

The Energy Response of LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) Crystals for GECAM

Authors: Pei-Yi Feng, Xi-Lei Sun, Zheng-Hua An, Yong Deng, Cheng-Er Wang, Huang Jiang, Jun-Jie Li, Da-Li Zhang, Xin-Qiao Li, Shao-Lin Xiong, Chao Zheng, Ke Gong, Sheng Yang, Xiao-Jing Liu, Min Gao, Xiang-Yang Wen, Ya-Qing Liu, Yan-Bing Xu, Xiao-Yun Zhao, Jia-Cong Liu, Fan Zhang, Hong Lu, Pei-Yi Feng, Xi-Lei Sun, Zheng-Hua An, Hong Lu

Date: 2023-12-15T00:00:00+00:00

Abstract

The GECAM satellite series employs LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) crystals as scintillator materials for gamma-ray detectors (GRDs). To investigate the nonlinearity in low-energy gamma-ray detection and address calibration errors in the energy-channel (E-C) relationship, comprehensive testing and comparative studies of the three aforementioned crystals were conducted using Compton electrons, radioactive sources, and monoenergetic X-rays. The nonlinearity test results for Compton electrons and X-rays revealed significant discrepancies, with all three crystals exhibiting greater nonlinearity for X/ γ -rays than for Compton electrons. Despite the LaBr₃(Ce) and LaBr₃(Ce,Sr) crystals possessing higher absolute light yields, they displayed a pronounced nonlinear decrease in light yield, particularly at energies below 400 keV. The NaI(Tl) crystal demonstrated an “excess” light output in the 6–200 keV range, reaching a maximum “excess” of 9.2% at 30 keV in X-ray testing and up to 15.5% at 14 keV during Compton electron testing, indicating a significant advantage in low-energy gamma-ray detection. Furthermore, we explored the underlying mechanisms responsible for the observed nonlinearity in these crystals. This study not only elucidates the detector response characteristics of GECAM, but also initiates a comprehensive investigation into the nonlinearity of domestically produced lanthanum bromide and sodium iodide crystals.

Full Text

The Energy Response of LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) Crystals for GECAM

Pei-Yi Feng,^{1,2,3,†} Xi-Lei Sun,^{4,5,‡} Zheng-Hua An,^{1,2,§} Yong Deng,⁶ Cheng-Er Wang,⁷ Huang Jiang,⁵ Jun-Jie Li,⁶ Da-Li Zhang,² Xin-Qiao Li,² Shao-Lin Xiong,² Chao Zheng,^{2,3} Ke Gong,² Sheng Yang,² Xiao-Jing Liu,² Min Gao,² Xiang-Yang Wen,² Ya-Qing Liu,² Yan-Bing Xu,² Xiao-Yun Zhao,² Jia-Cong Liu,^{2,3} Fan Zhang,² and Hong Lu^{1,2,¶}

¹Particle and Astrophysics Center, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

²Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

³University of Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing 100049, China

⁴Experimental Physics Center, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

⁵State Key Laboratory of Particle Detection and Electronics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

⁶School of Nuclear Science and Technology, University of South China, Hengyang 421001, China

⁷National Engineering Research Center for Rare Earth, Grirem Advanced Materials Co., Ltd. and General Research Institute for Nonferrous Metals, Beijing 100088, China

The GECAM series of satellites utilizes LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) crystals as sensitive materials for gamma-ray detectors (GRDs). To investigate the non-linearity in the detection of low-energy gamma rays and address errors in the calibration of the energy-channel relationship, comprehensive tests and comparative studies of these three crystals were conducted using Compton electrons, radioactive sources, and mono-energetic X-rays. The non-linearity test results demonstrated substantial differences between Compton electrons and X/ γ -rays, with all three crystals exhibiting higher non-linearity for X/ γ -rays than for Compton electrons. Despite their higher absolute light yields, the LaBr₃(Ce) and LaBr₃(Ce,Sr) crystals showed a noticeable non-linear decrease in light yield, especially below 400 keV. The NaI(Tl) crystal demonstrated an “excess” light output in the 6–200 keV range, reaching a maximum “excess” of 9.2% at 30 keV in X-ray testing and up to 15.5% at 14 keV during Compton electron testing, indicating a significant advantage in low-energy gamma-ray detection. Furthermore, we explored the underlying causes of the observed non-linearity. This study not only elucidates the detector responses of GECAM but also initiates a comprehensive investigation of the non-linearity of domestically produced lanthanum bromide and sodium iodide crystals.

Keywords: LaBr₃(Ce) detector, LaBr₃(Ce,Sr) detector, NaI(Tl) detector, GECAM, Energy Response, Light Yield Non-linearity

INTRODUCTION

Recent groundbreaking advancements in various branches of astrophysics, such as gravitational waves, fast radio bursts, and cosmic rays, have ushered in a new “multi-messenger, multi-wavelength” era in astronomy [?, ?, ?, ?, ?]. These discoveries emphasize the importance of efficient detection methods for understanding high-energy astronomical phenomena. Transient gamma-ray sources, including gamma-ray bursts and magnetar flares, play a vital role in astronomical studies [?, ?, ?, ?, ?, ?].

The Gravitational wave burst high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) series, comprising satellites GECAM-A/B, GECAM-C, and GECAM-D, was developed to monitor various high-energy electromagnetic events such as gamma-ray bursts and magnetar flares [?, ?, ?, ?, ?]. These satellites employ gamma-ray detectors (GRDs) that utilize different scintillating crystals: LaBr₃(Ce) and LaBr₃(Ce,Sr) for GECAM-A/B, a combination of LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) to validate new detector technologies for GECAM-C, and NaI(Tl) crystals for GECAM-D, which is scheduled for launch in early 2024. The main characteristics of the GRDs are listed in Table 1 .

GRDs serve as the primary detectors in the GECAM payload, with GECAM-A/B utilizing an innovative solution that employs LaBr₃ crystals coupled with silicon photomultiplier (SiPM) readout technology (Fig. 1 [Figure 1: see original paper]) [?, ?, ?, ?]. LaBr₃ crystals are advanced inorganic scintillators known for their high light output, excellent energy and timing resolution, good energy linearity, and short decay times. The SiPM, which replaces conventional photomultiplier tubes (PMTs), offers advantages such as a simple and compact structure, ease of miniaturization, and efficient readout capability.

For GECAM-C (Fig. 2 [Figure 2: see original paper]), the GRDs employ both NaI(Tl) and LaBr₃ crystals coupled to SiPM readout arrays [?, ?]. The NaI(Tl) crystal is a high-performance traditional inorganic scintillator with excellent luminescence properties that provide good resolution for both X-rays and gamma rays. Inorganic scintillators are widely preferred for high-energy X/ γ -ray detectors in space applications due to their versatility in shaping and sizing, stability, reliability, reasonable cost, inclusion of heavy elements, high density, and efficient detection capabilities.

The crystals used in the GECAM satellite series were obtained from the Beijing Glass Research Institute. To optimize detector performance, we conducted an in-depth study involving X-ray, Compton electron, and gamma-ray tests on the LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) crystals used in these satellites [?, ?, ?]. Our findings indicate that the non-linearity of the three crystals varied when exposed to different excitation sources. The LaBr₃(Ce,Sr) crystal exhibited the strongest linear response to Compton electrons in the low-energy range, whereas the NaI(Tl) crystal demonstrated the best linear response to X-rays.

Consistent with previous studies on iodide crystal non-linearity [?, ?], domes-

tically produced NaI(Tl) crystals exhibited a light yield “excess” phenomenon, indicating unexpected advantages in low-energy gamma-ray detection. These insights not only contribute to a better understanding of the detector response of the GECAM series but also provide invaluable information for evaluating the performance of these domestically produced scintillating crystals in the 3–400 keV low-energy range [?]. Manufacturers can refer to this study to enhance their understanding of crystal non-linearity, potentially facilitating optimization and improvement of crystal growth processes and doping ratios. Furthermore, this study addresses the issue of non-linearity in crystals for low-energy gamma-ray detection, which is highly significant for correcting errors in detector calibration related to the energy-channel relationship. Based on these results, we will further investigate the intrinsic resolution of crystals in future studies.

II. EXPERIMENTAL SETUP AND TEST PROCEDURE

A. The Wide-Angle Compton Coincidence Technology

Figure 3 [Figure 3: see original paper] presents the wide-angle Compton coincidence (WACC) experimental setup, which primarily comprises a radioactive source, a high-purity germanium (HPGe) detector, the scintillation detector under examination, and a data acquisition system [?, ?, ?, ?, ?, ?]. LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) cylindrical samples with diameters of 25.4 mm were selected for this study. Silicone oil was used to couple the encapsulated crystals to PMTs (R6233-100, Hamamatsu Photonics, Japan) [?, ?]. According to the user manual of the BE2020 planar germanium spectrometer manufactured by Canberra, the HPGe crystal had a thickness of 20 mm and a volume of 40,000 mm³, enabling an energy detection range of 3 keV–3 MeV [?, ?]. Based on experimental data, the energy resolutions, indicated by the full width at half maximum (FWHM), of the HPGe detector were determined to be 1.58 keV (for ⁶⁰Co at 1.33 MeV) and 1.15 keV (for ¹³⁷Cs at 662 keV).

The experiment involved placing a ¹³⁷Cs radioactive source at a quarter-circle position around the center of the crystal, with a distance of 13 cm between them. Gamma photons emitted by the source underwent Compton scattering upon striking the crystal, generating Compton electrons that were absorbed by the crystal while certain scattered photons escaped and were absorbed by the nearby HPGe detector. The distance between the tested crystal and HPGe detector was maintained at approximately 15 cm [?]. Lead blocks were positioned between the ¹³⁷Cs source and HPGe detector to provide shielding and minimize direct irradiation of the HPGe detector by primary gamma photons. Coincidence events across a broad energy range were obtained by adjusting the source position and varying the angle between the source, crystal, and HPGe detector.

As indicated by the Compton scattering formula (Equation 1) [?], as the incident angle () of the gamma photon increased, the energy of the Compton electrons in the crystal also increased:

$$E_e = E_\gamma - \frac{E_\gamma}{1 + \frac{m_{ec}^2}{E_\gamma(1-\cos\theta)}}$$

where E_γ is the energy of the gamma ray from the source, E_e is the energy of the Compton electron, E'_γ is the energy of the scattered photon, θ is the Compton scattering angle, and m_{ec}^2 is the electron rest mass energy. Five scattering angles were selected during the experiment to obtain data over a broad energy range.

A desktop waveform acquisition device with 10-bit resolution at 2 GS/s (interleaved) or 1 GS/s, the DT5751 digitizer [?], was utilized to collect signals from the crystal and HPGe detectors (Fig. 4 [Figure 4: see original paper]). The HPGe detector signal, operating at +3500 V, underwent shaping and filtering using an ORTEC 572A amplifier before being sent to channel 0 of the DT5751. The output signal from the PMT anode, operating at +1300 V, was routed to channel 1 of DT5751 after photoelectron multiplication by the dynodes [?].

The signals from both detectors successively underwent low-threshold discrimination, delayed stretching, and logical coincidence. The resulting coincidence output signal served as an external trigger for the DT5751, which recorded the corresponding coincidence events and generated two data files when triggered externally. The secondary particles produced by Compton scattering were absorbed by the two detectors in a specific temporal sequence. For a “true coincidence event,” the waveform signal from the crystal appeared before that from the HPGe detector.

Figure 5 presents the coincidence matrix representing all collected events. In Fig. 5(a), the horizontal axis represents energy deposited in the HPGe detector, while the vertical axis corresponds to energy deposited in the crystal. The diagonal points demonstrate the “true coincidence events” of interest, with each point corresponding to a specific scattering angle where the combined deposited energies in both detectors remain constant at 661.6 keV. The uneven “spread” along the diagonal at different energy levels is due to the diverse energy resolutions of the crystal for Compton electrons, while the non-linear response of the crystal determines the “linearity” of the diagonal. Analysis of the coincidence matrix enabled extraction of the energy resolution and non-linear response of the crystal to Compton electrons.

The horizontal and vertical lines in Figure 5 indicate accidental coincidence events simultaneously detected by both detectors. The horizontal line represents the finite resolution of the crystal, while the vertical line represents the excellent resolution of the HPGe detector. Other points on the graph denote events where only partial energy was deposited in the detector or where detection occurred after scattering through surrounding materials.

The WACC method accurately measures the energy response and resolution of crystal detectors to Compton electrons. Before the Compton experiments, it was necessary to calibrate the energy-channel relationship of the HPGe detector,

which can be obtained from energy spectra of multiple radioactive sources or directly using the vertical lines in the coincidence matrix. The HPGe detector offers outstanding energy resolution, making it an excellent standard detector. The energy deposited in the crystal was calculated by subtracting the scattered photon energy in the HPGe detector from the known gamma-ray source energy. In actual data processing, the cut width of the HPGe energy axis must be determined based on Compton scattering event statistics. Within this range, the central value is considered the energy deposited in the HPGe detector, and Equation 2 is used to calculate the energy deposited in the crystal:

$$\langle E_{scin} \rangle = E_{\gamma} - \langle E_{HPGe} \rangle$$

where E_{γ} is the known gamma-ray source energy, $\langle E_{HPGe} \rangle$ is the deposited energy in the HPGe detector, and $\langle E_{scin} \rangle$ is the deposited energy in the crystal.

To understand the effect of cut width or energy window width, we measured the energy resolution of the LaBr3(Ce,Sr) crystal for 46.6 keV Compton electrons at different cut widths. The results indicated that energy resolution remained reasonably stable until a cut width of 4 keV was reached (Fig. 6 [Figure 6: see original paper]). Wider cut widths led to a broadened scattering angle range for relevant valid events and increased FWHM of the Compton electron spectrum, subsequently degrading resolution. The energy resolution of the HPGe detector was within 1–2 keV, which must be considered when determining a reasonable cut width while ensuring sufficient event statistics. Therefore, a cutoff width of 4 keV was used when the energy deposited in the HPGe detector was less than 615 keV, and a cutoff width of 2 keV was selected when the deposited energy was in the 615–661.6 keV range.

Multiple truncations of the HPGe energy axis were performed to obtain crystal spectra for various Compton electron energies. Figure 7 [Figure 7: see original paper] illustrates this approach, where a data range of events from 614 to 616 keV was considered at an HPGe energy of 615 keV with a 2 keV cut width to produce the Compton electron spectrum (Fig. 7(b)). A Gaussian-shaped single-energy electron peak was visible and fitted with a Gaussian function, yielding an energy resolution of $15.81 \pm 0.25\%$ for 46.6 keV Compton electrons in the LaBr3(Ce,Sr) crystal.

Atoms or molecules become excited when incident particles deposit energy in a crystal, leading to emission of scintillation photons with wavelengths similar to visible light [?]. The light yield, defined as the number of scintillation photons per unit energy deposited in the crystal, is described by Equation 3:

$$S = \frac{ADC}{E \cdot ADC_{spe}}$$

where S is the light yield of the crystal, ADC represents the peak position of the spectrum after baseline subtraction, E is the deposited energy in the crystal,

and $ADC_{spe} = 8.0321$ channels denotes the single-photoelectron response of the Hamamatsu R6233-100 PMT at a high voltage of +1300 V. This response was calibrated using the LED-triggered charge method [?, ?].

B. Measurements with Radioactive Sources

Radioactive sources of ^{133}Ba , ^{137}Cs , ^{241}Am , ^{152}Eu , and ^{207}Bi were employed across a γ -ray energy range of 30.85 keV to 1063.7 keV to investigate gamma-ray responses. The tested crystal was coupled to a Hamamatsu R6233-100 PMT via silicone oil, and the DT5751 digitizer acquired signal waveforms in self-triggering mode. ROOT, a data analysis framework developed by CERN [?], was used to analyze experimental data, including baseline subtraction, fitting of the full-energy peak, and analysis of peak position and FWHM.

C. Single-Energy X-ray Measurements Using the Hard X-ray Calibration Facility

We employed two sets of hard X-ray calibration facilities (HXCF, Fig. 8 [Figure 8: see original paper]) established by the National Institute of Metrology (NIM) in Beijing Changping, China [?, ?, ?] to investigate the energy responses of the three crystals to X-rays in the 8–120 keV range. The HXCF, which plays a substantial role in calibrating gamma-ray detectors on GECAM, CubeSats, and SVOM satellites [?, ?, ?], was originally built for the high-energy telescope of HXMT as a calibration facility [?] and comprises four primary components: an X-ray generator, monochromator, collimator, and standard detector. To shield stray light from the X-ray generator, the collimator features apertures of various sizes at the entrance and exit. A low-energy HPGe detector (Canberra Industries) served as the standard. Before testing, we calibrated the HPGe detector for energy linearity, resolution, and detection efficiency using various standard radioactive sources [?].

The entire testing equipment, including the data acquisition system, was placed inside an X-ray testing chamber (Fig. 9 [Figure 9: see original paper]) and remotely controlled from a control room. The energy and flux of the X-rays were determined using an HPGe detector. The testing procedures are shown in Fig. 10 [Figure 10: see original paper]. We used GENIE 2000 spectroscopic data acquisition and analysis software to record spectral data from the HPGe detector. The crystal detector was coupled to a PMT (Hamamatsu Model CR160) using silicone oil. Signals from the crystal detector were collected using a digitizer (DT5751) and analyzed with computer software to obtain corresponding spectra.

The X-ray testing range was 8–120 keV in this study, with fine measurements of the crystal absorption edge at a step size of 0.1 keV. The performance of the crystal detector gradually changed as X-ray energy increased, allowing for a reduced number of test energy points. Due to testing at room temperature (22–23 °C), detector noise was slightly higher, limiting the starting test energy

points to the 8–10 keV range. For the two LaBr3 crystals, the coupled PMTs operated at -800 V, whereas the NaI(Tl) crystal PMT operated at -1000 V.

III. RESULTS AND DISCUSSION

A. Light Yield Non-linearity to Compton Electrons

The light yields of the LaBr3(Ce), LaBr3(Ce,Sr), and NaI(Tl) crystals were normalized to “1” at 662 keV. Figure 11 [Figure 11: see original paper] demonstrates the non-linearity of light output for the three crystals in response to Compton electrons within the 3–400 keV energy range. To better quantify crystal non-linearity, we introduced a metric called the non-linearity standard deviation (NLSD), defined by Equation 4, where x_i represents the relative light yield at each energy point:

$$NLSD = \sqrt{\sum (x_i - 1)^2} \quad (n = 1, 2, 3\dots)$$

The NLSD values for LaBr3(Ce), LaBr3(Ce,Sr), and NaI(Tl) crystals were 0.11, 0.03, and 0.06, respectively, with larger NLSD values indicating more significant non-linearity.

For both LaBr3 crystal types, light yield non-linearity gradually increased as Compton electron energy decreased. Within the measured electron energy range, the LaBr3(Ce,Sr) crystal exhibited better linearity than LaBr3(Ce), particularly below 20 keV. We hypothesize that Sr²⁺ doping may improve the internal energy transfer mechanism within the LaBr3(Ce,Sr) crystal, enhancing energy transfer efficiency in the low-energy region and thereby ameliorating non-linearity. Both crystals exhibited a 10% “defect” in light output at approximately 5 keV and 20 keV, respectively. The minimum measurable energy using WACC was 3.1 keV, at which the LaBr3(Ce,Sr) crystal showed a “defect” of approximately 24%, whereas LaBr3(Ce) exhibited 35%. This experiment validated simulation results presented by Chao et al. [?], confirming the non-linearity of electrons and affirming the accuracy and rationality of both the model and experimental work conducted by the GECAM research team.

In contrast to the two LaBr3 crystals, the NaI(Tl) crystal did not exhibit monotonic “defect” luminescence as Compton electron energy decreased. At approximately 14 keV, the NaI(Tl) crystal reached its maximum light yield, showing an “excess” light output of approximately 15.5%. Beyond 14 keV, light yield gradually decreased with increasing energy, while below 14 keV, light yield also decreased. The lowest test energy point was 4.1 keV, at which the NaI(Tl) crystal demonstrated a luminosity non-linearity “defect” of approximately 14%.

B. The Absolute Light Yield of Crystals

The three crystals were irradiated with multiple radioactive sources to obtain energy spectra for each crystal. The single-photoelectron responses of the Hama-

matsu R6233-100 PMT used in the measurements were calibrated using the LED-triggered charge method at various voltages, enabling calculation of the absolute light yields. The absolute light yields and energy resolutions of the samples at 661.6 keV are listed in Table 2.

Table 2. The absolute light yield and energy resolution of crystals for 661.6 keV gamma rays.

Crystal Type	Size	Light Yield (ph/MeV)	Energy Resolution (%)
LaBr3(Ce)	1"×1"	3.00 ± 0.02	7.18 ± 0.07
LaBr3(Ce, Sr)	1"×1"	3.03 ± 0.01	—
NaI(Tl)	1"×1"	—	—

C. Energy Resolution

Figure 12 [Figure 12: see original paper] illustrates the energy resolution of LaBr3(Ce), LaBr3(Ce,Sr), and NaI(Tl) crystals for Compton electrons in the 3–400 keV range. The energy resolution of NaI(Tl) was comparable to that of the LaBr3 crystals at 16–30 keV. The energy resolution of the crystals was expressed using the FWHM of the X-ray full-energy peak. Figure 13 [Figure 13: see original paper] presents the energy resolution of LaBr3(Ce,Sr), LaBr3(Ce), and NaI(Tl) crystals for X-rays in the 8–100 keV range, as measured by HXCF. The LaBr3(Ce,Sr) crystal exhibited the best energy resolution within this range. At 100 keV, the resolution of LaBr3(Ce,Sr) was $8.74 \pm 0.0681\%$, while those of LaBr3(Ce) and NaI(Tl) were $9.41 \pm 0.0976\%$ and $10.39 \pm 0.1168\%$, respectively. Furthermore, a slight degradation in energy resolution of less than 1% was observed near the K-shell electron binding energies.

D. Comparison of X/γ-Ray and Compton Electron Responses

All data in this study were standardized using the full-energy peak response of 662 keV gamma rays from a ^{137}Cs source as the normalization factor. Figure 14 [Figure 14: see original paper] shows the non-linearity of LaBr3(Ce,Sr) crystal light yield for Compton electrons and gamma rays in the 3–1000 keV range. Notably, the response to Compton electrons exhibited excellent linearity at approximately 70 keV, with non-linearity less than 2%. However, a “deficiency” in light output occurred when Compton electron energy fell below 70 keV, whereas substantial non-linearity was observed in the gamma-ray response below approximately 200 keV.

A more detailed test of the photon response below 120 keV was conducted using HXCF. Figure 14 presents the non-linear light yield response curve of the LaBr3(Ce,Sr) crystal to X-rays in the 8–120 keV range. Because the error bars are similar in size to the data point symbols, they are not visible in the figure. Ideally, the relative light yield should be “1” at all energy points; however, varying degrees of light-yield deficiencies were observed. Below 40 keV, the LaBr3(Ce,Sr) crystal exhibited substantial non-linearity in relative light yield

response to X-rays, with non-linearity exceeding 10%. As energy decreased, the curve slope increased, reaching 36% non-linearity at 8 keV. When X-ray energy exceeded 40 keV, the non-linear curve approached the ideal state with a milder slope, indicating small fluctuations in the number of photons generated per unit energy absorbed by the LaBr3(Ce,Sr) crystal in the 40–120 keV range. The LaBr3(Ce,Sr) crystal exhibited absorption edges at 13–15 keV and 38–40 keV, with slight reductions in relative light yield observed within these intervals.

The NLSD values for LaBr3(Ce,Sr) crystal testing with X-rays and Compton electrons were 0.17 and 0.03, respectively, indicating greater non-linearity in response to X-rays than to Compton electrons. This can be attributed to different interaction mechanisms between these particles and atoms in matter. For X/ γ -rays ranging from a few keV to several hundred keV, two interaction processes are possible with the crystal: (1) a direct photoelectric cascade sequence or (2) Compton scattering followed by a photoelectric cascade sequence. These processes generate several primary electrons (e.g., Compton electrons and primary photoelectrons) and multiple secondary electrons (e.g., Auger electrons and secondary photoelectrons), with final light emission being the sum of contributions from secondary electrons of different energies. Notably, these electrons are products of interactions between incident photons and matter, and their energies cannot exceed those of the incident particles. Therefore, the light output induced by photons in the LaBr3(Ce,Sr) crystal was always lower than that caused by Compton electrons of equivalent energies.

We conducted detailed testing of the LaBr3(Ce) crystal using identical experimental procedures and data processing methods. Figure 15 [Figure 15: see original paper] illustrates the non-linear light yield response of the LaBr3(Ce) crystal to Compton electrons and gamma rays in the 3–1000 keV range. The non-linear curves tended to be flat, with similar results for Compton electrons and gamma rays above 200 keV; however, significant differences were observed below 200 keV. As energy decreased, the LaBr3(Ce) crystal exhibited lower response to the full-energy peak of gamma rays than to Compton electrons of the same energy. This finding is consistent with results for the LaBr3(Ce,Sr) crystal, indicating that particle interaction mechanisms directly affect crystal light output. For gamma rays in the several hundred keV range, Compton scattering is the most likely initial interaction, and most gamma rays require multiple interactions for full absorption. The high-energy primary and secondary electrons resulting from these interactions exhibited good linear responses, reflecting excellent linearity in response to high-energy gamma rays.

Figure 15 also demonstrates the non-linearity curve of the LaBr3(Ce) crystal to X-rays in the 8–120 keV range. Compared to LaBr3(Ce,Sr), this response curve deviated more significantly from the ideal state, with nearly all measured energy points exhibiting scintillation responses below 90%. Light output decreased sharply near the K-shell binding energies (13–15 keV and 38–40 keV) of Br and La, leading to greater non-linearity in the LaBr3(Ce) crystal response curve to X-rays. Data points below 28 keV exhibited non-linearity greater than 20%, and

light output at 8 keV was only 58% of the ideal state.

As X-ray energy decreased, the energies of induced secondary electrons in the crystal decreased, resulting in more significant light “defects.” The NLSD values obtained from testing the LaBr₃(Ce) crystal with X-rays and Compton electrons were 0.22 and 0.11, respectively. The LaBr₃(Ce) crystal exhibited greater non-linearity toward both X-rays and Compton electrons compared to LaBr₃(Ce,Sr), particularly below 100 keV, which may be attributed to the doping process and indicates that Sr²⁺ ion doping can improve the non-linearity of LaBr₃ crystals.

To better understand differences in non-linearity among crystal types, the NaI(Tl) crystal was selected as the third test subject (Fig. 16 [Figure 16: see original paper]). Unlike the two LaBr₃ crystals, NaI(Tl) exhibited a pronounced “excess” response to Compton electrons in the 8–80 keV range, with non-linearity exceeding 4%. At electron energies below 6 keV, the crystal displayed slight “defects” in light output, whereas above 80 keV, the curve flattened, indicating good linear response to high-energy electrons.

Figure 16 also demonstrates the non-linearity of NaI(Tl) crystal light yield to X-rays in the 8–120 keV range. Compared to the Compton electron response, X-ray test results exhibited a similar trend, with NLSD values of 0.06 for both. However, differences in curve slopes were observed. Direct photoelectric interactions with matter are most likely for photons in the tens-of-keV range. Assuming this photoelectric absorption occurs with iodine K-shell electrons (probability of 83% when photon energy exceeds 33.17 keV), the resulting photoelectrons have energies within a range that produces substantial “excess” light output. The total light emission induced by all secondary electrons generated from photons exceeded that caused by Compton electrons of equivalent energies. Therefore, in the 40–70 keV range, the NaI(Tl) crystal exhibited higher relative light output to X-rays, producing more photons per unit X-ray-deposited energy compared to Compton electron incidence.

The response of the NaI(Tl) crystal to X-rays was similar to that of Compton electrons at approximately 33 keV, which is related to the binding energy (33.17 keV) of iodine K-shell electrons, as photons with lower energies cannot excite K-shell electrons from iodine atoms. Nearly all photon energy was transferred to electrons, with only a small fraction of low-energy photons interacting with iodine L-shell electrons (binding energy 5.19 keV) to produce lower-energy X-rays through the photoelectric effect. Within the measured X-ray energy range, the NaI(Tl) crystal exhibited varying degrees of “excess” light output, which can also be explained by the photoelectric effect cascade sequence. The low-energy electron response demonstrated an “excess” that reached its maximum at 14 keV, as shown in Fig. 16. Therefore, when photons undergo a series of interactions producing multiple low-energy secondary electrons, a “burst” phenomenon occurs in light output, explaining why the photon response reached a maximum at approximately 30 keV instead of 14 keV. As incident photon energy increased, light output gradually decreased but remained above 100% due to the more complex distribution of secondary electron energies, resulting in numerous

secondary electrons with energies below 6 keV. The electron response below 6 keV exhibited a “deficient” luminous response, forming a so-called “compensation” effect with the “excess” phenomenon observed in the tens-of-keV range.

IV. CONCLUSION

We employed the WACC technique and HXCF/radioactive sources to compare the energy responses of domestically produced LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) crystals to Compton electrons and X/γ-rays. The NLSD values obtained through X-ray testing of LaBr₃(Ce), LaBr₃(Ce,Sr), and NaI(Tl) crystals were 0.22, 0.17, and 0.06, respectively, while Compton electron testing yielded NLSD values of 0.11, 0.03, and 0.06. The non-linear curves of these domestic crystals exhibited different slopes (Fig. 14, Fig. 15, and Fig. 16), indicating varying degrees of non-linearity at low energies. Based on experimental results, the non-linearity of all three crystals to X/γ-rays exceeded that to Compton electrons, attributable to distinct interaction mechanisms between incident particles and material.

The NLSD values for LaBr₃(Ce) were 1.29 times higher for X-rays and 3.67 times higher for Compton electrons compared to LaBr₃(Ce,Sr), indicating that LaBr₃(Ce,Sr) exhibits better linearity and that Sr²⁺ ion doping can improve non-linearity. However, the absolute light yield of LaBr₃(Ce,Sr) was slightly lower than that of LaBr₃(Ce) (Table 2), potentially requiring further optimization of growth processes and doping ratios by domestic manufacturers. The energy resolution of our LaBr₃(Ce,Sr) crystal was inferior to that reported by foreign counterparts [?], possibly due to inherent performance variations among crystals, differences in measurement methods when coupled with PMTs, or distinctions in growth processes and raw materials between Chinese and Saint-Gobain crystals.

The NaI(Tl) crystal exhibited an “excess” light output of up to 9.2% in X-ray testing and 15.5% in Compton electron testing, distinguishing it as advantageous for low-energy X/γ-ray detection. The calibration and in-orbit performance of GECAM-C validated that NaI(Tl) crystals exceeded expectations [?, ?]. Although energy resolution is not the primary concern in gamma-ray burst detection and NaI(Tl) crystals may not match the energy resolution and absolute light yield of LaBr₃ crystals, test results demonstrated satisfactory performance in the 10–1000 keV range. Furthermore, NaI(Tl) crystals can be manufactured in large sizes and are cost-effective, leading to their selection as sensitive detection materials for GECAM-D.

We conducted a study on the light yield and non-linearity of three crystals produced by the Beijing Glass Research Institute and found that different calibration standards are required for gamma-ray and electron detection. While current GECAM satellite GRDs lack electron-gamma discrimination capabilities, the non-linearity results for Compton electrons may be applied to future corrections for electron detection.

REFERENCES

- [1] B. Abbott, R. Abbott, T. Abbott, et al., Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.* 116, 061102 (2016). Doi: 10.1103/PhysRevLett.116.061102
- [2] B. Abbott, R. Abbott, T. Abbott, et al., Gravitational waves and gamma-rays from a binary neutron star merger: Gw170817 and grb 170817a. *Astrophys. J. Lett.* 848, L13 (2017). Doi: 10.3847/2041-8213/aa920c
- [3] B. Abbott, R. Abbott, T. Abbott, et al., Gw170817: observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.* 119, 161101 (2017). Doi: 10.1103/Phys-RevLett.119.161101
- [4] B. Abbott, R. Abbott, T. Abbott, et al., Multi-messenger observations of a binary neutron star merger. *Astrophys. J. Lett* 848, L12 (2017). Doi: 10.3847/2041-8213/aa91c9
- [5] T. Li, S. Xiong, S. Zhang, et al., Insight-hxmt observations of the first binary neutron star merger gw170817. *Sci. China.-Phys. Mech. Astr.* 61, 1–8 (2018). Doi: 10.1007/s11433-017-
- [6] V. Connaughton, M. Briggs, A. Goldstein, et al., Localization of gamma-ray bursts using the fermi gamma-ray burst monitor. *Astrophys. J. Suppl. S.* 216, 791–804 (2015). Doi: 10.1088/0067-0049/216/2/32
- [7] M. Stanbro, M. Briggs, O. Roberts, et al., A fermi gamma-ray burst monitor event observed as a terrestrial gamma-ray flash and terrestrial electron beam. *J. Geophys. Res.-Space.* 124, 10580–10591 (2019). Doi: 10.1029/2019JA026749
- [8] X. S., X. S.L., C. C., et al., Energetic transients joint analysis system for multi-instrument (etjasmin) for gecam – i. positional, temporal, and spectral analyses. *Mon. Not. R. Astron. Soc.* 2 (2022). Doi: 10.1093/mnras/stac999
- [9] M. Stanbro, M. Briggs, O. Roberts, et al., A study of consecutive terrestrial gamma-ray flashes using the gamma-ray burst monitor. *J. Geophys. Res.-Space.* 123, 9634–9651 (2018). Doi: 10.1029/2018JA025710
- [10] S. Xiong, Special topic: sky monitor. doi:<https://doi.org/10.1360/SSPMA-2020-0457> *Sin.-Phys. Mech.* (2020). Doi:
- [11] L. Lin, S. Xiao, Y. Huang, et al., Observational prospects for magnetars with gecam. *Sci. Sin.-Phys. Mech. Astr.* 50, 129521– (2020). Doi: 10.1360/SSPMA-2019-0397. doi:<https://doi.org/10.1360/SSPMA-2019-0397>
- [12] Y. Huang, Q. Luo, B. Zhang, et al., Ultra-long gamma-ray bursts and ultra-soft gamma-ray bursts. *Sci. Sin.-Phys. Mech. Astr.* 50, 129504– (2020). Doi: 10.1360/SSPMA-2019-0415. doi:<https://doi.org/10.1360/SSPMA-2019-0415>
- [13] Y. Su, W. Chen, S. Xiong, et al., Monitoring and research of high-energy solar flare emissions with gecam. *Sci. Sin.-Phys. Mech. Astr.* 50, 129505– (2020). Doi: 10.1360/SSPMA-2020-0012. doi:<https://doi.org/10.1360/SSPMA-2020-0012>
- [14] X. Li, X. Wen, Z. An, payload. doi:<https://doi.org/10.1360/SSPMA-2019-0417> (2020). Doi:
- [15] Z. An, X. Sun, D. Zhang, et al., The design and performance of grd onboard the gecam satellite. *Radiat. Detect. Technol. Methods* 006 (2022).

Doi: 10.1007/s41605-021-00289-y

- [16] D. Zhang, C. Zheng, sipm-based mance gecam-c. Nucl. doi:<https://doi.org/10.1016/j.nima.2023.168586> al., The perfor- Instrum. Methods Phys. Res. A. 1056, 10.1016/j.nima.2023.168586.
- [17] C. Zheng, W.X. Peng, X.B. Li, et al., Electron non-linear light yield of labr3 detector aboard gecam. Nucl. Instrum. Methods Phys. Res. A. . Doi: 10.1016/j.nima.2022.167427
- [18] W. Lu, L. Wang, Y. Yuan, et al., Monte carlo simulation for performance evaluation of detector model with a monolithic labr3 (ce) crystal and sipm array for γ radiation imaging. Nucl. Sci. Tech. 33, 107 (2022). Doi: 10.1007/s41365-022-01081-3
- [19] C. Zheng, Z. An, W. Peng, et al., Ground calibration of gamma-ray detectors of gecam-c. arXiv preprint arXiv:2303.00687 . Doi: 10.48550/arXiv.2303.00687
- [20] W. Wang, X. Li, J. Wu, et al., Development and performance study of a dual-layer compton camera (in chinese). Nucl. Tech. 46, 030401–030401 (2023). Doi: 10.11889/j.0253-3219.2023.hjs.46.030401
- [21] F. Hua, Y. Ye, X. Yang, et al., Several nuclear physics experiments based on the beijing cyclotron (in chinese). Nucl. Tech. 46, 080004–080004 (2023). Doi: 10.11889/j.0253-3219.2023.hjs.46.080004
- [22] J. Zhao, S. Jiang, Y. Li, et al., The contribution of 4-400 mev cosmic ray protons to the annihilation radiation in near-lunar space orbit gamma spectra (in chinese). Nucl. Tech. 46, 050201–050201 (2023). Doi: 10.11889/j.0253-3219.2023.hjs.46.050201
- [23] M. Moszynski, A. Syntfeld-Kauch, L. Swiderski, et al., scintillation detectors. Nucl. Energy resolution of strum. Methods Phys. Res. A. 805, 25–35 (2016). Doi: 10.1016/j.nima.2015.07.059
- [24] P. Limkitjaroenporn, W. Hongtong, W. Chaiphaksa, et al., The light yield non-proportionality and electron energy resolution study of csi(tl) scintillator by comp- (cct). Mat. Today-Proc. 5, ton coincidence technique 15110–15114 (2018). Doi: 10.1016/j.matpr.2018.04.066. doi:<https://doi.org/10.1016/j.matpr.2018.04.066>
- [25] G. Yang, L. Hua, F. Lu, et al., Response functions of a 4π summing γ detector in β -oslo method. Nucl. Sci. Tech. 33, 68 (2022). Doi: 10.1007/s41365-022-01058-2
- [26] M. Dong, Z. Yao, Y. Xiao, Development and preliminary results of a large-pixel two-layer labr3 compton camera prototype. Nucl. Sci. Tech. 34, 121 (2023). Doi: 10.1007/s41365-
- [27] V. Ranga, S. Rawat, S. Sharma, et al., Intrinsic resolution of compton electrons in cebr3 scintillator using compact cct. IEEE T. Nucl. Sci. 65, 616–620 (2017). Doi: 10.1109/TNS.2017.2779888
- [28] K. Roemer, G. Pausch, C. Herbach, et al., in IEEE NSS/MIC 2009, A technique for measuring the energy resolution of low-z scintillators. IEEE, 2009, pp. 6–11, doi: 10.1109/NSS-MIC.2009.5401909
- [29] L. Swiderski, R. Marcinkowski, M. Szawłowski, et al., Non-proportionality of electron response and energy resolution of compton electrons in scintillators. IEEE T. Nucl. Sci. 59, 222–229 (2012). Doi: 10.1109/TNS.2011.2175407
- [30] S. Zhang, J. Xia, T. Sun, et al., Transition edge sensor-based detector: from

- x-ray to γ -ray. Nucl. Sci. Tech. 33, 84 (2022). Doi: 10.1007/s41365-022-01071-5
- [31] Hamamatsu (2023). <https://www.hamamatsu.com.cn/cn/zh-cn/product/optical-sensors/pmt.html>.
- [32] X. Han, S. Wang, H. Wu, et al., Csi-bowl: an ancillary detector for exit channel selection in γ -ray spectroscopy experiments. Nucl. Sci. Tech. 34, 133 (2023). Doi: 10.1007/s41365-023-01289-x
- [33] Canberra (2023). <https://www.mirion.com/products/technologies/spectroscopy-scientific-analysis>.
- [34] BEGe(2023). <https://www.gammapdata.se/assets/Uploads/BEGe-SS-C49318.pdf>
- [35] X. Li, J. Ren, X. Ruan, et al., Particle discrimination measurement of liquid scintillators using dt5751. Ann. Inst. Atom. En. 00, 147–147 (2014). Doi: Rep. Chin. CNKI:SUN:YNXB.0.2014-00-055
- [36] T. Liu, H. Song, Y. Yu, et al., Toward real-time digital pulse process algorithms for csi (tl) detector array at external target facility in hirfl-csr. Nucl. Sci. Tech. 34, 131 (2023). Doi: 10.1007/s41365-023-01272-6
- [37] X. Qian, H. Sun, C. Liu, et al., Simulation study on performance optimization of a prototype scintillation detector for the grandproto35 experiment. Nucl. Sci. Tech. 32, 51 (2021). Doi: 10.1007/s41365-021-00882-2
- [38] Y. Wei, M. Guan, W. Xiong, et al., Consistency test of pmt spe spectrum from dark-noise pulses and led low-intensity light. Radiat. Detect. Technol. Methods 2, 11 (2018). Doi: 10.1007/s41605-018-0042-6
- [39] M. Li, Z. Wang, C. Liu, et al., Performance of compact plastic scintillator strips with wavelength shifting fibers using a photomultiplier tube or silicon photomultiplier readout. Nucl. Sci. Tech. 34, 31 (2023). Doi: 10.1007/s41365-023-01175-6
- [40] H. Wu, C. Li, A root-based detector test system. Nucl. Sci. Tech. 32, 115 (2021). Doi: 10.1007/s41365-021-00952-5
- [41] S. Guo, J. Wu, D. Hou, The development, performances and 10.1007/s41365-021-00937-4 J. Sun,
- [42] D. Hou, J. Wu, S. Guo, et al., The realization and study of (21–301) kev monochromatic x-rays. Nucl. Instrum. Methods Phys. Res. A. 927,. Doi: 10.1016/j.nima.2019.02.024
- [43] S. Guo, Z. Jiang, J. Wu, et al., Research on a tunable monochromatic x-rays source in (540) kev. Appl. Radiat. Isot. 181, 110096– (2022). Doi: 10.1016/j.apradiso.2022.110096
- [44] J. He, Z. An, W. Peng, et al., Ground-based calibration and characterization of labr3-sipm-based gamma-ray detector on gecam satellite: 8–160 kev. Mon. Not. R. Astron. Soc. 525, 3399–3412 (2023). Doi: 10.1093/mnras/stad2439
- [45] J. Wen, X. Zheng, J. Yu, et al., Compact cubesat gamma-ray detector for grid mission. Nucl. Sci. Tech. 32, 99 (2021). Doi:
- [46] X. Wen, J. He, et al., Calibration study of the gamma-ray monitor onboard the svom satellite. Nucl. Instrum. Methods Phys. Res. A. 165301 (2021). Doi: 10.1016/j.nima.2021.165301
- [47] X. Li, C. Liu, Z. Chang, et al., Ground-based calibration and characteriza-

tion of the he detectors for insight-hxmt. J. High. Energy Astrophys. 24,. Doi: 10.1016/j.jheap.2019.09.003

[48] L. H.R., W. J.J., L. J.C., et al., Lege detector intrinsic efficiency calibration for parallel incident photons. Appl. Radiat. Isot. 109, 551–554 (2016). Doi: 10.1016/j.apradiso.2015.11.102

[49] M. Alekhin, J. Haas, I. Khodyuk, et al., Improvement of c-ray energy resolution of labr3 :ce3+ scintillation detectors by sr2+ and ca2+ co-doping. Appl. Phys. Lett. 102,. Doi: 10.1063/1.4803440

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

Source: ChinaXiv — Machine translation. Verify with original.