A calculation of relative efficiencies of a GEM-based neutron detector using different solid neutron converters

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Abstract. A Gas Electron Multiplier (GEM) detector is one of the most promising particle detectors nowadays due to its excellences in high rates of detection capability, good spatial resolution, and flexibility in designs. In addition to typical applications of ionizing particle detection, the GEM detector could also be modified to detect thermal neutrons by coating suitable solid neutron converters to its GEM drift cathode. Although, wide selections of materials are available to be used as neutron converters, most suitable ones must have high neutron-absorption-cross-section properties as more chances of nuclear interactions between thermal neutrons and their nuclei are desirable. Another factor that plays important roles to detection efficiencies in addition to types of materials is thicknesses of coating layers. Although thicker layers mean higher numbers of nuclei available for interactions with neutrons, ionizing particles produced after the interactions have less chances of successfully penetrate thick layers to ionize gas molecules for detection. Consequently, an optimum thickness for each material is crucial for GEM-based thermal neutron detector and must be carefully determined. This article aims to illustrate in-depth calculations to find these optimum thicknesses and their corresponding relative efficiencies for different solid neutron converters including $^6$Li, $^{7}$Li, $^{10}$B, $^{10}$B, $^{113}$Cd, $^{115}$Cd, $^{149}$Sm, and $^{150}$Sm, using a simulation and actual data of GEM’s properties. Basic information of GEM detector and neutron detection, simulations, efficiency calculations, results, and discussion will be thoroughly reported in this article.

1. Introduction

1.1. Gas Electron Multiplier (GEM) detector

A Gas Electron Multiplier (GEM) detector is a gaseous charge amplification detector invented by F. Sauli in 1997 [1,2]. Since the invention, the GEM detector has been developed and used in great numbers of nuclear and high energy particle researches including the large size GEM for Super Bigbite Spectrometer (SBS) polarimeter for Hall A 12 GeV program at Jlab [3], large size GEM for future PREX-like experiments [4], a triple-GEM for CMS muon detector upgrade, and a triple-GEM tracker for KLOE experiment [5]. In addition to scientific researches, the GEM detector is also utilized in various applications including low energy x-ray monitor for burning plasmas in tokamaks [6] and Single-Photon Emitted Computed Tomography (SPECT) combined with x-rays Computed Tomography (CT) in medical applications [7].

The standard triple-GEM detector is a cascade of...
- **GEM drift cathode**: a thin aluminized polyimide film placed topmost of the cascade with the most negative voltage to guide ionized electrons towards the GEM readout.
- **GEM foils**: a thin polyimide film coated by metal clads (usually copper) on both sides of the film. A GEM foil is perforated with a regular matrix of 70-μm holes. These holes are closely spaced with a pitch of ~140 μm from one center of the hole to centers of the closest neighboring holes. The first GEM foil is placed 3 mm below the GEM drift cathode, while all GEM foils are spaced 2 mm from each other. The third GEM foil is placed 2 mm above the GEM readout.
- **GEM readout**: in most applications, the GEM readout consists of two sets of thin wires running perpendicular to each other (XY configuration). However, the GEM readout could also be designed as arrays of micro-sized square pads depending on intended applications. The GEM readout is usually connected to a common ground (highest voltage) of electronic circuits. Amplified numbers of electrons are transferred through connectors that connect to data acquisition system (DAQ) for data processing. Major components of a standard GEM detector are shown in figure 1.

**Figure 1.** Side views of a complete assembly of a GEM detector, a GEM foil with magnified GEM holes, and a GEM drift cathode, which is coated by a solid neutron converter film for thermal neutron detection.

Since GEM’s properties heavily rely on properties of gas used, selection of appropriate gas flow is important to operate the detector. In principle, a pure noble gas such as helium or argon could be used, however, in order to increase stability of the detector, a quenching gas such as CO₂ or C₄H₁₀ is usually added to the gas mixture. For general applications, a gas mixture of Ar/CO₂ (70:30) is normally used. Another important factor needed to be considered is the gas flow rate. Although there was a report that high gas flow rates (up to 10.5 L/hr) did not have significant effects on a standard 10 cm x 10 cm GEM’s properties [8], the gas flow rate should be high enough to flush 10 times of a volume of a GEM detector such that new gas could sufficiently replace depleted gas for better detection. For example, a standard 10 cm x 10 cm GEM prototype needs at least 3.0 L/hr of gas flow rates to efficiently operate the detector.

1.2. **GEM-based thermal neutron detector**
Although GEM detector is known for their excellences in ionizing particle and low-energy photon detection, it could be modified by coating its GEM drift cathode with a high-neutron-absorption-cross-section converter [9] as shown in figure 1 for thermal neutron detection. Criteria for selecting a
suitable solid neutron converter depends on intended applications, however, major points that are crucial for consideration are:

- **Neutron-absorption-cross-section of a material.** Since neutrons are electrically neutral, they do not directly ionize gas molecules, leading to extremely low detection efficiency. In order to increase the efficiency, a process to convert neutrons to secondary ionizing particles is required. This process could be done via nuclear reactions between thermal neutrons and nuclei of neutron converters as shown in figure 2.

![Figure 2. Nuclear interaction between an incoming thermal neutron and a $^{10}$B nucleus, which produces an alpha particle and $^{7}$Li traveling in opposite directions.](image)

Examples of commonly used high-neutron-absorption-cross-section converters are $^{6}$Li, $^{6}$Li, $^{10}$B, $^{10}$B, $^{113}$Cd, $^{113}$Cd, $^{149}$Sm, and $^{149}$Sm. Although $^{6}$Li, $^{10}$B, $^{113}$Cd, and $^{149}$Sm isotopes have much higher neutron-absorption-cross-section values than their natural composites, they require sophisticated procedures to enrich, which could significantly increase complications and costs of manufacturing. Equations showing interactions between thermal neutrons and selected nuclei are shown in equations (1.1)-(1.4).

\[
^{6}$Li + n $\rightarrow$ $^{3}$H (2.75 MeV) + α (2.05 MeV) \tag{1.1}
\]

\[
^{10}$B + n $\rightarrow$ $^{7}$Li (0.84 MeV) + α (1.47 MeV) \tag{1.2}
\]

\[
^{113}$Cd + n $\rightarrow$ $^{114}$Cd + γ (0.558 MeV) \tag{1.3}
\]

\[
^{149}$Sm + n $\rightarrow$ $^{146}$Nd (1.66 MeV) + α (8.96 MeV) \tag{1.4}
\]

- **Thickness of a coating layer.** Thicker layers of neutron converters mean more numbers of available nuclei to interact with neutrons per unit area, leading to better detection ability. However, too thick layers could inversely reduce efficiencies as secondary ionizing particles produced from the interactions could not penetrate through the converter layer to ionize gas molecules for detection. Consequently, an optimum thickness of each coating layer must be thoroughly calculated in order to maximize detection ability.

- **Types/energies of secondary ionizing particles produced.** As shown in equations (1.1)-(1.4), secondary ionizing particles produced depend on types of neutron converters. For $^{6}$Li, $^{10}$B, and $^{149}$Sm, alpha particles (α) are produced, while gamma (γ) is produced in the case of $^{113}$Cd. Generally, an alpha particle has extremely short ranges in matter (usually in micrometer
ranges) due to its relatively high electric charge. On the other hand, gamma is an electromagnetic wave that could travel much further in matter due to their less chances of interactions and low Linear Energy Transfer (LET). These properties of secondary ionizing particles must be taken into considerations when selecting neutron converters.

As several factors could play roles in defining GEM-based thermal neutron detection, a careful and thorough determination must be performed in order to maximize detection efficiencies. This article aims to report details of calculations and analysis to find optimum thicknesses for different solid neutron converters: $^6$Li, $^{nat}$Li, $^{10}$B, $^{nat}$B, $^{113}$Cd, $^{nat}$Cd, $^{149}$Sm, and $^{nat}$Sm. Results will be useful for all GEM-based neutron detector in both basic and applied researches.

2. Methodology

To calculate relative efficiencies ($\varepsilon_{rel}$) for each solid neutron converter, two main parts that are needed to be considered are reaction rates per unit area ($RR$) of neutrons and nuclei of neutron converters, and corrections ($\kappa$) from trajectories of emitted ionizing particles ($\kappa_\theta$) and GEM’s efficiency to detect that particular ionizing particles ($\kappa_{eff}$). The equation that relates $\varepsilon_{rel}$, $RR$, and $\kappa$ is shown in equation (2.1).

$$\varepsilon_{rel} \propto RR \times \kappa$$

(2.1)

2.1. Reaction rates per unit area ($RR$)

For a uniform neutron flux on an active area of GEM detector, reaction rates per unit area ($RR$) of the interactions between incoming thermal neutrons and nuclei of solid neutron converters are a function of incoming neutron flux ($\Phi$), number of solid neutron converter’s nuclei per unit area ($N$), and neutron-cross-section of solid neutron converter ($\sigma$) as shown in equation (2.2).

$$RR = \Phi \times N \times \sigma$$

(2.2)

However, $N$ could be expressed as

$$N = n \times t$$

(2.3)

$$N = \left(\frac{\rho}{M}\right) \times t$$

(2.4)

where $n$ is the nuclear density, $t$ is the thickness of the solid neutron converter’s layer, $\rho$ is the mass density, and $M$ is the molecular mass of the solid neutron converter’s nuclei. As a result, when considering only factors from designs and properties of neutron converter materials, $RR$ is related to $\rho$, $M$, $t$, and $\sigma$ as

$$RR \propto \left(\frac{\rho}{M}\right) \times t \times \sigma$$

(2.5)

Values of $\rho$, $M$, and $\sigma$ for each type of solid neutron converters are shown in table 1.

| Element  | $\rho$ (g/cm$^3$) | $M$ (g) | $\sigma$ ($10^{-24}$ cm$^2$) |
|----------|-------------------|---------|-----------------------------|
| $^6$Li    | 0.535             | 6.00    | 940.4                       |
| $^{nat}$Li| 0.535             | 6.94    | 70.5                        |
| $^{10}$B  | 2.460             | 10.00   | 3835.9                      |
| $^{nat}$B | 2.460             | 10.81   | 767.8                       |
| $^{113}$Cd| 8.650             | 113.00  | 20600.4                     |
| $^{nat}$Cd| 8.650             | 112.41  | 2520.5                      |
| $^{149}$Sm| 7.353             | 149.00  | 42080.4                     |
| $^{nat}$Sm| 7.353             | 150.36  | 5922.5                      |
2.2. Corrections ($\kappa$)

2.2.1. Trajectories of emitted ionizing particles ($\kappa\theta$). As nuclear interactions occur, emitted ionizing particles could travel in any direction with equal probability. However, only particles that travel downwards with distances shorter than its ranges are able to penetrate through solid neutron converter layers and ionize gas molecules for detection.

![Figure 3](image_url)

**Figure 3.** Trajectory of emitted ionizing particles. Only particles that travel within $2\theta$ are able to penetrate through solid neutron converter layer and ionize gas molecules for detection.

As shown in figure 3, only particles that are emitted within $2\theta$ are considered to be active particles for detection. Thus, a correction factor for trajectory of emitted ionizing particles ($\kappa\theta$) could be calculated as

$$\kappa\theta = \frac{2\theta}{2\pi} = \frac{\theta}{\pi}$$  \hspace{1cm} (2.6)

To calculate $\theta$, ranges of emitted ionizing particles ($R$) and average depth of interactions ($d$) must be determined. Since different types/energies of ionizing particles have different values of $R$ depending on types of materials encountered, simulations must be done to find $R$. To serve this purpose, a software called SRIM-2013 [10] was used and results of simulations are shown in figure 4 and table 2.

![Figure 4](image_url)

**Figure 4.** Simulations using SRIM-2013 to find ranges of alpha particles emitted from interactions between neutrons and $^6$Li/nat Li (left), $^{10}$B/nat B (middle), and $^{149}$Sm/nat Sm (right) nuclei respectively.

In the case of $^{113}$Cd and nat Cd, $\gamma$ with the energy of 0.558 MeV is emitted. Since gamma has low Linear Energy Transfer (LET), its ranges are much longer than the thickness of materials ($R >> t$) used in this efficiency calculations.

**Table 2.** Ranges of emitted ionizing particles for all solid neutron converters.
| Element          | Emitted particles | Energy (MeV) | Ranges (μm) |
|------------------|-------------------|--------------|-------------|
| $^6\text{Li}/^{nat}\text{Li}$ | α                 | 2.05         | 23.3        |
| $^{10}\text{B}/^{nat}\text{B}$ | α                 | 1.47         | 3.5         |
| $^{113}\text{Cd}/^{nat}\text{Cd}$ | γ                 | 0.558        | $\gg t$     |
| $^{149}\text{Sm}/^{nat}\text{Sm}$ | α                 | 8.96         | 38.5        |

As shown in equation 2.5, $RR$ is directly proportional to $t$, i.e. numbers of interaction increase linearly with $t$. By assuming that numbers of incoming neutrons are large and $t$ is much smaller than ranges of neutrons in the materials, the average interaction depth ($d$) could be simplified to be at the midpoint of the materials, i.e. $d = t/2$. Although the actual interaction depth could vary throughout the materials, this simplification is sufficient for relative efficiency calculation. Hence, $\theta$ could be expressed as

$$\theta = \arccos \left( \frac{t}{2R} \right)$$

and consequently,

$$\kappa_\theta = \frac{\arccos \left( \frac{t}{2R} \right)}{\pi}$$  \hspace{1cm} \text{(2.8)}

2.2.2. GEM’s efficiency ($\kappa_{eff}$). GEM has different detection efficiencies for different types of ionizing particles. In the case of alpha particles, the efficiency is almost 100% [11], while only 4% in the case of gamma [12]. These reported efficiencies were measured using standard gas mixtures of Ar/CO$_2$ (70:30), while the gas flow rates did not significantly affect detection efficiency of GEM as shown in [8]. Thus, the overall corrections ($\kappa$) could be expressed as

$$\kappa = \kappa_\theta \times \kappa_{eff}$$

where $\kappa_{eff} = 1.00$ for $^6\text{Li}$, $^{nat}\text{Li}$, $^{10}\text{B}$, $^{nat}\text{B}$, $^{149}\text{Sm}$ and $^{nat}\text{Sm}$, while $\kappa_{eff} = 0.04$ for $^{113}\text{Cd}$ and $^{nat}\text{Cd}$.

3. Results and discussion

Using (2.5) and data in table 1, $RR$ as a function of $t$ could be calculated. Results of relative $RR$ using the value from $^{149}\text{Sm}$ at $t = 40 \mu m$ as a reference for normalization is shown in figure 5.

**Figure 5.** Relative reaction rates ($RR$) of nuclear interactions between thermal neutrons and $^6\text{Li}$, $^{nat}\text{Li}$, $^{10}\text{B}$, $^{nat}\text{B}$, $^{113}\text{Cd}$, $^{nat}\text{Cd}$, $^{149}\text{Sm}$, and $^{nat}\text{Sm}$ using the value from $^{149}\text{Sm}$ at the thickness of 40 $\mu m$ for normalization.
As shown in figure 5, relative RR for $^{149}$Sm and $^{113}$Cd are much higher than other nuclei. These behaviors are mainly due to their much higher $\sigma$. However, when factoring in corrections $\kappa_d$ and $\kappa_{eff}$, $\varepsilon_{rel}$ behaves differently from results of relative RR. Results of $\varepsilon_{rel}$ with $t$ varying from 0 to 40 $\mu$m and from 0 to 8 $\mu$m are shown in figure 6 and figure 7 respectively.

![Figure 6](image_url)

**Figure 6.** Relative efficiency ($\varepsilon_{rel}$) of GEM-based neutron detection using $^6$Li, $^{nat}$Li, $^{10}$B, $^{nat}$B, $^{113}$Cd, $^{nat}$Cd, $^{149}$Sm, and $^{nat}$Sm as solid neutron converters (thicknesses of coating layers from 0 to 40 $\mu$m). Results are normalized using the value from $^{149}$Sm at the thickness of 40 $\mu$m as a reference.

![Figure 7](image_url)

**Figure 7.** Relative efficiency ($\varepsilon_{rel}$) of GEM-based neutron detection using $^6$Li, $^{nat}$Li, $^{10}$B, $^{nat}$B, $^{113}$Cd, $^{nat}$Cd, $^{149}$Sm, and $^{nat}$Sm as solid neutron converters (thicknesses of coating layers from 0 to 8 $\mu$m). Results are normalized using the value from $^{149}$Sm at the thickness of 40 $\mu$m as a reference.

As shown in figure 6, a solid neutron converter made of $^{149}$Sm has the highest $\varepsilon_{rel}$ due to its high $\sigma$, relatively longer $R$ of its 8.96-MeV emitted alpha particles ($\sim$38.5 $\mu$m), and almost perfect alpha detection efficiency of GEM detector. On the other hand, $\varepsilon_{rel}$ of $^{113}$Cd is significantly reduced due to much lower (only 4%) gamma detection efficiency of the GEM detector. Furthermore, the importance of thickness is greatly emphasized in the case of $^{10}$B and $^{nat}$B, where both types of nuclei have their highest $\varepsilon_{rel}$ at the thickness of $\sim$4.5 $\mu$m and decrease substantially to zero at the thickness of $\sim$7 $\mu$m.
These behaviors are due to their 1.47-MeV emitted alpha particles having low values of $R$ (~3.5 μm) where thicker coating layer absorbs most of alpha particles and reduces $\varepsilon_{rel}$.

4. Conclusions

The GEM-based thermal neutron detector could be used to detect neutrons with different efficiencies depending on types/thicknesses of solid neutron converters. For this study, data of high-neutron-absorption-cross-section nuclei including $^6$Li, $^{nat}$Li, $^{10}$B, $^{nat}$B, $^{113}$Cd, $^{nat}$Cd, $^{149}$Sm, and $^{nat}$Sm along with actual GEM properties are used to calculate relative efficiencies. Results show that, $^{149}$Sm has the highest detection efficiency, mostly due to its highest neutron-cross-section, longer ranges of its 8.96-MeV emitted alpha particles, and almost perfect alpha detection efficiency of GEM detector.

Information from this study would be useful for all GEM-based neutron detection researches as researchers could utilize an optimum thickness for each selected solid neutron converter to maximize neutron detection efficiency.

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References

[1] Sauli F 1996 A new concept for electron amplification in gas detectors Nucl. Instr. and Meth. A. 386 531—34
[2] Sauli F 2004 Progress with the gas electron multiplier Nucl. Instr. and Meth. A. 522 93-98
[3] Gnanvo K, et al. 2015 Large Size GEM for Super Bigbite Spectrometer (SBS) polarimeter for Hall A 12 GeV program at Jlab Nucl. Instr. and Meth. A. 782 77—86
[4] Saenboonruang K and Liyanage N 2015 Q$^2$ Measurement and Challenges in PREX Kasetsart J. (Nat. Sci.) 49 277—87
[5] Sauli F 2016 The gas electron multiplier (GEM): Operating principles and applications Nucl. Instr. and Meth. A. 805 2—24
[6] Murtas F 2013 Applications of triple GEM detectors beyond particle and nuclear physics Proc. Int. Conf. on Micro Pattern Gaseous Detectors (Zaragoza, Spain) (IOP Science) C01058
[7] Tsyganov E, et al. 2008 Gas Electron Multiplying detectors for medical applications Nucl. Instr. and Meth. A. 597 257—65
[8] Saenboonruang K, et al. Effects of High Gas Flow Rates on the Standard 10 cm x 10 cm GEM prototype Chiang Mai J. Sci. 43(4) 876—83
[9] Park S H, Kim Y K and Kim J K 2005 Neutron detection with a GEM IEEE Trans. Nucl. Sci. 52 1689—92
[10] Ziegler J F Interactions of ions with matter; Available from: http://www.srim.org/. Accessed: 2016-07-14.
[11] Charpak G, Benaben P, Breuill P and Peskov V 2008 Detectors for alpha particles and X-rays operating in ambient air in pulse counting mode or/and with gas amplification J. Instrum. 3 P02006
[12] Lee S, Jung J H and Lee R 2014 Research of Efficiency for Gas Electron Multiplier Detector to Monitor Low Energy Gamma-Ray and Beta-Ray Progress. Med. Phys. 25(2) 95—9