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# Studies of Nuclear Reactions of Light Nuclei in the Energy Range up to 2.2 MeV at the VITA Tandem Accelerator

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**Abstract**—Parameters of nuclear reactions $p$ + Li, $d$ + Li, $p$ + B and $d$ + B at ion energies up to 2.2 MeV were measured at the vacuum-insulated tandem accelerator VITA using alpha, gamma, and neutron spectrometers: particle yield, reaction cross section, decay path, angular and energy distribution of products. The article provides a brief description of the facility, presents, discusses the results of the research, and declares the plans.

**Keywords:** nuclear reactions, reaction cross section, angular and energy distribution of reaction products

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## INTRODUCTION

At the Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences, an accelerator neutron source VITA [2–4] was proposed and developed for boron neutron capture therapy of malignant tumors (BNCT) [1], which provides a therapeutic neutron beam that best meets the requirements of BNCT. The BNCT center in Xiamen (China) is equipped with the accelerator neutron source VITA-IIα where clinical trials of the BNCT technique began on October 9, 2022, making China the second country in the world to master the new treatment technique. The Blokhin National Medical Research Center of Oncology in Moscow will soon be equipped with the accelerator neutron source VITA-IIβ in order to begin clinical trials of the BNCT technique in the Russian Federation from 2025. The VITA facility at the BINP SB RAS site is used to develop dosimetry tools and methods for BNCT, to evaluate new drugs for targeted boron delivery, to treat large domestic animals with spontaneous tumors, to test promising materials under radiation conditions, and to measure the parameters of a number of nuclear reactions important for BNCT, thermonuclear fusion, and other applications.

The paper briefly describes the used facility, substantiates the importance of measuring the parameters of a number of nuclear reactions, and presents the research results.

## EXPERIMENTAL SETUP

The study was conducted at the VITA accelerator neutron source, which includes a tandem accelerator with vacuum insulation to produce a stationary proton or deuteron beam, a lithium target for generating neutrons, and a number of systems for shaping a neutron beam of various energy ranges. The facility is equipped with modern diagnostic equipment, including γ-, α- and neutron spectrometers and dosimeters. The setup diagram is shown in Fig. 1.

The produced ion beam is highly monochromatic and has energy stability of 0.1%, and a current stability of 0.4%; its energy can be varied from 0.1 to 2.2 MeV, and its current can be varied from 0.5 to 10 mA. The ion beam current is measured by a noncontact NPCT current sensor (Bergoz Instrumentation, France) and a calibrated resistor connected to the target unit, electrically isolated from the setup, using the latter as a deep Faraday cup.

The lithium target is a copper disk with a diameter of 144 mm and a thickness of 8 mm. A uniform layer of lithium of crystalline density is applied to one side of the disk in its center inside a circle with a diameter of 84 mm using the vacuum thermal spraying method. On the reverse side of the copper disk, inside a diameter of 122 mm, spiral channels are made for water cooling; this side of the copper disk is pressed by an aluminum disk with a thickness of 16 mm. The lithium target is integrated into the target unit, equipped with a gate valve and diagnostic nozzles. Natural lithium produced by the Novosibirsk Chemical Concentrates Plant is used for spraying, in which the content of lithium itself is 99.956%; the remaining 0.044% are impurities. The content of isotope 7 in natural lithium is assumed to be 92.5%.

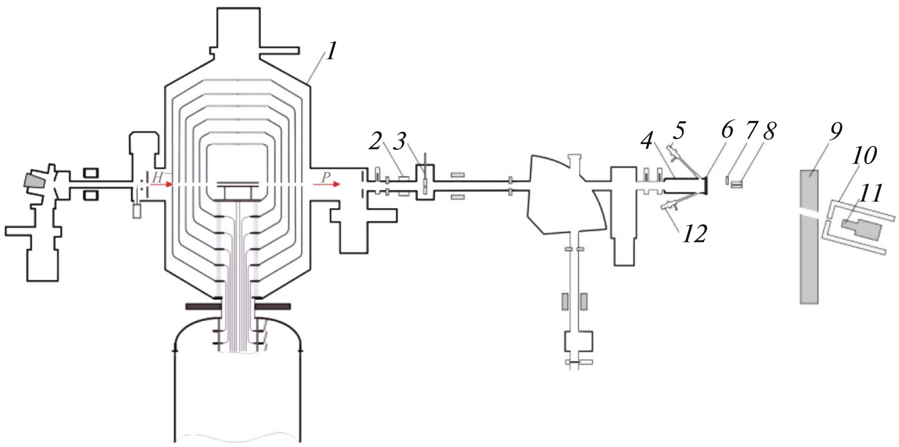


**Fig. 1.** Schematic diagram of the experimental setup: (*1*) tandem accelerator with vacuum insulation, (*2*) noncontact current sensor, (*3*) retractable cooled collimator, (*4*) target unit, (*5* and *12*) α-spectrometer, (*6*) lithium target, (*7*) temporarily placed lead sheet, (*8*) fast neutron spectrometric radiometers with a diamond detector, (*9*) temporarily constructed concrete wall, (*10*) lead collimator, (*11*) γ-spectrometer.

The energy spectrum of neutrons is measured by two fast neutron radiometers with diamond spectrometric detectors (ITER Project Center, Moscow), α particles by an α-spectrometer with a silicon semiconductor detector PDPA 1K (Institute of Physical and Technical Problems, Dubna), and γ-radiation by a γ-radiation spectrometer SEG 1KP (Institute of Physical and Technical Problems, Dubna) based on a semiconductor detector made of high-purity germanium.

## INTERACTION OF PROTONS WITH LITHIUM

The reaction $^7$Li($p$,$n$)$^7$Be provides generation of neutrons for BNCT. When planning therapy, the calculated neutron yield data from the paper [5] are used, since the experimentally measured values differ significantly from each other and from the calculated one: 2 times less than the calculated one [6], 1.7 times less than in Ref. [7], and from 7 times less to 1.4 times more than in Ref. [8]. It was necessary to experimentally confirm the neutron yield from the lithium target.

To measure the neutron yield, the fact was used that the product of the $^7$Li($p$,$n$)$^7$Be reaction is not only a neutron, but also a radioactive atomic nucleus beryllium-7. If the release of beryllium from the target is prevented, then measuring the target activation allows one to determine the number of $^7$Be nuclei produced, which is equal to the number of generated neutrons. To measure the neutron yield, the lithium target is irradiated with a proton beam to a certain fluence, using a rotating magnet as an energy analyzer and monitoring the position of the proton beam on the target surface with video cameras, thermocouples, and small-sized neutron sensors to maintain the proton energy with high accuracy. The next day, the target unit is disassembled and the activation of the target and the rest of the target unit is measured with a γ-spectrometer (to ensure that the beryllium had moved off the target insignificantly). The detection efficiency of the γ spectrometer at the 478-keV line was determined with high accuracy using two powerful photon radiation sources with the radionuclide cesium-137 and barium-133, seven-point reference radionuclide photon radiation sources from the OSGI RT set, three weak self-made point sources of photon radiation, as well as a detailed study of the effect of the detector dead time on the reliability of the measurement and consideration of the finite size of the detector. As a result, it was demonstrated that the measured neutron yield agrees with the calculated one with an accuracy of 5%, which is important for planning the therapy that began in Xiamen (China) using a lithium target. The results of the study are described in detail in the paper [9].

The interaction of a proton with lithium leads not only to the generation of neutrons, but also 478-keV photons due to inelastic scattering on lithium atomic nuclei $^7$Li($p$,$p'\gamma$)$^7$Li, comparable in the flux. During BNCT, these photons give an unwanted nonselective dose of γ radiation. Experimental data on the photon yield in the $^7$Li($p$,$p'\gamma$)$^7$Li reaction are scarce and contradictory, so the calculated data presented in the paper [10] are used to estimate the dose. It was necessary to experimentally measure the yield of 478-keV photons from a lithium target. The radiation intensity and cross section of the $^7$Li($p$,$p'\gamma$)$^7$Li reaction were measured with the γ-spectrometer positioned at an angle of 15° and 110° to the proton beam direction. It was found that the radiation is isotropic. The results are shown in Fig. 2. It was found that the measured photon radiation intensity is approximately 1.7 times

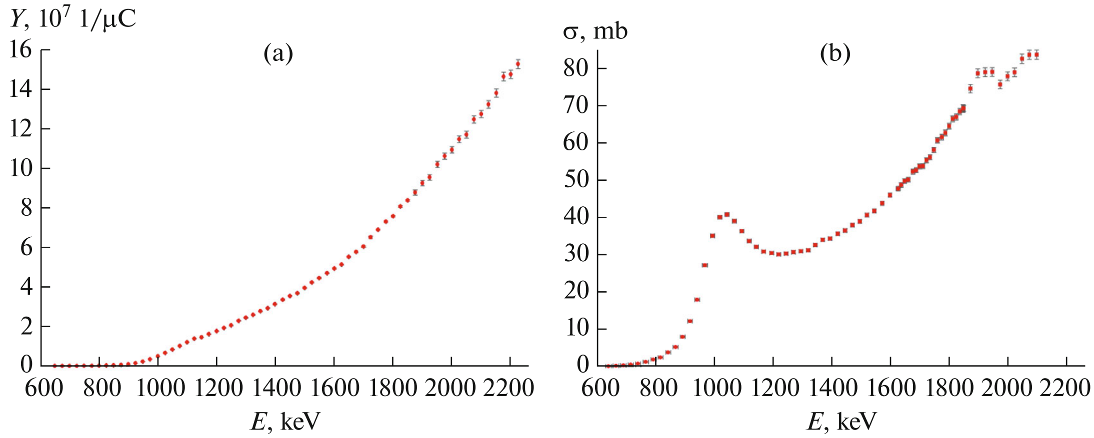


**Fig. 2.** The yield of 478-keV photons from a thick lithium target with natural content of lithium isotopes (a) and the cross sections of the reaction $^7$Li($p$,$p'\gamma$)$^7$Li as a function of the proton energy $E$ (b).

less than the calculated one [10]. The values obtained of the cross section of the $^7$Li($p$,$p'\gamma$)$^7$Li reaction and the yield of 478-keV photons from a thick lithium target are presented in tabular form in the published paper [11] and entered into the IBANDL and Exfor databases. Later, similar measurements were conducted by a Greek group at proton energies from 1 to 4 MeV, which obtained results that coincided with those measured by us [12].

The measured dependence of the yield of 478-keV photons from a thick lithium target on the proton energy made it possible to propose and implement an in situ method for measuring the thickness of the lithium layer. The essence of the method consists in irradiating the target with protons and measuring the count rate of 478-keV γ-quanta with a γ-spectrometer. Two lithium targets are used in the measurement: the one being studied and the thick one. A thick target is one in which the protons have slowed down in lithium to an energy below 478 keV, the threshold of the $^7$Li($p$,$p'\gamma$)$^7$Li reaction. A thin target is one, in which the protons have slowed down in lithium to an energy above 478 keV. If the target under study is not thick, the yield of 478 keV photons from it will be less than from a thick one. By measuring the ratio of the count rate of 478 keV photons from the target under study and a thick target, it is possible to determine the lithium thickness, since the rate of energy loss by a proton in lithium is known. This method for measuring the thickness of the lithium layer is described in detail in the paper [13].

The interaction of a proton with a lithium nucleus also leads to a comparable flux of α-particles in the $^7$Li($p$,$\alpha$)$^4$He reaction, characterized by a high energy yield of 14.347 MeV. This reaction is one of the thermonuclear reactions involved in the stellar cycle of heavy element synthesis in the Universe and can be used for in situ control of the lithium layer thickness in the target. The curious thing about the situation is that the reaction cross section recommended by the JENDL database is twice as large as the cross section recommended by the ENDF/B and TENDL databases. It was necessary to understand which data to believe. The characteristic energy spectrum of the charged particles registered by the spectrometer is shown in Fig. 3. It is evident that it is quite simple to identify: the useful signal of α-particles is separated from the signal of backscattered protons by the gap of no signal in the recording channels.

The measurement results in comparison with the data presented in the databases are shown in Fig. 4. It can be seen that the measured cross section of the $^7$Li($p$,$\alpha$)$^4$He nuclear reaction is consistent with the values given in the JENDL-4.0 nuclear reaction database and is approximately two times larger than the values given in the ENDF/B VIII.0 and TENDL 2019 nuclear reaction databases. The measurement results are published in the paper [14] and entered into the IBANDL and Exfor nuclear reaction databases. The reliability of the obtained data is given by the fact that the thickness of the lithium target was measured by six independent methods: most accurately by comparing the intensity of 478-keV photons from the thick and studied target, as well as by the mass of deposited lithium, by the conductivity of the water that washed off the lithium, by the shift and width of the peak of α-particles, by the amplitude of the signal of protons backscattered by lithium atomic nuclei.

## INTERACTION OF DEUTERON WITH LITHIUM

The interaction of deuterons with energies less than 2.2 MeV with natural lithium nuclei results in 10 nuclear reactions, in five of which neutrons are

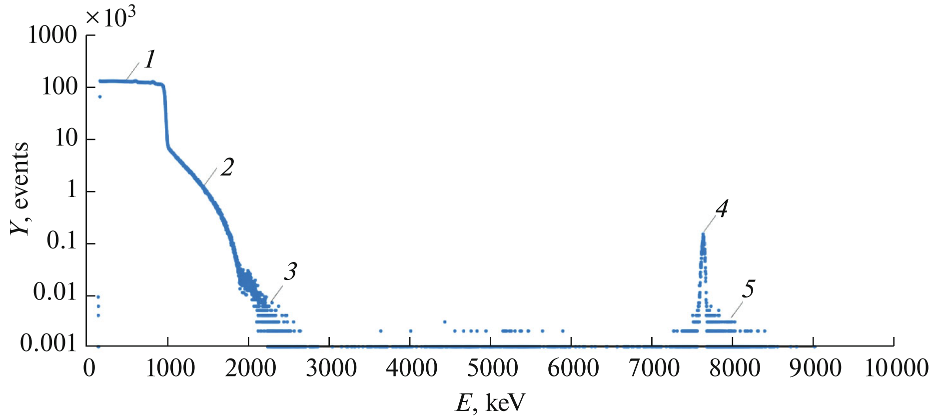


**Fig. 3.** Spectrum of charged particles registered by the α spectrometer at a proton energy of 1 MeV: (*1–3*) backscattered protons (*1*) single events, (*2*) double, (*3*) triple, (*4*) α particles, (*5*) simultaneous detection of α particle and proton.

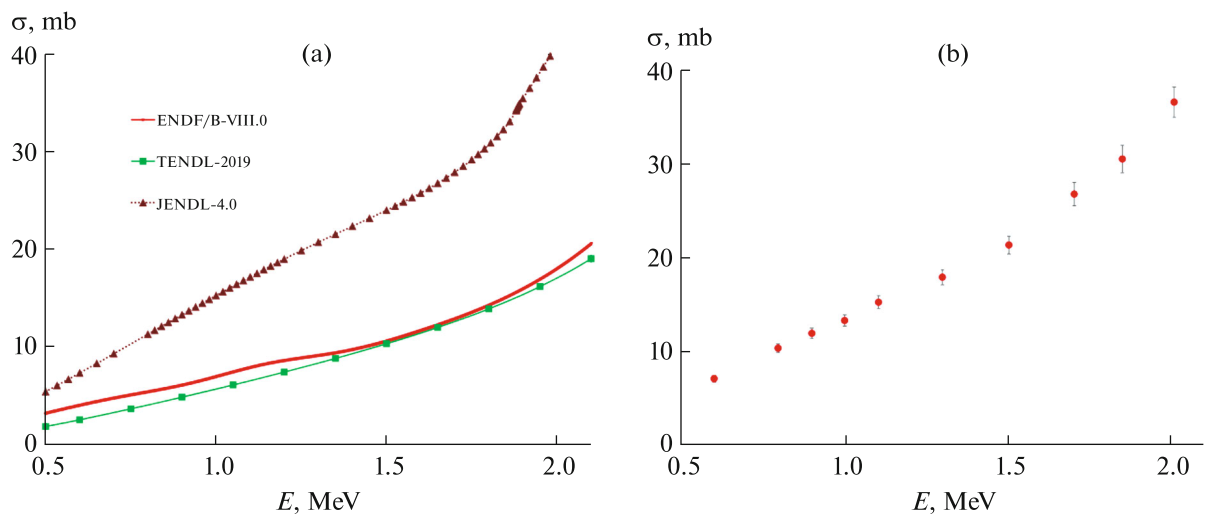


**Fig. 4.** Cross section of the reaction $^7$Li($p$,α)$^4$He, presented in the databases (a) and measured (b).

generated. These reactions provide the highest yield of neutrons per unit current of the charged particle beam, starting with the energy of 0.7 MeV. However, data on the cross-section of these reactions are scarce and often missing. The ENDF/B database contains data only for two reactions: $^6$Li($d$,α)$^4$He and $^6$Li($d$,$p$)$^7$Li, the TENDL database contains the same reactions, but with a reference to the fact that they are taken from the ENDF/B database, and the JENDL database does not contain data. The EXFOR and IBANDL libraries provide data from the original papers, and in these libraries, in addition to the data on the reactions $^6$Li($d$,α)$^4$He and $^6$Li($d$,$p$)$^7$Li, there are data on the cross section of the reactions $^7$Li($d$,α)$^5$He ($^5$He → α + $n$) and $^6$Li($d$,$p$)$^7$Li*.

The characteristic energy spectrum of charged particles registered by the spectrometer is shown in Fig. 5. We measured the cross section of six reactions: $^6$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($d$,$n$α)$^4$He [15] and $^7$Li($d$,$n$)$^8$Be. Figure 5 shows the measured cross section of the $^6$Li($d$,α)$^4$He reaction in comparison with that presented in the ENDF/B database and the measured cross sections of the $^7$Li($d$,α)$^5$He, $^7$Li($d$,$n$α)$^4$He and $^7$Li($d$,$n$)$^8$Be reactions with the formation of the Be nucleus in the ground and first excited states. Thus, the cross sections of three of the five neutron generation reactions have been measured. The remaining two neutron generation reactions, $^6$Li($d$,$n$)$^7$Be and $^6$Li($d$,$^3$He)$^5$He ($^5$He → α + $n$), are difficult to measure due to the low energy of the reaction products, but due to the low content of the $^6$Li isotope in natural lithium, they can make a small contribution to the total neutron yield. Therefore, the available data allow one to estimate the energy spec-

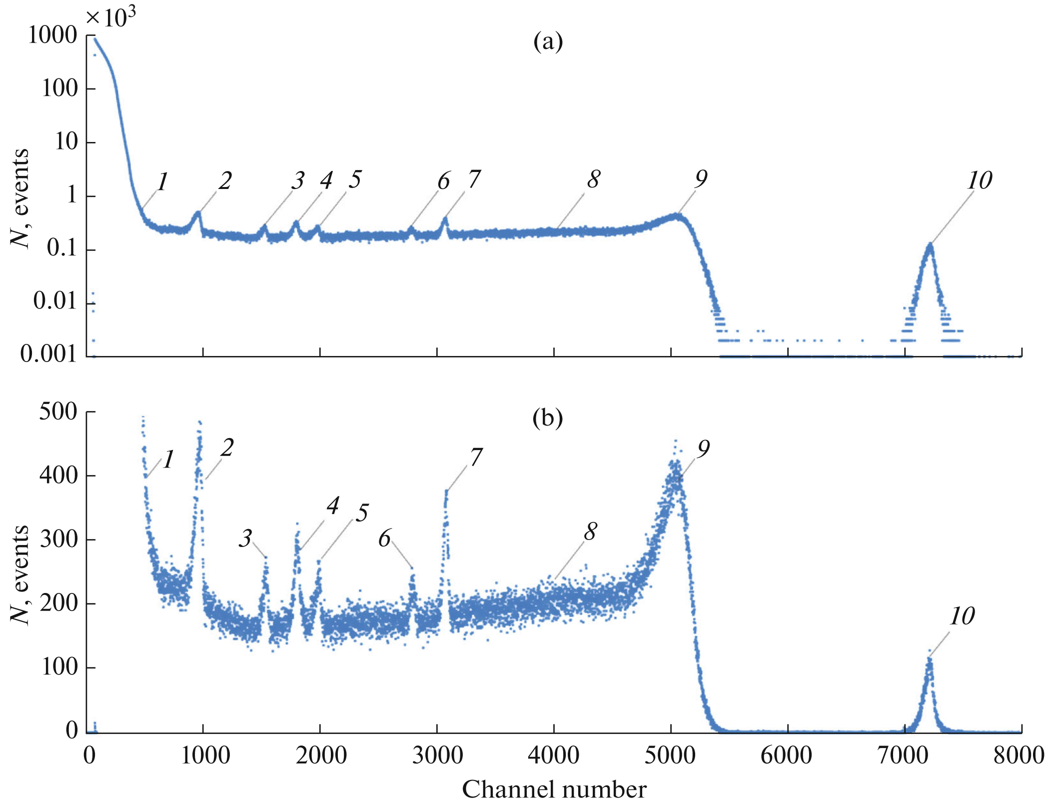


**Fig. 5.** Signal of the α-spectrometer used in a 0.6-MeV deuteron beam: (*1*) backscattered deuterons, (*2*) protons of the $^{16}O(d,p_1)^{17}O^*$ reaction, (*3*) protons of the $^{16}O(d,p_0)^{17}O$ reaction, (*4*) α-particles of the $^{16}O(d,\alpha)^{14}N$ reaction, (*5*) protons of the $^{12}C(d,p_0)^{13}C$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

trum of the generated neutrons. Note that the cross section of the $^{6}Li(d,n)^{7}Be$ reaction can be measured by measuring the activation of the target by the $^{7}Be$ isotope, and this study is expected to be performed in the near future. It is also expected that the cross sections of the $^{6}Li(d,p)^{7}Li$ and $^{6}Li(d,p)^{7}Li^*$ reactions can be measured more accurately using a lithium target enriched in the $^{6}Li$ isotope.

## INTERACTION OF A PROTON WITH A BORON NUCLEUS

Synthesis reaction of proton and boron has attracted attention since the inception of nuclear physics due to its relevance and potential application in various fields, from neutron-free nuclear fusion to astrophysics and hadron therapy. This reaction has been studied since the 1930s, but the data from different authors differ. Obtaining reliable experimental data on fundamental quantities (e.g., direct, or sequential decay, cross section, energy spectrum of α-particles, orbital angular momentum of α-particles) is still relevant. The measured energy spectrum of α particles (Fig. 7) allows us to state that the direct process of formation of three α particles is unlikely, and the reaction proceeds by sequential decay, first into an α particle and a $^{8}Be$ nucleus in the ground or excited state, and then the $^{8}Be$ nucleus decays into two α particles [16]. The measured reaction cross sections are shown in Fig. 5.

## INTERACTION OF A DEUTERON WITH A BORON NUCLEUS

Irradiation of a boron target used in studying the interaction of a proton with a boron nucleus with a deuteron beam allowed us to measure the cross section of the reactions $^{10}B(d,\alpha)^{8}Be$, $^{10}B(d,\alpha)^{8}Be^*$, $^{11}B(d,\alpha)^{9}Be$, $^{11}B(d,\alpha)^{9}Be^*$, $^{10}B(d,p_2)^{11}B$ and $^{11}B(d,p_3)^{11}B$. The results are currently being processed.

## CONCLUSIONS

The VITA tandem accelerator with vacuum insulation, developed at the BINP SB RAS, was used to study nuclear reactions of light nuclei in the energy

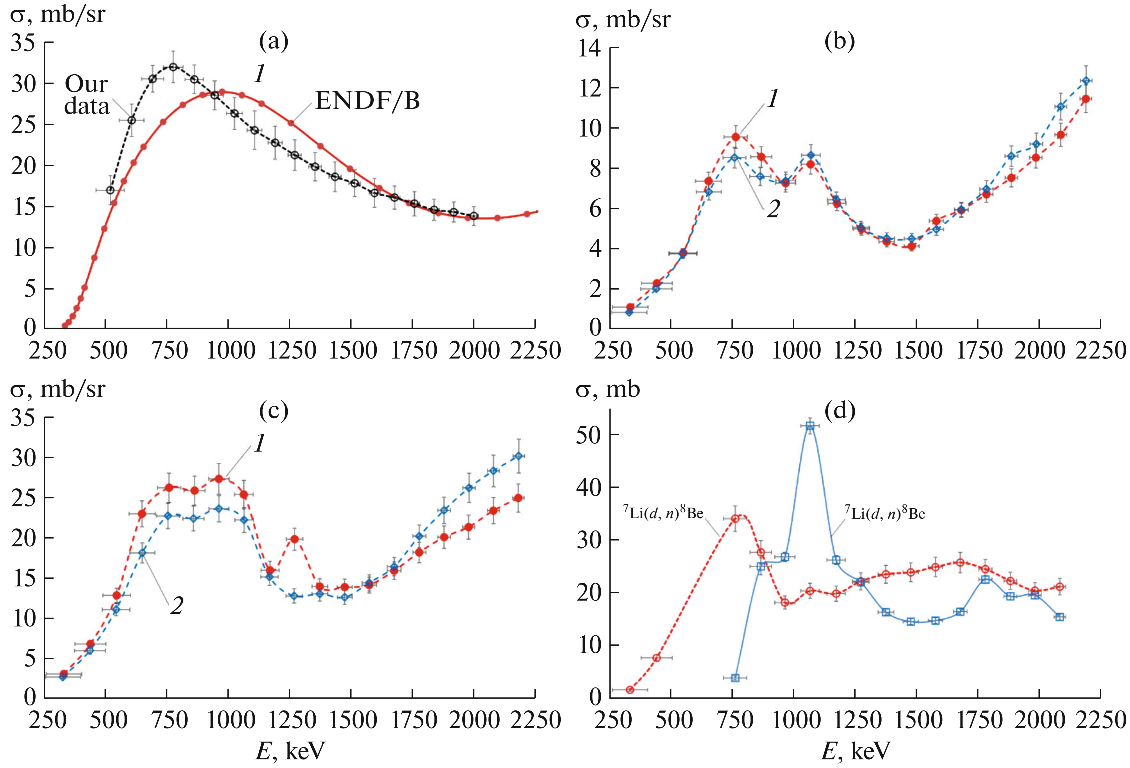


**Fig. 6.** Measured cross section of the reaction $^{6}Li(d,\alpha)^{4}He$ (a), $^{7}Li(d,\alpha)^{5}He$ (b), $^{7}Li(d,n\alpha)^{4}He$ (c), $^{7}Li(d,n)^{8}Be$, and $^{7}Li(d,n)^{8}Be^{*}$ (d); (*1*) at an angle of 135°, (*2*) at an angle of 168°.

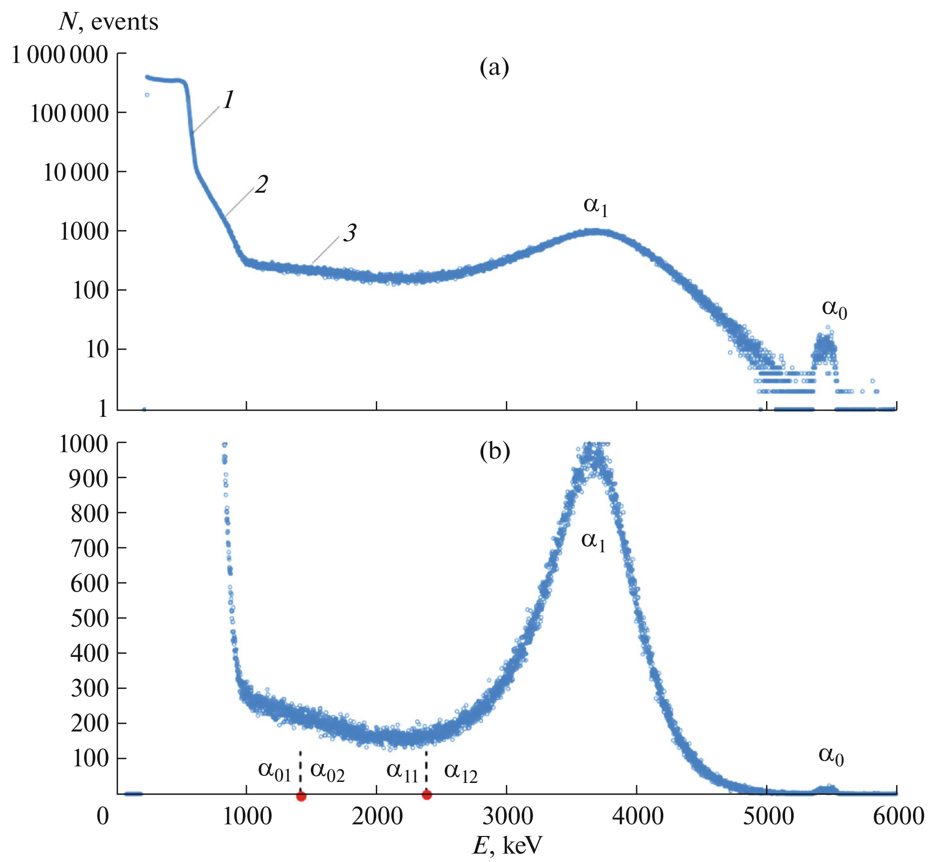


**Fig. 7.** Signal of the α-spectrometer used in a 0.6-MeV deuteron beam and an angle of 168°: (*1–2*) backscattered deuterons ((*1*) single events, (*2*) double), (*3*) α-particles.

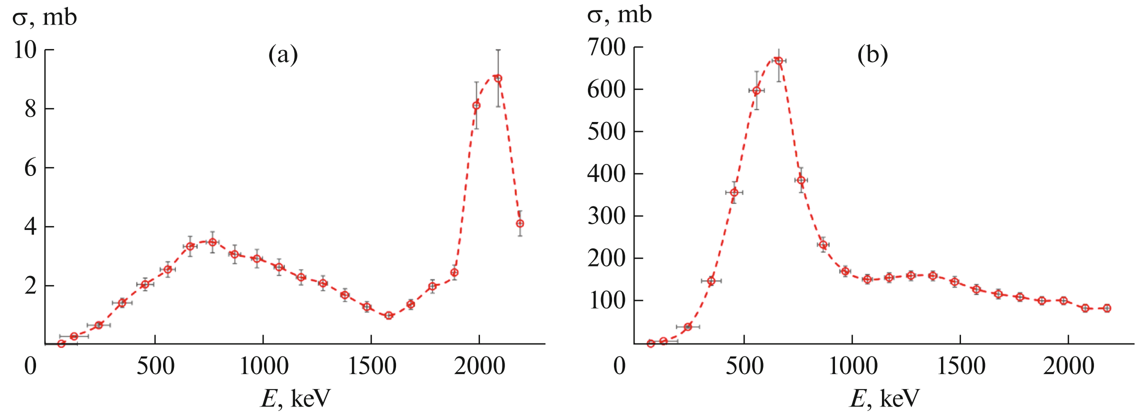


**Fig. 8.** Measured cross-section of the reactions $^{11}$B($p$,$\alpha_1$)$^8$Be (a) and $^{11}$B($p$,$\alpha_1$)$^8$Be* (b).

range up to 2.2 MeV: the neutron yield in the $^7$Li($p$,$n$)$^7$Be reaction, the photon yield in the $^7$Li($p$,$p'\gamma$)$^7$Li reaction, the cross section of the reactions $^7$Li($p$,$p'\gamma$)$^7$Li, $^7$Li($p$,$\alpha$)$^4$He, $^6$Li($d$,$\alpha$)$^4$He, $^6$Li($d$,$p$)$^7$Li, $^6$Li($d$,$p$)$^7$Li*, $^7$Li($d$,$\alpha$)$^5$He, $^7$Li($d$,$n\alpha$)$^4$He, $^7$Li($d$,$n$)$^8$Be, $^7$Li($d$,$n$)$^8$Be*, $^{11}$B($p$,$\alpha_1$)$^8$Be, $^{11}$B($p$,$\alpha_1$)$^8$Be*, $^{10}$B($d$,$\alpha$)$^8$Be, $^{10}$B($d$,$\alpha$)$^8$Be*, $^{11}$B($d$,$\alpha$)$^9$Be, $^{11}$B($d$,$\alpha$)$^9$Be*, $^{10}$B($d$,$p_2$)$^{11}$B, and $^{11}$B($d$,$p_3$)$^{11}$B, and radiation isotropy were measured. The obtained data are important for boron neutron capture therapy, neutron-free thermonuclear energy production, for generating a powerful flux of fast neutrons and other applications.

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## CONFLICT OF INTEREST

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

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