PROCEEDINGS OF SCIENCE

Development status of the SMILE-3 balloon experiment

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MeV gamma-ray astronomy remains relatively underexplored, despite extensive worldwide efforts to investigate this crucial energy range. To address this challenge, we have demonstrated the high-performance capabilities of an electron-tracking Compton camera (ETCC) during the Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment (SMILE) missions. The ETCC employs a gaseous time-projection chamber (TPC) as the primary scatterer, surrounded by pixelated scintillator arrays (PSAs) that function as absorbers. The gas TPC measures the momentum vector of the recoil electron, while the PSAs simultaneously determine the energy of the scattered gamma ray. This capability enables a bijective reconstruction of both the direction and energy of the incident gamma ray, which enhances the sensitivity compared to classical Compton reconstruction that constrains the incident direction only by a circular region. The SMILE-2+ experiment, which consisted of a 26-hour balloon flight over Australia, successfully detected the Crab Nebula and Galactic diffuse emissions around the Galactic Center at a significance level exceeding 4σ. Following this achievement, we have initiated the successor project, SMILE-3, to enable a more detailed investigation of diffuse emissions. The detector design has been upgraded to achieve a larger effective area and a wider dynamic range, thereby increasing photon collection power. The first flight for SMILE-3 is currently planned for early 2027. In this paper, we present an overview of the SMILE-3 experiment and report the current status of our R&D efforts.

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

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

PoS(ICRC2025)777

1. Introduction

MeV gamma-ray astronomy remains one of the least explored regimes in high-energy astrophysics, despite its critical importance for understanding various fundamental processes. This energy band holds key information on nucleosynthesis in supernovae, cosmic-ray acceleration and interactions, positron annihilation, and the decay or annihilation of exotic particles such as dark matter.

A particularly significant open question is the origin of diffuse gamma-ray emission from the Galactic Center and the Galactic plane. In the line emission domain, the 511 keV positron annihilation line has been detected by *INTEGRAL*/SPI with high significance [1], but poor angular resolution has hampered source localization. In the continuum domain, observations by COMPTEL [2] and the COSI balloon experiment [3] have revealed significant excesses over standard inverse Compton scattering models, but the physical origin of this so-called MeV excess remains uncertain. Potential explanations include unresolved point sources, non-standard cosmic-ray populations, dark matter annihilation, and the existence of primordial black holes. Accurate spatial mapping of this diffuse emission is essential for discriminating among these models, but previous observations have been limited by poor angular resolution and insufficient sensitivity.

Technically, the principal challenge in this energy range arises from the difficulty of imaging MeV gamma rays and from overwhelming instrumental and atmospheric backgrounds. Classical Compton cameras, like COMPTEL, suffer from intrinsic limitations because they constrain the incident gamma-ray direction only to a circle on the celestial sphere, making robust background suppression difficult. Coded aperture telescopes have been similarly constrained by poor imaging performance and heavy structural requirements.

To overcome these challenges, we have developed the Electron-Tracking Compton Camera (ETCC), which achieves event-by-event reconstruction of both the direction and energy of incident gamma rays. By simultaneously measuring the recoil electron track in a gaseous time projection chamber (TPC) and the scattered gamma ray in pixelized scintillator arrays (PSAs), the ETCC enables bijective imaging with a well-defined point spread function (PSF) on the celestial sphere [4, 5]. This reconstruction capability provides strong kinematic constraints, enhancing background rejection and enabling imaging spectroscopy for MeV gamma rays.

As part of the SMILE (Sub-MeV/MeV gamma-ray Imaging Loaded-on-balloon Experiment) program, we have conducted a series of balloon-borne experiments to validate the ETCC concept under realistic observational conditions. SMILE-I demonstrated background suppression at high altitudes [6], and SMILE-2+ marked a milestone by detecting MeV gamma rays from astrophysical sources [4]. Building on these achievements, we have initiated the SMILE-3 project, which aims to achieve an order-of-magnitude sensitivity improvement over SMILE-2+ and to perform wide-area mapping of Galactic diffuse emission. In this paper, we present a review of the ETCC principle, outline the detector upgrades for SMILE-3, and report the current status of our development efforts.

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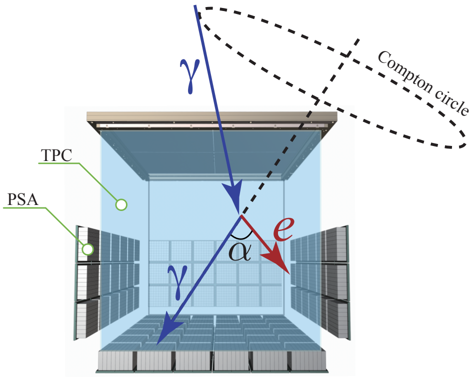

Figure 1: Schematic view of the ETCC configuration and the event reconstruction process for incident gamma rays. Unlike classical Compton cameras, the ETCC can determine the arrival direction not as a circle but as a point on the celestial sphere.

2. ETCC Concept and Demonstrations

2.1 Principle of the ETCC

Our electron-tracking Compton camera (ETCC) employs a gaseous time projection chamber (TPC) as the primary scatterer, surrounded by pixelated scintillator arrays (PSAs) that serve as absorbers. The TPC measures the three-dimensional track and energy of the recoil electron, allowing determination of its momentum vector. Simultaneously, the PSAs measure both the energy and the interaction position of the scattered gamma ray. This configuration enables full reconstruction of both the direction and energy of the incident gamma ray through a bijective imaging process, offering a significant advantage over classical Compton cameras, which can constrain only the incident angle along a Compton cone. It should be emphasized that this capability is fundamentally different from classical Compton reconstruction as discussed in Refs [4, 5]

Figure 1 illustrates the ETCC configuration and the reconstruction of incident gamma rays. One key advantage of the ETCC is its ability to impose kinematic constraints, such as the angle between the measured recoil electron direction and the scattered gamma-ray direction (referred to as the "α cut"). The interaction position determined by the TPC and the absorption position detected by the PSA yield the geometrical scattering angle $\alpha_{\rm geo}$. Independently, the energies of the recoil electron (K_e) and the scattered gamma ray (K_γ) allow calculation of the kinematic scattering angle $\alpha_{\rm kin}$ based on the Compton-scattering formula: $\alpha_{\rm kin} = \cos^{-1}\left(1 - \frac{mc^2}{K_\gamma}\right)\sqrt{\frac{K_e}{K_e+2mc^2}}$, where mc^2 is the electron rest energy. By requiring consistency between $\alpha_{\rm geo}$ and $\alpha_{\rm kin}$, non-Compton background events, such as accidental coincidences, cosmic-ray induced backgrounds, and internal radioactivity from detector materials, can be substantially suppressed [9].

Another unique background-rejection capability of the ETCC is based on the energy loss rate (dE/dx) obtained from the TPC. By applying event selection in the track length versus measured energy deposit plane, events induced by cosmic-ray muons and neutron scattering within the TPC volume can be effectively reduced [4, 6]. Furthermore, machine-learning-based track reconstruction techniques have been investigated and shown to further improve the angular resolution of the ETCC,

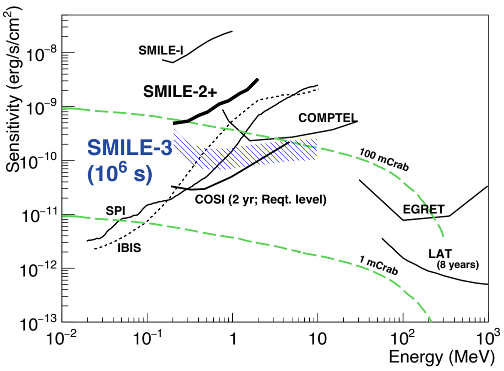

Figure 2: Expected SMILE-3 sensitivity with an exposure of 10^6 s for continuum emission.

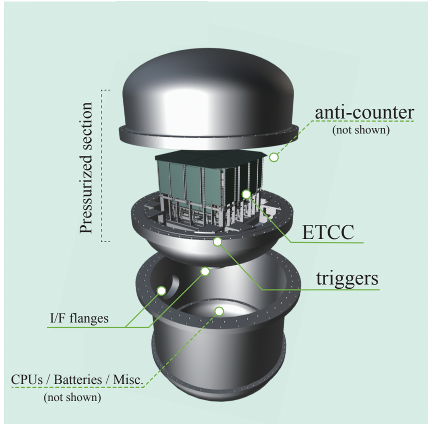

Figure 3: Overview of preliminary SMILE-3 vessel.

as reported by Ikeda et al. [7].

2.2 Balloon-borne Demonstration with SMILE-2+

The SMILE program has conducted a series of balloon-borne experiments to validate the ETCC concept under realistic observational conditions. In particular, the SMILE-2+ mission, conducted in 2018, involved a 26-hour balloon flight from Alice Springs, Australia, and marked a major milestone for MeV gamma-ray astronomy. During this flight, the ETCC successfully detected gamma rays from both the Crab Nebula [4] and diffuse gamma-ray emission from the Galactic Center region [8], with significance levels exceeding 4σ for both.

In addition to these source detections, detailed background analyses of the SMILE-2+ flight data have been reported [9]. These studies identified that the dominant background components around 1 MeV were accidental coincidences, gamma rays from internal radioactive isotopes in GSO(Ce) scintillators, and atmospheric gamma rays. Importantly, these background components were effectively suppressed by applying ETCC-specific event selections, including the α cut and dE/dx-based discrimination. These results experimentally validated the ETCC's background-rejection capability and confirmed its suitability for future diffuse gamma-ray observations, including wide-area mapping of the Galactic plane.

3. Upgrade to SMILE-3

Building on the achievements of the SMILE-2+ experiment, the SMILE-3 mission aims to advance MeV gamma-ray astronomy by enabling wide-area surveys and more detailed studies of diffuse gamma-ray emissions from the Galactic plane, extragalactic background gamma rays, and other astrophysical sources. The primary goal of SMILE-3 is to improve the detection sensitivity by an order of magnitude compared to SMILE-2+, which will be achieved through a larger effective area, improved energy and angular resolutions, and an extension of the energy coverage up to 10 MeV. Figure 2 shows an expected sensitivity of the SMILE-3 mission. To achieve this, we have implemented several major upgrades including TPC gas optimization, PSA readout improvement,

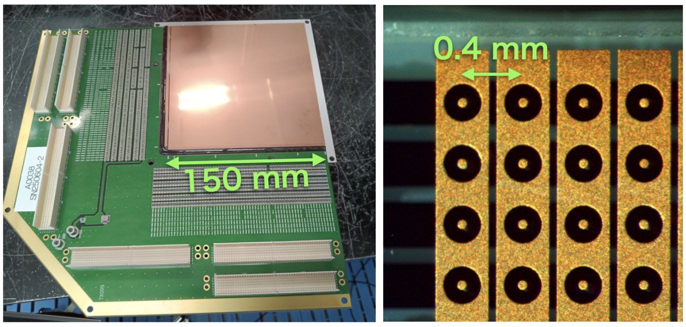

Figure 4: Picture of the TGV μ-PIC module (left) and its close-up view (right).

trigger logic redesign, and attitude determination enhancement. In addition to hardware upgrades, data analysis techniques for improving the effective area at higher energies have been developed. Specifically, a new event selection method that utilizes high-energy events in which recoil electrons escape the TPC volume and deposit energy in the PSA has been established [10].

The first flight of SMILE-3 is currently planned for early 2027, with a one-day balloon flight from Australia. Figure 3 shows a preliminary design of the SMILE-3 vessel. Preparatory work for flight qualification, environmental testing, and calibration is currently underway.

3.1 Gaseous Time Projection Chamber

The gaseous time projection chamber (TPC) in SMILE-3 serves as the primary scatterer for incident gamma rays in the ETCC. The TPC consists of a gas vessel filled with pressurized gas, providing a drift volume with a typical electric field strength of approximately 250 V/cm/atm. Recoil electrons generated by Compton scattering within the gas volume drift towards the gas amplification and readout section. The drifting electrons are first amplified by multiple layers of gas electron multipliers (GEMs) and then read out in two dimensions by a micro pixel chamber (μ-PIC) positioned below the GEM stack. This configuration allows precise measurement of both the three-dimensional track and energy deposit of recoil electrons, which is essential for event-by-event Compton kinematic reconstruction. To further enhance these capabilities, several upgrades have been implemented for SMILE-3.

A major change is the adoption of a 3 atm CF_4-based gas mixture, replacing the 2 atm argon-based gas used in SMILE-2+. This change reduces the photoabsorption probability while increasing the Compton scattering probability by lowering the atomic number and increasing the number of target electrons per unit volume. Additionally, the reduced electron diffusion in CF_4 leads to improved track resolution. We are also investigating the use of iso-C_4H_{10} as a quencher gas, including ongoing studies of potential Penning effect enhancements to improve gas gain under high-pressure conditions. To compensate for the lower gas gain expected at higher pressures, we are increasing the operational voltages of both the GEM and the micro pixel chamber (μ-PIC). To improve discharge tolerance, we have developed and adopted the Thick Glass Via (TGV) μ-PIC, in which the traditional polyimide substrate has been replaced with a glass substrate. For the SMILE-3 TPC, four 15 cm $\times$ 15 cm TGV μ-PIC modules shown in Figure 4 are combined to form a 30 cm $\times$ 30 cm readout area.

Furthermore, the μ-PIC readout pitch has been reduced from 0.8 mm to 0.4 mm, effectively doubling the spatial resolution and further enhancing track reconstruction accuracy. This reduction in pitch has increased the total number of readout channels, necessitating the development of new encoder boards to manage the higher channel density efficiently. These hardware upgrades, including the new gas system, TGV μ-PICs, and encoder boards, have been successfully tested in laboratory experiments confirming their operational stability and performance.

3.2 Pixelized Scintillator Arrays

The pixelized scintillator arrays (PSAs) in SMILE-3 serve as absorbers for the scattered gamma rays and play a critical role in determining both the energy and interaction position of the scattered photons. Each PSA unit consists of an 8×8 array of GSO(Ce) scintillator crystals with pixel dimensions of 6 mm $\times$ 6 mm. Two thicknesses are employed: 13 mm and 26 mm, corresponding approximately to 1 and 2 radiation lengths, respectively. Each thickness defines a separate PSA unit type. In the overall ETCC configuration, the 13 mm-thick units are positioned along the lateral sides of the TPC, while the 26 mm-thick units are placed beneath the TPC, providing enhanced absorption efficiency for scattered gamma rays over a wide solid angle.

For SMILE-3, the optical sensors have been entirely replaced with multi-pixel photon counters (MPPCs; S13361-3050NE-08). The spectral sensitivity of MPPCs matches well with the emission wavelength of GSO(Ce), leading to a substantial improvement in energy resolution compared to the multi-anode photomultiplier tubes (MAPMTs; H8500C, Hamamatsu) used in SMILE-2+. Additionally, the compactness of MPPCs allows for gapless array assembly, reducing the probability of escape for scattered gamma rays. The low power consumption of MPPCs also contributes to the overall power efficiency of the instrument. The improvement in PSA energy resolution not only enhances the energy resolution of the entire ETCC system but also improves the angular resolution for incident gamma rays by reducing the uncertainty in Compton kinematics. This leads to reduced contamination between sources in sky maps and enhances diffuse emission mapping capabilities.

The PSA readout electronics have also been redesigned [11]. A single readout board now handles six scintillator units, transmitting data via Ethernet through FPGA-based processing. To extend the dynamic range towards higher energies, the signal processing chain incorporates dual-gain amplifiers with different magnification factors. Pulse waveforms from each MPPC are digitized by sampling ADCs. The sampling rate has been reduced from 4.5 Msps to 2.5 Msps to lower power consumption, with laboratory test results confirming that this reduction does not degrade the energy resolution.

The scintillator crystals themselves are being reused from the SMILE-2+ payload after disassembly. To minimize systematic uncertainties arising from internal radioactivity, all GSO(Ce) crystals have been individually characterized for intrinsic background levels, as reported in Iiyama et al.[11].

Figure 5 shows reconstructed position and energy spectrum of ^{137}Cs source irradiation. This data demonstrates that all the pixels are clearly resolved and that the energy resolution at 662 keV has improved from 12% (SMILE-2+ case) to below 8%.

Furthermore, the trigger generation mechanism has been redesigned. In SMILE-2+, the trigger was generated within the FPGA after waveform acquisition. For SMILE-3, a dedicated

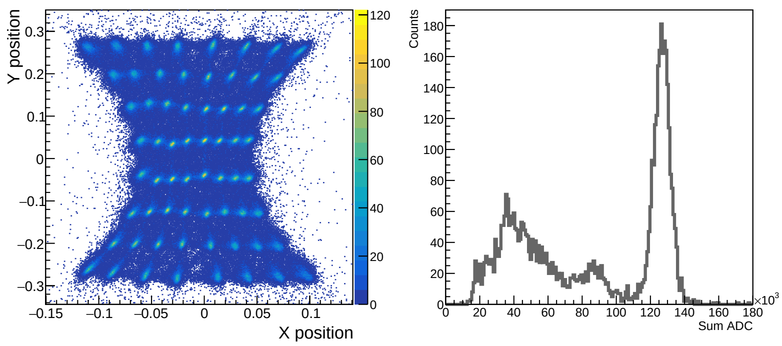

Figure 5: Reconstructed interaction positions and energy spectrum for 662 keV gamma-rays.

analog comparator circuit has been implemented at the front-end stage to issue trigger signals, thereby reducing processing load and latency.

At present, mass production of the PSA readout boards is underway. The complete system will consist of 18 boards to cover the full set of PSA units.

3.3 Other Subsystems

To reduce system dead time and improve observational efficiency, the trigger logic in SMILE-3 has been fundamentally redesigned. In SMILE-2+, a common-start trigger scheme was used, where detection of a hit in the PSA initiated the readout sequence, with the system waiting for the electron drift time in the TPC (approximately 9.5 μs) before completing event recording. Because the PSA hit rate was over two orders of magnitude higher than the true coincidence rate with the TPC, this approach resulted in substantial dead time, reaching approximately 20% during the SMILE-2+ flight. For SMILE-3, we have adopted a common-stop trigger logic. In this new scheme, the system continuously monitors TPC activity and, upon detection of a TPC hit, searches backward in time for corresponding PSA trigger signals within the expected time window. Laboratory tests have confirmed that this approach reduces the dead time by more than half compared to the SMILE-2+ configuration. A newly developed central trigger board manages time alignment and communication between the TPC and PSA readout boards and interfaces with the anti-coincidence detector for additional background suppression.

For attitude determination, a new star camera system has been developed. This upgrade was necessary because the pointing accuracy achieved by the geomagnetic aspect meter and clinometers used in SMILE-2+ was comparable to the expected angular resolution of the SMILE-3 ETCC, making them insufficient for the desired performance level. The new system consists of a CMOS camera coupled with a Raspberry Pi 4 for onboard image processing. It has successfully passed thermal vacuum tests and has already been flight-tested in a separate piggyback balloon experiment.

4. Summary

The SMILE-3 mission is being developed as a next-generation balloon-borne experiment to advance MeV gamma-ray astronomy. Building on the achievements of SMILE-2+, several major upgrades have been implemented to improve detection sensitivity, background rejection, and observational efficiency. Key improvements include the introduction of a 3 atm CF_4-based gas mixture and enhanced micro-pattern gas detectors in the TPC for better track resolution, the replacement of MAPMTs with MPPCs in the PSA for improved energy resolution and reduced power consumption, and a complete redesign of the trigger logic to reduce system dead time. Supporting subsystem upgrades, including a newly developed star camera and optimized anti-coincidence active shield, are also underway.

Currently, subsystem-level integration tests such as element integration tests, thermal vacuum tests, and full system compatibility checks are ongoing in preparation for the launch site shipment. The first flight is planned for early 2027 from the same launch site used for the SMILE-2+ mission in Alice Springs, Australia. The flight profile will follow a similar daytime one-day flight path as the previous mission. This mission is expected to contribute significantly to MeV gamma-ray astronomy by enabling sensitive observations of diffuse Galactic gamma-ray emission and other astrophysical targets.

Acknowledgement

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 performed at the BL1U of UVSOR Synchrotron Facility, Institute for Molecular Science (IMS program 25IMS6607).

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