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Research Article

Effect of Photomultiplier Tube Voltage on the Performance of Sealed NaI (Tl) Scintillator Detectors

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We explored the nonlinear characteristics of energy resolution (ER) for the sealed NaI (Tl) scintillator detector by using a gamma-ray spectroscopy system and Monte Carlo simulation. Our research focused on the two primary factors of energy resolution including the photomultiplier tube (PMT) voltage and the distance between the gamma-ray sources (^{137}Cs and ^{60}Co) and the scintillator detector. The experimental results showed that energy resolution decreased when the PMT voltage increased, and the energy resolution of NaI (Tl) detectors reached a smaller value (6.92%, 6.76%, and 6.56%), especially with the PMT voltage in the range of 575–595 V. In addition, a suitable distance between the gamma-ray source and the scintillator (5 cm) can also effectively reduce the energy resolution. We established the simulation models of the experimental NaI (Tl) detectors and simulated their energy spectra. The simulation results in the peak area agreed with the experimental results. A possible better PMT voltage choice has been proposed to obtain a smaller energy resolution.

1. Introduction

Thallium-doped sodium iodide (NaI (Tl)) is an alkali metal halide inorganic scintillator, which exhibits excellent optical performance and high luminous efficiency. Detectors made of NaI (Tl) possess several advantages, including a large sensitive volume, high detection efficiency, and low cost. Due to its simple operation, strong environmental adaptability, and stable physical and chemical properties, it is widely used in various fields, such as nuclear physics experiments, radiation monitoring, and medical imaging [1–3].

Scintillator detectors are effective for detecting gamma-rays. Detectors operate by having a gamma photon interact with the scintillator, which then causes the formation of a photoelectron through various main effects such as photoelectric effect and Compton scattering. The signal is then processed by a multichannel analyzer (MCA), and the spectrum acquisition software produces a value-counting spectrum.

The photomultiplier tube (PMT) plays a vital role as a crucial component in scintillator detectors, which convert the weak light from the scintillator into photoelectrons and then amplified by the dynode chain and output as an energy-dependent signal by MCA.

The energy resolution (ER) is a crucial indicator for scintillator detectors. ER percentage determines the width of the detected spectrum curve, and smaller ER percentage indicates that different energy gamma-rays can be more easily resolved, leading to better performance of scintillator detectors [4–6]. The energy resolution of NaI (Tl) scintillator detectors is typically around 7%. Previous studies have discussed changes in ER of scintillator detectors caused by different scintillator mass and volume, scintillator packaging structure, and various application environments. However, it has been a lack of detailed research on the effects of the following two factors: the photomultiplier tube (PMT) voltage and the distance between the radiation source and the scintillator [7–10].

Our study aimed to investigate the influence of two factors on the energy resolution of scintillator detectors, namely, PMT voltage and the distance between gamma-ray sources and the scintillator [11, 12]. Two different sizes of

NaI (Tl) scintillators (scintillators diameter and height recorded as 1 × 1 inch and 2 × 2 inch, respectively), ^{137}Cs and ^{60}Co sources, different gamma-ray source distances (1 cm, 5 cm, and 10 cm), and a wide PMT voltage range (525 V–650 V) were used in experiments [13, 14].

In order to ascertain the accuracy of the experimental data, an advanced and highly sophisticated software tool known as the MCNP5 program was employed to simulate the intricate process of photon transport [15, 16]. Through this rigorous simulation process, the MCNP5 program was used to describe this complex process, which provided a valuable benchmark for comparing and evaluating the experimental findings [17–20].

In this paper, we have presented the nonlinear effect of PMT voltage on the energy resolution of the sealed NaI (Tl) detector. We conducted experiments at different PMT voltage settings. Based on our findings, we identified the engineering feasible PMT voltage setting range (575–595 V) for achieving the smaller energy resolution for NaI (Tl) scintillator samples. In addition, we analyzed the impact of the distance between gamma-ray sources and the scintillator on the energy resolution. It is found that the appropriate selection of the distance between the gamma-ray source and the scintillator (5 cm) can reduce the energy resolution. Thus, we propose a feasible working condition for obtaining better performance of these detectors in practical applications.

2. Materials and Methods

2.1. Experimental Setup. In this study, we utilized an experimental setup to obtain the energy spectrum of the NaI (Tl) scintillator detector [21–23]. The experimental apparatus, as depicted in Figure 1, consisted of an opaque sealed lead box housing a photomultiplier tube (PMT) from Hamamatsu CR105-05 (Japan, which bias voltage is 400–1000 V) and a gamma-ray source. The distance between the gamma-ray sources and the scintillator could be adjusted by means of a telescopic stainless-steel frame, and the lead shield used in the experiment is a cylinder structure with a height of 15 cm, an inner diameter of 10 cm, and an inner diameter of 0.5 cm. The overall material is composed of lead. The photoelectron generated by the NaI (Tl) scintillators were converted into a pulse signal by the PMT, amplified, and processed by an amplifier (9302, Ortec, and the amplifier gain was 20) and a multichannel analyzer (EASY-MCA 2k, Ortec) and then eventually output in Canberra spectroscopy software. NaI (Tl) scintillators were placed in close contact with the photomultiplier tube and applied a layer of silicone oil as the coupling agent to ensure that the interface was seamless. We applied the silicone oil evenly to prevent any bubbles. Finally, the instrument needs to be stabilized for thirty minutes prior to the experimental measurement.

Different sizes of NaI (Tl) scintillators were used in the experiment and encapsulated in an inert gas glove box (MB200MOD, Germany). We also used aluminum (AL) as the external material for encapsulation, and magnesium oxide (MgO) was used as the reflective layer material on the interior [24–26]. To prevent deliquescence, we filled an extremely thin sponge between the external material and the

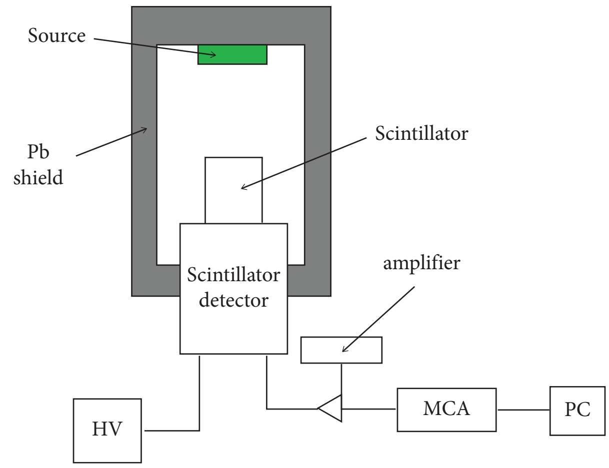

Figure 1: Experimental setup for energy resolution measurement of NaI (Tl) detectors.

reflective layer material at the upper end, while the smaller end was encapsulated in optical glass. The structure is illustrated in Figure 2.

To minimize the impact of visible light in the experiment, scintillators were sealed and covered with the lead shield (shielding layer) to ensure a controlled experimental environment. Then, ^{137}Cs and ^{60}Co gamma-ray sources were used to excite NaI (Tl) scintillators. The ^{60}Co gamma-ray source was used to improve the accuracy of scaling in the spectroscopy software. In this experiment measurement system, the energy resolution (ER) is defined as the ratio of full width at half maximum (FWHM) to the peak energy. We fit the spectra of the ^{137}Cs and ^{60}Co and calculated the full width at half maximum (FWHM) height of the Gaussian peak and determined the calibration parameters by the following equation [27, 28]:

$$\text{FWHM} = a + b\sqrt{E + cE^2}, \tag{1}$$

where a, b, and c are the calibration parameters determined by the all-energy peak. The units of a, b, and c are MeV, $\text{MeV}^{1/2}$, and MeV^{-1}. Two standard gamma-ray sources including three gamma energies in the range from 662 keV to 1.33 MeV were used to obtain the measured gamma-ray spectrum for determining a, b, and c as parameters specifying the full width at half maximum.

Since ^{137}Cs and ^{60}Co have different full-energy peaks (^{137}Cs: 662 keV and ^{60}Co: 1.170 MeV, 1.330 MeV) with two gamma-ray spectra, we could reduce the systematic error of the spec-tral software during calibration by substituting the measured data into formula (1), and we can obtain the specific values of a, b, and c. We obtained the address, peak area, and FWHM of each full-energy peak by calibrating the two full-energy peaks of ^{60}Co and then obtained a more accurate energy resolution.

2.2. Monte Carlo Simulation. In order to validate whether the experimental variables result, it is necessary to create a model with the same position structure, scintillator size, and scintillator encapsulation using the MCNP5 program.

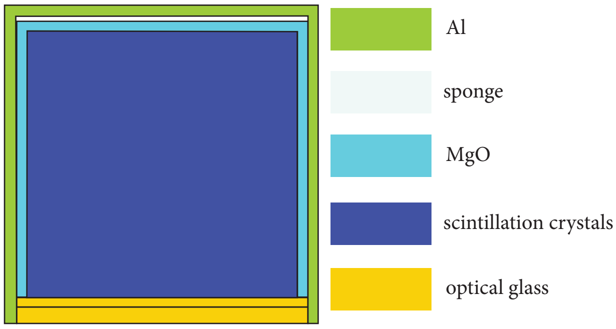

Figure 2: The structure of the sealed scintillator.

Table 1: Material parameters for model simulation.

Material	Density/(g/cm^3)	Size/(diameter × height, inch)
NaI (Tl)	3.67	2 × 2 (group 2)
NaI (Tl)	3.67	1 × 1 (group 1)
MgO	3.58	
Al	2.7	
Optical glass	2.3	
Sponge	0.045	
Pb shielding layer	11.34	
Silicone oil	0.96	

When creating the MCNP model, it is essential to define each material used in the model. Table 1 shows the material parameters for the input card. In order to simplify the description, the sizes of the scintillators of two scintillator samples (diameter and height recorded as 1 × 1 inch and 2 × 2 inch) were abbreviated as 1 inch and 2 inch.

The MCNP5 program based on the Monte Carlo method was used to establish a simulation model, which was analyzed using a two-dimensional axisymmetric model due to its good symmetry. This model assumes a seamless contact between the scintillator and PMT and uniform distribution of MgO in the encapsulation. We use the MCNP5 program input card code to describe the simulation model, which is presented in Figure 3.

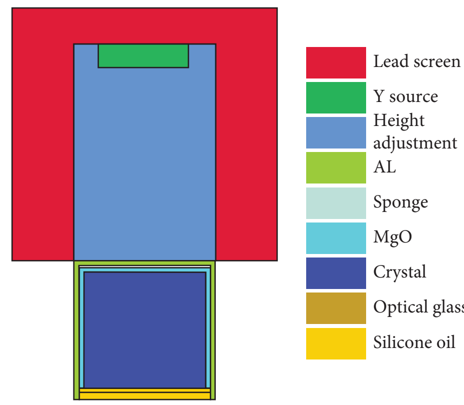

Figure 3: The Monte Carlo simulation model of detectors.

3. Results and Discussion

3.1. Experimental Data Analysis. To measure the energy resolution, it was essential to determine the range of PMT load voltage allowed by the experiment. Initially, a wide voltage range was selected and conducted measurements and recorded the channel distribution (peak channels at 662 V) of 2 × 2 inch scintillator samples (diameter and height, recorded as 2 × 2 inch, which was abbreviated as 2 inch) in Table 2, in which the distance between the scintillator and the source are 1 cm, 5 cm, and 10 cm. .

From Table 2, a conspicuous phenomenon is observed that with the increase of PMT voltage, the channel address also increases, causing the full-energy peak to shift towards the right side [29]. During the experiment, when the PMT load voltage exceeds 650 V, the full-energy peak of ^{60}Co is about to exceed the channel range. In addition, when the voltage is below 525 V, it is challenging to calibrate the full-energy peak of ^{137}Cs. Therefore, we selected the voltage threshold range to be 525–650 V.

The energy resolution limit of the scintillator detector can be calculated from the following formula [6]:

$$\eta = \frac{\Delta E}{E} = 2.36 v_h = 2.36\sqrt{\frac{1}{\overline{n}_{ph}\cdot T}\left[1 + \frac{\delta}{\delta_1}\cdot\left(\frac{1}{\delta - 1}\right)\right]}, \quad (2)$$

where δ_1 is the magnification of the first dynode in the PMT and δ is the magnification of the other dynodes. $\overline{n}_{ph}\cdot T$ is the number of photoelectrons collected by the first dynode, $\overline{n}_{ph}$ is the light yield of the scintillator, and T is the coefficient that the photocathode generates photoelectrons and received by the first dynode.

In the formula (2), the dynode coefficient can be derived from the following formula:

$$\delta = k(\Delta V)^a, \quad (3)$$

where ΔV is the voltage between the multiplying electrodes. k is a constant decided by materials. a is a constant of 0.7.

The gamma spectrum of the NaI (Tl) scintillator is measured and the energy resolution is calculated according to the experimental bench shown in Figure 1. To eliminate the influence of scintillator size, two different sizes of NaI (Tl) scintillators (diameter and height recorded as 1 × 1 inch and 2 × 2 inch, which were abbreviated as 1 inch and 2 inch) were selected in the experiment, and their energy resolution trends and numerical differences were compared in the voltage range (525 V–650 V). The results are presented in Figure 4.

From Figure 4, it was observed that the energy resolution plots changes for the two different sizes of NaI (Tl) scintillators (diameter and height recorded as 1 × 1 inch and 2 × 2 inch, which were abbreviated as 1 inch and 2 inch) are similar. When the voltage intensity is below 575 V, the energy resolution of the two sizes of scintillators shows a downward trend, and there is an oscillation phenomenon in voltage intervals. However, when the voltage increases to 575 V, although the energy resolution curve still oscillates, the oscillation phenomenon gradually disappears as the PMT voltage increases. Within this voltage range, the energy resolution is briefly increased to 7-8% and quickly stabilized.

Table 2: The measurement results of the energy spectrum.

Voltage (V)	Peak channels 2 inch 1 cm	Peak channels 2 inch 5 cm	Peak channels 2 inch 10 cm
525	102.00	117.00	106.00
535	120.00	133.00	124.00
545	137.00	151.00	162.00
555	156.00	171.00	183.00
565	178.00	194.00	207.00
575	203.00	222.00	235.00
585	228.00	250.00	277.00
595	257.00	281.00	301.00
605	290.00	316.00	336.00
615	335.00	354.00	377.00
625	377.00	399.00	386.00
635	421.00	447.00	415.00
645	470.00	498.00	455.00
650	495.00	524.00	490.00

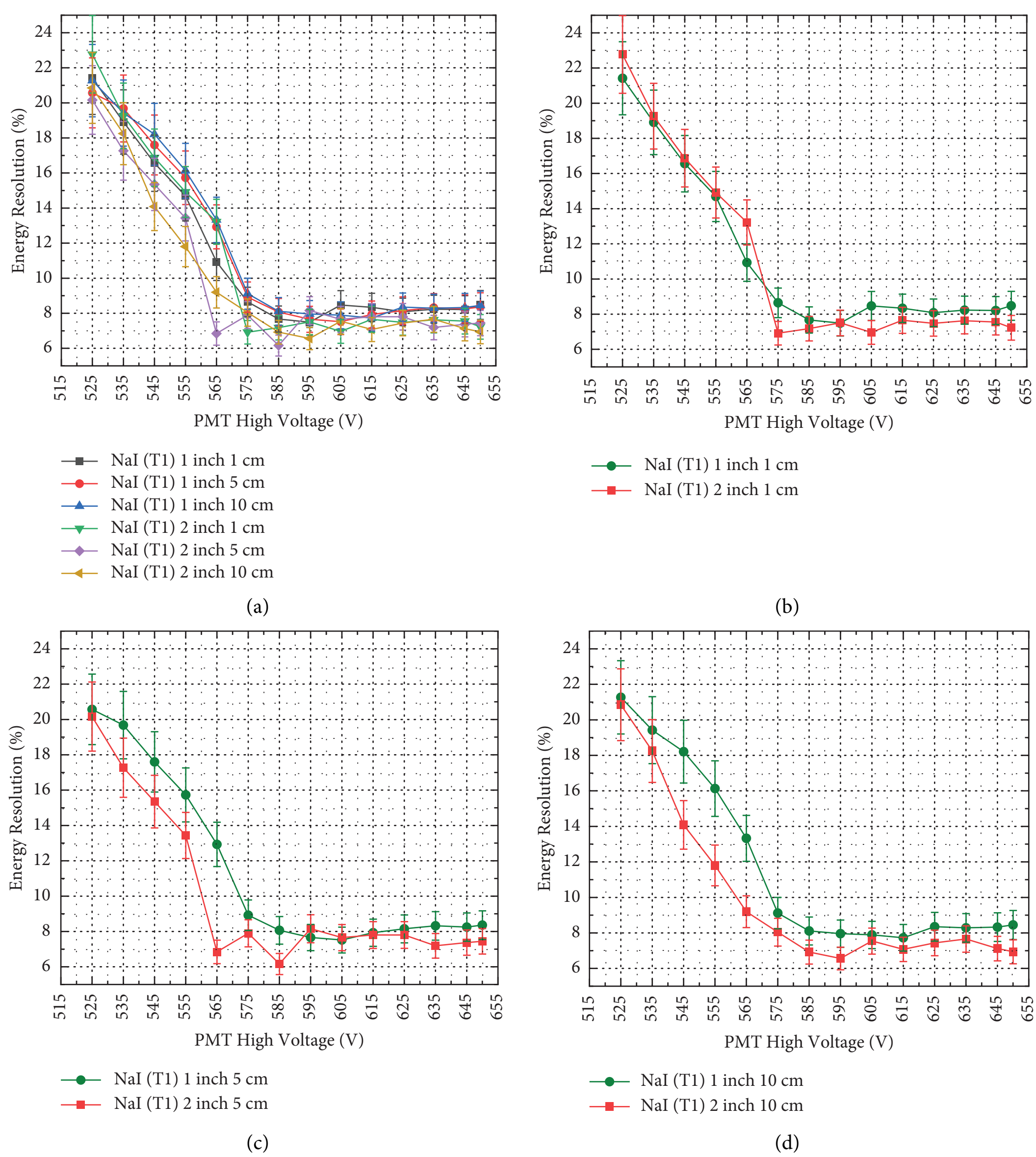

Figure 4: Energy resolution for different NaI (Tl) scintillator sizes. (a) Overview of experimental results. (b) Comparison of energy resolution at 1 cm. (c) Comparison of energy resolution at 5 cm. (d) Comparison of energy resolution at 10 cm. The error bars is 1σ, and the statistical error is 6.6%.

The reason why the energy resolution curve first decreases rapidly and then oscillates stably can be explained by formulas (2) and (3). When the PMT voltage increases, it can be seen from formula (2) that δ increases with the increase of voltage, so photoelectrons are concentrated, which reduces the energy resolution, and the energy resolution curve shows a downward trend. When the PMT voltage rises to a certain extent, in formula (3), increasing the PMT voltage value will result in larger values for the parameters $\delta 1$ and δ. When the voltage is large enough, it can be found in formula (2) that δ has a limit, $\delta - 1$ approaches δ, and $\delta/\delta_1 \cdot (1/\delta - 1)$ approach 0. In this case, the energy resolution is only related to $\overline{n}_{\mathrm{ph}} \cdot T$. Associating formulas (2) and (3), it can be found that higher voltages lead to a better energy resolution, and the energy resolution changes little at this time. In addition, the noise of the photomultiplier tube is large at this time, so the photomultiplier tube obtains a better signal-to-noise ratio, and the energy resolution curve is stable [12, 29]. Moreover, the energy resolution of the 2 inch scintillator in the three experimental control groups is smaller. In order to obtain better experimental results, our research was focused on 2 inch scintillators in this voltage range, which is consistent with the conclusion in previous studies [21].

In order to establish the experiment of the 2 inch scintillator (diameter and height recorded as 2×2 inch, which was abbreviated as 2 inch), which were adjusted at four different heights (1 cm, 5 cm, 10 cm, and 50 cm). The measured energy resolution curve is shown in Figure 5.

From Figure 5, it can be observed from the experimental results that the energy resolution of NaI (Tl) scintillators decreases with the voltage increasing in the range of 525 V–650 V, and this phenomenon can be explained by formulas (2) and (3). In formula (3), increasing the PMT voltage value will result in larger values for the parameters $\delta 1$ and δ. When the voltage is large enough, it can be found in formula (2) that δ-1 approaches δ and $\delta/\delta_1 \cdot (1/\delta - 1)$ approach 0. In this case, the energy resolution is only related to $\overline{n}_{\mathrm{ph}} \cdot T$. Associating formulas (2) and (3), it can be found that higher voltages lead to a better energy resolution. In formula (2), though the light yield of the scintillator can determine the performance of energy resolution, the corresponding electronic devices can influence the energy resolution deeply. An optimum measurement condition can improve the energy resolution. In Figure 5, a more accurate voltage range can greatly decrease the numerical value of the energy resolution of the NaI (Tl) detector. Similarly, from Figures 4 and 5, it can be found that in this reduced voltage range, and there will be a voltage value that can obtain the extreme value of the smaller energy resolution and a voltage range with relatively stable energy resolution. It is worth noting that when the voltage is lower than 575 V, the energy resolution is relatively high due to the increase of noise, while the energy resolution of the scintillator is relatively stable in the voltage range of 575 V–650 V. After exceeding 595 V, due to the saturation effect of PMT and the increase of noise level, the energy resolution begins to rise and finally stabilizes near 7%. Therefore, our voltage range should be 575–595 V, in which energy resolution becomes smaller (6.92%, 6.76%, and 6.56%).

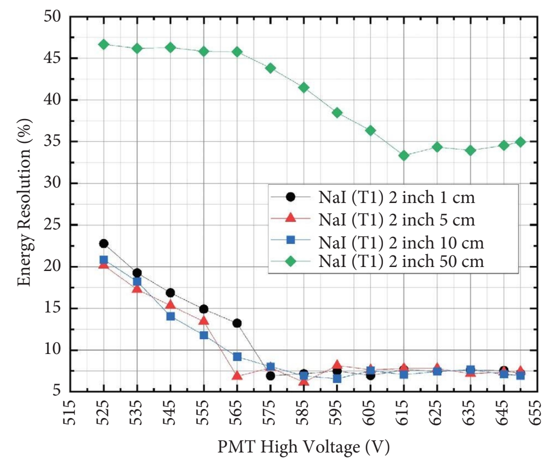

Figure 5: The energy resolution of NaI (Tl) at different PMT voltages.

However, even with an increase in voltage, the influence of distance cannot be completely eliminated. From the energy resolution curve corresponding to 2 inch 50 cm (diameter and height recorded as 2×2 inch, which was abbreviated as 2 inch), it can be seen that when the distance between the gamma-ray source and the scintillator is amplified to a certain extent, and it is difficult for a given photomultiplier tube to distinguish the energy spectrum peak of the unknown gamma-ray source, so the energy resolution of the detector is weakened. It should be clear that the smaller the figure for energy resolution, the better the detector will be able to distinguish between two radiations whose energies lie near each other. Therefore, the distance also has an impact on the energy resolution. It can be seen from Figure 5 that the lower energy resolution appears on the 5 cm curve, so an excellent working condition at 575–595 V PMT voltage can be obtained: the distance between the gamma-ray source and the scintillator, which is consistent with the previous studies of Ermis and Celiktas [14].

3.2. MCNP5 Simulation Results. In previous experiments, we explored the relationship between PMT voltage and energy resolution, obtained the curve of energy resolution with voltage distribution, and obtained a smaller energy resolution and its corresponding voltage. At the same time, the experimental results also show that the distance between the scintillator and gamma-ray sources also affects the energy resolution. In order to further discuss the influence of the distance between the PMT voltage and the distance between the scintillator and the gamma-ray source on the energy resolution, we constructed the MCNP5 model and simulated the energy spectrum peak (662 keV), which was compared with the energy spectrum peak obtained from the experimental results, as shown in Figure 6.

We adjusted the distance between the gamma-ray source and the scintillator in the input card to simulate three sets of experiments. The energy spectrum peak simulated by the MCNP5 program is in good agreement with the ^{137}Cs full-energy peak corresponding to the PMT voltage in the

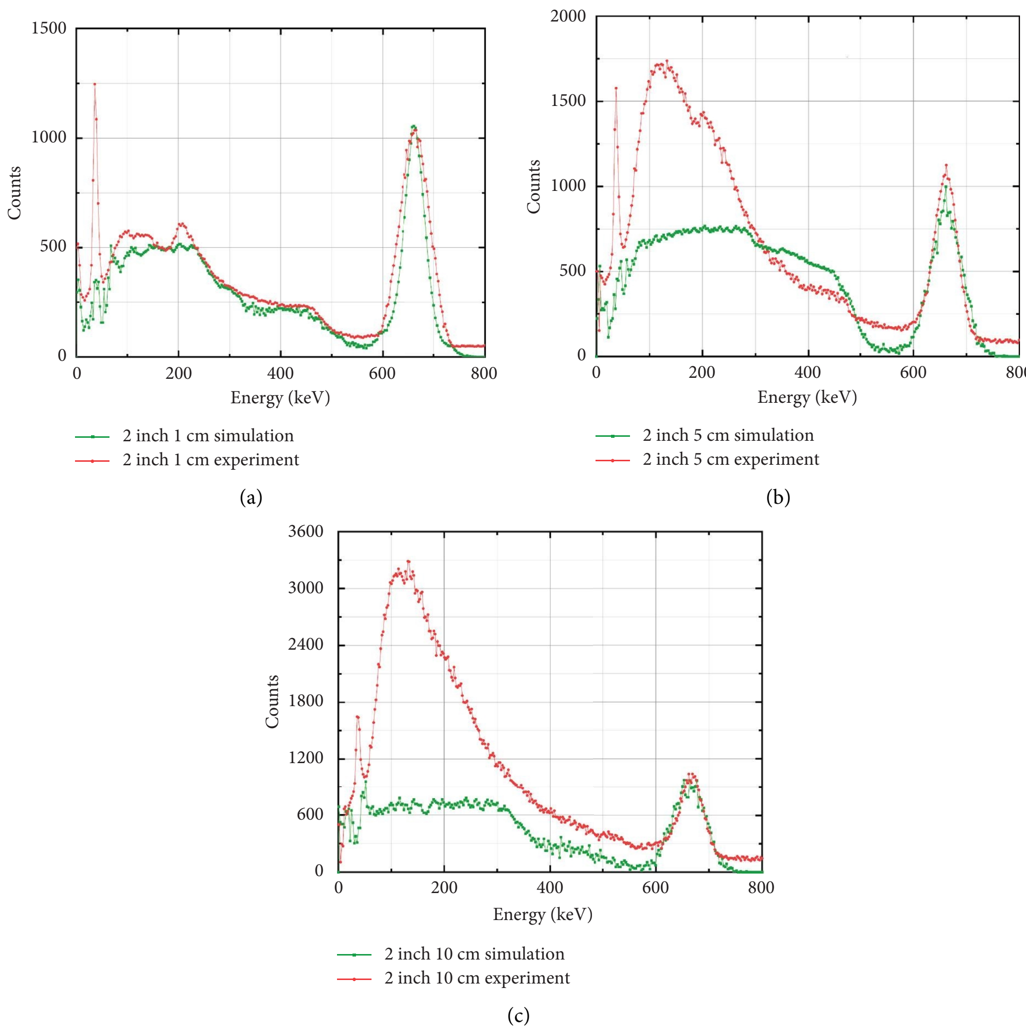

Figure 6: ^{137}Cs energy spectrum measured by NaI (Tl) detector and simulation results under different heights. (a) NaI (Tl) 2 inch 1 cm; (b) NaI (Tl) 2 inch 5 cm; and (c) NaI (Tl) 2 inch 10 cm.

experiment, especially in terms of peak area and energy resolution. Although the simulation results are different from the experimental results in the low energy region, this does not affect the accuracy of the simulation results because the energy spectrum curve in the simulation has a Gaussian distribution at the energy spectrum peak, which makes the coincidence result at the peak position better, and this phenomenon does not exist in the low energy region [30]. From the Monte Carlo simulation results, our experimental results are relatively ideal. According to the simulation results shown in Figure 6, we find that the experimental energy spectrum is in good agreement with the simulated energy spectrum. Specifically, three sets of experiments with different distances between the gamma-ray source and the scintillator can achieve a smaller energy resolution in the voltage range of 575–595 V. For MCNP5 simulation, although PMT cannot be included in the simulation, the reason for the change of energy resolution can be explained by formula (2). The MCNP5 model can be explained using formula (2) without the $\delta/\delta_1 \cdot (1/\delta - 1)$ term. The influence of distance can be reflected in formula (2) that as the distance increases, the energy reaching the scintillator decreases, making $\overline{n}_{ph}$ decrease and η rise instead, which means the energy resolution value will rise soon. As is shown in Figure 6, it can be observed that at the selected voltage, the experimental full-energy peaks match well with the simulation results (^{137}Cs total peak area ratio: 0.8085,0.9091, and 0.8057), which is consistent with previous studies [11], indicating that the optimal operating voltage for the PMT is in the range of 575–595 V.

4. Conclusions

In our work, we studied the energy resolution of sealed NaI (Tl) scintillator detectors which performed the experiment with different PMT voltage and the distance between gamma-ray sources and the scintillator, and Monte Carlo simulation had been used to validate experimental spectra peaks characteristic. Experimental results showed that the energy resolutions of NaI (Tl) changed nonlinearly with the PMT voltage and distance increasing. At the same time, the statistical characteristics of NaI (Tl) scintillator experimental results are confirmed by Monte Carlo simulation. Through theoretical formula analysis, we find that higher voltage leads to better energy resolution of the scintillator detector, but there exists a PMT voltage range that can improve the energy resolution greatly in experimental results. When the PMT voltage is near 575–595 V, the energy resolution of the NaI (Tl) scintillator detector reaches a smaller value. Also, appropriate detection distance (5 cm) can improve detection ability under the same voltage. To improve the energy resolution, voltages ranging from 575 V to 595 V are feasible for NaI (Tl) scintillator detectors.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Hongchi Zhou contributed to software, validation, formal analysis, data curation, visualization, and writing the original draft. Fang Liu contributed to methodology, conceptualization, and editing. Xin Yuan, Jun Wu, and Guanda Li contributed to resources, supervision, analysis, and reviewing and editing. All the authors have read and agreed to the published version of the manuscript.

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