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Simulation of Suppression of Gamma Sensitivity of 'Fission Electron-Collection' Neutron Detector *

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The fission electron-collection neutron detector (FECND) is a current-type neutron detector. Based on the analysis of the generation process of the gamma signals of the FECND, a mechanism utilizing symmetrical structure is proposed and discussed to suppress the gamma signals. According to this mechanism, the electrons generated from the gamma rays can be well compensated for by the adjustment of the electrodes' thickness and distance. In this study, based on the Monte–Carlo simulation of the gamma signals of the FECND, the varying patterns are obtained between the gamma signals and the detector parameter settings. As indicated by the simulation results, the gamma electrons can be compensated for completely by simply adjusting the coated electrode substrate thickness and distance. Moreover, with a proposed optimal parameter setting, the gamma sensitivity can be as low as 3.39×10^{-23} *C·cm*^{2}*, while the signal-to-noise ratio can be higher than 200:1. The compensation results of the γ-rays in the FECND will be slightly affected by the manufacturing error or the assembly error.*

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Neutron measurements are very important for many studies such as in nuclear physics[1,2] and high energy density physics.[3–5] However, in most cases, the neutron fields are accompanied with γ-rays generally in MeV energy level, and γ-induced signals require additional discrimination and suppression. For electrical-type neutron detectors, their working modes can be classified into three types:[6] the current mode, the pulse mode and the Campbelling mode.

As for the neutron detector operating in the pulse mode, its γ-sensitivity can be well decreased by the pulse shape discrimination (PSD) technique based on the analysis of pulse shape, which has been widely validated in the scintillating detectors.[7,8] Then, for the neutron detector operating in the Campbelling mode, the contribution of the γ-rays (small in amplitude while large in number) is suppressed by measuring the variance of the detector current, whose success can be well demonstrated in the application of the fission chamber.[9] Finally in dealing with the neutron detector operating in the current mode, it is very difficult to remove the γ-rays' contribution, due to the fact that the currents generated by the γ-rays are commonly mixed with the neutron-induced currents. This is just the case for the fission chamber[10] and the self-powered detector.[11]

As a detector working in the current mode, the fission electron-collection neutron detector (FECND) is characterized by simplified structure, flat energy response and rapid time response,[12] etc., making it a favorite option for the measurement of high-intensity pulse neutron flux. In this Letter, the analysis of the generation mechanism of the γ-signals of this neutron detector will be presented. Based on this, the feasibility to suppress the γ-signals is discussed. Based on the Monte–Carlo simulation of the γ-signal output from detectors with various parameter settings, the varying patterns of output signals with the changes of the parameters are concluded. Finally, the optimal parameter setting of the detector is proposed as well as the corresponding γ sensitivity.

The structure of the FECND is given in Fig. 1. As seen in Fig. 1, the detector consists of two types of electrodes, and the coated electrode in the middle is plated with fissile material on both sides (deep in color). In addition to the coated electrode, there are two collection electrodes to collect the electrons. All three electrodes are accommodated into a vacuum container. When the FECND is irradiated with neutrons, fission reactions will take place inside the fissile layers and will produce energetic fission fragments, which will then interact with the layer materials to generate a great number of electrons. The electrons escaping from the layer will finally be collected by the collection electrodes.

The interaction between the γ-rays and the materials is of three types: the photoelectric effects, the Compton effects and the electron pair effects. All of these effects will generate secondary electrons. Within an energy range of several MeV, the Compton effects will contribute the majority. In some cases, γ-rays will disappear after the interaction with the material, e.g., photoelectric effects. In other cases, γ-rays will continue to interact with the material with different angles and energy, e.g., the Compton effects. The positron induced by the electron pair effects will be rapidly annihilated with other electrons and continue to generate additional γ-rays, which can also be con-

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sidered as the same situation as the Compton effects. Due to the small mass of the electrons, scattering in a large angle will easily occur when they are interacting with the nucleus. In this context, the movement of the γ-ray-induced secondary electrons among the electrodes will be rather complicated. They can be transmitted either forward or backward. Moreover, some of the escaped electrons can also be reflected back by other parts of the detector.

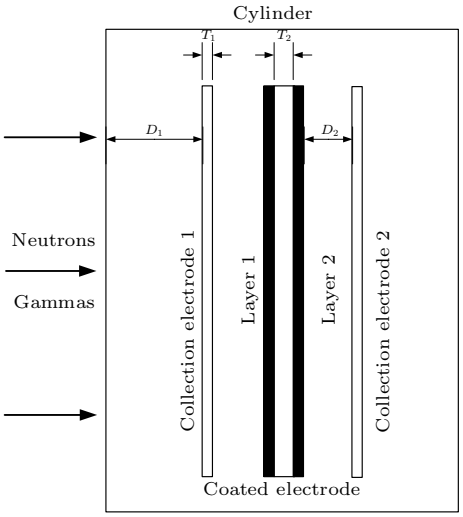

Fig. 1. The structure of the fission electron-collection detector.

As required by the working principle of the FECND[12] (also known as the vacuum FC[13]), a one-side-coated electrode and a collection electrode can be good enough for the neutron measurement. The amplitude of the detector signals is dependent on the number of the charge deposition on the coated electrode, and the number of charge deposition is then dependent on the number of the electrons entering into and leaving the layer. If the coated electrode is plated on both sides and two collection electrodes are placed beside the coated electrode, by adjusting the thicknesses of electrodes and the distances between electrodes, a number of incident γ-induced secondary electrons entering into the layer can approximately equal to the number leaving from the layer. In other words, the signal induced by the γ-rays approaches to zero. In this way, the suppression of the detector's γ-sensitivity can be achieved.

MCNP5 was used in the Monte–Carlo simulation, and the geometrical setup is described in Fig. 1. The container consists of the cylinder, the front window and the back window. The coated electrode and the collection electrodes were accommodated in the container. The distance from the collection electrodes to the front/back window was D_1, the distance between the coated electrode and the collection electrodes was D_2, and the thicknesses of the collection electrode and the coated electrode's substrate were T_1 and T_2, respectively. To provide a good vacuum condition, the front and back windows were made of 50-μm-thick Fe material. The geometries and material settings are enlisted in Table 1.

Table 1. The Monte–Carlo simulation settings of geometries and materials.

Item	Description	Parameter
Cylindrical surface	Material	Fe
	Diameter	150 mm
	Thickness	4 mm
Collection electrodes	Material	Al
	Diameter	100 mm
	Thickness	T_1
Substrate of coated electrode	Material	Fe
	Diameter	100 mm
	Thickness	T_2
Fission layer	Material	U_3O_8 (90% ^{235}U and 10% ^{238}U)
	Diameter	100 mm
	Thickness	2 μm
Front/back window	Material	Fe
	Thickness	50 μm
Electrode gap	Distance between collection Electrodes and front/back window	D_1
	Distances between the coated Electrode and the collection electrodes	D_2

As for the MCNP5 settings, the γ-source was a plane source parallel with the electrodes, the flying directions of the γ-photons were also parallel to the detector's axis, and the size of the plane source covers 90% of the total surface area of the electrodes. The γ-energy spectrum distribution was the ^{235}U fission energy spectrum distribution.[14] The +F8 tally card was used to record the net charge deposition in the electrode's substrate and the two layers, whose results were calibrated and validated by F1 tally card. Throughout the calculation, the numbers of the incident gamma rays were 5×10^7. The calculation results were represented by the average electron counting for each of the incident particles. In the MCNP calculation, the R value is used to evaluate the statistical relative error of the calculation results at the 1σ level, and $R < 0.1$ is generally needed. In this work, the relative errors of the charge deposition calculation results (R-value) were all below 0.01.

Considering the dependence of the detector's sig-

nal on the electrodes' gaps, the collection electrodes and the coated electrode's substrate were set to be 5 mm and 9 mm in thicknesses (T_1 and T_2), respectively, the distances from the collection electrodes to the front/back window were 10 mm (D_1), and the other parameters in Table 1 were fixed. With this setup, the charge depositions in the coated substrate and the two layers in accordance with an electrodes' gap range of 2–14 mm (D_2) were calculated, whose results are given in Fig. 2.

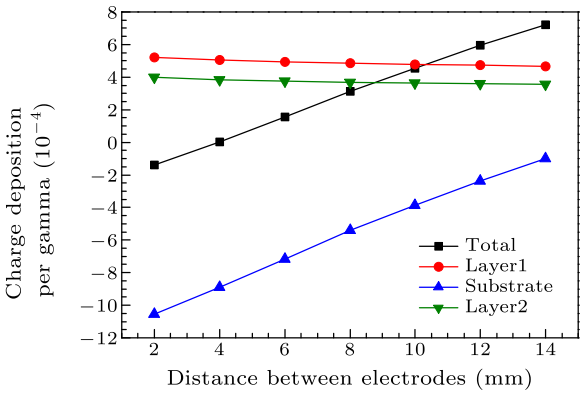

Fig. 2. The relationship between charge deposition and electrodes' distance.

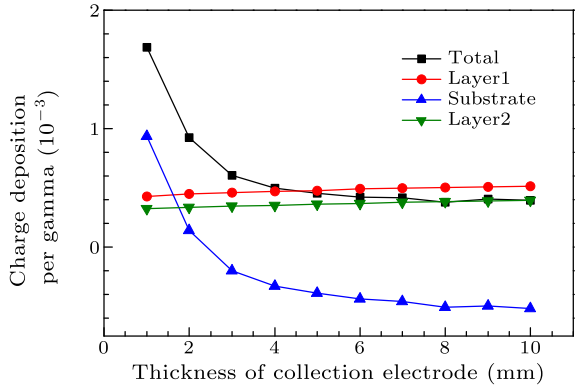

Fig. 3. The relationship between charge deposition and the collection electrodes' thickness.

It should be noticed that the negative value of charge deposition means gain of electrons and the positive value means loss of electrons.

As shown in Fig. 2, with a fixed thickness of the layers, the charge depositions in the layers have slight change. As for the charge deposition in the coated electrode's substrate, it will be increased with the electrodes' gaps (D_2). This is also just the case for the total charge deposition, which is also increased with D_2. Notably, the increase of the total charge deposition with increasing D_2 will follow a negative-to-positive process (zero-crossing point). In this way, it can be well predicted that the total charge deposition will be zero if D_2 is adjusted appropriately and deliberately.

Then, in dealing with the relationship between the total charge deposition and the change of the collection electrodes' thickness, the thickness of the layer electrode's substrate (T_2) was set to be 9 mm, the distances from the collection electrodes to the front/back windows (D_1) were 10 mm, and the electrodes' gaps (D_2) were 10 mm. Under these conditions, calculations were made to obtain the total charge deposition on the coated electrodes' substrate and the two layers within a collection electrodes' thickness range of 1–10 mm, whose results are given in Fig. 3. As shown in Fig. 2, the charge deposition in the layer has slight change, while the evolution tendency of the total charge deposition was the same as that of the charge deposition in the coated electrode's substrate. Both of them will be decreased with increasing the thickness of the collection electrodes, but will never reach the zero point.

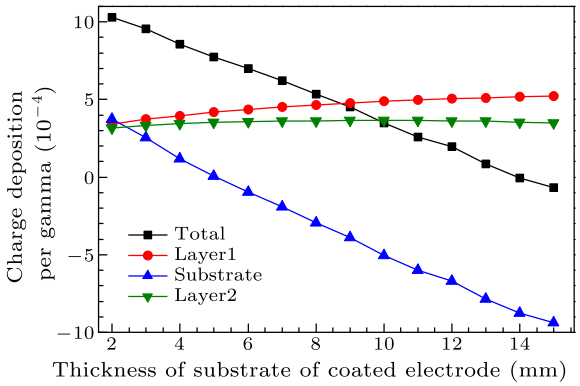

Fig. 4. The relationship between charge deposition and the coated electrode substrate thickness.

Thirdly, in dealing with the relationship between the total charge deposition and the coated electrode's substrate thickness, the thickness of the collection electrodes (T_1) was set to be 5 mm, the distances from the collection electrodes to the front/back windows (D_1) were 10 mm, and the electrodes' gaps (D_2) were 10 mm. Under these conditions, calculations were made to obtain the charge deposition on the coated electrode's substrate and the two layers within a thickness range of 2–15 mm for the coated electrode's substrate, whose results are given in Fig. 4. As shown in Fig. 4, the evolution tendency of the total charge deposition is the same as that of the charge deposition in the coated electrode's substrate. Moreover, there is also a negative-to-positive process (zero-crossing point) with increasing T_2. In this case, just like what we can carry out by adjusting the electrodes' gaps (D_2), the total charge deposition can also be zero if the T_2 is adjusted appropriately and deliberately.

Finally, let us deal with the effects of the distances from the collection electrodes to the front/back windows on the detector's output signal. In this case, the thickness of the collection electrodes (T_1) was set to be 5 mm, the thickness of the coated electrode's substrate (T_2) was 9 mm, and the electrodes' gaps (D_2) were set to be 10 mm. As indicated by the calculations, with given D_1 values of 10 mm and 20 mm, the change of the total charge deposition was less than 2%. This is a very slight effect that can be effectively negligible.

In general, due to its fixed thickness, the layer will have slight effect on the total charge deposition of the

detector's signals. As for the changes of the electrodes' gaps and the coated electrode's substrate thickness, both of them will lead to zero-crossing points in the total charge deposition, while the change of the collection electrodes' thickness will not lead to the zero-crossing point. Thus if other conditions remain unchanged, the electrodes' gaps and the coated electrode's substrate thickness can be adjusted and can provide a charge deposition approaching to zero in value. In this way, the γ-sensitivity of the FECND can be efficiently suppressed.

In dealing with the current-mode neutron detectors such as the fission chamber and the self-powered detectors, whose γ-signal currents are mixed with the neutron signal currents and are hard to discriminate, the γ-sensitivity is very difficult to suppress. As for the FECND characterized in symmetric structure, the γ-ray-induced electrons can compensate for each other. Actually, in the special environment where the γ-rays are transmitted in random directions (such as in the reactor core), the signal currents of FECND induced by the γ-rays can nicely compensate for each other automatically. The reason can be well attributed to its symmetric structure. Comparably, other current-type neutron detectors like the fission chamber and self-powered detectors can never provide such a performance.

Based on considerable simulations and calculations, the optimized structure parameter setup can be satisfactorily proposed for the FECND. In this proposal, the collection electrodes' thickness (T_1) and the coated electrode substrate thickness (T_2) were set to be 5 mm and 9 mm, respectively. The distances from the collection electrodes to the front/back windows (D_1) were set to be 10 mm, the electrodes' gaps (D_2) were set to be 4 mm, while the rest of the parameters were set in accordance with Table 1. With this setup, nearly all of the signals induced by the γ-rays can be compensated for. If we define the ratio between the output electricity and number of injected particles that reach the detector surface per unit area, the γ-sensitivity of the detector can be as low as 3.39×10^{-23} C·cm^2. Then, according to the computational model proposed in Ref. [12], for a neutron detector with the same setup, the neutron sensitivity can be calculated as 8.27×10^{-21} C·cm^2, and the SNR of the detector is higher than 200:1.

However, such a theoretical calculation of the γ-sensitivity does not take into account the errors of manufacturing and assembly of the detector's components and devices. Such errors include the layer thickness and the thickness of the metal electrodes (or the substrate), which cannot be highly precise due to the fabrication technology. Furthermore due to the fitting process, the electrodes' gaps also possibly lead to additional errors. If the compensation results of the γ-rays are highly sensitive to these errors, the suppression results of the FECND will be eventually seriously damaged.

In dealing with this, additional calculations and analysis for the γ-sensitivity and SNR of the neutron detector were made to evaluate the error-induced effects under a package of error conditions, where the thickness of the electrodes (or electrode's substrate), the electrodes' gaps and the layer thickness were ± 0.1 mm, ± 0.2 mm, and ± 0.2 μm in errors, respectively. As indicated by the calculations, even if with the highest γ-sensitivity of 8.32×10^{-22} C·cm^2 (in the worst case), the detector's SNR can still remain higher than 9. In this way, it can be effectively concluded that the compensation results of the γ-rays in the FECND will be slightly affected by the manufacturing error or the assembly error.

In conclusion, the sensitive region of the FECND (as a current-type detector) can be deliberately designed into symmetric structure to suppress the γ-sensitivity. In particular, in a γ field where the γ-rays transmit in random directions, the symmetric structure of the FECND can provide automatically a fairly good suppression effect of the γ-induced signals. As for the γ-rays transmission in fixed directions, the compensation can be achieved by adjusting the thickness of the coated electrode's substrate, the thickness of the collection electrodes and electrodes' gaps. Moreover, the change of the distances from the collection electrodes to the front/back windows will have slight and negligible effect on the detector's γ-sensitivity. Due to the fact that the suppression of the detector's γ-sensitivity will be minimally sensitive to the errors of manufacturing and assembly of the detector's components and devices, the FECND can provide a fairly good SNR in the actual measurement.

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