Vol. 48 (2017) *ACTA PHYSICA POLONICA B* No 10

GEANT4 SIMULATIONS OF A BEAM SHAPING ASSEMBLY DESIGN AND OPTIMIZATION FOR THERMAL/EPITHERMAL NEUTRONS*

R. Avagyan, R. Avetisyan, V. Ivanyan†, I. Kerobyan

A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia

(Received August 17, 2017)

The possibility of obtaining thermal/epithermal neutron beams using external protons from cyclotron C18/18 is studied based on Geant4 simulations. The design and optimization characteristic of the Beam Shaping Assembly (BSA) for neutron flux from thick ^{9}Be target was studied with Geant4 program. To obtain the thermal/epithermal neutron beam, appropriate materials for moderator and reflector with optimal thicknesses were determined. In this model of the Geant4 simulation, two programs for physics lists were used. These are one of the most important parts of the creation the correct model, which will be as close as possible to the future experiment. The formed neutron beam will be used not only in fundamental research, but also for practical purposes, in particular, to explore the possibility of applying it in the Boron Neutron Capture Therapy (BNCT).

DOI:10.5506/APhysPolB.48.1693

1. Introduction

The work is dedicated to the formation of thermal/epithermal neutron beams based on the external proton beam of cyclotron C18/18 from IBA [2]. The cyclotron C18/18 produces proton beams with energies of 18 MeV and current of up to 100 μA. The modified C18/18 has a vacuum tube for passing protons through it from cyclotron to the experimental hall. Before bombarding the target, proton beam passes through the 500 μm thick aluminum, which is installed for keeping the vacuum inside the tube. After passing through the aluminum foil, protons lose part of the energy from 18 MeV to 14.8 MeV.

---

[*] Presented at the 2$^{\rm nd}$ Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Kraków, Poland, June 3–11, 2017.

[†] Corresponding author: `vahagnivanyan@mail.yerphi.am`

To get yield of neutrons as high as possible, in the simulations the Be target with 2.5 mm thickness was used. There will not be any protons after this thick target. The list of ^{9}Be (p,xn) reactions with thresholds less than 14.8 MeV was recently presented elsewhere [3].

2. Geant4 model of the experiment

In Geant4 [4] model created for a description of the experiment two physics lists: G4EmStandardPhysics for electromagnetic processes and G4HadronPhysicsQGSP_BERT_HP for hadronic processes were used. During simulations, the arrangement of future experiment was taken into account. The target with radius 5 mm must be installed after the vacuum tube at 3 cm distance. Proton beam with radius of the target must be passed through the 3 cm air layer and then hit the target. Installed virtual sensitive detector has a shape of tube with 2.5 cm radius and it is constructed for detecting neutrons, but it could be changed for detecting another particles.

Before detection, neutrons must be passed through some special materials for forming thermal/epithermal neutron beam. It is really difficult to get only thermal and epithermal neutrons even by simulations, when neutrons from ^{9}Be (p,xn) reactions have energies up to 12 MeV (figure 1).

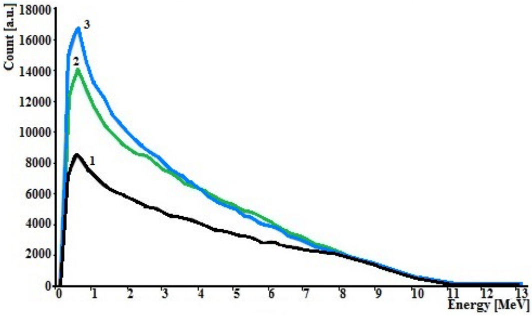

Fig. 1. Energy spectra of neutrons for 0.5 mm (1), 1 mm (2) and 2.5 mm (3) thicknesses of Be.

With the unique Geant4 model, simulations for the creation and formation appropriate BSA are closer to the real processes which will happen in real experiment, even air used in the simulations has the same pressure and temperature that we have in the experimental hall. First of all, the optimal thickness of the target for obtaining a higher yield of neutrons was determined. The simulation of energy spectra of neutrons for 0.5 mm, 1 mm and 2.5 mm thicknesses of beryllium target at proton beam energy 14.8 MeV was performed. The neutron yield growth as a function of beryllium target thickness is observed (figure 1). The 2.5 mm thickness of Be corresponds to the thickness of the stopping of protons with an energy of 14.8 MeV in Be. Using target thicker than 2.5 mm is unfavorable, because in this case emitted neutrons will be captured.

So as an optimal thickness of the target ^{9}Be to produce neutron beams, thickness of 2.5 mm was chosen, for which further calculations were performed.

3. Geant4 simulations of beam shaping assembly

The design characteristics of BSA, including the appropriate materials and thicknesses of reflector and moderator, were considered. To create optimal BSA by Geant4 modeling, we have taken into account the possibility of increasing neutron flux before moderation. For that purpose, 5 cm thick bismuth plate was installed immediately after the Be target. Figure 2 shows the energy spectra of neutrons before and after a sheet of 5 cm thick Bi, installed after the Be target. In the energy region up to 2 MeV, the neutron flux increases, on the other hand, it decreases in the region from 2 to 12 MeV. This is due to ^{209}Bi $(n, 2n)$ ^{208}Bi and ^{209}Bi $(n, 2n\gamma)$ ^{208}Bi reactions (Table I). The secondary neutrons increase the flux in the region up to 2 MeV neutrons. The threshold of these reactions starts from 7.5 MeV.

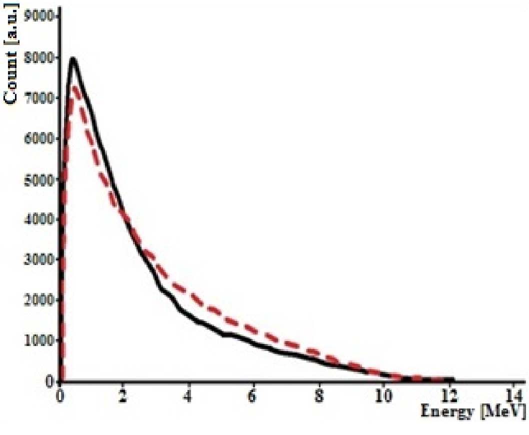

Fig. 2. Energy spectra of neutrons before (solid) and after installation of 5 cm thick Bi sheet (dashed).

By Geant4 simulation, a search for the material possessing the best moderator and reflector properties for neutrons with energies up to 12 MeV was conducted. The BSA used for these simulations has a diameter of 1 m, with 20 cm thick lead reflector, surrounding moderators and encircling the target with 8 mm inner radius and 10 cm thick lead reflector. BSA also includes a conical-shape lead reflector. The moderators have a diameter of 60 cm

TABLE I

^{209}Bi (n, xn) reactions (where $N = 1 \sim 6$) with thresholds less than 12 MeV.

$n + {}^{209}\text{Bi} \rightarrow {}^{208}\text{Bi} + 2n$
$n + {}^{209}\text{Bi} \rightarrow {}^{208}\text{Bi} + 2n + N\gamma$
$n + {}^{209}\text{Bi} \rightarrow {}^{209}\text{Bi} + n + N\gamma$
$n + {}^{209}\text{Bi} \rightarrow {}^{209}\text{Bi} + n$

and their composition is slightly changed to suppress the high energy neutrons. The neutron spectrum was calculated across the exit window with 10 cm diameter. Energy distribution of neutrons after 5 cm thick bismuth and 50 cm thick iron is presented in figure 3 (a). After installation of 50 cm thick iron layer, most of calculated neutrons have energies up to 1 MeV, as iron is a good moderator material for neutrons with energies from 1 MeV to 14 MeV [5].

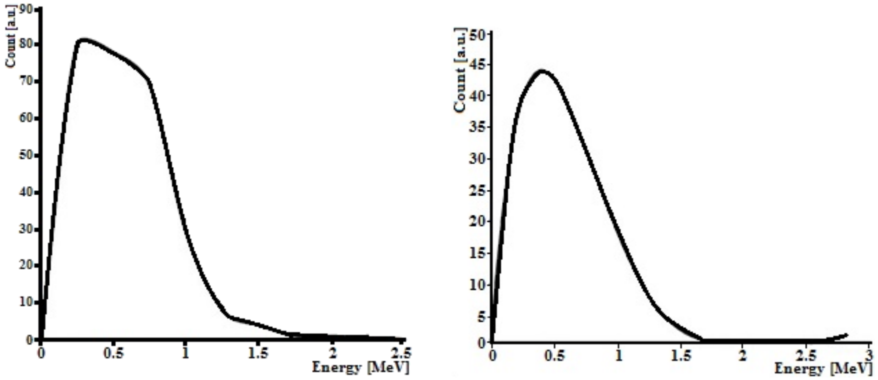

Fig. 3. Energy spectra of neutrons (a) after 5 cm Bi, 50 cm Fe, and (b) after 5 cm Bi, 50 cm Fe, 10 cm Al and 5 cm graphite.

To achieve neutrons with energies less than 1 MeV 10 cm, thick Al and 5 cm thick graphite layers after the Fe moderator were installed. By using Al and graphite materials, the energy of neutrons will decrease (figure 3 (b)) as these are better materials for moderation of neutrons with energies from 90 keV to 1 MeV [5]. On the other hand, we must take into account that calculated neutrons have energies higher than thermal/epithermal neutrons, of course, it is difficult to create just thermal/epithermal neutron beam, but we could increase the percentage of low-energy neutrons in the beam. For example, after the installation of 5 cm thick bismuth, 50 cm thick iron, 10 cm thick aluminum and 5 cm graphite, just 6.25% of simulated neutrons have energies less than 200 keV.

The emphasis in the design of a BSA was on decreasing the high-energy neutron flux to a level as low as possible. One of the moderator designs consisting of 5 cm thick Bi, 50 cm thick Fe, 15 cm thick Al, 5 cm thick graphite and 4 cm thick Pb gives the result shown in figure 4 (a) (solid line). We presented also the energy distribution of neutrons, when BSA consists of 5 cm thick Bi, 50 cm thick Fe, 15 cm thick Al, 5 cm thick graphite and 4 cm thick aluminum (dotted line). The energy of neutrons reduced by these moderators has better distribution and the neutrons with energies up to 200 keV are 18.2% for 4 cm thick Pb, and 20.1% for Al from the total flux of neutrons. To increase the percentage of neutrons with energies up to 200 keV, different materials with different thicknesses have been used. In figure 4 (b), we show neutron spectra when using moderator from 5 cm thick Bi, 55 cm thick Fe, 15 cm thick Al, 5 cm thick graphite with 85 cm water (solid line) inside of the conical reflector, and 85 cm heavy water (dash-dotted line) used instead of water. For both neutrons up to 200 keV constitute 20.7% of whole detected neutrons. One of the best results for the design of BSA consisted of the moderator from 5 cm thick Bi, 55 cm thick Fe, 15 cm thick Al, 150 cm thick graphite (dashed line) as shown in figure 5 (a). 27.5% of neutrons have energies up to 200 keV. When increasing the thickness of graphite, some part of neutrons will be captured that is why after installation of 165 cm thick graphite instead of 150 cm, inside the conical reflector, neutrons up to 200 keV are only 26.7% of the total. The best moderator design, for which neutrons with energies up to 200 keV are 61.1% of all neutrons, consisted of 5 cm of Bi, 55 cm of Fe, 5 cm of graphite and 10 cm of ^{7}LiF. In figure 5 (b), neutron spectrum for this moderator is shown. The layer of ^{7}LiF was used to increase the flux of epithermal neutrons, which are approximately 50% of neutrons with energies up to 200 keV.

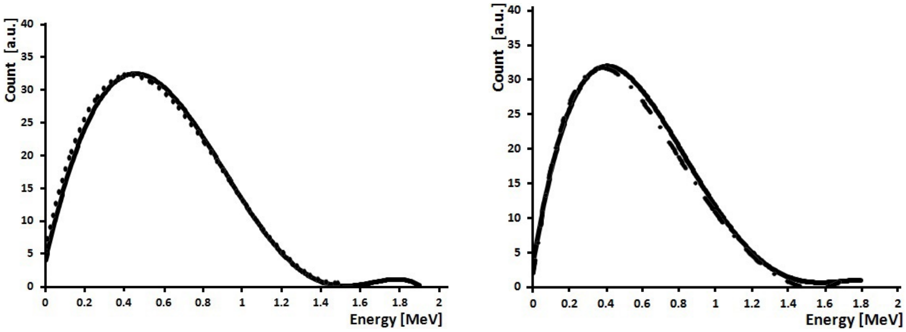

Fig. 4. Energy spectra of neutrons after (a) 5 cm Bi, 50 cm Fe, 15 cm Al, 5 cm graphite with 4 cm Pb (solid line) and with 4 cm Al (dotted line), and (b) after 5 cm Bi, 55 cm Fe, 15 cm Al, 5 cm graphite with 85 cm water (solid line) and with 85 cm heavy water (dash-dotted line).

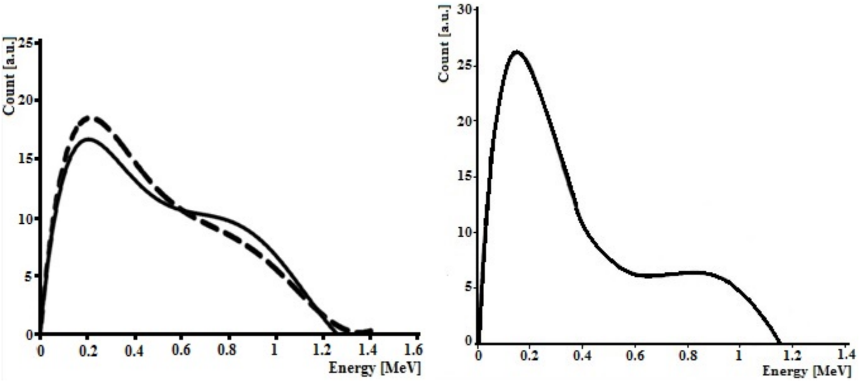

Fig. 5. Energy spectra of neutrons after 5 cm Bi, 55 cm Fe, 15 cm Al with (a) 150 cm graphite (dash) and 165 cm graphite (solid) and with (b) 5 cm graphite and 10 cm ^{7}LiF.

The use of this kind of BSA (figure 6) means that neutron beam flux, for up to 100 μA proton current from cyclotron, will be 0.96×10^6 $n/\mathrm{s\,cm}^2$.

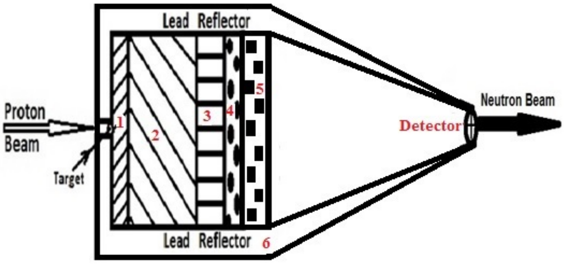

Fig. 6. BSA: 2.5 mm ^{9}Be target, 5 cm Bi (1), 55 cm Fe (2), 10 cm Al (3), 5 cm graphite (4), 10 cm ^{7}LiF (5), Pb reflector (6).

4. Conclusion

The best model of BSA designed by Geant4 consists of 5 cm thick Bi, 55 cm thick Fe, 5 cm thick graphite and 10 cm thick ^{7}LiF moderator surrounded with 20 cm thick side reflector from lead, also 1.5 m length conical reflector again made from lead and 10 cm thick lead reflector which has 8 mm inner radius and surrounds the target (figure 6). Neutron beam flux on the virtual sensitive detector is equal to 0.96×10^6 $n/\mathrm{s\,cm}^2$.

This work was supported by the State Committee of Science MES RA, in the frame of the research project No. SCS 14CYC-1c01.

REFERENCES

[1] `https://en.wikipedia.org/wiki/Neutron_capture_therapy_of_cancer`

[2] `http://ehyadarman.com/wp-content/uploads/downloads/2014/07/IBA.pdf`

[3] R. Avagyan, R. Avetisyan, V. Ivanyan, I. Kerobyan, *Nucl. Instrum. Methods Phys. Res. B* **402**, 247 (2017).

[4] `http://geant4.cern.ch/`

[5] J.M. Verbeke, J.L. Vujic, K.-N. Leung, *Nucl. Technol.* **129**, 257 (2000).