Performance of real-time neutron_{gamma} discrimination method

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Abstract

Nuclear safety protection typically requires simultaneous detection of neutrons and gamma rays, and the real-time neutron/gamma pulse discrimination capability of detectors is a key performance parameter. In recent years, dual-readout detectors employing Cs2LiLaBr6 (CLLB) crystals have attracted widespread attention. This paper investigates the discrimination performance of charge comparison method, amplitude comparison method, time comparison method, and pulse gradient method, as well as the discrimination effect of Sallen-Key filters. Experimental results demonstrate that with appropriate filtering, the figure of merit (FOM) for all four methods is improved. Among them, the charge comparison method exhibits the best noise immunity and is most suitable for real-time neutron/gamma pulse discrimination in CLLB detectors. Its discrimination performance depends on the parameters, , and . At the moment corresponding to 10% of the pulse peak, , only a delay of 640-740 ns is required. At this moment, corresponding to 3.1-3.3 MeV, the optimal FOM of the charge comparison method is greater than 1.46. The difference between the calculated value of the proposed Maximum Discrimination Difference Model (MDDM) and the optimal FOM is less than 3.9%, indicating that this model can effectively guide parameter selection for the charge comparison method.

Full Text

Performance of Real-Time Neutron/Gamma Discrimination Methods

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Abstract

Nuclear security applications typically require simultaneous detection of neutrons and gamma rays. Recent advances in crystalline materials have drawn considerable attention to $Cs_2LiLaBr_6$ (CLLB) dual-readout detectors, for which real-time neutron/gamma pulse discrimination is the critical performance factor. This study investigated the discrimination performance parameters of CLLB detectors, evaluating the charge comparison, amplitude comparison, time comparison, and pulse gradient methods, along with the effects of Sallen–Key filtering on their performance.

Experimental results demonstrate that proper filtering improves the figure of merit (FOM) for all four methods. Among them, the charge comparison method exhibits excellent noise resistance and proves most suitable for real-time discrimination with CLLB detectors. However, its discrimination performance depends critically on parameter selection. When the parameter t_1 corresponds to the moment at which the pulse reaches 10% of its peak value, the parameter t_3 requires only a 640–740 ns delay relative to t_1 to achieve potentially optimal FOM. Under these conditions, the FOM calculated for the 3.1–3.3 MeV energy range exceeds 1.46. The FOM obtained using the proposed maximized discrimination difference model (MDDM) differs from the potentially optimal FOM by less than 3.9%, indicating that the model can provide effective guidance for parameter selection in the charge comparison method.

Keywords: Charge comparison, Maximized discrimination difference model, Pulse filtering, Real-time, n-γ discrimination

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1 Introduction

Neutron and gamma detection is essential for numerous nuclear security applications, including isotope identification [?, ?], radiation monitoring [?, ?, ?], and fissile material detection [?, ?]. These applications typically require detectors capable of sensing both radiation types while remaining portable and compact. In recent years, the $Cs_2LiLaBr_6$ (CLLB) detector—an elpasolite scintillator—has been developed [?], offering advantages of small size, high light output, and excellent energy resolution. Through pulse shape discrimination, CLLB enables dual radiation detection in handheld instruments [?].

Since the 1960s, researchers have recognized that scintillators produce distinct pulse shapes when interacting with different particles [?], leading to numerous waveform discrimination methods. These techniques fall into three categories: time-domain, frequency-domain, and intelligent methods. Time-domain approaches include charge comparison [?] (CC), time comparison (TC), amplitude comparison (AC), and pulse gradient (PG) methods [?]. Frequency-domain methods comprise frequency gradient [?], wavelet transform [?], and fractal spectrum analysis [?]. Intelligent methods encompass multilayer perceptron [?], support vector machine [?, ?], and deep learning networks [?].

Time-domain methods feature simple calculations but typically yield low FOM values. Frequency-domain methods involve extensive Fourier computations that are complex and difficult to implement in real time, though they offer greater noise immunity than time-domain approaches. Intelligent methods generally achieve the highest FOM but require numerous floating-point matrix operations, resulting in complicated computational processes. Moreover, the discrimination performance of intelligent methods typically depends on training set size and neural network parameter count. With limited computational and storage resources, completing the calculations required by frequency-domain and intelligent methods becomes nearly impossible. Additionally, as waveform sample points increase, the computational complexity of frequency-domain and intelligent methods rarely scales linearly. Consequently, time-domain methods remain preferred for real-time analysis. It is therefore necessary to identify discrimination methods and preprocessing techniques that achieve good FOM with adequate noise immunity while remaining suitable for real-time implementation on modest computational resources.

Zuo et al. [?] explored the discrimination effectiveness of several time-domain methods for plastic scintillator detectors, finding that filtering could enhance discrimination performance. However, the applicability of these findings to CLLB detectors remains unknown. Furthermore, time-domain methods are all sensitive to their parameters, requiring laborious trial-and-error searches to optimize discrimination performance.

To address these challenges, we examine the discrimination effectiveness of the CC, TC, AC, and PG time-domain methods for CLLB detectors, along with the impact of Sallen–Key (SK) filter preprocessing on real-time performance. We propose a novel SK recursive expression based on the second-order Runge–Kutta method to reduce error and validate it experimentally. Results demonstrate that appropriate filtering enhances discrimination performance for all time-domain methods, with the CC method proving most suitable for real-time CLLB analysis. However, CC performance depends on parameter settings. We analyze the effects of CC parameters on discrimination performance and propose a maximized discrimination difference model (MDDM) to guide parameter selection. This approach can be adapted to model parameter settings for other time-domain methods.

The remainder of this paper is organized as follows: Section 2 describes the experimental setup, Section 3 presents the numerical methods, Section 4 discusses discrimination results and the impact of filtering and MDDM, and Section 5 presents conclusions.

2.1 Detector and Radioactive Source

A CLLB crystal detector from Saint-Gobain [?] was used, featuring a 2-inch diameter scintillator crystal sealed in an aluminum housing and directly coupled to a Hamamatsu R6231-100 photomultiplier tube (PMT), as shown in [Figure 1: see original paper]. An ORTEC 556 high-voltage power supply provided 800 V to the detector. A ^{137}Cs gamma source served as the energy calibration source, while a ^{252}Cf source provided the mixed neutron/gamma radiation field.

[Figure 1: see original paper] Neutron/gamma signal discrimination system based on CLLB detector

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2.2 Data Acquisition System

The experiment employed a custom data acquisition system developed by our research group, comprising a PXIe chassis with an embedded controller and electronics card. The main electronics card's signal input connected directly to the CLLB detector. The card primarily consists of analog signal conditioning components, high-speed analog-to-digital converters (ADCs) (14-bit, 500 Msps), a clock jitter cleaner, and a field-programmable gate array (FPGA) (type xc7k325tffg900). The rise time of the CLLB detector's electrical signal is approximately 30 ns. When processed directly by a 500 Msps ADC, the rising edge contains no fewer than 15 sampling points. A signal with a rising edge $ $30 ns corresponds to a frequency spectrum of 16.7 MHz, which is much lower than the waveform digitization module's sampling rate. The hardware of the main electronics card is nearly identical to that used for neutron flux monitoring in the Experimental Advanced Superconducting Tokamak [?], except that the analog signal conditioning component gain is 8 V/V to accommodate the CLLB detector and PMT output signals (<100 mV), and the FPGA code differs. Data processed by the FPGA algorithm are transmitted to the chassis-embedded controller via the PXIe bus in direct memory access mode for display or storage [?].

The FPGA pulse acquisition mode is illustrated in [Figure 2: see original paper], where L_{pulse} represents the total recorded pulse length, L_{base} is the sliding average length for baseline calculation, L_{offset} is the pulse trigger offset determining the baseline calculation starting point, and t_{trig} is the pulse trigger moment. In this experiment, the baseline was defined as the average of sampling points from

48–64 ns before pulse triggering, and the total pulse recording time was 1008 ns.

[Figure 2: see original paper] Pulse recording mode

2.3 Pulse Preprocessing

The detector was first energy-calibrated using the ^{137}Cs gamma source. Pulse waveforms with equivalent gamma energies of 3.1–3.3 MeV (the energy band containing the thermal neutron peak) were then extracted from the ^{252}Cf source data, allowing investigation of neutron/gamma discrimination performance in this energy band. A total of 33,782 waveforms were measured. Pulse width and amplitude analysis removed severely overlapped or truncated waveforms, leaving 33,246 pulse waveforms. Finally, the baseline value was subtracted from each pulse's sampled data.

3.1 SK Filter

In 1955, R.P. Sallen and E.L. Key first proposed the Sallen–Key filter based on discrete components, successfully achieving Gaussian shaping of pulse signals. SK filters are widely used for signal filtering and pulse shaping, outperforming other methods in energy resolution and computational workload [?]. The SK filter is a second-order filter circuit with a simple structure, extensively applied in nuclear signal pulse shaping [?, ?]. [Figure 3: see original paper] shows the SK low-pass filter. When $R_1 = R_2 = R = 3.99\,\mathrm{k\Omega}$ and $C_1 = C_2 = C = 1.5\,\mathrm{pF}$, the corresponding bandwidth is 16.7 MHz.

[Figure 3: see original paper] Schematic diagram of SK low-pass filter

3.2 Real-Time Discrimination Method

The **charge comparison (CC)** method discriminates based on different integration values of neutron and gamma pulse tails, as illustrated in [Figure 4a: see original paper]. The discrimination parameter is calculated using Eq. (1):

$$R_{CC} = \frac{Q_{tail}}{Q_{total}} = \frac{\int_{t_2}^{t_3} V(t)\,dt}{\int_{t_1}^{t_3} V(t)\,dt}$$

where Q_{total} and Q_{tail} are the total and tail integrals, respectively. The integration intervals are determined by parameters t_1, t_2, and t_3, representing the pulse front and tail regions. If the interval is set too large, the difference between neutron and gamma pulse falling portions diminishes, causing R_{CC} to approach 0.

Conversely, if the interval is too small, information from useless pulses increases, causing R_{CC} to approach 1. Therefore, integration intervals must be selected based on the detector's pulse waveform response. In CLLB detectors, neutron pulses exhibit smaller values than gamma pulses because neutrons decay faster than gammas—unlike the typical behavior in liquid scintillators.

The **amplitude comparison (AC)** method, shown in [Figure 4b: see original paper], selects a moment t after the peak for amplitude comparison. The different amplitudes of neutrons and gammas at this moment serve as the discrimination basis, where $V_\gamma(t)$ and $V_n(t)$ represent the gamma and neutron pulse amplitudes, respectively. This method requires calculating only one sampling point but is highly susceptible to noise effects. Consequently, amplitudes were normalized before comparison.

The **time comparison (TC)** method, illustrated in [Figure 4c: see original paper], can be considered the inverse of the AC method. A fixed threshold line is chosen, and the difference in time for neutron and gamma pulses to decay from their peaks to the threshold line serves as the discrimination basis. The parameters t_γ and t_n represent the times from the intersection of the decaying gamma and neutron pulses with the threshold line to the peak.

The **pulse gradient (PG)** method selects peak and post-peak sampling points for gradient calculation, as shown in [Figure 4d: see original paper]. It is expressed in Eq. (2):

$$G = \frac{V_{peak} - V(t_{peak} + \Delta t)}{\Delta t}$$

where G is the pulse gradient, V_{peak} is the pulse peak amplitude, and $V(t_{peak} + \Delta t)$ is the amplitude at a specific time interval after the pulse peak. The parameters t_{peak} and $t_{peak} + \Delta t$ correspond to the moments of the pulse peak and post-peak sampling points, respectively. Similarly, the gradient is susceptible to strong amplitude effects and was calculated using normalized amplitudes.

[Figure 4: see original paper] Schematic diagram of discrimination methods

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3.3 Evaluation Criteria

The figure of merit (FOM) serves as an objective evaluation criterion for discrimination performance, as shown in [Figure 5: see original paper]. The FOM is defined [?] in Eq. (3):

$$\text{FOM} = \frac{S}{FWHM_n + FWHM_\gamma}$$

where $FWHM_n$ and $FWHM_\gamma$ are the half-height widths of the neutron and gamma peaks, respectively, and S is the distance between the neutron and gamma peaks. A larger FOM indicates better neutron/gamma discrimination capability.

[Figure 5: see original paper] Criteria for evaluating neutron/gamma discrimination

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3.4 MDDM

Among the four methods described, only the CC method utilizes all waveform information, providing superior noise immunity. The discrimination performance of the CC method depends on three parameters: t_1, t_2, and t_3. The values t_1 and t_3 typically correspond to the pulse rising edge start and decay end, respectively, while parameter t_2 is the most difficult to determine.

We propose a model that maximizes the discrimination difference to determine parameter t_2 and achieve excellent CC method performance. When neutrons and gamma rays deposit energy in the CLLB detector, the photon pulse generated by the scintillation crystal can be expressed as in Eq. (4):

$$L(t) = \alpha_f e^{-t/\tau_f} + \alpha_s e^{-t/\tau_s}$$

where τ_f and τ_s are the fast and slow decay time constants, respectively, and α_f and α_s represent the proportions of fast and slow components. In the linear region, the pulse output from the CLLB detector can be represented by the convolution of the photon pulse with the PMT and readout electronics response function. However, the final expression still contains the decay time constant factors [?]. Because the pulse rises rapidly, this portion can be approximated by a linear function. Thus, the gamma and neutron pulse responses can be written as in Eqs. (5) and (6), respectively:

$$V_\gamma(t) = \begin{cases} A_\gamma \left(\frac{t-t_0}{t_1-t_0}\right), & t_0 \le t < t_1 \\ A_\gamma \left(\alpha_{\gamma f} e^{-(t-t_1)/\tau_{\gamma f}} + \alpha_{\gamma s} e^{-(t-t_1)/\tau_{\gamma s}}\right), & t \ge t_1 \end{cases}$$

$$V_n(t) = \begin{cases} A_n \left(\frac{t-t_0}{t_1-t_0}\right), & t_0 \le t < t_1 \\ A_n \left(\alpha_{nf} e^{-(t-t_1)/\tau_{nf}} + \alpha_{ns} e^{-(t-t_1)/\tau_{ns}}\right), & t \ge t_1 \end{cases}$$

where $\alpha_{\gamma f}$ and $\alpha_{\gamma s}$ represent the fast and slow components of the pulse response to gamma rays, and α_{nf} and α_{ns} represent the fast and slow components of the neutron response. The response amplitude A is proportional to the deposited energy. In the actual detector impulse response, the pulse first rises and then decays, as shown in [Figure 6: see original paper].

[Figure 6: see original paper] Model of output pulse response of CLLB detector

The rise time to peak is identical for rays of different energies. The moments t_0, t_1, and t_3 represent the pulse start, peak, and complete decay, respectively. The parameter S_n represents the integration area of neutron and gamma pulses from t_0 to t_3. Neutrons and gammas of the same energy can be considered to have identical integration area during the pulse rising phase. The parameter S_{n_tail} represents the neutron pulse integration area from t_2 to t_3. Because the gamma response pulse has a more significant slow component in the decaying portion, S_{g_tail} represents the excess integration area of the gamma pulse compared to the neutron pulse. The R values for gammas and neutrons in the CC method are calculated as in Eqs. (8) and (9), respectively:

$$R_\gamma = \frac{S_{g\_tail}}{S_n}$$

$$R_n = \frac{S_{n\_tail}}{S_n}$$

The difference in R values between neutrons and gammas is strongly correlated with S in Eq. (3). Therefore, the CC method's FOM is expected to be highest when t_2 corresponds to the moment of maximum difference between gammas and neutrons. The difference function is given by Eq. (10):

$$D(t_2) = R_\gamma(t_2) - R_n(t_2) = \frac{S_{g\_tail}(t_2) - S_{n\_tail}(t_2)}{S_n}$$

The moment t_2 at which the difference between gamma and neutron R values is maximized is found by solving Eq. (11):

$$\frac{dD(t_2)}{dt_2} = 0$$

By calculating t_2, the CC method parameters yielding optimal FOM can be obtained.

4.1 Comparison of Methods

The discrimination effectiveness of the time-domain methods discussed above depends on parameter values. To evaluate each method objectively, we first define the parameter domains and then determine the best FOM through trial-and-error as the method's discrimination performance. Let t_{rise} be the time required for the pulse to rise to 10% of its peak value, t_{peak} be the moment of the pulse peak, and t_{end} be 700 ns after t_{peak}. For the CC method, $t_1 = t_{rise}$,

$t_2 \in [t_{peak}, t_{end}]$, and $t_3 = t_{end}$. For the AC method, the comparison moment t satisfies $t \in [t_{rise}, t_{end}]$. For the TC method, the threshold range is taken from 0.1 to 1 peak at intervals of 1% of the peak. For the PG method, the interval parameter Δt is varied within the same range.

The FOM values without filtering are shown in [Figure 7: see original paper]. Only the CC method can distinguish between neutron and gamma pulses at the current noise level, achieving its best FOM when parameter t_2 is set to 212 ns after t_{peak}.

[Figure 7: see original paper] Discrimination performance of different methods without filtering

As shown in [Figure 3: see original paper], the shaping effect of the SK low-pass filter depends on the RC value. With increasing RC, the cutoff frequency decreases, stop-band attenuation increases, and filtering improves. The AC method is strongly affected by noise, which correlates highly with filtering effectiveness. The TC method exhibits low overall FOM and cannot reliably distinguish neutron and gamma signals because the shaped pulse shows large temporal oscillations, making it unsuitable for neutron/gamma discrimination. The PG method is also strongly noise-affected, with its FOM closely correlated with filtering performance. Additionally, the PG method's FOM is similar to that of the AC method because amplitude difference dominates the discrimination calculation in Eq. (3). Consequently, the CC method is the most suitable processing method for real-time neutron/gamma discrimination.

4.2 Effect of MDDM

With the CC method parameters fixed as described in Section 4.1, we define $t_2 = \{t_{peak} + 60 + 20k,\ k = 0, 1, 2, 3, \dots, 28\}$. The FOM of the CC method for these t_2 values is shown in [Figure 8: see original paper]. The FOM curve is convex, indicating that the best FOM can be obtained by treating FOM as a function of the single parameter t_2, thereby confirming the suitability of the MDDM proposed in Section 3.4.

[Figure 8: see original paper] Effect of t_2 on FOM of CC method

Let region A be near t_{peak}, region B be the middle region, and region C be near t_{end}. The slopes in regions A and C are larger, indicating rapid FOM improvement when t_2 is near t_{peak} and rapid FOM decrease when t_2 is near t_{end}. In contrast, region B shows a smaller slope, indicating a slower FOM decrease over a large range. Thus, CC method performance is somewhat independent of the t_3 value.

To solve Eq. (11) for t_2, only the parameters τ_{n_slow}, τ_{g_slow}, α_n, and α_g need to be calculated. These were obtained by fitting neutron/gamma pulse waveforms using Eqs. (5) and (6) through the following procedure:

1. Neutron and gamma pulse signals were separately extracted using the CC method (with parameters achieving the performance shown in [Figure 7: see original paper]), with 2000 pulse waveforms each for neutrons and gammas.
2. The average waveforms of neutron and gamma pulses were calculated and fitted with Eqs. (5) and (6) for neutrons and gammas, respectively, to obtain τ_{n_fast}, τ_{n_slow}, α_n, τ_{g_fast}, τ_{g_slow}, and α_g.
3. The average rise time of the fitted neutron and gamma waveforms was taken as $t_1 - t_0 = 30$ ns, and the average t_1 was obtained as 81.51 ns.
4. By substituting $t_1 = 81.51$ ns into Eqs. (5) and (6), we obtained $\alpha_{g\_slow} = 0.868$, $\alpha_{g\_fast} = 0.132$, $\alpha_{n\_slow} = 0.837$, and $\alpha_{n\_fast} = 0.163$.

These parameters satisfy Eq. (11). For a fixed t_1 value, [Figure 9: see original paper] compares the FOM obtained using t_2 values calculated by the MDDM with the potentially optimal FOM for $t_e = \{t_{rise} + 300 + 20k,\ k = 0, 1, 2, 3, \dots, 30\}$. The potentially optimal FOM versus t_e curve (black dots) remains convex, indicating that t_3 need not cover the entire pulse to achieve optimal CC method discrimination performance, thereby reducing integration computation time.

[Figure 9: see original paper] Comparison of FOM obtained using MDDM and optimized parameters

Experimental tests show that when t_3 is set between 640 and 740 ns after t_{rise}, the potentially optimal FOM exceeds 1.46. Additionally, when t_3 is set in this range, the difference between the FOM obtained using the t_2 value calculated by MDDM and the potentially optimal FOM is less than 3.9%, confirming that MDDM can effectively improve CC method performance.

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5 Conclusion

This work investigated four real-time discrimination methods for CLLB detectors. The FOM for all four methods improved when pulses were properly filtered. The charge comparison method, exhibiting excellent FOM and noise immunity, proved most suitable for real-time discrimination with CLLB detectors. Experimental tests demonstrated that when t_1 in the CC method is set to the moment when the pulse rises to 10% of its peak, t_3 should be within 640–740 ns after t_{rise} to achieve potentially optimal FOM. In this parameter range, the FOM obtained using the t_2 value calculated by MDDM differs from the potentially optimal FOM by less than 3.9%, providing effective guidance for CC method parameter selection. The MDDM analysis concept can be extended to model parameter settings for other time-domain methods and guide parameter selection.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and data analysis were performed by Shi-Xing Liu, Wei Zhang, Zi-Han Zhang, Shuang Lin, Hong-Rui Cao, Cheng-Xin Song, Jin-Long Zhao, and Guo-Qiang Zhong. The first draft was written by Zi-Han Zhang, and all authors commented on previous manuscript versions. All authors read and approved the final manuscript.

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

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