A NEW FISSION CHAMBER NEUTRON DETECTOR BASED ON HELIUM SCINTILLATION

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Abstract: A prototype helium scintillation fission chamber neutron detector was developed. A thin $^{235}UO_2$ target foil was used as a radiator, which could produce fragments when it undergoes fission reactions with incoming neutrons. Helium in the gas chamber could be excited by the charged particles from a fission event, and emitted visible light photons, which were detected by a photomultiplier. The sensitivity to neutrons of this detector was about 10^{-15}C·cm^2, and the sensitivity to gamma ray was about 10^{-17} C·cm^2. The good gamma suppression ability of the detector makes it suitable for pulsed neutron detection with the presence of gammas.

Key Words: helium scintillation; neutron detector; flat energy respond; fission fragments; n/γ discrimination

1. Introduction

In the pulse fission radiation field, the neutron measurement is very important, which can indicate the case of the fission matter could encounter some problems, such as the great influence of gamma rays, the lower intense neutrons and so on. Therefore, the neutron detectors should have higher neutron sensitivity and relatively lower γ sensitivity. A helium scintillation fission chamber neutron detector was designed to solve those problems.

In this detector, a thin $^{235}UO_2$ target foil was used as a radiator, which could produce fragments when it undergoes fission reactions with incoming neutrons. When the fragments passes through the helium gas, the molecules of the gas can be excited and emit visible or ultraviolet light [1], which were detected by a photomultiplier .The helium scintillator have many advantages: (i)The light yield is in proportion to the energy deposit [2]; (ii)The scintillation efficiency is independent of the ions [2], for example, the helium scintillator has the same scintillation efficiency to fission fragments and electrons; (iii)The helium scintillator has lower stopping power for gamma rays and electrons because of the smaller atomic number and lower density. Those advantages make helium scintillator to be more suitable for detecting fission fragments than solid or liquid scintillators [3], when the detector is exposure to a great deal of gamma rays.

Moreover the fission of uranium also brings some advantages: (1) The fission section changes little with the neutron energy [4]; (2) The energy of fragments is independent of neutron energy [5]; (3) The fragments can fly a short distance in the helium, which makes sure the maximum energy deposit. So the uranium can behave well in measuring the number of neutrons.

2. The design of the detector

The structure of the detector is shown in Fig.1. The chamber is designed to be airproof that could hold helium gas. Two $^{235}UO_2$ target foils are laid face to face, which could enhance the neutron sensitivity and prevent the photomultiplier acquiring the photons coming from the area that is not between the two target foils. The side of the chamber is made up of quartz glass, which could let the light enter the photomultiplier.

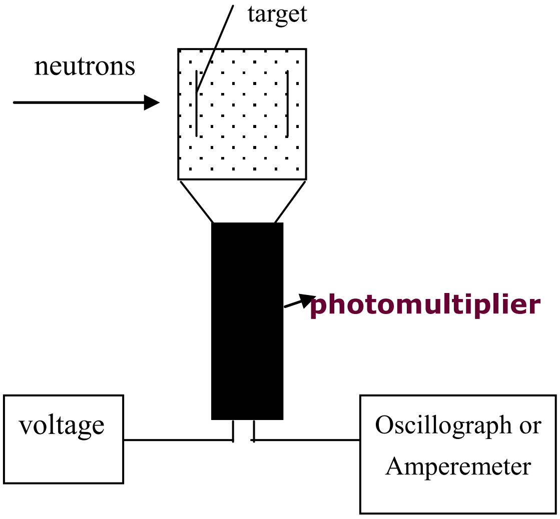

Fig.1. The structure of the detector.

2.1 The distance between two target foils

The distance between two target foils should be decided by the thickness of the foils, because the energy of fragments can change with the thickness. If the distance is longer than the range of fragments flying in the helium, there will be more energy deposit of γ-rays, which can enhance the γ-ray sensitivity. The relation between the range of fragments and the targets' thickness is obtained by the method of Monte Carlo. Fig.2 shows the average range of fragments in helium from different thick ^{235}U targets. When the thickness is more than 7.7mg/cm^2, the range of fragments keeps invariable.

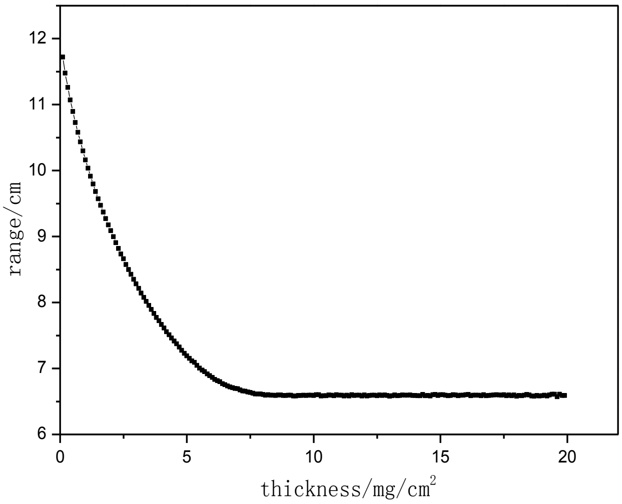

Fig.2. The average range of fragments from different thick ^{235}U targets.

2.2 The thickness choice of the target foils

The average energy of fragments can decrease with the thickness of targets increasing, but the number of fragments increases as the thickness increases. So there should be optimum thickness of targets that the energy deposit of fragments is a maximum. Fig.3 shows the relation curve between energy deposit of fragments and the thickness. Fig.4 shows the relation curve between energy deposit of γ-rays and the thickness, which is calculated by the method of MCNP.

It can be found that the optimum thickness of targets is about 6mg/cm^2 from the Fig.3 and Fig.4.

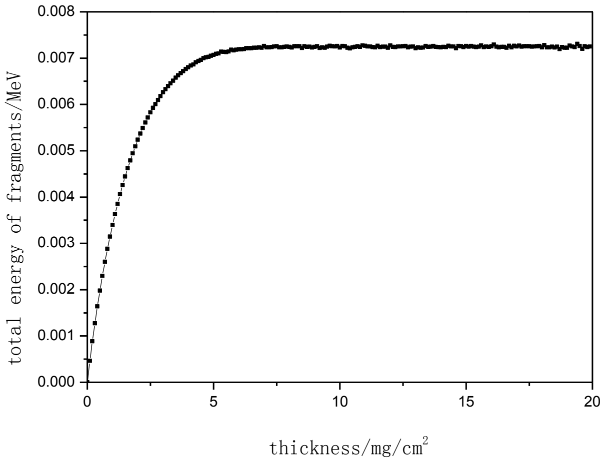

Fig.3. The relation curve between energy deposit of fragments and the thickness.

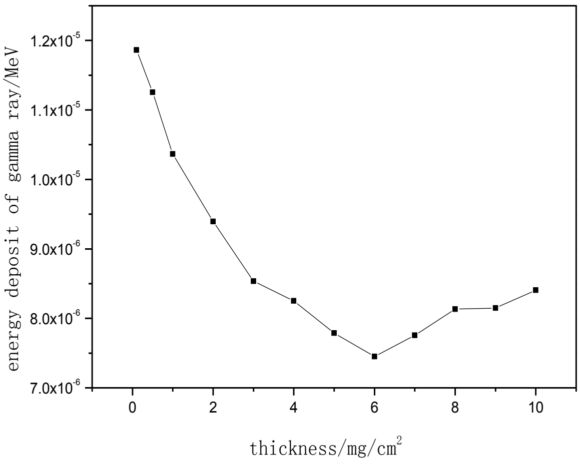

Fig.4. The relation curve between energy deposit of γ-rays and the targets' thickness.

3. The performance of the detector

The chamber was filled with atmospheric pressure helium, when the detector was used actually. The thickness of a $^{235}UO_2$ target foil is about 1mg/cm^2, and the diameter is about 40mm.The distance between two foils is about 10cm. Measurements are made with a glass-windowed EMI 9215SB photomultiplier, which works at the voltage of -1000 volts. The Fig.5 shows the photo of the detector.

Fig.5. The photo of the detector.

3.1 The neutron sensitivity of the detector

The neutron sensitivity is an important performance of the detector, which is calculated by the formula

$$Sn=(En+E_U)\,\eta\varepsilon\zeta Ge\ , \tag{1}$$

where E_n is the energy deposit of neutrons in the helium, E_U is the energy deposit of fragments in the helium, η is the scintillation efficiency of helium scintillator, ε is the light collection efficiency by the photomultiplier, ζ is the quanta efficiency of the photomultiplier, G is the gain of the photomultiplier, e is the charge of a electron.

The final calculation results are shown in Fig.6. The energy spectrum of neutrons is from 0.1 MeV to 15 MeV. The neutron sensitivity is about 10^{-15}C·cm^2.

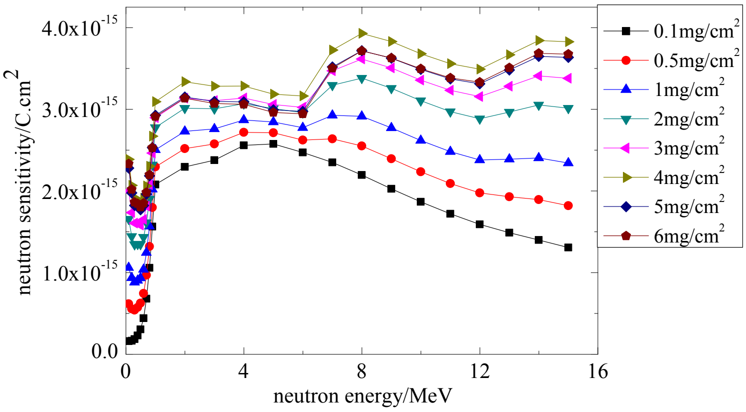

Fig. 6. The theory calculation results of neutron sensitivity.

3.2 The γ-ray sensitivity of the detector

The γ-ray sensitivity of the detector is also important, which decides whether the neutron detector can be used in mixed radiation field. The γ-ray sensitivity is calculated by the formula

$$S_\gamma=E_\gamma\eta\varepsilon\zeta Ge, \tag{2}$$

where the alphabetic symbols have the same meanings as the formula (1), except E_γ is the energy deposit of γ-rays in helium, which is calculated by the method of MCNP.

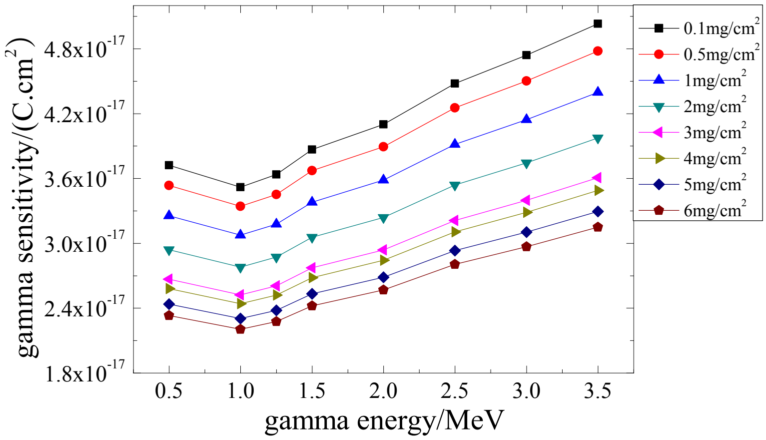

Fig. 7. The theory calculation results of γ-ray sensitivity.

The results of γ-ray sensitivity are shown in Fig.7. The γ-ray sensitivity is about 10^{-17}C·cm^2. Compared Fig. 2 with Fig. 3, the 14 MeV neutron sensitivity is about 100 times more than the 1.25 MeV γ-ray sensitivity.

3.3 The time response of the detector

The time response of the detector can be decided by the flying time of the fragments, the time decay of helium, and the time response of the photomultiplier.

The flying time of the fragments can be calculated by the formula (3), where *E* is the energy of the fragment, *S* is the flying distance of the fragment, *m* is the mass of the fragment.

$$t_{\mathrm{f}} = \frac{\sqrt{2mS}}{\sqrt{E}} \tag{3}$$

The value of S is calculated by the method of Monte Carlo. Table 1 show the flying time of the fragments in helium.

Table 1 The average flying time of the fragments

Thickness/mg·cm^{-2}	0.1	0.5	1	2	3	4	5	6
Average energy/MeV	78.3	69.1	61.4	50.9	44.0	39.2	35.7	33.6
Average flying distance/cm	11.7	10.9	10.2	9.1	8.3	7.7	7.2	6.9
Average flying time /ns	22.3	22.1	22.0	21.5	21.1	20.8	20.4	20.1

The time function of fragments can be show by the formula, where η is the scintillation efficiency of helium scintillator, E_{d} is the average energy deposit of fragments in the helium.

$$g_{\mathrm{f}}(t) = \begin{cases} \eta E_{\mathrm{d}}, 0 \le t \le t_{\mathrm{f}} \\ 0, t > t_{\mathrm{f}} \end{cases} \tag{4}$$

The time function of the detector can be show by the formula [6]

$$g_{\mathrm{sys}} = \begin{cases} \dfrac{I_0 \eta E_{\mathrm{d}} \tau}{\tau_2 - \tau_1}\left[(\tau_2 - \tau_1) - \dfrac{(\tau_2 - \tau_1)\tau^2}{(\tau - \tau_1)(\tau - \tau_2)}\exp(-\dfrac{t}{\tau}) + \dfrac{\tau_2{}^2 \exp(-t/\tau_2)}{\tau - \tau_2} - \dfrac{\tau_1{}^2 \exp(-t/\tau_1)}{\tau - \tau_1}\right], 0 \le t \le t_{\mathrm{f}} \\ \dfrac{I_0 \eta E_{\mathrm{d}} \tau}{\tau_2 - \tau_1}\left\{ \dfrac{\tau_1{}^2}{\tau - \tau_1}[\exp(\dfrac{t_{\mathrm{f}} - t}{\tau_1}) - \exp(\dfrac{-t}{\tau_1})] - \dfrac{\tau_2{}^2}{\tau - \tau_2}[\exp(\dfrac{t_{\mathrm{f}} - t}{\tau_2}) - \exp(\dfrac{-t}{\tau_2})] + \right. \\ \qquad \left. \dfrac{(\tau_2 - \tau_1)\tau^2}{(\tau - \tau_1)(\tau - \tau_2)}[\exp(\dfrac{t_{\mathrm{f}} - t}{\tau}) - \exp(\dfrac{-t}{\tau})] \right\}, t > t_{\mathrm{f}} \end{cases} \tag{5}$$

4. Experiments

Some experiments were carried out to measure the neutron sensitivity and the γ-ray sensitivity of the detector. The neutron measurement experiment was performed with the D-T neutrons, of which energy was about 14 MeV. The neutron sensitivity was about 2.56×10^{-15}C·cm^2/n that was inconsistent with the theory calculation, because the pressure of helium was 0.7 atm in this experiment. The process of neutron measurement is shown in Fig.8.

The γ-ray sensitivity measurement experiment was performed with the ^{60}Co source, of which energy was about 1.25 MeV. The γ-ray sensitivity was about 3.04×10^{-17} C·cm^2/γ that was consistent with the theory calculation. The experiment of γ-ray sensitivity measurement is shown in Fig.9

It could be found that the 14 MeV neutron sensitivity was about 80 time more than the 1.25 MeV γ-ray sensitivity from the experiment results.

Fig. 8. The neutron measurement experiment.

Fig. 9. The γ-ray measurement experiment.

The time respond measurement experiment was performed with DPF, of which energy was about 14 MeV. The result of time respond was about 29 ns that was consistent with the theory calculation. The experiment of time respond measurement is shown in Fig.10. The result of the experiment is shown in Fig.11.

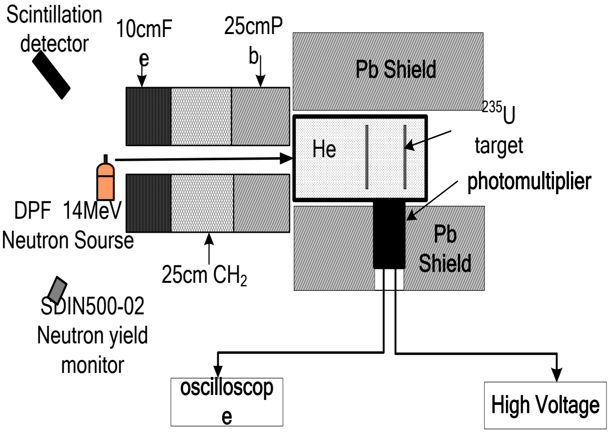

Fig. 10. The time respond experiment.

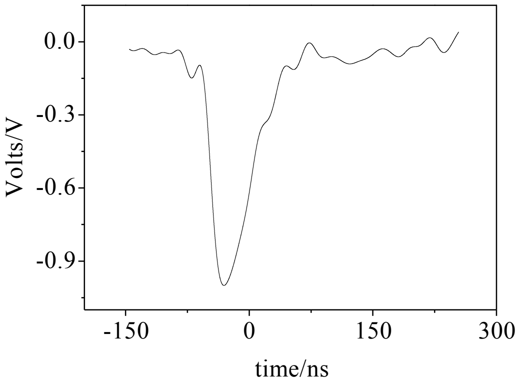

Fig. 11. The wave of experiment.

5. Conclusion

The helium scintillation fission chamber neutron detector combines the advantage of fissionable material and helium scintillator. The neutron sensitivity of the detector is about 10^{-15} C·cm^2/n, which is about 80 time more than γ-ray sensitivity. The excellent n/γ discrimination makes the detectors be used well in the low intensity fission radiation field.

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