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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Measurement of Cross-Section of the $p + {}^{7}$Li, d + Li, $p + {}^{11}$B, and d + B Reactions at the Ion Energies up to 2.2 MeV

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Abstract—The interaction of a proton beam with lithium is considered the best reaction for boron neutron capture therapy. The interaction of a deuteron beam with lithium is characterized by a high yield of neutrons, high energy of neutrons, and a large variety of reactions. The interaction of a proton with boron-11 is considered a promising reaction for aneutronic fusion. The reliable data for the reactions cross-sections are important for many applications, including radiation astrophysics, aneutronic fusion, hadron therapy, boron neutron capture therapy, testing of advanced materials and equipment. The experimental data on the cross-sections differ greatly from one author to another; for a number of reactions there are no data on the cross-section in the databases. Measurements of the reactions cross-sections were carried out at the accelerator-based neutron source VITA at Budker Institute of Nuclear Physics (Novosibirsk, Russia), using a HPGe γ-spectrometers, an α-spectrometers, and a diamond neutron spectrometers. The ^{7}Li(p, $p'\gamma$)^{7}Li, ^{7}Li(p, α)^{4}He, ^{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, $n\alpha$)^{4}He, ^{7}Li(d, n)^{8}Be, ^{11}B(p, α_0)^{8}Be, ^{11}B(p, α_1)^{8}Be*, ^{10}B(d, α)^{8}Be, ^{10}B(d, p)^{11}B, ^{11}B(d, α)^{9}Be, and ^{11}B(d, p)^{12}B reactions cross-sections at the ion energies up to 2.2 MeV have been measured. Measurements of the differential cross sections of the reactions were carried out for two angles which made it possible to determine the angular distribution of emission of the reaction products and calculate the total reactions cross sections. The results obtained are distinguished by their reliability.

Keywords: nuclear reaction, cross-section

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INTRODUCTION

The interaction of protons and deuterons with light nuclei is characterized by a wide variety of nuclear reactions. The reliable data for these reactions cross-sections are important for many applications, including radiation testing of advanced materials and equipment, aneutronic fusion, astrophysics, and hadron therapy. The experimental data on the cross-sections differ greatly from one author to another; for a number of reactions there are no data on the cross-section in the databases. Measurements of the reactions cross-sections were carried out at the accelerator-based neutron source VITA at Budker Institute of Nuclear Physics (Novosibirsk, Russia), using a HPGe γ-spectrometer, an α-spectrometers, and a diamond neutron spectrometer.

The article briefly introduces the facility, substantiates the importance of measuring the parameters of nuclear reactions, and presents the research results.

EXPERIMENTAL FACILITY

The study was carried out at the accelerator based neutron source VITA [1–3], which includes the vacuum insulated tandem accelerator for producing a stationary beam of protons or deuterons and the target for generating γ-rays, α-particles, and neutrons. The vacuum insulated tandem accelerator *1* generates proton or deuteron beams and directs beams to the lithium or boron target *4* through the collimator *3*. The HPGe γ-spectrometer, the α-spectrometer, and the diamond neutron spectrometer measured the energy spectra of emitted in the nuclear reactions particles.

PROTON INTERACTION WITH LITHIUM

The ^{7}Li(p, n)^{7}Be reaction provides neutrons for boron neutron capture therapy (BNCT) [4]. The calculated neutron yield data from the article [5] is used

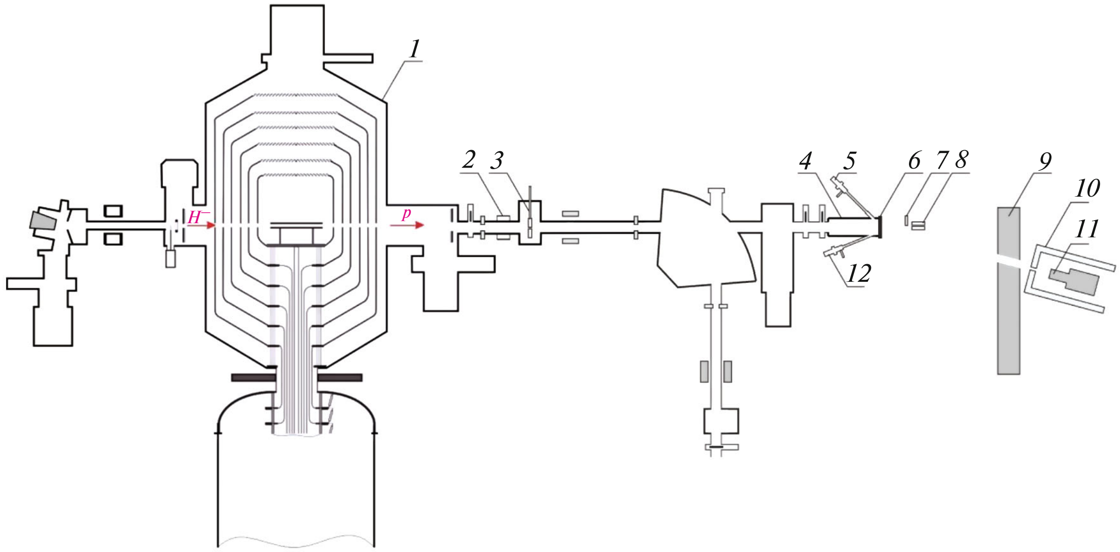

Fig. 1. Scheme of the experimental facility: (*1*) vacuum insulated tandem accelerator, (*2*) non-destructive DC current transformer, (*3*) collimator, (*4*) target assembly, (*5*) α-spectrometer at 135°, (*6*) lithium or boron target, (*7*) temporarily placed lead sheet, (*8*) spectrometric radiometers of fast neutrons with a diamond detector, (*9*) temporary concrete wall, (*10*) lead collimator, (*11*) γ-ray spectrometer, (*12*) α-spectrometer at 168°.

in treatment planning system since previously there was no reliable experimental data of the neutron yield from a lithium target in the ^{7}Li(p, n)^{7}Be reaction. The neutron yield was measured by its activation with the radioactive isotope beryllium-7 using the γ-spectrometer based on a semiconductor detector made of high purity germanium (HPGe γ-spectrometer). The agreement of the measured yield and the calculated one is shown; this is important for the treatment planning [6].

The interaction of a proton with lithium leads to the generation of 478 keV photons due to the inelastic scattering on lithium atomic nuclei ^{7}Li(p, p'γ)^{7}Li. These photons provide an unwanted non-selective γ-ray dose in BNCT. The experimental data on the photon yield in the ^{7}Li(p, p'γ)^{7}Li reaction are scarce and contradictory; therefore, the calculated data given in the article [7] are used to estimate the γ-ray dose. Measurements of the reaction cross-section and photon yield were taken using a NaI and HPGe γ-ray spectrometers. The measured photon yield turned out to be 1.7 times less than the calculated one [7]. The results of the study are presented in detail in [8].

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 in situ method for measuring the thickness of a lithium layer. The essence of the method is to irradiate a target with protons and measure the counting rate of 478 keV photons using a γ-spectrometer. We used two lithium targets for measurements: a test target and a thick one. The thick one is a target in which protons are stopped in lithium to an energy below 478 keV, which is the threshold energy of the ^{7}Li(p, p'γ)^{7}Li reaction. A target in which protons are stopped in lithium to an energy above 478 keV is called the thin one. If the target under study is not thick, then the yield of 478 keV photons from it will be less than from the thick one. By measuring the ratio of the count rate of 478 keV photons from the test target and the thick target and knowing the rate of proton energy loss in lithium, we can determine the thickness of the lithium layer. This method of measuring the thickness of the lithium layer is described in detail in [9].

The interaction of a proton with a lithium nucleus also leads to the generation of α-particles in the ^{7}Li(p, α)^{4}He reaction, characterized by a high energy yield of 17.347 MeV. This reaction is one of the thermonuclear reactions involved in the stellar fusion cycle of heavy elements in the Universe and can be used to in situ control the thickness of the lithium layer in the target. The curious thing about the situation is that the reaction cross-section recommended by the JENDL database is 2 times larger than the cross section recommended by the ENDF/B and the TENDL databases. Our measured data are in better agreement with the JENDL data. The results of the study are presented in detail in [10]. The reliability of our data is confirmed by the fact that the thickness of the lithium target was measured by six independent methods.

DEUTERON INTERACTION WITH LITHIUM

The interaction of deuterons with energies less than 2.2 MeV with natural lithium nuclei leads to 10 nuclear reactions, five of which generate neutrons. These reactions provide the highest neutron yield per unit current of a charged particle beam, starting at the energy of 0.7 MeV. At the same time data on the cross sections of the reactions are scarce and often absent. We measured the ^{6}Li(d, α)^{4}He, ^{6}Li(d, p)^{7}Li, ^{6}Li(d, p)^{7}Li*, ^{7}Li(d, α)^{5}He, and ^{7}Li(d, $n\alpha$)^{4}He reactions cross-sections using the α-spectrometer [11], and ^{7}Li(d, n)^{8}Be and ^{7}Li(d, n)^{8}Be* reactions cross-sections using a neutron spectrometer [12]. The obtained data on the reactions cross sections make it possible to estimate the energy spectrum of the generated neutrons.

PROTON INTERACTION WITH BORON

Proton boron fusion reaction draws attention since the dawn of nuclear physics for its relevance and potential application in different fields. This reaction has been studied since the 1930s but data from different authors differ. The energy spectrum of α-particles we measured allows us to assert that the direct process of formation of three α-particles is unlikely, and the reaction proceeds through the sequential decay: first, ^{12}C* breaks up into an α-particle and a ^{8}Be nucleus in the ground or the excited state; second, the ^{8}Be nucleus decays into two α-particles. The results of the study are presented in detail in [13].

DEUTERON INTERACTION WITH BORON

Irradiation of a boron target, used in studying the interaction of a proton with a boron atomic nucleus, with a deuteron beam allowed us to measure the cross sections of the ^{10}B(d, α)^{8}Be, ^{10}B(d, α)^{8}Be*, ^{11}B(d, α)^{9}Be, ^{11}B(d, α)^{9}Be*, ^{10}B(d, p_2)^{11}B, and ^{11}B(d, p_3)^{11}B reactions [14].

CONCLUSIONS

The accelerator based neutron source VITA was used to study the nuclear reactions of protons and deuterons in the energy range up to 2.2 MeV. The neutron yield of the ^{7}Li(p, n)^{7}Be reaction, the photon yield of the ^{7}Li(p, $p'\gamma$)^{7}Li reaction, the cross-sections of the ^{7}Li(p, $p'\gamma$)^{7}Li, ^{7}Li(p, α)^{4}He, ^{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, $n\alpha$)^{4}He, ^{7}Li(d, n)^{8}Be, ^{7}Li(d, n)^{8}Be*, ^{11}B(p, α_0)^{8}Be, ^{11}B(p, α_1)^{8}Be*, ^{10}B(d, α)^{8}Be, ^{10}B(d, α)^{8}Be*, ^{11}B(d, α)^{9}Be, ^{11}B(d, α)^{9}Be*, ^{10}B(d, p_2)^{11}B, and ^{11}B(d, p_3)^{11}B reactions were measured. The obtained data are important for boron neutron capture therapy, aneutronic fusion, intense fast neutron fluxes, astrophysics, hadron therapy, and other applications.

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CONFLICT OF INTEREST

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

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