# Efficiency-determined method for thermal neutron detection with inorganic scintillator postprint

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## Abstract

Due to the shortage of 3He, sintillator is a promising alternative for neutron detection in the fields of thermal neutron scattering and imaging. Furthermore, the neutron detection efficiency is difficult to determine. In this paper, the efficiency of inorganic scintillator for thermal neutron detection is presented based on probability principles, assuming that the scintillator material has a uniform elemental distribution and that the attenuation length of scintillation light is longer than the thickness of the scintillator. The efficiencies of two lithium glass samples were determined using this method, demonstrating that the method is useful for determining the efficiency of thermal neutron detection.

## Full Text

## Preamble

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### Efficiency-Determined Method for Thermal Neutron Detection with Inorganic Scintillator

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**Abstract**

Due to the global shortage of $^3$He, scintillator-based detectors represent a promising alternative for thermal neutron detection in scattering and imaging applications. However, determining the neutron detection efficiency remains challenging. This paper presents a method for calculating thermal neutron detection efficiency in inorganic scintillators using probability principles, assuming uniform elemental distribution and that the attenuation length of scintillation light exceeds the scintillator thickness. The efficiencies of two lithium glass scintillators were determined using this method, demonstrating its utility for thermal neutron detection efficiency determination.

**Key words**
Detection efficiency, Inorganic scintillator, Thermal neutron, Lithium

## Introduction

The construction of more intense reactor and spallation neutron sources has enabled the production of high-flux thermal neutrons for scattering and imaging applications in materials science and other fields. Thermal neutrons are defined as those with energies reduced below 1 eV, having an average kinetic energy of approximately 0.025 eV at 20°C—comparable to the thermal motion of atoms or molecules in the medium—and undergoing elastic scattering interactions.

Neutron detectors have traditionally relied on $^3$He gas, but the worldwide shortage of $^3$He has necessitated the development of alternative technologies. Inorganic scintillator detectors doped with neutron-sensitive elements such as $^6$Li, $^{10}$B, or $^{155}$,$^{157}$Gd show particular promise. However, determining the detection efficiency for scintillator detectors is complicated by several factors.

First, it is difficult to obtain a well-characterized standard neutron source while simultaneously suppressing the accompanying gamma-ray background that interferes with neutron signals. Second, neutrons are rarely monoenergetic, and detection efficiency varies with neutron energy, particularly below 5 MeV. Finally, efficiency depends on both detector properties and experimental counting geometry. Despite these challenges, accurate efficiency determination is essential for experimental design, detector development, and engineering applications.

The Monte Carlo (MC) method can be employed to calculate neutron detection efficiency, and when properly accounting for neutron energy, electronic thresholds, and scintillator geometry, simulations can yield highly accurate results. However, simulation outcomes are sensitive to underlying input data and associated uncertainties. Alternatively, detection efficiency ( ) can be calculated analytically using Eq.(1):

$$\varepsilon_A = 1 - e^{-n\sigma l} \quad (1)$$

where $n$ is the atomic number density of the material, $\sigma$ is the neutron capture cross-section, and $l$ is the scintillator thickness. For lithium glass, Eq.(1) can achieve 5% accuracy for energies below 100 eV.

While these approaches provide useful information, they cannot fully satisfy the requirements of experimental and engineering design, where the absolute detector efficiency must be known precisely. In practice, relative methods can be used to determine neutron flux, but measured efficiencies depend critically on the reference detector, which must itself be carefully characterized. This paper presents and discusses an experimental method for determining thermal neutron detection efficiency using inorganic scintillators, with efficiencies for two lithium glass samples measured and compared against theoretical calculations.

## 2.1 Efficiency Definition

Neutron detection efficiency is typically subdivided into absolute and intrinsic efficiency. Absolute efficiency ( ) is defined as:

$$\varepsilon_a = \frac{N}{N_s} \quad (2)$$

where $N$ is the number of neutron pulses recorded by the detector and $N$ is the number of neutrons emitted by the source. Because depends on both detector properties and source-detector geometry, it is difficult to measure directly.

Intrinsic efficiency ( ) is defined as:

$$\varepsilon_i = \frac{N}{N_d} \quad (3)$$

where $N$ is as defined above and *N_d* is the number of neutrons incident on the detector. If the detector subtends a solid angle Ω to a point neutron source, then equals Ω × / $4\pi$. When a detector completely surrounds a point source ($\Omega = 4\pi$), Eqs.(2) and (3) yield identical results, making it convenient to scale absolute efficiency using intrinsic efficiency. Unless otherwise specified, all subsequent discussions refer to intrinsic efficiency.

Because absolute and intrinsic efficiencies are difficult to determine directly, relative efficiency ( ) is commonly used instead, defined as:

$$\varepsilon_r = \frac{N \times \varepsilon_{ref}}{N_{ref}} \quad (4)$$

where *N_{ref}* is the count recorded by a reference detector and *_{ref}* is its known detection efficiency.

## 2.2 Efficiency-Determined Method

Neutrons, being neutral particles, travel in straight lines until they collide with nuclei, scattering into new directions or being absorbed. Table 1 shows the total cross-sections for thermal neutron interactions with elements commonly found in inorganic scintillators (data from ENDF/B-VII.0). For most host elements in inorganic scintillators, these cross-sections are small and negligible, resulting in minimal energy loss in the thermal energy range. The maximum energy loss per collision is easily calculated to be no more than 2%, making energy loss from host elements negligible. Consequently, incident neutrons in a scintillator face only two outcomes: escape or capture by neutron-sensitive elements such as $^{6}$Li, $^{10}$B, or $^{155}$,$^{157}$Gd.

For inorganic scintillator detectors based on nuclear reactions with these sensitive elements, neutrons penetrate the scintillator material until a nuclear interaction occurs. When a photomultiplier tube (PMT) coupled to the scintillator detects the resulting scintillation light, it records an effective pulse. By selecting an appropriate PMT and threshold setting, the electronic system efficiency for a scintillation detector can approach 100%.

Consider a thick scintillator of thickness $L$ with uniform elemental distribution. The scintillator can be conceptually divided into $n$ equal-thickness layers ($L$ ), each with identical detection efficiency. This thick scintillator can thus be modeled as a stack of thin scintillators with perfect junctions that do not affect uniformity or optical properties. Fig. 1 [Figure 1: see original paper] illustrates this concept, where dashed lines represent the partition divisions of Scin  (i = 1, 2, …, n), all identical to one another.

Let $N_1$ be the number of neutrons detected by Scin$_1$, and $N$  be the total counts from Scin$_1$ through Scin . The detection efficiency of the thick scintillator is defined as  . The detection efficiency for Scin$_1$ alone is:

$$\varepsilon = \frac{N_1}{N_d} \quad (5)$$

and the total efficiency is:

$$\varepsilon_t = \frac{N_n}{N_d} \quad (6)$$

If the scintillation light attenuation length exceeds $L$, then  can be expressed in terms of  through the following probabilistic analysis. For an incident neutron, the detection probability in Scin$_1$ is  , and the undetection probability is 1– . Since all Scin  layers are identical and energy loss is negligible, the undetection probability for Scin$_2$ is also 1– , making the detection probability for either Scin$_1$ or Scin$_2$ equal to 1–(1– )$^2$. After passing through Scin , the detection probability for the combined stack is:

$$\varepsilon_t = 1 - (1 - \varepsilon)^n \quad (7)$$

Combining Eqs.(5)–(7) yields:

$$\frac{\varepsilon}{1-(1-\varepsilon)^n} = \frac{N_1}{N_n} \quad (8)$$

Equation (8) shows that scintillator detection efficiencies can be obtained from relative count ratios, enabling determination of thick scintillator efficiency from thinner scintillator measurements without requiring absolute efficiency values.

## 3.1 Glass Properties and Test Setup

The lithium glass compositions are listed in Table 2 . The $^{6}$Li isotopic abundance is approximately 90%, with a mass density of 2.31 g/cm$^3$. Lithium glass samples of 1 mm and 3 mm thickness (5 cm diameter) were used in this study. The light yield was measured to be approximately 5671 photons per neutron and 3768 photons per MeV of gamma-ray deposition. The 3-mm thick lithium glass can be considered as three 1-mm layers with perfect junctions, giving $n = 3$ in Eq.(8).

The test setup is shown in Fig. 2 [Figure 2: see original paper]. A point neutron source ($^{252}$Cf) with an activity of 5$×10^{6}$ Bq is shielded in a box. Emitted neutrons are thermalized and guided through a 10-cm diameter channel, producing a thermal neutron flux of approximately 1–2 Hz/cm$^2$. The glass scintillator, coupled to a PMT (XP2020) with a gain of 1.2$×10^{7}$ using silicon grease, is packaged with Tyvek films for light collection. The total system efficiency, including PMT quantum efficiency, is approximately 10%. Because the PMT is sensitive to single photons, neutron-induced scintillation light is detected efficiently. A 5-cm thick lead plate shields gamma rays in front of the PMT. For background measurements, a 3-mm thick cadmium plate is placed between the moderator and lead plate to absorb neutrons.

The PMT signal is fed into a charge-sensitive amplifier (CSA) for shaping and amplification to prevent multiple discriminations of a single pulse. The CSA output is discriminated (Lecroy 623B) and counted (Caen Mod.N145). To ensure reliable discrimination and counting, the discriminator threshold is set as low as possible—easily achievable given the high light output of the glass and high PMT gain. Under these conditions, the electronic system and light collection efficiency can be considered approximately 100%, making the neutron detection efficiency determined solely by the lithium glass.

Fig. 3 [Figure 3: see original paper] shows the PMT pulse output. Fig. 3(a) displays the original pulse, while Fig. 3(b) shows both the original and amplified pulses after CSA processing. The CSA smoothes and enlarges the pulse (Channel 2), preventing multiple discriminations and reducing missed detection probability. With a 90 mV threshold—comparably low relative to pulse height—the discriminator can reliably process pulses lasting up to 8 s, sufficient for the neutron flux in this experiment.

## 3.2 Experimental Efficiencies

Detection efficiencies are measured in two steps: background counts and total counts (background + signal). Background is recorded with a cadmium plate between the lead plate and moderator; total counts are recorded without the cadmium plate.

Table 3 shows the measured counts for 1-mm and 3-mm lithium glass samples. $C$ and $C\_b$ represent counts without and with the cadmium plate, respectively, where $C-C\_b$ gives the net neutron events after background subtraction.

**Table 3** Lithium glass neutron counts in 1400 s

| Lithium glass (mm) | $C-C\_b$ | Eff (%) |
|---|---|---|
| 1 | 26274 | 65.6 |
| 3 | 38402 | 95.9 |

From Eq.(8), the $C-C\_b$ values for 1-mm and 3-mm lithium glass correspond to $N_1$ and $N_3$. Assuming the 1-mm lithium glass efficiency is  , the single-variable equation becomes:

$$\frac{\varepsilon}{1-(1-\varepsilon)^3} = \frac{26274}{38402}$$

Solving yields  = 65.6% for the 1-mm glass, and 1–(1– $)^3$ = 95.9% for the 3-mm glass, as listed in Table 3.

## 3.3 Theoretical Efficiencies

Neutron reaction probabilities were simulated using Geant4 for $^6$Li glass. Since electronic and light collection efficiencies are considered 100%, the PMT can be ignored in the simulation. The lithium glass is positioned on the x–y plane with its center at the origin. A point beam gun emits 25.3 meV thermal neutrons from (0 mm, 0 mm, 10 mm). The QGSP_{{{BERT}}_{{HP}}} physics list recommended by Geant4 for low energies is used. After 100,000 neutron histories, the $^6$Li(n,$\alpha$)$^3$H reaction probabilities are recorded for both glass thicknesses, with capture efficiencies approaching the detection efficiencies listed in Table 4 .

For comparison, detection efficiencies were also calculated using Eq.(1) with $\sigma$ = 940 barns for 25.3 meV neutrons.

**Table 4** Lithium glass efficiencies from simulation and analytical calculation

| Lithium glass (mm) | Simulated (%) | Calculated (%) |
|---|---|---|
| 1 | 65.2 | 65.2 |
| 3 | 95.8 | 95.8 |

Discrepancies between Tables 3 and 4 may arise from several uncertainties. First, Table 3 reflects actual experimental counts, while Table 4 represents probabilities of $^6$Li(n,$\alpha$)$^3$H interactions—not every interaction necessarily produces a pulse height above the experimental threshold, though simulations and analytical calculations assume they do. Second, Table 4 assumes all neutrons are exactly 25.3 meV, whereas actual neutron energies distribute around this value after moderation (Fig. 2).

At a threshold of 555 pC, the detection efficiency is 65.2% for 1-mm lithium glass and 95.8% for 3-mm glass, closely matching our results. The gamma suppression capability is 1.8\$×10^{-3}\$ at 95.8% efficiency, confirming the credibility of the presented method for determining neutron scintillator detection efficiency.

## 4 Conclusion

An efficiency-determination method for neutron scintillators has been presented and modeled using probability principles. The efficiencies of two lithium glass samples were studied, yielding 65.6% for the 1-mm thick glass and 95.9% for the 3-mm thick glass, in agreement with theoretical predictions.

The method assumes uniform elemental distribution in the scintillator and that the scintillation light attenuation length exceeds the scintillator thickness. If the scintillator is too opaque or thick, light generated in earlier layers may be attenuated before reaching the PMT. However, these assumptions are readily satisfied for many neutron detection scintillators through appropriate material selection.

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*Note: Figure translations are in progress. See original paper for figures.*