

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 LaBr₃(Ce)/CsI(Tl) Phoswich Scintillator

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We have designed an anti-coincidence shielding γ -ray detector based on a $\text{LaBr}_3(\text{Ce})/\text{CsI}(\text{Tl})$ phoswich scintillator for studying Compton suppression and cosmic ray rejection. In this design, the $\text{LaBr}_3(\text{Ce})$ scintillator serves as the main crystal and is completely surrounded by the $\text{CsI}(\text{Tl})$ scintillator. Due to differences in their pulse shapes, we conducted a series of studies using pulse shape analysis (PSA) methods. By employing digital charge integration (QDC), we obtained energy resolutions of 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 $^{137}\text{Cs}/^{60}\text{Co}$ based on Fast and Slow Component Ratios (FCR-SCR). Furthermore, almost all cosmic rays can be rejected by filtering events above 10 MeV in 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. The Compton continuum represents the primary source of noise in energy spectra, reducing the peak-to-total (P/T) ratio of observed low-energy photopeaks and even swamping smaller peaks. This is particularly problematic in nuclear spectroscopy studies, as it reduces detection sensitivity in low-energy regions and compromises the accuracy of spectral analysis [1]. Consequently, suppressing the Compton continuum becomes crucial for improving sensitivity in low-energy regions. For example, Compton-suppressed spectrometers comprising a high-energy-resolution Ge detector assisted by scintillation detectors can measure γ spectra with energies below 2 MeV [2–5]. In these systems, scintillation detectors arranged around the Ge detector capture scattering events, which are then vetoed during data processing to produce cleaner energy spectra for analysis.

Moreover, effective suppression of cosmic ray backgrounds is essential for specific high-energy γ -ray detection systems. γ rays above 10 MeV are significantly affected by cosmic rays because the measurement efficiency for these events is very low. For instance, studying the Giant Dipole Resonance (GDR) through fusion evaporation reactions is important 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} to 10^{-4} of the neutron yield. As a result, experimental observations are severely contaminated by cosmic rays, making accurate measurement difficult and sometimes completely swamping the signal. In conventional experimental setups, organic scintillator detectors are typically arranged around the main detector (such as

NaI(Tl), BGO, BaF₂, etc.) to veto cosmic ray events and obtain optimal energy spectra. However, these traditional measurement systems involve complex equipment, and the placement of shielding detectors is constrained by spatial limitations, creating significant experimental inconvenience. Fortunately, the rapid development of digital acquisition systems has greatly simplified hardware requirements [11, 12], while new inorganic scintillators with improved resolution have emerged [13]. These advances have facilitated the development of more functional and portable detectors.

To simplify complex equipment configurations while maintaining anti-coincidence capability, researchers have developed novel phoswich detectors by combining various inorganic scintillators and analyzing experimental data using pulse shape analysis (PSA) methods [14], such as LaBr₃(Ce) + NaI [15], GAGG + CsI(Tl) [16], and CsI(Tl) + BGO [17]. These Compton-suppression-oriented detectors typically use two inorganic scintillators because they can be manufactured in various shapes and have higher density, making them more effective at capturing Compton scattering events. 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 matched to the main crystal [18]. Analysis therefore focuses primarily 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 paper presents our research on a phoswich detector that achieves both Compton suppression and cosmic ray anti-coincidence using LaBr₃(Ce)/CsI(Tl) scintillator combinations. The LaBr₃(Ce) scintillator was chosen as the main crystal due to its excellent energy resolution (3% for 662 keV) and fast decay time (16 ns) [19]. The CsI(Tl) scintillator serves as the shielding crystal with high effective atomic number and density, enabling effective capture of scattering events. Moreover, its decay time (1000 ns) is much longer than that of LaBr₃(Ce), facilitating pulse shape discrimination (PSD) [20]. We carefully studied the Compton suppression effect in the low-energy region using pulse analysis methods and conducted an in-beam experiment of the fusion evaporation reaction ($52 \text{ MeV } ^{11}\text{B} + ^{142}\text{Ce}$) 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 LaBr₃(Ce)/CsI(Tl) phoswich scintillator. Section III describes the experiments and results, including $^{60}\text{Co}/^{137}\text{Cs}$ measurements and the in-beam measurement. Section IV discusses 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 a single PMT suitable for the main crystal, so the analysis results tend to reflect the characteristics of the main crystal.

The shielding crystal has two important features: (1) the portion between the main crystal and the PMT window captures small-angle scattering events, and (2) the entrance window helps capture back-scattering events. However, the entrance window introduces some absorption of 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 types [22]. The output pulses can be accurately described by Eq. 1 without considering PMT time fluctuations [23]:

$$V(t) = \begin{cases} \frac{-GNeR}{\tau - \tau_s} (e^{-t/\tau_s} - e^{-t/\tau}) & \text{if } \tau \neq \tau_s \\ \frac{GNeR}{\tau^2} \cdot t \cdot e^{-t/\tau} & \text{if } \tau = \tau_s \end{cases}$$

where G , e , and R represent the PMT gain, electron charge, and circuit resistance, respectively; N represents the number of photoelectrons emitted by the cathode, proportional to the product of energy and light yield; τ_s and τ represent the scintillator decay time and output circuit time constant, respectively. Table 1 compares various typical inorganic scintillators, including density, maximum emission wavelength, 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)			

By setting the time constant τ to 20 ns and using the same energy condition in calculations, 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 benefits shape discrimination.

From Fig. 2, it is evident that crystals with short decay times and high light yields generate tall, narrow pulses, whereas those with long decay times and low light yields produce short, wide pulses. These differences in pulse characteristics are crucial for realizing PSD.

B. Pulse Analysis Method

Since the phoswich detector has two scintillators, it outputs pulses of different shapes that must be discriminated. One method called Fast and Slow Component Ratios (FCR-SCR) can separate pulses with different falling edges based on the Charge Comparison Method (CCM). Taking Fig. 2 as an example, pulses are divided into different integration segments by setting 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 before the pulse trigger point. Then integrate over intervals T1, T2, and T3 to obtain integral values S1, S2, and S3, respectively. The intervals are set according to the pulse width of the main crystal. Finally, FCR and SCR are obtained using:

$$\text{FCR} = \frac{S2 - S1}{S3}$$

$$\text{SCR} = \frac{S3 - S2}{S3}$$

It is worth noting that Eq. 3 is a modified version of the formula from [14]. An appropriate choice of integration range can reduce baseline fluctuation effects on integration results in practice. Since there is an inclusion relationship among S1, S2, and S3, both FCR and SCR range from 0 to 1.

Fig. 3 [Figure 3: see original paper] shows the distribution of different scintillators in the FCR-SCR two-dimensional plot. The integral values for T1, T2, and T3 are 120 ns, 240 ns, and 1200 ns, respectively. Under these conditions, integration segment T1 can almost fully integrate the LaBr₃(Ce) pulse, so its FCR and SCR values are near 1. Fig. 3 demonstrates that the LaBr₃(Ce) and CsI(Tl) scintillators can be selected as an excellent combination for the phoswich scintillator due to their excellent discrimination.

C. The LaBr₃(Ce)/CsI(Tl) Phoswich Scintillator

The schematic diagram of the LaBr₃(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 LaBr₃(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. EJ550 optical silicon grease is used between crystals to ensure optical transmission.

The image of the phoswich detector after encapsulation is shown in Fig. 4b. The selected photomultiplier tube (PMT) is Hamamatsu's R6233, with a matching voltage divider model E1198-27. The detector is enclosed in a model E989-15 magnetic shielding case and provides some shading. The time constant τ (23 ns) of this PMT base is fast, making it suitable for the $\text{LaBr}_3(\text{Ce})$ scintillator. The outer silver-white aluminum casing also provides some electron absorption.

Fig. 5a [Figure 5: see original paper] shows the predicted pulses from the phoswich detector. The $\text{LaBr}_3(\text{Ce})$ pulse is represented in black, the $\text{CsI}(\text{Tl})$ pulse in blue, and the $\text{LaBr}_3(\text{Ce})+\text{CsI}(\text{Tl})$ pulse in red. The latter is also referred to as the "coincidence pulse." During calculation, τ was set to 20 ns to match the $\text{LaBr}_3(\text{Ce})$ decay time, so the $\text{CsI}(\text{Tl})$ pulse amplitude is significantly lower than the $\text{LaBr}_3(\text{Ce})$ pulse. The tail of the coincidence pulse comes from $\text{CsI}(\text{Tl})$ contribution, while the front part mainly comes from $\text{LaBr}_3(\text{Ce})$. In the calculation, the energy deposited in $\text{LaBr}_3(\text{Ce})$ was set to 1.173 MeV and in $\text{CsI}(\text{Tl})$ to 1.332 MeV, with the coincidence pulse being the sum of the two. Fig. 5b shows experimental pulses corresponding to the same energy. The calculation results agree well with experimental results, except for some jitter in the experimental pulses.

III. EXPERIMENTS AND RESULTS

The general-purpose digital data acquisition system (GDDAQ) developed by Peking University was used for data collection [25–27]. This system consists of 16 channels, each operating at a sampling rate of 250 million samples per second (MSPS), with incoming pulses digitized at 14-bit resolution. GDDAQ's properties make it suitable for collecting $\text{LaBr}_3(\text{Ce})$ pulses. Using FPGA for pulse processing greatly simplifies equipment requirements and improves data acquisition efficiency [28].

The experimental diagram in Fig. 6 [Figure 6: see original paper] depicts the setup where the detector's two ends are connected—one to positive high voltage and the other to GDDAQ. Under FPGA logic control (trigger/filter), the analog pulse is converted by the ADC into a digital pulse 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 ensures the time window is sufficiently long to capture pulses from the $\text{CsI}(\text{Tl})$ crystal ($\tau = 1000$ ns). Considering noise fluctuations, the baseline is typically set at 10% of the maximum range rather than at zero. We primarily store acquired pulses for flexible later-stage analysis in each measurement.

^{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 source to analyze and discriminate three pulse types from the phoswich detector. The source was placed in front of the detector during measurement. These three pulse types obtained under these voltage conditions are shown in Fig. 5b.

To achieve excellent anti-coincidence effects, the integration interval widths for T1, T2, and T3 were set to 120 ns, 240 ns, and 1200 ns based on our calculations. The FCR-SCR two-dimensional scatter plot for ^{137}Cs is clearly presented in Fig. 7 [Figure 7: see original paper]. Region 1 and Region 2 represent single events in $\text{LaBr}_3(\text{Ce})$ and $\text{CsI}(\text{Tl})$, respectively. Region 3 shows coincidence events of $\text{LaBr}_3(\text{Ce})$ and $\text{CsI}(\text{Tl})$. Scattered data in other regions primarily consist 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 $\text{LaBr}_3(\text{Ce})$ pulses, while events farther from Region 1 resemble $\text{CsI}(\text{Tl})$ pulses. Fig. 7 demonstrates that anti-coincidence simply requires selecting desired $\text{LaBr}_3(\text{Ce})$ -only events from the total events.

2. Energy Spectra Although the $\text{LaBr}_3(\text{Ce})$ crystal exhibits relatively high detection efficiency and reasonable energy resolution compared to other typical scintillation crystals, it has internal radiation from the natural abundance of ^{138}La and ^{227}Ac decay products, contributing to inevitable background events [29-31]. The background count rate is about 80 cps, with characteristic peaks appearing in energy spectra.

Energy spectra were obtained using QDC. The integration interval width was set to 120 ns, allowing nearly full integration of pulses captured by the $\text{LaBr}_3(\text{Ce})$ scintillator. Energy calibration was performed based on $\text{LaBr}_3(\text{Ce})$ channels. The results are shown in Fig. 8 [Figure 8: see original paper]. When the radioactive source is 5 cm from the detector, the energy resolutions are 3.8% for 662 keV, 3.7% for 1173 keV, and 3.2% for 1332 keV before Compton suppression. After Compton suppression, the energy resolutions are 3.8% for 662 keV, 3.1% for 1173 keV, and 2.8% for 1332 keV. These results indicate energy resolution worsening of 17% to 11% in the ^{60}Co spectrum. This phenomenon can only be eliminated by increasing the distance, which will be discussed in Section IV A.

The inserted figures in Fig. 8 show that ^{60}Co exhibits photopeak narrowing after Compton suppression when the source is close to the detector, while ^{137}Cs does not show this feature. The energy resolutions of this detector are 3.7% (662 keV), 3.1% (1173 keV), and 2.8% (1332 keV) before and 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 conducted an in-beam measurement. A fusion evaporation reaction experiment was performed at the China Institute of Atomic Energy, measuring the reaction $^{11}\text{B} + ^{142}\text{Ce}$ at $E_{\text{beam}} = 52$ MeV. Our detector was placed at 60 degrees relative to the beam line, 25 cm from the target within reasonable spatial limits. The measurement focused primarily on γ rays above 10 MeV, corresponding to GDR γ rays. The GDDAQ system was again used for data acquisition, with voltage adjusted to +600 V to ensure high-energy pulses could be captured within the dynamic range.

During the beam experiment, the overall count rate fluctuated between 3000 and 4500 cps. Approximately 2.45×10^8 pulses were collected over 23 hours of measurement. As shown in Fig. 9 [Figure 9: see original paper], the blue energy spectrum represents the raw in-beam spectrum, while the red spectrum shows the result after anti-coincidence. Due to low collection efficiency in the high-energy region (>10 MeV), most pulse data is concentrated below 2 MeV, with a difference of 5 to 6 orders of magnitude. Even with broader bin widths, some characteristic peaks remain visible below 2 MeV and become 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 $^{138}\text{La}/^{227}\text{Ac}$ in the detector, confirming that the peak in the high-energy region originates from cosmic rays (green curve). The simulation above 20 MeV is higher than experimental results because we did not have an ideal setup for realistic environments.

IV. DISCUSSION

A. Energy Resolution of Cascade γ -rays

In Fig. 8, we measured energy spectra with the radioactive source at different distances and found that the energy resolution of cascade γ rays degrades when the source is close to the detector but improves after Compton suppression. SCR-Energy two-dimensional scatter plots help analyze this phenomenon. As shown in Fig. 10a [Figure 10: see original paper] and Fig. 10b, they provide energy information on the x-axis and distribution of different event types on the y-axis. Taking Fig. 10a as an example, $\text{LaBr}_3(\text{Ce})$ -only events are distributed at $\text{SCR} > 0.96$, $\text{CsI}(\text{Tl})$ -only events at $\text{SCR} < 0.3$, and others are coincidence events. Line-1 and Line-2 represent 1173 keV and 1332 keV γ rays undergoing multiple Compton scattering in the $\text{LaBr}_3(\text{Ce})$ crystal and being captured by the $\text{CsI}(\text{Tl})$ crystal until fully deposited in $\text{CsI}(\text{Tl})$. These two trends eventually merge in the $\text{CsI}(\text{Tl})$ -only events and cannot be distinguished because the QDC selection range is not properly adapted for $\text{CsI}(\text{Tl})$ pulses. Line-3 comes from the sum peak, indicating that the total energy in the phoswich detector is 2505

keV in Region 1 (two dark dots). This shows that both crystals simultaneously captured the two cascade γ rays. The pulses in Fig. 5b were also selected from these regions based on Fig. 10a. Fig. 10a clearly demonstrates the energy deposition characteristics of γ rays entering the phoswich detector: they may deposit entirely in $\text{LaBr}_3(\text{Ce})$, entirely in $\text{CsI}(\text{Tl})$, or undergo Compton scattering in one crystal to be captured completely or partially by the other. Since the SCR interval for Compton suppression is selected above 0.96, the photopeak narrowing after suppression is caused by Region 1 (Fig. 7). Fig. 10b shows a much cleaner distribution compared to Fig. 10a because ^{137}Cs emits single γ rays.

To better understand why energy resolution improves after Compton suppression, Geant4 simulation was used to analyze experimental data because it can output physical information [32, 33]. We obtained energy deposition results through simulation and converted them to pulses using Eq. 1, which were consistent with experimental results (Fig. 5). The simulated PSA scatter plots are shown in Fig. 10c and Fig. 10d. Similar to Region 1 in Fig. 10a, this phenomenon suggests that the $\text{LaBr}_3(\text{Ce})$ crystal captures one γ ray while the $\text{CsI}(\text{Tl})$ crystal captures the other. Specifically, when this phoswich detector was exposed to the ^{60}Co source with strong cascading effects, 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 $\text{LaBr}_3(\text{Ce})$ scintillator while the 1332 keV cascade γ ray was captured by the $\text{CsI}(\text{Tl})$ scintillator, eventually converging on Line-3. The energy projection spectrum for ^{60}Co simulation without energy broadening (inserted in Fig. 10c) shows a peak appearing after each photopeak. After broadening, such events are swamped by the photopeak tail, worsening resolution. Therefore, energy resolution improves 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 $\text{CsI}(\text{Tl})$ event effects on the $\text{LaBr}_3(\text{Ce})$ photopeak energy resolution, but pulse discrimination ability deteriorates. In conclusion, the phoswich detector's energy resolution for cascade γ rays decreases when the radiation source is close, but improves when the source is moved farther away because the probability of capturing both γ rays decreases.

B. Compton Suppression

We present energy spectra measured using ^{60}Co and ^{137}Cs sources and extract different event spectra using the FCR-SCR method in Fig. 8. After Compton suppression, events in the Compton continuum are significantly reduced. For the Compton continuum, we defined energy ranges 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 [34]. The Compton suppression factor is defined as:

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

where ζ 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. Higher ζ values indicate better suppression.

As shown in Fig. 11 [Figure 11: see original paper], to highlight count variation at photopeak positions, the energy interval selection range is appropriately extended from the Compton continuum to the photopeak. In the Compton continuum, 50 bins are selected per point, with error bars obtained using error propagation formulas. By selecting LaBr₃(Ce)-only events, we effectively filter out cosmic ray components from the energy spectrum.

Fig. 11 shows that ζ is close to 1 at photopeak positions, indicating almost no loss at photopeaks (suppression factors are 1.04 for 662 keV, 1.06 for 1173 keV, and 1.02 for 1332 keV). There is some suppression effect between the two ⁶⁰Co photopeaks, likely due to scattering from the 1436 keV photopeak (Fig. 10). The suppression factor increases significantly in the Compton continuum due to effective suppression. For the ¹³⁷Cs photopeak, suppression in this energy region ranges from 2 to 5 times. For the two ⁶⁰Co photopeaks, the Compton continuum suppression effect reaches 2–6 times. Due to the detector's structural design with a 1.0 cm thick CsI(Tl) top layer near the radiation source to capture back-scattering events, some suppression effect is also achieved at the Compton edge (corresponding to back-scattering events). The suppression effect is more effective in the low-energy part of the Compton continuum than in the high-energy part, indicating that small-angle scattering events have higher detection efficiency compared to back-scattering events.

C. Cosmic Rays Anti-coincidence

As shown in Fig. 9, γ rays with energy above 10 MeV are completely buried by cosmic rays and cannot be observed in the in-beam spectrum. Atmospheric cosmic ray muons constantly pass through the detector, causing energy loss, and incident muons follow a zenith angle distribution from top to bottom [35, 36]. For the phoswich detector, muons entering from top to bottom generate two pulse types: (1) captured only by the CsI(Tl) crystal, and (2) captured by both CsI(Tl) and LaBr₃(Ce) crystals.

As shown in Fig. 12 [Figure 12: see original paper], muon pulses show clear distinction from γ pulses in both amplitude and width. Therefore, by using the FCR-SCR method to select LaBr₃(Ce)-only events, we can effectively filter out cosmic ray components from the energy spectrum. The resulting energy spectrum after selecting LaBr₃(Ce)-only events is shown as the red spectrum in Fig. 9. 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, meaning almost all cosmic rays can be rejected. This

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 in the background spectrum, the in-beam spectrum shows a “bump” above 10 MeV characteristic of GDR γ rays after anti-coincidence [37]. This fully demonstrates that, given the structural characteristics, cosmic rays can be eliminated through PSA and the detector can be used to study high-energy γ rays such as GDR 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) [37, 38]. This could be a direction for future research, but ensuring sufficient measurement data is essential.

V. SUMMARY

This work introduced a novel anti-coincidence shielding phoswich detector consisting of $\text{LaBr}_3(\text{Ce})$ and $\text{CsI}(\text{Tl})$ scintillators. The $\text{LaBr}_3(\text{Ce})$ scintillator serves as the main crystal and the $\text{CsI}(\text{Tl})$ 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 $\text{LaBr}_3(\text{Ce})$ pulse width in QDC calculations, $\text{CsI}(\text{Tl})$ events are primarily concentrated in the low-energy region of the spectrum in radioactive source measurements. The detector achieves energy resolutions of 3.7% for the 662 keV line of ^{137}Cs , and 3.1% for 1173 keV and 2.8% for 1332 keV of ^{60}Co after excluding cascade γ -ray influence. The detector suppresses the Compton continuums of $^{60}\text{Co}/^{137}\text{Cs}$ by factors of 2–5 with almost no loss at photopeaks. Furthermore, we conducted an experiment focusing on high-energy γ rays (>10 MeV) from the fusion evaporation reaction $^{11}\text{B} + ^{142}\text{Ce}$ at $E_{\text{beam}} = 52$ MeV to study cosmic ray shielding effects. We successfully applied PSD to mitigate high-energy cosmic ray impact, rejecting almost all cosmic rays by filtering events above 10 MeV. After anti-coincidence processing, the energy spectrum clearly displayed the “bump” feature of GDR γ rays.

This phoswich detector not only suppresses the Compton continuum—crucial for enhancing measurement sensitivity in low-level radioactivity measurements—but also realizes anti-coincidence shielding against cosmic rays in the high-energy range, enabling measurement of high-energy γ rays such as GDR γ rays.

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