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Thermal neutron response of a boron-coated GEM detector via GEANT4 Monte Carlo code

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HIGHLIGHTS

- The results of boron-coated GEM for thermal neutrons are described.
- The simulations were performed by GEANT4 MC code.
- The evaluation was determined by GEANT4 using two physics lists.
- The response of the detector was taken for E_n=25–100 meV.

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ABSTRACT

In this work, we report the design configuration and the performance of the hybrid Gas Electron Multiplier (GEM) detector. In order to make the detector sensitive to thermal neutrons, the forward electrode of the GEM has been coated with the enriched boron-10 material, which works as a neutron converter. A total of 5×5 cm^2 configuration of GEM has been used for thermal neutron studies. The response of the detector has been estimated via using GEANT4 MC code with two different physics lists. Using the *QGSP_BIC_HP* physics list, the neutron detection efficiency was determined to be about 3%, while with *QGSP_BERT_HP* physics list the efficiency was around 2.5%, at the incident thermal neutron energies of 25 meV. The higher response of the detector proves that GEM-coated with boron converter improves the efficiency for thermal neutrons detection.

1. Introduction

Historically, the Gas Electron Multiplier (GEM) was first developed by F. Sauli in 1996 at the Center of European Nuclear Research (CERN) (Sauli, 1997, 2000; Buzulutskov, 2007). Gas Electron Multiplier is a part of the micropattern gas detectors and is considered one of its most useful configurations. Because of their useful features, GEM-based radiation detectors are getting much attention. In particular, with their attractive applications, GEM-based detectors are being used in high energy physics, nuclear physics, astrophysics, and the medical-imaging field (Buzulutskov, 2007). At present, GEM based detectors are used in tracking detectors (Altunbas et al., 2002; Ketzer et al., 2004; Aulchenko et al., 2002; Bozzo et al., 2004; GDD) including those operating in intense particle fluxes (Bachmann et al., 2001), fast detectors for trigger systems (Alfonsi et al., 2004a, 2004b), end-cap detectors for time-projection chambers (TESLA, 2001; Karlen et al., 2005; Ableev et al., 2005; TPC, 2006), Cherenkov detectors (Fraenkel et al., 2005; Kozlov et al., 2004) and many other detector experiments (Buzulutskov 2007; GDD).

The GEM detector is usually composed of a thin structure of two metal electrodes with an insulating foil inserted in between them. This layer is perforated with holes, wherein the electron multiplication can take place, upon applying the potential difference (Ostling, 2006). A typical GEM detector consists of 50 μm thin Kapton foil coated with a 5 μm copper electrode layers on both sides. This set-up is chemically etched with double conical holes

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with a hexagonal pattern holes. The diameter of the holes is kept as 70 ± 5 μm for the copper and 50 ± 5 μm for the Kapton, while the holes have a pitch of 140 μm (Ostling, 2006).

Upon applying an electric potential difference between the two electrodes, a strong electric field is focused within the holes of GEM set-up. While injecting an electron into a hole it is accelerated by strong electric field, and creates an avalanche of secondary electrons. Ever since the GEM works in the region of proportional multiplication, the total number of electrons produced in such way can be controlled by the applied potential by its electrodes. The ions created in this process move upwards, either to the GEM-top electrode or further up in its configuration. Some of the avalanche electrons are attracted towards the GEM-bottom electrode, and the rest of them emerging from the holes are transferred downstream (Ostling, 2006). As a unique application such GEM-based detector could be employed for the detection of thermal neutrons. For this purpose an investigation of thermal neutrons based on a converter coated-GEM has been reported in this work. A hybrid GEM-chamber has been configured in C++ (object oriented language) and simulated with GEANT4 Monte Carlo code (Agostinelli et al., 2003). Here, the results of the study taken with the two physics lists are presented in detail.

2. Boron convertor

As the neutrons are neutral particles, they cannot be detected by the detector directly, without converting them into charged particles. For this purpose a converter material is employed. The converter is a special and suitable material used inside the detector gas gap for the interaction of the thermal neutron that generates charged particles (Sen et al., 2009). According to Ref. Neutron Cross Section (1976) Gd, ^{10}B and ^{7}Li are the three suitable materials which have the highest neutron absorption cross section. Upon comparison with the highly reactive and expensive ^{6}Li, a solid ^{10}B layer seems to be much more suitable for use as a neutron converter. Also ^{10}B can easily be produced in reasonable sizes via evaporation or sputtering techniques. Further ^{10}B (enrichment > 99%) is commercially available (Zhou et al., 2011). Therefore in this work, we have employed ^{10}B as converter material for the detection of thermal neutron. The enriched boron-10 has been coated on one surface of copper cathode plate. Thermal neutrons have been detected using the following neutron reactions:

$$n + {}^{10}\text{B} \rightarrow \alpha + {}^{7}\text{Li} + 2.79\ \text{MeV}(7\%)$$

$$n + {}^{10}\text{B} \rightarrow \alpha + {}^{7}\text{Li}^{*} + 2.31\ \text{MeV}(93\%)$$

When the thermal neutrons induce the ^{10}B (n, α) ^{7}Li reaction, 93% of all the reactions lead to the first excited state of ^{7}Li, which further decays spontaneously (~73 fs half-time) to the ground state of ^{7}Li by emitting the 0.48 MeV gamma ray, and 7% of the reactions result in the ground state of ^{7}Li. When the reaction proceeds to the first excited state of ^{7}Li, 0.84 MeV ^{7}Li and 1.47 MeV α particles are produced. The thermal neutron (0.0253 eV) cross section of the ^{10}B (n, α) ^{7}Li reaction is 3840 barn, which drops rapidly with an increase in thermal neutron energy (Zhou et al., 2011).

3. Boron-coated GEM detector configuration

For the detection of thermal neutrons, we employed the ^{10}B converter-coating on the forward electrode of the double-layer GEM configuration. A schematic view of the converter based GEM detector can be seen in Fig. 1. The configuration of the detector set-up has been built in with C++ for the GEANT4 (Agostinelli et al., 2003) MC simulation.

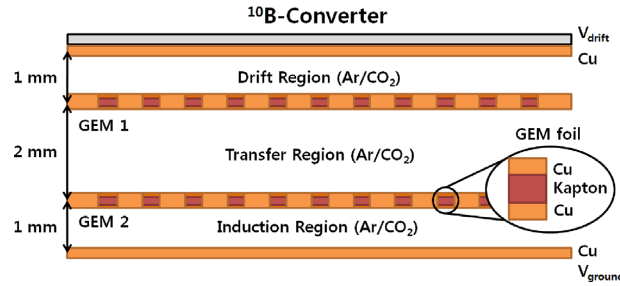

Fig. 1. A schematic view of the converter-based GEM detector.

Table 1
Thermal neutron detection efficiencies taken with different thicknesses of converter coatings.

Thickness (μm)	*QGSP_ BIC_ HP* detection efficiency	*QGSP_ BERT_ HP* detection efficiency
0.1	0.01549	0.01554
0.5	0.02049	0.02178
1.0	0.02488	0.02437
2.0	0.02526	0.02456
3.0	0.02458	0.02354
5.0	0.02268	0.02325
7.0	0.02232	0.02167
10.0	0.02136	0.02063
20.0	0.01870	0.01891
25.0	0.01656	0.01665
30.0	0.01461	0.01498
40.0	0.01342	0.01429
50.0	0.00839	0.00889

The basic configuration of GEM detectors consists of double-GEM layer sandwiched between the copper electrodes. The thickness of the drift gap, transfer gap and induction gap was set as 1 mm, 2 mm and 1 mm, respectively. The GEM foils are made of 50 μm thick Kapton sheets sandwiched between copper cladding of 5 μm. The GEM-detector is filled with a standard mixture of Ar and CO_2 (70%:30%). For this study, a total area of the ^{10}B-coated GEM was taken as 5 × 5 cm^2.

4. Detector response obtained via GEANT4

GEANT4 (Agostinelli et al., 2003) based MC simulation code has been used to simulate the detector response known as sensitivity for incident thermal neutrons. With this GEANT4 code, the response of the detector has been evaluated as a function of incident neutron energy with two different physics lists i.e., *QGSP_BIC_HP* and *QGSP_BERT_HP*. In our simulation, the probability for a neutron to produce a charged particle (α or ^{7}Li) coming out of the converter layer as a function of neutron energy has been evaluated for the event generation. The detection efficiency of the detector has been evaluated with GEANT4, upon accumulating both the charged particle (α or ^{7}Li) coming out of the converter layer as a function of neutron energy. Thus the total efficiency evaluated here is the sum of both the charged particle signals from (α or ^{7}Li). In order to minimize the uncertainties in the simulated results for each neutron energy, a total of 10^6 monoenergetic thermal neutron beams have been generated via the GEANT4 code.

The evaluated detector efficiency at E_n=25, as a function of converter thickness taken with two physics lists, is shown in Table 1. Similarly Fig. 2 demonstrates the detector sensitivities evaluated for the incident thermal neutrons with energies of 25–100 meV as a function of ^{10}B converter thickness. The maximum sensitivity for a double layer ^{10}B-GEM was found at converter thickness of 1–3 μm. According to these results at

E_n=25 meV, with few micron converter thickness, the sensitivity is quite low. As the converter thickness increases, the sensitivity also increases with a peak at 2.52% and 2.45% found with *QGSP_BIC_HP* and *QGSP_BERT_HP* physics lists, respectively. Upon further increase in converter thickness, the sensitivity drops down. The similar detector's response has been achieved for all the other thermal neutron energies.

A detailed comparison of the detector sensitivity taken with 3 μm and 5 μm converter thicknesses taken with the both physics list is presented in Fig. 3. According to the results, the detector's response taken with 3 μm remained higher than the 5 μm converter thickness case. Table 2 predicts the detector's response with and without converter attachment. A close look to these results shows that ^{10}B-based GEM response is quite higher for the thermal

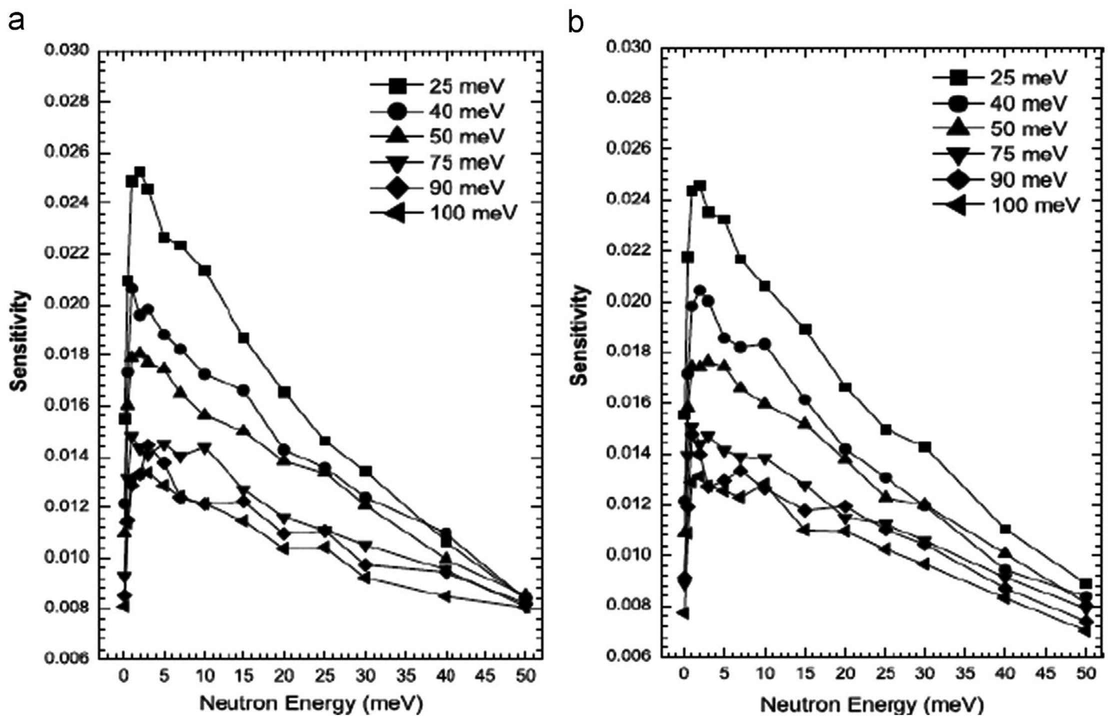

Fig. 2. Converter-based GEM detector sensitivities for the thermal neutrons at different energies. (a) QGSP_BIC_HP, and (b) QGSP_BERT_HP.

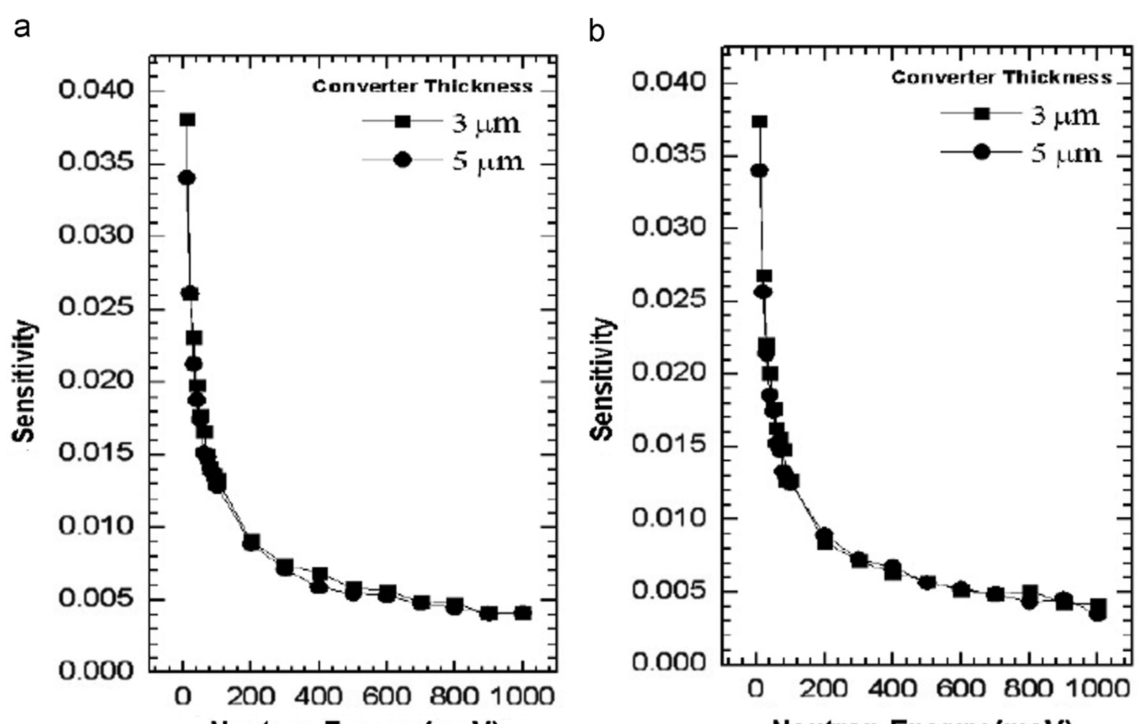

Fig. 3. Detection response evaluated for the double-layer GEM with 3 μm and 5 μm converters, as a function of thermal neutron energies. (a) QGSP_BIC_HP, and (b) QGSP_BERT_HP.

Table 2
Neutron sensitivities with- and without the converter coatings taken by the GEM detector.

Thermal neutron	**GEM-sensitivity (with ^{10}B converter)**		**GEM-sensitivity (without converter)**	
Energies (meV)	GEANT4 *QGSP_ BIC_ HP*	GEANT4 *QGSP_ BERT_ HP*	GEANT4 *QGSP_ BIC_ HP*	GEANT4 *QGSP_ BERT_ HP*
25	0.02458	0.02354	0.00001	0.00001
40	0.01982	0.02003	0.00001	0.00001
50	0.01770	0.01763	0.00001	0.00001
70	0.01408	0.01471	0.00001	0.00001
90	0.01444	0.01269	0.00001	0.00001
100	0.01335	0.01272	0.00001	0.00001

Table 3
The obtained thermal neutron simulation results vs experimental findings.

Particles	Converter material	GEANT4 simulation results		Experimental results (Ohshita et al., 2010)
		QGSP_ BIC_ HP	QGSP_ BERT_HP	
Thermal neutrons	^{10}B	0.02526	0.02456	0.0269

neutrons detection than the GEM detector without converter response, which verifies that ^{10}B-coating enhances the GEM detector ability for low neutrons detection.

For the confirmation a comparison of the present simulation results with available experimental results (Ohshita et al., 2010) has been performed in Table 3, which predicts a close agreement, and validates our findings taken by GEANT4 MC code.

5. Conclusions

In this paper, we have demonstrated a possibility to utilize the GEM-based detector for the detection of thermal neutrons. In order to make the detector sensitive to low-energy neutron B-convertor is coated on the electrode surface of the GEM-detector. For the first time, the response of the boron-coated GEM detector has been estimated by the GEANT4 MC code using the two physics list *QGSP_BERT_HP* and *QGSP_BIC_HP*. The results demonstrate that using the both physics list the detector response remained around ~3%. The obtained results verify that GEM-based detector attached with ^{10}B-converter can be efficiently used for the detection of thermal neutrons.

Thermal neutron detection technique reported in the current work is simple, feasible and efficient that can be employed easily. A reasonable improvement in the detection efficiency can be obtained by using the stacked or multi-layer GEM detectors (Park et al., 2005). The low energy neutron detection method reported in this work can be utilized for the other neutron detectors such as thin-film coated semiconductor detectors as well (Park et al., 2006).

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