

Geant4 Simulations of the Responses of the GdI₃:Ce Scintillator Detector to Thermal Neutrons and Gamma-rays

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Abstract—A simulation model based on the Geant4 packages was developed for the GdI₃:Ce scintillator detector in order to investigate its responses to thermal neutrons and gamma-rays, and explore the appreciate parameters to improve its performance for thermal neutron detection. The characteristic gamma-ray and internal conversion (IC) electron yields of GdI₃:Ce induced by a thermal neutron beam were obtained by simulation, and were used to analyze the IC electron detecting capability versus the scintillator thickness. Results show that the performance for detecting IC electrons is hardly improved when the scintillator thickness is more than 250 μm whilst the detection efficiency to gamma-rays keeps increasing. The detection performances of 250 μm thickness GdI₃:Ce scintillator to thermal neutrons and gamma-rays in an energy range from 20 keV to 1000 keV showed that the scintillator achieved a 65.3% detection efficiency to thermal neutrons and a high detection efficiency to gamma-rays below 200 keV. That means the detector is need to be shielded to reject low-energy gamma background while detecting thermal neutrons. The thermal neutron peaks are located mainly at 30, 40, 70 and 80 keV, thus the energy discrimination method can be used to effectively discriminate thermal neutron signals from gamma background.

Keywords—gadolinium neutron absorption; geant4 simulation; internal conversion electrons; scintillator detector; gamma-ray rejection

I. INTRODUCTION

Gadolinium(Gd) has an extremely high cross-section for thermal neutrons [1], a 200 microns layer of ^{nat}GdI₃ scintillator has >95% thermal neutron stopping efficiency. A large quantity of internal conversion (IC) electrons are emitted after neutrons are captured by Gd [2] with total yield of 0.67 per capture. The maximum penetration depth (MPD) of IC electrons is several tens of microns [1]. Therefore, Gd-based scintillator has been widely studied as a promising material for high contrast and spatial resolution neutron images in recent years [3-6].

The recently discovered GdI₃:Ce scintillator exhibits excellent properties including a high light output of 58,000 photons/MeV, a fast rise time of ~0.5 ns, and a primary decay time of ~39 ns. However, it is sensitive to gamma due to its high density of 5.2 g/cm³ and high effective atomic number of 57 [6]. The gamma sensitivity of GdI₃:Ce can be reduced by lowering the thickness of the scintillator. In this study, we investigated the IC electron detecting capability versus the

scintillator thickness by using Geant4 simulation [7], and then analyzed the appropriate thickness for detecting IC electrons while rejecting gamma background. To find effective ways to reject gamma-rays, we also simulated and analyzed the detection performance of GdI₃:Ce to gamma-rays in an energy range from 10 keV to 1000 keV.

II. RESULTS OF SIMULATIONS

A. Characteristic Gamma-ray and IC Electron Yield

The structure of GdI₃:Ce scintillator detector used for simulation study is shown in FIGURE I. Part 1 is the housing surrounding the detector. Part 2 is the GdI₃:Ce scintillator, and Part 3 is the photocathode. The two main nuclear reactions induced by thermal neutrons are described by the following equations (1) and (2) :



Natural Gd was used in this paper, and the chemical compositions of the GdI₃:Ce scintillator are listed in TABLE I. The scintillator was defined as a cylinder with a size of 20 mm in diameter and 300 μm in thickness. This thickness is enough for thermal neutron stopping. In order to clearly discuss the interactions between the scintillator and thermal neutrons or gamma-rays and eliminate the interferences of the housing, the material of the housing was defined as vacuum in this paper. Thermal neutrons with energy $E_0=0.0253\text{eV}$ emitted perpendicularly to the surface of the scintillator, from a point source positioned at a distance of 20 cm from the scintillator surface.

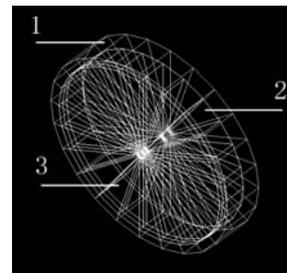


FIGURE I. PROBE OF SCINTILLATION DETECTOR

TABLE I. CHEMICAL COMPOSITION OF THE SCINTILLATOR

Element	Mole fraction (%)
Natural Gd(^{nat} Gd)	48
Iodine(I)	50
Cerium(Ce)	2

The IC electron yield of GdI₃:Ce is shown in FIGURE II(a). The energy of IC electrons converges at 30, 40, 70, 80 keV.

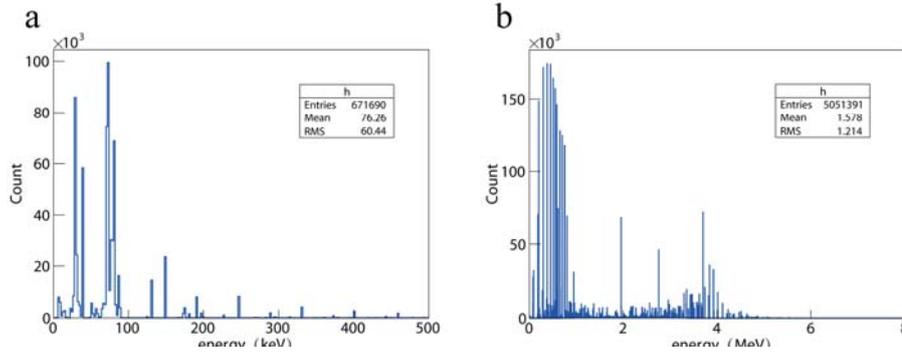


FIGURE II. YIELD (A) IC ELECTRON ; (B) CHARACTERISTIC GAMMA-RAY (N_N=10⁶)

B. IC Electron Detecting Capability Versus the Scintillator Thickness

The maximum penetration depth (MPD) of IC electrons in GdI₃:Ce scintillator is several tens of microns, so IC electrons can absolutely deposit their energy in a very thin GdI₃:Ce layer. However, when the GdI₃:Ce is too thin, the IC electrons are likely to escape the layer, which will result in a low detection efficiency to thermal neutrons.

In this simulation, the IC electrons are generated from Gd neutron capture, and the set of the thermal neutron source and

C. Detection Performance of 250 μm Scintillator to Thermal Neutrons

In this simulation, the set of the thermal neutron source and the position of the scintillator is the same as before, and the size of the scintillator is set as Φ 20 mm × 250 μm.

the position of the scintillator is the same as before. The number of incident neutrons for each certain thickness is 10⁶.

The IC electron detecting capability versus the scintillator thickness is illustrated in FIGURE III. It shows that the performances for detecting thermal neutrons and IC electrons are hardly improved when the scintillator thickness is more than 250 μm while the detection efficiency to gamma-rays keeps increasing. Thus, 250 μm is an appropriate thickness for detecting IC electrons while rejecting gamma background.

Following the absorption of thermal neutrons, IC electrons and characteristic gamma-rays are emitted. The energy deposit spectra of them are separately presented in FIGURE IV(a) and FIGURE IV(b).

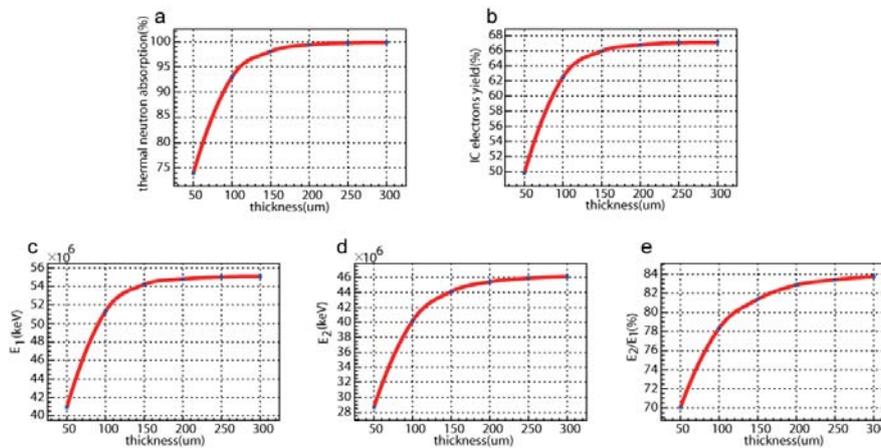


FIGURE III. IC ELECTRON DETECTING CAPABILITY VERSUS THE SCINTILLATOR THICKNESS (A) CAPTURE EFFICIENCY OF THERMAL NEUTRONS; (B) YIELD OF IC ELECTRONS; (C) TOTAL ENERGY OF IC ELECTRONS (E₁); (D) TOTAL ENERGY DEPOSITION OF IC ELECTRONS (E₂); (E) E₂/E₁

An average of 0.5896 IC electrons deposit energy in GdI₃:Ce. Compared with FIGURE II(a), the peaks at 30, 40, 70 and 80 keV are only a little lower in FIGURE IV(a), and the positions and shapes of them are almost the same. This suggests IC electrons can well deposit their energy in 250 μm GdI₃:Ce layer.

According to the data in FIGURE II(b) and FIGURE IV(b), 5.0514×10⁶ characteristic gamma-rays were emitted following the absorption of 10⁶ neutrons, and 1.5109×10⁵ of them deposit their energies in 250 μm GdI₃:Ce layer. The proportion is only 2.9911%, suggesting a very low characteristic gamma detection

efficiency when the GdI₃:Ce scintillator is a thin film. Besides, even though the energy range of characteristic gamma-rays is wide, the energy deposition of them is small, almost below 200 keV.

FIGURE IV(c) shows the energy deposit spectrum of thermal neutron capture, these energy deposition comes from both the IC electrons and characteristic gamma-rays. Compared with the data in FIGURE IV(a), it shows the thermal neutron detection efficiency has an improvement of 6% due to characteristic gamma-rays.

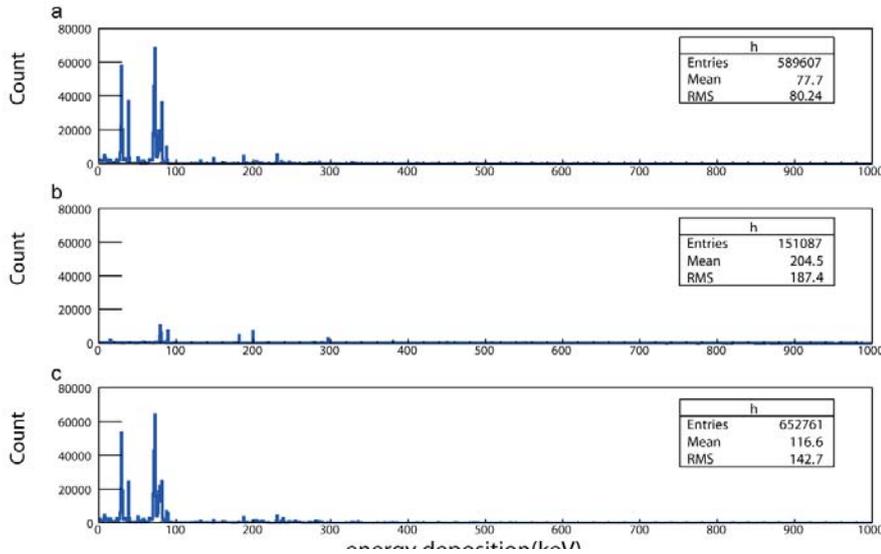


FIGURE IV. DETECTION PERFORMANCE TO THERMAL NEUTRONS (A) ENERGY DEPOSITION SPECTRUM OF IC ELECTRONS; (B) ENERGY DEPOSIT SPECTRUM OF CHARACTERISTIC GAMMA-RAYS; (C) ENERGY DEPOSIT SPECTRUM OF THERMAL NEUTRONS (N_N=10⁶)

D. Detection Performance of 250 μm Scintillator to Gamma-rays

There is always a high gamma-ray background in the environment when detecting neutrons. In order to analyze the interference of gamma background while detecting thermal neutrons, the detection performance of 250 μm GdI₃:Ce scintillator to gamma-rays in an energy range from 20 keV to 1000 KeV was simulated. Gamma-rays emitted perpendicularly to the surface of the scintillator, from a point source positioned at a distance of 20 cm from the cylindrical scintillator, and the size of the scintillator is 20 mm in diameter and 250 μm in thickness. The number of incident gamma-rays with certain energies, i.e., 20, 50, 100, 200, 500 and 1000 keV, is 10⁶. The corresponding total energies of the them are listed in TABLE II.

The detection performances of this scintillator to gamma-rays are shown in FIGURE V. It demonstrates that the GdI₃:Ce scintillator has a high detection efficiency to gamma-rays below 200 keV. It is important to shield the detector to reject low-energy gamma background while detecting thermal neutrons. The cross-section of gamma above 200 keV is relatively small. With increasing gamma energy, the detection performance of the scintillator slides down rapidly. Thus, high-energy gamma rays have less interference with neutron detection.

The energy deposit spectra of gamma-rays in different energy ranges are shown in FIGURE VI. Here we find the detection performance of the scintillator drops rapidly with the increase of gamma energy. There is a long Compton continuum below the photo-peak in each spectrum, which will contribute to the interference with neutron detection. According to FIGURE IV, the energy deposition of thermal neutron capture is mainly below 100 keV, therefore, the energy discrimination method can be used as an effective way to reject gamma-rays by treating signals above 100 keV as gamma background.

TABLE II. TOTAL ENERGY OF INCIDENT GAMMA-RAYS (E_γ)

E _γ (keV)	E _γ (keV)
20	2×10 ⁷
50	5×10 ⁷
100	1×10 ⁸
200	2×10 ⁸
500	5×10 ⁸
1000	1×10 ⁹

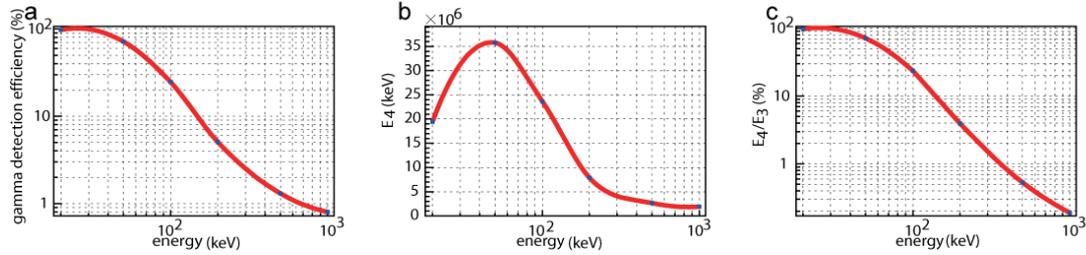


FIGURE V. DETECTION PERFORMANCE TO GAMMA-RAYS (A) GAMMA DETECTION EFFICIENCY; (B) TOTAL ENERGY DEPOSITION OF GAMMA (E_4); (C) E_4/E_3

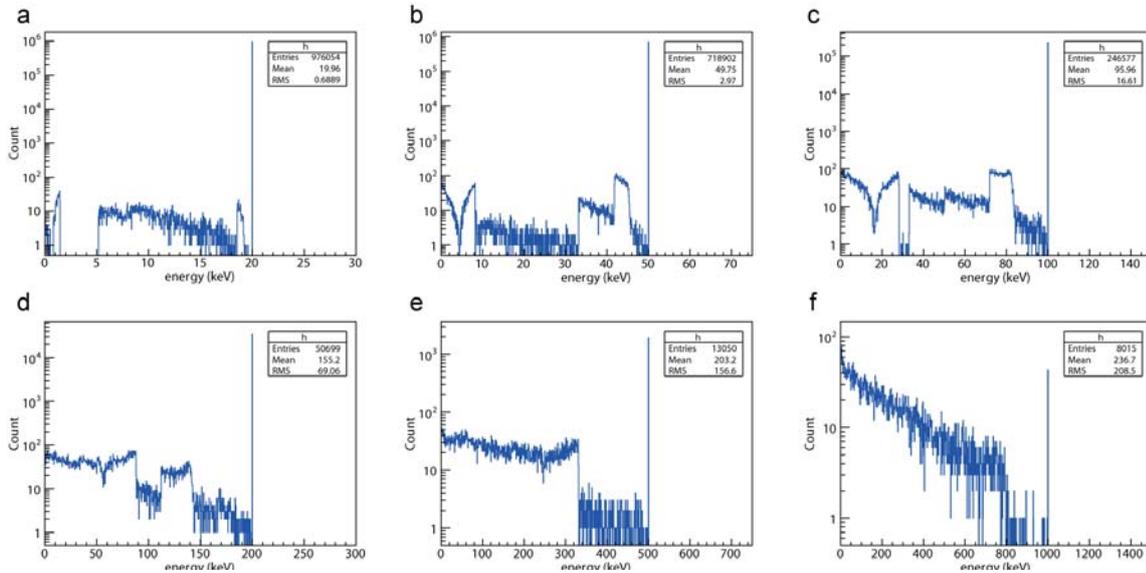


FIGURE VI. ENERGY DEPOSIT SPECTRA OF GAMMA WITH DIFFERENT ENERGY (A) 20 KEV; (B) 50 KEV; (C) 100 KEV; (D) 200 KEV; (E) 500 KEV; (F) 1000 KEV

III. CONCLUSIONS

By means of Geant4 simulation, the characteristic gamma-ray and internal conversion(IC) electron yields of $GdI_3:Ce$ induced by thermal neutrons were obtained. By analysis of IC electron detecting capability versus the scintillator thickness, it is found that $250 \mu m$ is an appropriate thickness for detecting IC electrons emitted by neutron capture while rejecting gamma-ray background. Simulation results show that $250 \mu m$ $GdI_3:Ce$ scintillator has a high detection efficiency to gamma-rays below 200 keV, therefore, it is important to shield the detector carefully to reject low-energy gamma background while detecting neutrons. The energy deposition of thermal neutron capture in $250 \mu m$ scintillator is mainly below 100 keV, so the energy discrimination method can be used to effectively reject gamma-rays above 100 keV.

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