ISSN 1063-780X, Plasma Physics Reports, 2026, Vol. 52, No. 3, pp. 273–280. © Pleiades Publishing, Ltd., 2026.

PLASMA DIAGNOSTICS

Measuring Nuclear-Reaction Cross Sections for Thermonuclear Applications

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Received November 17, 2025; revised January 14, 2026; accepted January 25, 2026

Abstract—Data on the cross section of nuclear reactions are important for the development of nuclear energy, thermonuclear fusion, nuclear medicine, materials research, and other applications. The cross sections of nuclear reactions important for fusion applications, including radiation testing of materials and the development of neutron-free fusion power, were measured. The study was conducted on a accelerator-based neutron source at the Budker Institute of Nuclear Physics, which produces a monoenergetic beam of protons or deuterons with an energy of up to 2.2 MeV. The intensity and energy of reaction products emitted from a lithium or boron target are measured using an α-spectrometer and a diamond detector. It has been shown that the measured cross sections of nuclear reactions make it possible to recover the energy spectrum of neutrons generated during the interaction of deuterons with lithium-7, one of the most productive neutron-generation reactions. It is shown that the obtained value of the cross section of the reaction of interaction of a proton beam with boron-11 in resonance is half the value often used in assessing the prospects of neutron-free thermonuclear energy.

Keywords: thermonuclear fusion, neutrons, nuclear-reaction cross section

DOI: 10.1134/S1063780X25604286

INTRODUCTION

Testing new materials that are being developed for next-generation fusion reactors requires powerful neutron beams. A promising solution for this purpose is the interaction of deuterons with lithium, which is characterized by the highest neutron yield per ion beam current, starting from an ion energy of 0.7 MeV, and a wide variety of reactions. Experimental data on the reaction cross section are highly contradictory [1], and for some reactions they are absent. The aim of the work is to measure the cross section of nuclear reactions of interaction of deuteron with lithium.

Another aim of the work is to measure the cross section of nuclear reactions involving protons and boron, which is important for the development of promising neutron-free thermonuclear energy and for assessing the feasibility of implementing proton–boron capture treatment. Despite the significant number of theoretical works describing the reaction mechanisms, experimental data on the reaction cross section in different works differ greatly, and there is no agreement on the definition of the decay mechanism.

EXPERIMENTAL SETUP

The experimental study was carried out on the accelerator-based neutron source VITA at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) [2, 3]. The facility diagram is shown in Fig. 1. The facility includes tandem electrostatic accelerator of charged particles *1* of original design for purposes of obtaining a stationary monoenergetic beam of protons or deuterons with energy varying from 100 keV to 2.3 MeV. The monochromaticity and energy stability of the ion beam is 0.1%. The ion beam current is about 1 mA, and its stability is 0.4%. The beam current is measured by noncontact current sensor *2* (Bergoz Instrumentation, France).

During the study, the proton/deuteron beam current on the target *6* is specifically reduced to a value of less than 1.5 μA by placing cooled collimator *3* in its path, located 4 m from the target. The collimator is a copper rectangular parallelepiped 16 mm thick with 64 × 64-mm sides. A 1-mm-diameter hole is drilled in the center of the diaphragm and a 10-mm-diameter countersink is made on both sides. The position and size of the proton/deuteron beam on the target is

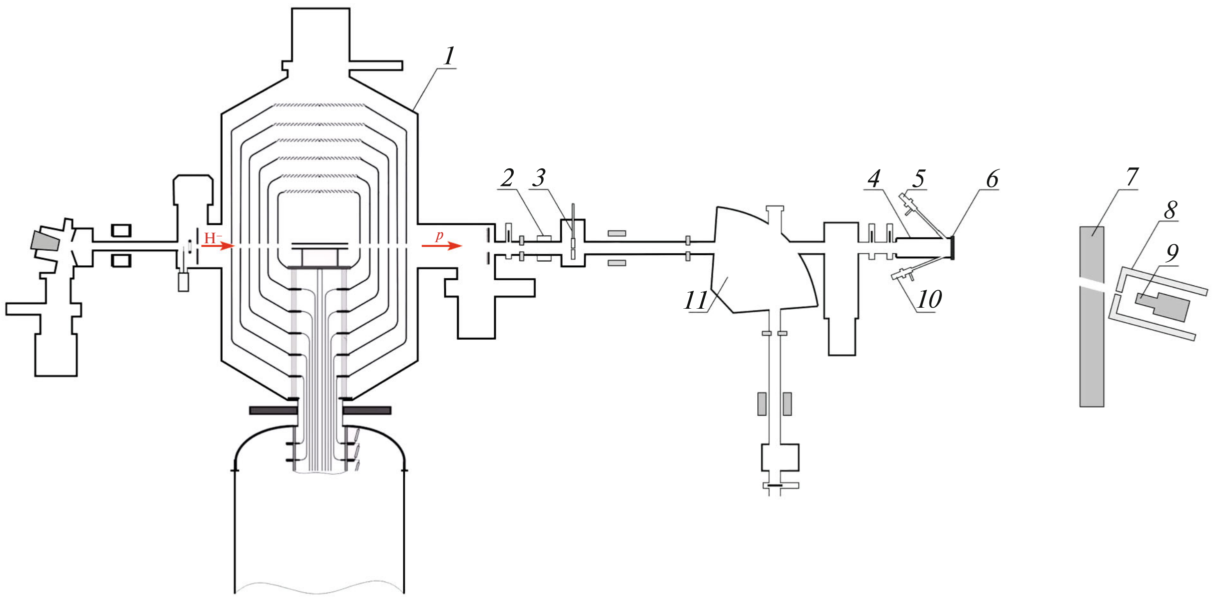

Fig. 1. The layout of the experimental facility: (*1*) vacuum insulated tandem accelerator; (*2*) non-destructive DC current transformer; (*3*) collimator; (*4*) target assembly; (*5*) α-spectrometer at an angle of 135°; (*6*) target; (*7*) temporary concrete wall; (*8*) lead collimator; (*9*) γ-ray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

monitored by a Hikvision video camera, which records the luminescence of the target under the influence of ions.

When conducting scientific research, target units 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 α-spectrometer *7* with a PDPA-1K silicon semiconductor detector (Institute of Physical and Technical Problems, Dubna, Russia).

The current of the proton/deuteron beam hitting the target is measured by a resistive voltage divider using target node *4*, electrically isolated from the installation, as a deep Faraday cup.

LITHIUM TARGET

The lithium target is a thin layer of pure metallic lithium deposited on a thin copper substrate with efficient heat dissipation. The substrate is a copper disk with a diameter of 144 mm and a thickness of 8 mm. From the side of the proton beam, a thin layer of lithium with a crystalline density and a diameter of 84 mm is thermally evaporated on it in a vacuum. Natural lithium is used for evaporating. Lithium is deposited uniformly, the layer thickness is controlled and varies from ~1 to ~100 μm. The lithium target is part of the target assembly. During the study, a target unit with two nozzles located at angles of 135° and 168° to the beam axis was used. When an α-spectrometer is installed on one nozzle to measure the intensity and energy of the reaction products, a CCD camera is installed on the second nozzle to monitor the target surface and the position of the ion beam on the target. When measurements are taken at a different angle, the equipment on the pipes is mutually interchanged.

The thickness of the lithium layer in this study was measured by the proposed and implemented by in situ method [4]. The method is based on a comparison of the yield of 478-keV photons from the lithium layer under study and from a thick layer irradiated with 1.85-MeV protons. A layer of lithium is considered thick if it is thicker than the proton range in lithium up to the energy of the threshold reaction ^{7}Li(p, $p'\gamma$)^{7}Li, which is equal to 478 keV. The measurements were carried out using a γ-spectrometer (*9* in Fig. 1). The measured thickness of lithium was 1.79 ± 0.07 μm.

Interaction of Lithium with a Deuteron Beam

When lithium interacts with a deuteron with an energy below 2.2 MeV, a wide variety of reactions are observed:

$$1.\ {}^7\text{Li} + d = n + {}^8\text{Be} + 15.028\ \text{MeV},$$

$$2.\ {}^7\text{Li} + d = n + {}^8\text{Be}^* + 12.148\ \text{MeV},$$

$$3.\ {}^7\text{Li} + d = \alpha + {}^5\text{He} + 14.162\ \text{MeV}$$

$${}^5\text{He} \rightarrow n + \alpha + 0.957\ \text{MeV},$$

$$4.\ {}^7\text{Li} + d = n + \alpha + \alpha + 15.121\ \text{MeV},$$

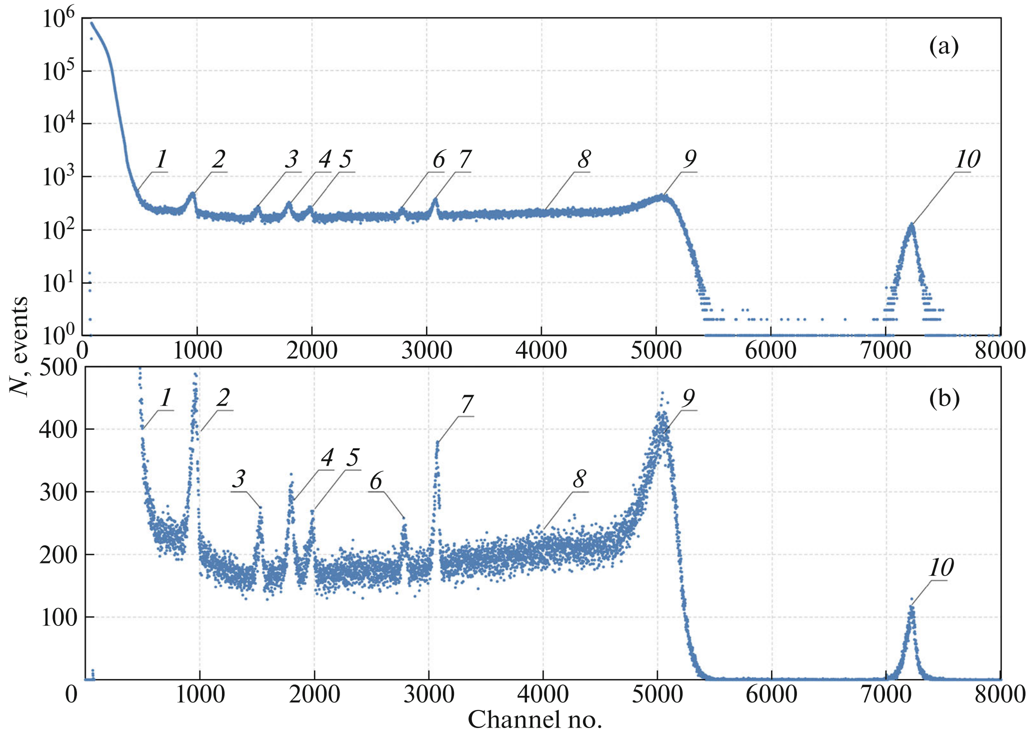

Fig. 2. α-spectrometer signal with a 0.6-MeV deuteron beam: (*1*) backscattered deuterons; (*2*) protons of the reaction $^{16}O(d, p_1)^{17}O^*$; (*3*) protons of the reaction $^{16}O(d, p_0)^{17}O$; (*4*) α-particles of the reaction $^{16}O(d,\alpha)^{14}N$; (*5*) protons of the reaction $^{12}C(d, p_0)^{13}C$; (*6*) protons of the reaction $^{6}Li(d, p_1)^{7}Li^*$; (*7*) protons of the reaction $^{6}Li(d, p_0)^{7}Li$; (*8*) α-particles of the reaction $^{7}Li(d, n\alpha)^{4}He$; (*9*) α-particles of the reaction $^{7}Li(d, \alpha)^{5}He$; (*10*) α-particles of the reaction $^{6}Li(d, \alpha)^{4}He$ (the ordinate scale is presented (a) in logarithmic scale, (b) in linear scale).

5. $^{6}Li + d = \alpha + \alpha + 22.38$ MeV,

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

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

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

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

10. $^{6}Li + d = {}^{3}He + {}^{5}He + 0.840$ MeV,

$^{5}He \rightarrow n + \alpha + 0.957$ MeV,

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

The measurement process is as follows: over a certain period of time t, a beam of deuterons with current i irradiate a layer of lithium with a thickness l and the α-spectrometer records α-particles emitted into the solid angle Ω at an angle of 168° ± 0.5° and at an angle of 135° ± 0.5° to the momentum of deuterons. The measurements were carried out at deuteron energies from 0.3 to 2.2 MeV with a step of 100 keV.

The spectrum obtained by the α-spectrometer is shown in Fig. 2. We measured the cross sections of nuclear reactions nos. 1 and 2 with a diamond detector and reactions nos. 3–5, 7, and 8 using an α-spectrometer [5, 6].

The simplest reaction to measure the cross section is reaction no. 5: $^{6}Li(d, \alpha)^{4}He$ (*10* in Fig. 2). The reaction products, two α-particles, have the same high energy (~8.5 MeV) and their signal is a single peak, easy to count events. The measured differential cross sections of this reaction are shown in Fig. 3. It can be seen that the reaction is isotropic at low energies and becomes less isotropic with increasing energy. Based on the obtained results, calculations were made for the differential cross section in the system of center of mass, for which the $1 + A(E)\cos^2\theta$ dependence was determined, with coefficient A having been calculated; thus, the total cross section of the reaction $^{6}Li(d, \alpha)^{4}He$ was restored, which is shown in Fig. 4. It is clear that our reaction cross-section values are in good agreement with the values from the ENDF/B-VIII.0 Evaluated Nuclear Reaction Data Library database [7], which adds confidence in obtaining reliable data.

Let us move on to examining neutron-generating reactions during the interaction of lithium with a deuteron; there are six of them in total, they are presented under nos. 1–4, 6, and 10. Let us consider the interac-

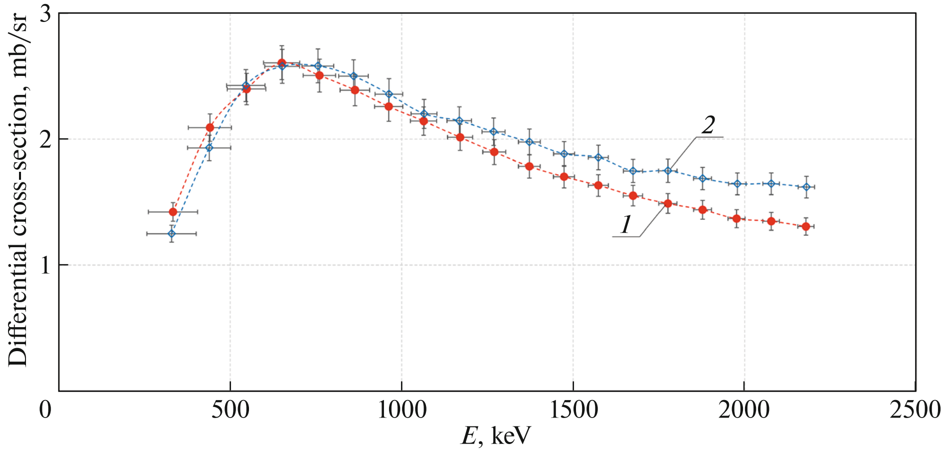

Fig. 3. Measured differential cross section of ^{6}Li(d, α)^{4}He: (*1*) 135°; (*2*) 168°.

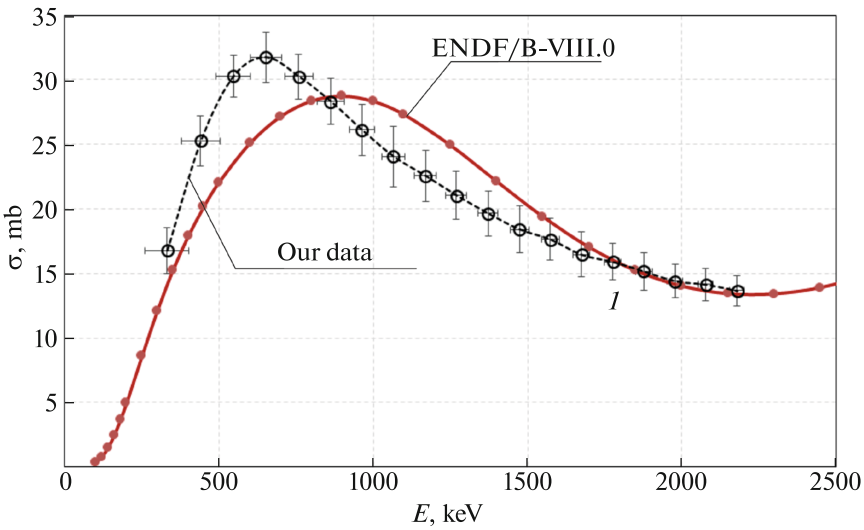

Fig. 4. Measured cross section of the reaction ^{6}Li(d, α)^{4}He and as presented in the ENDF/B-VIII.0 Evaluated Nuclear Reaction Data Library [7].

tion of a deuteron with lithium-7; this isotope predominates in natural lithium, its share being 92.5%, and that of lithium-6, 7.5%, respectively.

The main nuclear reaction of interaction is the reaction ^{7}Li(d, nα)^{4}He (*8* in Fig. 2). We calculated the differential cross-sections for two angles (Fig. 5). Let us estimate the total cross section at resonance energy. Let us take the average value for the differential cross section as 25 mb/sr, and then the value of the total cross section will be approximately ~400 mb at resonances in the region of 0.7–1.1 MeV, provided that we consider the reaction to be isotropic within the limits of measurement errors.

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

It is noticeable that the shape of the cross section approximately repeats the shape of the ^{7}Li(d, nα)^{4}He reaction cross section, with resonance also at deuteron energies of 0.7–1.1 MeV. In the approximation of isotropy of the reaction products, we determine from the differential cross section the total cross section for two angles. The results are presented in Fig. 7. It can be seen that they agree well in the range up to 1.5 MeV and diverge slightly with increasing deuteron energy. The total cross section at resonance will be ~150 mb (Fig. 7), which is approximately 2.5 times less than the estimate for the reaction ^{7}Li(d, nα)^{4}He.

Next, we will consider neutron-generating reactions nos. 1 and 2: ^{7}Li(d, n)^{8}Be and ^{7}Li(d, n)^{8}Be*,

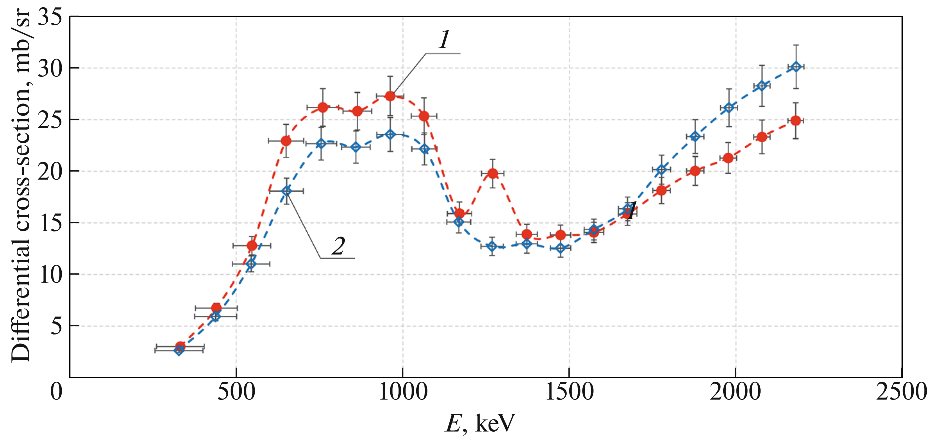

Fig. 5. Measured differential cross section of ^{7}Li(d, $n\alpha$)^{4}He: (*1*) 135°; (*2*) 168°.

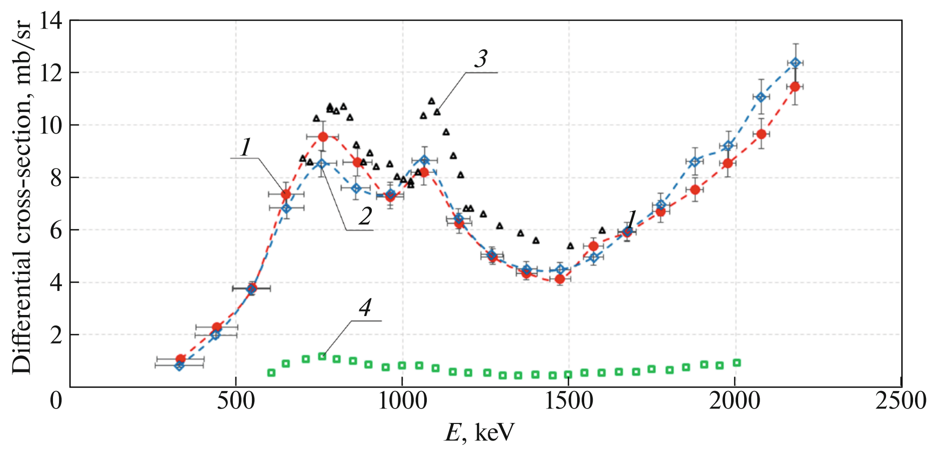

Fig. 6. Measured differential cross section of ^{7}Li(d, α)^{5}He: (*1*) 135°; (*2*) 168°. For comparison, ENDF/B-VIII.0 data [7] are provided: (*3*) Delbrouck-Habaru (1969) 154°, (*4*) Friendland (1971) 90°.

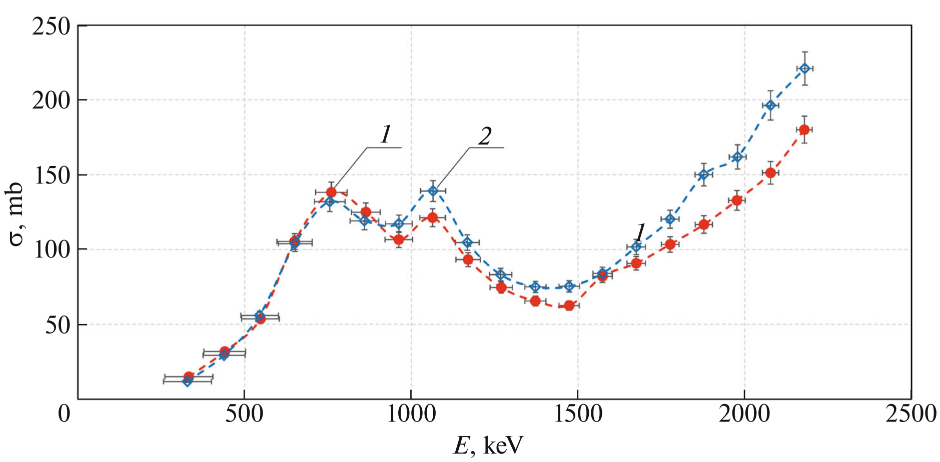

Fig. 7. Measured differential cross section of ^{7}Li(d, α)^{5}He: (*1*) 135°; (*2*) 168°.

respectively. The measured cross sections and a detailed description of the experiment are published in article [6]. Here we will also give the values of the total cross sections at resonance. For the reaction through the ground state of beryllium-8 (no. 1), this value is ~30 mb, while it is 50 mb for the reaction through the excited state of beryllium. In the first case, the cross section was 13 times smaller than the cross section of the main reaction ^{7}Li(d, $n\alpha$)^{4}, and in the second case it was eight times smaller.

Thus, we obtained data on all neutron-generating reactions during the interaction of lithium-7 with a deuteron beam. Based on estimates of the total reaction cross sections within the isotropic picture, the following was obtained: ^{7}Li(d, $n\alpha$)^{4}He is 400 mb, ^{7}Li(d, α)^{5}He is 150 mb, ^{7}Li(d, n)^{8}Be* is 50 mb, and ^{7}Li(d, n)^{8}Be is 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 to recover for the energy spectrum in the reaction of lithium-7 with a deuteron the first time.

The only unmeasured neutron-producing reactions remaining were reactions nos. 6 and 10. Both of these reactions occur when interacting with lithium-6 and are characterized by low-energy emitted neutrons. We recently measured the first reaction, ^{6}Li(d, n)^{7}Be, by activating the target with the radioactive isotope beryllium-7: the cross section at maximum is ~100 mb. In the second reaction, ^{6}Li(d, ^{3}He)^{5}He, the ^{5}He nucleus decays into a low-energy α-particle and a neutron, and it is necessary to separate the α-particles from the backscattered deuterons using mass spectrometry to measure its cross section.

BORON TARGET

The reaction of boron-11 interaction with a proton is of interest as one of the promising reactions for neutron-free thermonuclear fusion. The ^{11}B(p, α)$\alpha\alpha$ reaction is characterized by a high energy yield of 8.7 MeV. It is known that the nuclear reaction of interaction of boron-11 with a proton with the production of α-particles proceed in three ways: ^{11}B(p, α_0)^{8}Be, ^{11}B(p, α_1)^{8}Be*, and ^{11}B(p, α)$\alpha\alpha$, however, there is a large scatter in the values of the cross sections presented in the databases. Here, the designation ^{8}Be* implies that the beryllium-8 nucleus is in an excited state.

The boron target created for this experiment is a copper disk onto which a thin layer of boron was deposited using magnetron sputtering at the Institute of High Current Electronics in Tomsk. The thickness of the boron layer was determined by the previously described in situ method for a lithium target [4], comparing the yield of α-particles from a thin (studied) target and from a thick one. Boron carbide was used as a thick target. The linear thickness of the boron was equal to $(9.0 \pm 0.9) \times 10^{18}$ atoms/cm^2, which corresponds to a boron thickness of crystalline density equal to 0.7 ± 0.07 μm.

Interaction of Boron with a Proton Beam

A detailed description of the measurement performed is presented in article [8]. A typical spectrum obtained with an α-spectrometer is shown in Fig. 8. It is noticeable that the cascade decay process predominates; the small peak on the right corresponds to α-particles from the reaction ^{11}B(p, α_0)^{8}Be, and the main signal, forming a broad peak, is due to α-parti-

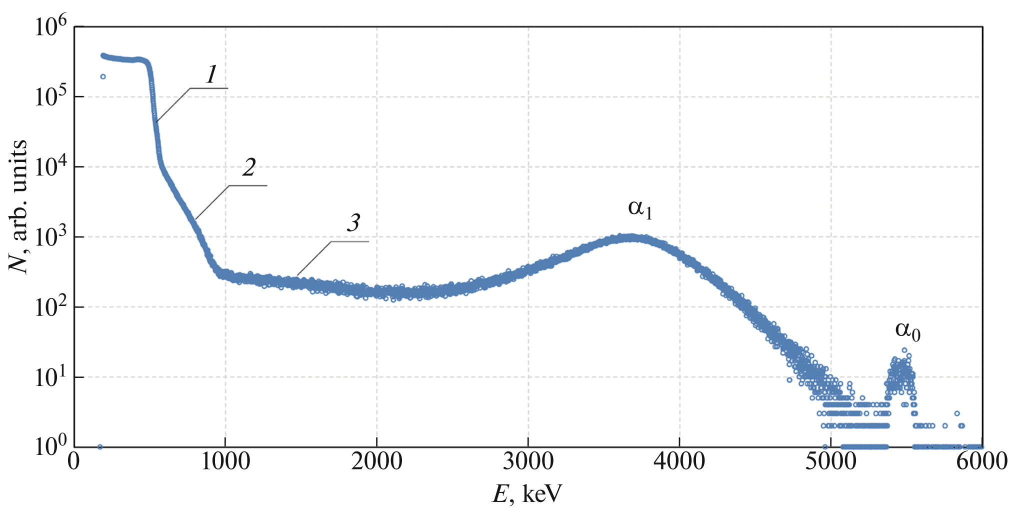

Fig. 8. Signal of the α-spectrometer with a 0.6-MeV proton beam at an angle of 168° relative to the beam axis: (*1*, *2*) backscattered protons from the copper target substrate (*1*, single events; *2*, double); (*3*) α-particles.

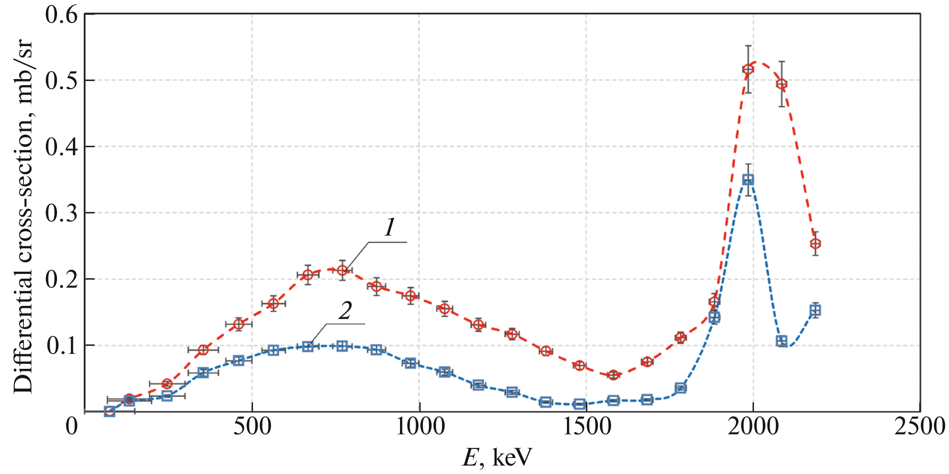

Fig. 9. Measured differential cross section of $^{11}B(p, \alpha_0)^8Be$: (*1*) 135°; (*2*) 168°. Differential sections are presented in the center of mass system.

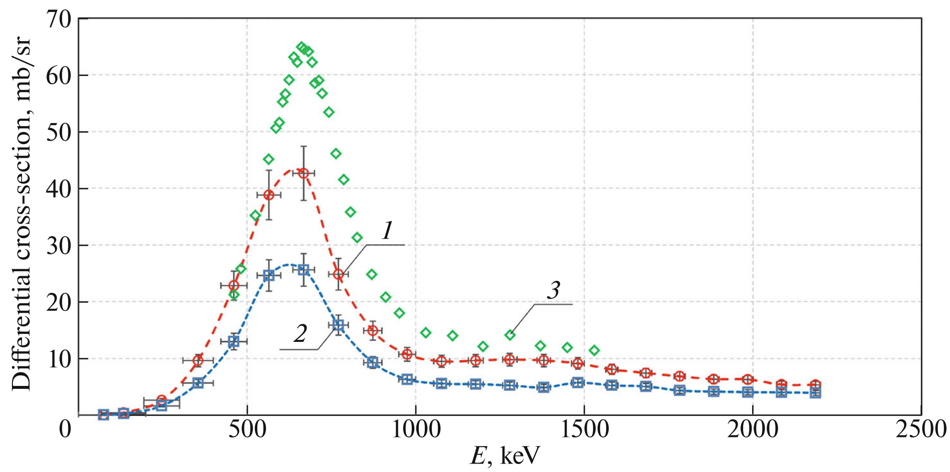

Fig. 10. Measured differential cross section of $^{11}B(p, \alpha_1)^8Be^*$: (*1*) 135°; (*2*) 168°. Differential sections are presented in the center of mass system. The reaction cross section measured at an angle of 150° (*3*) from article [9] is also shown.

cles from the reaction $^{11}B(p, \alpha_1)^8Be^*$. Differential cross sections for the reactions $^{11}B(p, \alpha_0)^8Be$ and $^{11}B(p, \alpha_1)^8Be^*$ are presented in Figs. 9 and 10, respectively.

It has been established that the reaction of interaction between a proton and boron occurs predominantly in the form of decay into an α-particle and a beryllium-8 nucleus in an excited state, with its subsequent decay into two α-particles. The measured reaction cross section in the approximation of isotropy of the reaction products was at most 700 mb at an energy of 600 keV, which is approximately half the reaction cross section often used when considering the prospects of neutron-free thermonuclear fusion [10, 11]. The second decay path through the beryllium nucleus in the ground state is less probable (10–100 times less) and has a maximum at a proton energy of around 2 MeV.

Since the reaction of boron-11 interaction with a proton occurs not only through a cascade pathway, it is of interest to conduct an assessment 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 α-particle peak from the reaction $^{11}B(p, \alpha_0)^8Be$. Summing up all the events to the right of this peak, we obtained a probability of direct decay that is 2000–3000 times lower than that of cascade decay.

We plan to continue studying this reaction and measuring its angular distribution. We have already created a special vacuum chamber for this purpose, allowing measurements at nine angles. We have also purchased additional equipment that will allow us to measure simultaneously at two angles, thereby ensuring control and increasing the accuracy of the measurements.

CONCLUSIONS

At the Budker Institute of Nuclear Physics (Novosibirsk, Russia), using an α-spectrometer and diamond neutron detector, the cross sections of nuclear reactions of interaction of deuteron with lithium, ^{6}Li(d, α)^{4}He, ^{6}Li(d, p)^{7}Li, ^{6}Li(d, p)^{7}Li*, ^{7}Li(d, α)^{5}He, ^{7}Li(d, nα)^{4}He, ^{7}Li(d, n)^{8}Be, and ^{7}Li(d, n)^{8}Be*, as well as a proton with boron, ^{11}B(p, α_0)^{8}Be and ^{11}B(p, α_1)^{8}Be*, were measured. The obtained data make it possible to recover for the first time the energy spectrum in the reaction of lithium-7 with a deuteron. It has been established that the reaction of interaction between a proton and boron occurs predominantly in the form of decay into an α-particle and a beryllium-8 nucleus in an excited state, with its subsequent decay into two α-particles. The value that we obtained for the cross section of the reaction of proton-boron interaction in resonance is half the value often used in assessing the prospects of neutron-free thermonuclear energy.

ACKNOWLEDGMENTS

The authors era grateful to their colleagues A.G. Nikolaev and E.M. Oks from the Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences (Tomsk, Russia), as well as N.B. Rodionov, Yu.A. Kashchuk, S.Yu. Obudovsky, A.S. Djurik, T.M. Kormilitsyn, R.N. Rodionov, and V.N. Amosov from the Private Institution Project Center ITER of State Atomic Energy Corporation Rosatom (Moscow, Russian).

FUNDING

The study was supported by a grant of the Russian Science Foundation, no. 19-72-30005 (https://rscf.ru/project/19-72-30005/).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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