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Investigation of epithermal neutron angular flux for a compact moderator system design with GEANT4

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1. Introduction

Accelerator-based neutron sources for Boron Neutron Capture Therapy (BNCT) mainly use the Be(p,n) and Li(p,n) reactions [1]. These (p,n) reactions also serve as key neutron sources in various applications. However, the neutrons produced through these nuclear reactions have much higher energies than epithermal neutrons, requiring a moderator for energy reduction.

Higher energy of neutrons necessitate a thicker moderator. However, increasing the moderator thickness reduces the epithermal neutron flux. This means that the lower the neutron energy generated from the target, the fewer neutrons are lost as they pass through the moderator. Experimental measurements of neutron production at various angles for Be(p,n) show that the maximum and mean energy of neutrons decrease as angles increase [2].

In this study, GEANT simulation [3] was conducted to examine the influence of beam direction variations on the epithermal neutron flux when a moderator applied.

2. Neutron energy spectra of the Be(p,n) reaction at various beam angles

The simulations were carried out with 8 MeV proton using GEANT4. In these simulations, the diameter and thickness of the target were set to 2 cm and 1 mm, respectively. A total of 10^9 protons were incident on the target. A proton beam was generated as a point source on the target surface, and the position and energy of the neutrons passing through at a point 20 cm away from the target center were recorded. The neutron energy spectrum was obtained by setting the beam direction to 0° and increasing it in 10° increments around the target.

Fig. 1 shows the number of neutrons detected at each angle from ^{9}Be(p,n) for 8 MeV proton beam. The x-axis represents angles from the beam line, and y-axis represents the number of neutrons obtained a given angle. The neutron count decreases as the angle increases from 0° to 90°, with the highest count being approximately three times the lowest count. Fig. 2 displays the maximum and mean energies at each angle. The triangles and circles are the maximum and mean energies obtained energy spectra. The maximum and mean energies gradually decrease as the angle increases from 0° to 180°. The difference between the maximum and minimum values of the E_{max} is 2.50 MeV, and it is 0.87 MeV for E_{mean}. Fig. 3 presents energy spectra at four angles: 0°, 30°, 60°, and 90° from the beam direction. As the angle increases, the spectrum changes, and the maximum energy decreases.

As the neutron energy decreases, the moderator thickness can be reduced, which can increase the epithermal neutrons. Therefore, it is meaningful to study how the epithermal neutron fluxes change at various beam angles.

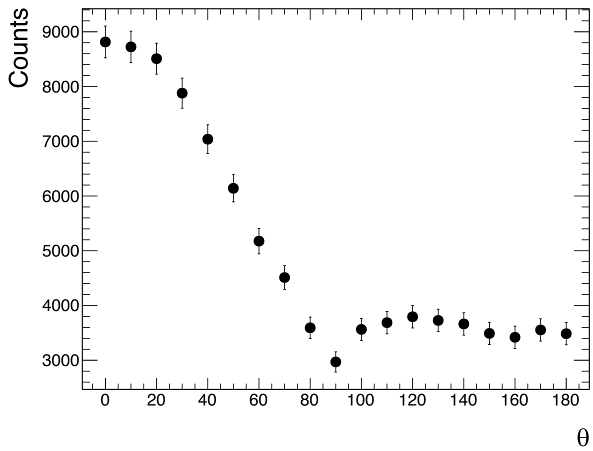

Fig. 1. The number of neutrons as a function of angle. The circles are the number of neutrons from ^{9}Be(p,n) for 8 MeV proton beam. The threshold is not applied.

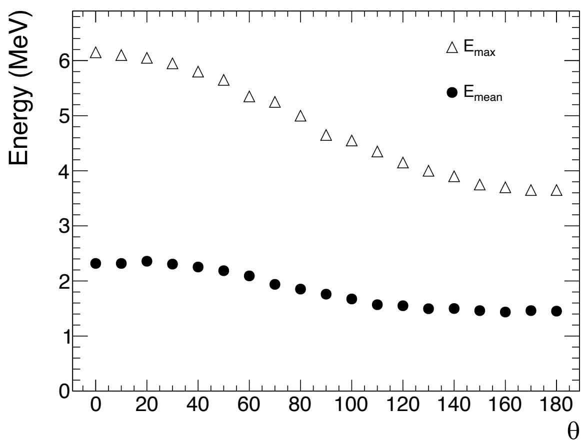

Fig. 2. The maximum and mean neutron energies as a function of angle. The triangles and circles are the maximum and mean energies obtained energy spectra from ^{9}Be(p,n) for 8 MeV proton beam. The threshold is not applied.

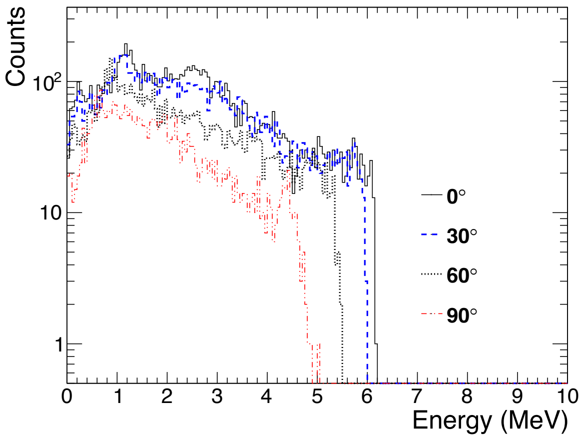

Fig. 3. The neutron energy spectra at four angles: 0°, 30°, 60°, 90°.

3. Epithermal neutron flux comparison at different beam angles

As neutron energy decreases, a thinner moderator is required to moderate neutrons to the epithermal energy range. Since the neutron energy distribution varies with beam direction, epithermal neutron flux passing through the moderator can change at different beam angles. Therefore, we examined the influence of beam direction variations on the epithermal neutron flux when a moderator applied.

The epithermal neutron flux passing through the moderator was calculated for 10^9 protons, each with an energy of 8 MeV, incident on a Be target. We obtained the number of epithermal neutrons ejected from the moderator. The same moderator design of [4] was used. The epithermal neutron flux was obtained by adjusting the MgF_2 thickness, at which $f_{epi}/f_{fast} > 20$ was satisfied. One of the IAEA-recommended conditions for BNCT is that f_{epi}/f_{fast} should be larger than 20 [5].

Table 1 presents the epithermal neutron flux obtained at different four angles. The results indicate that as the angle increases, the epithermal neutron flux decreases. This reduction is attributed to a decline in the total number of neutrons even though a simultaneous decrease in both the maximum and mean neutron energies.

Angle (°)	0	30	60	90
f_{epi} (n/cm^{-2}s^{-1})	7.68×10^8	7.46×10^8	6.93×10^8	6.45×10^8

Table 1 The comparison of epithermal neutron flux at different beam angles after applying a moderator.

4. Conclusions

In summary, we analyzed the angular distribution of neutrons generated by the Be(p,n) reaction using GEANT4 simulations. The energy spectrum at each angle revealed that both the mean and maximum neutron energies decreased as the beam angle increased. Specifically, when a Be target was irradiated with 8 MeV protons, the maximum energy decreased from 6.15 MeV at 0° to 4.65 MeV at 90°, while the mean energy decreased from 2.33 MeV ° to 1.76 MeV.

To precisely assess the effect of beam angle variation, a moderator was introduced, and the resulting epithermal neutron flux was compared across different angles. The results revealed that the highest flux occurred at 0°, suggesting that changing the beam angle does not improve neutron production in this system. This is because lowering neutron energy also reduces the total neutron yield, negating any potential benefits of angle variation.

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