Simulation Study of the Neutron Scattering Camera Based on Plastic Scintillator and MPPC

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Abstract. Nuclear safety has always been the lifeline of the development of the nuclear industry, and the supervision and management of special nuclear materials is a very important part of nuclear safety. By measuring fission neutron generated by the special nuclear materials, the type and position of special nuclear materials can be determined. In this paper, a neutron scattering camera (NSC) based on plastic scintillator and MPPC was designed to detect the fission neutron in the n-γ mixed field, and then to realize the localization and discrimination of fission materials. The designed NSC contains two layers of detector arrays. The first and second layers are consisted of five and nine detection units, respectively. In order to discriminate neutrons and gamma-rays, EJ-276 plastic scintillator is chosen as the detection medium because of its PSD performance. At the same time, MPPC was used to collect the fluorescence generated in the scintillator. For optimizing the NSC, the Geant4 Monte Carlo simulation toolkit is used to study the whole detection process of the NSC. In the simulation, the factors affecting image reconstruction in neutron source image reconstruction have studied by simulation. The influences of the thickness and radius of the detection units in two layers, the distance between two layers on the image reconstruction were studied in detail. According to the simulation results, the thickness of front detector unit, radius of detector unit, thickness of back detector unit and distance between two layers were determined to be 3 cm, 5 cm, 8 cm and 50 cm, respectively.

Keywords: Neutron Scattering Camera · Plastic Scintillator · Image Reconstruction · MPPC · TOF

1 Introduction

Special nuclear measurement is a very important part of nuclear material supervision and management. In order to safely use and transport these special nuclear materials, it is usually necessary to add corresponding shielding structures on the outside. The energies of characteristic gamma-rays emitted from the radionuclides in special nuclear materials are rather low. For example, the energy of characteristic gamma-rays of ^{235}U is 185.7 keV, which has limited penetration in high Z materials. So, it is difficult to

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measure special nuclear materials by detecting gamma-rays directly. Since uranium and transuranic elements can release fission neutrons through spontaneous fission or induced fission, it is possible to measure special nuclear materials in the shielding structure by detecting fission neutrons [1].

Neutron scattering camera (NSC) can detect the fission neutron, combined with the image reconstruction algorithm, the localization and discrimination of special nuclear materials can be realized [2–5]. It can provide an important means for the supervision of special nuclear materials and plays a very important role in nuclear security, non-proliferation, customs inspection and counter-terrorism. At present, it is mainly used liquid scintillator coupled photomultiplier tube (PMT) as detection unit to detect neutrons in NSC. Liquid scintillator has certain toxicity and is not easy to package. Besides, the use of PMT also makes the NSC has larger volume, which is not conducive to the portable improvement of NSC system.

EJ-276 plastic scintillator not only has the same n-γ discrimination ability as liquid scintillator, but also has the advantages of non-toxic and not easy to leak. Compared to the liquid scintillator, EJ-276 has many advantages, such as more convenient to use, safer operation and more stable physical properties. At the same times, multi-pixel Photon Counter (MPPC) has strong anti-magnetic field interference ability and smaller volume. In this paper, the NSC based on EJ-276 plastic scintillator and MPPC is studied, and the Geant4 [6] Monte Carlo method is used to optimize the NSC.

2 Principle and Performance Index of Neutron Scattering Camera

2.1 Principle of Neutron Scattering Camera

The schematic diagram of NSC was shown in Fig. 1. NSC is consisted of two layers of organic scintillator detector arrays. The incident neutron was firstly interacted with the hydrogen nucleus through the elastic scattering in the front detector array layer, and the recoil proton and the scattered neutron were generated. The scattered neutron entered the back detector array layer and may occur another elastic scattering. If there is only one scattering event occurs in the front and the scattered neutron is detected by the back detector layer, then this is an effective detection event for the neutron scattering camera.

Since the recoil proton has a large mass, its energy can be completely deposited in the front detector, so the recoil proton energy *Ep* can be measured by the response of the front detector layer. The scattered neutron energy *E'n* can be calculated by the time of flight method. Then, the incident neutron energy can be acquired by adding *Ep* and *E'n*. According to the conservation of kinetic energy and momentum in the elastic scattering process, the neutron scattering angle θ and the incident neutron energy *En* can be calculated as follows:

$$\tan^2\theta = \frac{E_p}{E_n'} \tag{1}$$

$$E_n = E_p + E_n' \tag{2}$$

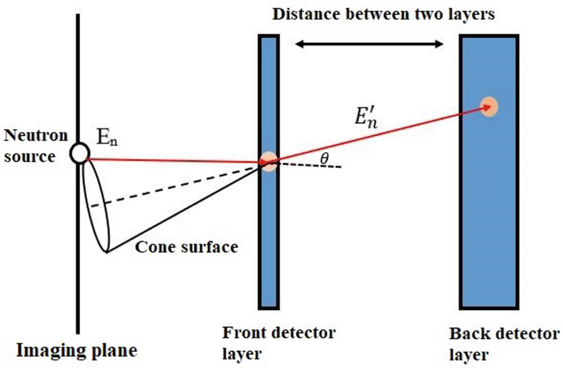

Fig. 1. The schematic diagram of NSC

According to the interaction position of elastic scattering of neutrons in the two detector array layers and neutron scattering angle θ, a cone can be reconstructed, and any position on the conical surface may be the position of the neutron source. But, one cone surface cannot accurately determine the position of the neutron source, the position of the neutron source can be determined by intersection area of multiple cone surfaces.

Simplified Back projection is a common image reconstruction algorithm for neutron scattering camera. The plane where the neutron source is located is called imaging plane X_b. The projection of the reconstructed cone from each neutron scattering event on X_b is an ellipse. X_b is divided into $M \times N$ pixel grids of the same size. When any one, two or three of the four vertices of the grid are fallen into the ellipse, it can be determined that the grid is passed through by the ellipse. The entire imaging plane is traversed to judge the grid passed through by the ellipse, and the pixel value of the grid passed through by the ellipse is added by one until the determination of all conforming events. The region with the largest pixel value is the location of the neutron source.

2.2 Performance Index of Neutron Scattering Camera

The performance indexes of NSC include position resolution of neutron source, primary scattering ratio, coincidence ratio of primary scattering and detection efficiency. The details of them are as follows.

(1) The grid with the largest pixel value in the reconstructed image is the reconstructed position of the point source. By intercepting the pixel value distribution of the point source position along the Y or Z direction, the one dimensional distribution of the neutron source direction can be obtained. Using Gaussian fitting to fit the one dimensional distribution, and the full width at half maximum (FWHM) of the fitting curve is the position resolution of the neutron source.

(2) The primary scattering ratio refers to the ratio of the number of neutrons that have only one elastic scattering in the front detector to the number of neutrons that have elastic scattering in the front detector, and is related to the size of the front detector. The coincidence ratio of primary scattering refers to the ratio of number of effective

detection events to the number of coincidence neutrons detected by the front and back detector layers. It is a performance indicator of the NSC system and is related to the geometric parameters of the NSC.

(3) The detection efficiency is defined as the ratio of detected neutrons to the number of neutrons emitted from neutron source. In Geant4 simulation, in order to improve the simulation efficiency, the cone angle of neutron emission is set as 2θ, and the absolute detection efficiency is given as following

$$\varepsilon = \frac{N_c}{N_{2\theta} \times \frac{4\pi}{\Omega}} \tag{3}$$

where *EC* is the number of effective detection events, *E2θ* is the total number of neutrons emitted from neutron source when the emission cone angle is 2θ, Ω represents the solid angle of cone angle and is calculated as following:

$$\Omega = 2\pi(1 - \cos\theta) \tag{3}$$

3 Simulation

The structural schematic diagram of designed NSC was shown in Fig. 2. There are five and nine detector units in front and back detector layer, respectively. In the front detector array, the distance between adjacent detector units is 20 cm, and the fifth detector unit is located in the center position. In the back detector array, the distance between adjacent detector units is also 20 cm.

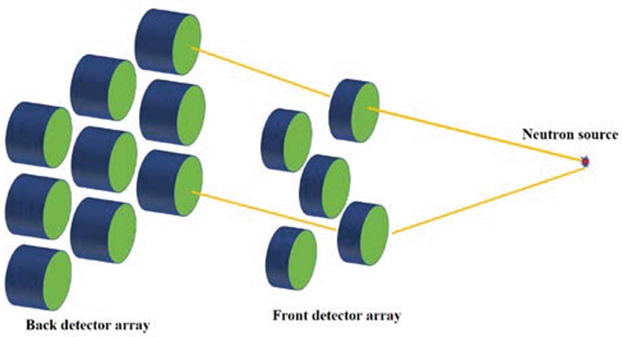

Fig. 2. The structural schematic diagram of NSC

The uranium and plutonium are special nuclear materials, and both of them can generate fission reaction with the neutrons. ^{252}Cf neutron source is spontaneous fission neutron source, and its fission neutrons energy range is similar to that of uranium and plutonium. So, the neutron sources used in Geant4 simulation is chosen to ^{252}Cf neutron sources. In Geant4 simulation, the ^{252}Cf point source was set at the center of the imaging plane which is 2m away from the front detector array, and the cone angle of emission neutrons was 90°. The neutron emission spectrum of the ^{252}Cf neutron source was defined according to the probability density function of the emission neutron energy, as shown in Fig. 3.

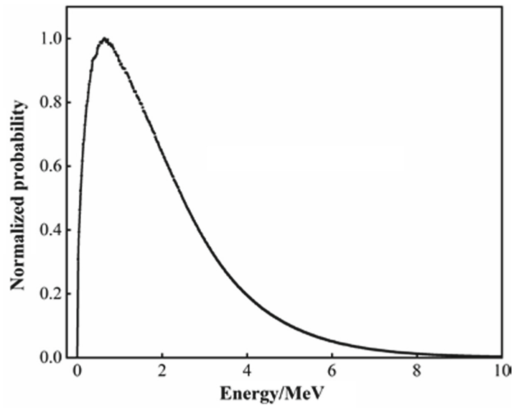

Fig. 3. The spectrum of the ^{252}Cf neutron source [6]

Using Geant4 simulation toolkit, the influences of the thickness and radius of the front and back detector unit and the distance between front and back detector on the image reconstruction were studied. Based on simulation results, the structural parameters of the neutron scattering camera were optimized.

3.1 The Thickness of the Front Detector Unit

The thickness of the front detector will not only introduce the scattering point position error to affect the resolution of neutron source of the reconstructed image, but also affect the primary scattering ratio, coincidence ratio of primary scattering and the absolute detection efficiency. The thickness range of the front detector unit was set from 1 to 8 cm with an interval of 1 cm in the simulation. At the same time, the thickness of the back detector unit was set to 8 cm, the radius of the detector units was set to 5 cm, and the distance between two layers was set to 50 cm.

The influences of thickness of front detector unit on primary scattering ratio and coincidence ratio of primary scattering were shown in Fig. 4. As the thickness of the front detector unit increases, both the primary scattering ratio and coincidence ratio of primary scattering were decreased. This may be caused by the increasing of probability of multiple scattering of neutrons in the front detector layer when the thickness of the front detector unit increases. When the thickness increases from 1 to 8 cm, the primary scattering ratio decreases from 96.5% to 85.6%, and the coincidence ratio of primary scattering decreases from 98.3% to 92.9%, indicating that the thickness of front detector unit has a great influence on the primary scattering ratio and the coincidence ratio of primary scattering.

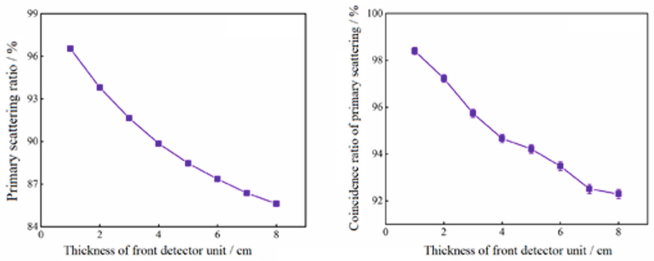

Fig. 4. The thickness of front detector unit Vs. Primary scattering ratio and coincidence ratio of primary scattering

The influences of thickness of front detector on absolute detection efficiency were shown in Fig. 5. The absolute detection efficiency increases with the increase of the thickness. When the thickness of front detector is about 7cm, the absolute detection efficiency basically reaches saturation at about 2.6×10^{-6}.

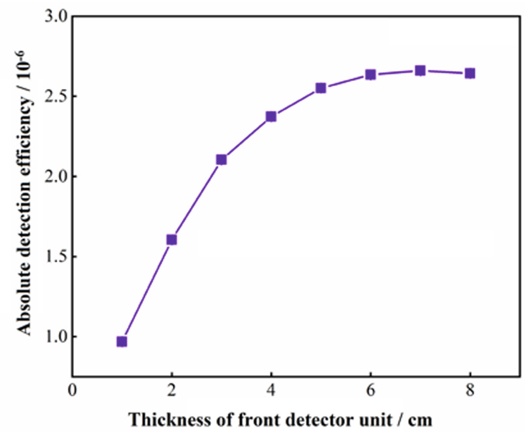

Fig. 5. The thickness of front detector unit Vs. Absolute detection efficiency

The influences of thickness of front detector unit on position resolution of neutron source were also studied and shown in Fig. 6. The position resolution was slightly deteriorated with the increase of thickness. When the thickness increases from 1 to 8 cm, the position resolutions were remained between 500 and 600 mm. Although with the increase of the thickness of front detector unit, the error of scattering point position is introduced to impact the position resolution, but this effect is very limited because the thickness of the front detector unit is quite small when compared to 50 cm distance between two layers.

Considering the simulation results comprehensively, the thickness of the front detector unit is selected as 3 cm. At this circumstance, the primary scattering ratio is bigger than 90%, and the absolute detection efficiency is about 2.2×10^{-6}.

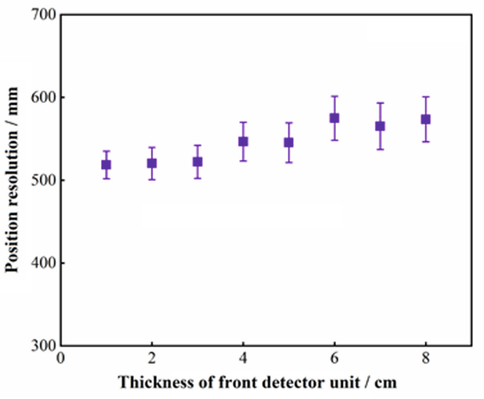

Fig. 6. Front detector thickness unit Vs. Position resolution

3.2 The Radius of the Detector Unit

The radius of detector unit was set from 2 to 8 cm, with interval of 1 cm. At same time, the thickness of the front and back detector units were set to 3 cm and 8 cm, respectively. The distance between the two layers was 50 cm. The relationships of radius of detector unit and primary scattering ratio and coincidence ratio of primary scattering were shown in Fig. 7. With the increase of the radius of detector unit, the primary scattering ratio was continuously decreased. This is because the increasing of the radius increases the probability of multiple scattering of neutrons in the front detector array. The coincidence ratio of primary scattering increases with the increasing of the radius and tends to be saturation at about 5 cm. When the radius increases from 2 to 8 cm, the primary scattering ratio only decreases from 93.5% to 91%, while the coincidence ratio of primary scattering increases from 73.7% to 95.5%, indicating that increasing of the radius has a small effect on the primary scattering ratio, but has a significant effect on the coincidence ratio of primary scattering.

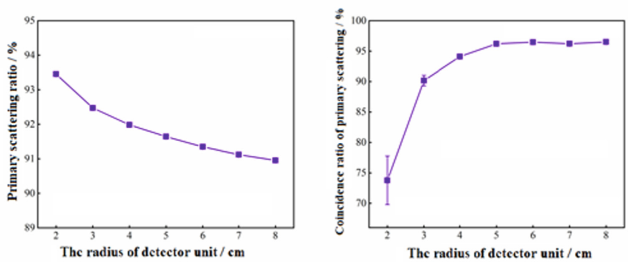

Fig. 7. The radius of detector unit Vs. Primary scattering ratio and coincidence ratio of primary scattering

The absolute detection efficiency under different radius was shown in Fig. 8. It can be seen that the absolute detection efficiency increases with the increasing of radius. When the detector radius increases from 2 cm to 8 cm, the absolute detection efficiency was increased from 1.78×10^{-8} to 1.07×10^{-5}, which were increased about 600 times. This indicates that the radius has a significant influence on the absolute detection efficiency.

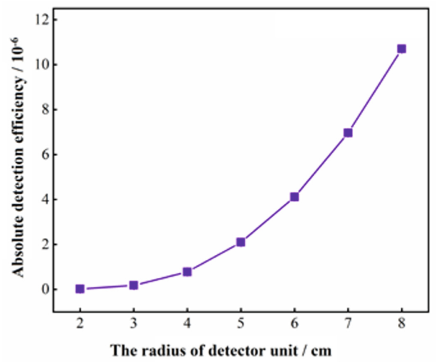

Fig. 8. The radius of detector unit Vs. Absolute detection efficiency

The influence of radius on position resolution of neutron source was shown in Fig. 9. With the increasing of the radius, the position resolutions of neutron source were got worse and worse. When the radius increases from 3 cm to 8 cm, the position resolution of neutron source was increased from 305 mm to 766 mm, indicating that the radius has a significant effect on the position resolution.

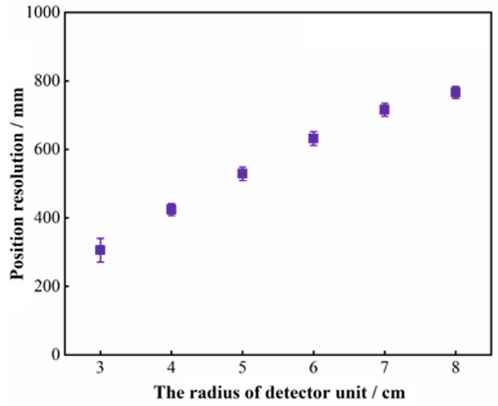

Fig. 9. The radius of detector unit Vs. Position resolution

Considering the simulation results comprehensively, when the radius of the detector unit was 5 cm, the better absolute detection efficiency and coincidence ratio of primary scattering can be obtained. Besides, the NSC also has better position resolution of neutron source. So, the radius of the detector unit was determined to be 5 cm.

3.3 The Thickness of the Back Detector Unit

In the simulation, the thickness of the back detector unit was from 5 to 20 cm with the interval of 1 cm, while the thickness of front detector unit was set as 3 cm, the radius of the detector units in two layers was set as 5 cm, and the distance between two layers was set as 50 cm. Figure 10 shows the influences of the thickness of the back detector unit on the coincidence ratio of primary scattering. The coincidence ratio of primary scattering was increased slightly with the increasing of the thickness of back detector unit. When the thickness was increased from 5 to 20 cm, the coincidence ratio of primary scattering was located between 95.7% and 96.4%, indicating that the thickness of the back detector unit has little influence on the coincidence ratio of primary scattering.

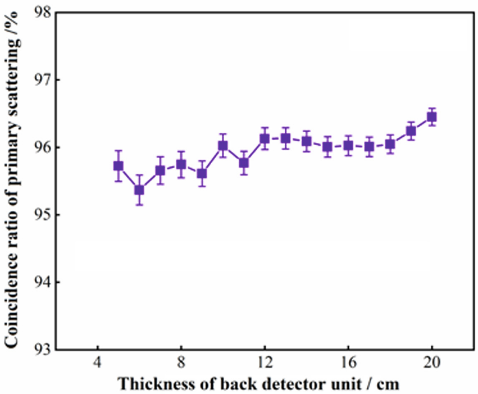

Fig. 10. The thickness of back detector unit Vs. Coincidence ratio of primary scattering

The influence of thickness of back detector unit on absolute detection efficiency was shown in Fig. 11. The absolute detection efficiency was increased linearly with the increase of the thickness of the back detector unit. When the thickness increases from 5 to 20 cm, the absolute detection efficiency was increased from 1.14×10^{-6} to 3.12×10^{-6}, indicating that the thickness of the back detector unit has a certain influence on the absolute detection efficiency.

Figure 12 illustrates the influence of thickness on point source position resolution. With the increase of the thickness of the back detector unit, the position resolutions of neutron source were maintained between 500 and 600 mm. This indicates that the increase of the thickness of the back detector unit has little influence on the position resolutions.

In conclusion, the thickness of the back detector unit mainly affects the detection efficiency. As the thickness of the back detector unit increased, the detection efficiency increases linearly. Considering the absolute detection efficiency and economic cost, the thickness of the detector is determined to be 8 cm.

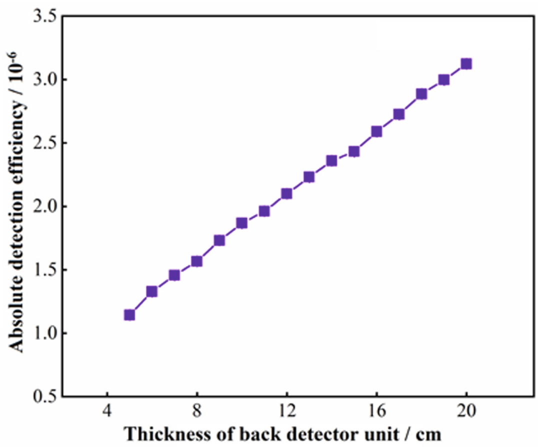

Fig. 11. The thickness of back detector unit Vs. Absolute detection efficiency

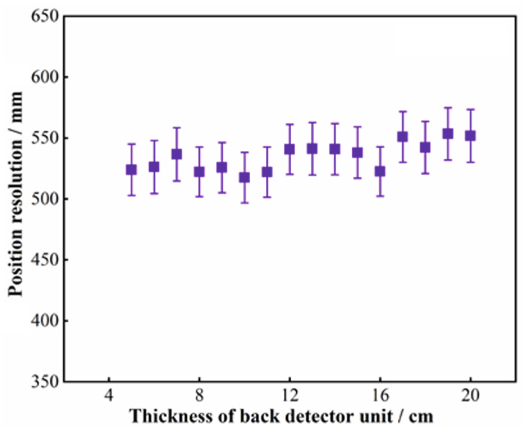

Fig. 12. The thickness of back detector unit Vs. Position resolution

3.4 The Distance Between the Two Layers

The distance between two detector layers was ranged from 30 to 100 cm with interval of 10 cm, while the thickness of the front and back detector unit were 3 and 8 cm, and the radius of the detectors unit was 5 cm. The influence of distances on the coincidence ratio of primary scattering was simulated and shown in Fig. 13. With the increasing of distance, the coincidence ratio of primary scattering was always decreased. When the distance increased from 30 to 100 cm, the coincidence ratio of primary scattering was decreased from 96.8% to 90.2%, indicating that the distance has a great influence on the coincidence ratio of primary scattering.

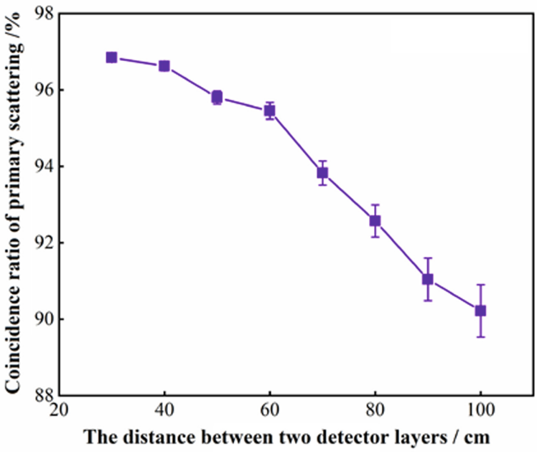

Fig. 13. The distance between two layers Vs. Coincidence ratio of primary scattering

The relationship between distance and absolute detection efficiency was given in Fig. 14. The absolute detection efficiency was decreased with the increasing of distance. With the increasing of distance, the absolute detection efficiency decreases from 5.13×10^{-6} to 2.74×10^{-7}, indicating that the distance has a great influence on the absolute detection efficiency.

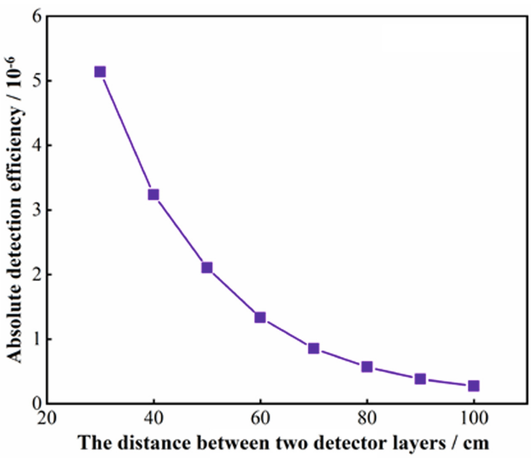

Fig. 14. The distance between two layers Vs. Absolute detection efficiency

The influence of distance between two layers on position resolution of neutron source was given in Fig. 15. With the increase of distance, the position resolution becomes better and better. When the plane distance was increased to 100 cm, the position resolution was changed from 750 to 300 mm, indicating that the plane distance has an obvious influence on the position resolution.

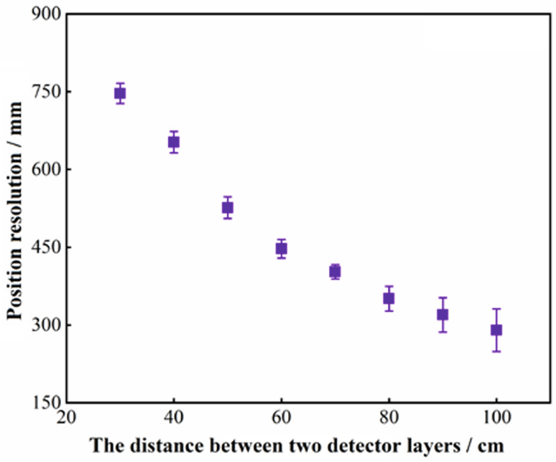

Fig. 15. The distance between two layers Vs. Position resolution

Based on the simulations, it can be seen that the distance mainly affects the coincidence ratio of primary scattering, absolute detection efficiency and point source position resolution. When the distance was 50 cm, the NSC not only has a high coincidence ratio of primary scattering and absolute detection efficiency, but also has a good position resolution. So, the distance was determined to be 50 cm.

4 Conclusions

In this paper, the effects of the thickness and radius of detector units and distance between two layers on image reconstruction were studied by the Geant4 to optimize the geometric parameter of the NSC. The simulation results show that the thickness of front detectors mainly affects the primary scattering ratio and the coincidence ratio of primary scattering, the radius of detector unit and distance between two layers mainly affect the first scattering coincidence ratio,

detection efficiency and position resolution of neutron source. Based on the simulation results, the thickness of the front detector, the radius of the detector, the thickness of the back detector and the distance between two layers were determined to be 3 cm, 5 cm, 8 cm and 50 cm, respectively.

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