Experimental research on a THGEM-based thermal neutron detector *

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Abstract: A new thermal neutron detector with a domestically produced THGEM (Thick Gas Electron Multiplier) was developed as an alternative to ^{3}He to meet the needs of the next generation of neutron facilities. One type of Au-coated THGEM was designed specifically for neutron detection. A detector prototype has been developed and the preliminary experimental tests are presented, including the performance of the Au-coated THGEM working in Ar/CO_2 gas mixtures and the neutron imaging test with ^{252}Cf source, which can provide the reference for experimental data for research in the future.

Key words: THGEM, boron convertor, thermal neutron detector, two-dimensional position sensitivity

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1 Introduction

Neutrons are used to investigate the structure and dynamics of a material. Many efforts have recently been devoted to the development of the next generation of neutron facilities, which include SNS in the USA, J-PARC in Japan, ISIS in the UK, CSNS (China Spallation Neutron Source) in China and ESS in Europe [1]. The neutron detector is one of the key components of the neutron scattering instruments. With the international development of new generation neutron sources, the traditional neutron detector based on ^{3}He has not been able to satisfy very well the demand of the application of high flux. Also, facing the global crisis of ^{3}He supply [2], research on a new style of the neutron detector which can replace the ^{3}He based detection technology has become extremely urgent.

As a good candidate, a boron-coated GEM became the focus of attention recently [3, 4], first designed by Martin Klein using a CERN standard GEM in 2006 [4]. It has excellent characteristics, such as high counting rate capability (>10 MHz/mm^2), good spatial resolution and timing properties, radiation resistance, flexible detector shape and readout patterns [5]. In 2011, IHEP [6] and UCAS [7] first successfully developed a kind of thick Gas Electron Multiplier (THGEM), manufactured economically by standard printed-circuit drilling and etching technology in China. Compared with the CERN standard GEM, THGEM has higher gain, sub-millimeter spatial resolution and the possibility of the industrial production capability of robust large-area detectors [8], which is very suitable for the application of neutron detection.

In this paper, we present experimental research on a new kind of neutron detector based on the domestically produced THGEM which was provided by Xie Yuguang's group at IHEP. It is an Au-coated THGEM with a thickness of 300 μm, a hole diameter of 250 μm, pitch of 600 μm and a rim of 80 μm. The THGEM was made of FR4 glass epoxy substrate, with copper cladding on both sides and then Au coated on the copper, which had an active area of 50 mm×50 mm. In order to study its basic characteristics as the references for the development of this kind of THGEM-based neutron detector, the performances of the counting rate plateau, the energy resolution and the gain had been measured in the different Ar/CO_2 gas mixtures with different high voltages. According to the tests, the optimized working conditions of the THGEM have been obtained.

By using this kind of THGEM, a detector prototype had been developed. In order to study the characteristics of the prototype including its data acquisition system,

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and make a good preparation for the neutron beamline test in the next step, a preliminary imaging measurement with ^{252}CF neutron source was carried out at IHEP. According to the experiments, this should be very helpful for the design of this kind of THGEM-based neutron detector in the future [9, 10].

2 Design of the detector prototype

The detector mainly consists of the neutron convertor, the single THGEM for gas multiplication (~100), and the 2-D strips structure for signal readout. Fig. 1(a) shows the schematic view of the detector and Fig. 1(b) is the image of the detector. The resistance chain is used to provide three channels of high voltage supply. With a ^{10}B layer coated on the drift cathode as the neutron convector, when a neutron is captured, either an α ion or a^{7}Li ion is emitted into the drift gas volume, where it releases along its track a large number of Secondary Electrons (SE), which is proportional to the energy deposited in the drift gas volume (~3×10^4 SE for 1 MeV). The THGEM is employed for SE multiplication and can provide an effective gain of several hundreds. Then, the signal will be induced on the 2-D strip structure to determine the spatial and timing information by the readout electronics and data acquisition. The detector is operated in flow mode with Ar/CO_2 mixtures at atmospheric pressure. The continuous purge of cheap counting gas avoids the ageing effects encountered in other detectors so as to get long-term stability as well as a long lifetime. Table 1 shows the design specifications of the detector prototype.

Table 1. Specifications of the detector prototype.

parameter	specification
active Area	50 mm×50 mm
neutron flux	$<10^8$n/(cm^2·s)
spatial resolution(FWHM)	<3 mm
timing resolution	<1 μs
efficiency@1.8Å	~4%
max counting rate	>1 MHz
working mode	real-time

The data acquisition system of the detector is based on the analogue front-end readout ASIC chip and modern Field-Programmable Gate Array (FPGA) technology (Fig. 2). The 2-D strips are followed directly and read out by a front-end electronics of 64 channels CIPix ASIC-based daughter board. The strip period is 1.56 mm with a gap of 0.26 mm. For each dimension, there are 32 channels for readout. The CIPix ASIC was originally developed by the Heidelberg ASIC lab in 2000 for the DESY H1 experiment. A single chip integrates 64 channels of a low noise charge sensitive preamplifier followed with a shaper and discriminator. In typical neutron detection, no external trigger is available. On the contrary, individual neutron events are entirely uncorrelated. The FPGA is employed to realize the high bandwidth data

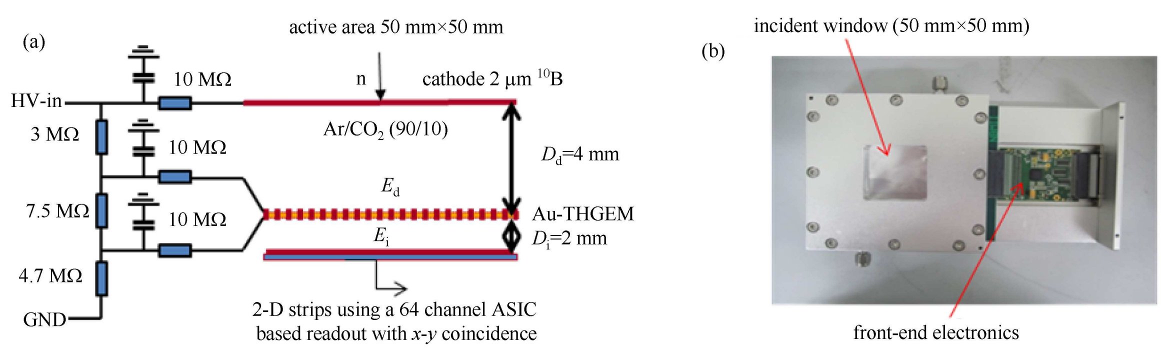

Fig. 1. Schematic of the detector prototype.

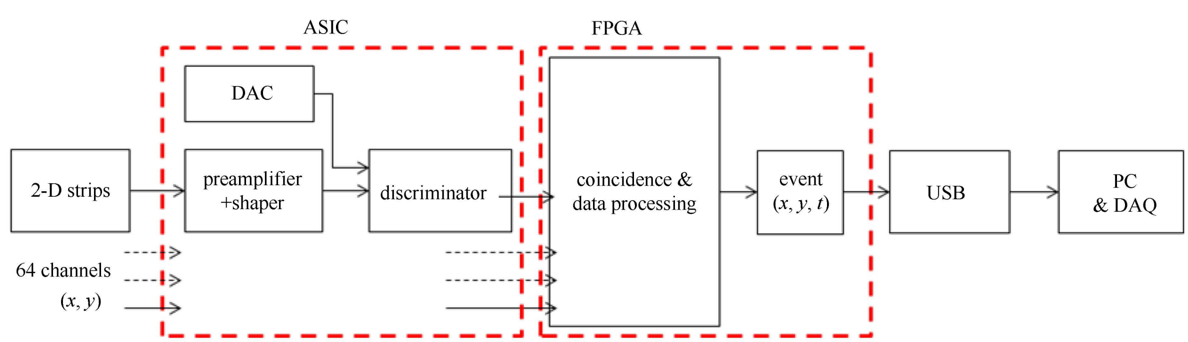

Fig. 2. Schematic of the data flow and processing.

processing. As one neutron is detected, a cloud of electron charges, drifting onto the readout structure, will be collected by electrode strips corresponding to both dimensions x and y. Thus, the detection of a neutron at the corresponding (x, y) coordinates will be obtained by means of simultaneous coincidence of signals on x- and y-readout channels. After coincidence, the time stamp of each neutron will be added and then an event reconstruction including the spatial and timing information (x, y, t) is completed. Finally, the data will be transferred to the PC for data acquisition and analysis.

3 Thermal neutron efficiency

Compared with the highly reactive and expensive ^{6}Li, a solid ^{10}B layer seems to be much more favourable and suitable for use as a neutron converter. It can easily be produced in reasonable sizes using evaporation or sputtering techniques. ^{10}B (enrichment >99%) is commercially available. The enriched ^{10}B is coated on one surface of the copper cathode plate. Neutrons are detected by the following neutron reactions:

$$
\begin{aligned}
&\mathrm{n}+{}^{10}\mathrm{B}\rightarrow\alpha+{}^{7}\mathrm{Li}+2.79\ \mathrm{MeV} \quad 7\% \quad E_{\alpha}=1.78\ \mathrm{MeV} \quad E_{\mathrm{Li}}=1.0\ \mathrm{MeV}\\
&\mathrm{n}+{}^{10}\mathrm{B}\rightarrow\alpha+{}^{7}\mathrm{Li}^{*}+2.31\ \mathrm{MeV} \quad 93\%\\
&\qquad\qquad \alpha+{}^{7}\mathrm{Li}+\gamma+2.31\ \mathrm{MeV} \quad E_{\alpha}=1.47\ \mathrm{MeV} \quad E_{\mathrm{Li}}=0.84\ \mathrm{MeV}
\end{aligned}
$$

When the thermal neutron induces the ^{10}B(n, α)^{7}Li reaction, 93 % of all the reactions lead to the first excited state of ^{7}Li*, which 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. The thermal neutron (0.0253 eV) cross section of the ^{10}B(n, α)^{7}Li reaction is 3840 barn and it drops rapidly with the increasing thermal neutron energy. The maximum conversion efficiency is about 5% for thermal neutrons through a single pure ^{10}B-layer with the thickness of 2.5 μm. For charged ions α and ^{7}Li, the gas detector can reach its efficiency very close to 100%. As a result, the neutron efficiency can be considered as the conversion efficiency. For the thickness of 2.0 μm used in the prototype, the thermal neutron efficiency calculated by Geant4 is 4.6%.

4 Results and discussion

4.1 Tests on THGEM foil

In order to study its basic characteristics as the reference for the development of this kind of THGEM based neutron detector, the performances of the counting rate plateau, the energy resolution and the gain have been measured in different Ar/CO_2 mixtures with different high voltages. The THGEM foil was tested using a ^{55}Fe X-ray source (activity 10 mCi) which was positioned in such a way that a collimated beam (Φ1 hole) of X-rays perpendicularly entered the upper drift region. The signal was induced by a cathode pad and read out with an ORTEC 142IH preamplifier followed by an ORTEC 572A amplifier (shaping time $t=2$ μs) and an ORTEC multi-channel analyzer (trump-usb-8k).

First of all, several THGEM foils were tested to check the stability of the gain over 12 hours. One of these foils which showed the best performance was chosen for the next tests, below. After 200 minutes, the effective gain would become stable as shown in Fig. 3(a). Consequently, the THGEM was warmed up about 200 minutes before every test. Fig. 3(b) shows the gain in the different Ar/CO_2 mixtures with the different high voltages. The THGEM can provide an effective gain range from

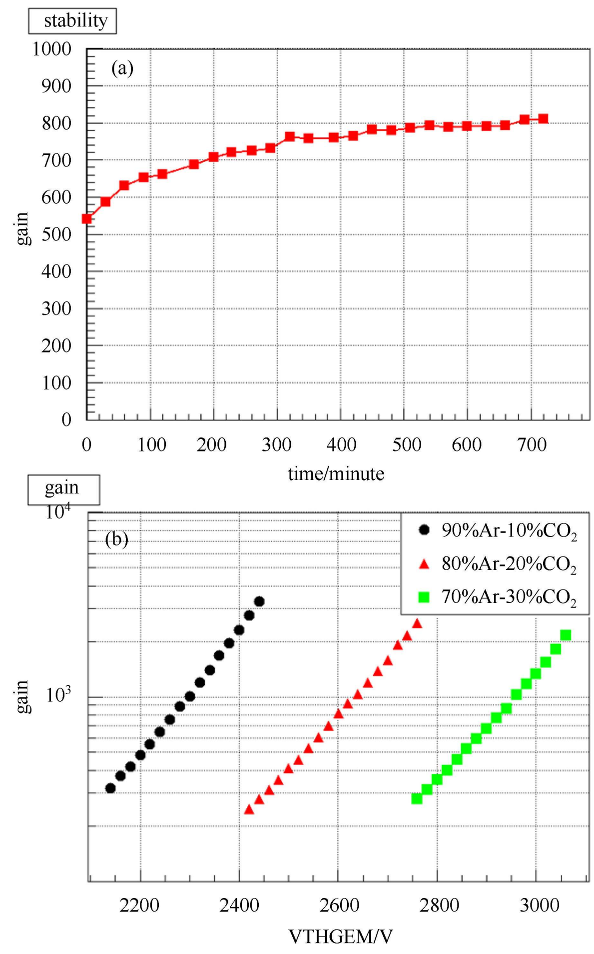

Fig. 3. Gain and stability of the THGEM.

300 to 3000 in Ar/CO_2 mixtures. For the gas mixture Ar/CO_2 (90%/10%), the working voltage will be lower to give the same gain.

In order to know the suitable working voltage of the detector in different Ar/CO_2 mixture, its counter plateau was measured for different total voltage. During the experiment, the total flow of Ar and CO_2 gas was 50 SCCM to ensure the amount of effective working gas in the chamber. The counts were recorded every one minute and the voltage of THGEM was increased by increments of 20 V until spark discharge occurred. As Fig. 4 shows, it has a longer plateau in the Ar/CO_2 mixture ratio of 90%/10% and the THGEM works at a lower voltage. For the gas mixture Ar/CO_2 (90%/10%), the plateau range of the THGEM is from 2200 V to 2400 V and its plateau slope is smaller than 3%/100 V, as shown on the left of Fig. 4. This optimization will be helpful to know the working range of the THGEM and find the conditions at lower HV.

Energy resolution is one of the most important parameters related to the detector performance. By using the 5.9 keV ^{55}Fe X-ray source, the energy resolution was measured. A much better energy resolution is obtained in the Ar/CO_2 (90%/10%) gas mixture. Fig. 5 shows the pulse height spectrum obtained with a ^{55}Fe source in the Ar/CO_2 (90%/10%) gas mixture. To obtain the energy resolution, it is fitted with a Gaussian function. This indicates the energy resolution (FWHM) of the detector based on THGEM about 34% at 2440 V. With such an energy resolution, the detector can entirely separate the 3 keV of Ar escape peak from the ^{55}Fe main X-ray peak located at 5.9 keV.

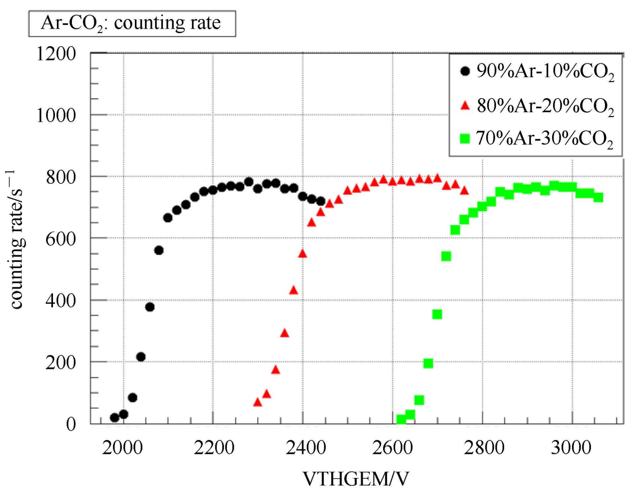

Fig. 4. Counting rate plateau with total HV.

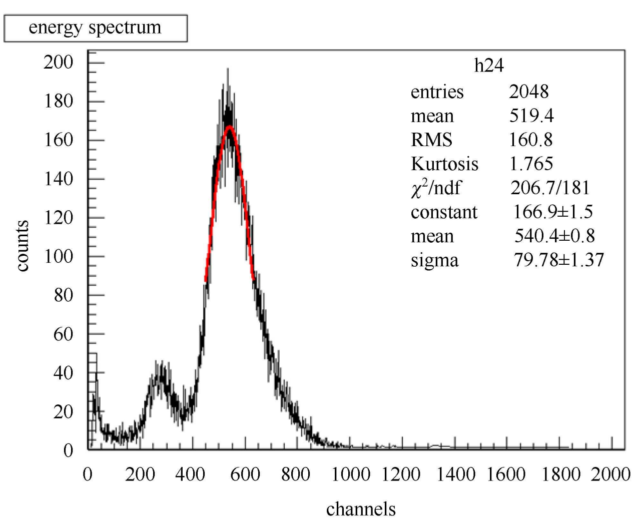

Fig. 5. A pulse height spectrum in the Ar/CO_2 (90%/10%) gas mixture.

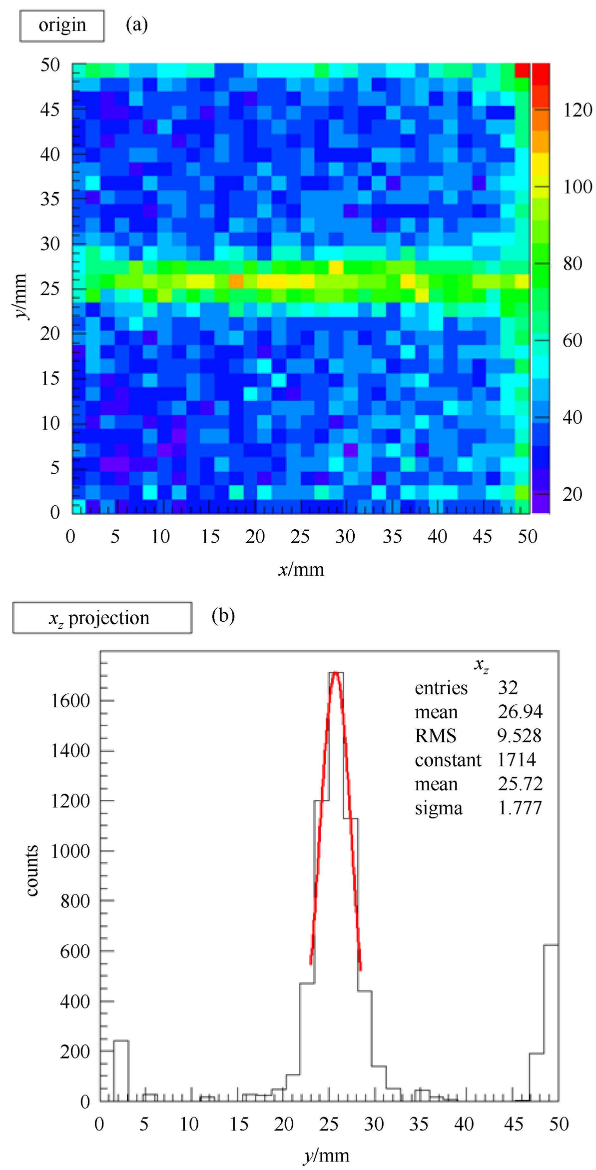

Fig. 6. Spatial distribution.

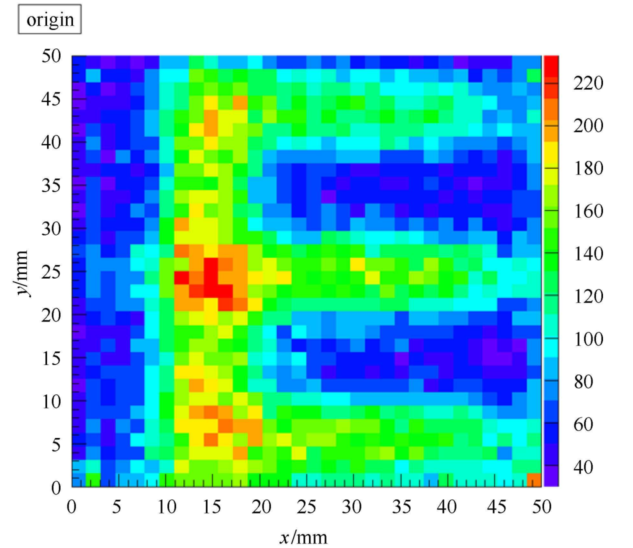

Fig. 7. Neutron imaging.

4.2 Neutron tests in ^{252}Cf source

In order to study the characteristics of the prototype, including its data acquisition system, and make a good preparation for the neutron beamline test, a preliminary measurement was carried out with an isotopic neutron source ^{252}Cf ($\sim 1\times 10^6$ n/s), which was placed in a special shielding box with an open hole with a diameter of 100 mm in the side. The detector was mounted onto the exit of the hole. To obtain larger counts, no neutron moderation was used in the test.

The neutrons emitted from ^{252}Cf source follow the fission spectrum and its average energy is 2.3 MeV. The single cadmium mask cannot absorb all the neutrons. For the measurement of the spatial resolution, the mask with a slit 3 mm wide was made of 25 mm thick boron plastic and 1 mm thick cadmium. Due to the weak source, the test took 24 hours. The 2-D counts image is shown in Fig. 6(a), and Fig. 6(b) is the projection on the y axis. The count distribution is fitted with a Gaussian function and the FWHM of spatial distribution is 4.2 mm, which is worse than expected. The reason is because the neutrons emitted from the ^{252}Cf source have lots of energy and the mask with the slit cannot absorb all the neutrons completely. This is the main reason why a monoenergetic neutron beam line is needed for accurate measurement.

To test the imaging ability of the whole system, a mask with a letter E was used, which was made of 25 mm thick boron plastic and 1 mm thick cadmium. The test took 24 hours as well. Due to the same reason, the image (Fig. 7) is not good. However, it is clear that the detector prototype works normally as expected for neutron detection.

5 Summary

In this paper, a new type of neutron detector based on a domestically produced Au-coated THGEM is introduced and a preliminary experimental study is presented, including the performance of the Au-coated THGEM working in Ar/CO_2 mixtures and the neutron test of the detector prototype using a ^{252}Cf source. This work is considered as the preparation of the accuracy measurement at the neutron beamline in the reactor, which will be reported in the near future.

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