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PHYSICS AND TECHNIQUE OF ACCELERATORS

Development of a System for Forming a Beam of Cold Neutrons for the VITA Accelerating Neutron Source

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Abstract—Cold neutrons (with energy 10^{-7}–10^{-4} eV) have found broad application in many areas of modern physics. A new and prospective field of application of low-energy neutrons is the boron neutron capture therapy of oncological illness. This method is based on neutron capture by boron-10, previously accumulated in a tumor, and reaction ^{10}B(n,α)^{7}Li with following escape of energetic α particle and lithium atomic nucleus. The delivery of cold neutrons directly to the area of a malignant tumor can make it possible to increase the localization of the therapeutic dose in the tumor, exclude any impact on healthy cells, and increase the effectiveness of boron neutron capture therapy (BNCT), both in the case of deep-lying malignant tumors and those on the surface. The research described in the article is devoted to the generation of cold neutrons on the VITA accelerator-based epithermal neutron source. This paper describes the cold neutron beam shaping assembly (BSA) that has been designed. The simulation of neutron passage through the BSA performed using Geant4 software is described. The possibility of generating cold neutrons on the VITA accelerator-based epithermal neutron source was demonstrated.

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1. INTRODUCTION

Boron neutron capture therapy (BNCT) is a promising technique for the treatment of malignant tumors [1]. To develop the BNCT method, it is proposed to use cold neutrons (with an energy of 10^{-7}–10^{-4} eV). Cold neutrons have pronounced wave properties, which will make it possible to transport them through flexible neutron guides directly to the area of a malignant tumor [2]. The use of cold neutrons in BNCT is expected to improve the localization of therapeutic dose during neutron irradiation, expand the scope of BNCT applications, and improve the effectiveness of therapy.

To produce cold neutrons, large research nuclear reactors are usually used [3, 4]. To introduce BNCT into clinical practice as a neutron source, it is necessary to use more compact installations—accelerator neutron sources [5]. The generation of cold neutrons at an accelerator neutron source is an urgent problem and is discussed in this article.

In order to reduce the energy of neutrons, moderators are used, i.e., a medium through which neutrons lose their energy [6, 7]. This article describes the proposed system for forming a beam of cold neutrons (beam shaping assembly (BSA)) using heavy water as a moderator for the accelerator source of epithermal neutrons (VITA). The results of studies of the moderating properties of plexiglass, water, and heavy water are presented and discussed, and the results of modeling the passage of neutrons through the BSA in the Geant4 environment are presented, demonstrating the possibility of generating cold neutrons at the VITA neutron source.

2. EXPERIMENTAL SETUP AND EXPERIMENTAL DESIGN

The VITA accelerator source, used in the experiment to generate the initial neutron beam, is optimized for the generation of neutrons in the epithermal energy range [8]. The experimental design is shown in Fig. 1a.

A beam of negative hydrogen ions injected from ion source *1* focuses on accelerator input *2*. Next, the negative ion beam is accelerated to 1 MeV, after which, in the gas stripping target *3* installed inside the high-voltage electrode of the accelerator, negative ions with a probability of 90–95% lose 2 electrons, become protons, and then accelerate to 2 MeV. The proton beam is then directed to lithium target *5*. Lithium was chosen as the target material because the reaction ^{7}Li(p, n)^{7}Be, which has the maximum yield and minimum neutron energy, is best suited for the formation

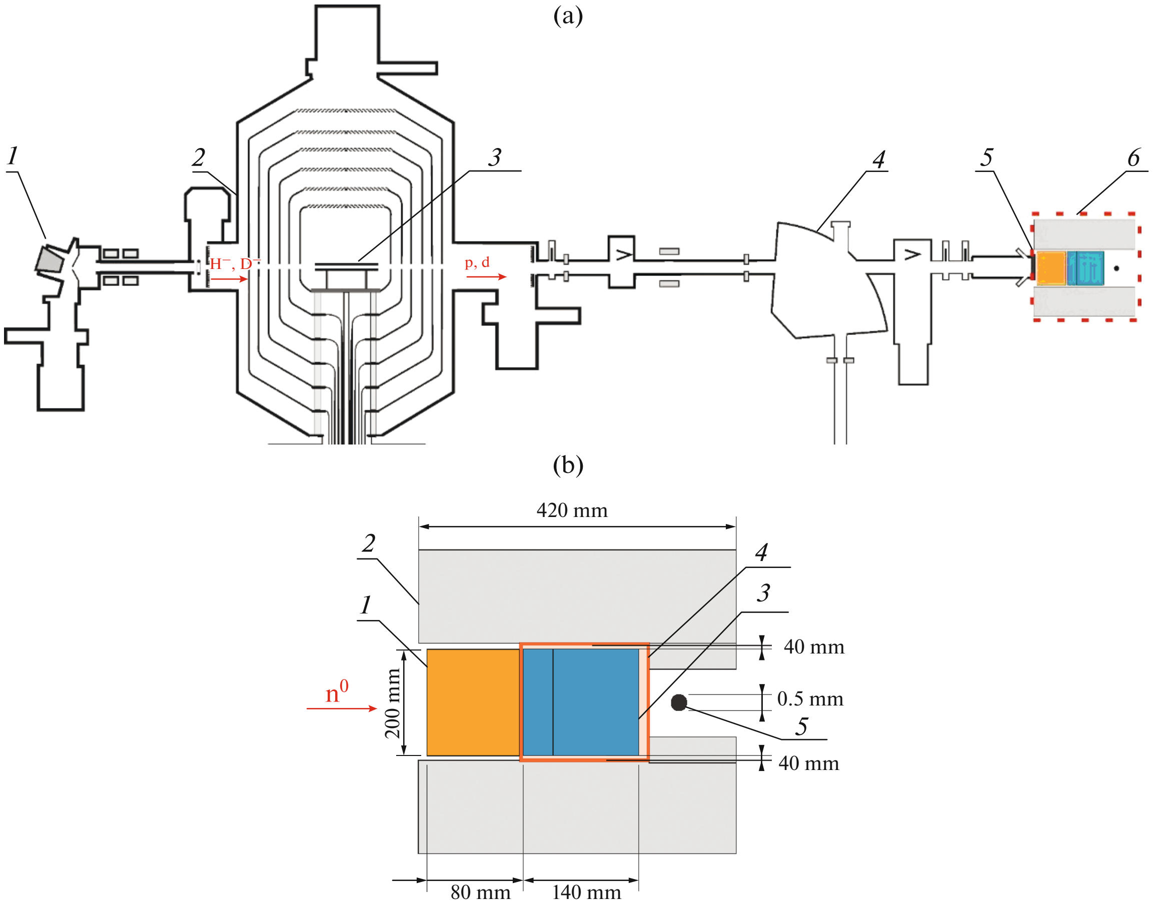

Fig. 1. (a) Experiment scheme: (*1*) source of negative hydrogen ions, (*2*) tandem accelerator with vacuum insulation, (*3*) peeling target, (*4*) rotary magnet, (*5*) lithium target, and (*6*) system for forming a beam of cold neutrons. (b) Diagram of the cold neutron beam formation system: (*1*) source of neutrons, (*2*) plexiglass, (*3*) heavy water, (*4*) aluminum vessel, and (*5*) neutron detector.

of a neutron beam in the epithermal energy range [9]. Neutrons are directed to a cold neutron beam formation system *6*. A diagram of the cold neutron beam formation system is shown in Fig. 1b. After passing through the BSA, the moderated neutrons were detected by a boron-enriched polystyrene scintillation neutron counter (IHEP, Protvino) [10]. The registration of neutrons occurs due to the reaction $^{10}\mathrm{B}(n, \alpha)^7\mathrm{Li}$ in a plastic scintillator. The a particles born in the reaction cause scintillation pulses that are amplified by the photomultiplier tube. The generation of neutrons in the presented study occurred at a proton beam energy of 2.05 MeV.

The accelerator neutron source also allows the generation of neutrons in a nonthreshold reaction $^7\mathrm{Li(d,n)}^8\mathrm{Be}$ [11]. In this mode of operation of the source, neutrons of a wide range of energies are generated, including fast neutrons. The neutron generation scheme in this mode is similar to the main mode of neutron generation during bombardment with a proton beam, the only difference is that negative deuterium ions from the source *1* pass the peeling target *3* and, at the exit from the tandem accelerator, obtainted deutrons are also directed to the lithium target *5*.

An important task for the generation of cold neutrons at the VITA accelerator neutron source is to choose of the nuclear reaction of the initial neutron beam. To do this, we simulated the passage of neutrons through the BSA in the Geant4 environment for cases of neutron generation in nuclear reactions: $^7\mathrm{Li(p,n)}^7\mathrm{Be}$ and $^7\mathrm{Li(d,n)}^8\mathrm{Be}$. The simulation diagram is shown in Fig. 2. The geometry for the simulation was described as follows: from the source, neutrons were directed, in accordance with a given angular distribution, to a system for generating a cold neutron beam. The moderation system consisted of plexiglass, heavy water, lead plates, and concrete. After passing through the moderation system, the neutrons entered a sensitive area, in which information about their energy was collected and histograms were accumulated. The physics of processes occurring during the passage of neutrons through BSA was described by the G4NeutronHP package [12, 13]. The neutron source in the simulation corresponded to the real spectrum of neutrons generated at the VITA accelerator neutron

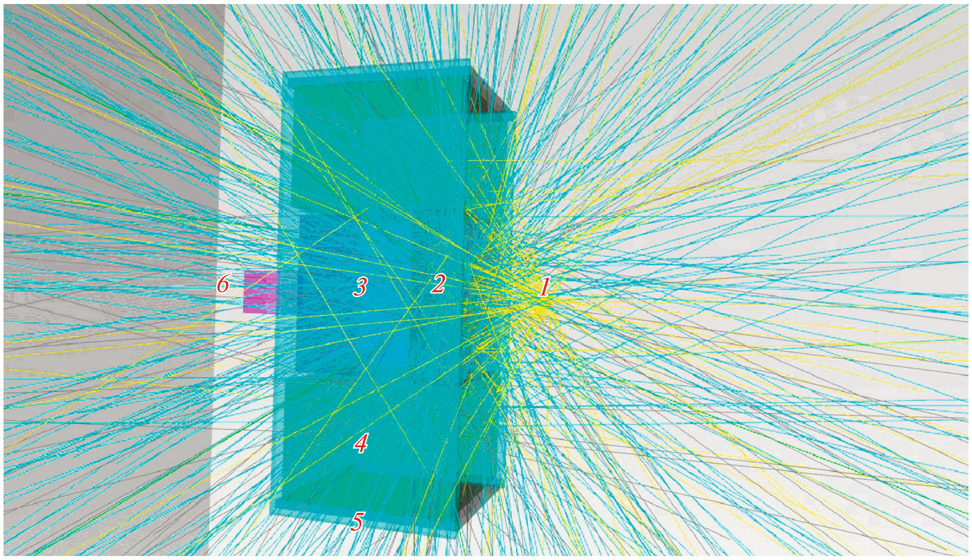

Fig. 2. Geometry of modeling the passage of neutrons through the cold neutron beam formation system: (*1*) source of neutrons, (*2*) plexiglass, (*3*) heavy water, (*4*) concrete, (*5*) lead plates, and (*6*) sensitive area.

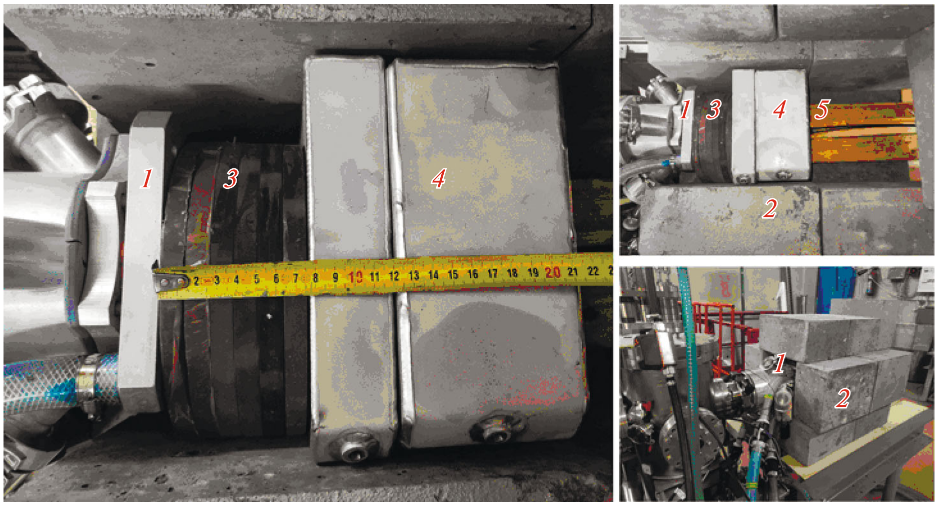

Fig. 3. Photos of the experiment: (*1*) lithium target, (*2*) concrete blocks enriched with boron, (*3*) plexiglass plates, (*4*) water/heavy water moderator, and (*5*) neutron detector.

source. The spectrum of neutrons generated in the reaction ^{7}Li(p, n)^{7}Be was obtained in advance by modeling in the Geant4 environment [14]. The spectrum of neutrons produced in the reaction ^{7}Li(d, n)^{8}Be was obtained experimentally using the UNSD-15 spectrometer earlier.

Photographs of the experiment are shown in Fig. 3. Plexiglas plates were used as moderators $(C_5O_2H_8)_n$ (density 1.18 g/cm^3, diameter 10 mm, and thickness 12 mm) and vessels with volumes of 2079 and 4620 cm^3 (2.079 L and 4.620 L), filled with ordinary or heavy water at room or cryogenic (73 K) temperature [15–17]. The system elements were located as follows: immediately after the lithium target *1* placed plexiglass plates *3,* followed by vessels with water/heavy water *4.* In each test, the neutron moderation thickness was changed by removing plexiglass plates or water vessels. Along the perimeter of the moderating part, concrete blocks were used as reflectors and radiation protection elements *2.* The measurements were carried out for 90 s, and repeated twice. The results show average detector readings. Thus, in a series of experiments, the dependences of the number of neutrons moderated after thermalization on the length of the moderator were obtained.

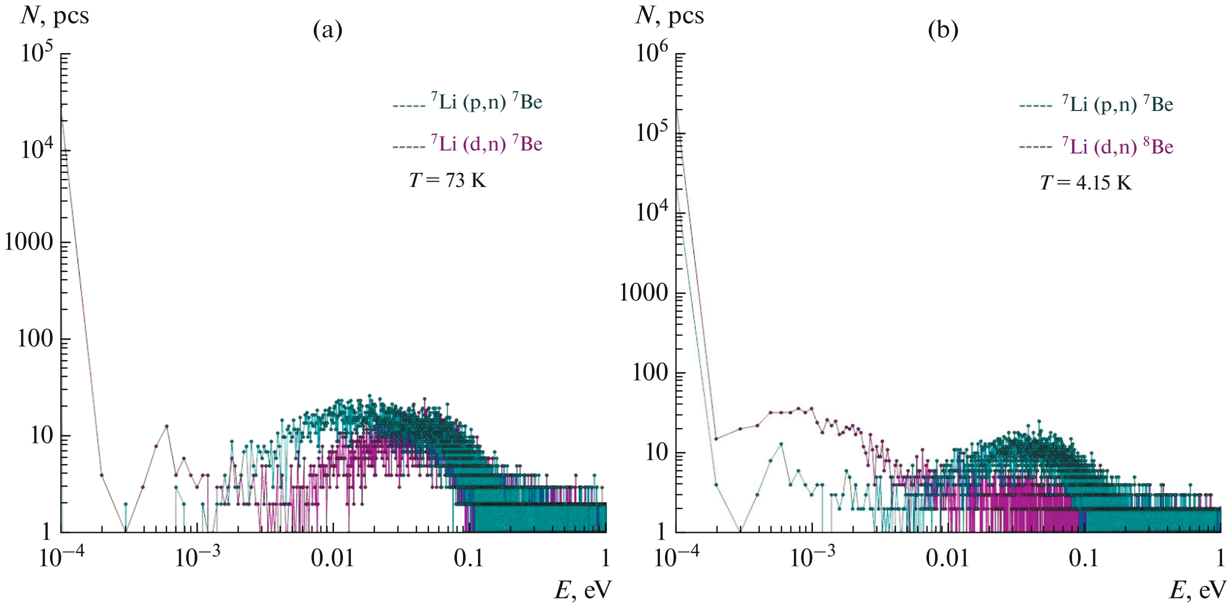

Fig. 4 Neutron spectrum obtained by modeling 10^8 particles with the following parameters: (a) heavy water moderator 150 mm at a temperature of 73 K; (b) moderator made of heavy water 150 mm at a temperature of 4.15 K.

3. RESULTS AND DISCUSSION

Simulating the passage of neutrons through a cold neutron BSA resulted in the slow neutron spectrum shown in Fig. 4. With a total number of neutrons of 10^8, most of them are at level 10^5, with energy from 0 to 0.001 eV. The simulation showed the effectiveness of the materials chosen for the system and the possibility of producing cold neutrons with its help.

Before the experiments began, it was expected that, when receiving cold neutrons, the detector would detect a larger number of neutrons than when working with thermal or fast neutrons. This is due to the fact that the neutron capture cross section of boron increases with decreasing neutron energy. During the research, the hypothesis was confirmed; indeed, with the optimal volume of the moderator, an increase in the number of neutrons registered by the boron detector was recorded. This is how the primary optimization of the geometric parameters of the BSA cold neutron moderating elements was carried out.

Figure 5 shows the dependence of the neutrons recorded by the detector on the moderation length on plexiglass obtained during the experiment. Up to the 36-mm mark, the number of detected neutrons increases, which indicates a more efficient capture of neutrons by boron and, therefore, their thermalization.

In the course of research, it was found that, for the premoderating part of the BSA of cold neutrons, 36 mm of plexiglass or 45 mm of water at room temperature can be effectively used. The dependence shown in Fig. 6 reflects the process of moderating neutrons thermalized on plexiglass: the first point corresponds to the number of detected neutrons that passed from the lithium target without a moderator. The second point reflects the number of neutrons passing through 72 mm of plexiglass. The following points show the moderation of thermalized neutrons using a water or heavy water moderator at room temperature.

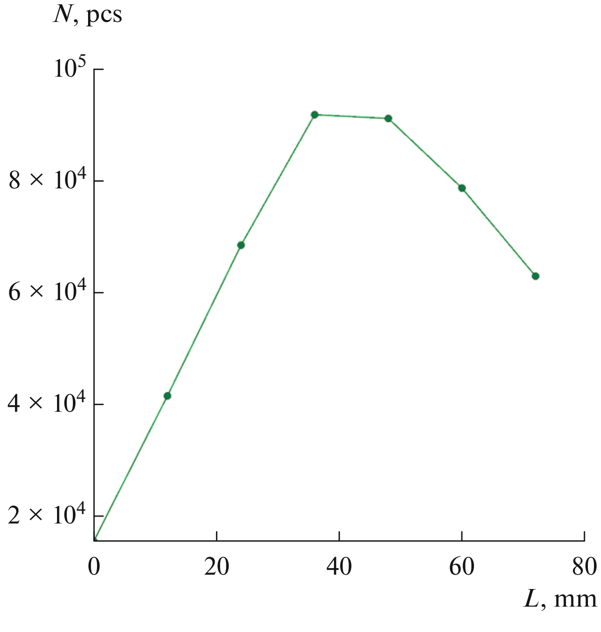

Fig. 5. Dependence of neutrons on the moderation length on plexiglass at room temperature.

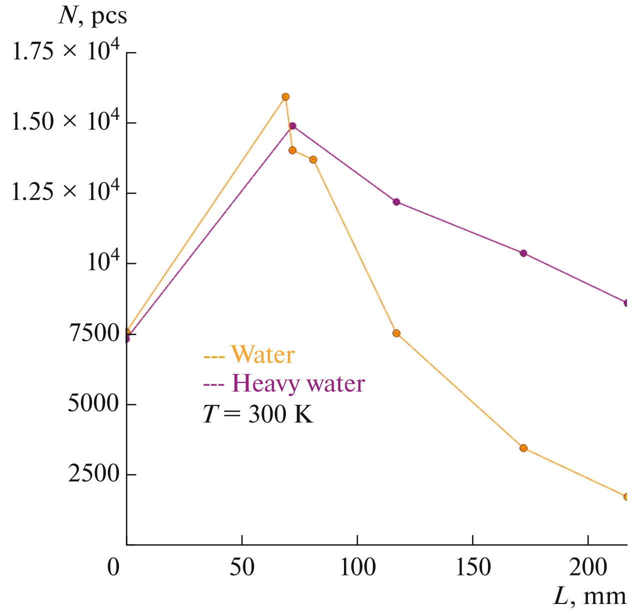

Fig. 6. Dependence of detected neutrons on the moderation length on water and heavy water at room temperature.

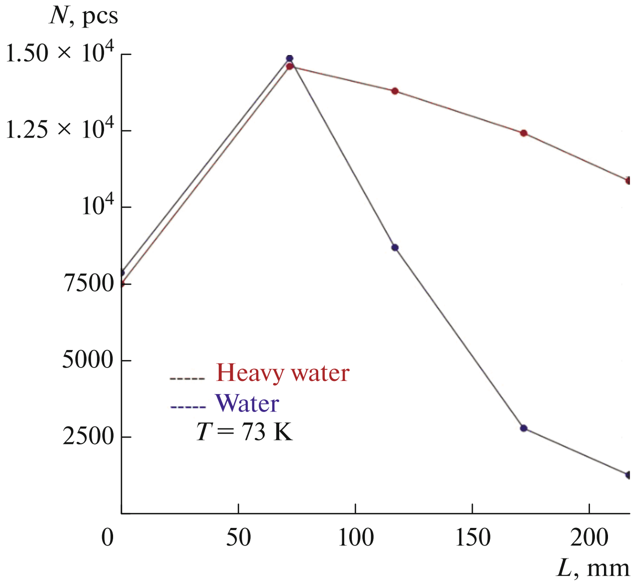

Fig. 7. Dependence of detected neutrons on the moderation length on water and heavy water at cryogenic temperatures.

It has been shown that, as a cold moderator for BSA cold neutrons, the optimal moderator is heavy water at cryogenic temperature in a tank longer than 145 mm. Figure 7 shows a similar relationship to that shown in Fig. 6, but at cryogenic temperature. As a result of the moderation of thermalized neutrons by 145 mm of warm moderator, 89% of the neutrons from the initial moderator flux were lost in water and 48% in heavy water. In the case of a cold moderator, 84% of the water moderator and 26% of the heavy water moderator. A smooth decrease in the number of registered neutrons with increasing length of the heavy water moderator indicates that heavy water almost does not absorb neutrons.

In further research, it is planned to continue optimizing the parameters of cold neutron BSA elements and conduct experiments on obtaining cold neutrons during the generation of the initial neutron beam in a ^{7}Li(d,n)^{8}Be nuclear reaction.

CONCLUSIONS

This article describes a system for generating a cold neutron beam for the VITA accelerator neutron source with vacuum insulation. The main elements of the system are considered: a premoderator for thermalization of neutrons, a cold moderator, reflectors, and elements that limit the passage of gamma rays from the system. The results of simulation in the Geant4 development environment on neutron moderation in the BSA are discussed. According to the simulation results, the possibility of producing cold neutrons at the VITA accelerator neutron source with the BSA is shown. Experiments aimed at producing cold neutrons confirmed the hypothesis that heavy water at a temperature of 73 K is the optimal neutron moderator for further testing. The geometric parameters of the cold neutron BSA moderating elements have been experimentally established: 36 mm of plexiglass or 45 mm of water at room temperature for the premoderator part and more than 145 mm of heavy water at cryogenic temperature for the cold moderator.

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CONFLICT OF INTEREST

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

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