation method and in the $60 < E_p < 180$ keV range by detecting α-particles directly.

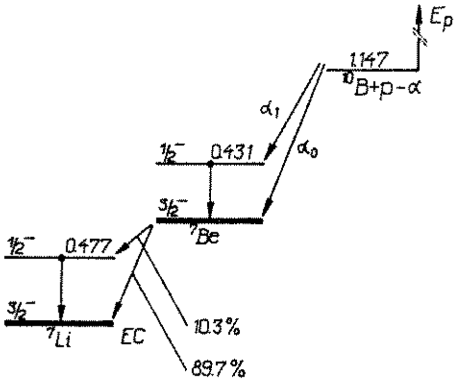

Fig. 1. Energy levels of ^{7}Be for the ^{10}B(p, α)^{7}Be reaction.

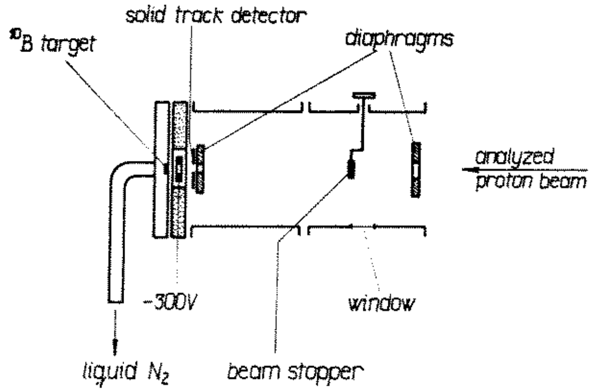

Fig. 2. Schematic drawing of the experimental arrangement.

2. Experimental techniques

For the measurements a Cockcroft-Walton generator of 180 keV was used. The intensity of the analysed proton beam on the target was about ≈ 10 μA, which was continuously measured by a current integrator circuit [2]). The arrangement of the target chamber, the α-detectors and the target samples are shown in fig. 2. The measurements were made with a thick target of ^{10}B, the enrichment being to 93 % ^{10}B.

The 477.6 keV γ-rays arising from the decay of ^{7}Be (see fig. 1) were detected by a NaI(Tl) scintillation detector of 7.6 × 5.0 cm. The photo-peak efficiency of the detec-

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^{54}Mn (834.7 keV) standard γ-s

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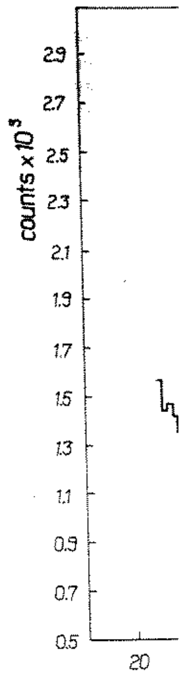

Fig. 3. Spectrum of the 477.6 ke
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tor was determined with ^{113}Sn(391.7 keV), ^{22}Na (511.0 keV), ^{137}Cs (661.6 keV) and ^{54}Mn (834.7 keV) standard γ-sources. The detector was placed in a low-background chamber; the background index in the interval of 100–1000 keV was found to be 4.3 c.p.m./cm^3.

For the γ-ray energy of 477.6 keV the energy resolution and the efficiency of the detector were 115 keV and ≈ 13 %, respectively. No effect above the background has been obtained at E_p = 80 keV where the target current was 4 μA and the irradiation and counting periods were 50 and 30 h, respectively.

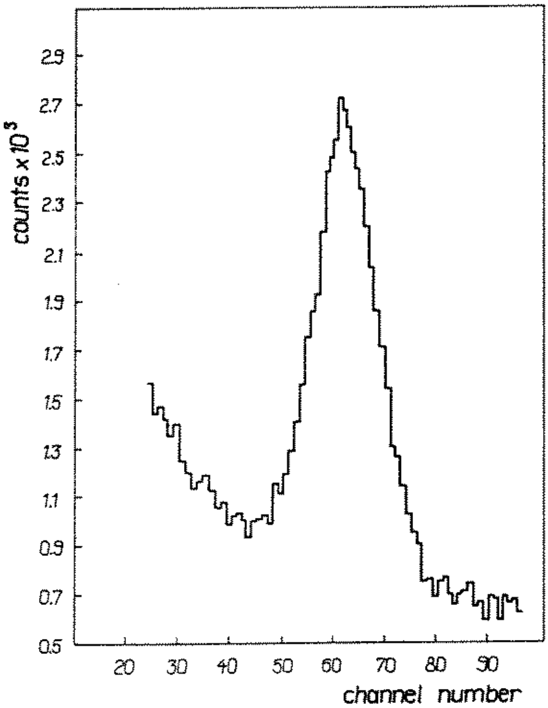

Fig. 3. Spectrum of the 477.6 keV γ-rays emitted in decay of ^{7}Be produced by the ^{10}B(p, α)^{7}Be reaction at a bombarding energy of E_p = 120 keV.

The cross section of the reaction ^{10}B(p, α)^{7}Be has also been determined directly by detecting the α-particles. For the detection of α-particles solid-state (cellulose acetate, T-cellit) detectors were used. The solid-state track detectors were placed into the diaphragm on the side adjacent to the target (see fig. 2).

The etching reagent

$$90\text{g } H_2O + 20\text{g NaOH} + 16\text{g KOH} + 4.5\text{g KMnO}_4,$$

with a 1 h etching time was used [3]). No measurable effect has been obtained at E_p = 40 keV with a target current of 2 μA and an irradiation time of 210 h.

3. Cross-section determination

Measurements by the activation method were performed in the interval $100 < E$ < 180 keV in steps of 20 keV. The advantage of this method is that by measuring the activity of the residual nucleus, background processes can be eliminated and the total cross section can easily be determined. In this investigation background from the $^{10}B(p, \gamma)^{11}C$ reaction could be eliminated by the significant difference between the

TABLE 1

The measured total cross-section data for the $^{10}B(p, \alpha)^7Be$ reaction

E_p (keV)	σ (μb) (activation method)	σ(μb) (direct α method)
180	882 ± 125	1277 ± 164
160	560 ± 88	744 ± 96
140	332 ± 38	320 ± 38
120	148 ± 17	202 ± 17
100	51.0 ± 8.5	60.9 ± 6.9
80		16.2 ± 1.3
60		1.41 ± 0.04

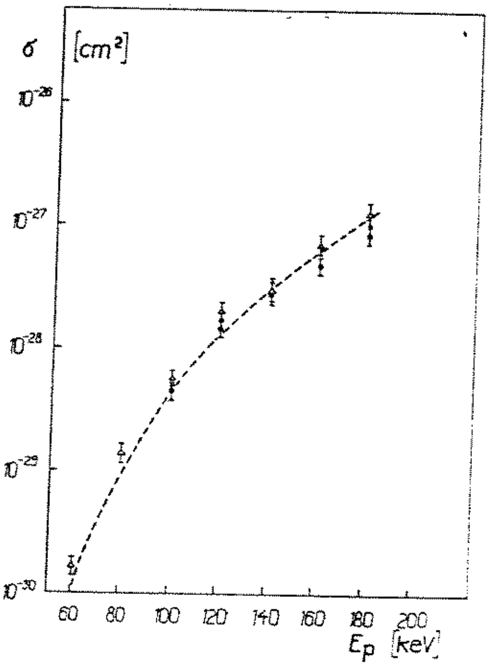

Fig. 4. Total cross-section values for $^{10}B(p, \alpha)^7Be$ reaction *versus* bombarding energy. The dashed line was calculated using constants $S(E)$ and was normalized to the experimental points at $E_p = 140$ keV. The cross-section values are marked with symbols ● and △ measured by the activation and the direct α methods, respectively.

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where W_0 is the penetration factor belonging to $l = 0$ (s-wave) and

$$W_0 = -1.05(ARZ_1Z_2)^{\frac{1}{2}}+31.28Z_1Z_2A^{\frac{1}{2}}E^{-\frac{1}{2}}\left[1+\frac{2}{3\pi}\left(\frac{E}{E_C}\right)^{\frac{3}{2}}\right]. \tag{3}$$

The quantities in eq. (3) are the following: $A = A_1A_2/(A_1+A_2)$, the reduced atomic weight of the Z_1 and Z_2 nuclei; $R = r_{0,\mathrm{p}}A_{\mathrm{p}}^{\frac{1}{3}}+r_{0,\mathrm{B}}A_{\mathrm{B}}^{\frac{1}{3}}$, the sum of the nuclear radii of the proton and the ^{10}B nucleus, where $r_{0,\mathrm{p}} = 1.03$ fm and $r_{0,\mathrm{B}} = 1.47$ fm; E_C, the height of the Coulomb barrier.

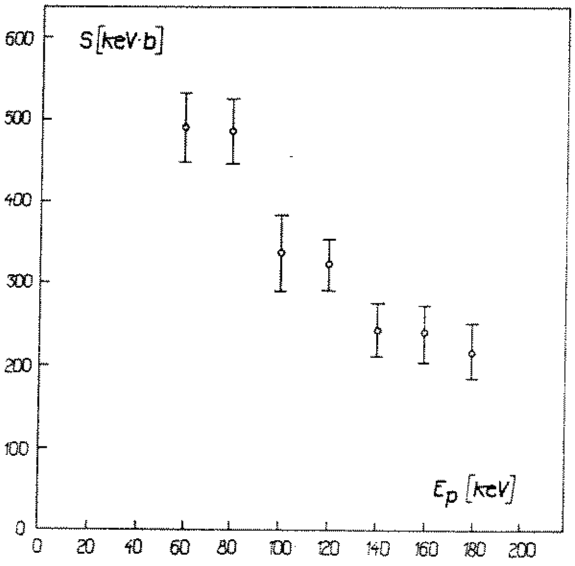

Fig. 5. The cross-section factor $S(E)$ *versus* bombarding proton energy. From $E_p = 180$ keV to 100 keV the $S(E)$ values are given as the averages of the activation and direct α methods, while at $E_p = 80$ and 60 keV only from the latter one.

As can be seen in fig. 4, there are significant differences between the measured and calculated data in the low-energy region. This means that the $\sigma = \sigma(E)$ cross-section curve cannot be described by eq. (2) assuming a constant cross-section factor. Using the experimental σ_{tot} data, the $S(E)$ values have been calculated. The $S = S(E)$ function obtained both by the activation method and by direct α-counting increases with decreasing proton energy as can be seen in fig. 5. This tendency of $S(E)$ can be explained by the presence of the 8.694 MeV state in the compound nucleus ^{11}C but even the role of the 8.651 MeV state cannot be excluded [9]).

Using the relation for the $S(E)$ cross-section factor that is valid for a resonance [8]), the width of the 8.694 MeV state was found to be $\Gamma \approx 300$ keV.

From the astrophysical point of view the cross-section value is especially important at the Gamow energy (E_0). For a temperature of $T_6 = 13$ this energy value is 19.1

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keV. Using the $S(E$
$\sigma(E_0) \approx 1.0\times10^{-36}$
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half-lives of the ^{7}Be and ^{11}C nuclei. Fig. 3 shows the γ-spectrum of ^{7}Be measured at $E_p = 160$ keV.

Measurements with solid-state detectors were performed in the interval $60 < E_p < 180$ keV in steps of 20 keV. At each bombarding energy a few thousand α-tracks were counted. For the cross-section determination the angular distribution of α-particles from the ^{10}B(p, α)^{7}Be reaction was assumed to be isotropic ^{1,4,5}).

The cross-section values were calculated by the formula

$$\sigma(E_0) = \frac{1}{N}\left(\frac{\mathrm{d}Y}{\mathrm{d}E}\right)_{E_0}\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{E_0}, \qquad (1)$$

which is valid for a thick target, where N is the number of ^{10}B nuclei per cm^3 of the target, $(\mathrm{d}Y/\mathrm{d}E)_{E_0}$ is the slope of the yield curve at E_0 and $(\mathrm{d}E/\mathrm{d}x)_{E_0}$ is the specific energy loss of the bombarding particles in the target material ^{6}).

Cross-section values, determined by the activation method as well as direct α-counting are plotted in fig. 4 *versus* bombarding energy and summarized in table 1.

For energies $E_p \geqq 160$ keV the cross section data obtained by the direct α-measurements are higher than the corresponding values measured with the activation method and are outside the error limits. The difference is due to the reaction ^{11}B(p, α)^{8}Be which has a resonance at $E_p = 163$ keV.

4. Determination of the branching ratio ^{7}Be(ε)^{7}Li

The present arrangement also made it possible to determine the branching ratio (R) (fig. 1). The principle of the method is:

(i) to determine the number of ^{7}Be nuclei from the ^{10}B(p, α)^{7}Be reaction by counting the α-particles leading to the first excited and the ground states of ^{7}Be, and

(ii) to determine the number of ^{7}Be decaying to the first excited state of ^{7}Li by measuring the intensity of the 477.6 keV γ-rays.

The determination of the branching ratio was performed at $E_p = 120$ keV; at this energy the background α-particles from the ^{11}B(p, α)^{8}Be reaction could be neglected, and the γ-intensity and α-track density could easily be measured.

The branching ratio ^{7}Be(ε)^{7}Li was found to be $R = 0.104 \pm 0.003$ in a good agreement with ref. ^{7}).

5. Conclusions

The experimental cross-section values were compared with those calculated from the formula ^{8})

$$\sigma(E) = \frac{S(E)}{E}\exp(-W_0), \qquad (2)$$

keV. Using the $S(E)$ value extrapolated to the Gamow energy the cross section $\sigma(E_0) \approx 1.0 \times 10^{-36}$ cm^2 was estimated.

Our result for the energy dependence of $S(E)$ confirms the tendency experienced by Burcham and Freeman in the energy region $E_p = 200$–500 keV. Their $S(E)$ value at $E_p = 200$ keV is in good agreement with ours if the energy-independent term in eq. (3) is neglected. In this case the data obtained by Burcham *et al.* and by us are $S(E) \approx 11$ MeV · b and 12 MeV · b, respectively.

It should be noted that our definition of $S(E)$ differs from that of Burcham *et al.* who used the formula

$$S(E) = \sigma(E)E \exp(31.28 Z_1 Z_2 A^{\frac{1}{2}} E^{-\frac{1}{2}}).$$

If the first term in eq. (3) is neglected our definition will be the same as theirs.

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