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A novel ceramic GEM used for neutron detection

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ABSTRACT

A novel ceramic Gas Electron Multiplier (GEM) has been developed to meet the demand of high counting rate for the neutron detection which is an alternative to ^{3}He-based detector at China Spallation Neutron Source (CSNS). An experiment was performed to measure the neutron transmittance of ceramic-GEM and FR4-GEM at the small angle neutron scattering (SANS) instrument. The result showed the ceramic-GEM has higher transmittance and less self-scattering especially for cold neutrons. One single ceramic GEM could give a gain of 10^2-10^4 in the mixture gas of Ar and CO_2 (90%:10%) and its energy resolution was about 27.7% by using ^{55}Fe X ray of 5.9 keV. A prototype has been developed in order to investigate the performances of the ceramic GEM-based neutron detector. Several neutron beam tests, including detection efficiency, spatial resolution, two-dimensional imaging, and wavelength spectrum, were carried out at CSNS and China Mianyang Research Reactor (CMRR). The results show that the ceramic GEM-based neutron detector is a good candidate to measure the high intensity neutrons.

1. Introduction

The neutron detector is one of the most important devices of neutron scattering instruments used to study the structure and dynamic behavior of materials. The new generation of neutron sources, such as SNS in the USA [1], ISIS in the UK [2], ESS in Europe [3], J-PARC in Japan [4] and CSNS in China [5], have been established. The counting rate capability of ^{3}He-based neutron detectors was limited to several ten kHz for the comparatively slow drift velocity of ions [6,7]. ^{3}He-based neutron detectors were faced with the challenge of high counting rate due to the rise of the neutron intensity. At the same time, the price of ^{3}He gas rose exponentially in the past ten years because of the decreasing global supply and massive use in homeland security in US [8]. Thus its large-scale use was prevented in scientific applications including neutron scattering facility such as CSNS. It was an urgent demand to develop the new type of the neutron detectors with high counting rate and economical price as an alternative to ^{3}He based detectors.

The GEM detector was a type of micro-pattern gaseous detector with 50-μm-thick polyimide developed by Sauli at CERN in 1997 [9]. With the booming development in the last decades, the family of the micro-pattern gas detector has been broadened to many types, such as 400–800 μm thick GEM (THGEM) with FR4 in Israel [10], 100 μm thick GEM with liquid crystal polymer (LCP) in Japan [11], and 200–800 μm thick THGEM with FR4 in China [12]. Combining with neutron converter, the GEM could be fabricated to be a neutron detector with high counting rate (~10 MHz). Boron was chemically inert, economical and could be easily concentrated to high enrichment level of ^{10}B. It was commonly used as a thermal neutron converter for the neutron detectors, which render a large area coverage feasible with a relative low cost. Many efforts have been devoted to the neutron GEM detectors with boron convertor

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in recent years [13–15]. At Heidelberg University in Germany, Dr. Klein and Dr. Schmidt firstly developed the CASCADE neutron detector using standard GEM from CERN [16]. In order to develop a special GEM to satisfy high counting rate neutron detectors, a new style of ceramic GEM has been developed for the thermal neutron detection at CSNS since 2013. It was manufactured economically using the printed circuit board technology. The 200 μm diameter holes with a pitch of 600 μm were mechanically drilled in a double-copper coated ceramic foil of 200 μm thickness, followed by Cu-etching to form the hole rims [17]. Benefited from the use of the ceramic substrate, it was with better radiation resistance and stability, less self-absorption and self-scattering with neutrons than those made of FR4. A single ceramic GEM could be used as the neutron beam monitor of a low efficiency, and a cascaded ceramic GEM could be used as the high efficient neutron detector applied in neutron scattering and imaging instruments.

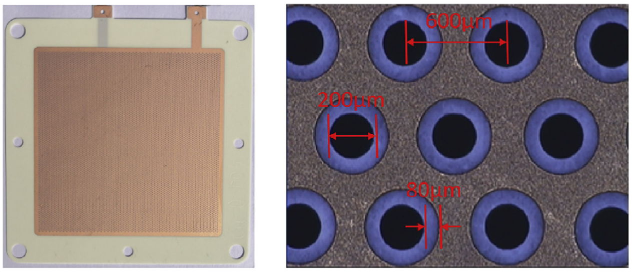
This paper presents the new style of ceramic GEM used for neutron detection and its basic characteristics. In order to verify its feasibility, a prototype was developed to evaluate the performances of the detector.

2. Ceramic GEM

The ceramic GEM was a 170 μm thick ceramic substrate, sandwiched between 15 μm thick copper claddings on both sides. It was a micro-structure with a regular hexagonal grid of 200 μm diameter holes at a spacing of 600 μm and with a rim of 80 μm (shown in Fig. 1) [17]. The main components of the ceramic GEM were oxygen, aluminum and silicon of which the neutron total cross-sections are 3.98b, 1.69b and 2.20b respectively (shown in Table 1). Compared with the FR4 substrate, it had less concentration of light elements with larger neutron cross-section. The concentration of hydrogen with neutron total cross-section of 30.61b was almost zero. Thus, it had less neutron scattering and absorption. In order to verify it, the neutron transmittance of the ceramic GEM was measured at the SANS [18].

2.1. Transmittance

The transmittance was defined as the ratio of the number of neutrons passing through the samples including ceramic or FR4 GEM to that of the incident neutrons. At SANS, there were two neuron beam monitors which were placed before and after the sample. The neutron transmittances of the ceramic GEM and the FR4 GEM with the same dimensions were shown in Fig. 2. They were approximately 97% and 94% respectively for thermal neutrons. The ceramic GEM showed about half the absorption that the FR4 GEM did. It indicated that the ceramic GEM was more suitable for neutron detection. The difference of the transmittances was prominent as the neutron wavelength increased.



(a) (b)

Fig. 1. (a) The ceramic GEM; (b) microphotography of the ceramic GEM.

Table 1
The main components of ceramic GEM and FR4 GEM.

Element	Total cross section/b (0.0253eV)	Mass ratio	
		FR4	Ceramic
H	30.60	1.3%	/
C	4.94	13.2%	/
O	3.98	40.7%	48.5%
Na	3.93	7.6%	2.4%
Al	1.69	/	8%
Si	2.20	26.7%	34.3%
Ca	3.43	8.5%	0.2%

* The neutron total cross-sections are from ENDF/B-VII.1.

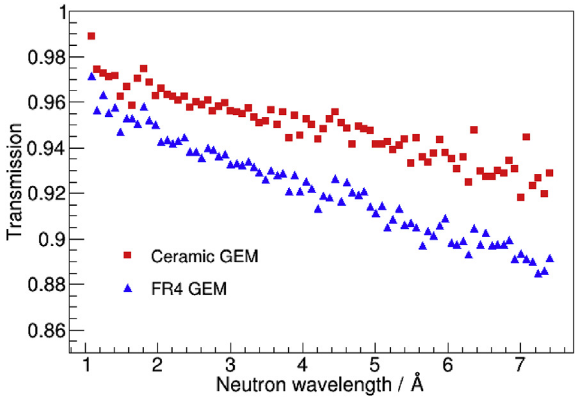


Fig. 2. The transmittances of ceramic GEM and FR4 GEM.

2.2. Characteristics of the ceramic GEM

The basic characteristics of the ceramic GEM including gain and energy resolution were measured in different voltages using a^{55}Fe X-ray source. The working gas was a mixture of Ar and CO_2 (90%:10%). The preamplifier (ortec142AH), main amplifier (ortec572A) and multichannel analyzer (trump-usb-8k) were used to construct a data acquisition system. As shown in Fig. 3(a), the gain could be up to 3000 or more, which was enough for neutron detection (around 100). Fig. 3(b) showed the energy spectrum of ^{55}Fe X-ray of 5.9 keV. The full energy peak and escape peak were clearly distinguished and the energy resolution was about 27.7% (FWHM). Although the energy resolution was not as good as the standard GEM, it was enough to meet the demands since the signal charge was not needed to be measured in the readout electronics.

3. Ceramic GEM-based neutron detector

The ceramic GEM was suitable for neutron detection due to its low neutron scattering. In order to investigate the performances of the ceramic GEM, a prototype was developed and tested with neutron beams.

3.1. Prototype setup

A schematic view of the detector prototype was shown in Fig. 4(a). The cathode with an effective area of 50 mm × 50 mm was coated with 2 μm thick ^{10}B. The incident neutron was converted to charged particles by the reaction $^{10}B\,(n,\,^{7}Li)\alpha$. Either α or ^{7}Li may enter the drift region and produce primary ionization. Then, the generated electrons were multiplied by the GEM. The detector prototype picture was shown in Fig. 4 (b). It was mainly made of aluminum with the incident window of 0.1 mm thick foil.

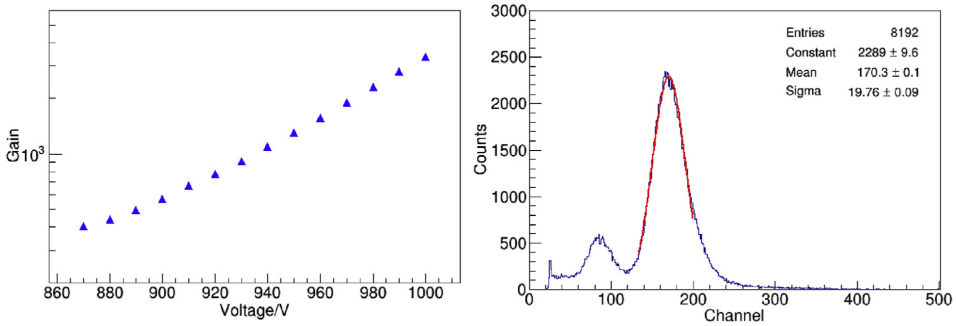


Fig.3. (a) The gain curve, (b) the energy spectrum of X-ray.

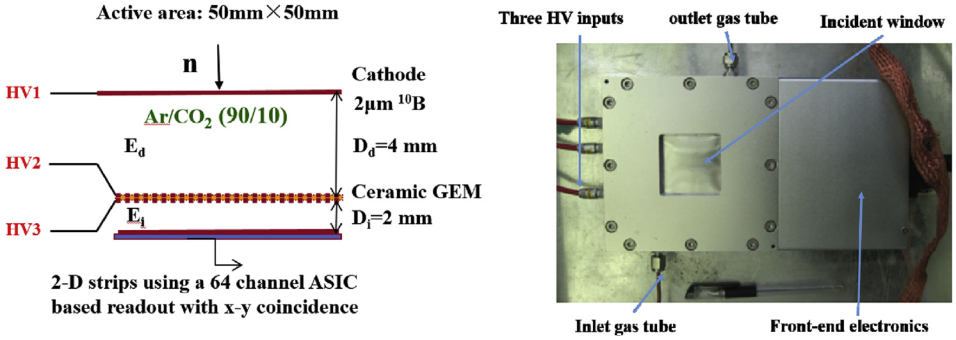


Fig. 4. (a) A schematic view of the prototype, (b) the prototype appearance.

The cathode, single ceramic GEM and the readout board were installed in a gas chamber with the mixture of Ar and CO_2 (90%:10%) on the flow mode. The high voltages were applied to the cathode and the single GEM through three independent high-voltage (HV)supplies. The ASIC front-end electronics and the HV board were placed in the other side chamber for the electromagnetic shielding.

To obtain the two-dimensional position, cross-strips were fabricated symmetrically on the top surface of the readout board with a strip pitch of 1.56 mm. There were a total of 64 electronic channels connected to the readout board, where 32 channels were assigned to strips in the x direction and 32 in the y direction. The signals were read out with one CIPix ASIC chip developed by the Heidelberg ASIC lab [19]. The front-end electronics was composed of one CIPix chip which integrated 64 channels of a low-noise charge-sensitive preamplifier followed by a shaper and a discriminator. The two-dimensional position of the incident neutron was realized through a coincidence of correlation of signals in time and space domain. One neutron event (x, y, t) could be obtained by the real-time event reconstruction algorithm in the FPGA using incoming data from the cross strips together with the time stamping. Communication and data transfer from the electronics were realized through a USB link.

3.2. *Performances of the prototype*

In order to investigate the performances of the ceramic GEM, the detection efficiency, spatial resolution and two-dimensional imaging capability of this prototype detector were studied using the monoenergetic neutron beam of the 1.59 Å wavelength at the Powder Diffraction instrument at CMRR [20]. The wavelength spectrum was measured by TOF method at CSNS BL20.

3.2.1. *Detection efficiency*

The detection efficiency of the prototype was evaluated by comparing with the standard 12.7 mm, 10 atm ^{3}He counting tube. The neutron beam was collimated by a 2 mm thick cadmium plate with a small hole ($\Phi = 1.5$ mm) at the center. The hole was aligned to the center of the ^{3}He tube or prototype detector. The Geant4 simulation result showed the detection efficiency of the ^{3}He tube was 68.5% for 1.59 Å neutrons at CMRR. The detection efficiency of the prototype was estimated to be 4.9 ± 0.1%, where ±0.1 was the statistical deviation. The detection efficiency was also calculated by using Geant4 (4.2% @1.59 Å) [21], as shown in Fig. 5. The possible reasons of the deviation between results of the measurement and the simulation are uncertainty of the boron coating thickness and the ^{3}He gas pressure.

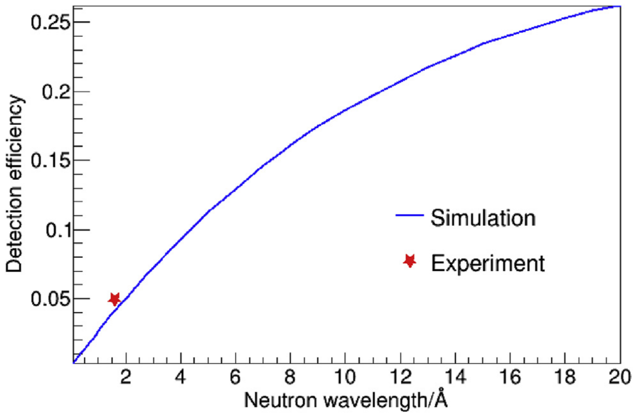


Fig. 5. Neutron detection efficiency. The neutron detection efficiency vs the neutron wavelength given by the Geant4 simulation (curve) and the measurement (star).

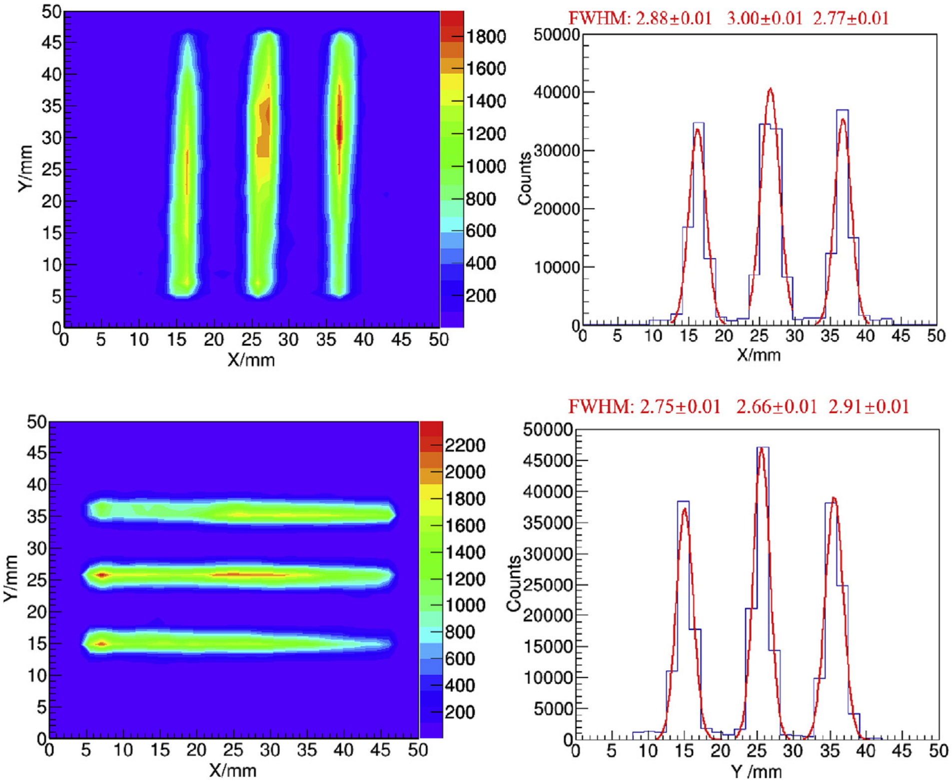


Fig. 6. Spatial resolution: (a) *x* direction; (b) *y* direction.

3.2.2. Spatial resolution and two-dimensional imaging

Spatial resolution was one of the most important specifications for the two-dimensional position-sensitive neutron detector. The spatial resolution could be measured with a sufficiently narrow slit. A 2 mm-thick Cadmium mask, with three slits 0.5 mm wide at a pitch of 10 mm, was mounted in the front of the prototype. The resolutions in the x and y directions were measured by rotating the Cadmium mask by 90°. Fig. 6 showed the detector's response to the neutron beam with the mask. The spatial resolution, defined as the FWHM of a peak, was obtained by Gaussian fitting of the projected count distributions in the x (Fig. 6(b)) and y directions (Fig. 6(d)). The results in the two directions revealed the spatial resolution were below 3.00 ± 0.01 mm (FWHM), where ±0.01 was the statistical uncertainty.

The two-dimensional imaging was performed using a cadmium plate of 1 mm thick with a carved pattern of “CSNS”. As shown in Fig. 7, it showed the image was consistent with pattern and the background signal level is low.

3.2.3. Wavelength spectrum with TOF method

The neutron wavelength spectrum was measured using the TOF method at CSNS BL20 with a decoupled poisoned hydrogen moderator of CSNS. An external T0 signal (TTL) was used as trigger with a continuous 25 Hz frequency from the accelerator. The diameter of the beam collimator was 20 mm. The neutron detector was put in the collimator exit to measure the direct beam. For the validation evaluation, the wavelength spectrum obtained by the neutron detector was compared with that by the ORDELA 4562 N detector. The spectra were normalized to the overall sum of counts. Fig. 8 showed that the spectral shape measured by the prototype was identical to that measured by the ORDELA 4562 N detector.

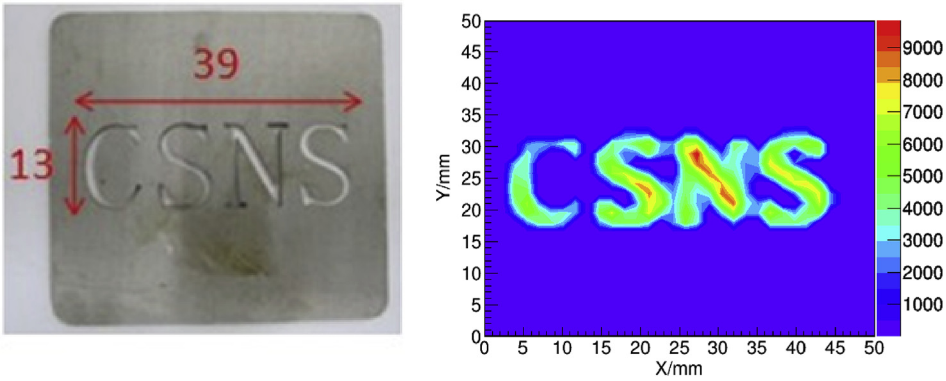


Fig. 7. Two-dimensional imaging (a) Mask with carved pattern (b) Imaging result.

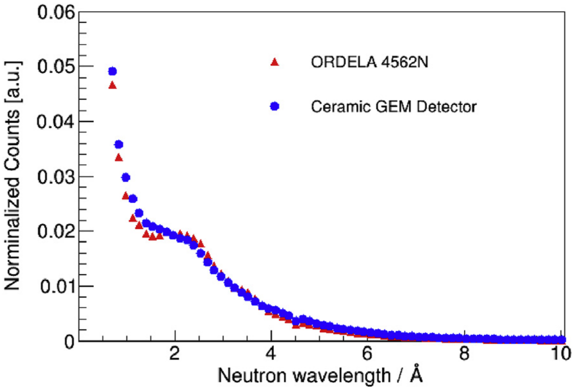


Fig. 8. Neutron wavelength Spectra (normalized to the sum of counts).

4. Conclusion and outlook

A novel ceramic GEM has been successfully applied in the neutron detection as an alternative to ^{3}He-based neutron detectors. Compared with FR4 GEM, it had higher transmittance and less self-scattering especially for cold neutrons. In order to verify its feasibility, a prototype was developed to evaluate the performances of the detector by neutron beam tests. The results showed that the ceramic GEM-based neutron detector is a good candidate to measure the high intensity neutrons. In the future, many kinds of neutron detectors based on the ceramic GEM will be developed for various applications, such as beam monitors, imaging and scattering detectors with high efficiency at CSNS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.11.021.

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