Developments of a 2D Position Sensitive Neutron Detector

TIAN Li-Chao,1,2) TANG Bin, WANG Xiao-Hu, LIU Rong-Guang, ZHANG Jian,1 CHEN Yuan-Bo, SUN Zhi-Jia,2,3) XU Hong, YANG Gui-An, ZHANG Qiang,2,3)

1 Graduate University of the Chinese Academy of Sciences, Beijing, 100049, China
2 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, China
3 China University of Petroleum, Beijing, 102249, China

Abstract Chinese Spallation Neutron Source (CSNS) one project of the 12th five-year-plan scheme of China, is under construction in Guangdong province. Three neutron spectrometers will be installed at the first phase of the project, where two-dimensional position sensitive thermal neutron detectors are required. Before the construction of the neutron detector, a prototype of two-dimensional 200mm × 200mm Multi-wire Proportional Chamber (MWPC) with the flowing gas of Ar/CO\(_2\) (90/10) has been constructed and tested with the 55Fe X-Ray using part of the electronics in 2009, which showed a good performance.

Following the test in 2009, the neutron detector has been constructed with the complete electronics and filled with the 6atm.\(^3\)He + 2.5atm.C\(_3\)H\(_8\) gas mixture in 2010. The neutron detector has been primarily tested with an Am/Be source. In this paper, some new developments of the neutron detector including the design of the high pressure chamber, the optimization of the gas purifying system and the gas filling process will be reported.

The results and discussion are also presented in this paper.

Key words Thermal Neutron Detector, Two Dimensional MWPC, Am/Be Neutron Source

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1 Introduction

Thermal neutron scattering techniques are playing an important role in the diffraction experiments in determination of the molecular and crystal structures in biology, condensed state physics and polymer chemistry requiring a high flux neutron sources. Chinese Spallation Neutron Source (CSNS), as the first spallation neutron source in the developing countries, will be working at the beam power of 0.1 MW and the neutron flux of 2 × 10\(^16\) cm\(^{-2}\)·s\(^{-1}\). Three spectrometers will be installed at the first phase of the project. Efficient detectors with high position resolution, high detection efficiency and low gamma sensitivity are required for neutrons in the wavelength range from 1.8 Å to about 8 Å. Because of the high cross-section for neutrons absorption (5330 b @ 1.8 Å), the \(^3\)He gas is widely used in many instruments\(^{4,5}\). The detector based on Multi-wire Proportional Chamber (MWPC) filled with \(^3\)He gas can be built in large size, with relatively good energy and position resolution, high efficiency and shows no radiation damage compared to the solid state and scintillation detectors.

Usually to meet the characteristics of high neutron detection efficiency and high position resolution, the \(^3\)He based neutron detectors are working in a high pressure state. The neutron detector consists of a MWPC and a high gas pressure container filled with the operating gas. To optimize the parameters of the MWPC, the main part of the neutron detector, and guarantee that it can show excellent performance in neutron test, it is necessary to construct a prototype of the MWPC and test it by X-Ray with flowing gas firstly. Good results have been achieved in the X-Ray test in 2009, then a high pressure container was constructed and the MWPC was fixed in it. Later on, the operating gas was filled with good gas tightness and the neutron detector equipped with the complete electronics was tested with the Am/Be source at the Institute of High Energy Physics (IHEP).
2 The MWPC prototype [4]

A prototype of a two-dimensional MWPC with atmospheric pressure and flowing gas for X-Ray has already been constructed prior to the neutron detector. The geometry of the two-dimensional MWPC is shown in Fig. 1. The MWPC with 200 mm × 200 mm sensitive area is of conventional design with a cathode plane, an anode plane and two orthogonal readout planes symmetrically located about the central anode plane. The cathode is made of a thin metal foil pasted on the window. The anode plane is made up of 15 µm diameter gold-plated tungsten wires (with the tension of 25 g per wire) with an inter-wire spacing of 2 mm. The X readout plane is made up of 50 µm diameter gold-plated tungsten wires (with the tension of 40 g per wire) with an inter-wire spacing of 1 mm. Every four wires are connected together to form one readout-strip. The direction of the readout wires is parallel to the anode wires. The Y readout grid is made up of 1.6 mm wide copper strips in the orientation orthogonal to the anode wires with an inter-strip spacing of 2 mm. Every two copper strips are connected together to form one readout strip.

Fig. 1. layout of the planes of the MWPC

Tested by $^{55}$Fe 5.9keV X-ray in 1 atm. Ar/CO$_2$ (90/10) mixture with part of the electronics, an energy resolution (FWHM) of about 23% for $^{55}$Fe 5.9keV X-ray, and a spatial resolution (FWHM) of about 210 µm along the anode wire direction were obtained (See Fig. 2). The successful construction of the prototype laid the foundation for the neutron detector construction.

3 Developments

The main structure of the thermal neutron detector is the same as the prototype (See Fig. 1). The neutron absorption by $^3$He induces a fission reaction and emission of two charged particles, one triton and one proton, in opposite direction with a total kinetic energy of 764 keV which induces the primary ionization in the gas. The position of the neutron is considered to be the centroid of the primary electrons associated with the nuclear reaction point. But actually the ionization centroid is displaced to the point of 0.4 times of the proton moving range apart from the nuclear reaction point [5]. To meet the characteristics of high neutron detection efficiency and high position resolution, the wire planes should be sealed in a high pressure chamber with 6 atm. $^3$He as detection medium and 2.5 atm. C$_4$H$_8$ as stopping gas. A high pressure chamber has been designed, the gas purifying system was updated and all the electronics were tested before the performance test with the Am/Be source.

3.1 High pressure chamber

As will be working under high pressure, all the wire planes should be fixed in a high pressure container, which consisted of a circle front cover made of aluminum alloy 6061-T6 and a circle back-plate made by stainless steel (See Fig. 3). Double "O" shape rings were used to seal the container. A 9 mm thick window with area of 210 mm × 210 mm was constructed in the center of the front cover to minimize the neutron scattering. The 25 mm thick back-plate provided structural rigidity under the maximum gas pressure of 10 atm. The anode signals and the cathode signals were transferred to the readout electronics via flanges deployed on the back-plate. A gas purifying system, consisting of a pump and a filter, was also included, so as to guarantee the purity of the operating gas [6].

Fig. 3. the pictures of the high gas pressure chamber

3.2 Gas filling

The gas purifying system has been updated since there was a little gas leakage and the gas filling pro-
cess has been completed in Beijing Nuclear Instrument Factory in February, 2010. Some unnecessary tubes were removed to reduce the gas leaking probability. To test the gas tightness, 9 atm. of $^4$He gas has been filled in the chamber and kept for about two months without obvious leakage. Before being filled with the operating gas, the chamber was first heated to 60°C and evacuated until a stable vacuum was obtained (about $3 \times 10^{-4}$ Pa) to release the residual gas in the materials. Kept the vacuum state for 48 hours, and then flowed the pure argon through the chamber for 5 hours, so as to take away the leftover gas in the chamber. Secondly, the chamber was evacuated to vacuum again. Finally, $^4$He/C$_3$H$_8$ mixture was filled. Fig. 4(a) shows the changes of the gas pressure and the temperature after the 8.5 atm. of operating gas filled in 45 days. The fluctuation was caused by the temperature. Fig. 4(b) shows the ratio of the calculated pressure, corrected by temperature, to the initial pressure in each day, which are within the accepted reading error limits.

![Pressure and temperature](image1)

![Ratio of calculated pressure to the initial pressure](image2)

Fig. 4. Pressure variety of the Chamber

Presumed it is an exponential leaking, the ratio changes with time as the function \( R = e^{-0.0001526t+0.002111} \), so the leakage lifetime is \( T_0 = 18 \) years. It means that 18 years later the gas pressure will be \( 1/e \) of the initial pressure. Since the C$_3$H$_8$ molecules are much larger than $^4$He atoms, the main leaking gas will be $^4$He. There will be effects on the detection efficiency and the gas gain as the gas leaking, which are shown in Table 1, assuming the detector is working with the same high voltage. So, in actual running to keep the uniformity of the gas gain the operation high voltage should be decreased as time.

\[
R = e^{-0.0001526t+0.002111}
\]  

Table 1. The effects on the detector performance caused by the gas leakage (simulated by Garfield with same high voltage).

| Elapsed time | Detection efficiency | Relative change of Gain |
|--------------|----------------------|-------------------------|
| Initial state| 75%                  | 1                       |
| 6 years \( (T_0/3) \) | 59%                  | 196%                    |
| 9 years \( (T_0/2) \) | 50%                  | 241%                    |
| 18 years \( T_0 \)  | 25%                  | 407%                    |

3.3 Electronics

The location of the neutron is assumed to be the gravity center of the induced charges read out from the cathode strips. There are two aspects which should be taken into account during the electronic design. First of all, the detector should own a pretty good performance in n/\( \gamma \) discrimination. The \( \gamma \) rays can be discriminated from neutrons due to the differences of energy deposit in the gas. Secondly, we have to obtain the distribution of the induced charge on the cathode strips to get the center of gravity to reconstruct the position of the neutrons. A total of 100 individual position readout channels, 50 in each direction, and one anode readout channel are developed by the electronic group in IHEP. The total charge collected on the anode wire is used to get the energy loss information to trigger the readout. The analogue signal from the charge-sensitive preamplifier is directly converted to digital signals by a 10 bit 40 MHz FADC. Then the peak finding circuits based on FPGA, which can handle 16 channels at the same time, obtain the charge of each readout channel and deduct the baseline, and then keep the results in a local buffer (See Fig. 5). All the electronics after the preamplifiers are built on the VME daughter card. The DAQ can read the buffer through the VME bus and save the raw data in a local hard disk for the offline analysis. All the electronics has been calibrated together with the VME crate, which showed a good long-term stability.
4 Test with the Am/Be source

4.1 Experimental Setup

The neutron detector was firstly tested with an Am/Be source, which was sufficient for uniform irradiation testing, but not powerful enough to generate collimated beams for high spatial resolution testing. The experimental equipment was set up as Fig. 4. In our experiment, the fast neutrons emitting from the Am/Be source were moderated through a 40 cm thickness polythene block firstly and then went through a 12 mm thick Pb (as the shield of the gamma rays). Finally, the moderated neutrons entered the detector with a cadmium mask placed in front of the detector window. The whole detector was put in a Cd-box to absorb the surrounding thermal neutrons.

4.2 Results

A) Spectrum

The energy spectrum is the main basis in the n/γ discrimination. The energies deposited in the detector under different testing conditions are shown in Fig. 7. The spectrum (a) was tested with the $^{137}$Cs gamma ray source; the spectrum (b) was tested with an Am/Be source with a moderator and Pb in front of the window shown in the Fig. 6; the spectrum (c) was tested under the same condition with (b) but with 4 mm thick cadmium more in front of the window to absorb the thermal neutrons from the source. Three spectrums had been normalized by the run time. The peaks on the right side corresponded to the energy disposed by neutrons, while the middle ones near the 200 channel corresponded to the gamma rays. The left peak was caused by the fake triggers due to the electronic noise.

With appropriate thresholds selected, the gamma ray could be discriminated from the neutron easily through the comparing of the spectrum (a) with (b). But there were many upper-Cd neutrons and high energy gamma rays (together about 17% of the thermal neutrons) which could still penetrate the cadmium and be captured in the detector from the comparing of the spectrum (b) with (c). They were the main background in the thermal neutron test.

B) 2D Imaging

A two-dimensional image was obtained by placing a mask (Shown in Fig. 8(a)) in front of the detector’s window. The mask with 2mm thick was made up of a cadmium plane with a hole of the character "H". In order to get a sharp image we had to make the strokes of the character a little wider, due to the low intensity of the source and the high neutron scattering in the moderator. To collect enough neutron events the whole system had to be taking data for at least 10 hours. The charge collected on the anode, the number of fired strips, the maximum charge and the sum of the charge induced on fired strips were used to discriminate the gamma rays and neutrons in the analysis. This image (Shown in Fig. 8(b)) could also illustrate the good uniformity of response.

C) The position linearity

The position resolution was tested in the direction paralleling to the anode wires (Y direction) at variable positions. Due to the low flux of Am/Be source, only a rough position resolution about 4.9 mm (sigma) was achieved. The position linearity was tested and the fit function of the measured positions to the actual positions was $y=1.0117x+0.0811$. (See Fig. 9). The linear correlation coefficient was 0.9998, which showed a good linearity.

4.3 Discussion

The spatial resolution of the neutron detector is mainly determined by the proton moving range in the
operation gas and the intrinsic position resolution of the MWPC. The proton moving range is determined primarily by the propane pressure - it is about 1.43 mm for our choice of 2.5 atm. from the SRIM simulation. The approximate intrinsic position resolution of MWPC was 210 µm from the $^{55}$Fe test. So, the theoretical neutron position resolution should be the quadratic addition of the error caused by the proton moving range and the intrinsic position resolution, which is better than 1.45 mm (FWHM) according to the equation (2).

$$\sigma_n = \sqrt{\sigma_g^2 + \sigma_i^2} \quad (2)$$

Where, $\sigma_n$ is theoretical neutron position resolution; $\sigma_i$ is the intrinsic resolution from the X-Ray test; $\sigma_g$ is the error caused by the proton moving range.

The reasons why the position resolution in our test was not so good as the expected result were as follows:

i. The high background.

The background, mainly the upper-Cd neutrons and high energy gamma rays from the surrounding, was too high even though the detector was put in a Cd-Box since there were other neutron sources and gamma sources in the lab. The signal to noise ratio was very low. The intensity of thermal neutron from the moderator was not high enough that we had to take data for long time.

ii. Hard to collimate the neutrons.

The neutrons through the moderator could be considered as a plane source in front of the detector window since the neutron emitting direction, the angle between the emitting direction and the normal line of the detector’s window, was about from 0 ∼ 90 degree shown in Fig. [10]. So, most of the thermal neutrons could not go into the detector perpendicular to the window, which made the edge of the character "H" not clear enough.

![Fig. 10. the thermal neutron emitting angle distribution form the moderator (simulation result)](image)

5 Conclusion

The two-dimensional thermal neutron detector has been constructed with the complete electronics system and filled with the 6 atm. $^3$He+2.5 atm. C$_3$H$_8$ gas mixture in 2010. The leakage lifetime of the chamber was about 18 years after the updates of the gas purity system. The whole electronic system had good long-term stability. The detector had a good ability in n/γ discrimination. As for the low intensity Am/Be source being not powerful enough to generate collimated beams, only a 2D image was obtained with the position resolution of 4.9 mm in sigma. But good position linearity was achieved also. A much better spatial resolution is expected to be achieved on the collimated thermal neutron source where there is much higher flux thermal neutrons.

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