

LANTHANUM BROMIDE DETECTOR ARRAY OF ATOMKI (LABDA)*

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*Received 22 October 2025, accepted 10 December 2025,
published online 31 March 2026*

Recently, a $\text{LaBr}_3(\text{Ce})$ γ -spectrometer called LABDA has been designed and built at the HUN-REN Institute for Nuclear Research, Debrecen, Hungary. To advance the use of the detector system for nuclear physics and nuclear application measurements, the performance parameters were determined. For the suppression of the intrinsic α -background of the detectors caused by the production technology, pulse shape discrimination methods were applied using digital pulse processing. A quantitative study of the different methods confirms that the LABDA detector system is suitable for low-background high-energy γ -ray measurements.

DOI:10.5506/APhysPolBSupp.19.1-A32

1. Introduction

Scintillator crystals are among the most commonly used detectors in γ -ray spectroscopy measurements. Earlier BaF_2 , then NaI , while more recently $\text{LaBr}_3(\text{Ce})$ and GAGG detectors were introduced. These detectors offer good timing properties and high detection efficiency, the latter feature making them suitable for studying low-probability phenomena. Among scintillators, $\text{LaBr}_3(\text{Ce})$ crystals provide the best energy resolution.

During the last five years, a $\text{LaBr}_3(\text{Ce})$ γ -ray spectrometer called LABDA (which means ball in Hungarian) was designed and built at the HUN-REN Institute for Nuclear Research (HUN-REN ATOMKI) primarily for research on the hypothetical $X17$ boson [1]. More recently, the detectors were also employed in other nuclear spectroscopy and nuclear astrophysics experiments. For the LABDA array, 15 cylindrically shaped $\text{LaBr}_3(\text{Ce})$ crystals of

* Presented at the XXXVIII Mazurian Lakes Conference on Physics, Piaski, Poland, August 31–September 6, 2025.

$3'' \times 3''$ were procured from Saint-Gobain. A hemispherical detector geometry was implemented using 12 crystals. To facilitate the use of the LABDA detector system, we have characterized key performance parameters of the array, including energy resolution, energy non-linearity, detection efficiency in a wide γ -energy range, and intrinsic background.

2. Energy resolution, non-linearity, and efficiency of the LABDA system

For the performance measurements, we used the hemispherical setup of 12 $\text{LaBr}_3(\text{Ce})$ detectors, arranged in two concentric rings at angles of 42° and 79° with respect to the beam axis. The target was positioned 20 cm from the detectors. Energy resolution, energy linearity, and efficiency of the array were determined with standard ^{60}Co , ^{152}Eu , ^{137}Cs , ^{133}Ba sources and via $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$, $^{14}\text{N}(p, \gamma)^{15}\text{O}$ direct capture reactions at the Tandatron accelerator of HUN-REN ATOMKI.

With the help of the applied radioactive sources and nuclear reactions, the characteristics of the detector array were determined between γ -ray energies of 0.3–10.7 MeV. The energy resolution of the LABDA array, obtained as an average value of the 12 scintillators, was measured to be 4.8%, 2.4%, and 1.0% at 0.3 MeV, 1.3 MeV, and 10.7 MeV, respectively. Literature reports deviations from linearity in the energy-channel relationship below 100 keV [2] and above 9 MeV [3] γ -ray energy. For the LABDA array, the higher photomultiplier tube voltage (~ -700 V) caused the energy-channel dependence to become non-linear above 5 MeV. At a γ -ray energy of 10.7 MeV, the deviation reached 8%. For the present configuration, the total photo-peak efficiency of the array was determined to be approximately 3.7%, 2.5%, and 0.2% at γ -ray energies of 0.3 MeV, 1.3 MeV, and 10.7 MeV, respectively.

3. Pulse shape discrimination

Due to the manufacturing process of lanthanum bromide detectors, intrinsic radioactive contamination from ^{227}Ac is present in the crystals [4]. This contributes significantly to the intrinsic background of the detector, particularly through α decays above 1.6 MeV. To suppress this background, we investigated different pulse shape discrimination (PSD) techniques already applied for $\text{LaBr}_3(\text{Ce})$ detectors [5, 6]. Due to the larger size of the $3'' \times 3''$ crystals, the differences in pulse shapes of the γ and α events were relatively small, making event discrimination more challenging. Therefore, several PSD methods were evaluated and their performance was compared using experimental data collected from individual detector modules in a low-background setup with lead shielding and paraffin blocks. For these measurements, signals were processed by a CAEN V1730D 14-bit 500 MS/s

desktop digitizer. The advantage of this digitizer is that it provides an adequate sampling rate, while remaining capable of pulse-height analysis via firmware implementing a trapezoidal shaping algorithm (CAEN DPP-PHA). PSD performance typically benefits from higher sampling rates.

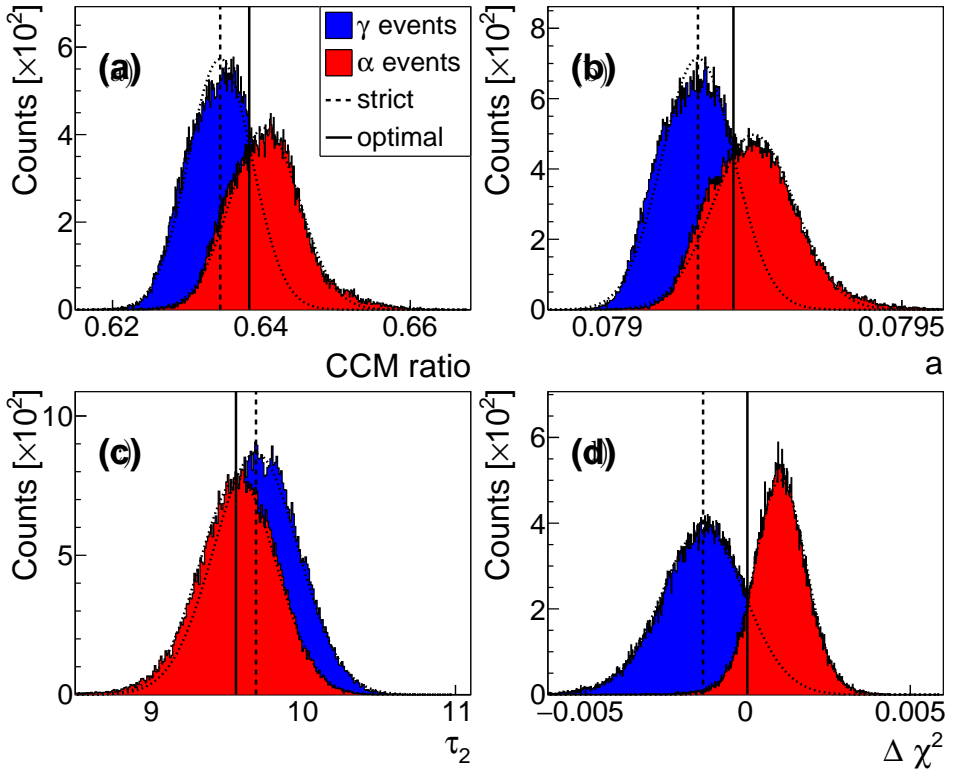


Fig. 1. (Color online) Distributions of parameters used to distinguish between the signal types. From top to bottom, left to right: CCM (a), FEFM (b), F3M (c), and GAMA method (d). The γ and the α distributions are shown in dark gray/blue and in gray/red, respectively; the strict threshold is drawn with a dashed line, and the ‘optimal’ threshold is illustrated with a continuous line.

The obtained γ and α signals showed slight differences in the slopes of both the rising and falling edges. To investigate these subtle shape variations, we examined which parameters derived from the various PSD methods provided the best separation between α and γ events. The resulting parameter distributions were approximately Gaussian, enabling threshold-based discrimination. The discrimination efficiencies were then determined by constructing subtracted spectra using thresholds of varying strictness.

The *Charge Comparison Method (CCM)* characterizes the pulse shape by comparing the signal over two distinct time intervals — typically the total pulse and its tail — to separate the two event types [5]. In our implementation, the inflection points of each signal were used to define these intervals, as the differences between α and γ pulses are most pronounced in this part of the waveform. The resulting ratios form reasonably separated distributions for each event type, as illustrated in Fig. 1(a).

Using an alternative approach called the *Falling Edge Fitting Method (FEFM)*, the falling edge of each pulse was fitted with an exponential function. The a decay constant obtained from the fits was used to separate the α and the γ events. The distributions of the decay constants are shown in Fig. 1(b).

Using the *Full Function Fitting Method (F3M)*, we implemented a modified version of the function proposed in [6] to provide a better fit for the shape of the signals measured by the applied LaBr₃(Ce) detectors

$$\begin{cases} P_n (1 - e^{-t/\tau_1})^k (A e^{-t/\tau_2}) + \text{baseline}, & t \geq 0 \\ \text{baseline}, & t < 0 \end{cases}, \quad (1)$$

where P_n is a normalization factor, and the remaining variables describe the numerical parameters of the pulse. Each pulse was fitted individually, and the resulting parameter distributions were analysed. Among the fit parameters τ_2 provided the clearest separation between the α and γ events, as shown in Fig. 1(c), and was therefore used to define the discrimination thresholds.

In Ref. [5], the *Gamma-Alpha Model Analysis (GAMA)* method was introduced. Applying this method to the measured data set, prototype γ and α signals were created by averaging pulses from regions where each event type is predominantly expected. Unknown pulses were then compared to both prototype signals and the $\Delta\chi^2$ difference of the deviations was determined. The distributions of the difference are presented in Fig. 1(d).

To quantitatively analyse the discrimination efficiency of the applied PSD methods, we determined their Figure of Merit (FoM) [5] and deduced the discarded signal rates by event types. In order to optimize for the subtraction of the α events or the selection of the γ events, a strict threshold and an ‘optimal’ threshold were introduced as shown in panels of Fig. 1. The strict threshold was set at the mean of the Gaussian curve fitted to the γ events, while the ‘optimal’ threshold at the crossover point of the Gaussian curves fitted to the two event types. Then, the subtracted spectra were sorted using different PSD methods and thresholds, and the discarded signal rates were determined for all cases. The values obtained are summarized in Table 1. Evaluating the resulting separation qualities and efficiencies

using both the fraction of event reduction and the FoM values, the GAMA method provided the best results for our setup. The constructed energy spectra using this method are shown in Fig. 2.

Table 1. The efficiency of the event reductions using strict or ‘optimal’ thresholds, as well as the Figure of Merit for the applied PSD methods.

Method	Efficiency				FoM
	Opt. th.		Str. th.		
	η_γ [%]	η_α [%]	η_γ [%]	η_α [%]	
CCM	18.2	66.0	50.6	89.7	0.287
FEFM	16.9	66.3	49.3	90.9	0.310
F3M	32.8	49.4	48.9	67.6	0.096
GAMA	14.1	90.1	51.0	99.4	0.489

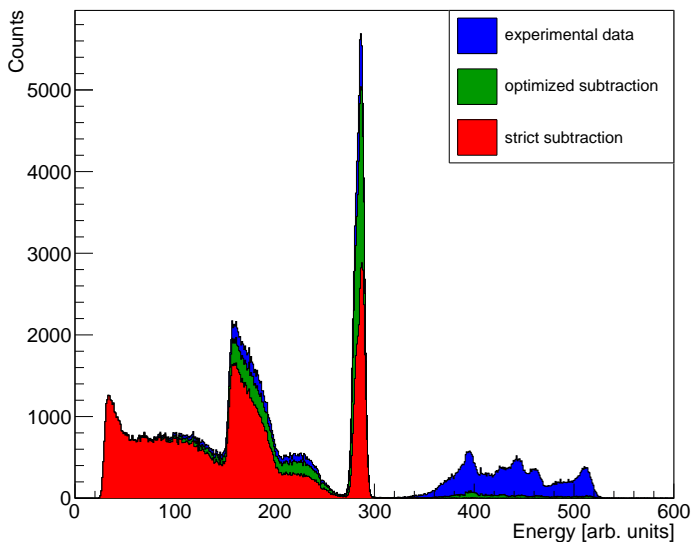


Fig. 2. (Color online) Shielded full (dark gray/blue), optimal-threshold-subtracted (light gray/green), and strict-threshold-subtracted (gray/red) intrinsic and natural background spectra obtained by the GAMA method.

4. Conclusion

In the last five years, a $\text{LaBr}_3(\text{Ce})$ γ -spectrometer called LABDA was designed and built at the HUN-REN Institute for Nuclear Research, Debrecen,

Hungary. The key performance parameters of the setup were determined to facilitate the use of the detector system for nuclear physics and nuclear application measurements.

To reduce the intrinsic α -background of the detectors due to the production technology, different pulse shape discrimination methods were tested. A comparison of the different methods showed that the GAMA method gives the best results for the array and confirmed that the LABDA detector system is suitable for low-background high-energy γ -ray measurements, despite the relatively large $3'' \times 3''$ crystal size.

This work was supported by the HUN-REN Office of Supported Research Groups (project ID: 3510217), by the National Research, Development and Innovation Fund of Hungary (NKFIH) financed by projects with contract No. TKP2021-NKTA-42 and GINOP-2.3.3-15-2016-00034. L.Cs. acknowledges the support of the János Bolyai Reserach Scholarship of the Hungarian Academy of Science. M.B. was supported by the EKÖP-25-3 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

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