

Simulation Study of a Wide-Energy-Range Neutron Beam Monitor Based on TMSR-PNS

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Abstract

To address the problems of neutron beam loss or beam instability caused by sparking during the operation of the Thorium-based molten salt reactor pulsed neutron source (TMSR-PNS), it is necessary to design and develop a neutron beam monitor with high count rate, low impact on the neutron beam, and high neutron/gamma discrimination performance. Using the Geant4 Monte Carlo simulation software, the influence patterns of key parameters such as neutron converter layer thickness, scintillator thickness, and housing material on the thin-film scintillator were systematically studied for thin-film plastic scintillator neutron beam monitors. The analysis results show that when the neutron converter layer thickness of the scintillator is approximately 2 m, it has a relatively appropriate intrinsic detection efficiency; when the scintillator thickness is 2 mm and the discrimination threshold is 0.1 MeV, the monitor possesses gamma-ray insensitivity. Simultaneously, by comparing the effects of different housing materials on electron generation from γ -rays, iron, which produces fewer electrons, was selected as the housing material. The research results can provide a theoretical basis for subsequent physical fabrication of the neutron beam monitor.

Full Text

Preamble

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Simulation Study of a Wide Energy Range Neutron Beam Monitor for TMSR-PNS

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Abstract

[Background] During operation of the Thorium Molten Salt Reactor-Particle and Neutron Source (TMSR-PNS), neutron beam instability or misfire events necessitate the development of a neutron beam monitor featuring high count rate capability, minimal neutron beam perturbation, and excellent neutron/gamma discrimination performance. **[Purpose]** This study investigates the influence of structural parameters on neutron beam monitor performance. **[Methods]** Considering that the TMSR-PNS energy spectrum primarily spans from thermal neutrons to 1 MeV, LiF was selected as the neutron conversion material. The SRIM program calculated the ranges of secondary charged particles in both the conversion layer and scintillator, providing preliminary thickness references. A physical model was then constructed in Geant4 and irradiated with neutrons and gamma rays of various energies. Simulation results were subsequently used to evaluate how parameters including neutron conversion layer thickness, scintillator thickness, metal housing, and PMT placement angle affect detector performance. **[Results]** The scintillator's neutron conversion layer thickness of approximately 2 μm yields relatively suitable intrinsic detection efficiency. With a scintillator thickness of 2 mm and a discrimination threshold of 0.1 MeV, the monitor demonstrates gamma-ray insensitivity. Furthermore, by comparing the effects of different housing materials on electron generation from gamma rays, iron—which produces fewer electrons—was selected as the housing material. **Conclusions** The parameter influence relationships obtained in this study provide theoretical guidance for subsequent physical detector fabrication.

Keywords: White neutron source, Neutron beam monitor, Geant4

Introduction

To meet the nuclear data requirements for the thorium-uranium cycle in TMSR, the Shanghai Institute of Applied Physics, Chinese Academy of Sciences, designed and constructed an electron linac-driven white neutron source (TMSR-PNS) for measuring key nuclear data of thorium-uranium cycle nuclides [1]. The facility focuses primarily on the thermal and epithermal neutron energy regions, particularly for measuring neutron cross sections in resonance regions, providing reliable total and capture cross-section data for the TMSR evaluated database [2].

Due to potential beam loss or discharge issues in white neutron source facilities, the incident neutron flux varies over time [3]. To reduce errors caused by neutron beam instability, a neutron beam monitor is required in addition to the main detector at the beam terminus. Currently, TMSR-PNS positions the neutron beam monitor off-axis at the beam end to minimize neutron beam

perturbation, but this arrangement cannot accurately measure the neutron flux incident on the sample target in real time under intense neutron/gamma irradiation backgrounds. To address this critical issue, a neutron beam monitor with high count rate capability, low neutron beam perturbation, and high neutron/gamma discrimination performance must be developed.

Boron-coated GEM neutron beam monitors are widely used in various neutron sources due to their high count rate, good position resolution, and minimal neutron beam perturbation. The Chinese Spallation Neutron Source (CSNS) installed seven ceramic GEM-based time-of-flight 2D position-sensitive neutron beam monitors on its first three spectrometers [4]. However, compared with CSNS, TMSR-PNS has a special environment with a smaller experimental hall and only a 6 m neutron flight path. Since the neutron beam monitor primarily measures neutron flux rather than position resolution, and must adapt to the confined installation space, GEM gas detectors are unsuitable for TMSR-PNS.

Wide-bandgap semiconductors such as SiC exhibit excellent radiation resistance [5] and have been applied in neutron beam monitors. Jiang et al. [6] used SiC detectors for neutron beam monitoring and developed a monitor for the neutron reflectometer at the Mianyang Research Reactor. Liu et al. [7] controlled impurity injection through oxygen atom plasma treatment to successfully prepare high-quality single-crystal diamond, which was tested at CSNS. Results demonstrated effective neutron pulse energy monitoring with high-reliability TOF spectra and minimal detector fluctuation effects, proving its suitability for fast neutron beam monitoring. However, growth process limitations restrict the fabrication of large-area devices for novel semiconductor materials, and internal defects may act as charge trapping centers, reducing the signal-to-noise ratio and limiting count rate capability [8].

Thin-film scintillator detectors offer advantages including fast time response, excellent radiation resistance, strong neutron/gamma discrimination, and minimal neutron beam perturbation [9]. Additionally, combined with a neutron conversion layer, they can simultaneously measure thermal neutrons, making them ideal for high-precision neutron beam monitoring.

Based on these considerations, this paper systematically analyzes the influence of structural parameters—including neutron conversion layer type and thickness, scintillator thickness, and housing material—on detector performance for thin-film scintillator detectors as neutron beam monitors for TMSR-PNS using the Geant4 Monte Carlo simulation software. The results provide a theoretical basis for subsequent prototype fabrication.

1.1 Detector Operating Principle

The thin-film scintillation detector consists primarily of a metal housing, neutron conversion layer, plastic scintillator, deflection magnet, and photoelectric conversion device, as shown schematically in [Figure 1: see original paper].

The housing, made of metal that scatters few neutrons and generates limited electrons, provides encapsulation and protection for the scintillator and photoelectric conversion device. The deflection magnet redirects electrons generated by gamma-ray interactions with the housing to reduce background. The neutron conversion layer and plastic scintillator form the core detection component, working with the photoelectric conversion device to generate photoelectric signals. The detection principle involves: thermal neutrons reacting with the conversion layer to produce secondary charged particles, while fast neutrons produce recoil protons in the scintillator. These particles deposit energy in the scintillator, generating visible photons that are captured by the photocathodes of photoelectric conversion devices positioned on both sides, producing current signals.

The scintillator used in subsequent simulations is the EJ212 plastic scintillator from Eljen Technology, specifically manufactured for thin applications (<5 mm) and capable of detecting alpha, beta, gamma, and neutron radiation. EJ212 features a short decay time, enabling high count rates in intense neutron beams, and exhibits stronger radiation resistance compared to other scintillators. The physical properties of EJ212 are listed in .

Common neutron conversion materials include ${}^6\text{Li}$, ${}^{10}\text{B}$, and ${}^{157}\text{Gd}$, which typically have high thermal neutron absorption cross sections. ${}^{157}\text{Gd}$ has the highest thermal neutron reaction cross section (24,000 barn) but produces gamma rays and internal conversion electrons of varying energies, resulting in poor neutron/gamma discrimination. ${}^{10}\text{B}$ has a thermal neutron reaction cross section of 3,840 barn and similarly emits ~0.48 MeV gamma rays, which is unfavorable for discrimination. Although ${}^6\text{Li}$ has a lower thermal neutron cross section of only 940 barn, its larger reaction energy produces secondary charged particles with greater kinetic energy that are easier to distinguish from gamma rays. Since elemental lithium oxidizes readily in air, the stable compound LiF was selected as the neutron conversion layer material.

This neutron beam monitor offers several advantages: the neutron beam only passes through the front and rear windows of the metal housing, the conversion layer, and the scintillator, minimizing material in the neutron path to reduce perturbation; the plastic scintillator/conversion layer combination effectively extends the neutron detection energy range; and the thin-film scintillator allows secondary charged ions to deposit most of their energy while Compton electrons from gamma rays lose relatively little energy, reducing gamma sensitivity.

1.2 Simulation Object

TMSR-PNS is a white neutron source driven by a 15 MeV electron accelerator. The accelerator produces 15–20 MeV pulsed electrons that, after magnetic deflection, bombard a tungsten target to generate bremsstrahlung X-rays. These high-energy X-rays undergo photonuclear reactions with target nuclei to produce primary neutrons (peaked at 1 MeV), which are then moderated by an

appropriate polyethylene moderator to create a continuous neutron energy distribution [2]. The neutron and gamma-ray energy spectra after moderation at the neutron exit channel are shown in [Figure 2: see original paper].

Since TMSR-PNS measures neutron nuclear reaction cross-section data for the thorium-uranium fuel cycle, the moderated neutron spectrum is rich in both the 1 MeV and thermal neutron regions, with neutrons primarily distributed in the 0.0253 eV-1 MeV range. Gamma-ray energies range from 0.01 MeV to 10 MeV, peaking at 0.1 MeV.

2.1 Neutron Conversion Layer Thickness Simulation

First, SRIM (Stopping and Range of Ions in Matter) software calculated the ranges of secondary charged particles in the neutron conversion layer and plastic scintillator, providing preliminary thickness references for subsequent simulations. Results are shown in .

The conversion layer thickness is a critical factor for thermal neutron intrinsic detection efficiency. Theoretically, increasing LiF thickness produces more secondary particles, improving detection efficiency. However, efficiency does not increase linearly with thickness. Greater thickness increases energy loss of secondary particles within the conversion layer, causing some particles to lose most or all of their energy before reaching the scintillator, thereby reducing efficiency. Geant4 simulations of thermal neutron detection efficiency at various conversion layer thicknesses are presented in [Figure 3: see original paper]. The figure clearly shows that as LiF thickness increases, thermal neutron detection efficiency first rises to a peak then gradually declines due to self-absorption of secondary charged particles in the conversion layer. The simulation indicates maximum detection efficiency (~3.6%) occurs at a LiF thickness of 30 μm .

[Figure 4: see original paper] shows the energy deposition spectra of secondary particles entering the scintillator at different conversion layer thicknesses. At 1 μm thickness, the 2.05 MeV alpha peak and 2.73 MeV triton peak are clearly visible, with the triton peak showing higher counts as alpha particles are more easily blocked in the conversion layer. As thickness increases, the probability of both particles escaping the conversion layer decreases, and severe self-absorption causes rapid peak broadening. Since alpha particles experience greater ionization energy loss than tritons in the conversion layer, the alpha and triton spectra overlap, degrading neutron/gamma discrimination performance.

For neutron beam monitors, detection efficiency is typically required to be 0.1%-1% [11]. Considering this requirement, a LiF thickness of 2 μm was selected, yielding an intrinsic detection efficiency of 1%.

2.2 Thin-Film Scintillator Thickness Simulation

The plastic scintillator thickness selection depends on two factors: (1) complete energy deposition of secondary charged particles to ensure adequate neutron

pulse signal amplitude, and (2) minimal thickness during complete deposition to achieve a sufficiently high neutron/gamma sensitivity ratio ($1000\times$). Based on the conversion layer simulation results, the influence of different scintillator thicknesses was investigated with a $2\ \mu\text{m}$ LiF conversion layer.

According to [1], the triton ($2.73\ \text{MeV}$)—the higher-energy secondary particle from the conversion layer—has a range of $61\ \mu\text{m}$ in plastic scintillator, requiring thickness $>61\ \mu\text{m}$ for complete energy deposition.

With identical scintillator and photomultiplier tube, the relative neutron/gamma sensitivity depends only on the number of scintillation photons produced per unit radiation intensity incident on the scintillator. Geant4 simulated the relative sensitivity to determine scintillator thickness. The simulation used thermal neutrons and $1\ \text{MeV}$ gamma rays with $N=10^7$ particles each. Varying plastic scintillator thickness from $0.1\ \text{mm}$ to $1\ \text{mm}$, the light yields L_n and L_γ for neutrons and gamma rays were calculated, with the neutron/gamma sensitivity ratio K defined as:

Since secondary charged particles lose approximately two orders of magnitude more energy in the scintillator than electrons produced by gamma-ray interactions, electron ranges far exceed those of secondary charged particles. [Figure 5: see original paper] shows that K increases as scintillator thickness decreases, exceeding 10 when thickness falls below $0.3\ \text{mm}$.

However, this does not meet the low gamma sensitivity requirement (neutron/gamma sensitivity ratio of $1000\times$), and neutron/gamma discrimination remains challenging. To further reduce gamma interference, a gamma discrimination threshold method was implemented to improve neutron/gamma discrimination performance.

First, the energy deposition distribution of secondary charged particles in the plastic scintillator was simulated to determine an appropriate gamma discrimination threshold range. As shown in [Figure 4: see original paper] and [Figure 6: see original paper], neutron secondary particle energy deposition concentrates in $0\text{--}2.73\ \text{MeV}$, while gamma-ray secondary electrons increase with scintillator thickness, concentrating in $0\text{--}0.6\ \text{MeV}$. Accordingly, the gamma discrimination threshold was set between $0\text{--}0.6\ \text{MeV}$.

The detection efficiency loss rates for neutrons and gamma rays within this threshold range were calculated using:

where η_{loss} represents detection efficiency loss due to threshold setting, η_{no} is efficiency without threshold, and $\eta_{\text{threshold}}$ is efficiency at different thresholds. [Figure 7: see original paper] shows that neutron and gamma detection efficiencies gradually decrease as the discrimination threshold increases. Since neutron secondary particles primarily have energies above $0.6\ \text{MeV}$, neutron detection efficiency decreases slowly—only $\sim 10\%$ loss at a $0.6\ \text{MeV}$ threshold. In contrast, gamma detection efficiency drops dramatically, with $>98\%$ loss at the same threshold, demonstrating that threshold setting is extremely effective

for reducing gamma interference.

The neutron/gamma sensitivity ratio at various scintillator thicknesses and gamma discrimination thresholds is shown in [Figure 8: see original paper]. Multiple thickness/threshold combinations achieve the required $1000\times$ ratio. To minimize neutron detection efficiency loss, a scintillator thickness of 2 mm with a gamma discrimination threshold of 0.1 MeV was selected, satisfying the $1000\times$ neutron/gamma sensitivity ratio requirement and achieving gamma-ray insensitivity.

2.3 Metal Housing

Housing material selection is critical in scintillation detector design to ensure structural strength while minimizing noise signal interference. Aluminum or iron are commonly used for their mechanical strength, but these metals also affect gamma-ray interactions. When gamma rays strike the metal entrance window, they generate numerous electrons that enter the scintillator as background noise, affecting detector performance. To understand material effects on noise, simulations compared electron emission when 1 MeV gamma rays irradiate iron and aluminum housings.

In Geant4, 10^7 gamma rays were uniformly and parallelly incident on $50\text{ mm} \times 1\text{ mm}$ iron or aluminum shells. A thin vacuum-filled geometry behind the entrance window recorded escaping electron numbers and energies. The resulting electron spectra in [Figure 9: see original paper] show that most emitted electrons from both materials have energies of 0-0.8 MeV, with aluminum producing more electrons than iron. Total emitted electrons were 50,737 from aluminum and 39,135 from iron, with total energies of 23,245.18 MeV and 18,737.580 MeV, respectively. Based on lower electron number and energy, iron was selected as the housing material.

2.4 Deflection Magnet

After selecting iron as the housing material, Geant4 simulations investigated its effect on the neutron/gamma sensitivity ratio. Simulations used 0.0253 eV neutrons and 1 MeV gamma rays with 1 mm iron housing thickness and 10 cm spacing between the housing front window and scintillator. Scintillators of 1 mm, 2 mm, and 3 mm thickness (50 mm diameter) compared light yield changes with and without iron housing, as shown in . The results indicate minimal impact on neutron light yield but significant increase in gamma light yield with iron housing.

[Figure 10: see original paper] compares neutron/gamma sensitivity ratios with and without iron housing, showing that iron housing reduces the ratio. Therefore, installing a magnet behind the housing entrance window can alter the trajectory of gamma-generated electrons, preventing them from reaching the scintillator. Compton electrons from iron housing concentrate in 0-0.8 MeV. At

maximum electron kinetic energy of 0.8 MeV, the velocity is $0.77c$, approaching light speed, requiring relativistic considerations for magnetic field calculations.

For electrons, the magnetic field strength B relates to kinetic energy E_k and deflection radius R by:

From [Figure 9: see original paper], the maximum electron energy from 1 MeV gamma rays penetrating the metal housing is 0.8 MeV, giving $E_k + 1.022 = 0.8$ MeV. Required magnetic field strength varies with distance between housing front window and scintillator: larger deflection radius requires smaller field strength. Calculations using the above formula are presented in , providing guidance for selecting appropriate magnet strength based on actual geometry during detector fabrication.

2.5 Photomultiplier Tube Positioning

In conventional scintillation detection systems ([Figure 11: see original paper] left), the photomultiplier tube (PMT) is typically placed behind the scintillator with light guide coupling to maximize scintillation photon collection efficiency. However, for thin-film scintillation neutron detectors placed directly in the neutron beam, direct neutron irradiation of the PMT entrance window (usually borosilicate glass) could produce interference signals stronger than scintillator signals. Additionally, to minimize neutron beam perturbation, the PMT cannot be placed behind the scintillator. Similar to the CSNS neutron beam monitor scheme (where conversion material and substrate are in-beam while the sensitive layer collects secondary particles outside the beamline) [11], the PMT can be positioned outside the neutron beamline ([Figure 11: see original paper] right).

Although this layout avoids direct neutron beam irradiation, it reduces scintillation photon collection efficiency because the thin scintillator limits side-emitted photons. To maximize collection efficiency under these conditions, Geant4 simulated the angular distribution of scintillation photons emitted from the scintillator.

Four PMT-scintillator configurations are shown in [Figure 12: see original paper]. Since the neutron conversion layer on the beam entrance side blocks photons, configurations (b) and (d) are preferred.

Simulations of photon emission angle distributions for various scintillator thicknesses are shown in [Figure 13: see original paper], where $\theta = 0^\circ$ indicates the scintillator entrance window is parallel to the neutron beam direction. Maximum photon emission occurs at $\theta = 20^\circ$, independent of scintillator thickness. Therefore, positioning the PMT at $\theta = 20^\circ$ (PMT central axis at 70° to scintillator normal) is recommended for optimal light collection. Since configurations (b) and (d) are symmetric about the beam axis, they provide equivalent collection efficiency, allowing selection based on PMT entrance window size and potential use of multiple PMTs for signal readout.

Conclusions

This study systematically investigated conversion layer thickness, plastic scintillator thickness, housing material, deflection magnet strength, and PMT relative position using Geant4 Monte Carlo simulations for TMSR-PNS. The results show:

1. For low neutron conversion efficiency requirements, a 2 μm thick ^6LiF conversion layer yields 1% intrinsic detection efficiency for thermal neutrons.
2. When scintillator thickness is below 0.3 mm, the neutron/gamma sensitivity ratio exceeds 10, insufficient for gamma insensitivity. By implementing a gamma discrimination threshold, the ratio improves to 1000 \times ; a 2 mm scintillator with 0.1 MeV threshold meets this requirement.
3. Iron was selected as housing material due to its minimal impact on gamma-ray transmission.
4. Magnets can be installed behind the metal housing entrance window to reduce effects of gamma-generated electrons on the scintillator.
5. Maximum fluorescence collection efficiency is achieved when the PMT central axis is at approximately 70° to the plastic scintillator normal.

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