CONFERENCE PRE-PRINT

MEASUREMENT OF NUCLEAR REACTION CROSS-SECTION FOR THERMONUCLEAR APPLICATIONS

M.I. BIKCHURINA
Budker Institute of Nuclear Physics
Novosibirsk State University
Novosibirsk, Russian Federation
Email: M.I.Bikchurina@inp.nsk.su

[1,2]T.A. BYKOV, G.D. VERKHOVOD, D.A. KASATOV, YA.A. KOLESNIKOV, G.M. OSTREINOV, A.A. SHUKLINA, E.O. SOKOLOVA, [3]A.V. KRASILNIKOV, S.A. MESHCHANINOV, G.E. NEMTSEV and [1,2]S.YU. TASKAEV
[1]Budker Institute of Nuclear Physics, Novosibirsk, Russian Federation
[2]Novosibirsk State University, Novosibirsk, Russian Federation
[3]Institution Project Center ITER, State Atomic Energy Corporation Rosatom, Moscow, Russian Federation

Abstract

An accelerator-based neutron source based on a vacuum insulated tandem accelerator (VITA) and a lithium target was proposed and created at the Budker Institute of Nuclear Physics SB RAS in Novosibirsk, Russian Federation. The accelerator generates stable proton/deuteron beams with an energy of up to 2.3 MeV and a constant current of up to 10 mA. The facility is equipped with gamma, alpha, and neutron spectrometers and dosimeters. VITA is used to develop boron neutron capture therapy technique, radiation testing of promising materials, and many other applications. Recently, VITA has been actively used to measure cross-sections of nuclear reactions.

The article will describe the facility, present its characteristics, and present the results of measuring the cross-sections of nuclear reactions of deuterons with lithium and protons with boron, which are important for materials science and for aneutronic thermonuclear energy.

1. INTRODUCTION

The interaction of a deuteron beam with lithium is characterized by high neutron yield, high neutron energy, and a wide variety of reactions. Neutron beam generation with such characteristics is necessary for such topical issues as testing of promising materials, including material for the first wall of tokamak, and equipment, production of radioactive isotopes, and other applications. Experimental cross-section data in databases [1] are very discrepant, and for some reactions are missing.

Studying the interaction of a proton beam with boron is important for the developing neutronless fusion and proton-neutron capture therapy. Despite a considerable number of theoretical works describing the reaction mechanisms, experimental data on the cross-section in different works strongly disagrees, and there is no agreement in the determination of the decay mechanism as well.

2. EXPERIMENTAL FACILITY

The studies were carried out at the accelerator-based neutron source VITA at the Budker Institute of Nuclear Physics (Novosibirsk, Russian Federation) [2]. The layout of the experimental facility is shown in Fig. 1. The facility includes the tandem electrostatic charged particle accelerator of the original design *1* which produces a beam of protons or deuterons and directs it to the target *6*. The beam energy ranges from 100 keV to 2.3 MeV (0.1% stability), and the current ranges up to 10 mA (0.4% stability). The beam current is measured with a non-destructive DC current transformer (Bergoz Instrumentation, France) *2*.

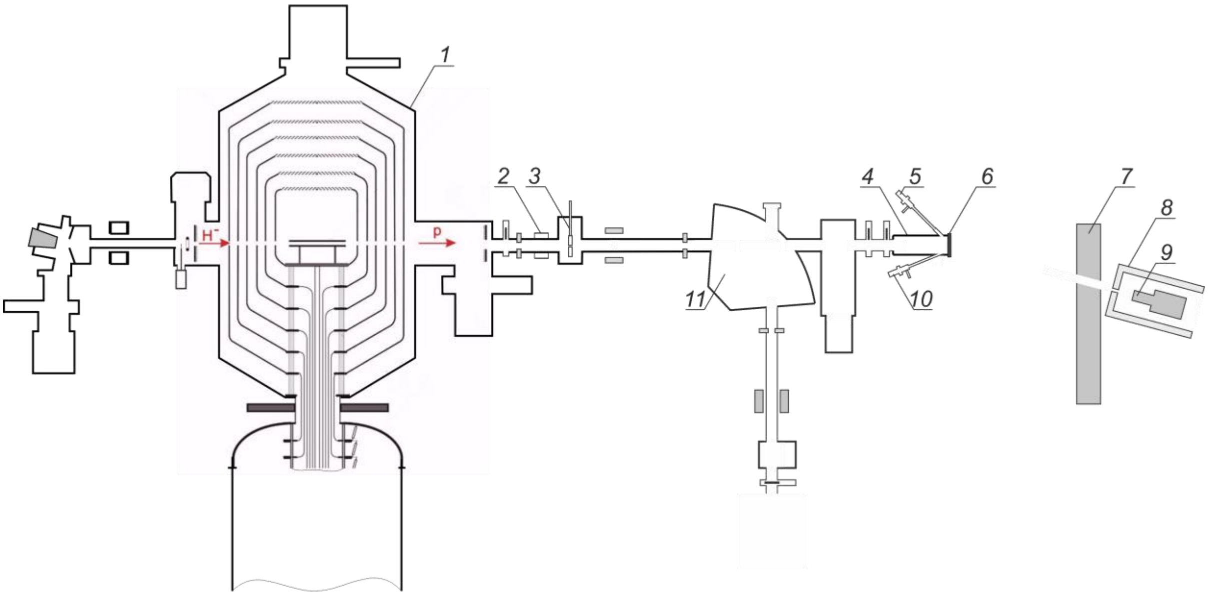

FIG. 1. The layout of the experimental facility: *1* – vacuum insulated tandem accelerator, *2* – non-destructive DC current transformer, *3* – collimator, *4* – target assembly, *5* – α-spectrometer at 135°, *6* – target, *7* – temporary concrete wall, *8* – lead collimator, *9* – γ-ray spectrometer, *10* – α-spectrometer at 168°, *11* – bending magnet.

To conduct research, the proton/deuteron beam current on the target is reduced to less than 1.5 μA by placing a cooled collimator *3* located 4 m from the target in its path. The collimator is a 16 mm thick rectangular copper parallelepiped with sides 64 x 64 mm. A hole with a diameter of 1 mm is drilled in the center of the diaphragm. The position and size of the proton/deuteron beam on the target is monitored by a Hikvision video camera that records the luminescence of the target under the action of ions.

When conducting scientific research, target assembly with two nozzles located at an angle of 135° and 168° to the beam axis are used for observation or placement of diagnostic equipment. The intensity and energy of deuterons and α-particles are measured with an α-spectrometer *7* with a PDPA-1K silicon semiconductor detector (IPTP, Dubna, Russia).

The current of a proton/deuteron beam hitting a lithium target is measured with a resistive voltage divider using a target assembly *4*, electrically isolated from the facility, like a deep Faraday cup.

3. LITHIUM TARGET

The developed lithium target is a thin layer of pure lithium metal deposited on a thin copper substrate with an efficient heat sink. The substrate is a copper disc with a diameter of 144 mm and a thickness of 8 mm. From the side of the proton beam, a thin layer of lithium of crystalline density with a diameter of 84 mm is thermally deposited onto it. Natural lithium is used for deposition. The lithium target is part of the target assembly. When conducting scientific research, target assemblies with two nozzles located at angles of 135° and 168° to the beam axis are used for observation or placement of diagnostic equipment.

The lithium target is used for various purposes, such as the generation of epithermal spectrum neutrons in the ^{7}Li(p,n)^{7}Be reaction for boron neutron capture therapy, obtaining fundamental knowledge and for materials science, since a powerful stream of fast neutrons is generated in the reaction of lithium with deuteron. The process of lithium-deuteron interaction is interesting in the framework of the development of thermonuclear energy.

3.1. Interaction of lithium with a deuteron beam

A wide variety of reactions is observed in the interaction of lithium with deuteron with an energy below 2.3 MeV:

1 ^{7}Li + d = n + ^{8}Be + 15.028 MeV

2 $^7Li + d = n + {}^8Be^* + 15.027$ MeV

3 $^7Li + d = \alpha + {}^5He + 14.162$ MeV, $^5He \rightarrow n + \alpha + 0.957$ MeV

4 $^7Li + d = n + \alpha + \alpha + 15.121$ MeV

5 $^6Li + d = \alpha + \alpha + 22.38$ MeV

6 $^6Li + d = n + {}^7Be + 3.385$ MeV

7 $^6Li + d = p + {}^7Li + 5.028$ MeV

8 $^6Li + d = p + {}^7Li^* + 4.550$ MeV

9 $^6Li + d = {}^3H + {}^5Li + 0.595$ MeV

10 $^6Li + d = {}^3He + {}^5He + 0.840$ MeV, $^5He \rightarrow n + \alpha + 0.957$ MeV

11 $^6Li + d = {}^3H + p + \alpha + 2.6$ MeV

We measured the cross-sections of nuclear reactions № 1, 2 with a diamond detector and reactions № 3, 4, 5, 7, 8 using an α-spectrometer and [3, 4]. The spectrum obtained by the α-spectrometer is shown in figure 2.

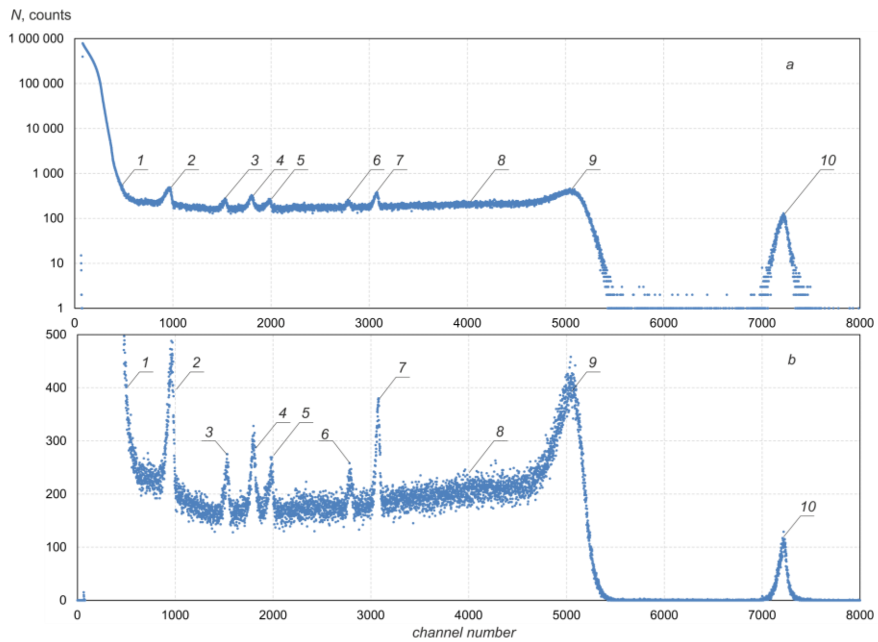

FIG. 2. The signal from the α-spectrometer at 0.6 MeV deuteron beam: *1* – back scattered deuterons; *2* – $^{16}O(d,p_1)^{17}O^*$ reaction protons; *3* – $^{16}O(d,p_0)^{17}O$ reaction protons; *4* – $^{16}O(d,\alpha)^{14}N$ reaction α-particles; *5* – $^{12}C(d,p_0)^{13}C$ reaction protons; *6* – $^6Li(d,p_1)^7Li^*$ reaction protons; *7* – $^6Li(d,p_0)^7Li$ reaction protons; *8* – $^7Li(d,n\alpha)^4He$ reaction α-particles; *9* – $^7Li(d,\alpha)^5He$ reaction α-particles; *10* – $^6Li(d,\alpha)^4He$ reaction α-particles (*a* – the ordinate scale is represented on a logarithmic scale, *b* —on a linear scale).

The thickness of the lithium layer was measured by the proposed and implemented *in situ* method [5]. The method is based on comparing the output of 478 keV photons from the studied lithium layer and from a thick one irradiated with 1.85 MeV protons. The measurements were carried out using a gamma-ray spectrometer (*9* in fig. 1). A thick layer is called a lithium layer with a thickness of more than the proton path in lithium up to the energy threshold of the reaction $^7Li(p,p'\gamma)^7Li$, equal to 478 keV. Thus, the thickness of lithium is 1.8 microns, with an accuracy of 3%.

The simplest reaction for measuring the cross-section is reaction № 5 ^{6}Li(d,α)^{4}He (*10* in Fig. 2). The reaction products α-particles have the same energy. The measurement process is as follows: for a certain time *t*, a lithium layer with a thickness of *l* is irradiated with a proton beam with a current *i*, and an α-spectrometer registers α-particles flying into a solid angle Ω at an angle of 168 ± 0.5° and at an angle of 135 ± 0.5° to the deuteron pulse. The measurements were carried out at a deuteron beam energy from 0.3 MeV to 2.2 MeV in increments of 100 keV. Thus, a set of spectra was obtained that make it possible to calculate the differential cross-sections of the nuclear reaction shown in figure 3.

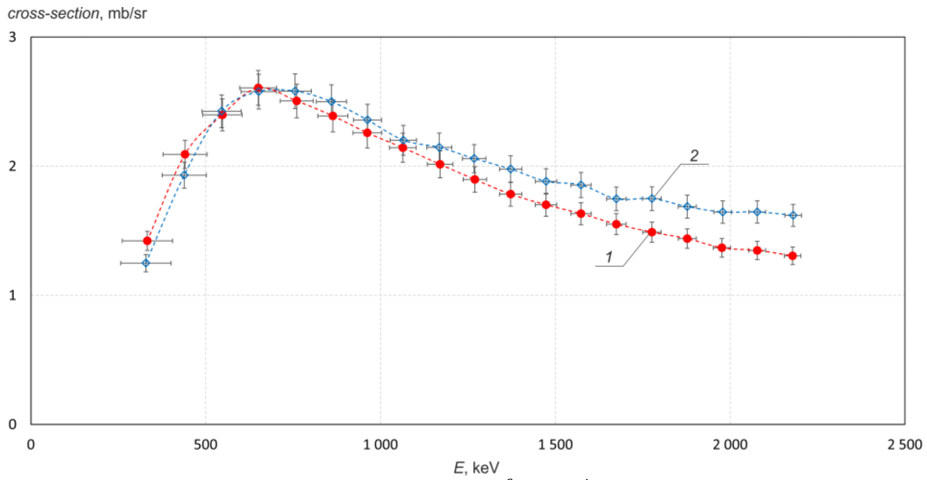

FIG. 3. The measured differential cross-section of the ^{6}Li(d,α)^{4}He reaction at 135° (*1*) and 168° (*2*).

It can be seen that the reaction is isotropic at low energies and becomes less isotropic with increasing energy. Based on the results obtained, calculations of the differential cross-section in the center of mass system were performed. For this purpose, the dependence was determined: $1 + A(E)\cos^2\theta$, calculating the coefficient A. Thus, it is already possible to reconstruct the complete reaction cross-section ^{6}Li(d,α)^{4}He, shown in figure 4. Our data are compared with values from the database ENDF/B-VIII.0 Evaluated Nuclear Reaction Data Library. There is a good agreement, which adds confidence in obtaining reliable data.

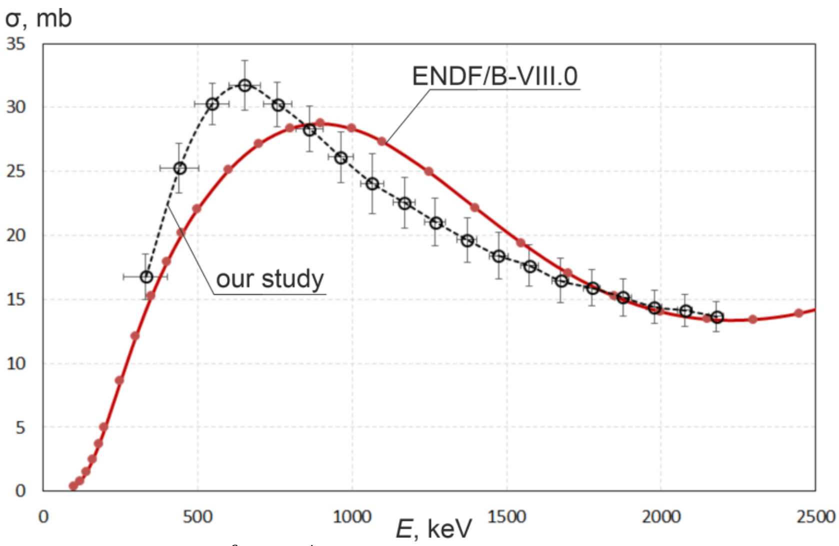

FIG. 4. The measured cross-section of the ^{6}Li(d,α)^{4}He reaction and presented in the ENDF/B-VIII.0 Evaluated Nuclear Reaction Data Library [6].

Let's turn to the consideration of neutron-generating reactions in the interaction of lithium with deuteron, there are six of them in total, they are presented under the numbers 1, 2, 3, 4, 6, 10. Consider the interaction of deuteron with lithium-7, this isotope predominates in natural lithium, its share is 92.5%, and lithium-6 is 7.5%, respectively.

The main nuclear reaction of the interaction is the ^{7}Li(d,nα)^{4}He reaction, as can be seen from the spectrum, *8* in figure 2. We have calculated the differential cross-sections for the two angles (fig. 5).

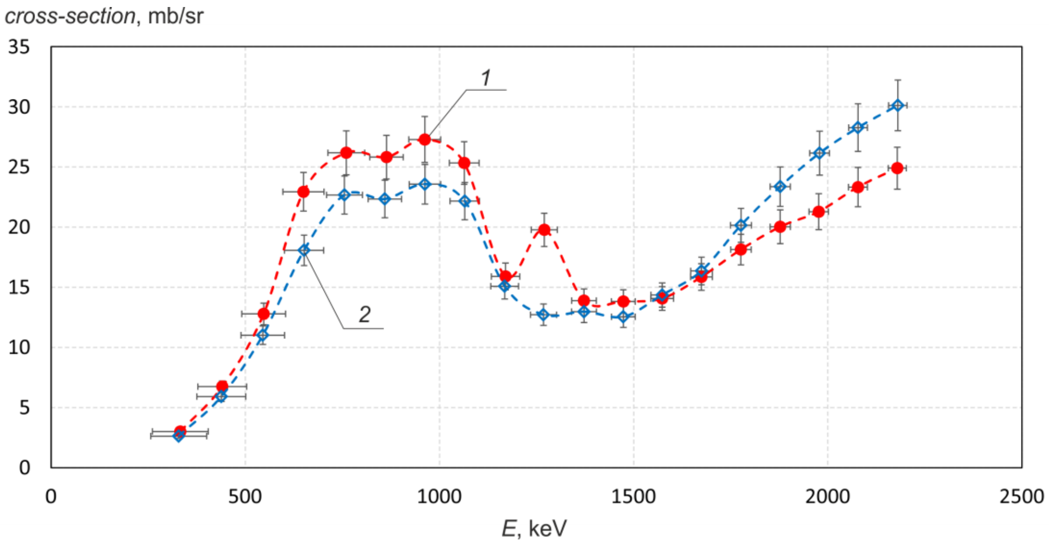

FIG. 5. The measured differential cross-section of the $^{7}Li(d,n\alpha)^{4}He$ reaction at 135° (*1*) and 168° (*2*).

Let's estimate the total cross-section at the resonance energy. Let's take the average value for the differential cross–section – 25 mb/sr, then the value of the total cross-section will be approximately ~ 400 mb at resonances in the range of 0.7-1.1 MeV, provided that we consider the reaction to be isotropic within the measurement errors.

The next largest channel of lithium-7 interaction with deuteron is the reaction of $^{7}Li(d,\alpha)^{5}He$ (*9* in figure 2), helium-5 instantly decays into an α-particle and a neutron. The calculated differential cross-sections are shown in figure 6.

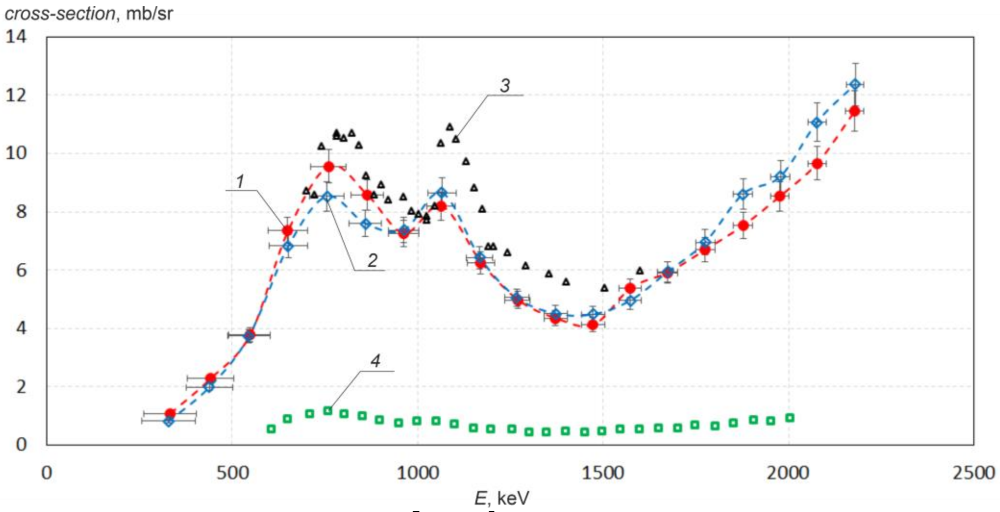

FIG. 6. The measured differential cross-section of the $^{7}Li(d,\alpha)^{5}He$ reaction at 135°(*1*) and 168°(*2*). For comparison, data from the ENDF/B-VIII.0 [6] is provided: *3* – Delbrouck-Habaru (1969) 154°, *4* – Friendland (1971) 90°.

It is noticeable that the cross-section shape is similar to that of the $^{7}Li(d,n\alpha)^{4}He$ reaction, and the resonance is also at a deuteron energy of 0.7 – 1.1 MeV. Considering the reaction to be isotropic, we determine from the differential cross-section the total cross-section for the two angles. The results are shown in figure 7. It can be seen that they agree well in the range up to 1.5 MeV and slightly diverge with increasing deuteron energy. The total cross-section in the resonance will be ~ 150 mb (fig. 7), which is about 2.5 times less than the estimate for the $^{7}Li(d,n\alpha)^{4}He$ reaction.

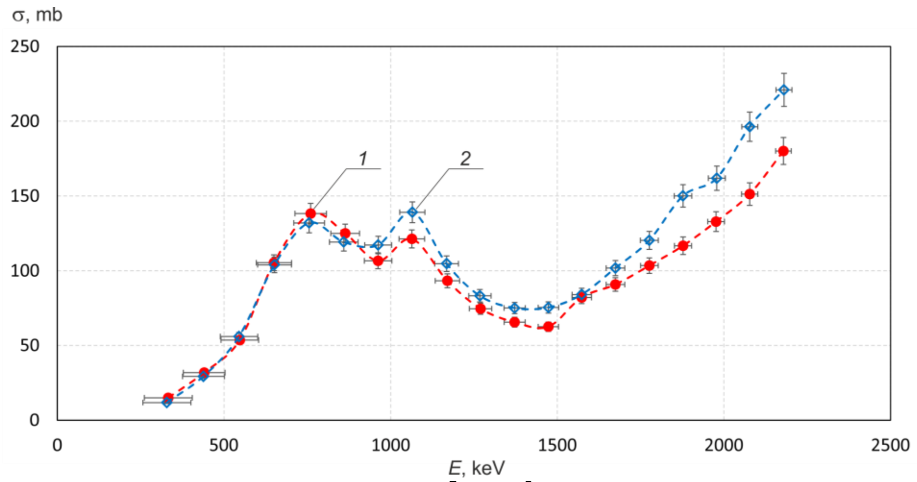

FIG. 7. The measured cross-section of the $^{7}Li(d,\alpha)^{5}He$ reaction at 135° (*1*) and 168° (*2*).

Next, we consider neutron-generating reactions numbered 1 and 2 – $^{7}Li(d,n)^{8}Be$, $^{7}Li(d,n)^{8}Be^{*}$, respectively. The measured cross-sections and a detailed description of the experiment are published in the article [4]. Here we will also give the values of the total cross-sections in the resonance. For the reaction through the ground state of beryllium-8 (№ 1), this is ~ 30 mb, and for the reaction through the excited state of beryllium, it is 50 mb. In the first case, the cross-section is 13 times smaller than that of the main reaction $^{7}Li(d,n\alpha)^{4}He$, in the second case it is 8 times smaller.

Thus, we have obtained data on all neutron-generating reactions during the interaction of lithium-7 with a deuteron beam. According to estimates of the total reaction cross-sections within the framework of the isotropic case, the following results were obtained $^{7}Li(d,n\alpha)^{4}He$ – 400 mb, $^{7}Li(d,\alpha)^{5}He$ – 150 mb, $^{7}Li(d,n)^{8}Be^{*}$ – 50 mb, $^{7}Li(d,n)^{8}Be$ – 30 mb. The total cross-section, taken at resonance energies (0.7 – 1.1 MeV), will be ~ 630 mb. The data obtained make it possible for the first time to reconstruct the energy spectrum in the reaction of lithium-7 with deuteron. The use of lithium enriched with the lithium-7 isotope as a target material provides the highest neutron yield of all reactions at deuteron energies above 0.7 MeV.

Regarding the remaining two neutron-generating reactions during the interaction of deuteron with lithium-6 (№ 6, 10), further research in this area is planned. In the first reaction of $^{6}Li(d,n)^{7}Be$, we plan to measure the yield by activation of beryllium-7, the second reaction of $^{6}Li(d,^{3}He)^{5}He$, ^{5}He decays into an alpha particle and a neutron, which will require separation of a beam of alpha particles and protons, since the energy output is low.

4. BORON TARGET

The reaction of boron-11 with a proton is interesting as one of the promising reactions for aneutronic thermonuclear fusion. Reaction $^{11}B(p,\alpha)\alpha\alpha$ is characterized by a high energy yield of 8.7 MeV. It is known that the nuclear reaction of boron-11 with a proton proceeds in three ways: $^{11}B(p,\alpha_0)^{8}Be$, $^{11}B(p,\alpha_1)^{8}Be^{*}$ and $^{11}B(p,\alpha)\alpha\alpha$, however, there is a wide variation in the values of the cross-sections presented in the databases.

The boron target created for this experiment is a copper disk on which a thin layer of boron (~ 1 microns) is deposited by magnetron sputtering at the Institute of High Current Electronics, Tomsk. Deposition is carried out in an atmosphere of high purity nitrogen (99.999%), therefore, the target contains not only natural boron of crystalline density, but also compounds of boron with nitrogen. The thickness of the boron layer was determined by the previously described *in situ* method for a lithium target [5], comparing the yield of α-particles from a thin (studied) target and from a thick one. Boron carbide was used as a thick target.

4.2. Interaction of boron with a proton beam

A detailed description of the experiment is presented in the article [7]. A typical spectrum obtained by an α-spectrometer is shown in figure 8. It is noticeable that the cascade decay process prevails, the small peak on the right corresponds to α-particles from reaction $^{11}B(p,\alpha_0)^{8}Be$, and the main signal forming a wide peak corresponds to α-particles from reaction $^{11}B(p,\alpha_1)^{8}Be^{*}$. The differential cross-sections for reactions $^{11}B(p,\alpha_0)^{8}Be$ and $^{11}B(p,\alpha_1)^{8}Be^{*}$ are shown in figures 9 and 10, respectively.

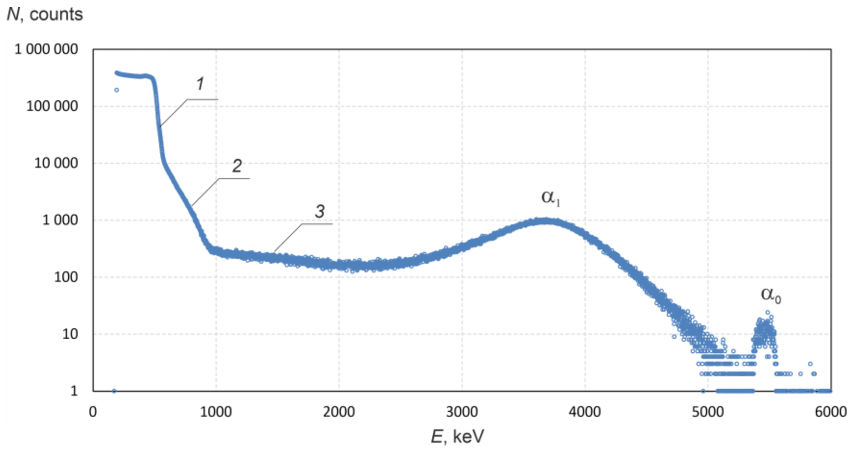

FIG. 8. The signal registered by the α-spectrometer at 0.6 MeV proton beam and 168°: *1 – 2*–protons backscattered on the copper substrate of the target (*1* – single events, *2* – double), *3* – α-particles

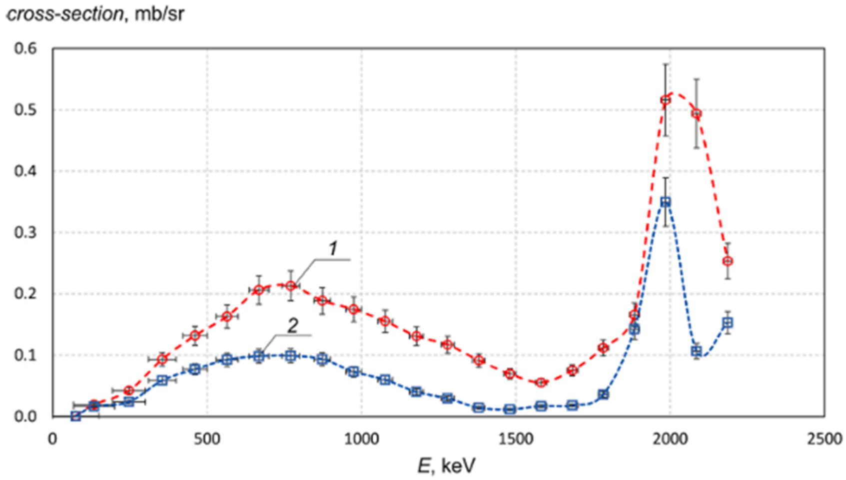

FIG. 9. The measured differential cross-section of the $^{11}B(p,\alpha_0)^8Be$ reaction at 135° (*1*) and 168° (*2*). Differential cross-sections are in the center-of-mass system.

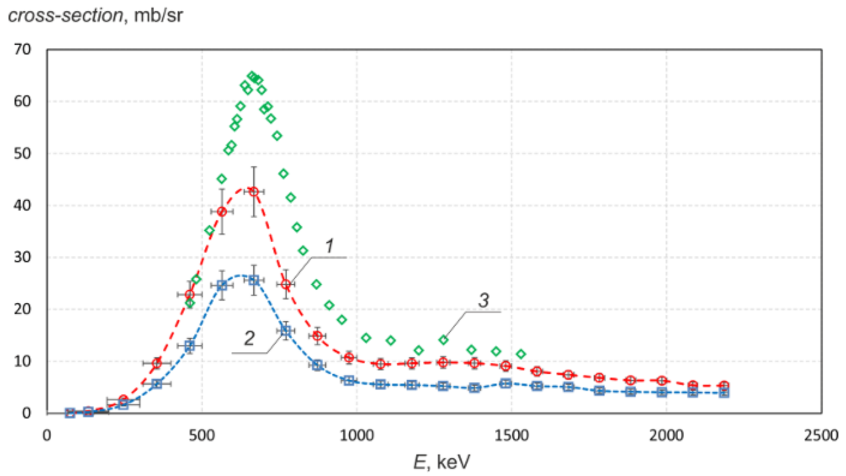

FIG. 10. The measured differential cross-section of the $^{11}B(p,\alpha_1)^8Be^*$ reaction at 135° (*1*) and 168° (*2*). Differential cross-sections are in the center-of-mass system. The reaction cross-section at 150° (*3*) from article [8] is also presented.

It has been established that the reaction of proton interaction with boron occurs mainly in the form of decay into an alpha particle and a beryllium-8 nucleus in the excited state, followed by its decay into two alpha particles. The measured reaction cross-section in the isotropic case reached a maximum of 700 mb at an energy of 600 keV, which is about 2 times less than the reaction cross-section often used when considering the prospects of aneutronic thermonuclear fusion. The second decay path through the beryllium nucleus in the ground state is less likely (10–100 times less) and has a maximum at a proton energy in the region of 2 MeV.

Since the reaction of boron-11 with a proton does not only cascade, it is interesting to evaluate for direct decay. In the case of direct decay, the energy of α-particles is in the range from 0 to 9 MeV. Thus, only events from direct decay or a noise signal can be located to the right of the peak of α-particles from reaction $^{11}B(p,\alpha_0)^8Be$. Summing up all the events to the right of this peak, we obtained a 2000–3000 times lower probability of direct decay compared to the cascade one.

We plan to continue studying this reaction and measure the angular distribution, for which we have already created a special vacuum chamber that allows measurements to be made at nine angles, as well as purchased additional equipment that will allow us to measure simultaneously at two angles and thereby ensure control and improve measurement accuracy.

5. CONCLUSIONS

Cross-sections of nuclear reactions of deuteron interaction with lithium were measured at the accelerator-based neutron source VITA at the Budker Institute of Nuclear Physics SB RAS in Novosibirsk, Russian Federation: $^6Li(d,\alpha)^4He$, $^6Li(d,p)^7Li$, $^6Li(d,p)^7Li^*$, $^7Li(d,\alpha)^5He$, $^7Li(d,n\alpha)^4He$, $^7Li(d,n)^8Be$, $^7Li(d,n)^8Be^*$; as well as protons with boron: $^{11}B(p,\alpha_0)^8Be$ and $^{11}B(p,\alpha_1)^8Be^*$. Knowledge of the full cross-section of lithium-7 interaction with a deuteron beam has been obtained. The data obtained make it possible for the first time to reconstruct the energy spectrum in the reaction of lithium-7 with deuteron. It has been established that the reaction of proton interaction with boron occurs mainly in the form of decay into an alpha particle and a beryllium-8 nucleus in the excited state, followed by its decay into two alpha particles. It is shown that the value of the reaction cross-section obtained by us in resonance is two times less than the generally accepted value.

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