Performance Study of a Custom LaBr3 Fast-Timing Detector

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Date: 2023-11-25T00:00:00+00:00

Abstract

In this work, a LaBr3(Ce) detector was customized based on a domestically produced 2 $×$2 LaBr3(Ce) crystal coupled to a Hamamatsu R13089 fast timing response photomultiplier tube. The results indicate that the customized LaBr3(Ce) fast timing detector achieved an energy resolution of 3.6% and a full-energy peak detection efficiency of 0.09% for 662 keV γ-rays, and a timing resolution of 270 (22) ps for the 1173-1332 keV cascade γ-rays from 60Co. The detector' s intrinsic background count rate is 4824 (69) Counts/h/cm3. This paper also presents the test results of Saint-Gobain B380 and B390 detectors for reference.

Full Text

Investigation on the Properties of Customized Fast-Timing $LaBr_3$(Ce) Detector

Vol. 32, No. 3
Nov., 2023
Nuclear Physics Review
Article ID: 1007-4627(2023) 03-0001-06

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Abstract

This work presents a customized $LaBr_3$(Ce) detector based on a domestically produced $ 2"*LaBr{3}(Ce)crystalcoupledwithaHamamatsuR*13089*fast* − *timingphotomultipliertube*(*PMT*)*.ThestudydemonstratesthatthecustomizedLaBr*{3}$(Ce) fast-timing detector achieves an energy resolution of 3.6% and a full-energy-peak detection efficiency of 0.09% for 662 keV γ-rays. The time resolution for the cascade 1173-1332 keV γ-rays from a ^{60}Co source is measured to be 270(22) ps. The detector' s intrinsic radiation count rate is 4824(69) Counts/h/cm^3. For reference, this paper also presents measurement results for Saint-Gobain B380 and B390 detectors.

Keywords: $LaBr_3$(Ce) detector; energy resolution; detection efficiency; time resolution; intrinsic radiation
CLC number: TL812+.1
Document code: A
DOI: 10.11804/NuclPhysRev.32.01.01

Introduction

Lanthanum bromide ($LaBr_3$(Ce)) is a novel inorganic scintillator featuring a hexagonal (UCl_3-type) crystal structure with the $P6_3/m$ space group. This crystal structure facilitates efficient energy conversion and light emission, thereby enhancing its energy and time resolution. The light yield typically reaches 6$×10^{4}$ photons/MeV, equivalent to 160% of standard NaI(Tl) scintillators. At 662 keV (^{137}Cs), $LaBr_3$(Ce) detectors achieve an energy resolution of approximately 3%, surpassing similar scintillation detectors such as NaI(Tl) and BaF_2. With a light output decay time of about 16 ns and an emission spectrum peaking near 380 nm, $LaBr_3$(Ce) offers significant advantages for time measurements. Due to these exceptional properties, $LaBr_3$(Ce) scintillators have been extensively investigated for radiation imaging, detection efficiency, spectroscopic analysis, and intrinsic radiation studies. Their high energy resolution, fast decay time, broad emission spectrum, and stable temperature response make them widely applicable in space physics, environmental monitoring, medical imaging, radionuclide identification, and geological exploration/nuclear well logging. These merits also render them crucial for resolving short-lived excited states, precise nuclear lifetime measurements, and nuclear structure research.

However, $LaBr_3$(Ce) detectors exhibit relatively high intrinsic background radiation, typically one to two orders of magnitude higher than NaI(Tl) detectors. This background originates primarily from two sources: self-irradiation from the naturally occurring radioisotope ^{138}La and contamination from ^{227}Ac impurities along with their five short-lived daughter nuclei. Such background radiation reduces γ-ray detection sensitivity and limits applications in low-background or extremely low-trigger-rate experiments, including space-based γ-ray detection, rare event searches, and construction of high-performance γ-ray detector arrays.

This paper presents a comprehensive study of a customized $LaBr_3$(Ce) detector optimized for high time resolution, focusing on energy resolution, detection efficiency, time resolution, and intrinsic radiation intensity, with Saint-Gobain detectors serving as references.

1. Experimental Measurement

The customized $LaBr_3$(Ce) fast-timing detector consists of a \$ 2"$LaBr\_\{3\}$\$(Ce) crystal produced by the Beijing Glass Research Institute coupled with a Hamamatsu R13089 photomultiplier tube. The PMT employs Hamamatsu' s recommended voltage divider circuit with the anode grounded, optimized voltage ratios for the photocathode and grid, and appropriate RC matching adjustments. These design choices aim to maximize time resolution while maintaining high energy resolution. For comparison, we also measured Saint-Gobain B380 and B390 detectors. The B380 comprises a \$ \$3" crystal coupled with an R10233-100 PMT, while the B390 uses a \$ \$3" crystal with an R6233-100 PMT. All three detector models differ in crystal dimensions and photomultiplier specifications.

summarizes the characteristics of the three PMT models used in these detectors. The R10233-100 and R6233-100 feature high quantum efficiency, which benefits energy resolution, while the R13089 exhibits smaller transit time spread, enabling faster temporal response.

1.1 Energy Resolution After comprehensive consideration of factors including crystal light output and PMT nonlinearity, operating voltages of 700 V and -1200 V were selected for the Saint-Gobain and customized $LaBr_3$(Ce) fast-timing detectors, respectively. Energy spectra were measured using standard γ sources (^{137}Cs, ^{60}Co, ^{22}Na, ^{152}Eu, and ^{133}Ba) covering energies from 31–1408 keV and including sum peaks from cascade radiation. The energy resolution varies with γ-ray energy Eγ according to the approximate functional relationship [26]:

$$\ln(\eta) = -\frac{1}{2}\ln(E_\gamma) + C \quad (1)$$

[Figure 1: see original paper] presents the energy resolution for all three $LaBr_3$(Ce) detector models. The customized $LaBr_3$(Ce) fast-timing detector shows a consistent trend in ln( ) with the Saint-Gobain detectors. For 662 keV γ-rays, the energy resolution is 3.6%, compared to 2.8% (B380) and 2.4% (B390) for the Saint-Gobain models. For 1173 keV γ-rays, the resolution is 2.6% versus 2.2% (B380) and 1.8% (B390). Both PMT gain and quantum efficiency influence the energy resolution.

1.2 Detection Efficiency Curve Detection efficiency is a critical performance metric. We measured the full-energy-peak detection efficiency of the customized $LaBr_3$(Ce) fast-timing detector using standard γ sources positioned 17 cm from the detector surface center. The full-energy-peak efficiency is defined as the ratio of counts in the full-energy peak to the number of γ photons emitted by the source during the measurement period:

$$\varepsilon = \frac{N}{AB_\gamma t} \times 100\%$$

where N is the net count in the full-energy peak, A is the source activity, Bγ is the γ-ray branching ratio, and t is the measurement time.

[Figure 2: see original paper] shows the measured full-energy-peak efficiency curve for the customized $LaBr_3$(Ce) fast-timing detector. The -Eγ relationship is described by a polynomial [7]:

$$\ln \varepsilon = a_0 + a_1 \ln E_\gamma + a_2(\ln E_\gamma)^2 + a_3(\ln E_\gamma)^3$$

The efficiency decreases gradually with increasing γ-ray energy. The detector achieves 0.29% efficiency for 121 keV γ-rays, 2.2 times higher than the 0.09% efficiency at 661 keV. This occurs because higher-energy γ-rays have lower interaction probabilities with the crystal and smaller photoelectric effect cross sections.

1.3 Time Resolution Time resolution was investigated for all three $LaBr_3$(Ce) detector models using coincidence measurements. The detectors were positioned at the vertices of an equilateral triangle with 120° separation angles. A ^{60}Co source was placed at the geometric center, 7 cm from each detector, as shown in [Figure 3: see original paper]. Detector signals were split: one branch fed into a main amplifier (N968) and the other into a constant-fraction discriminator (584). Amplified signals were recorded by an ADC (V785N) for amplitude information, while discriminated timing signals were recorded by a TDC (V1290A). A trigger was generated when any two channels registered coincidence, enabling simultaneous recording of amplitude and timing information.

The measured quantity is the system time resolution ΔT_t, which comprises contributions from the intrinsic time resolutions of two detectors (t_{x1}, t_{x2}) and the electronics resolution (t_s) [27]:

$$\Delta T_t = \sqrt{t_{x1}^2 + t_{x2}^2 + t_s^2}$$

To extract the detector' s intrinsic time resolution t_x, we replaced the $LaBr_3$(Ce) detector signals with a precision pulse generator and repeated the measurement to determine the electronics resolution t_s, which was then subtracted.

[Figure 4: see original paper] displays the two-dimensional coincidence energy spectrum between Saint-Gobain B390 and the customized $LaBr_3$(Ce) fast-timing detector. Events corresponding to the 1173 keV and 1332 keV full-energy peaks were selected in each detector, as indicated by red dashed lines, and used for time resolution analysis. [Figure 5: see original paper] shows the time difference distribution for these selected coincidence events, whose full width at half maximum (FWHM) reflects the system time resolution ΔT_t. Three combinations of detector pairs yielded three system time resolutions ΔT_{ti} (i=1,2,3). Solving the system of equations based on the time resolution formula yields each detector' s intrinsic time resolution t_x. The electronics system resolution t_s was measured to be approximately 60 ps.

The customized $LaBr_3(Ce)$ fast-timing detector demonstrates superior time resolution performance at 270(22) ps, compared to 348(17) ps for Saint-Gobain B380 and 425(14) ps for B390. The R13089 PMT' s fast rise time and small transit time spread [25] produce pulses with faster leading edges. Additionally, the smaller crystal volume reduces photon travel path lengths, decreasing light transport time and thereby improving timing performance. The combination of excellent timing PMT and smaller crystal size enhances the customized detector' s time resolution, enabling more precise temporal measurements.

1.4 Intrinsic Radiation $LaBr_3(Ce)$ detectors exhibit elevated intrinsic background due to ^{138}La self-activity and contamination from ^{227}Ac and its daughters. Intrinsic radiation spectra were measured in a low-background chamber using self-triggering. The lead-shielded chamber effectively suppresses environmental natural radioactivity.

[Figure 6: see original paper] presents the intrinsic radiation spectra for all three detector models, with the vertical axis showing counts per hour per cubic centimeter. The leftmost spectral feature corresponds to the combined response from characteristic X-rays and 5.6 keV Auger electrons emitted during ^{138}La electron capture (EC) decay. This is followed by the β continuum from ^{138}La β^- decay and a continuous spectrum extending rightward from the 788.7 keV peak caused by simultaneous energy deposition of the 788.7 keV γ-ray and β particles. The ^{138}La EC-decay characteristic X-ray combined with the 1435.8 keV γ-ray forms a doublet near 1461 keV [28]. α particles from ^{227}Ac and its daughters create multiple peaks in the 1.6–3.8 MeV region [9]. Strontium doping in the Saint-Gobain B390 crystal reduces the quenching factor for α particles, enhancing heavy ion light output. This shifts α peaks to higher energies compared to B380 and the customized detector, improving discrimination from environmental γ-rays. Similar improvements could be applied to domestic crystals to enhance performance.

Spectral analysis yielded count rates for ^{138}La and ^{227}Ac components in their respective energy regions, summarized in . The ^{138}La and ^{227}Ac count rates for Saint-Gobain B380 and B390 agree with previously reported values [9]. In the 0.02–1.6 MeV range, the customized $LaBr_3(Ce)$ fast-timing detector shows a relatively lower ^{138}La count rate, approximately 91% of that in the Saint-Gobain detectors. In the 1.6–3.8 MeV range, all three detectors exhibit similar α-particle count rates from ^{227}Ac decay, indicating comparable contamination levels. Overall, the customized $LaBr_3(Ce)$ fast-timing detector' s average intrinsic radiation count rate is slightly lower than that of the Saint-Gobain B380 and B390 detectors.

2. Conclusion

We have developed a $LaBr_3$(Ce) detector by coupling a domestic $ 2"$LaBr{3}(Ce)crystalwithaHamamatsuR1
fast-timing detector achieves energy resolutions of 3.6% and 2.6% for 662 keV and 1173 keV γ-rays, respectively. The full-energy-peak detection efficiency for 121 keV γ-rays is 2.2 times higher than for 661 keV γ-rays. The time resolution for ^{60}Co cascade γ-rays is 270(22) ps, attributable to the R13089 PMT’ s fast rise time and small transit time spread. The average intrinsic radiation count rate is 4824(69) Counts/h/cm^3, 6% lower than Saint-Gobain detectors. The ^{138}La count rate is approximately 91% of Saint-Gobain values, while ^{227}Ac and daughter α-particle count rates are consistent within uncertainties.

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