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Study on the performance of a large-size CsI detector for high energy γ-rays

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Abstract The measurement of high-energy γ-rays is an important experimental method to study the giant resonance in a nucleus, γ reaction in nuclear astrophysics, and so on. The performance of a large-size CsI detector for γ-rays detection is studied by comparison between the experimental measurements and GEANT4 simulation. The reliability of the simulated efficiency for low-energy γ-rays is verified by comparing with the experimental data. The efficiency of the CsI detector for high-energy γ-rays was obtained by the GEANT4 simulation. The simulation shows that the detection efficiency of 20 MeV γ-rays can reach 3.8%.

Keywords CsI:Tl · Scintillation detector · Full absorption efficiency · Energy resolution · GEANT4 simulation

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1 Introduction

In recent decades, many new phenomena have been discovered in nuclear physics experiments, especially the exotic properties of cluster structures and halo structures. Compared with stable nuclei, exotic characteristics like large radius and narrow valence nucleon momentum distribution exhibit in halo nuclei [1, 2]. These properties are mainly caused by large space distribution or low orbital angular momentum of the valence nucleon in the nucleus. Furthermore, pygmy dipole resonance (PDR) was observed in neutron halo nuclei, which is different from the giant dipole resonance (GDR) phenomena in stable nuclei. In experiments, the giant dipole resonance in a nucleus is an important field of nuclear physics research. Giant resonance exists in a variety of nuclear reactions, which often generates high-energy γ-rays [3–14]. Therefore, measuring these high-energy γ-rays has become an important experimental method for studying giant resonance.

In the Phase II project of the Shanghai Synchrotron Radiation Facility (SSRF), the Shanghai Laser Electron Gamma Source (SLEGS) is an energy-adjustable X/γ-ray source [15]. A good quasi-polarization monochromatic γ beam can be produced, which provides a good opportunity for photon-nuclear physics and giant resonant experiments.

The energy of a γ-ray from the GDR is over dozens of MeV, and the energy of the supernova γ-ray is tens to hundreds MeV. Therefore, γ detectors need similar performance to that of space borne γ detectors. Usually a large-size crystal detector is used to ensure high detection efficiency for high-energy γ, which is a necessary condition to perform GDR experiment study. It is difficult to determine detection efficiency for high-energy γ-ray due to the lack of a high and single energy γ-ray source. The feasible methods are a combination of experimental measurement and Monte Carlo simulation for studying the detector performance.

GEANT4 (GEometry ANd Tracking) is a simulating toolkit based on C++ language for nuclear physics and high-energy physics experiments, which was developed by the European Organization for Nuclear Center (CERN). It can provide a variety of particle–material interaction cross sections for calculating the transport of particles in the medium transport process and give various related physical quantities of the particles in the transmission process [16]. Therefore, GEANT4 can be used to simulate the interaction of γ-ray in scintillation crystal, and the performance parameters of the cesium iodide (CsI) detector will be obtained.

In this paper, we have simulated the interaction of γ-ray in CsI crystals at different energies. At the same time, the simulation results were compared with the experimental data of the standard γ source to check its reliability.

2 Experimental measurements with CsI detector

2.1 Introduction and result of experiment

Using a CsI detector is the easiest way to test a detector using standard radioactive sources. However, the energy of γ-rays produced by the radioactive sources is usually very low. Although the efficiency and energy resolution of the detector for some energy can be obtained directly, the range of energy calibration is relatively small. Therefore, simulation is required for extrapolating the detector performance to the high-energy region.

Three radioactive sources, ^{137}Cs, ^{60}Co, and ^{228}Th, were selected for the experiment. γ-ray of 2.614 MeV energy can be obtained from ^{228}Th so that energy range of detector calibration is between 662 keV and 2.614 MeV. Since our main goal is the detection of high-energy γ-ray, the efficiency of γ for energy less than several hundred keV is not studied. Thus, the ^{152}Eu source is not used as an experimental radioactive source.

The CsI(Tl) detector used in this study was developed by the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. It is a sub-project of the Thorium-based Molten Salt Reactor (TMSR) pilot project. The initial aim of this detector is to measure the neutron capture reaction. A large number of CsI(Tl) detectors are installed around the experimental sample. For several MeV γ-rays from neutron capture reaction, the main requirement for the γ detectors is high detection efficiency. Since the CsI crystal is very long, it also provides favorable conditions for measuring the high-energy γ-ray.

The whole CsI(Tl) crystal detector is a hexagonal prism, which is 200 mm long, and the distance between parallel edges of intersection surface is 55 mm. The crystal is produced by the Shanghai Institute of Ceramics, Chinese Academy of Sciences, and is covered with 1 mm polytetrafluoroethylene and 2-mm-thick aluminum as shielding materials. The photomultiplier tube connecting to one side of the crystal is R1828-01 (Hamamatsu company) [17]. Figure 1 shows the assembly diagram of the detector and a photograph of the detector.

The main amplifier MSCF-16 is used in our test, and the signal is amplified and inputted to the ADC (CAEN v785) for A–D conversion and read out by the VME data acquisition system.

Figuer 2 presents the γ spectra measured by the CsI detector. As we can see, the energy spectra of ^{137}Cs and ^{60}Co is clear, just one or two peaks, but the spectrum of ^{228}Th has a number of peaks. The peak at 238.6 keV is high while the peak at 2.614 MeV is relatively very low, because the fractional ratio is relatively smaller and the detection efficiency of γ-ray decreases with the increase in

Fig. 1 (Color online) Structure diagram of the CsI detector unit

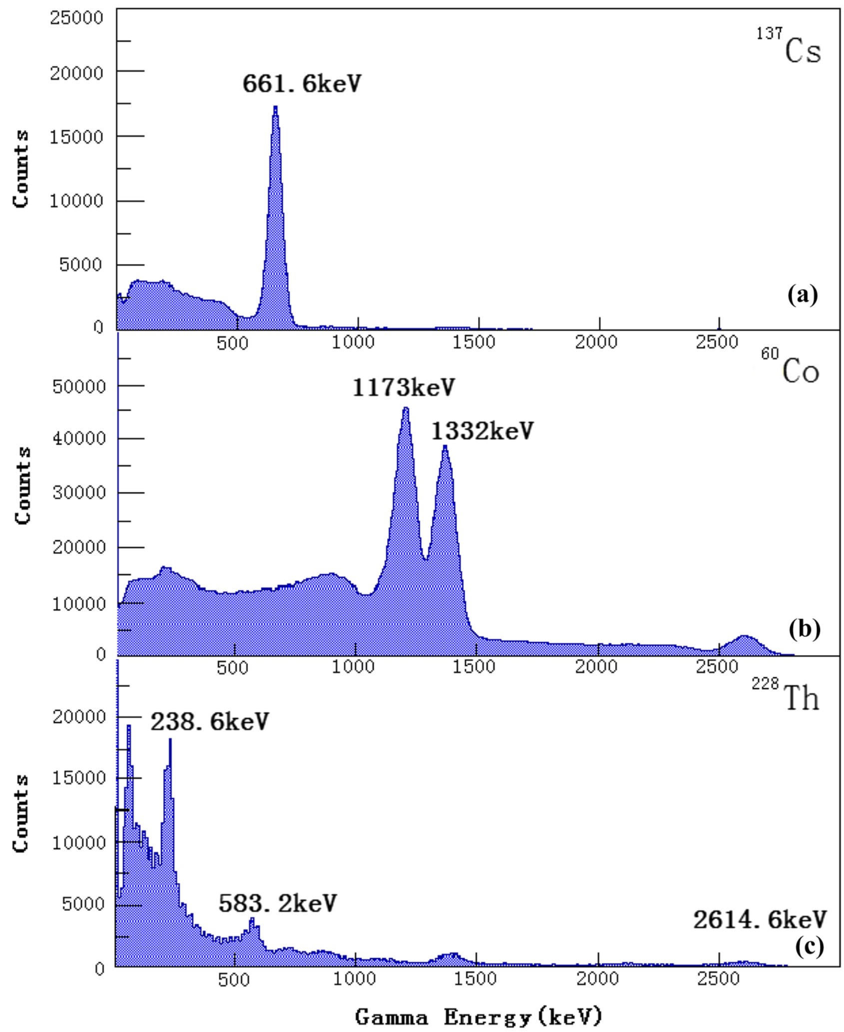

Fig. 2 (Color online) Measured γ-ray spectra of ^{137}Cs, ^{60}Co, and ^{228}Th

energy. Despite this, the peaks are still identified clearly. Six peaks from the three sources are used to calibrate the γ energy signal of CsI. The energy calibration of the detector is presented in Fig. 3, and we can see good linear relationship between the energy and the channel number when the energy of γ-ray is below 2.6 MeV.

2.2 Energy resolution

Energy resolution is an important capability of the detector. It is defined as

$$\eta = \frac{\Delta E}{E} = \frac{\mathrm{FWHM}}{E}, \tag{1}$$

where E and FWHM represent the peak value and the full width of the γ energy spectrum [18]. The relative energy resolution of the detector is mainly related to the characteristics of the crystal itself and performance of the photomultiplier tube. The resolution of the CsI detector is correlated with the γ energy (E) [19, 20]. The results obtained by fitting the experimental data reduce from 17 to 3.5% with gamma sources energy growth, as shown in Fig. 4, The fitted results can be expressed by the following function

$$\frac{\mathrm{FWHM}}{E} = \sqrt{2.672(0.140)E^{-1} - 0.0002(0)}. \tag{2}$$

The uncertainties of the data are very small and negligible. This is consistent with some of the previous experimental results [21–23].

3 GEANT4 simulation and results

3.1 Detector construction model

The γ-ray emitted from radioactive sources used in the experimental measurements is isotropic in space. The crystal is a hexagonal prism type, and its surrounding space is vacuum. Every radioactive source with a very small

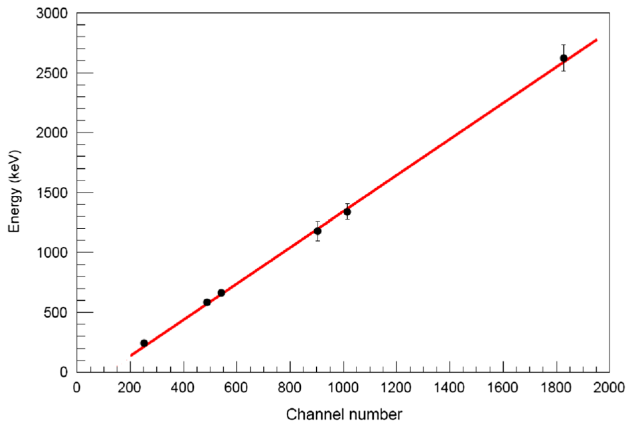

Fig. 3 (Color online) Linear fit between the channel number and the energy deposited in a CsI:Tl scintillation detector in an energy range from 200 keV to 3 MeV with a Hamamatsu R1828-01 phototube and the HV setting to 1600 V

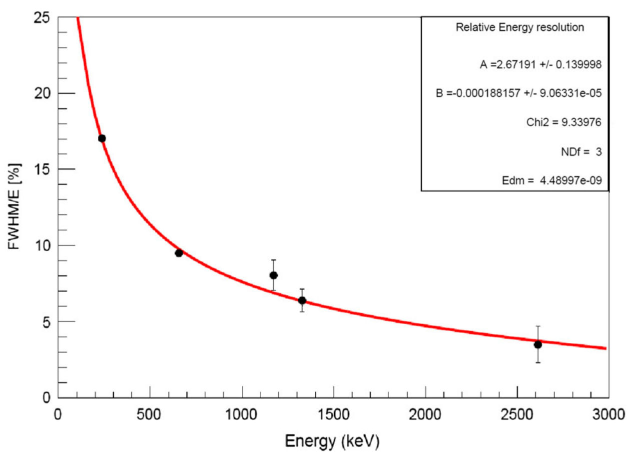

Fig. 4 Relative energy resolution for γ-rays in a CsI:Tl detector

surface was located 5 mm in front of the CsI crystal. The γ-ray comes out from the source in an isotropic emission way, so the γ photons fly into the crystal from different angles. Because the efficiency of the detector is our first concern, other factors such as visible photon emitting from the energy deposit of the γ-ray, transmission process of visible photons in the crystal, and the surface features of CsI crystal were not considered when we established the simulation environment.

3.2 Simulation results

GEANT4 toolkit plays the main role in simulating the whole energy deposition of γ-rays from the ^{137}Cs (662 keV) source and ^{60}Co (1173, 1332 keV) source. Two γ-rays energies from the ^{60}Co source were used in the simulation with the real emission probabilities at the same time. Since the simulation is about the energy deposition of the γ-ray, the simulation process does not include the production, transmission, and collection of scintillation light in the crystal. The statistical error and fluctuation from electronic noise of the photon-read device were not considered neither [20]. So we have used the energy resolution obtained by fitting the experimental data in the simulation to show the dispersion of energy deposition. The results are the same as Fig. 2. That means the simulation reproduces the test results of CsI detectors well. The simulated energy spectrum of ^{60}Co and ^{137}Cs is shown in Fig. 5.

By changing the energy of the γ-ray in GEANT4, we can simulate the effect of different energy, especially high-energy, γ-ray hitting in the large-volume CsI scintillation. A series of different energy spectra were obtained. As shown in Fig. 6, the inset plots are the energy spectra without considering the energy resolution, while the full-size plots are the energy spectra with the inclusion of the energy resolution effect [24].

It should be noted in Fig. 6 that as the energy of the γ-ray increases, a single electron escape peak and double electron escape peak begin to appear. When the energy is only 661 keV, the energy spectrum has only one sharp full absorption peak. When the energy reaches 8 MeV, we can find that the simulation results have not only the full absorption peak, but also the single electron escape peak and the double electron escape peak with 0.511 MeV shift in energy. As the energy increases, proportion of the full absorption peak over a single electron escape peak decreases gradually. If the energy resolution is introduced, the results should be consistent with the results of the detector test. As shown in Fig. 6, it can be found that as the

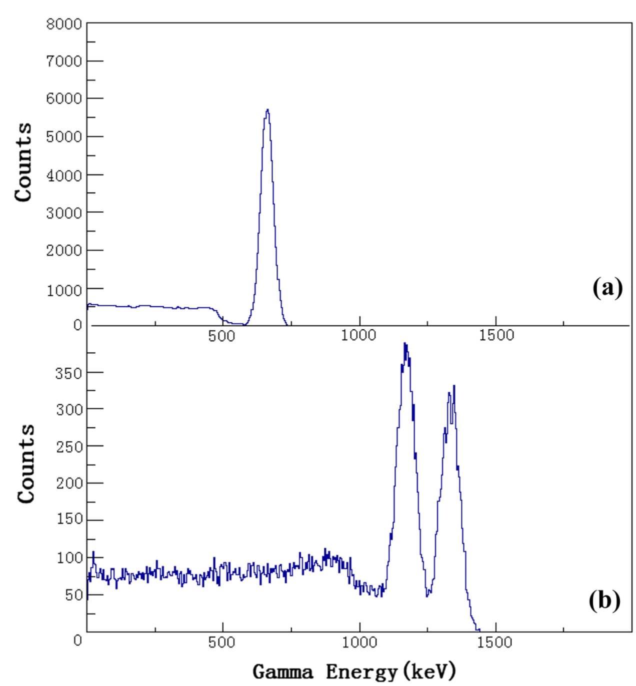

Fig. 5 Simulation results of γ in the CsI from ^{137}Cs (**a**), ^{60}Co (**b**)

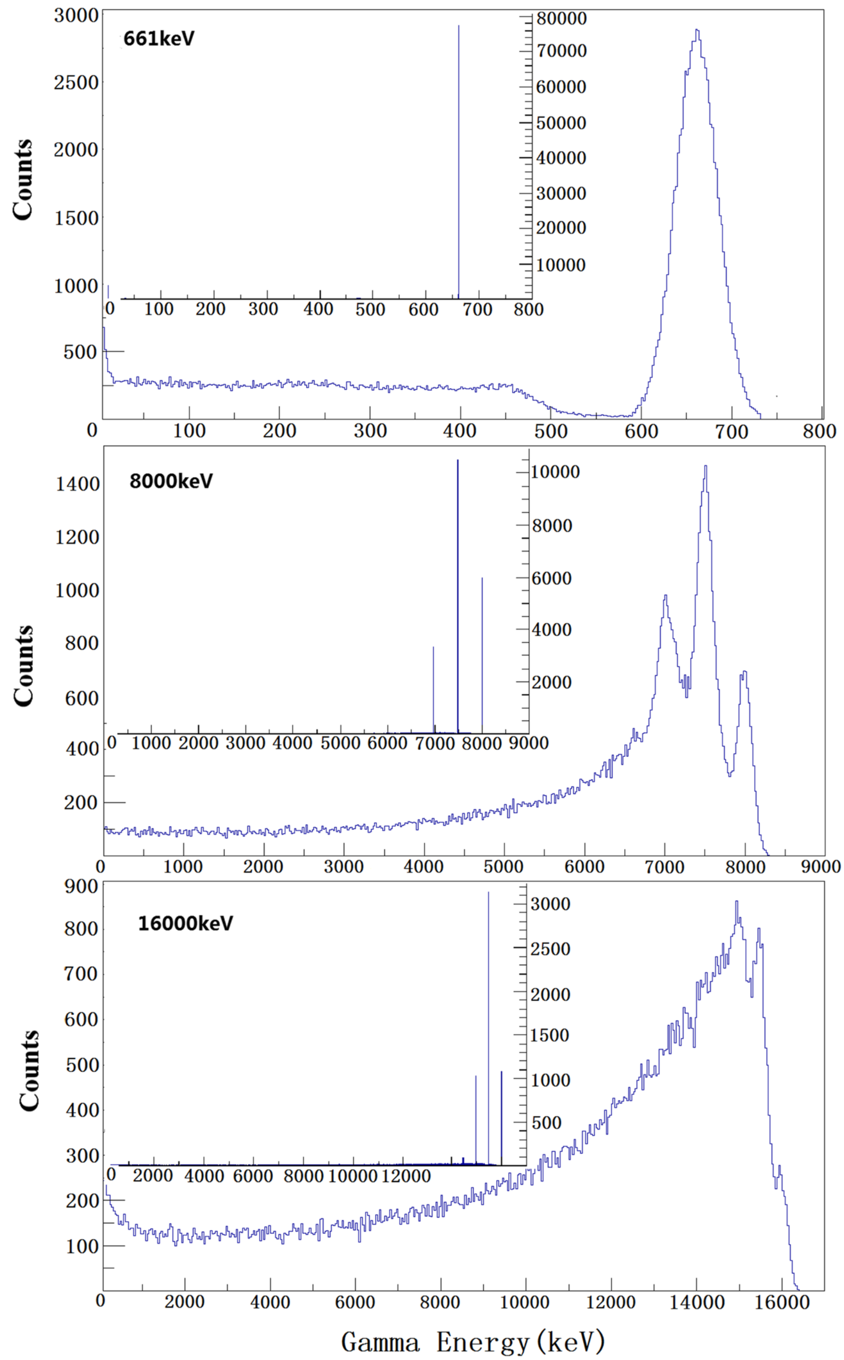

Fig. 6 Simulation of four kinds of isotropic gamma sources energy spectrum without (inner) and with the broadening effect (outer)

energy increases, the spectrum broadening increases. When γ energy reaches 16 MeV, the full absorption peak, single electron escape peak, and double electron escape peak have been overlapped together.

The detection efficiencies of the single and double escape peak were extracted from the simulation results. We can see from Fig. 7, the measured points were a little bit lower than the simulation results. The detection efficiency at low energy is in quite good agreement with the simulation results. Meanwhile, the detection efficiencies at the high-energy region are also predicted. The efficiency of a single escape peak is higher than the total absorption peak for the γ energies in the 5–15 MeV range, indicating that it is feasible to select it as the characteristic peak for efficiency study.

The emission style of γ source in our simulation is isotropic. But in some cases, for example, a photon nucleus reaction, the γ-ray is a parallel or quasi-parallel beam. So we have simulated and drawn the efficiency line using the

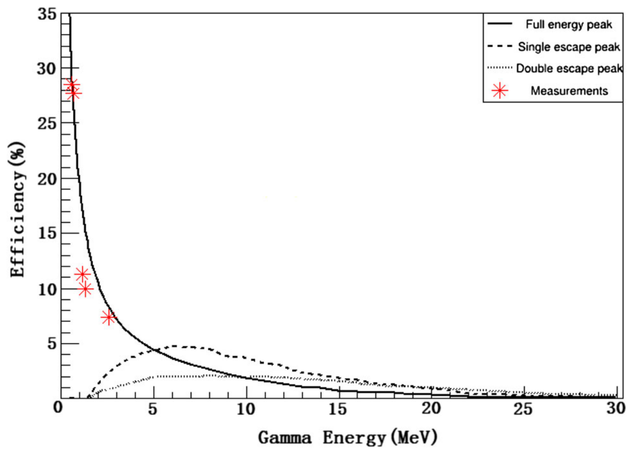

Fig. 7 The energy-dependent photopeak absorption efficiencies for isotropic incidence simulated by GEANT4.The experimental data are shown by the stars

same parameter except that the incident direction of γ is perpendicular to the cross section of the crystal.

When the γ ray hits vertically on the CsI crystal, the effective range of γ in the crystal increases, and the probability of deposited energy inside the crystal increases; thus, the efficiency will also increase. As Fig. 8 shows, the CsI detector has a high detection efficiency up to 66% for 1 MeV γ and 3.8% for 20 MeV γ.

In addition, from the simulation results, single electron escape and double electron escape are similar to those of the total energy peak at 20 MeV. If the single electron escape peak and double electron escape peak can be taken into account [25], a higher efficiency can be obtained. Moreover, the simulation results show that when the energy of the γ-ray increased, the three peaks will be overlapped together. Further study is needed to improve the efficiency of the detector for high-energy γ-rays.

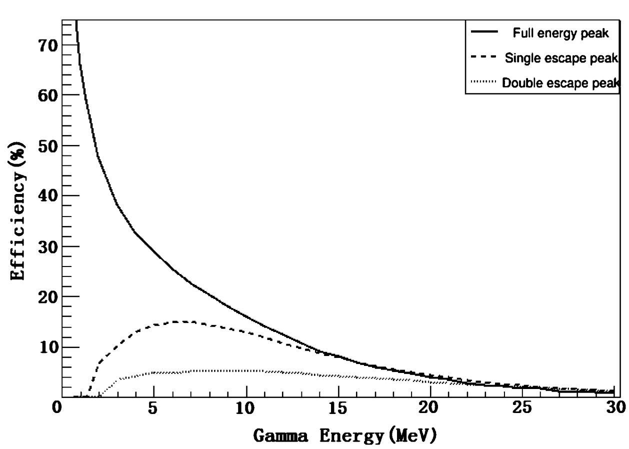

Fig. 8 The energy-dependent photopeak absorption efficiencies for normal incidence simulated by GEANT4

4 Summary

In this paper, the performance of a very long CsI crystal was investigated through experimental measurements and GEANT4 simulations. The energy resolution and the detection efficiency of the CsI detector were studied experimentally by several low-energy γ-ray sources. Obtained results show that the dependence between the channel number and energy was linear up 2.6 MeV energy. A nonlinear effect is not exhibited, but the results for high-energy γ-ray should be carefully investigated in future tests. The simulated and experimental results are consistent with each other at low energies. The simulated detection efficiency and energy resolution of high-energy γ-rays were obtained. The relative energy resolution is 17% at 0.238 MeV γ and 3.5% at 2.6 MeV γ. We have also obtained the efficiency curve when the γ-ray hits the CsI crystal normally. The detection efficiency of γ is higher than the case for isotropic incidence. The efficiency of the full absorption peak is about 66% at 1 MeV in the normal incidence condition, and it decays with the increase in energy and becomes only 3.8% at 20 MeV. Based on the experimental measurements and GEANT4 simulations, the performance of a CsI detector has been extrapolated to a very wide γ energy range. These results would be important and useful in γ detector design and high-energy γ-ray measurement.

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