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Study of the influence of moderator material on sensitivity of the epithermal neutron flux detector using the ^{71}Ga(n,γ)^{72}Ga reaction

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ABSTRACT

An intense epithermal neutron flux is necessary for boron neutron capture therapy (BNCT), a promising technique for the treatment of malignant tumors. The epithermal neutron flux is an essential characteristic of the BNCT neutron beam, and its measurement is directly related to the reliability of the treatment planning system. Such a tool could be a cylindrical activation detector using ^{71}Ga (n,γ)^{72}Ga reaction. In the detector, the activation material is positioned in the geometrical center of a cylinder moderator covered with cadmium foil. Two different teams of researchers calculated the sensitivities of detectors of the same size, but with different moderators which differ by a factor of 1.6. In this work, the effect of the moderator material on the sensitivity of the detector was experimentally studied.

1. Introduction

Boron neutron capture therapy (BNCT) is currently considered as a promising technique for treatment of malignant tumors (Ahmed et al., 2023; Dymova et al., 2020). As a result of the neutron absorption by boron, a nuclear reaction ^{10}B (n,α)^{7}Li takes place with a large energy release inside the cell which contains a boron nucleus that leads to the destruction of this cell. An intense epithermal neutron flux is necessary to treat deep-seated tumors.

The book by the International Atomic Energy Agency [1, p. 27] formulates the basic parameters required for a neutron beam used for the treatment of deep-seated tumors using boron-phenylalanine as a boron delivery drug. They are as follows: epithermal flux $\geq 5 \times 10^8$ cm^{-2} s^{-1}, thermal to epithermal flux ratio ≤0.05, fast neutron dose per unit epithermal fluence $\leq 7 \times 10^{-13}$ Gy cm^2, gamma dose per unit epithermal fluence $\leq 2 \times 10^{-13}$ Gy cm^2. It is also noted in this book [1, p. 31] that "*It is difficult to measure the neutron spectrum directly at all energies. The neutron energy spectrum is, therefore, evaluated by a combination of Monte Carlo simulations and measured values.*"

The results of a comparison of neutron beams used or planned for use in BNCT are presented in a recent article (Green et al., 2025). In conclusion it is written "*Through the optimisation process to design a suitable neutron BSA, accelerators producing very different initial neutron source spectra ultimately produce thermal neutron fluences in phantom which have a high degree of similarity*." This means that if the neutron beam meets the requirements of BNCT, then its energy spectrum is unimportant – the epithermal neutron flux is important. This circumstance significantly simplifies the verification of the neutron beam.

Activation detectors can be used to measure epithermal neutron flux. The article (Guan et al., 2017) showed that the using ^{71}Ga (n,γ)^{72}Ga reaction provide a more uniform sensitivity of the monitor in the range of epithermal energies of neutrons than other thoughtful reactions, i.e., ^{197}Au (n,γ)^{198}Au, ^{151}Eu (n,γ)^{152m}Eu, ^{127}I (n,γ)^{128}I, ^{115}In(n,γ)^{116m}In, ^{55}Mn (n,γ)^{56}Mn, ^{37}Cl (n,γ)^{38}Cl and ^{23}Na (n,γ)^{24}Na. Cylindrical activation detectors using ^{71}Ga (n,γ)^{72}Ga reaction have been developed to measure the epithermal neutron flux (Guan et al., 2019; Byambatseren et al., 2023). In the detector, the activation material is positioned in the geometrical center of a cylinder moderator covered with cadmium foil. Numerical neutron transport simulation shows that the use of high-density polyethylene (HDPE) or polymethyl methacrylate (PMMA) as a moderator makes it possible to achieve a flat sensitivity curve in the epithermal neutron energy range, while its sensitivities to thermal and

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fast neutrons are low. The sensitivity of detectors of the same size given in articles (Guan et al., 2019; Byambatseren et al., 2023) differs by 1.6 times. The reason for the discrepancy may be the use of different moderators and the use of reaction cross sections taken from different databases.

Previously we used the detector with PMMA moderator; it is described in the article (Byambatseren et al., 2023). We are currently using the detector with HDPE moderator. The aim of this work is to experimentally determine to what extent the use of different moderators (HPDE or PMMA) affects the sensitivity of the detector.

2. Design of the detector

The isometric view of the detector is shown in Fig. 1. The dimensions of the detector are 63.2 mm in height and 65.2 mm in diameter. In the detector, the activation material (gallium foil with a diameter of approximately 10 mm and a weight of approximately 50 mg) is positioned in the geometrical center of the neutron moderator in the form of a cylinder 63 mm in height and 65 mm in diameter. Previously we made a moderator from PMMA (Byambatseren et al., 2023), now from HDPE. The side surfaces and bases of the cylinder are covered with 0.1 mm thick Cd foil as thermal neutron absorber. The detector is made demountable in order to remove activated gallium foil and measure its activation. Gallium is placed in a recess of a disk 20 mm in diameter and 7 mm thick, which is wound onto a part of the moderator made in the form of a truncated cone. A cone with a wound disk is screwed into the main body of the detector so that the activation material is positioned in the geometrical center of the cylinder. The bases and side surface of the resulting cylinder are covered with 0.1 mm thick cadmium foil.

Detector sensitivity for a range of neutron energies is simulated by the Monte Carlo method using the NMC code (Yurov et al., 2012) and ENDF-VII library of evaluated incident-neutron data. The neutron flux determined by the detector is a cell flux. The neutron source ($5\ 10^7$ neutrons) is set in a circle with a diameter of 6.52 cm, located at a distance of 10 cm from the PMMA cylinder.

Detector sensitivities for a range of neutron energies are shown in Fig. 2. We used the ENDF-VII library of evaluated incident-neutron data to calculate the sensitivity of the detector with PMMA moderator. Chinese and Japanese colleagues in the article (Guan et al., 2019) used JENDL-4.0 library (Java-based nuclear information software JANIS) to calculate the sensitivity of the detector with HDPE moderator. The neutron source is set in a circle with a diameter of 6.52 cm, located at a distance of 10 cm from the detector. The mass of gallium is taken equal to 51.2 mg, the content of ^{69}Ga isotone is taken equal to 60.2 %, ^{71}Ga – 39.8 %. The detector temperature is set to 20 °C.

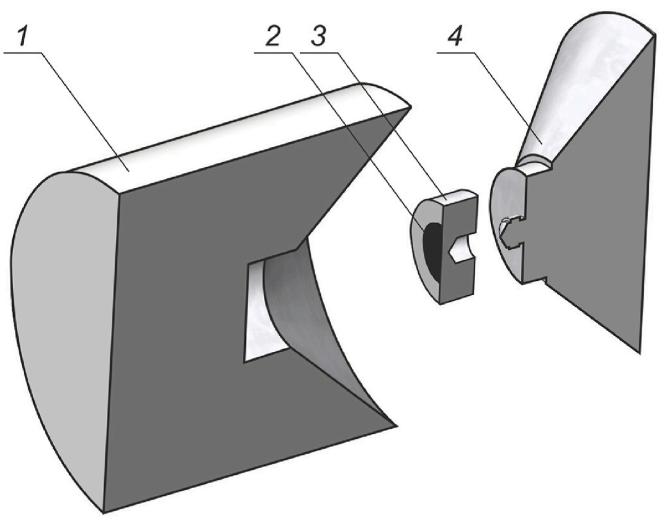

Fig. 1. Schematic view of the epithermal neutron flux detector: *1* – main part of the cylindrical moderator, *2* – gallium foil, *3* – foil placement disk, *4* – screw-in part of the cylindrical moderator.

The first thing you immediately pay attention to is the significant difference between these two results. The calculated sensitivity of PMMA detector averaged over the energy range from 1 eV to 10 keV is $\eta = (7.7 \pm 0.9)\ 10^{-4}$ count/(n/cm^2), which is 1.6 times less than the similar value of the HDPE detector.

The concentration of hydrogen atomic nuclei in PMMA is lower than in HDPE and neutron moderation occurs over a longer distance. As a result, the detection efficiency of the PMMA detector is lower according to comparative calculations. Let us determine experimentally to what extent the sensitivity of the detectors depends on the moderator material.

3. Experimental results

Experimental verification of the detector was carried out at accelerator based neutron source VITA at Budker Institute of Nuclear Physics, Novosibirsk, Russia (Taskaev et al., 2021) (Fig. 3). The detector (*6* in Fig. 3) is placed along the proton beam axis at a distance of 100 mm from the lithium layer of the neutron generating target (*4*). The detector is placed on a wooden platform held by a robotic arm.

To form a beam of neutrons with different energy spectra, we use a moderator (*5*) (not to be confused with the detector moderator). We place this moderator close to the target. This moderator is a PMMA disks 200 mm in diameter and 12, 24, 36, 48, 60 or 72 mm thick. We may also not place this moderator.

The target is irradiated with a 2 MeV proton beam with a fluence of 1.2 C. After that, it is disassembled, the HPGe spectrometer (SEG-1KP-IPTP 12, IPTP, Dubna, Russia) measures the activation of the gallium foil (in the 834 keV line), corrects for the mass of gallium, and restores the epithermal neutron flux. In the measurements carried out gallium foils with a mass from 90 mg to 102 mg were used, on average 95 ± 3 mg.

At proton energies of 2 MeV, neutrons are emitted in all directions, maintaining a forward direction due to kinematic collimation. The total neutron yield is $1.1\ 10^{11}$ n/mC, maximum neutron energy is 230 keV, mean neutron energy is 108 keV, mean neutron angle is 51° according to the calculated values presented in the article (Lee and Zhou, 1999). The article (Bikchurina et al., 2021) presents the results of experimental measurements of neutron yield, which are consistent with the calculated ones.

Although the stability of the proton energy and the accuracy of its measurement are high (0.1 % and 0.2 %), however, the uncertainty of the neutron yield is much higher – about 5 %, due to the closeness of the energy of 2 MeV to the threshold of the ^{7}Li (p,n)^{7}Be reaction (Lee and Zhou, 1999). The absolute sensitivity of the HPGe-spectrometer for the 834 keV γ-radiation line is determined with an accuracy of 5 % (Bikchurina et al.). The statistical measurement error was 1 %. As a result, the total measurement error was 7 %.

The results of the activation measurements are presented in Fig. 4. The ratio of the sensitivity of the detector with HDPE moderator to the sensitivity of the detector with PMMA moderator *A* on the thickness of the PMMA moderator placed between the target and the detector is shown in Fig. 5.

It can be seen that this ratio *A* is equal to 1.8 in the absence of a moderator between the target and the detector, and is approximately constant at the level of 1.26 when a moderator is placed. The different sensitivity of the detectors is due to their different ability to slow down neutrons due to the different density of hydrogen atomic nuclei. To understand this behavior, it is useful to look at the energy spectrum of neutrons shown in Fig. 6. It is evident that increasing the thickness of the moderator placed between the target and the detector leads to a softening of the neutron energy spectrum.

To characterize the neutron spectrum we define the median energy E_m, i.e. the energy when the number of neutrons with energies below the

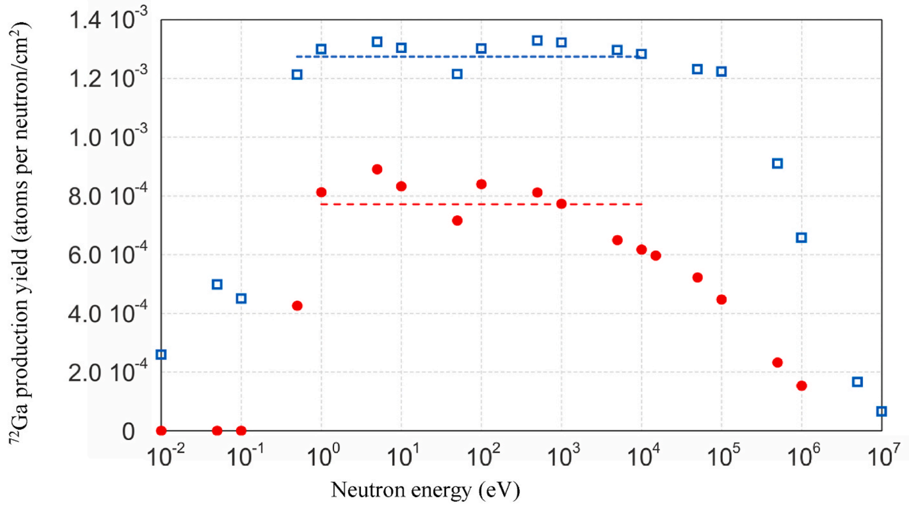

Fig. 2. Calculated sensitivities of the epithermal neutron flux detector: squares – detector with HDPE moderator (Guan et al., 2017), solid circles – detector with PMMA moderator (Guan et al., 2019). The sensitivity averaged over the neutron energy range from 1 eV to 10 keV is shown by the dashed lines.

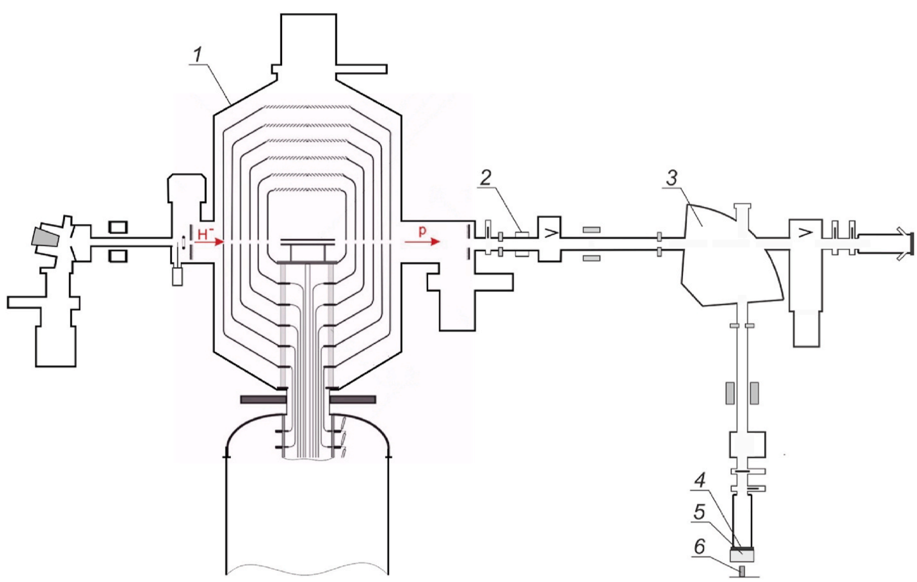

Fig. 3. A view of experimental facility: *1* – vacuum insulated tandem accelerator, *2* – non-destructive DC current transformer, *3* – bending magnet, *4* – lithium target, *5* – PMMA moderator, *6* – detector.

median value is equal to the number of neutrons with energies above the median value. The results are presented in Table 1. According to this table we can consider the neutron flux to be epithermal at a moderator thickness of 36, 48 and 60 mm. In these cases the average value of *A* is 1.24. As soon as the energy spectrum of neutrons becomes epithermal or close to it, the sensitivity of the detectors is determined only by their property of moderating neutrons and the sensitivity ratio of the detectors becomes constant.

Thus, the 1.6-fold difference in the sensitivity of the activation detectors described in the articles (Guan et al., 2019; Byambatseren et al., 2023) is partially (1.24 times) explained by the use of different moderators in the detectors. The sensitivity of the detector with HDPE moderator is 1.24 times higher than the sensitivity of the detector with PMMA moderator. This is explained by the fact that in HDPE, due to the higher density of hydrogen atomic nuclei (by 42 %), than in PMMA, the thermalization of neutrons is more efficient, which leads to higher sensitivity of the detector.

The remaining part (1.3 times) is well explained by the difference in the cross-sections used from different libraries (Yurov et al., 2012). We understand that measuring the cross section of a nuclear reaction is very difficult and we ourselves have encountered the fact that different databases provide different values. The most striking example is the ^{7}Li (p, α)^{4}He reaction; the cross section of this reaction in the JENDL-4.0 database is 2 times larger than in the ENDF/B-VIII.0 and the TENDL-2019 databases and we had to measure it ourselves (Taskaev et al., 2022). Or our other measurements showed (Taskaev et al., 2024) that the cross section of the promising ^{11}B (p,α)αα neutronless fusion reaction is two times smaller than previously thought, despite the fact that there is no data on this cross section in the databases. We don't have any ideas yet on how to measure the ^{71}Ga (n,γ)^{72}Ga reaction cross-section. Nevertheless, for practical use of the detector it is necessary to determine which of the used cross-sections is reliable.

It is also worth noting that the sensitivity of a detector with HDPE moderator to fast neutrons is significantly higher than the sensitivity of a detector with PMMA moderator (see Fig. 2). Therefore, it is desirable to use a detector with PMMA moderator to measure the flux of epithermal neutrons.

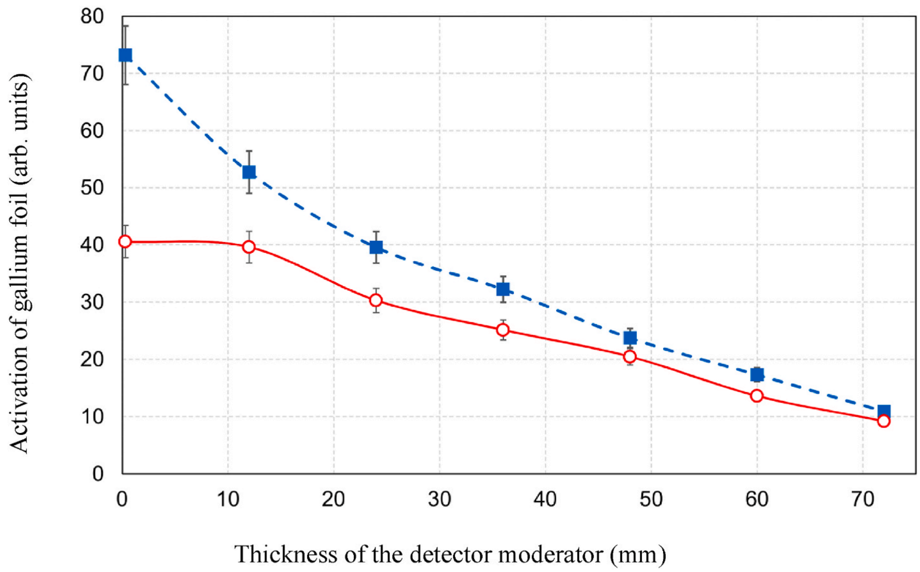

Fig. 4. Dependence of the gallium foil activation on the thickness of the PMMA moderator at a proton beam energy of 2 MeV: blue dashed line – detector with HDPE moderator, red solid line – detector with PMMA moderator placed between the target and the detector. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

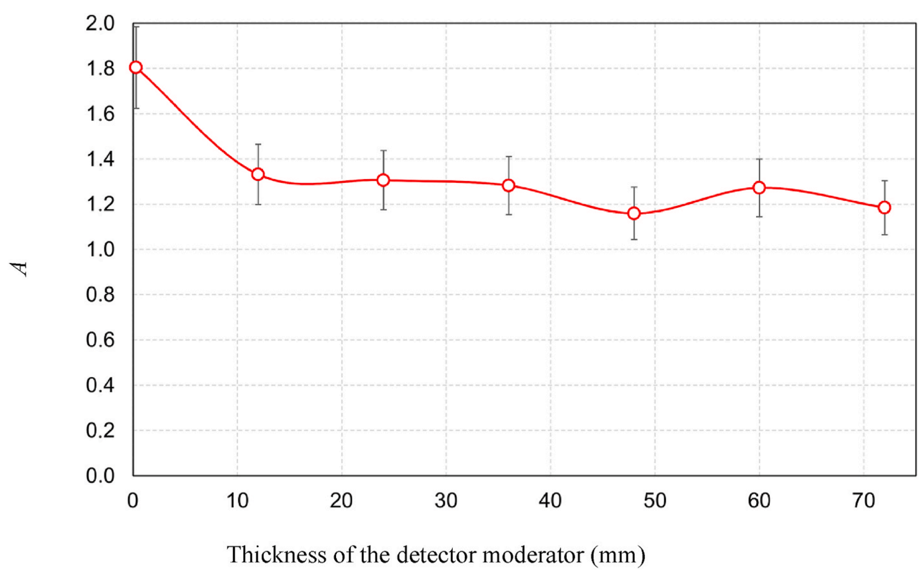

Fig. 5. Dependence of the ratio of the sensitivity of the detector with HDPE moderator to the sensitivity of the detector with PMMA moderator *A* on the thickness of the PMMA moderator placed between the target and the detector.

4. Conclusion

To measure the epithermal neutron flux which is important for planning boron neutron capture therapy, a cylindrical activation detector using ^{71}Ga (n,γ)^{72}Ga reaction can be used. Numerical neutron transport simulation shows that the detector is sensitive to epithermal neutrons and it has a flat sensitivity curve in epithermal neutron range, while its sensitivities to thermal and fast neutrons are low. Attention is drawn to the fact that the calculated efficiency of detectors of the same size but with different moderators described in articles (Guan et al., 2019) and (Byambatseren et al., 2023) differs by 1.6 times. The sensitivity of detectors with a moderator made of HDPE or PMMA was experimentally measured in this work. It was determined that the sensitivity of the detector with HDPE moderator is 1.24 times higher than the sensitivity of the detector with PMMA moderator. The remaining part (1.3 times) is well explained by the difference in the cross-sections used from different libraries. For practical use of the detector it is necessary to determine which of the used cross-sections is reliable.

CRediT authorship contribution statement

E. Byambatseren: Writing – original draft, Investigation. **T. Bykov:** Visualization, Software. **D. Kasatov:** Validation, Investigation, Formal analysis. **Ia Kolesnikov:** Investigation, Data curation. **S. Savinov:** Validation, Investigation. **T. Shein:** Validation, Software, Data curation. **S. Taskaev:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

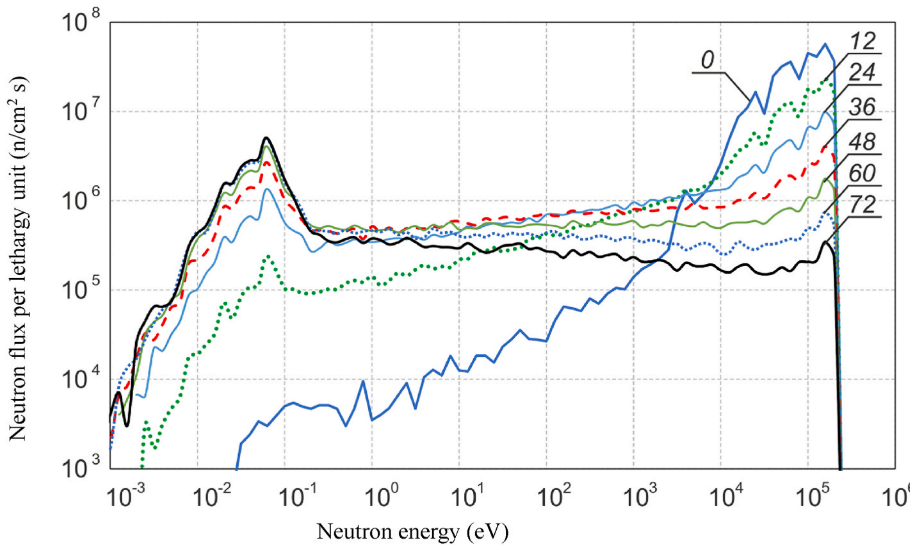

Fig. 6. The neutron energy spectrum depending on the thickness of the moderator placed between the target and the detector (shown in millimeters on the graphs).

Table 1
Dependence of the median energy E_m on the thickness of PMMA moderator.

Thickness of the PMMA moderator, mm	0	12	24	36	48	60	72
Median energy E_m, eV	80 000	63 000	25 000	600	10	0.3	0.06

the work reported in this paper.

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Data availability

Data will be made available on request.

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