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THE CROSS SECTION OF THE ^{9}Be (^{6}He, ^{4}He) ^{11}Be REACTION

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Abstract: The energy averaged cross section of the ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction is measured. The determined value 11 ± 4 mb compared with the theoretically calculated indicates that this reaction proceeds via a direct mechanism.

1. Introduction

It has been pointed out[1] that the study of ^{6}He induced reactions could provide a series of new interesting data in the fields of few-body problems, nuclear reaction mechanisms and nuclear spectroscopy. It has also been stated that the possible source of ^{6}He might be the ^{7}Li (t, ^{6}He) ^{4}He reaction when a secondary ^{6}He »beam« with a fairly defined energy is demanded and the ^{9}Be (n, ^{6}He) ^{4}He reaction when one is satisfied with a »white« energy spectrum and with the measurement of an energy averaged total cross section of a ^{3}He induced reaction.

Here we report our work on the ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction, which has proved feasible for the measurements of energy averaged total cross section with a »white« energy spectrum of ^{6}He, and which has also indicated that this type of reaction is going via a direct mechanism[2]. Preliminary reports on this work (ref. [3, 4, 1]) did not include the description of the experimental techniques and methods, used, nor a complete survey of the results obtained.

2. Experimental arrangement

This experiment was performed with the 1.5 MeV CW accelerator of the »Boris Kidrič« Institute. The deuteron beam of about 1 mA produces 10^{10} - 10^{11} n/s from the T (d, n) ^{4}He reaction. The neutron flux was monitored with a Si-counter using a version of the associated particle method[5,6]. T-D neutrons were used to irradiate a beryllium target in which the reaction ^{9}Be (n, ^{6}He) ^{4}He ($Q = -0.628$ MeV) takes place[7]. In Fig. 1 the irradiation set-up shows the positions of the T-target (A), the Si-counter monitor (B), the beryllium target, (C), while (D) is a mechanism which ensures the constant geometrical position of the Be target during neutron irradiation.

During neutron irradiation a flux of ^{6}He particles with a white energy spectrum ranging from 0 to 10.6 MeV was present inside the Be target. The reaction we studied was

$$^{9}\text{Be} + {}^{6}\text{He} \rightarrow {}^{11}\text{Be} + {}^{4}\text{He}, \qquad Q = +6.41 \text{ MeV}. \tag{1}$$

The reaction cross section was measured by detecting the decay of ^{11}Be.

These measurements were normalized to the data[8] for the ^{11}B (n, p) ^{11}Be reaction which was alternatively performed with the reaction (1).

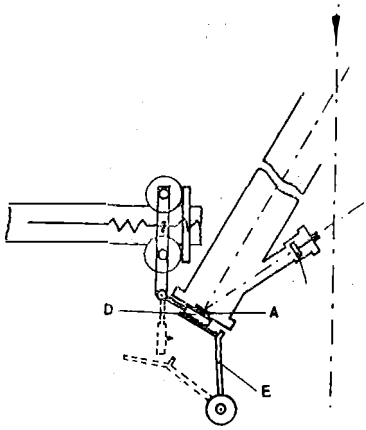


Fig. 1. General view of the external beam facilities of the 1.5 MeV accelerator and irradiation set-up.

During the experiment a beryllium, a boron and a background target were used. The critical point was the Be-target in the form of a 13.09 g Be-metal disc 1 in. dia, 0.5 in thick, which contained the minimum percentage of elementar Be(98.5%) with the maximum percentage of impurities 1.2% BeO, 0.14% Al, 0.15% C, 0.16% Fe, 0.08% Nrsg and 0.08% Si*. Since these impurities play a direct role in neutron induced reactions, their presence was essential in our work, particularly the presence of oxygen. The boron target consisted of 2.54 g natural boron (99.99%) in powder form, and it was packed in a polyethelene disc of 3 cm in diameter, 0.8 cm high, with a wall thickness of 0.5 cm. In order to control impurity contributions,we also made a »background target« which consisted of a mixture of impurities in precisely those ratios which result from the guaranteed maximum percentage of impurities in the Be target.

Special care was paid to the possible presence of boron impurity in the Be target, which could be critical in our experiment even if the content of boron would be far below the guaranteed impurity data. Here we used the fact that ^{8}Li is produced from the ^{11}B (n, ^{4}He) ^{8}Li reaction. The absence of the ^{8}Li decay in our data showed that our measurements were performed with the Be target containing less than $2 \cdot 10^{-3}$% of ^{11}B.

After irradiation the target (Fig. 1 - D) was transferred to a low-background area using a fast semiautomatic transporter (a).

The detection of ^{11}Be activity was performed by a 5 in × 6 in NaJ(Tl) detector and a in 5 in × 4 in plastic scintillator detector (Fig. 2). Both detectors were surro-

* as guaranteed by the producer.

unded by 10 cm of lead, and in addition the front of NaJ(Tl) was shielded from beta-rays by a 0.5 cm thick lead plate.

The energy calibration of the plastic scintillator detector was made by the beta spectra of ^{24}Na, ^{28}Al, ^{16}N and ^{11}Be, obtained by neutron irradiation of ^{23}Na, ^{27}Al, ^{16}O and ^{11}B respectively. The energy calibration of the NaJ(Tl) detector was performed using the gamma rays resulting from the decays of the above mentioned isotopes. While working in a fast-slow coincident mode the time setting of the electronic system was adjusted using the decay of ^{11}Be, looking for the maximum yield of coincidences of the 2.13 MeV gamma ray coming from 2.13 MeV level of ^{11}B and electrons from ^{11}Be going to that level.

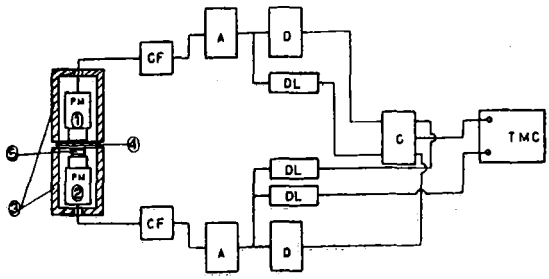


Fig. 2. Schematic diagram showing the detection system and the block diagram of the electronics used. 1. NaJ detector. 2. Plastic scintillator detector. 3. Lead shielding. 4. Lead plate. CF – Cathode follower. A – Amplifier. D. – Discriminator. DL – Delay lines. C – Fast-slow coincidence. TMC – 256-channel analyser.

The measurements were performed in three different modes:

I. Combined measurements of the time decay and energy spectrum of beta rays from ^{11}Be in coincidence with 2.13 MeV gamma rays;

II. The time decay measurements of beta rays from ^{11}Be without coincidence.

III. The time decay measurements of beta-gamma coincidence.

In all cases the irradiation time of Be, B or the »background« target was 1 minute.

In mode (I) the pulses from the plastic scintillator detector were led to a 256 channel TMC analyzer so that they were analyzed in four quarts (64 channel each) for periods of 24 sec, one after another. At the same time the coincidence gate was opened with pulses from the NaJ (Tl) detector corresponding to the 2.13 MeV photo peak defined by a window discriminator. After a 4 × 24 sec measurement the target sample was irradiated and measured again. In each group of measurements this procedure was repeated 200 times. There were four such sets differing from each other by the »waiting time«, i. e. the time between the end of irradiation and the beginning of the measurement in each of the four TMC quarts. In this way we obtained 16 series of coincident beta spectra corresponding to the »waiting times« from 10 sec to 150 sec.

In mode II the pulses from the plastic scintillator detector were led to the TMC working in a multiscaler mode each of 256 channels corresponding to 1 sec measuring time.

Previously a window discriminator was set to the region where an optimum ratio of neutron-on-boron made ^{11}Be and neutron-on-oxygen made ^{16}N counting

rates was obtained. In this mode a series of 10 irradiation measurements was performed with a waiting time of 10 sec.

In mode (III) the pulses from the plastic scintillator, treated as in mode (II), were also led to the TMC analyzer. However this time they were gated with windowed pulses from the NaJ(Tl) detector corresponding to the 2.13 MeV photo peak. With a »waiting time« of 10 sec 1500 irradiations and measurements were performed with the Be target for calibration control and 150 with the »background target«.

In all measurements special care was paid to the constancy of the neutron flux during irradiation. In all irradiations performed the neutron flux did not vary for more than $\pm$ 5%. However, the neutron flux was also varied deliberately for one set of runs, in order to have an independent coincidence test of the results with respect to the counting of the detectors and the electronic system.

3. Results

The results obtained in each of the modes (I-III) separately arethe following:

In mode I there are 15 beta spectra in coincidence with 2.13 MeV gamma rays. One of them is shown in Fig. 3. As it results from the background target measurements, on the left side there is a considerable contribution of Be-target impurities. Only that part on the right side from the mark »a« is taken into account. Using all of these spectra a decay curve which is shown in Fig. 4 is obtained. Two activities are evident: one corresponding to the ^{11}Be decay with 13.5 sec, and the other to the ^{16}N decay with 7.3 sec. Comparing the 13.5 sec curve with a similar one obtained from the B-target irradiation, we are able to determine the cross section for the ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction to 12 mb.

In mode II there are 25 measurements giving the cross section for our reaction in limits of 7-14 mb. The curve *a* in Fig. 5 is obtained with the discriminator bias at 1.8 MeV. It is seen that the 7.5 sec activity from ^{16}N and the 140 sec activity from ^{28}Al are too intense. In curve *b* which is obtained with the discriminator bias at the 6 MeV ^{28}Al activity is negligible, while the ^{16}N activity is reduced so much that the ^{11}Be activity is clearly seen. The decay curve from the »background target« with the 6 MeV bias did not show any sing of the ^{11}Be activity.

In mode III, where the coincidence beta-gamma measurement was performed, the contribution of the ^{11}Be activity versus the ^{16}N activity was increased and the background was reduced at longer waiting time. This resulted in a more precise determination of decay time dependences for both ^{11}Be and ^{16}N. Here also the »background target« measurements did not show any sign of ^{11}Be activity. All cross section determinations appear in the limits of 9-13 mb.

In order to establish an additional consistence of our results, we deliberately performed the measurements changing the neutron flux and consequently changing the counting rates. In Fig. 6 our results are grouped according to the neutron fluxes used during irradiation. There is no sign of any flux dependence.

Without respect either to the flux intensity or to the mode in which the measurements were performed, all of them give the cross sections from 7 to 15 mb, with

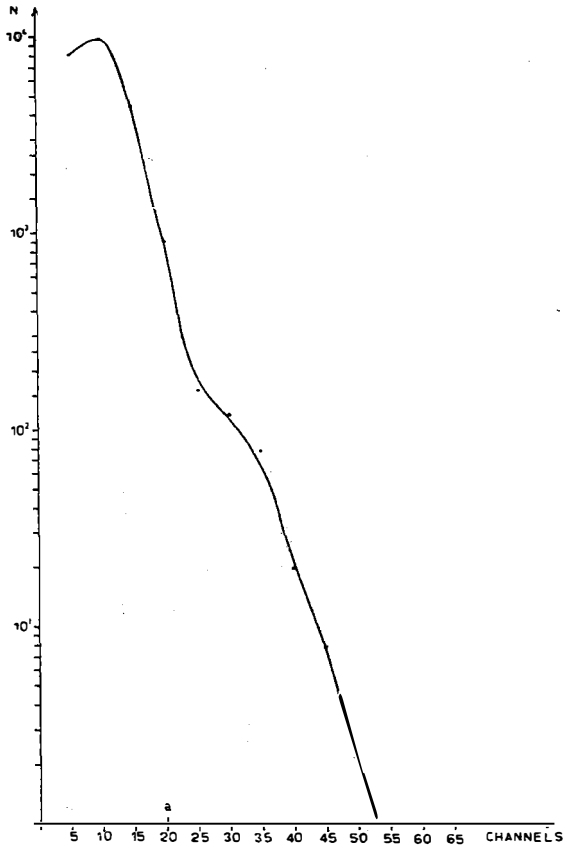


Fig. 3. Coincidence beta–ray spectrum obtained with the beryllium target.

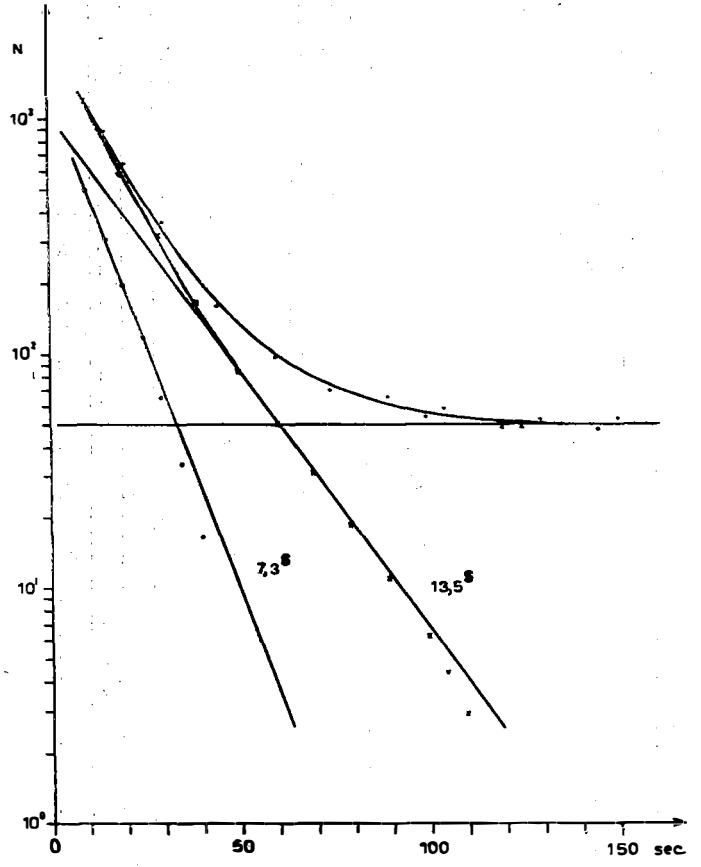


Fig. 4. Decay curve obtained with the beryllim target in Mode 1

the mean value at 11 mb and the standard derivation of 0.3 mb. However, if we take into account all other sources of errors which come from our setting of the absolute scale with respect to the cross section of the ^{11}B (n, p) ^{11}Be reaction, such as the errors inherent to the reaction itself, the errors in determining the geometry, selfabsorption, stopping power for ^{6}He etc., our final value is

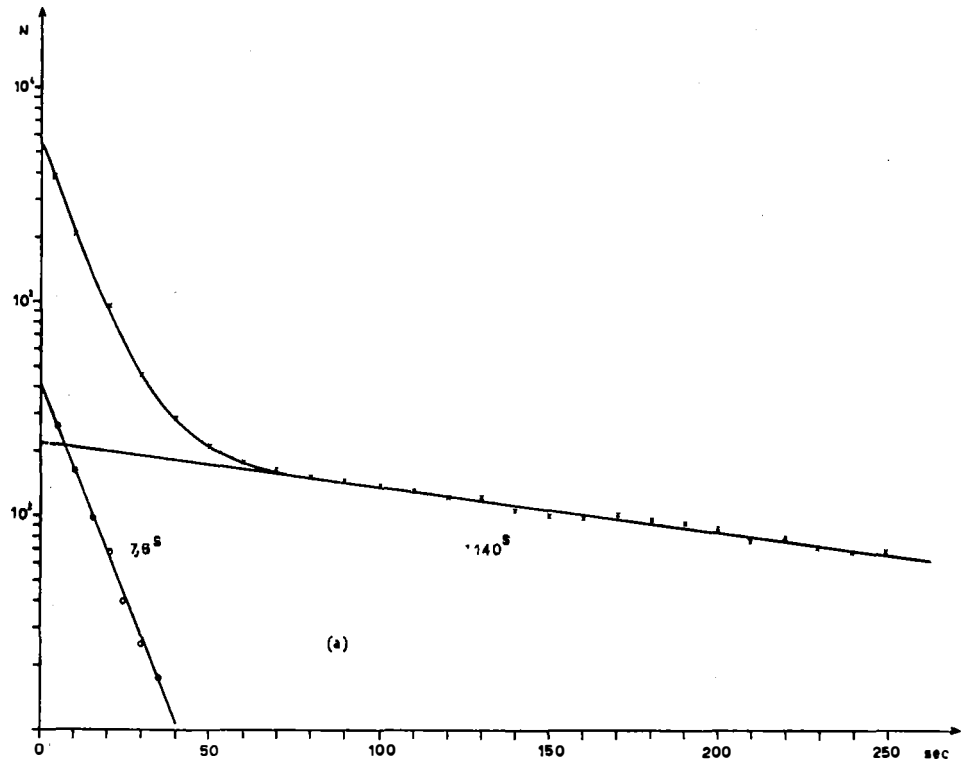
$$\sigma = 11 \pm 4 \text{ mb}.$$

4. Discussion

Our result could be compared with the cross section calculated theoretically for the same reaction by Marić and Žakula[2]. However, considerable care is needed for such a comparison, since we have actually determined the ratio of the yields

$$\frac{Y_{Be}}{Y_B} = R_0 N^*_{Be} \sigma^*_{Be},$$

where Y_{Be} is the yield of the ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction, Y_B is the yield of the ^{11}B (n, p) ^{11}Be reaction, R_0 is a factor taking care of all quantities independent of the energy of ^{6}He, N^*_{Be} is the number of Be atoms per cm^2 for the incident ^{6}He and σ^*_{Be} is the cross section for the ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction.



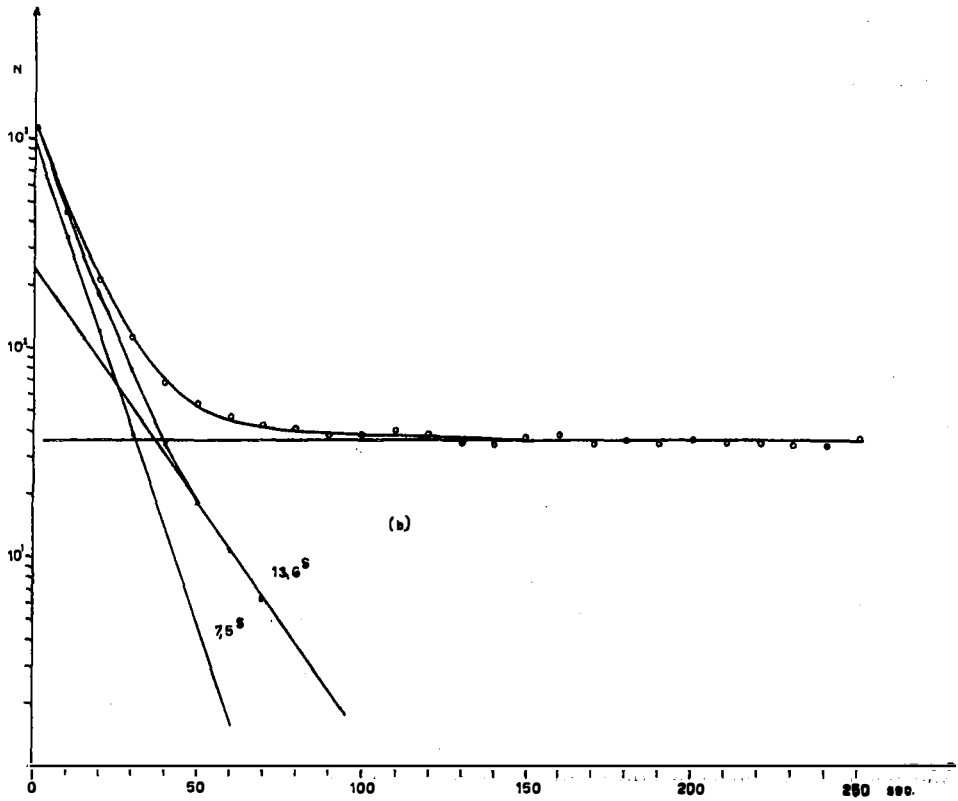


Fig. 5. Decay curves obtained with the beryllium target in Mode 2.

Since in our reaction we had practically a white spectrum of the incoming ^{6}He ranging from 0 to 10.6 MeV, the energy averaged cross section is given as

$$\bar{\sigma} = \frac{\langle N^*_{Be}\, \sigma^*_{Be} \rangle}{\langle N^*_{Be} \rangle}.$$

Here the energy average of the product $\langle N^*_{Be}\, \sigma^*_{Be} \rangle$ is simply $\frac{1}{R_0} \frac{Y_{Be}}{Y_B}$, while $\langle N^*_{Be} \rangle$ was calculated taking into account the angular distribution of the ^{9}Be (n, ^{6}He) ^{4}He reaction[7] and the range of corresponding ^{6}He in beryllium. It comes out that both of these factors favour the contributions of high energy ^{6}He; for instance the ratio of the average $\langle N^*_{Be} \rangle$ for $0 < E_{^6He} < 4$ MeV and of that for $4 < E_{^6He} < 10$ MeV is 1 : 7 approximately. Further we can take into account also that at $E_{^6He} < 4$ MeV the cross section should decrease because of the Coulomb barrier effect and that for $E_{^6He} > 4$ MeV the cross section for our reaction is a slowly decreasing function of the ^{6}He energy. So we come to the conclusion that our experimental results are in fair agreement with the corresponding theoretical calculation[2] made for $E_{^6He} = 8$MeV.

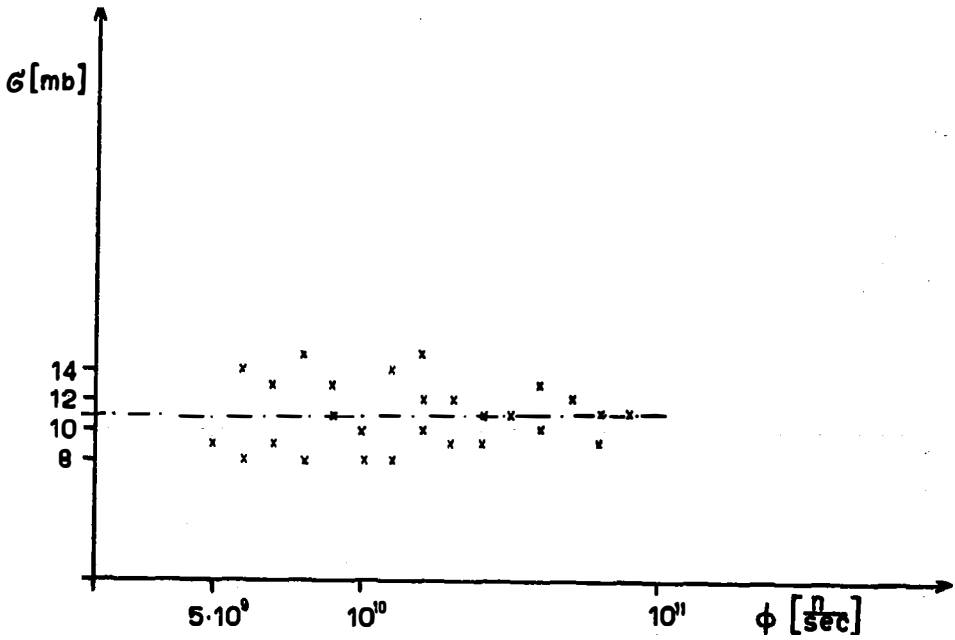


Fig. 6. Some of the cross sections obtained with different neutron fluxes.

We therefore conclude that our result proves the predominance of a direct mechanism in the case ^{9}Be (^{6}He, ^{4}He) ^{11}Be reaction.

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UDARNI PRESEK ZA REAKCIJU ^{9}Be (^{6}He, ^{4}He) ^{11}Be

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Sadržaj

Izmeren je srednji efikasni presek za energije $0 < E_{^{6}\mathrm{He}} < 10.6$ MeV-a ^{9}Be (^{6}He, ^{4}He) ^{11}Be reakcije. Dobivena vrednost 11 ± 4 mb slaže se s teorijski izračunatim efikasnim presekom ove reakcije, što daje indikacije da se reakcija odigrava direktnim mehanizmom.