



SMILE: A Balloon-Borne sub-MeV/MeV Gamma-ray Compton Camera Using an Electron-Tracking Gaseous TPC and a Scintillation Camera

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Abstract: We have been developing an Electron-Tracking Compton Camera (ETCC) as a next generation MeV gamma-ray detector, consisting of a gaseous electron tracker which measures the three-dimensional track and the energy of the Compton-recoil electron, and pixel scintillation arrays which measure the absorption point and the energy of the scattered gamma ray. As the first step toward a future all-sky survey with a planned sensitivity of one order magnitude higher than COMPTEL, we successfully observed the diffuse cosmic and atmospheric gamma rays at balloon altitudes with a small ETCC in the Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment I (SMILE-I). Building on the success of the SMILE-I ETCC, we are developing a large size ETCC for the next flight to observe celestial objects in the sub-MeV/MeV region. This larger detector is expected to achieve a sensitivity comparable to COMPTEL.

Keywords: MeV gamma-ray, balloon, Compton telescope, gasous detector.

1 Introduction

The exploration of the sky in the sub-MeV/MeV gamma-ray band is a good probe for investigations of high energy astronomical phenomena. This band is a unique window for gamma-ray lines produced by nuclear deexcitation which comes from radioactive nucleosynthesis products in supernovae, such as, ⁵⁶Ni, ⁵⁷Ni, and ⁴⁴Ti. Moreover, continuum emissions in this band are key to the survey of particle acceleration such as synchrotron radiation and/or inverse Compton scattering in supernova remnants.

To detect these soft gamma-rays a Compton telescope, which exploits Compton scattering to image the gamma rays, is one of the prominent methods. COMPTEL aboard the *Compton Gamma-Ray Observatory (CGRO)*, which is the first satellite-borne Compton telescope, successfully discovered ~ 30 steady gamma-ray sources in the 0.75-30 MeV band [1]. Observation in this band is, however, difficult, because in the soft gamma-ray band a detector suffers from large backgrounds of photons produced in hadronic process between cosmic rays and the instruments. In fact, the number of steady MeV gamma-ray sources observed by COMPTEL is quite limited in view of the fact that EGRET detected ~ 270 sources [2] in the sub-GeV/GeV band above 100 MeV, and *Fermi* found 1451 sources dur-

ing the first 11 months of the all-sky survey in the 0.1-100 GeV band [3].

Hence, we have developed an Electron-Tracking Compton Camera (ETCC) which uses a new detection method and has a powerful background rejection capability.

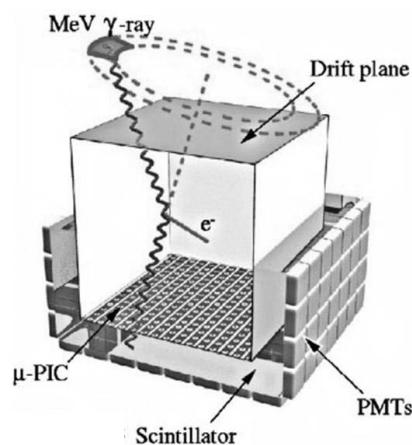


Figure 1: Schematic view of ETCC.

2 Instruments

A schematic view of the ETCC is shown in Fig. 1. The ETCC consists of two detectors; an electron tracker and a gamma-ray absorber. The former detects the three-dimensional track and energy of the Compton-recoil electron, the latter the absorption point and the energy of the Compton-scattered gamma-ray.

The conventional Compton telescope detects not the track but the interaction point of the Compton scattering, such that it can only reconstruct the direction of the incident gamma ray to an 'event circle'. On the other hand, the ETCC can measure the three-dimensional electron track, allowing the incident gamma-ray direction to be constrained to a reduced arc on the circle. Moreover, the residual angle between the scattering direction and the recoil direction provides a kinematical method of background rejection. This angle can not only be measured geometrically but can also be calculated by the kinematics of Compton scattering. By comparing these values, we can select Compton scattering events to obtain gamma-ray images with high signal to noise ratio.

2.1 A gaseous electron tracker

As an electron tracker, we use a gaseous time projection chamber (TPC) [4] using a micro pixel chamber: μ -PIC [5] and a gas electron multiplier: GEM [6, 7]. The μ -PIC, our own original detector, is a kind of micro pattern gas detector manufactured with Printed Circuit Board (PCB) technology. It has a pixel pitch of $400\ \mu\text{m}$ with strip readout and a high gas gain of about 6000 which remained stable during over 1000 hours of operation. Combining the μ -PIC and the GEM with a stable, high gas gain of about 35000, we can obtain the tracks of minimum ionization charged particles. The gas around the path of charged particle is ionized, producing electrons which drift through the electric field applied in the TPC with constant velocity. If we know the arrival time of the charged particle, we can obtain the distance between the ionization point and the anode using the traveling time of the drift electrons. Figure 3 shows the tracks of charged particles obtained by a 10 cm cubic TPC. The position resolution of the TPC is approximately $500\ \mu\text{m}$ as estimated using the tracks of cosmic muons. Taking advantage of the ease of making a large area with the PCB technology, we have already developed a large μ -PIC with an area of $30 \times 30\ \text{cm}^2$ (Fig. 2c).

2.2 Gamma-ray absorber

As a gamma-ray absorber, we selected $\text{Gd}_2\text{SiO}_5(\text{Ce})$ (GSO:Ce) pixel scintillator arrays (PSAs), since GSO:Ce has strong stopping power and high energy resolution. Each unit of PSAs installed in the ETCC consists of 8×8 pixels of $6 \times 6 \times 13\ \text{mm}^3$ of GSO:Ce coupled to the multi-anode position sensitive photomultiplier tubes, Hamamatsu flat-panel PMT H8500[8]. To reduce the number of readout

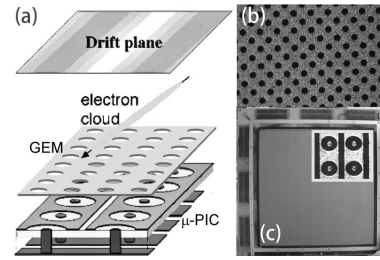


Figure 2: Schematic view of TPC (a), microphoto of GEM (b), photo of $30 \times 30\ \text{cm}^2$ μ -PIC and microphoto of pixel electrode (c).

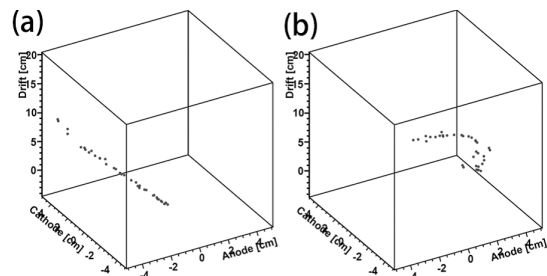


Figure 3: Obtained tracks of cosmic muon (a) and Compton-recoil electron produced by gamma ray using TPC.

circuits, we use resistor matrices and obtain the position of the hit pixel using the center of the weight from 4 readouts placed at the corners. The summation of the signals from the corners are used as the trigger for the TPC to tell the initial time. The typical average of energy resolution of PSAs is approximately 11% at full width at half maximum (FWHM) for 662 keV gamma rays.

3 Balloon-borne experiment: SMILE

We already confirmed our detector concepts with the ground-based experiments [9]. Since gamma rays from celestial objects are scattered or absorbed in the atmosphere, detectors must be positioned above the atmosphere to observe in the MeV band. Thus, as the step toward a future all-sky survey with a planned sensitivity that is one order of magnitude higher than that of COMPTEL, we planned the balloon-borne experiments "Sub-MeV gamma-ray Imaging Loaded-on-Balloon Experiment" (SMILE).

3.1 SMILE-I

For the first flight of SMILE (hereafter SMILE-I), we constructed a small size ETCC as the flight model, which consisted of a TPC with a volume of $10 \times 10 \times 14\ \text{cm}^3$, filling gas of Xe/Ar/C₂H₆ (80:18:2) at 1 atm, and 33 units of GSO:Ce PSAs. The effective area of the SMILE-I flight

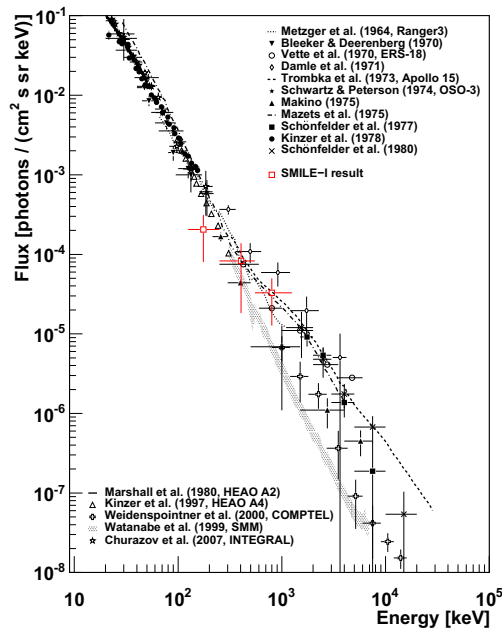


Figure 4: Observed flux of the diffuse cosmic gamma rays. Our SMILE-I results are represented with the open squares.

model was approximately 1 mm^2 in the energy range between 150 keV and 1.5 MeV at a zenith angle less than 60 degrees [10].

The SMILE-I flight model was launched from Sanriku Balloon Center, Japan, on September 1, 2006. The duration of the flight lasted 7 hours, that of level flight at an altitude of about 35 km was 4 hours (the live time: 3 hours). During the flight, we obtained about 2000 events which could be successfully reconstructed, and 420 downward events during the level flight, which is consistent with the expected number of 400 events determined using Geant4 simulation.

Using the dependence between the atmospheric depth and the counting rate, we calculated the fluxes of the diffuse cosmic and atmospheric gamma rays, which was consistent with those of other past observations, as shown in Fig. 4 [10].

3.2 SMILE-II

Building on the success of the SMILE-I ETCC, a larger ETCC incorporating a TPC with a size of $30 \times 30 \times 30 \text{ cm}^3$ is being developed for the next flight, SMILE-II. The motivation of SMILE-II is to observe a bright celestial source, for example, the Crab nebula, to test the imaging performance. To achieve this, we plan two balloon flights for SMILE-II: the first will launch from Taiki Aerospace Research Field (TARF), Japan, for a test of the system operation, and the second will observe the Crab nebula with a long duration, circumpolar balloon flight launched from

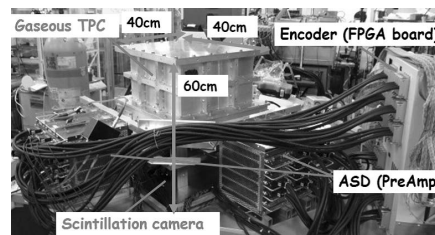


Figure 5: Photo of SMILE-II prototype for ground-based experiments.

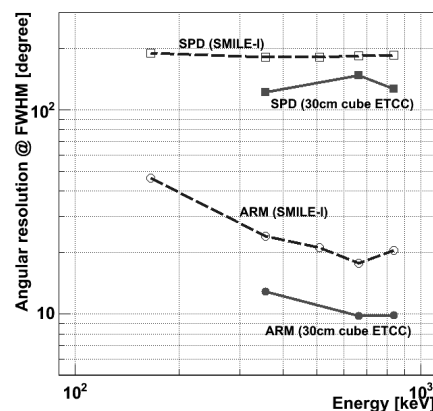


Figure 6: Angular resolutions of the SMILE-II prototype (30 cm cube ETCC) and the SMILE-I flight model.

Kiruna, Sweden. In the polar region, there are terrestrial gamma-ray bursts due to Relativistic Electron Precipitation (REP), which is key to the investigation of the generation and circulation of ozone and NO_x in the upper atmosphere[11]. Thus, we also plan a multiwavelength campaign to observe REP bursts in combination with the observation in the radio band by EISCAT. The ETCC is one of the best-suited detectors to observe REP bursts, because it has a wide field of view of about 3 str, an angular resolution of several degrees, and a high time resolution less than 1 ms.

4 Performance of SMILE-II prototype

For the purpose of the observation of the Crab nebula and the REP burst, the criteria of the SMILE-II ETCC are an effective area larger than 0.5 cm^2 and an angular resolution better than 10 degrees at FWHM, for 200 keV gamma rays. As the first step to attain these, we are developing a prototype ETCC consisting of a TPC with a volume of $23 \times 28 \times 30 \text{ cm}^3$ filled with a gas mixture of 90% argon and 10% ethane in the ratio of partial pressure and sealed at 1 atm, and 36 units of GSO:Ce PSAs as shown in Fig.

5. Figure 6 shows the angular resolutions of the ETCC described by two parameters. One is the angular resolution measure (ARM) representing the accuracy of the scattering angle. The other is the scatter plane deviation (SPD) representing the decision accuracy of the scatter plane. The ARM and SPD of the SMILE-II prototype are 9.8 degrees and 147 degrees at FWHM for 662 keV, respectively, which is better than that of the SMILE-I flight model. The energy resolution of the SMILE-II prototype is approximately 12% at FWHM for 662 keV, which is comparable with that of SMILE-I. The detection efficiency and the effective area of the SMILE-II prototype are 2.05×10^{-5} and $1.3 \times 10^{-2} \text{ cm}^2$ for 662 keV. To fulfill the requirements for SMILE-II, it is still necessary to increase the effective area.

5 Simulation for SMILE-II flight model

We have already developed a large ground-based ETCC as the SMILE-II prototype, and successfully demonstrated the imaging of gamma rays. Effective area is, however, still necessary to improve for the SMILE-II requirements. Therefore, we are considering to apply the following improvements.

First, we will optimize the filling gas in the TPC to use the $\text{Ar}/\text{CF}_4/\text{iso-C}_4\text{H}_{10}$ (54:40:6) gas at 1.4 atm, which improves the detection efficiency by a factor of about 2 compared with the $\text{Ar}/\text{C}_2\text{H}_6$ (90:10) gas at 1.0 atm [12]. Second, we will cover the TPC with more units of PSAs, from 36 units to 72 units on the bottom of the TPC and 36 units at each side of the TPC. In this way the SMILE-II flight model has a large geometrical coverage area by a factor of 6 than that of the SMILE-II prototype. Third, we will use a large GEM with an area of $31 \times 31 \text{ cm}^2$ and utilize the full size of a $30 \times 30 \text{ cm}^2$ μ -PIC to increase the fiducial volume.

We simulated the properties of the gamma-ray detection including these improvements, and then found that the effective area of the SMILE-II flight model is expected to be 0.5 cm^2 at 300 keV, which meets the requirement. From the result of SMILE-I, the dominant background events for the ETCC at balloon altitude are gamma rays, consisting of atmospheric, diffuse cosmic and instrumental gamma rays. The ratio of the number of events of instrumental gamma rays to that of all background gamma rays is approximately 20%. The effects of other particles are less than 0.2%. If the intensity of the instrumental gamma rays in SMILE-II is the same as that of SMILE-I, the detection sensitivity of SMILE-II flight model is expected to be about 50 times better than that of SMILE-I, as shown in Fig. 7.

6 Summary

We have developed an ETCC consisting of a gaseous time projection chamber and pixel scintillator arrays as a next generation MeV gamma-ray detector. As the first step toward a future all-sky survey, we observed diffuse cosmic

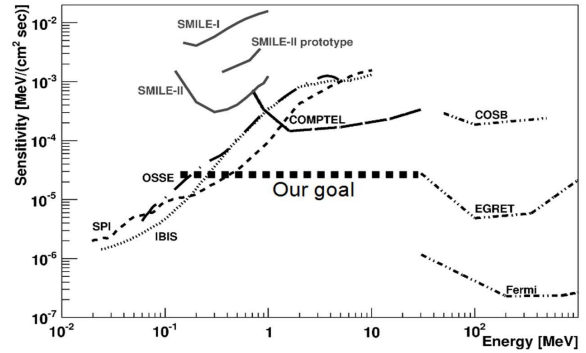


Figure 7: Sensitivity curves of SMILE-II prototype, SMILE-II flight model (expected), SMILE-I flight model, our goal and other missions. We assume $\Delta E = E$ and $T_{\text{obs}} = 10^6 \text{ sec}$.

and atmospheric gamma rays at balloon altitudes with the small ETCC (SMILE-I). Building on the success of the SMILE-I flight model, we have been developing a larger ETCC using the TPC with a volume of $30 \times 30 \times 30 \text{ cm}^3$ to observe the Crab nebula and REP bursts for the demonstration of the imaging property. A SMILE-II prototype has been constructed and is already under the stable operation. The prototype has angular resolutions of 9.8 degrees and 147 degrees of ARM and SPD at FWHM for 662 keV, respectively. With the improvements we plan to apply, the sensitivity of the SMILE-II flight model is expected to be about 50 times better than that of SMILE-I, which is comparable with that of COMPTTEL.

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