

## Feasibility study of a scintillator-based neutron spectrometry using GEANT4

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### 1. Introduction

Boron neutron capture therapy (BNCT) uses epithermal neutrons with energies ranging from 0.5 eV – 10 keV [1]. These neutrons are generated via Li(p,n) or Be(p,n) nuclear reactions and are then moderated in a moderator to reach the desired energy range. The neutron energy spectrum is typically determined using Bonner Sphere Spectrometer (BSS) or Neutron Activation Foil Spectrometry (NAFS) [2][3]. However, both methods present limitations. For instance, BSS requires sequential measurements with spheres of varying moderator thicknesses and thus necessitates repeated setup reconfiguration. Meanwhile, NAFS requires activated samples to be transferred following irradiation for gamma-ray spectrometry.

To overcome these limitations, this study evaluates the feasibility of a scintillator-based neutron spectrometry using GEANT4 simulations [4]. As neutrons slowed through moderation are captured by hydrogen, leading to the emission of characteristic gamma-rays. This study demonstrates the feasibility of determining neutron energy by using these gamma-rays.

### 2. Gamma production by neutron capture via ${}^1\text{H}(n,\gamma){}^2\text{H}$

The detection system in this study consists of a plastic scintillator composed of hydrogen and carbon and an NaI detector.

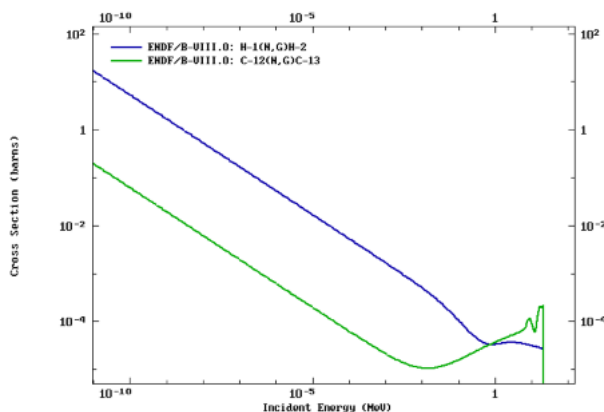


Fig. 1 Cross section of  ${}^1\text{H}(n,\gamma){}^2\text{H}$  and  ${}^{12}\text{C}(n,\gamma){}^{13}\text{C}$ , obtained from the ENDF/B-VIII.0 library and accessed via the IAEA Nuclear Data Services (<https://www-nds.iaea.org/xfor/endl.htm>) [5].

Specifically, hydrogen and carbon in the plastic scintillator capture neutrons, producing gamma-rays that are subsequently detected by the NaI detector. The 2.2 MeV gamma-rays is the most prominent radiation from neutron capture reaction, and its cross-section is depicted in Fig. 1. Here, as neutron energy decreases, the production of prompt gamma-rays via neutron capture increases.

A GEANT4 simulation was performed to evaluate how the number of 2.2 MeV gamma-rays varies with neutron energy and plastic scintillator thickness. The detector was configured as a 5 cm × 5 cm box, with the NaI detector thickness set to 6 mm. The top panel of Fig. 2 presents the energy distribution obtained from a 1 cm thick plastic scintillator at 0.1 eV incident neutron energy, while the bottom panel presents the corresponding energy distribution obtained from a 6 mm thick NaI detector. The top panel displays the Compton edge corresponding to 2.2 MeV, while the bottom panel shows the 2.2 MeV photopeak clearly.

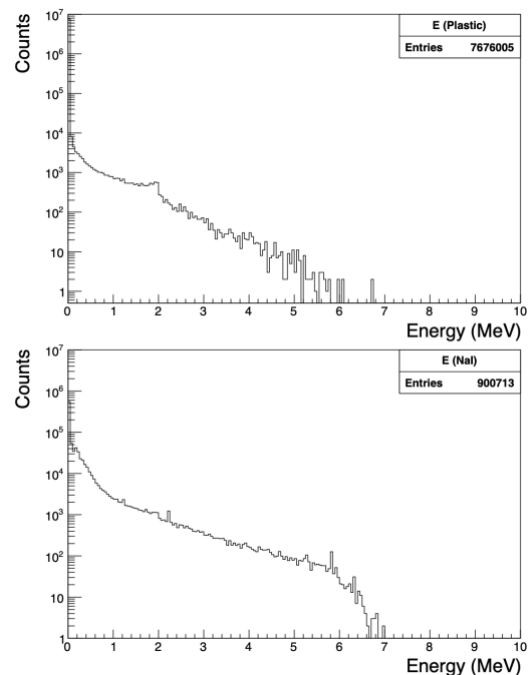


Fig. 2 Energy distributions obtained from a 1 cm thick plastic scintillator (top) and a 6 mm thick NaI detector (bottom) at 0.1 eV incident neutron energy.

### 3. Comparison of gamma-ray production in a plastic scintillator with that estimated from an NaI detector

Neutron energy was varied from 0.1 eV to 1 MeV, and  $10^7$  neutrons were generated for each energy. The number of 2.2 MeV gamma-rays produced in the plastic scintillator and the corresponding photopeak in the NaI detector were counted. To estimate the number of gamma-rays produced, the photopeak efficiency and the fraction of gamma-rays generated in the plastic scintillator and entering the NaI detector were taken into account after background subtraction.

Fig. 3 presents the 2.2 MeV gamma-rays production rate as a function of energy. Here,  $\text{Num}_\gamma$  denotes the number of 2.2 MeV gamma-rays, while  $\text{Num}_n$  and  $E_n$  represent the number of incident neutrons and neutron energy, respectively. Filled circles and triangles denote the number of 2.2 MeV gamma-rays generated in the plastic scintillator divided by the number of incident neutrons, while hollowed circles and triangles represent the corresponding predicted rates derived from photopeaks in the NaI detector at scintillator thicknesses of 1 cm and 10 cm, respectively. Fig. 3 shows that increasing the thickness of the plastic scintillator enhances neutron moderation, which in turn changes gamma-ray production.

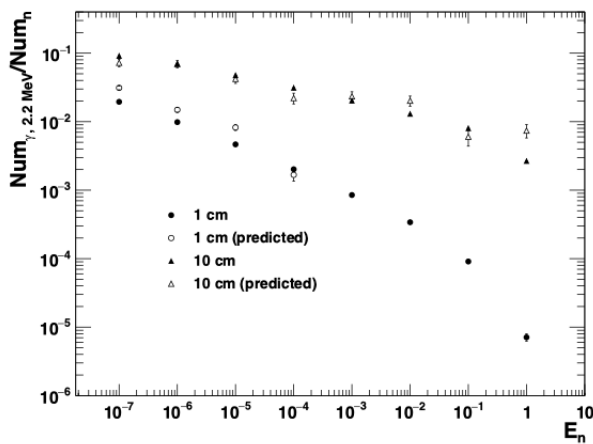


Fig. 3 Comparison of gamma-ray production obtained by direct counting and by photopeak-based estimation.

For a plastic scintillator thickness of 1 cm, no data points are obtained above 1 keV because gamma-ray production decreases significantly with increasing neutron energy. This indicates that a 1 cm thickness is insufficient to effectively moderate neutrons at these energies. At both thicknesses of 1 cm and 10 cm, the trends in directly counted and estimated 2.2 MeV gamma-ray production are similar, although differences remain. At 0.1 eV and a plastic scintillator thickness of 1 cm, the counted and estimated values are  $(19.47 \pm 0.04) \times 10^{-3}$  and  $(3.11 \pm 0.20) \times 10^{-2}$ , respectively, indicating a difference of approximately 60 %. This

difference is attributed to variations in the number of photopeaks and the number of gamma-rays entering the NaI detector.

### 4. Conclusions

In this study, GEANT simulations were used to evaluate the feasibility of a neutron spectrometer combining a plastic scintillator and an NaI detector. The analysis focused on predicting 2.2 MeV gamma-ray production using photopeaks measured by the adjacent NaI detector.

As illustrated in Fig. 3, at a fixed thickness, the number of gamma-rays produced by the  ${}^1\text{H}(n,\gamma){}^2\text{H}$  reaction increases as neutron energy decreases. However, the gamma-ray production differs from that shown in Fig. 1 because the neutron energy distribution changes with increasing thickness. At a thickness of 1 cm, gamma-ray production prediction was not feasible because no identifiable photopeak was observed when the neutron energy exceeded 1 keV; meanwhile, for the thickness of 10 cm, prediction was possible up to 1 MeV. Overall, the number of generated 2.2 MeV gamma-rays varied with both neutron energy and detector thickness.

Therefore, in future research, we plan to expand this approach by using multilayer configurations with varying thicknesses to enable measurements across specific energy ranges at individual layers.

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