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Effect of ⁹Be Target Thickness on Neutron Production Using Reactor-Based Gamma Sources: A Monte Carlo Study with PHITS

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ABSTRACT

This study uses Monte Carlo simulations with PHITS version 3.34 to examine the impact of beryllium (^{9}Be) target thickness on photoneutron production. Continuous photon and neutron energy distributions were taken from the base of a radial piercing beam port to model the gamma source spectrum using a research nuclear reactor as a basis. Because of its high photonuclear cross-section, pure beryllium was chosen, and different target thicknesses were simulated in order to assess surface fluence and neutron yield. The findings demonstrate that neutron production within the material increases with beryllium thickness, with a significant peak seen at about 5 cm thickness. After this, internal neutron absorption and increased photon attenuation cause neutron production to decline. Thinner targets (less than 5 cm) had the highest neutron flux emitted from the surface, indicating how sensitive the neutron escape probability is to target geometry. These results support earlier research and emphasize how crucial it is to optimize target dimensions for applications requiring particular neutron energy ranges, like Boron Neutron Capture Therapy (BNCT). In order to optimize photoneutron sources for industrial and medical applications, the study recommends additional experimental validation and concludes that there is a trade-off between maintaining efficient neutron escape and optimizing neutron yield.

Keywords: Photoneutron, gamma ray, reactor, beryllium, monte carlo, PHITS, BNCT

INTRODUCTION

In recent decades, there has been a growing interest in producing neutrons through photonuclear reactions, especially because of its potential for use in medical applications like BNCT and compact neutron sources. Because of its low reaction threshold (1.667 MeV), relatively high neutron yield, and the mechanical suitability of beryllium as a target material, the $^{9}Be(\gamma,n)^{8}Be$ reaction is unique among the available reactions (1,2). An appealing alternative for producing photoneutrons in controlled settings is the availability of high-energy gamma rays from research reactors, which offers a workable and practical way to initiate this reaction.

BNCT is a radiotherapy technique that exploits the nuclear reaction between low-energy (thermal or epithermal) neutrons and the stable isotope ^{10}B, which has been selectively accumulated in cancerous cells. When a neutron is captured, ^{10}B goes through a reaction that releases lithium nuclei and high linear energy transfer (LET) alpha particles, which causes localized cell death [3]. A high and adjustable neutron flux is necessary to guarantee the effectiveness of this technique, particularly in the epithermal range (~1 eV to 10 keV). Reactor-based gamma sources, coupled with beryllium targets, present a potentially efficient means to fulfil this requirement [4,5].

Previous studies have highlighted the dependence of photoneutron production on both the gamma energy spectrum and the physical properties of the beryllium target. Eshwarappa et al. [1] conducted experimental measurements on beryllium targets under the gamma spectrum of a research reactor and found that the neutron yield increases significantly with target thickness, but only up to a point. Beyond this optimal thickness, neutron production rates decreased due to gamma attenuation. Braccini et al. [6] confirmed that target geometry and material composition have significant effects on reaction yield by investigating the photonuclear cross-sections for a number of isotopes.

Monte Carlo methods have become a breakthrough for simulating such nuclear processes, enabling detailed evaluation of photon-neutron interactions across complex geometries and materials. The PHITS (Particle and Heavy Ion Transport code System) simulation package, in particular, has been widely validated for nuclear and medical applications, offering coupled photonuclear and neutron transport models suitable for this type of study [7]. It has been widely used in studies on radiotherapy, accelerator design, and reactor shielding. It integrates high-fidelity physical models and nuclear data libraries [7].

Despite these developments, the majority of earlier studies have mostly concentrated on total neutron yield, paying insufficient attention to spatial features like neutron flux at the beryllium target's surface. This surface flux has a direct impact on the neutron field available for beam shaping, moderation, and patient delivery, making it crucial for BNCT and other neutron beam applications [8]. Furthermore, because internal scattering, absorption, and escape probabilities are extremely sensitive to target thickness and geometry, surface neutron flux can deviate significantly from trends in bulk production [9].

Therefore, this study aims to evaluate both total neutron production and surface neutron flux from ^{9}Be targets of varying thicknesses under a typical reactor gamma spectrum. By analysing how the thickness affects these two quantities, we aim to provide quantitative guidance for the optimal design of beryllium-based photoneutron sources, particularly for BNCT-related applications. The inclusion of energy-dependent flux distributions and the use of realistic reactor spectra further distinguish this work from prior studies.

MATERIALS & METHODS

The simulations in this study were performed using PHITS (Particle and Heavy Ion Transport code System) version 3.34. PHITS is capable of handling complex geometries and simulating coupled photon, neutron, and charged particle transport, including photonuclear reactions such as the ^{9}Be(γ,n)^{8}Be reaction [2].

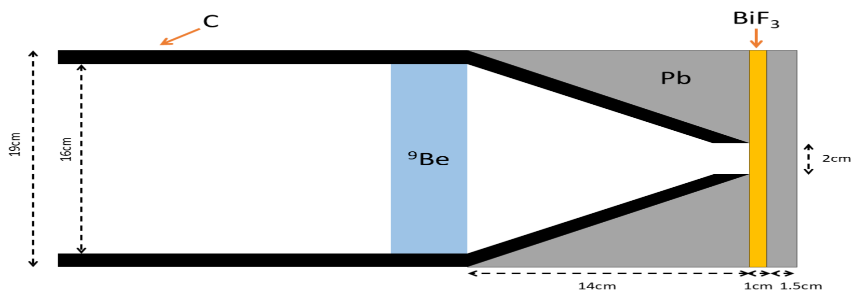

Figure 1. The design and material used, neutron are tracked before, inside, and after the ^{9}Be region

The source used in this simulation was modelled based on the neutron and gamma energy spectra measured at the radial piercing beam port of a research nuclear reactor, as reported by Zailani et al. [(10)]. This simulation employed a continuous energy spectrum to better represent the conditions of particle flux distribution at the reactor beam port. This approach allows for more accurate estimation of photoneutron production by accounting for the full energy range of incident photons and neutrons.

Pure beryllium (^{9}Be) is used as neutron generator which is being studied in this paper, varying from 0.1cm to 20cm in thickness. The beryllium has the density of 1.848 g/cm^3. It is selected due to its low atomic number, good mechanical stability, and low neutron absorption cross section, making it an efficient converter of high-energy gamma rays into neutrons through the (γ,n) reaction.

Graphite was used as a reflector surrounding the beryllium target to enhance neutron flux by reflecting escaping neutrons back into the active region. Graphite is chosen due to its low neutron absorption and high scattering cross-section for neutron with energies above 1 MeV [(12)].

Lead (Pb) is used as a shielding material. It is used because it has constant attenuation coefficient. 0.05cm^2/g to absorb the gamma rays 1 – 10 MeV energies at the end of the collimator (Turkmen et al., 2017). BiF3 is used to lower the energy of fast neutron since fluorine (F) has high scattering cross section [(13)].

The neutron spectra investigated in this study include three categories: (1) neutrons coming directly from the source toward the beryllium target, (2) neutrons produced inside the beryllium material, and (3) neutrons emitted from the surface of the target. The neutron fluence in each region was tallied using the [T-Track] scoring method in PHITS and the number of neutrons produced from photonuclear reactions within the beryllium target was recorded using the [T-Product] tally.

RESULT AND DISCUSSION

The number of particles in beryllium target region is represented in Figure 2. The results show that as the thickness of ^{9}Be target increases, the number of neutrons produced through the (γ, n) reaction also increases. This is expected because the thicker target offers a longer path for incident gamma photons to interact with the beryllium nuclei, increasing the possibility of photonuclear reactions [(12)].

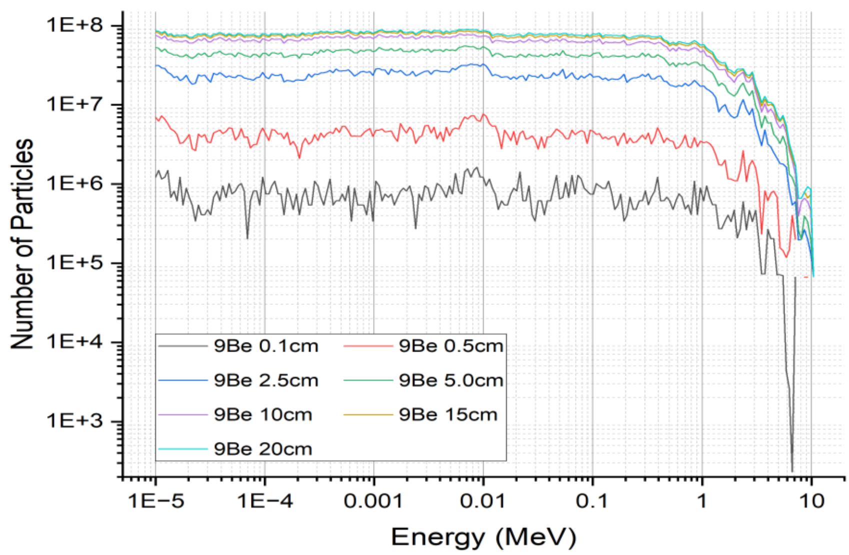

Figure 2. Number of photons inside different thickness of beryllium target

For all variation of the thickness, it can be seen that the number of neutrons increases sharply, but saturated at thickness of 10 cm. Beyond this number, the increase in neutron becomes marginal. This saturation is primarily due to the attenuation of incident photons. Gamma rays lose energy as they propagate through the dense beryllium medium, limiting their ability to reach deeper layers and trigger additional photonuclear reaction. Eswarappa et al. (1) reported the similar saturation effects in in experimental and simulated studies on photoneutron targets exposed to broad gamma spectra.

One contributing factor to the diminishing returns in thick target is the internal buildup of secondary photons and electrons, which may not have sufficient energy to trigger the photonuclear reaction. This is can be seen also in the region of neutron energy greater than 1 MeV. The number of particles above this boundary is lower than the other region, which have the order of 10^6 – 10^8, since the threshold energy for photonuclear reaction is relatively high near 1.7 MeV.

The result from (1) shows that for photon energy 8, 9, 10, 12 MeV produces neutron yield in the order of 10^9 – 10^{10} n/s. Meanwhile the data in Fig. 2 shows that there is a difference about 10^3–10^2. This was due to the fact that the source used in this study is a photon spectrum, having broad energy from 10^{-5} up to 100 MeV, instead of monoenergetic gamma rays.

Therefore, from both a theoretical and practical standpoint, an optimal target thickness exists beyond which additional beryllium becomes redundant. In this study, 10 cm appears to be the saturation threshold for neutron production under the given gamma spectrum. This suggests that in future applications—particularly those constrained by space, weight, or cost—a thickness of approximately 8–10 cm would provide a near-maximal neutron yield without unnecessary material usage.

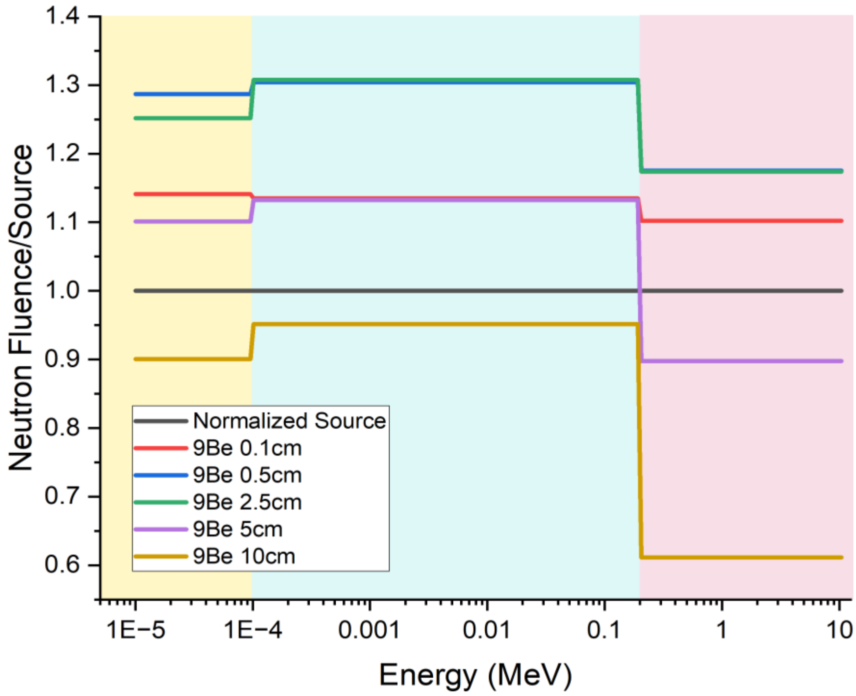

Figure 3. Neutron flux emmited from beryllium target, normalized to the incident flux entering the target, divided by 3 energy regions: epithermal (yellow), intermediate (blue), fast (red) neutron.

Unlike the total neutron production, the neutron flux—defined as the number of neutrons escaping the outer surface of the beryllium target—follows a different trend. For different beryllium (^{9}Be) target thicknesses, the simulated neutron fluence per source as a function of energy shows a distinct dependence on the interaction path length inside the target. Neutron fluence increases significantly across the thermal and epithermal energy ranges when the ^{9}Be thickness is increased from 0.1 cm to 5 cm, as Fig. 3 illustrates. The figure is divided into 3 regions: epithermal (0.4 – 100 eV), intermediate (100eV – 200keV), and fast neutron (>200keV) [14]. The epithermal region is where this increase is most noticeable, with the neutron fluence for the 0.5 cm target reaching up to 1.3 times the normalized source fluence. As gamma photons move through a thicker medium, there is a higher chance of (γ,n) reactions taking place, which increases the generation of neutrons and causes the increase in fluence.

It is interesting to note that, in comparison to the 5 cm target, the 10 cm target shows a discernible decrease in neutron fluence across all energy ranges. The fluence falls near or below the normalized source value in the thermal and epithermal energy regions. This decrease suggests that excessive gamma attenuation causes diminishing returns with additional thickness increases. There are fewer photoneutron reactions as a result of gamma photons being absorbed more and more before they can reach deeper areas of the target. Furthermore, before they can escape, a large number of neutrons produced deeper within the target are scattered or absorbed.

These findings highlight how crucial target geometry optimization is for photoneutron applications. Although it makes sense that thicker materials would result in higher reaction yields, excessive thickness lowers the probability of neutron escape and introduces internal self-shielding. The results of Eshwarappa [1] who identified an ideal thickness for optimizing photoneutron yield in beryllium targets, are in line with this. Geometric and transport constraints cause neutron production to plateau or even decrease after this point. Therefore, the optimal target should strike a balance between the efficiency of neutron escape and the probability of photon interaction.

The effects of thickness are less clear in the fast neutron region (>0.1 MeV), but they are still there. The 0.5 cm target again has the highest fluence of all the configurations, with values above 1.2 compared to the source. The 10 cm target, on the other hand, drops a lot to about 0.65 in this range. This means that most high-energy neutrons are either absorbed or redirected inside the target. This shows that the fast neutron escape is also affected by making the material too thick. If more neutrons are made but don't leave the target area, they don't add to the measured fluence.

In general, this study shows that the thickness of the beryllium target is very important for determining the neutron energy spectrum that comes from a photon-activated system. It is very important to understand these transport dynamics for neutron sources that are based on reactors, like those used in BNCT (Boron Neutron Capture Therapy). The best thickness for ^{9}Be is 5 cm, which gives the most neutrons across a range of energies. This makes it a good choice for use in industry or medicine. To make good neutron targets, you need to think carefully about how materials absorb and scatter neutrons. In the future, researchers may look into layering strategies or graded materials to increase neutron output even more without the self-attenuation effects seen in thicker monolithic targets.

CONCLUSION

Using the PHITS and a realistic gamma energy spectrum from a research nuclear reactor, this study looked into how the thickness of the beryllium target affects the production of photoneutrons. The results show that the number of neutrons produced goes up as the beryllium thickness increases, up to about 5 cm. After that, the increase becomes small and then stops. As the thickness of the beryllium increases, the chances of gamma interacting with the beryllium nuclei also rise. However, this is countered by photon attenuation and neutron self-shielding at greater depths. The best thickness for the beryllium target was found to be about 5 cm, where the neutron yield is highest before attenuation takes over. These results underline the crucial role that target geometry and composition play in maximizing neutron yields for scientific and medical applications, and they corroborate earlier experimental and computational investigations.

Future research might concentrate on confirming these results with experimental data from real reactor settings using beryllium targets of different thicknesses. Investigating composite or multilayered materials may also help maximize neutron output while reducing energy loss or undesired gamma radiation. The development of optimized photoneutron sources for BNCT, neutron radiography, and other new nuclear applications may benefit from these findings.

Declaration by Authors

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