

The current status of the Gas Electron Multiplier (GEM) research at Kasetsart University, Thailand

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Abstract. During the past decade, Gas Electron Multiplier (GEM) detectors have been greatly developed and utilized in numbers of applications including advanced nuclear and particle researches, medical imaging, astrophysics, and neutron detection for national security. Our GEM research group at the Department of Applied Radiation and Isotopes, Faculty of Science, Kasetsart University, Thailand, realized in its excellent properties/potentials and started extensive researches on GEM detectors. To build a strong foundation on our research group, two 10 cm × 10 cm triple GEM detectors were characterized on their important properties including absolute gains and detection uniformity. Moreover, to widen applications of the GEM detector, our group had modified the GEM detector by introducing either solid or gaseous neutron converters to the detector so that the detector could effectively detect neutrons. These modifications included coating a thin film of ^{10}B and $^{\text{nat}}\text{B}$ to the GEM drift cathode for thermal neutron detection and flowing a gas mixture of He/CO_2 (80:20 and 70:30) and $\text{C}_4\text{H}_{10}/\text{He}/\text{CO}_2$ (7:70:23) for fast neutron detection. Results showed that the modified GEM-based neutron detector could detect both types of neutrons with different relative efficiencies and gains depending on thicknesses and types of neutron converters. This article discusses basic knowledge of the GEM detector, construction and testing procedures, results, and discussion.

1. Introduction

Radiation detection has become one of the most important tools in scientific researches and industrial applications nowadays. Great numbers of advanced nuclear and particle physics researches have utilized and relied their precision and accuracy on radiation detection instruments. Examples are vertical drift chambers for the Hall A high-resolution spectrometers at Jefferson Lab [1], combinations of imaging calorimeters, plastic scintillator, and position sensitive sensors in LHCf at the CERN Large Hadron Collider [2], and a fast multi-parameter data acquisition system for microbeam analyses [3]. Not only scientific researches but also industrial and medical applications have benefited from the fast-developed radiation detection techniques including the detection of titanium ion release from dental and orthopedic implants [4], high performance silicon-based extreme ultraviolet (EUV) radiation detector for next-generation 13.5 nm wavelength lithography [5] and neutron detectors for soil moisture and its relevance to the landmine [6].

One particular interesting radiation detector named Gas Electron Multiplier (GEM) detector, in which Sauli F [7] invented in 1997, has gained popularity amongst researchers and has been proposed to replace former position-sensitive detectors such as the large size GEM for Super Bigbite Spectrometer (SBS) polarimeter for Hall A 12 GeV program at Jlab [8] and large size GEM for future



PREX-like experiments [9]. The GEM detector is a gaseous particle detector consisting of a cascade of a GEM drift cathode, GEM foils, and a readout board. The GEM drift cathode is a thin aluminized polyimide foil placed topmost of the cascade with the most negative voltage, while the GEM foils are made of 50 μm polyimide foils coated by thin copper plates on both sides of the foils. The GEM foils are perforated with a regular matrix of holes with 70 μm diameter and a pitch of 140 μm between two adjacent holes. In a standard triple-GEM detector, three GEM foils are approximately 2 mm spaced from each other and 3 mm below the GEM drift cathode. For a readout board, several designs are possible to use depending on intended applications. However, in most applications, a standard 10 cm \times 10 cm GEM readout board consists of two sets of 512 thin wires running perpendicular (X and Y) to each other. These wires are connected to data acquisition system (DAQ) for data processing. Schematic drawing of the GEM detector is shown in figure 1.

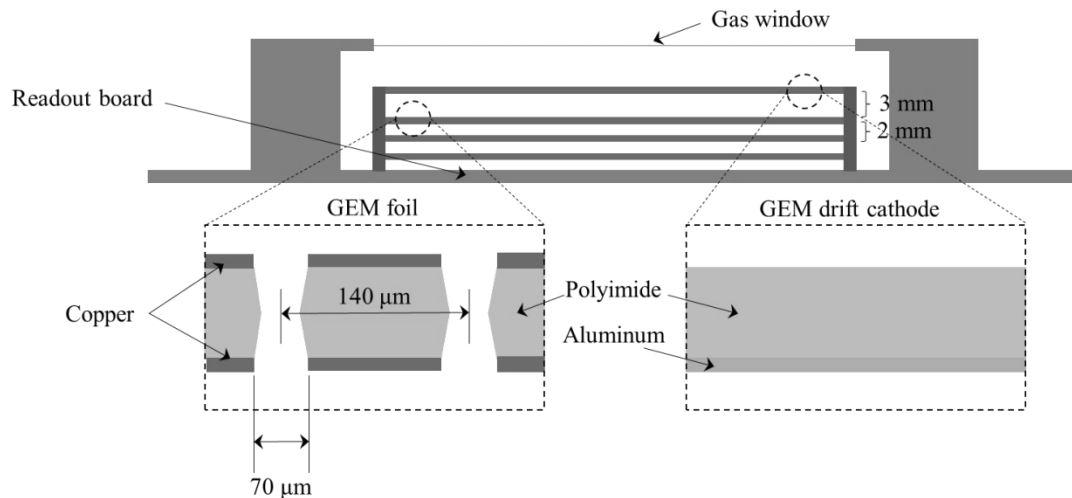


Figure 1. Schematic drawing of a GEM detector showing side views of a complete detector, a GEM foil and a GEM drift cathode.

Since GEM detector relies on ionizations of gas molecules from incoming ionizing radiation, types of gas flow play major roles in defining GEM properties. In principle, a pure noble gas such as argon (Ar) could be used to operate the detector, however, in order to increase stability, a gas mixture with a quencher is usually used. For example, a mixture of Ar/CO₂ in a ratio of 70:30 is usually used in most applications where Ar acts as the main ionized gas while CO₂ acts as a quencher.

Although the GEM detector is well known for its excellent properties when detecting ionizing particles and low-energy photons [10], the detector could be modified by adding suitable neutron converters such as high neutron absorption cross-section materials (³He or ¹⁰B) or high energy transferred materials (¹H or ⁴He) such that the detector is able to detect neutrons. The two main methods involving neutron detection are:

- Nuclear reaction between thermal neutrons and high neutron absorption cross-section nuclei.
- Elastic scattering of fast neutrons of light nuclei.

Each method of nuclear reaction and interaction are shown in figure 2.

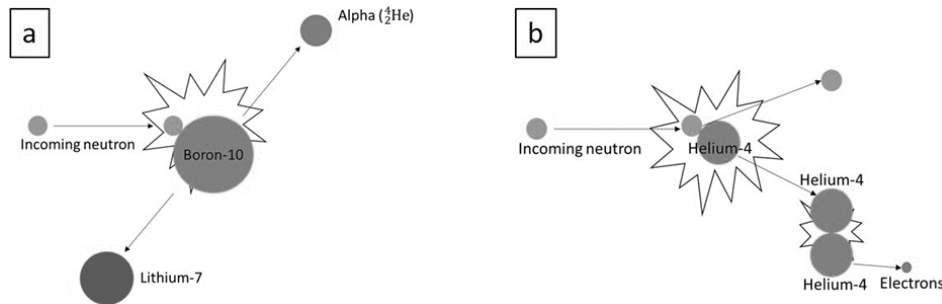


Figure 2. [a] The mechanism of a nuclear reaction between a thermal neutron and a ^{10}B nucleus, which produces a ^7Li nucleus and a 1.47 MeV alpha particle traveling in opposite directions and [b] the mechanism of an elastic scattering of a fast neutron off a ^4H nucleus where neutron energy is transferred to the recoiled ^4H nucleus.

In fact, neutron detection through nuclear reaction has better detection efficiencies than detection through elastic scattering due to its much larger neutron cross-section [11], however, the procedures to modify detector are considered more complicated as moderators and neutron converters must be introduced into the detection system [12] [13]. On the other hand, detection through elastic scattering is relatively simpler as the only modification required is to flow ^1H - or ^4He -contained gas mixtures through the detector, while other components remain the same.

Our GEM research group has emphasized on building a strong foundation on the first GEM research group in Thailand by investigating on important properties of the GEM detector including absolute gains and detection uniformity. Moreover, our group has also widened possible uses of the GEM detector by attempting to improve neutron detection ability by using either solid or gaseous neutron converters to detect fast neutrons and thermal neutrons.

2. Materials and methods

2.1. GEM construction and initial tests

Two complete sets of $10\text{ cm} \times 10\text{ cm}$ triple GEM detectors were ordered from a Gas Detection Development (GDD) group at CERN. Once receiving all components, GEM foils were tested in a N_2 -filled sealed box for current leakage. An acceptable GEM foil should have current leakage amplitudes less than 200 nA when supplied by a voltage of 500 V. All GEM foils used in the research must pass this requirement of current leakage tests. Then, GEM detectors were put together in a class-1000 cleanroom at the Thailand Institute of Nuclear Technology (TINT) and tested for possible gas leaks, discharged frequencies, and preliminary 5.9 keV x-ray detection. During the initial tests, a gas mixture of Ar/CO_2 (70:30) was flowed through the detector with a constant and optimized flow rate of 3.0 L/hr measured by a direct-reading flow meter (Cole-Parmer Model 3204776). A high voltage of -4100 V was supplied to the GEM detector via a voltage divider circuit shown in figure 3. Signals collected at the readout board were sent to a preamplifier (Canberra Model 2006), an amplifier (Ortec Model 590A), an oscilloscope (Hantek DSO 5202B), and a counter and timer (Canberra Model 2071A) for signal processing and analysis.

2.2. Absolute gain measurement

To measure absolute gains for different voltages supplied, signal currents from 5.9 keV x-ray detection were measured using a pico-ammeter that had a 20 fA current resolutions with the supplied voltages varied from -3900V to -4300V in 50 V increments.

From the equation

$$I = R \times N \times G \times e \quad (1)$$

where I is the detection current, R is the count rate of the 5.9 keV x-ray from ^{55}Fe photon source, N is the number of primary electrons, G is the gain of the detector, and e is the charge of an electron ($e = 1.6 \times 10^{-19}$ C), interested quantities could be calculated, given that other variables are accurately measured.

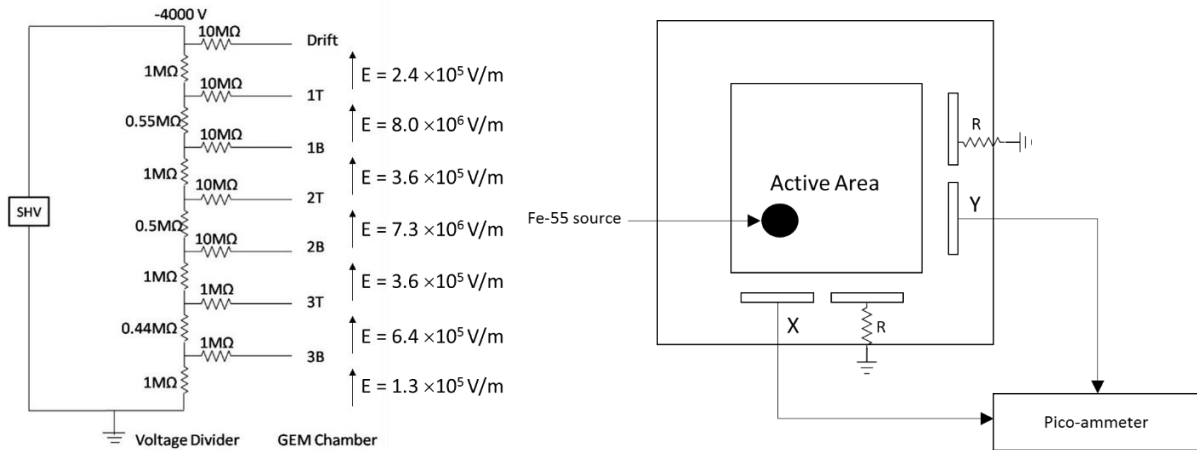


Figure 3. (Left) voltage divider circuit used during the tests and (right) diagram of setup for gain measurement.

In order to obtain G , values of I , R , and N must be carefully measured and evaluated. To measure R , the count rate of 5.9 keV x-ray at the counting plateau region was measured, while N could be estimated using the average energy dissipation per ion-pair (w -value) of the gas mixture Ar/CO₂ (70:30), which approximately equals 27.8 eV [14]. Assuming that only photoelectric effect occurs during the interaction between x-ray and gas molecules, N would be approximately 200 electrons.

2.3. Uniformity measurement

To test uniformity of the 10 cm × 10 cm triple GEM detector, the active area was divided into 36 equally spaced positions (6 rows and 6 columns). ^{241}Am source, which emitted 59 keV secondary gamma, was placed 0.5 cm above each position and 3 minute counting time were measured with a constant supplied voltage of -4100V and a constant gas flow rate of 3.0 L/hr. After completing all 36 positions, counts for each position were plotted using the OriginPro software to produce a contour of uniformity.

2.4. Thermal neutron detection

Since thermal neutron detection is most efficient with the addition of high neutron absorption cross-section nuclei, ^{10}B and ^{nat}B , which have neutron absorption cross-section of 3835.9 barns and 767.8 barns respectively, were selected and coated onto the GEM drift cathode. In the case of ^{10}B , the coating was performed by Richter Precision, Inc. (USA) using Tribo-Kote S-X1 technique [15]. However, the manufacturer could only coat with a thickness of 1 μm of ^{10}B . On the other hand, ^{nat}B was coated onto the drift cathode using an electron beam evaporation technique with the thicknesses of 2.5, 3.5, and 4.5 μm. Attempts to coat ^{nat}B thicker than 4.5 μm resulted in cracks along the film surface and could not be used. Setup for the thermal neutron test is shown in figure 4(a).

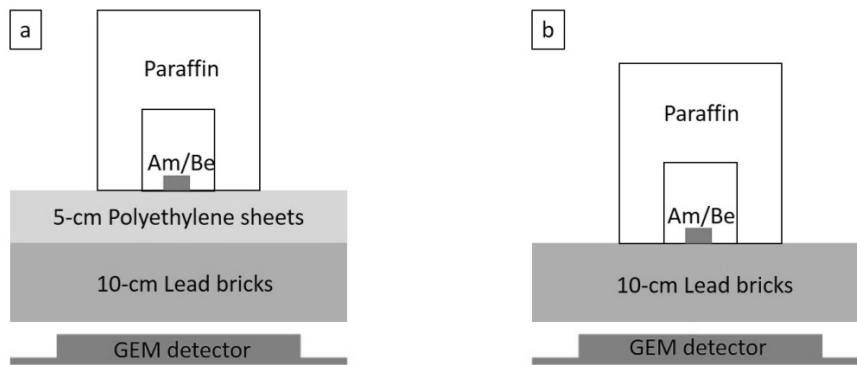


Figure 4. Setups of the GEM detector for [a] thermal neutron detection and [b] fast neutron detection.

From figure 4, the polyethylene (PE) sheets were used to thermalize fast neutrons from $^{241}\text{Am/Be}$, while 10 cm lead bricks were used to shield gamma. The thickness of PE sheets was varied and optimized at 5 cm for the highest yield of thermal neutrons measured using ^3He neutron detector. Also, to ensure the least counts of gamma and other types of ionizing radiation contributed to neutron counts, the GEM detector itself was used to measure backgrounds and subtracted from all neutron detection counts. A gas mixture of Ar/CO_2 (70:30) was flowed through the GEM detector to measure count rates and signal amplitudes, where biased voltages were varied from -3,900V to -4,400 V in 50 V increments. To determine the average thermal neutron count rate and signal amplitude for each voltage, 10 sets of neutron measurement at each 5 minutes counting time were performed. Counts and amplitudes of signals larger than threshold level were used to find average values. After completing all required measurement, a $1\ \mu\text{m}$ ^{10}B -coated drift cathode was replaced by a 2.5, 3.5, and $4.5\ \mu\text{m}$ ^{nat}B -coated drift cathodes respectively and all above procedures were repeated.

2.5. Fast neutron detection

Since fast neutron detection is most efficient with the addition of light nuclei such as ^4He due to their large energy transfer during the scattering, gas mixtures of $^4\text{He}/\text{CO}_2$ (80:20 and 70:30) and $^4\text{He}/\text{CO}_2/\text{C}_4\text{H}_{10}$ (70:23:7) were flowed through the GEM detector. The gas flow rates for all gas mixtures were kept constant at 3.0 L/hr throughout the measurement. To measure count rates and signal amplitudes for all three gas mixtures, the biased voltages were varied from -3900 to -4400 V in 50 V increments. For each high voltage bias setting, 10 sets of neutron measurement at each 50 minutes counting time were performed in order to find average count rate and signal amplitude. Proper background counts from cosmic radiation measured by the GEM detector without a neutron source presented were measured and subtracted from measured signal counts to ensure only neutron data was included in the calculations.

3. Results and discussion

3.1. Absolute gain measurement

In order to calculate gains (G), the count rate of 5.9 keV x-ray from ^{55}Fe source at plateau region (R) must be measured. As shown in figure 5, R was approximately 670 cps. From equation (1) along with current (I) values shown in figure 6(a), absolute gains of the GEM detector for each supplied voltage were calculated. As shown in figure 6(b), the absolute gains exponentially increased as the supplied voltages increased due to stronger electric fields inside GEM holes, resulting in higher electron multiplication.

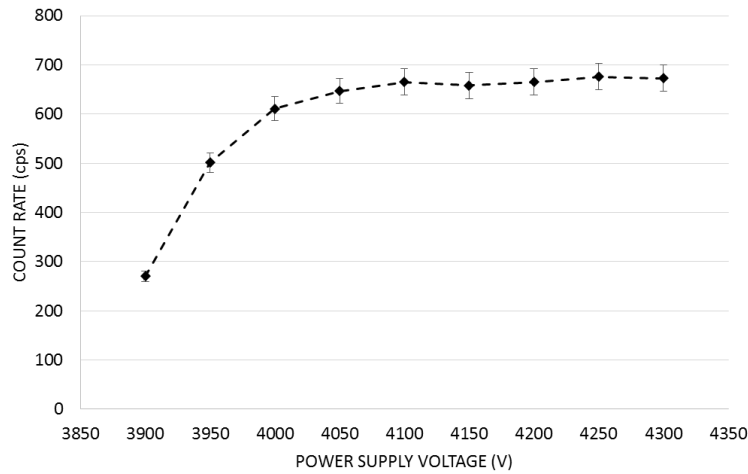


Figure 5. Count rates of 5.9 keV x-ray from ^{55}Fe showing the rate at plateau region was approximately 670 cps.

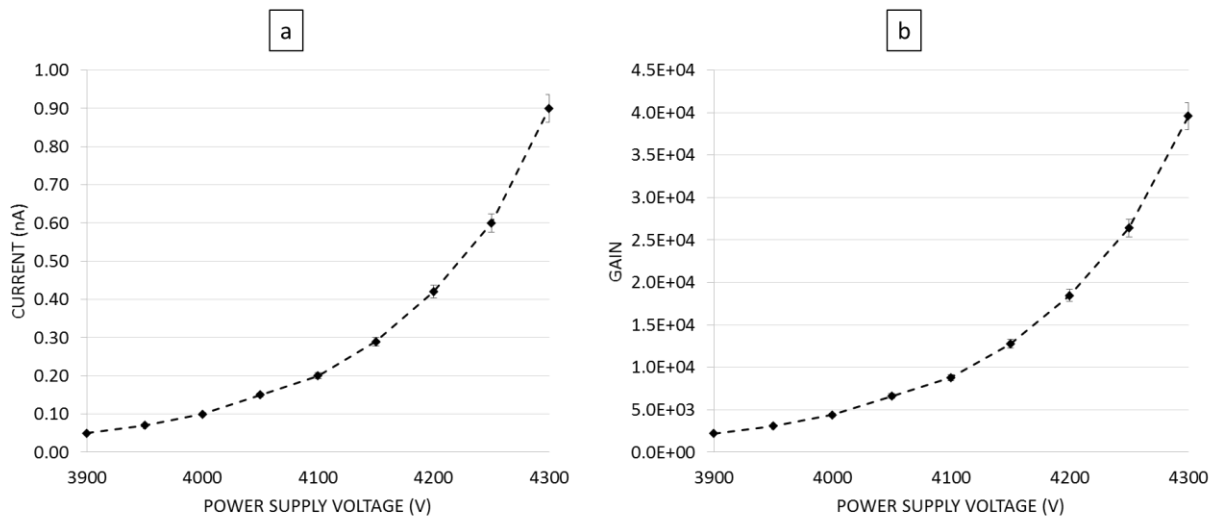


Figure 6. [a] Current measurement for each supplied voltage and [b] absolute gains for each supplied voltage.

4. Uniformity measurement

Figure 7 shows the uniformity of the GEM prototype using ^{241}Am as a gamma emitter. Areas near the center of the active area had higher relative efficiencies compared with areas near edges. This behavior was expected since incoming particles or ionized electrons occurred near edges had possibilities to drift out of the active area, lowering its overall sensitivities and signal amplitudes. However, if considering areas with at least 1 cm away from edges, the relative sensitivities were different less than 20% from each position.

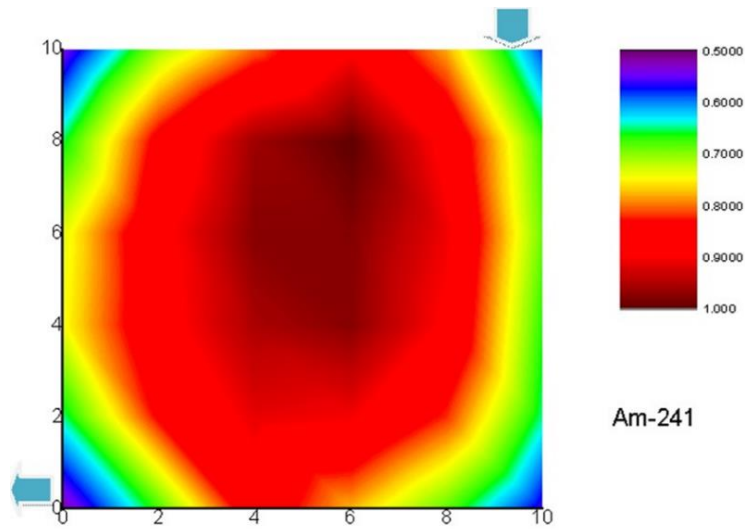


Figure 7. The detection uniformity of the GEM prototype. Higher relative efficiencies are clearly shown at the center of the detector

5. Thermal neutron detection

Figure 8(a) shows that thermal neutron count rates increased as supplied voltages increased and reached plateau when the voltage was approximately -4,200 V. Also, the setup, which the cathode was coated by $1\ \mu\text{m}$ ^{10}B , had the highest count rates compared to any other thickness of ^{nat}B . This is because, despite only $1\ \mu\text{m}$ thick, ^{10}B has the value of neutron absorption cross-section approximately 5 times higher than ^{nat}B , leading to more nuclear reactions between thermal neutrons and boron nuclei. However, as thicknesses of ^{nat}B increased, count rates of detection also increased as more ^{nat}B nuclei were available for nuclear reactions. Figure 8(b) shows that signal amplitudes increased as supplied voltages increased. The increase in the amplitudes was caused by stronger electric fields inside GEM holes, resulting in more ability to multiply electrons.

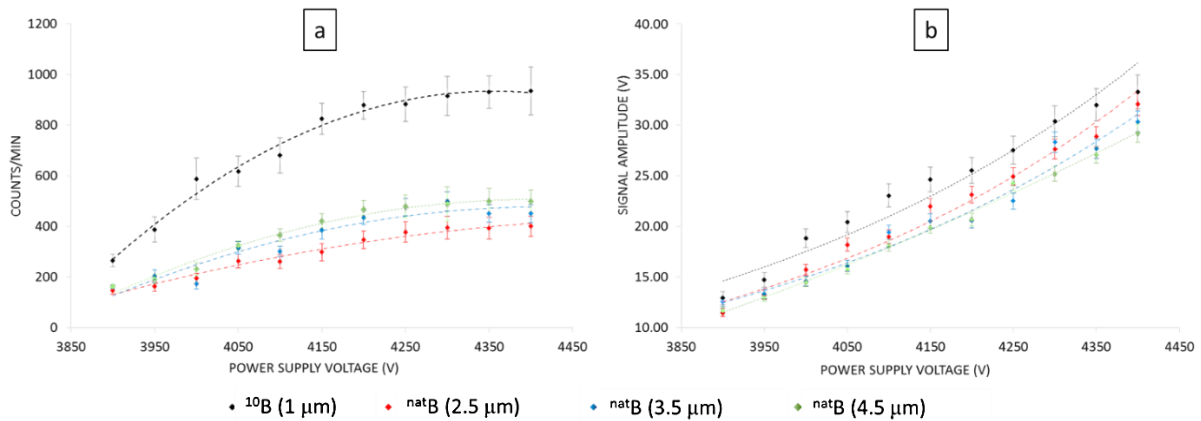


Figure 8. [a] Count rates and [b] signal amplitudes of the GEM-based thermal neutron detector using different solid neutron converters.

6. Fast neutron detection

As shown in figure 9(a), count rates increased as biased voltages increased and reached plateau region when the high voltage was approximately -4300 V, while flowing a gas mixture of $^4\text{He}/\text{CO}_2$ (80:20) yielded slightly higher count rates amongst all three gas types. This behavior was due to the highest concentration of light nuclei, specifically ^4He , in $^4\text{He}/\text{CO}_2$ (80:20), which the energy transfer from

incoming fast neutrons to recoil nuclei was larger. However, when considering stability of signals, it was found that the gas mixture of $^4\text{He}/\text{CO}_2/\text{C}_4\text{H}_{10}$ (70:23:7) gave more stable signals as less discharged frequencies and electrical noises were observed.

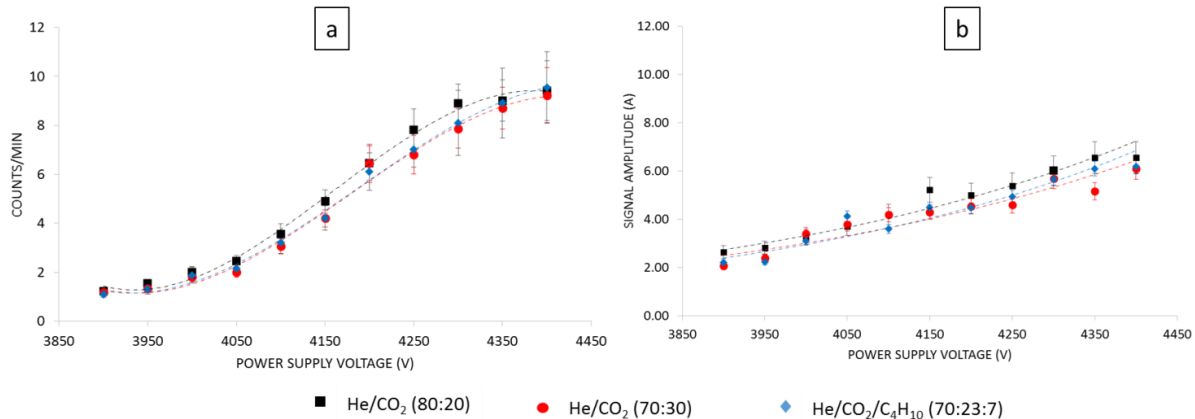


Figure 9. [a] Count rates and [b] signal amplitudes of the GEM-based fast neutron detector using different gaseous neutron converters.

7. Conclusions

Our GEM research has conducted both basic and applied researches on the GEM detector. In order to strengthen our understanding on GEM's characteristics, absolute gains and detection uniformity of the detector were investigated. Results showed that gains of the GEM detector increased exponentially with biased voltages due to stronger electric fields inside GEM holes, while relative detection sensitivity at the center of the active area had the highest detection ability compared to areas near edges. Furthermore, our research group has investigated on the possible uses of the GEM detector for neutron detection. By introducing a $^{10}\text{B}/\text{natB}$ -coated GEM drift cathode, the GEM detector was able to detect thermal neutrons. On the other hand, fast neutrons could be detected by flowing gas mixtures of $^4\text{He}/\text{CO}_2$ (80:20 and 70:30) and $^4\text{He}/\text{CO}_2/\text{C}_4\text{H}_{10}$ (70:23:7). However, fast neutron detection had much lower relative efficiencies than thermal neutron detection due to smaller neutron cross-sections of ^4He compared to $^{10}\text{B}/\text{natB}$ nuclei. These results are significant and useful for our research on GEM development and also for references in future GEM-related applications.

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