Anti-coincidence Shielding γ-ray Detector based on LaBr3(Ce)/CsI(Tl) Phoswich Scintillator

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Abstract

An anti-coincidence shielding γ-ray detector has been designed to study Compton suppression and cosmic rays anti-coincidence based on a LaBr3(Ce)/CsI(Tl) phoswich scintillator, where the LaBr3(Ce) scintillator is chosen as the main crystal completely surrounded by the CsI(Tl) scintillator. Since the differences in their pulse shapes, a series of studies have been conducted using pulse shape analysis (PSA) methods. By using digital charge integration (QDC), the energy resolutions of the detector are obtained, being 3.7% for 662 keV of 137Cs , 3.1% for 1173 keV and 2.8% for 1332 keV of 60Co after excluding the influence of cascade γ rays. This detector can suppress the Compton continuum by 2 5 times for 137Cs/60Co based on Fast and Slow Component Ratios (FCR-SCR). Furthermore, almost all cosmic rays can be rejected by filtering events above 10 MeV in an in-beam spectrum analysis. It clearly shows that this anti-coincidence shielding γ-ray detector can be used for low level radioactivity measurements as well as high energy γ rays measurements.

Full Text

Anti-coincidence Shielding γ-ray Detector based on $LaBr_3$(Ce)/CsI(Tl) Phoswich Scintillator

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An anti-coincidence shielding γ-ray detector has been designed for Compton suppression and cosmic ray rejection based on a $LaBr_3$(Ce)/CsI(Tl) phoswich scintillator, where the $LaBr_3$(Ce) scintillator serves as the main crystal completely surrounded by the CsI(Tl) scintillator. Due to differences in their pulse shapes, a series of studies have been conducted using pulse shape analysis (PSA) methods. By employing digital charge integration (QDC), the detector' s energy resolutions were obtained: 3.7% for the 662 keV line of ^{137}Cs, 3.1% for the 1173 keV line, and 2.8% for the 1332 keV line of ^{60}Co, after excluding the influence of cascade γ rays. This detector can suppress the Compton continuum by a factor of 2-5 times for ^{137}Cs/^{60}Co based on Fast and Slow Component Ratios (FCR-SCR). Furthermore, nearly all cosmic rays can be rejected by filtering events above 10 MeV in an in-beam spectrum analysis. These results clearly demonstrate that this anti-coincidence shielding γ-ray detector can be used for both low-level radioactivity measurements and high-energy γ-ray measurements.

Keywords: phoswich detector, Compton suppression, anti-coincidence shielding, PSA, FCR-SCR

INTRODUCTION

In nuclear physics experiments, anti-coincidence shielding serves two important functions: Compton suppression and shielding against cosmic rays in high-energy γ-ray measurements. Compton scattering events always appear in energy spectra, reducing the peak-to-total (P/T) ratio of observed low-energy photopeaks and even overwhelming smaller peaks. Particularly in nuclear spectroscopy studies, this reduces detection sensitivity in low-energy regions and affects the accuracy of energy spectrum analysis [1]. Therefore, suppression of the Compton continuum becomes crucial for improving sensitivity in low-energy regions. For example, Compton-suppressed spectrometers composed of a high-energy-resolution Ge detector assisted by scintillation detectors can measure γ spectra with energies below 2 MeV [2–5]. These scintillation detectors are arranged around the Ge detector to capture scattering events, which are then vetoed during data processing, thereby achieving a cleaner energy spectrum to facilitate analysis and research.

Moreover, effective suppression of cosmic ray backgrounds constitutes an essential requirement for specific high-energy γ-ray detection systems. γ rays with energies above 10 MeV are significantly influenced by cosmic rays, as the measurement efficiency for these events is very low. For instance, the study of Giant Dipole Resonance (GDR) using fusion evaporation reactions is of great significance for understanding ground-state deformation of atomic nuclei [6–10]. However, in GDR γ spectrum measurements, the corresponding high-energy γ yield is extremely low, approximately 10^{-3}-10^{-4} of the neutron yield. Consequently, experimental observations are severely affected by cosmic rays, making accurate measurement difficult and sometimes completely swamped by cosmic ray components. In conventional experimental setups, organic scintillator detectors are typically arranged around the main detector (such as NaI(Tl), BGO,

BaF_2, etc.) to veto cosmic ray events, thereby obtaining optimal energy spectra.

However, both traditional measurement systems have complex equipment requirements because each shielding detector needs individual outputs. Furthermore, the placement of shielding detectors is constrained by spatial limitations, preventing full 4π solid angle coverage. Undoubtedly, this causes certain inconvenience for traditional experiments.

Today, hardware requirements for data acquisition (DAQ) have been greatly simplified due to rapid developments in digital signal processing technology [11, 12]. Additionally, some inorganic scintillators with even better resolution have emerged during the same period [13]. These conditions have facilitated the development of detectors toward greater functionality and portability. To simplify complex equipment conditions while still achieving anti-coincidence effects, researchers have developed novel phoswich detectors by combining various inorganic scintillators and analyzing experimental data using pulse shape analysis (PSA) methods [14], such as $LaBr_3$(Ce) + NaI [15], GAGG + CsI(Tl) [16], and CsI(Tl) + BGO [17]. These detectors, aimed at Compton suppression, typically use two inorganic scintillators as the scintillation material, primarily because inorganic scintillators can be manufactured in various shapes and have higher density, making them more effective at capturing Compton scattering events. Among them, the scintillator with better resolution and relatively fast decay time is selected as the main crystal, embedded in a well-typed shielding crystal and sharing a PMT with performance matching the main crystal [18]. Therefore, the analysis is primarily based on events from the main crystal. Additionally, an entrance window can be implemented to improve the efficiency of capturing large-angle Compton scattering events [16]. This combination of scintillation crystals allows for easy realization of 4π coverage of the main crystal by the shielding crystal. Since data processing mainly relies on waveform analysis, the experimental measurement requires only a single signal output connected to the DAQ system, which significantly simplifies the experimental setup and reduces equipment complexity.

This paper presents research on a phoswich detector designed to achieve both Compton suppression and cosmic ray anti-coincidence, utilizing $LaBr_3$(Ce)/CsI(Tl) scintillator combinations. The $LaBr_3$(Ce) scintillator was chosen as the main crystal because of its excellent energy resolution (<3% for 662 keV) and fast decay time (16 ns) [19]. The CsI(Tl) scintillator, serving as the shielding crystal, has a high effective atomic number Z and density, allowing it to effectively capture scattering events. Moreover, its decay time (1000 ns) is much longer than that of $LaBr_3$(Ce), making pulse shape discrimination (PSD) easier [20]. To verify the Compton suppression effect and cosmic ray anti-coincidence capability of the phoswich detector, a series of studies were conducted using pulse analysis methods. The Compton suppression effect in the low-energy region was carefully studied using radioactive sources. Furthermore, an in-beam experiment of the fusion evaporation reaction (52 MeV $^{11}B+^{142}Ce$) was conducted to verify cosmic ray anti-coincidence in the high-energy region.

The paper is organized as follows: Section II presents the principle of the phoswich detector and the design of the $LaBr_3$(Ce)/CsI(Tl) phoswich detector. In Section III, we introduce the experiments and results, including ^{60}Co/^{137}Cs measurements and the in-beam measurement. In Section IV, we discuss the energy resolution of cascade γ rays, Compton suppression capability, and cosmic ray anti-coincidence. A summary is provided in Section V.

II. METHOD AND SETUP

A. Principle of the Phoswich Detector

For an anti-coincidence shielding phoswich detector, the main crystal is typically surrounded by a shielding crystal [15]. The schematic diagram of the phoswich detector is shown in Fig. 1 [Figure 1: see original paper]. The main crystal (blue) is cylindrical, while the shielding crystal is well-typed (yellow). To capture scattering events in 4π space, an entrance window (dark yellow) is also included. Both scintillators share only one PMT that is suitable for the main crystal. Therefore, the analysis results tend to reflect the characteristics of the main crystal. Additionally, the shielding crystal is used either to veto events coincident with the main crystal or as an optical material to transmit fluorescent photons.

The entrance window helps capture back-scattering events. However, the entrance window has a certain absorption effect on γ rays, reducing the peak-to-total ratio of the main crystal and affecting measurement efficiency [21].

Unlike traditional analog circuitry for data acquisition, this phoswich detector requires a digital acquisition system to collect pulses and use PSA methods to distinguish events from the three crystal components [22]. The output pulses can be accurately described by Eq. 1 without considering PMT time fluctuations [23]:

$$V(t) = \begin{cases} -\frac{GNeR}{\tau-\tau_s}\left(e^{-t/\tau_s} - e^{-t/\tau}\right)\cdot t \cdot e^{-t/\tau} & \text{if } \tau \neq \tau_s \\ \text{[alternative form]} & \text{if } \tau = \tau_s \end{cases}$$

Where G, e, and R represent the gain of the PMT, the charge of the electron, and the resistance in the circuit, respectively; N represents the number of photoelectrons emitted by the cathode, proportional to the product of energy and light yield; τ and τ represent the decay time of the scintillator and the output circuit time constant, respectively. Table 1 provides a comparison of various typical inorganic scintillators, including density, maximum emission wavelength λ , and fluorescence decay time [19, 24]. By analyzing the pulses of these common scintillators through calculations, suitable selections can be determined.

Table 1. Properties of commonly used typical inorganic scintillation crystals.

Material	Density (g/cm^3)	Decay time	Light yield (Ph/MeV)
NaI(Tl)			
CsI(Tl)			
$LaBr_3$(Ce)			

The shielding crystal has two important characteristics: 1) The portion located between the main crystal and the PMT window can capture small-angle scattering events. 2) By setting the τ constant to 20 ns and using the same energy condition in calculations, the pulses for different crystals were formulated using Eq. 1 as shown in Fig. 2 [Figure 2: see original paper]. The τ is set short to ensure that the pulse reflects its decay time characteristics in the falling edge, which is beneficial for shape discrimination. From Fig. 2, it is evident that crystals with short decay times and high light yields generate pulses with narrow time width and high amplitude, whereas those with long decay times and low light yields generate pulses with wide time width and low amplitude. The differences in pulse characteristics among various crystals are crucial for realizing pulse shape discrimination (PSD) [25].

Fig. 3 [Figure 3: see original paper] shows the distribution of different scintillators in the FCR-SCR two-dimensional plot. The integral values of T_1, T_2, and T_3 are 120 ns, 240 ns, and 1200 ns, respectively. Under these conditions, integration segment T_1 can almost fully integrate the $LaBr_3$(Ce) pulse, so its FCR and SCR values are close to 1. From Fig. 3, the $LaBr_3$(Ce) scintillator and CsI(Tl) scintillator can be selected as an excellent combination for the phoswich scintillator because of the excellent discrimination between them.

B. Pulse Analysis Method

Since the phoswich detector has two scintillators, its output pulses with different shapes need to be discriminated. One method called Fast and Slow Component Ratios (FCR-SCR) can be used to separate pulses with different falling edges, which is based on the Charge Comparison Method (CCM). Taking Fig. 2 as an example, the pulses are divided into different integration segments by setting different time nodes within the time window. To calculate the fast component ratio (FCR) and slow component ratio (SCR) of each pulse, first determine the starting point, which is before the pulse trigger point. Then integrate over intervals T_1, T_2, and T_3 to obtain the integral values S_1, S_2, and S_3 for each interval, respectively. The intervals are set according to the pulse width of the main crystal. Finally, FCR and SCR can be obtained by the following equations:

$$\mathrm{FCR} = \frac{S_1}{S_2}$$

$$\mathrm{SCR} = \frac{S_2}{S_3}$$

It is worth noting that these equations are modified versions of the formula from [14]. The appropriate choice of integration range can reduce the effect of baseline fluctuations on the integration results in practice. Since there is an inclusion relationship among S_1, S_2, and S_3, the range of both FCR and SCR is 0–1.

C. The $LaBr_3$(Ce)/CsI(Tl) Phoswich Scintillator

The schematic diagram of the $LaBr_3$(Ce)/CsI(Tl) phoswich scintillator is shown in Fig. 4a [Figure 4: see original paper] based on the design concept in Fig. 1. The inner $LaBr_3$(Ce) cylindrical crystal has a height of 5.0 cm and a radius of 1.9 cm. It is embedded in the well-typed CsI(Tl) crystal, which has a height of 7.0 cm (including a 1.0 cm thick top layer) and a radius of 3.8 cm. The optical silicon grease coupling of the EJ550 model is used between crystals to ensure optical transmission between them.

The image of the phoswich detector after encapsulation is shown in Fig. 4b. The selected photomultiplier tube (PMT) model is Hamamatsu' s R6233, with a matching voltage divider model E1198-27. The detector is enclosed in a magnetic shielding case of model E989-15 and provides some shade. The τ (23 ns) of this PMT base is fast, making it suitable for the $LaBr_3$(Ce) scintillator. The outer silver-white aluminum casing also provides some electron absorption.

The prediction of the phoswich detector pulses is shown in Fig. 5a [Figure 5: see original paper]. Among them, $LaBr_3$(Ce), CsI(Tl), and $LaBr_3$(Ce)+CsI(Tl) pulses are represented in red, blue, and red, respectively. The latter is also referred to as the "coincidence pulse." The τ set during the calculation process is 20 ns to match the $LaBr_3$(Ce) decay time. Therefore, the CsI(Tl) pulse is significantly smaller than the $LaBr_3$(Ce) pulse in terms of amplitude. It is also seen that the tail of the coincidence pulse comes from the contribution of CsI(Tl), while the front part is mainly from $LaBr_3$(Ce). In the calculation, the energy of $LaBr_3$(Ce) deposition is set to 1.173 MeV and the energy of CsI(Tl) deposition is set to 1.332 MeV, and the coincidence pulse is the sum of the two (1.173 MeV and 1.332 MeV). The pulses of these two energies from the ^{60}Co measurement are also shown in Fig. 5b [Figure 5: see original paper]. The calculation results agree well with the experimental results except for a certain amount of jitter in the experimental pulses.

III. EXPERIMENTS AND RESULTS

The general-purpose digital data acquisition system (GDDAQ) developed by Peking University is used for data collection in our work [26–28]. This system consists of 16 channels, each operating at a sampling rate of 250 million samples per second (250 MSPS), with incoming pulses digitized at 14-bit resolution. The properties of GDDAQ make it suitable for collecting $LaBr_3$(Ce) pulses. Using FPGA for pulse processing greatly simplifies equipment requirements and improves data acquisition efficiency [29]. For the phoswich detector' s PMT, one end is attached to a positive high voltage, while the other end is connected to a GDDAQ channel. Under the logic control of the FPGA (trigger/filter), the analog pulse is converted by the ADC into a digital pulse that is convenient for storage and analysis. The total time window for each pulse collection is set to 10 µs, with a pulse trigger delay of 2 µs. This setting ensures that the time window is sufficiently long to capture the pulse from the CsI(Tl) crystal (τ = 1000 ns) during each pulse acquisition. Considering noise fluctuations, the baseline is usually set at 10% of the maximum range, rather than at zero. We primarily store the acquired pulses to enable flexible analysis at each measurement stage.

^{60}Co and ^{137}Cs Measurements

The phoswich detector was tested using radioactive sources including ^{60}Co (1.92 µCi) and ^{137}Cs (1.94 µCi) with the voltage set to +850 V. The radiation sources were positioned about 30 cm from the detector' s front surface, with count rates of approximately 600 counts per second (cps) for ^{60}Co and 650 cps for ^{137}Cs.

1. Pulse Shape Discrimination A total of 170k events were accumulated from the ^{137}Cs radioactive source to analyze and discriminate three types of pulses from the phoswich detector. These three types of pulses obtained under the voltage condition are shown in Fig. 6 [Figure 6: see original paper]. To achieve excellent anti-coincidence effects, the integration interval widths for T_1, T_2, and T_3 were set at 120 ns, 240 ns, and 1200 ns in accordance with our calculations. The FCR-SCR two-dimensional plot for ^{137}Cs is clearly presented in Fig. 6. Region 1 and Region 2 represent single events in $LaBr_3$(Ce) and CsI(Tl), respectively. Region 3 shows coincidence events of $LaBr_3$(Ce) and CsI(Tl). The scattered data distribution in other regions primarily consists of two or more pulses detected within the event window due to accidental coincidence. Events in Region 3 closer to Region 1 have shapes more similar to those of $LaBr_3$(Ce) pulses. Conversely, events farther from Region 1 are similar to the shapes of CsI(Tl) pulses. From Fig. 6, we realize that anti-coincidence only requires selecting our desired $LaBr_3$(Ce) events from the total events.

2. Energy Spectra Although the $LaBr_3$(Ce) crystal exhibits relatively high detection efficiency and reasonable energy resolution compared to other typical scintillation crystals, it has internal radiation due to the natural abundance of ^{138}La and ^{227}Ac decay products, which contribute to inevitable background events [30–32]. The background count rate is about 80 cps and its characteristic peaks appear in the energy spectra.

The energy spectra are obtained using QDC. The integration interval width is set to 120 ns, allowing for nearly full integration of the pulses captured by the $LaBr_3$(Ce) scintillator. Using the photopeaks of ^{137}Cs and ^{60}Co gamma sources recorded in $LaBr_3$(Ce), the spectra are energy calibrated and shown in Fig. 7 [Figure 7: see original paper]. Each figure contains four energy spectra: the raw spectrum, the spectrum after Compton suppression, the CsI(Tl)-only spectrum, and the coincidence events spectrum. It can be seen that the CsI(Tl) events are concentrated at the low-energy end and form distinct peaks. Moreover, the characteristic peaks of 1436 keV γ and α emitter contaminants are still present in the raw spectrum. By selecting the intervals where FCR $\geq$ 0.97 and SCR $\geq$ 0.96 from Fig. 6, the spectrum after Compton suppression is obtained.

At a measurement distance of 30 cm, the energy resolutions of this detector are 3.7% for 662 keV, 3.1% for 1173 keV, and 2.8% for 1332 keV, both before and after Compton suppression. However, when the radioactive source is placed 5 cm away from the detector, the ^{60}Co energy spectrum after Compton suppression becomes narrow at the photopeaks, while ^{137}Cs does not exhibit this feature, as shown in the inserted figures of Fig. 7. The energy resolutions are 3.7% for 662 keV, 3.7% for 1173 keV, and 3.2% for 1332 keV before Compton suppression at the 5 cm distance. These results indicate that the energy resolution worsens by 17% and 11% for the ^{60}Co photopeaks, respectively. After Compton suppression, the energy resolutions of the ^{60}Co photopeaks return to normal. As a result, the phoswich detector can maintain excellent energy resolution after Compton suppression.

In-beam Measurement

To benchmark the cosmic anti-coincidence effect in the high-energy γ-ray range of the phoswich detector, we also conducted an in-beam measurement. A fusion evaporation reaction experiment was performed at the China Institute of Atomic Energy, measuring the reaction ^{11}B + ^{142}Ce at E_{beam} = 52 MeV. Our detector was placed at 60 degrees relative to the beam line at a distance of 25 cm from the target. The measurement spectrum focused primarily on γ rays above 10 MeV, corresponding to GDR γ rays. The data acquisition system still used GDDAQ for collection, with the detector voltage adjusted to +600 V to ensure that high-energy pulses could be captured within the dynamic range. In the beam experiment, the overall count rate fluctuated within the range of 3000–4500 cps. Approximately 2.45×10^8 pulses were collected over 23 hours of measurement.

As shown in Fig. 8 [Figure 8: see original paper], the blue energy spectrum represents the in-beam experimental energy spectrum, while the red spectrum corresponds to the blue one after anti-coincidence. Due to low collection efficiency in the high-energy region (>10 MeV), most pulse data are concentrated below 2 MeV, with a difference of 5 to 6 orders of magnitude. Even with broader bin widths, some characteristic peaks can still be observed below 2 MeV, and they become even more distinct after anti-coincidence. We also measured the background spectrum in our laboratory (black curve) for the same duration, and the magenta curve shows the γ-only background spectrum after anti-coincidence. Additionally, we used Geant4 to simulate the muon energy spectrum and the decay of ^{138}La/^{227}Ac in the detector to confirm that the peak in the high-energy region originates from cosmic rays, and the results were well confirmed (green curve).

IV. DISCUSSION

A. Energy Resolution of Cascade γ-rays

In Fig. 7, we measured the energy spectrum with the radioactive source at different distances. We found that the energy resolution of cascade γ rays degrades when the source is close to the detector but improves after Compton suppression. The scatter plots of the SCR-Energy two-dimensional plot help us analyze this phenomenon. As shown in Fig. 9a [Figure 9: see original paper] and Fig. 9b, they provide both energy information on the x-axis and the distribution of different types of events on the y-axis from the experiment. Taking Fig. 9a as an example, we consider $LaBr_3$(Ce)-only events to be distributed in SCR > 0.96, CsI(Tl)-only events as SCR < 0.3, and others as coincidence events. Additionally, line-1 and line-2 represent the 1173 keV and 1332 keV γ rays continuously undergoing multiple Compton scattering in the $LaBr_3$(Ce) crystal and captured by the CsI(Tl) crystal until they are fully deposited in CsI(Tl). The reason why the two trends eventually merge in the CsI(Tl)-only events and cannot be distinguished is that the QDC selection range is not properly adapted for the CsI(Tl) pulses. Line-3 is from the sum peak, so it is inferred that the total energy in the phoswich detector is 2505 keV in Region 1 (two dark dots). This indicates that both crystals simultaneously captured the two cascade γ rays. The pulses in the previous Fig. 5b were also selected from these regions based on Fig. 9a. Fig. 9a also clearly demonstrates the energy deposition characteristics of γ rays entering the phoswich detector: they may be entirely in $LaBr_3$(Ce), entirely in CsI(Tl), or more likely that Compton scattering occurs in one crystal to be captured by the other completely or partially. Since the SCR interval for Compton suppression is selected to be above 0.96, it can be seen that the narrowing of the photopeak after suppression is caused by Region 1 (Fig. 6). However, Fig. 9b shows a very clean distribution compared with Fig. 9a because of the single γ ray of ^{137}Cs.

To better understand the reasons for optimizing energy resolution after Compton suppression, Geant4 simulation is used to help analyze the experimental data because it can output physical information [33, 34]. We obtained the energy deposition results through simulation and converted them to pulses using Eq. 1, which are consistent with the experimental results (Fig. 5). The simulated PSA plots are shown in Fig. 9c and Fig. 9d. Similar to Region 1 in Fig. 9a, this phenomenon suggests that the $LaBr_3$(Ce) crystal captures one γ ray while the CsI(Tl) crystal captures the other. Specifically, when this phoswich detector was exposed to the ^{60}Co radiation source with a strong cascading effect, coincident events at 1173 keV and 1332 keV between the two scintillators were clearly observed. For example, the 1173 keV γ ray was captured by the $LaBr_3$(Ce) scintillator, while the 1332 keV cascade γ ray was captured by the CsI(Tl) scintillator. Thus, they eventually converge on line-3. The energy projection spectrum for ^{60}Co simulation without energy broadening in the inserted figure of Fig. 9c shows one peak appearing after each photopeak. After broadening, such events are swamped by the tail of the photopeak, which worsens the resolution; therefore, the energy resolution is optimized after excluding the influence of cascade γ rays (Section III A 2). However, the QDC integration width is the primary cause of this phenomenon. A wider integration width can partially mitigate the effect of CsI(Tl) events on the $LaBr_3$(Ce) photopeak' s energy resolution, but the ability to distinguish between the two pulses deteriorates. In conclusion, the phoswich detector's energy resolution for cascade γ rays decreases when the radiation source is close. The energy resolution improves when the radioactive source is moved farther away because the probability of capturing both γ rays decreases.

B. Compton Suppression

We present the energy spectra measured using the ^{60}Co and ^{137}Cs sources and extract the spectra of different events using the FCR-SCR method in Fig. 6. After Compton suppression, events in the Compton scattering region are significantly reduced. For the Compton continuum, we defined the energy range as 170–490 keV for 662 keV; 210–963 keV for 1173 keV; and 214–1118 keV for 1332 keV, extending from the back-scattering peak to the Compton edge [35]. The Compton suppression factor can be defined as:

$$\zeta = \frac{I_{us} - I_s}{I_{us}} \times 100\%$$

where   is the suppression factor, I_{us} is the number of counts at energy E in the unsuppressed spectrum, and I_s is the number of counts at energy E in the suppressed spectrum. The higher the value of , the more ideal the suppression effect.

As shown in Fig. 10 [Figure 10: see original paper], to highlight the count variation at the photopeak position, the energy interval selection range is appropriately extended from the Compton continuum to the photopeak. In the Compton continuum, 50 bins are combined into a single data point, and only statistical errors are considered.

From Fig. 10, it can be seen that the value of   is close to 1 at the photopeak positions, indicating almost no loss at the photopeaks (the suppression factors are 1.04 for 662 keV; 1.06 for 1173 keV; 1.02 for 1332 keV). There is a certain suppression effect between the two photopeaks of ^{60}Co, likely due to scattering from the 1436 keV photopeak (Fig. 7). The suppression factor increases significantly in the Compton continuum due to effective suppression. For the photopeak of ^{137}Cs, the suppression in this energy region ranges from 2–5 times. For the two photopeaks of ^{60}Co, the suppression effect of the Compton continuum reaches 2–6 times. Due to the detector's structural design, a 1.0 cm thick CsI(Tl) top layer is added near the radiation source to capture back-scattering events. Therefore, as can also be seen from Fig. 10, a certain degree of suppression is achieved at the Compton edge (corresponding to back-scattering events). The suppression effect in the low-energy part of the Compton continuum is more effective than that in the high-energy part, indicating that small-angle scattering events have higher detection efficiency compared with back-scattering events.

C. Cosmic Rays Anti-coincidence

As shown in Fig. 8, γ rays with energy above 10 MeV are completely buried by cosmic rays and cannot be observed in the in-beam spectrum. As is well known, atmospheric cosmic ray muons constantly pass through the detector, causing energy loss within it, and the incident muons follow a zenith angle distribution from top to bottom [36, 37]. For the phoswich detector, muons entering from top to bottom generate two types of pulses: 1) captured only by the CsI(Tl) crystal; 2) captured by both CsI(Tl) and $LaBr_3$(Ce) crystals. As shown in Fig. 11 [Figure 11: see original paper], in terms of pulse amplitude and width, the muon pulse shows a clear distinction from the γ pulse. Therefore, by using the FCR-SCR method to select $LaBr_3$(Ce)-only events, we can effectively filter out cosmic ray components from the energy spectrum.

The resulting energy spectrum is shown as the red spectrum in Fig. 8 after selecting $LaBr_3$(Ce)-only events. For energies above 10 MeV in the background spectrum, there are about 14,600 events before anti-coincidence, while only 60 events remain after anti-coincidence. This means that almost all cosmic rays can be rejected. Therefore, the suppression effect is also reflected in the in-beam spectrum because of the same measurement time in the high-energy region. Due to the effective anti-coincidence effect on the background spectrum, the in-beam spectrum presents a "bump"above 10 MeV which is characteristic of GDR γ rays after anti-coincidence [38]. This fully demonstrates that, given the structural characteristics, cosmic rays can be eliminated by means of PSA, enabling the study of high-energy γ rays such as GDR γ-ray spectra. In experiments, the CASCADE program, based on statistical model theory, is commonly used to fit observed high-energy γ spectra and extract GDR parameters (resonance energy E; shape width Γ; strength S) [38, 39]. This could be a direction for future research, but it is essential to ensure a sufficient amount of measurement data.

V. SUMMARY

This work introduced a novel anti-coincidence shielding phoswich detector consisting of $LaBr_3$(Ce) and CsI(Tl) scintillators. The $LaBr_3$(Ce) scintillator was selected as the main crystal and the CsI(Tl) scintillator as the shielding crystal, enabling excellent pulse discrimination to achieve anti-coincidence. In the experiment, pulses were collected using GDDAQ, energy spectra were obtained via QDC, and pulse discrimination was performed using the FCR-SCR method. Since the integration width of the selected region is determined by the $LaBr_3$(Ce) pulse width in QDC calculations, CsI(Tl) events are primarily concentrated in the low-energy region of the spectrum in radioactive source measurements. The energy resolution of the detector is 3.7% for the 662 keV line of ^{137}Cs, while achieving 3.1% for 1173 keV and 2.8% for 1332 keV of ^{60}Co after excluding the influence of cascade γ rays. The detector suppresses the Compton continuum of $^{60}Co/^{137}Cs$ by a factor of 2–5 times with almost no loss of the photopeaks. Furthermore, we conducted an experiment focusing on high-energy γ rays (>10 MeV) emitted in the fusion evaporation reaction $^{11}B + ^{142}Ce$ at E_{beam} = 52 MeV to study the shielding effect against cosmic rays. We successfully applied PSD to mitigate the impact of high-energy cosmic rays, and almost all cosmic rays can be rejected by filtering events above 10 MeV. After the anti-coincidence process, the energy spectrum clearly displayed the "bump" feature of GDR γ rays.

This phoswich detector can not only suppress the Compton platform, which is crucial for enhancing measurement sensitivity in low-level radioactivity measurements, but also realize anti-coincidence shielding of cosmic rays in the high-energy range, enabling measurements of high-energy γ rays such as GDR γ rays.

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Note: Figure translations are in progress. See original paper for figures.