PROCEEDINGS OF SCIENCE

Investigation of the intrinsic detector background for SMILE-3 balloon experiment

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MeV gamma-ray observations are a probe for uncovering various physical phenomena, such as the search for dark matter and primordial black holes, and the study of the nucleosynthesis in the Universe. To achieve high sensitivity in this band, we are developing an electron-tracking Compton camera (ETCC), which combines a gaseous time projection chamber (TPC) and pixelated GSO(Ce) scintillator arrays (PSAs). The ETCC tracks recoil electrons in the TPC and reconstructs Compton events to uniquely determine gamma-ray arrival directions.
We are now planning the Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment 3 (SMILE-3), which will use an upgraded ETCC from the previous balloon experiment, SMILE-2+, with improved dynamic range and effective area. The first one-day flight of SMILE-3 is scheduled for spring 2027 in Australia"
The ETCC has background events originating from radioactive isotopes contained in the GSO(Ce) scintillators. Therefore, we measured the intrinsic background of all GSO(Ce) scintillators to be used in SMILE-3 and investigated their properties to evaluate the feasibility of selecting low-background scintillators.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

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PoS(ICRC2025)690

1. MeV Gamma-ray Observation and the SMILE-3 Experiment

MeV gamma-ray observations are a probe for exploring various physical phenomena, including dark matter and nucleosynthesis in the Universe. However, little progress has been made in the MeV gamma-ray range since CGRO/COMPTEL, and these observations still suffer from lower sensitivity and larger uncertainties compared to those in the X-ray and GeV bands. For more detailed discussions, multiwavelength observations from X-rays to gamma rays are important, and in particular, higher-sensitivity MeV gamma-ray observations are necessary.

We are now conducting the Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment (SMILE), aiming for high-sensitivity observations of MeV gamma rays. As a part of SMILE, we have been developing the Electron-Tracking Compton Camera (ETCC)[1]. The ETCC applies a gaseous time projection chamber (TPC) as a scatterer positioned at its center, surrounded by pixelated scintillator array (PSA) detectors that serve as absorbers. The TPC measures the 3-D position of the gamma-ray interaction, the energy, and the recoil momentum of the electron. The PSA fully absorbs the scattered gamma rays and records their energy and interaction positions. This configuration allows complete reconstruction of the Compton scattering process by the ETCC. The ability to determine the incident direction of gamma rays to a single point is a major advantage of the ETCC, fundamentally distinguishing it from conventional Compton cameras that could constrain the direction only to a circle due to their inability to measure the recoil direction of the electron. Moreover, the TPC enables particle identification based on energy loss and achieves background suppression by requiring consistency between Compton kinematics and the geometrical scattering angle[2].

The newly developed ETCC for the SMILE-3 experiment aims to achieve an effective area of approximately $10\,\mathrm{cm}^2$ and an energy resolution of about 8% at 662 keV. Using this ETCC, a high-sensitivity observation of MeV gamma rays from the Galactic center will be conducted via a balloon flight in Australia, scheduled for spring 2027.

2. Development of PSA

The PSA for SMILE-3 uses 6 mm square Gd_2SiO_5(Ce) (GSO(Ce)) pixel scintillators arranged in an 8×8 array (Figure 1). The characteristics of several scintillators are presented in Table1, and GSO(Ce) performs better than the others in most aspects.

Table 1: Characteristics of each scintillator[3, 4].

scintillator	Gd_2SiO_5(Ce) (GSO(Ce))	NaI(Tl)	CsI(Tl)	$Bi_4Ge_3O_{12}$ BGO	$Gd_3(Al,Ge)_5O_{12}$(Ce) (GAGG(Ce))
effective atomic number	58	51	54	75	54.4
density (g/cm^3)	6.71	3.76	4.51	7.13	6.63
emission wavelength (nm)	440	415	420	480	530
light yield (ph/MeV)	9000	38000	65000	8200	50000
decay time (ns)	27	230	680	300	150
hygroscopicity	No	Yes	Yes (slightly)	No	No

A 13-mm-thick scintillator (equivalent to one radiation length) is used on the side of the ETCC, and a 26-mm-thick scintillator (two radiation lengths) is used at the bottom. A unit comprises a 2×3 configuration of GSO(Ce) arrays (Figure 2). A total of 18 such units are used in the ETCC: 6 on the sides and 12 on the bottom. The PSA used in SMILE-3 has been improved from that used in the previous experiment, SMILE-2+. In SMILE-3, the PSA will use Multi-Pixel Photon Counters (MPPCs) instead of the photomultiplier tubes used in SMILE-2+, taking advantage of their higher quantum efficiency at the scintillation wavelength of GSO(Ce). In SMILE-2+, analog signals from the MPPCs were digitized using ADCs, and trigger signals were generated with digital logic implemented on the FPGA. For SMILE-3, the trigger generation logic has been redesigned to improve efficiency. In the new design, analog signals from the MPPCs are summed and then fed into a comparator, which directly compares the signal against a predefined threshold to generate the trigger. Testing of the improved PSA board is currently in progress.

Figure 1: Pixelated GSO(Ce) scintillator. 13 mm thick (left) and 26 mm thick (right).

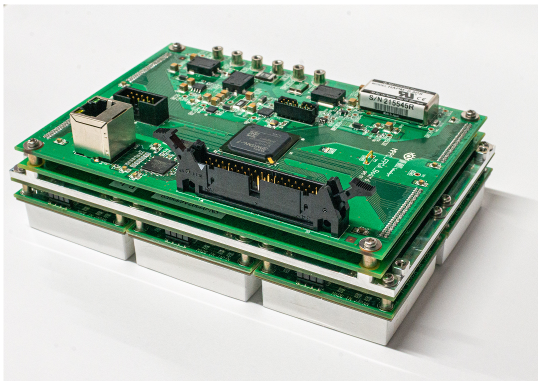


Figure 2: Photograph of the PSA.

3. Background Events in ETCC

Background events in the ETCC used in balloon observations have been investigated based on data from the previous experiment, SMILE-2+. They include events caused by interactions between cosmic rays (or secondary cosmic-ray particles) and the detector housing, atmospheric gamma rays, and accidental coincidences caused by internal noise. These accidental events occur when a trigger is generated by self-luminescence of the GSO(Ce) scintillator in the PSA. If a temporally unrelated TPC event happens to occur within 9.5 μs, it is recorded together as a single event. Such events dominate around 1 MeV [5] (Figure **??**). One cause of this self-luminescence is uranium/thorium-series radioactive isotopes unintentionally incorporated during GSO(Ce) production. Alpha particles with energies between 3.8 and 8.9 MeV, emitted by these isotopes, produce a background peak near 1 MeV [6].

Phenomena expected to appear around 1 MeV include a possible bump in the extragalactic diffuse gamma-ray background in the 1-3 MeV range [7, 8], and a possible spectral feature near 1 MeV in the Crab Nebula [9]. The significant uncertainties in the MeV range, combined with the low statistical significance of current observations, have hindered detailed studies of these phenomena. To enable more detailed discussions, it is crucial to achieve high sensitivity around 1 MeV, which requires a clear understanding of the dominant background caused by accidental events. As a first step toward this goal, the level of intrinsic background in the GSO(Ce) scintillator must be evaluated.

4. Measurement Setup

To evaluate the internal background in GSO(Ce), measurements were conducted using a PSA capable of simultaneously measuring 9 arrays in a single run. MPPCs and scintillators were coupled with optical grease and placed in a 5 °C thermostatic chamber, surrounded by lead shielding (Figure 3).

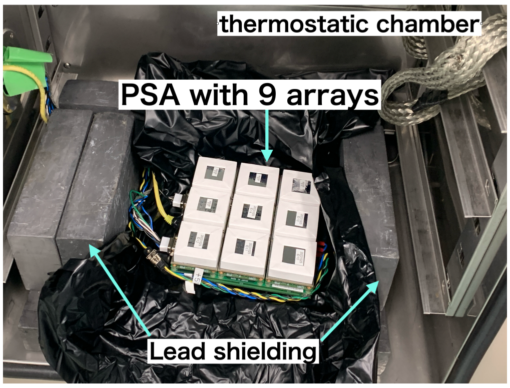


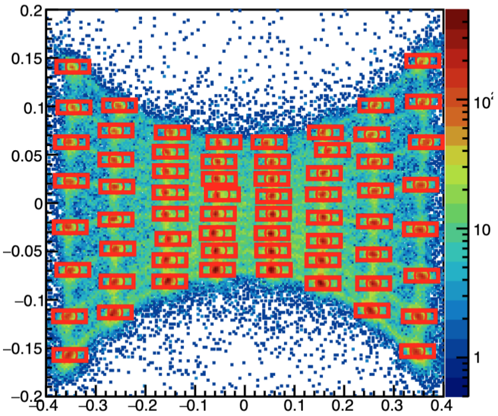
Figure 3: overview

Energy calibration was performed for about 3 hours using ^{137}Cs and ^{60}Co sources. Signals from the MPPCs were read out via four terminals using a resistor chain, which allowed reconstruction of two-dimensional position information. Energy histograms for each pixel were generated by extracting events within the corresponding pixel region from the two-dimensional histograms (Figure 4). Using measurements from ^{137}Cs (662 keV) and ^{60}Co (1.17, 1.33 MeV), the relationship between energy (E_{keV}) and ADC value (Q_{ADC}) was corrected for each pixel using the fitting formula:

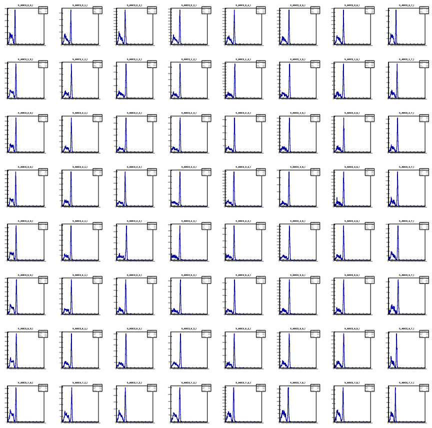
$$Q_{\mathrm{ADC}} = p_0 \left(1 - \exp\left(\frac{p_1 E_{\mathrm{keV}}}{p_0}\right)\right) + p_2 \tag{1}$$

where p_0, p_1, and p_2 are the fitting parameters determined individually for each pixel (Figure 5).

After applying the energy correction, background measurements were conducted without sources for approximately 2 days. Using the energy-corrected data, two-dimensional histograms were constructed. For each pixel, the background rate was determined by integrating the events within the 700-1200 keV energy range inside the region corresponding to that pixel (Figure 6), normalized by the measurement time. This process was repeated 8 times to measure all arrays. 70 arrays (4480 pixels) of 13-mm-thick scintillators and 40 arrays (2560 pixels) of 26-mm-thick scintillators were measured. Through this measurement, the intrinsic background of all GSO(Ce) scintillators required for the PSA in SMILE-3 was measured.

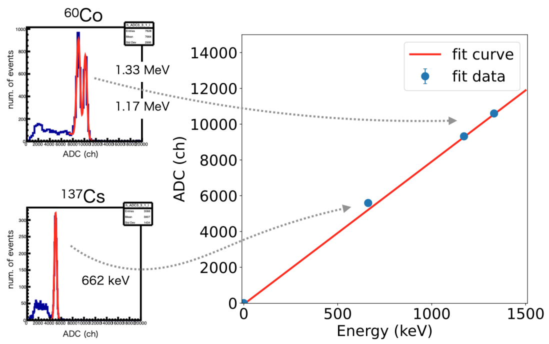


(a) Two-dimensional histogram. The red box indicates the region corresponding to a single pixel.

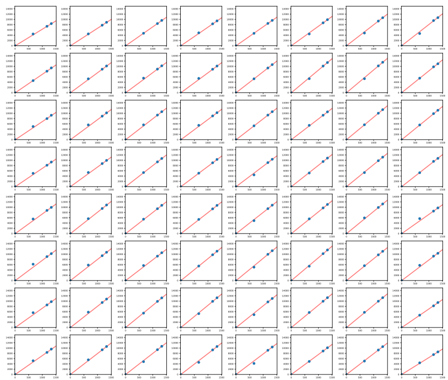


(b) Example spectra for each pixel of one array. The spectra were generated using only the events contained within the corresponding region of each individual pixel.

Figure 4: Event selection for each pixel using measurement data from ^{137}Cs.



(a) Example of energy calibration for a single pixel.



(b) Energy calibration curves for one array.

Figure 5: Energy calibration

5. Evaluation of Internal Background

The background rates per pixel show that most pixels cluster around 0.076 ± 0.0041 cnt/s for the 13-mm scintillators and around 0.070 ± 0.057 cnt/s for the 26-mm scintillators. However, some scintillators exhibit background rates more than twice the typical value. No clear threshold exists for identifying pixel scintillators with high background rates. Therefore, the comparison was made using the average value of the 64 scintillator pixels within each array. Averaging the background rates over the 64 pixels in each array revealed thresholds of approximately 0.015 cnt/s for the 13-mm arrays and 0.15 cnt/s for the 26-mm arrays, enabling the identification of arrays with relatively high average rates (Figure 7, 8). The average background rate per pixel position across all 70 arrays shows that pixels near the center exhibit higher background rates, indicating position dependence within arrays.

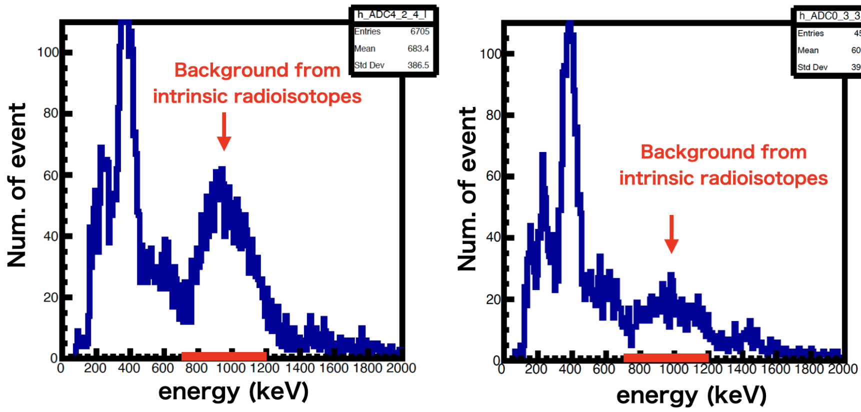


Figure 6: Background spectrum. Events in the 700-1200 keV range (shown in red) are defined as background events. These are examples of pixels with a high background event rate (left) and a low background event rate (right).

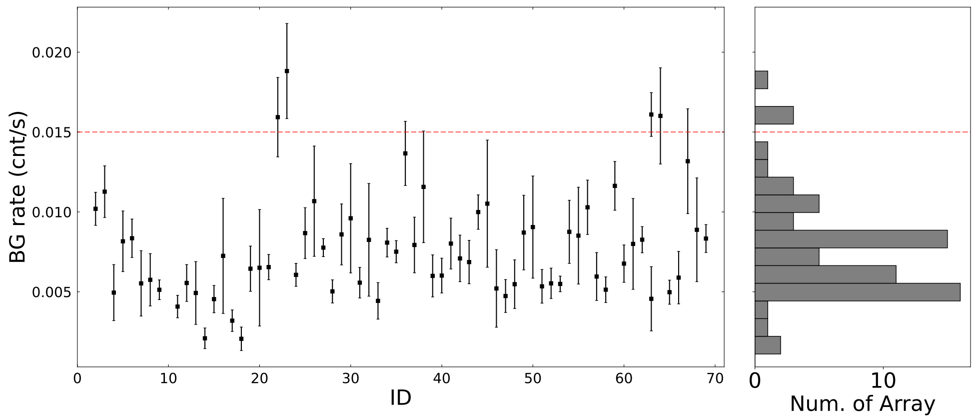


Figure 7: Average background rate for the 13-mm array (left) and its histogram (right). The red dashed line indicates a threshold of 0.015 cnt/s, used as a criterion for background rate selection.

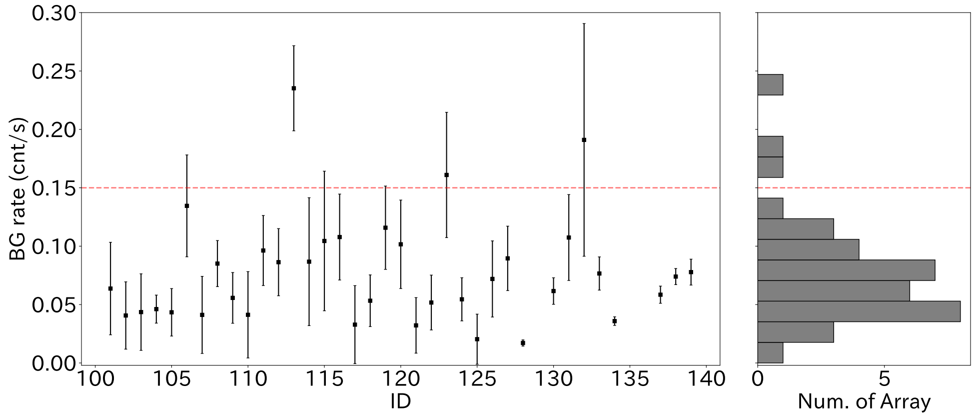


Figure 8: Average background rate for the 26-mm array (left) and its histogram (right). The red dashed line indicates a threshold of 0.15 cnt/s, used as a criterion for background rate selection.

6. Summary and Future Work

This study focused on the development of the PSA for SMILE-3 and the evaluation of intrinsic background in GSO(Ce) scintillators. Background measurements were performed for all 7040 GSO(Ce) pixel scintillators used in the ETCC. The dominant background near 1 MeV in ETCC observations originates from the internal background of the GSO(Ce) scintillators used in the PSA. Sensitivity around 1 MeV is especially important for investigating spectral features such as the turnover of the Crab Nebula and the extragalactic diffuse gamma-ray background. Therefore, accurate evaluation of this internal background is essential for understanding the ETCC response.

Although no clear threshold was found for classifying individual pixels by background rate, averaging the rates over the pixels within each array allowed the identification of arrays with relatively high internal background. Currently, there are no plans to replace or rearrange the scintillator arrays. However, since high-background pixels are concentrated in specific arrays, the effect of rearrangement is expected to be limited.

As future work, the results will be incorporated into Monte Carlo simulations to optimize array configuration and further refine the ETCC response.

7. Acknowledgements

The balloon-borne experiment was conducted by Scientific Ballooning (DAIKIKYU) Research and Operation Group, ISAS, JAXA. This study was supported by the Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (21224005, 16H02185, 15K17608, 23654067, 25610042, 16K13785, 20K20428, 22J00064, 23H05435), and the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo. A part of this work was conducted at the BL1U of UVSOR Synchrotron Facility, Institute for Molecular Science (IMS program 25IMS6607).

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