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PHYSICS AND TECHNIQUE OF ACCELERATORS

Study of the ^{11}B(p,α)αα Reaction in the 0.3–2.15 MeV Energy Range of the Proton Beam

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Abstract—The reliable value of the ^{11}B(p,α)αα reaction cross-section is of importance for the proton therapy of cancer, thermonuclear fusion, and nuclear astrophysics. Despite its relevance, the mechanism of the reaction is still an open issue. The goal of the study is to obtain new data on the reaction and to update and clarify the available data in the 0.3–2.15 MeV energy range of the proton beam. The results obtained have shown that the ^{11}B(p,α)αα reaction proceeds via two channels, ^{11}B(p,α_1)^{8}Be* and ^{11}B(p,α_0)^{8}Be, with unequal cross-sections, which agrees with current conceptions. A thin boron target will be studied later to measure the cross-sections of each channel.

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INTRODUCTION

Reliable knowledge of the cross-section of the ^{11}B(p,α)αα nuclear reaction is required in many areas. First, it is the use of boron as a radio sensitizer in proton therapy. Accumulation of ^{11}B in cancer cells followed by proton irradiation leads to a nuclear reaction with the generation of high-energy α particles, which makes it possible to increase the dose absorbed during proton therapy at the depth of the Bragg peak [1]. The second area is the perspective use of the boron-proton fusion reaction in thermonuclear power generation. Compared to alternative reactions, candidates for controlled fusion, energy production using boron does not produce residual radiation and increases the amount of effective energy as the ^{11}B(p,α)αα reaction occurs without generating neutrons [2]. The third area is the study of the primary nucleosynthesis mechanism for nuclear astrophysics [3]. Despite its importance, the physics of this reaction is still an open issue [4].

This study aims at obtaining new knowledge and updating and clarifying available data on the cross section of the promising ^{11}B(p,α)αα reaction in the proton energy range 0.3–2.15 MeV. To this end, a thick boron-containing target was irradiated with protons at the Vacuum Insulated Tandem Accelerator (VITA) at the Budker Institute of Nuclear Physics. Spectra of α-particles and backscattered protons formed as a result of the ^{11}B(p,α)αα reaction were measured at an angle of 135° to the direction of beam motion using a silicon semiconductor α-spectrometer PDPA-1K (Institute of Physical and Technical Problems, Dubna, Russia). Experimental data were analyzed and the interaction of a proton beam with a boron-containing target was numerically simulated using SIMNRA, version 7.03 software.

1. MATERIALS AND METHODS

1.1. Nuclear Reaction ^{11}B(p,α)αα

The nuclear reaction of the ^{11}B isotope with protons occurs in two stages (Fig. 1). When protons interact with ^{11}B, a ^{12}C atom in an excited state is formed. ^{12}C decays into an α particle and a ^{8}Be nucleus, which is in the ground or first excited state. The ^{8}Be nucleus decays into two α particles. Depending on whether ^{8}Be or ^{8}Be* decays into α particles, α_0 and α_1-reaction channels, respectively, are distinguished [5].

The reaction mechanism studied for the first time by Oliphant and Rutherford [6] and by Gilbert and Dee (1936) [7] has been investigated since 1933, but the data collected over almost 90 years vary significantly.

Figure 2 displays the dependence of the differential cross-section on the energy of the incident proton beam taken from the IBANDL database of nuclear reactions [4, 8, 9]. The results for scattering at angles close to 135°, close to those studied here, are presented. The data differ significantly especially in the 0.3–2 MeV energy range studied in this work.

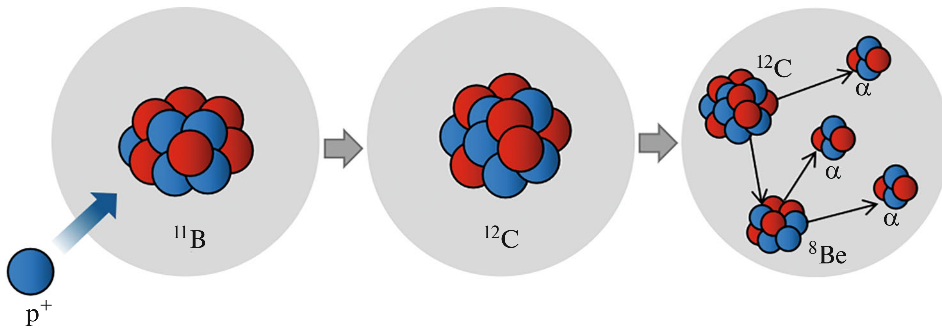

Fig. 1. Diagram of the nuclear reaction between ^{11}B and protons.

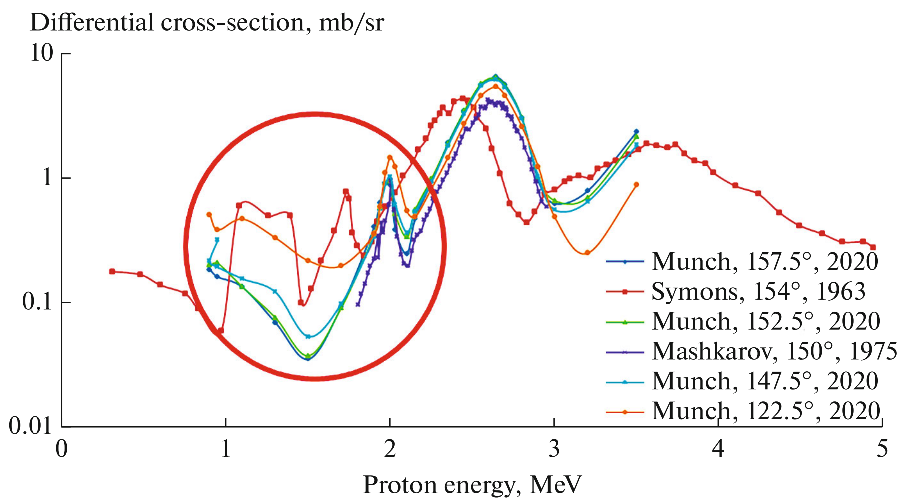

Fig. 2. Data on the cross section of the $^{11}B(p, \alpha)\alpha\alpha$ reaction taken from the IBANDL nuclear reaction database; the range under study is circled in red.

1.2. Experimental Setup

The experiments were carried out on the vacuum insulated tandem accelerator (VITA) at the Budker Institute of Nuclear Physics (Novosibirsk, Russia). The tandem accelerator provides protons with energies ranging from 0.3 to 2.2 MeV with a stability of 0.1% and a current of 1 to 5 mA with a stability of 0.4% [10, 11]. The experimental setup is displayed in Fig. 3.

In this study, a silicon semiconductor detector PDPA-1K (Institute of Physical and Technical Problems, Dubna, Russia) is used as an α-particle spectrometer.

Sensitive detector area $S = 20\ mm^2$; energy resolution is 13 keV; capacitance, 30 pF; energy equivalent of noise, 6 keV; and the entrance window thickness is 150 μm. When a thick boron target was irradiated with protons, the sensitive part of the α-detector was located at a distance of 870 mm from the boron target at an angle of 135° relative to the beam axis. The solid angle is $\Omega_{lab} = S/R^2 = 2.64 \times 10^{-5}$. An image of the detector mounted on the target unit is displayed in Fig. 4a.

The boron target made of boron carbide B_4C is 4 mm thick. A proton beam with a maximum energy of 2.15 MeV does not pass through the target, thus the target is considered thick.

The boron carbide plate was mounted on a cooled copper substrate (Fig. 4b) and installed in the target unit.

2. RESULTS AND DISCUSSION

A thick boron-containing target was irradiated with a proton beam in the energy range of 0.3–2.0 MeV in 100-keV steps and the 2.05–2.15 MeV range in 50-keV steps at a vacuum insulated tandem accelerator (VITA). At each energy, data were collected for 10 min. The parameters of the beam and α-spectrometer, when measuring spectra, are presented in Table 1. The beam current on the target did not exceed 10 μA, and the detector dead time was less than 0.04.

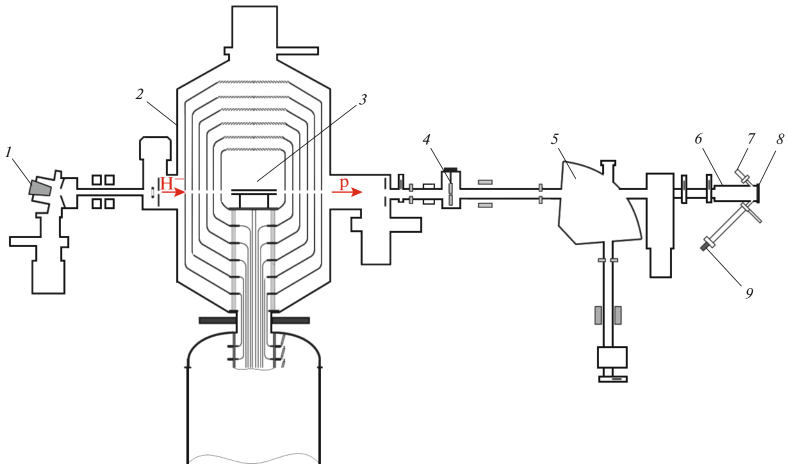

Fig. 3. Experimental setup: (*1*) ion source, (*2*) vacuum insulated tandem accelerator, (*3*) argon target; (*4*) cooled collimator with a 1 mm aperture; (*5*) bending magnet; (*6*) target assembly; (*7*) video cameras; (*8*) boron-containing target; (*9*) α-spectrometer.

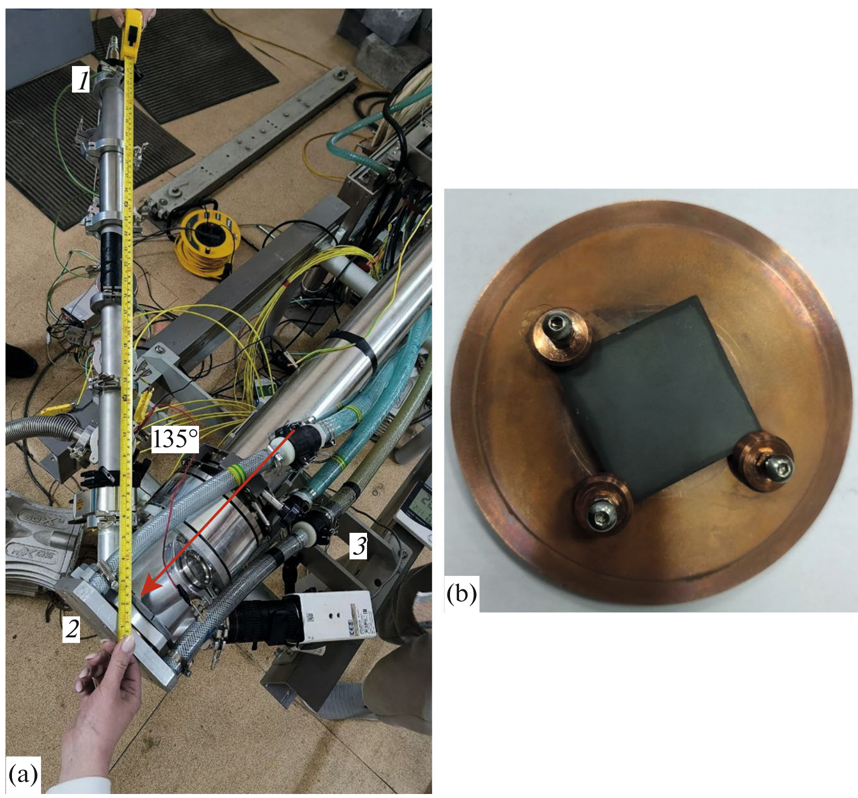

Fig. 4. (a) Image of the target unit: (*1*) α-spectrometer, (*2*) target; (*3*) video camera; the arrow shows the beam direction; (b) image of the boron-containing target mounted on a copper substrate.

Examples of spectra of α-particles and backscattered protons recorded at proton energies of 400, 700, 1000, and 2000 keV are presented in Fig. 5.

The sharp plateau in the 0–1200 channel range can be interpreted as elastic scattering on boron and carbon. The broad plateau in the 1200–3500 channel range may be interpreted as the α_1-reaction channel, and the rise in the 3500–4500 channel range, as α_0-reaction channel.

SIMNRA software [12] was used to determine the exact composition of the target under study. Experimental and simulated spectra are presented in Fig. 6.

Contributions from each element are shown separately. In addition to boron and carbon, the target con-

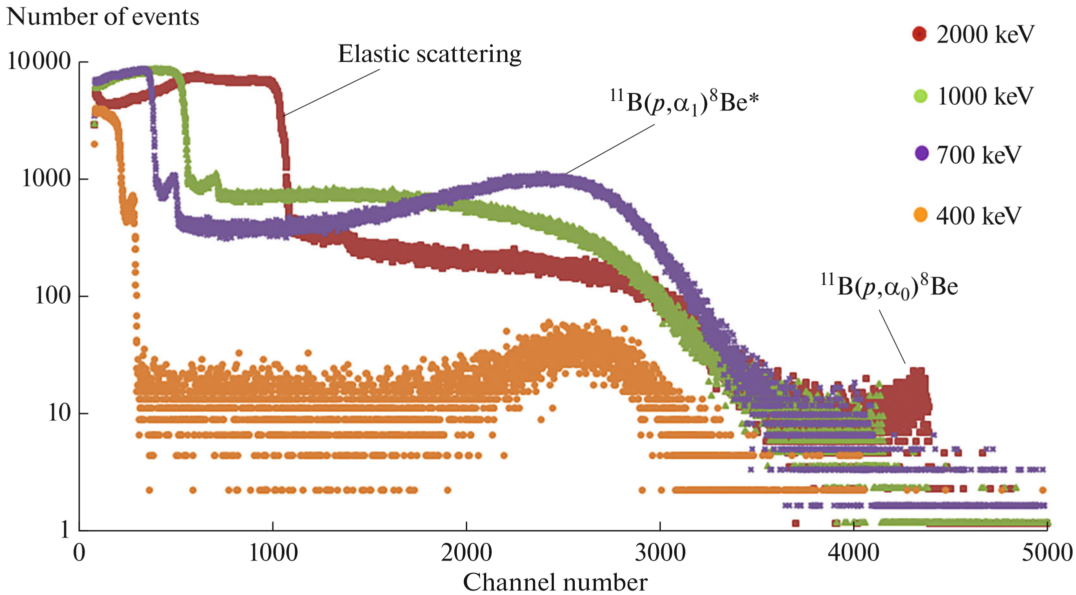

Fig. 5. Spectra of α-particles and backscattered protons.

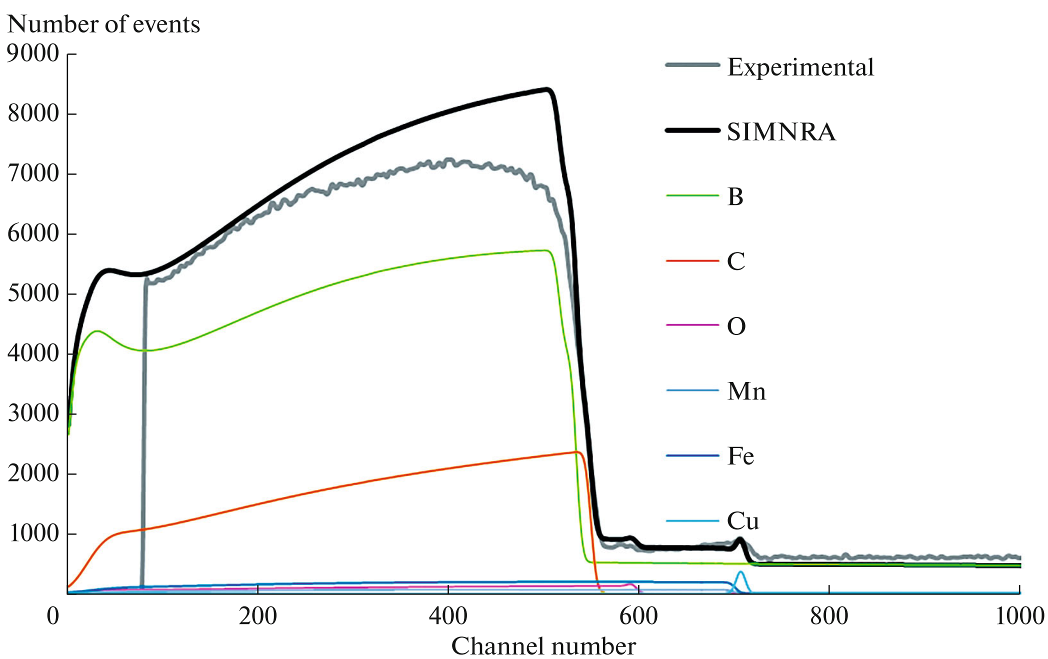

Fig. 6. Result of numerical simulation and experimental spectrum of α-particles and backscattered protons at a beam energy of 1000 keV.

tains small impurities of iron, manganese, and oxygen, which is due to the method of manufacturing. There is also a small amount of boron and copper oxide on the target surface.

3. CONCLUSIONS

A thick boron-containing target was irradiated with a 0.3–2.15 MeV proton beam at the vacuum insulated tandem accelerator (VITA) at the Budker Institute of Nuclear Physics (Novosibirsk, Russia). The spectra of α-particles and protons backscattered during the interaction of a proton beam with a thick boron target were measured. In the experimental spectra, α-particles are observed with different energies based on which we interpret them as α_1- and α_0-particles from the reactions $^{11}B(p,\alpha_1)^8Be^*$ and $^{11}B(p,\alpha_0)^8Be$, respectively. The results obtained confirm that the reaction $^{11}B(p,\alpha)\alpha\alpha$ has two channels, $^{11}B(p,\alpha_1)^8Be^*$ and $^{11}B(p,\alpha_0)^8Be$, with different cross-sections in line with modern concepts. The exact composition of the target

Table 1. Measurement parameters

Beam energy, keV	Detector dead time	Beam current, μA
300	0.0003	3.3
400	0.0013	4.5
500	0.0067	5.5
600	0.0129	6.3
700	0.0164	6.0
800	0.0192	6.3
900	0.0202	6.6
1000	0.0265	8.4
1100	0.0241	8.5
1200	0.0230	8.6
1300	0.0238	8.7
1400	0.0246	8.8
1500	0.0280	9.1
1600	0.0290	9.1
1700	0.0295	9.0
1800	0.0330	8.8
1900	0.0344	8.6
2000	0.0357	8.6
2050	0.0435	8.5
2100	0.0381	8.3
2150	0.0405	8.5

under study was determined using SIMNRA version 7.03. It is planned to study a thin boron target to measure the reaction cross-sections of each channel.

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CONFLICT OF INTEREST

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

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12. SIMNRA v. 7.03 with SigmaCalc 2.0 for single user. License No. 1801-4848-WTWA, Sept. 22, 2021.

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