Recent developments in GEM-based neutron detectors

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Abstract. The gas electron multiplier (GEM) detector is a relatively new gaseous detector that has been utilized for less than 20 years. Since the discovery in 1997 by F. Sauli, the GEM detector has shown excellent properties including high rate capability, excellent resolution, low discharge probability, and excellent radiation hardness. These promising properties have led the GEM detector to gain popularity and attention amongst physicists and researchers. In particular, the GEM detector can also be modified to be used as a neutron detector by adding appropriate neutron converters. With properties stated above and the need to replace the previous expensive $^3$He-based neutron detectors, the GEM-based neutron detector could be one of the most powerful and affordable neutron detectors. Applications of the GEM-based neutron detectors vary from researches in nuclear and particle physics, neutron imaging, and national security. Although several promising progresses and results have been shown and published in the past few years, further improvement is still needed in order to improve the low neutron detection efficiency (only a few percent) and to widen the possibilities for other uses.

1. Introduction
On the evening of 8 November 1985, Röntgen noticed that a piece of a cardboard coated with barium platinocyanide showed a faint, flickering, greenish light when electrical discharge took place in a Hittorf-Crookes tube near the cardboard. This observation, which was actually the X-ray detection, led to many inventions and developments of nowadays radiation detectors. The detection capabilities have widened to effectively detect charged particles such as betas, protons and alphas, or even neutral particles such as neutrons which are relatively harder to detect. In particular, the neutron detection has increased its importance in many aspects. One important example is the application of neutron detection in national security. Since plutonium (Pu) and uranium (U) are main ingredients for nuclear weapon enrichment, it becomes international threats if the materials are in terrorist possessions. Since these two elements are amongst other heavy elements that often undergo nuclear fission processes and emit neutrons, one possible and effective way to detect these heavy elements is to have a detector capable of detecting neutrons with high neutron detection efficiency while limiting false alarms from gamma detection. In the past, a helium-3 ($^3$He)-based detector was commonly used due to its high neutron absorption cross section, which leads to high neutron detection efficiency. $^3$He is a byproduct from the beta decay of tritium ($^3$H) and is separated from $^3$H as part of the tritium purification process for refurbishment and dismantlement of the nuclear stockpile. Lately, due to international agreement to reduce numbers of existing nuclear weapons and nuclear stockpiles, the production of $^3$He from $^3$H decay has significantly declined and could harm the supply of $^3$He for $^3$He-based neutron detector. On the other hand, after the terrorist attack on September 11, 2001 in USA, the demand for $^3$He has increased

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significantly as \(^3\)He-based neutron detectors were rapidly deployed around the world to detect illegal nuclear materials. These two phenomena lead to the reduction in production and the increase in demand of \(^3\)He. It is estimated that the total \(^3\)He demand is approximately 65,000 liters/year, while the total supply is approximately 15,000 liters/year. These numbers show the disparity between supply and demand of \(^3\)He and a prediction of a more severe shortage of \(^3\)He. In order to maintain national security at the highest level, \(^3\)He-free neutron detectors must be invented to replace the \(^3\)He-based neutron detectors.

In addition to the need of neutron detectors for national security purposes, many scientific and industrial researches also require high-performance neutron detectors. Some examples of research areas that require the uses of neutron detectors include

- Material sciences: The neutron detectors can be used to study and measure the substructures of materials and biological organs in the angstrom level by measuring elastic and inelastic scattering of neutrons off interested materials.
- Reactor instrumentation: The neutron detectors are used in monitoring power of nuclear power reactor and research reactor since the reactor power is linearly proportional to neutron flux.
- Astrophysics: The neutron detectors can be used to detect secondary neutrons, which are parts of the particle showers produced in Earth’s atmosphere by cosmic rays.
- Medical imaging: Detection of neutron radiation can be used for medical imaging of patients’ organs and tissues.

2. The Gas Electron Multiplier (GEM) detector
The Gas Electron Multiplier (GEM) detector is a gaseous charge amplification structure, invented by F. Sauli and his research group at CERN, Switzerland, in 1997 [1]. The main component of the GEM detector is a thin multilayer foil with many high precision holes, which is known as a GEM foil. The GEM foil consists of a thin insulating foil (polyimide). Polyimide foil has an excellent dielectric strength of 150-300 kV/mm for a thickness of 25-125 \(\mu\)m. The usual thickness for polyimide used in GEM foils is 50 \(\mu\)m and has metal clads (usually copper) on both sides and perforated with a regular matrix of holes. The holes are very closely spaced and have a diameter \(~70\ \mu\)m, and a pitch or a distance from one center of the hole to the center of the closest neighboring holes of \(~140\ \mu\)m.

![Figure 1. A magnified image of a GEM foil shows a regular matrix of holes. Holes have \(~70\ \mu\)m in diameter and a pitch of \(~140\ \mu\)m [2].](image1)

![Figure 2. A figure shows a cross sectional view of GEM holes](image2)
Another important component of the GEM detector is the gas flushing through the detector. In principle, the GEM detector can be operated in a pure noble gas such as argon (Ar). However, in order to increase the detector stability and to reduce discharge probability, a mixture of gasses is used. The standard gas mixture used in most applications is a mixture of Ar/CO$_2$ in a ratio of 70/30, where Ar acts as the main ionizing gas and CO$_2$ acts as a quencher.

The main operating principles of the GEM detector are as the following steps.

- By applying a potential difference about 300-400 V between the top and the bottom metal clads, strong electric fields develop inside the holes.
- A particle passes through the drift region of the detector and ionizes gas molecules inside the detector. These ionized electrons will then travel through the strong electric fields inside the GEM holes, gain more energy, and ionize other gas molecules creating electron avalanches.
- In the last amplification stage, the amplified electron avalanches will be captured by readout pads or readout strips depending on the applications. The moving of electron avalanches between the last GEM foil and the readout electrode will create detectable signals, which will be processed through an appropriate data acquisition (DAQ) system.

![Figure 3. The picture shows the three amplification stages inside the GEM detector. The last electron avalanches will be captured by the readout pads or the readout strips. The moving of electron avalanches between the last GEM foil and the readout electrode will create detectable signals and will be processed through DAQ system.](image)

### 3. GEM detector as a neutron detector

Although the GEM-based detector is mostly used to detect charged particles and low-energy photons, the detector can be modified by adding appropriate neutron converters to the detector such that it is now able to detect neutrons. The ability to detect neutrons relies on a conversion mechanism that yields charges in the drift volume of the detector. In the case of thermal neutrons, conversion takes place via a nuclear reaction with an appropriate isotope, while higher energy neutrons may cause nuclear recoils. To increase the probability of the conversion, an appropriate neutron converter is added to the detector. Examples of commonly used neutron converters include Helium-3 ($^3$He), boron-10 ($^{10}$B), lithium-6 ($^6$Li) or hydrogen-rich materials such as polyethylene ((C$_2$H$_4$)$_n$H$_2$) and polypropylene ((C$_3$H$_6$)$_n$). The nuclear reaction products are an alpha ($\alpha$) particle of $\sim$2 MeV and either a triton (for $^6$Li) or lithium ion (for $^{10}$B), isotropically emitted in opposite directions. Example of the nuclear reaction with $^{10}$B can be shown as the following:

\[
^{10}$B + n $\rightarrow$ $^7$Li + $\alpha$ + 2.79 MeV (6\%)
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\[
^{10}$B + n $\rightarrow$ $^7$Li* + $\alpha$ + 2.31 MeV (94\%)
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where $^7\text{Li}^*$ is an excited particle. The $^7\text{Li}^*$ spontaneously emits a 0.48 MeV gamma ray and returns to the ground state. These emitted alpha particles will ionize gas molecules inside the GEM detector, which will later be amplified in the amplification stages and get captured by readout pads. The efficiency of neutron detection depends on the neutron reaction rate which also depends on various factors. The neutron reaction rate is shown in (3.1).

$$R = \int \phi(E) N \sigma(E) dE$$  \hspace{1cm} (3.1)

where $\phi = \int \phi(E) dE$ is the neutron flux, $N$ is the number of $^{10}\text{B}$ atoms in the neutron converter, and $\sigma(E)$ is the neutron cross section. The value of neutron cross section is the most important quantity that defines the efficiency of the detector and is shown in figure 4.

As shown in figure 4, $^3\text{He}$ has the highest cross section and has been used widely for neutron detectors in the past. Due to a crisis in the shortage of $^3\text{He}$ and the sharp increase in the price of $^3\text{He}$, alternatives to $^3\text{He}$-based neutron detectors are urgently needed to maintain the highest level of national security and researches. These include the uses of thin film coated with $^{10}\text{B}$ or $^6\text{Li}$, or filling the detector with hydrogen-rich gas.

4. Recent development and result
Since the invention of the GEM detector, the growing interests in its capabilities have motivated scientists and researchers to develop and improve the detector for various applications. GEM-based neutron detector is one of applications that have been vastly developed in recent days. Some of the notable developments and results will be discussed in this section.

4.1 Manufacturing of boron-coated GEM foil
Since the performances of the GEM-based neutron detector especially the efficiency of the detection depend heavily on the neutron converting process occurred at the converters, the development of methods to apply converters ($^{10}\text{B}$) to drift cathode and GEM foils is very important. As shown by Se-Hwan Park et al. [4,5], $^{10}\text{B}$ was coated on the aluminized Mylar, which was used as a drift cathode, using electron-beam evaporator. The coated boron became stable with time. However, $^{10}\text{B}$ did not adhere to the GEM foil very well and could be peeled off as well as cracked easily from the GEM foil. The picture of borated GEM foil that peeled off is shown in figure 5.
Se-Hwan Park et al. had solved the problem by, instead of coating one full piece of $^{10}$B film on the GEM foil, the $^{10}$B film was segmented into small squares. To achieve that, the main additional procedure included the introduction of a stainless mesh placed in front of the substrate so that the $^{10}$B films were divided into ~$1.5 \times 1.5$ cm$^2$ squares and had the gap between the adjacent squares of 0.3 mm. Pictures of drift cathode and GEM foil that were coated with the new procedure are shown in figure 6.

The idea of segmenting $^{10}$B film into small squares reduced the stress on the film surface significantly and even if the crack occurred, the crack remained in the broken square and did not spread to other parts. The technology has improved the manufacturing of the $^{10}$B-coated GEM foil and significantly improved qualities of GEM-based neutron detector. Furthermore, the technique has increased the working duration of the foil and the detector.

4.2 Improvement on the configuration and layout of the converter
Since the ability to detect neutrons depends on the ability to convert neutrons to charged particles such as alphas or protons, the way the converter is introduced to the detector is highly important to the performances of the detector. In a traditional configuration, the converters such as $^{10}$B and polyethylene are coated directly onto the drift cathode and the GEM foils. However, this method of applying converters limits the conversion process to only at the surface of the detector. Furthermore, even if the thickness of the converter increases which would increase the conversion probability, charged particles produced cannot penetrate the thick converter. Hence, the thickness of the converter is limited to only
2-3 μm in the case of $^{10}$B. A. Pietropaolo et al. [6] has designed a new GEM-based neutron detector to remove these constraints by introducing layers of borated glass sheets as converters that are perpendicular to the drift cathode as shown in figure 7.

![Figure 7](image_url)

**Figure 7.** Schematic of GEM-based neutron detector designed by A. Pietropaolo et al.: The borated glass sheets were applied perpendicular to the drift cathode [6].

The main purpose of having layers of borated glass sheet aligned as in figure 7 is to loosen up the requirement that neutrons must be converted to charged particles at the very first μm-thick surface of the detector. The improvement consequently increases the probability of the conversion and, hence, the efficiency of the detector. The efficiency measured by A. Pietropaolo et al. showed that the efficiency of the neutron detection came out to be 4.8(5) % which was much better than previously reports of traditional configurations, which had the efficiency of less than 1%. A similar design was also used in the research conducted by M. Cortesi et al. [7] for fast neutron detection, which used polyethylene (HPDE) layers as converters. The reports showed that the estimated efficiency that could be achieved by this configuration was in the range of 5-8 % for 2.5 MeV neutrons.

5. Possible improvement and application

Although growing number of tests and researches have been conducted on the GEM-based neutron detector, there are still rooms for further improvement such as:

- Conducting extensive researches on various neutron converters including gaseous converters such as He-4 and other solid converters ($^6$Li), or a mix of both solid and gaseous converters used in the detector.
- Designing new layouts of converters such that there are more possibility of conversion. This might include adding more layers of borated glass sheets to the detector.

Since many reports have shown the excellences of the GEM-based neutron detector, more researches should be aimed to adapt the detector for applications. One example of applications was done by S. Uno et al. The GEM-based neutron detector was used to perform a 2-dimensional imaging of metal content, which could clearly show content of gold in a Japanese oval gold coin from Edo period. Furthermore, the detector could also be used to perform a 2-dimensional imaging of crystallite size of iron bars after bending [8][9]. These examples clearly show the wide areas of applications of the GEM-based neutron detectors and there are still plenty of rooms to explore.

6. Conclusion

The GEM detector has been development significantly since the invention in 1997. From the ability to detect charged particles and photons, the GEM detector has been adapted to be used in various applications. Neutron detector based on the GEM detector is one of the detection technologies that greatly benefit educational, industrial, medical, and national security sectors. Many research projects have been conducted to improve the performances of the detector. These include the attempts to improve the method to apply converters to the drift cathode and the GEM foils such that the converters could adhere to the surface better and increase the lifetime of the detector. Also, researchers have designed
new arrangements of the converters to improve the chances of the conversion by adding layers of borated glass sheets or HDPE perpendicular to the drift cathode. This design has increased efficiency of the detector to be in the range of 5%, which improves from previously reports of ~1%. Furthermore, attempts to adapt the GEM-based neutron detector to be used in various applications such as in material analysis, medical imaging, and national security should be emphasized and invested.

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