All Sky Survey with an Electron-Tracking Compton and Pair-Tracking Camera using a Gaseous Time Projection Chamber

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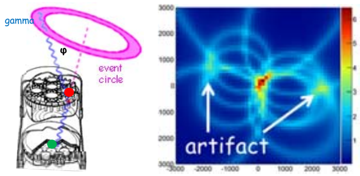
1. Difficulty of MeV gamma Observation

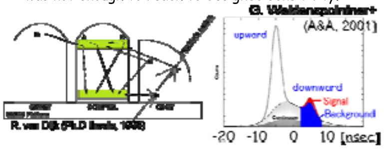
Difficulty of Imaging

Because usual Compton cameras can not detect the direction of Compton-recoil electron, the incident direction is restricted only to an 'event circle.' Therefore, many artifacts appear in the obtained images, and the signal-to-noise ratio (S/N) becomes low.



Huge Background

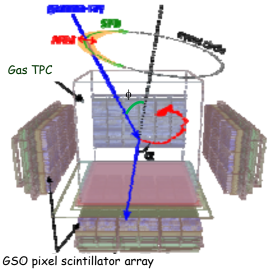
Cosmic rays create gamma rays, neutrons, and charged particles by the interaction with the satellite body. Especially, gamma rays from the excited nuclei have the energy within sub-MeV/MeV. COMPTEL tried to reject such background using the time of flight (TOF) between two detectors, but it was not enough to reach to designed sensitivity.



The requires for the next generation telescopes are …

- Good Angular resolution = Good Energy resolution
- Redundancy of Background rejection (TOF, Compton kinematics, dE/dx, …)
- Recoil direction (decision of scatter plane)

2. Electron-Tracking Compton Camera

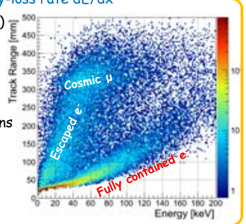


ETCC using a gaseous time projection chamber

Our ETCC consists of a gaseous time projection chamber (TPC), which detects the track and energy of the recoil electron, and a scintillator, which detects the absorption point and the energy of the scattered gamma ray. Using the direction of the recoil electron, we can reconstruct the Compton scattering completely and obtain the fully ray-traced gamma-ray image.

Particle identification by the energy-loss rate dE/dx

Because the energy-loss rate (dE/dx) depends on the mass, charge, energy of charged particles, we can identify the particle kind using dE/dx. A Compton scattering create only one electron. Utilizing this dE/dx event selection, an ETCC can reject neutrons and charged particles. The right figure shows the dE/dx distribution obtained by our ETCC. The events of fully-contained electron is clearly separated from other components.



Compton kinematics test

The angle α between the scattering direction and the recoil direction is measured geometrically

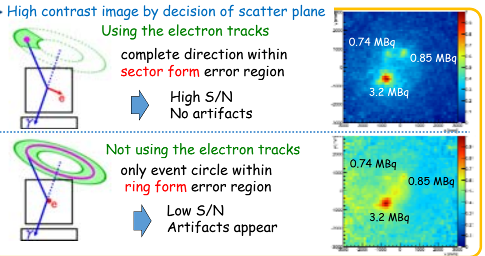
$$\cos\alpha_{geo} = \vec{g}\cdot\vec{e}$$

and also this angle is obtained by the calculation using the energies of the recoil electron and the scattered gamma ray

$$\cos\alpha_{kin} = \left(1-\frac{m_e c^2}{E_\gamma}\right)\sqrt{\frac{K_e}{K_e+2m_e c^2}}$$

Therefore we can select the good events of which the kinematical calculated angle is consistent with the measured one. Because of the background rejection by the angle α, the ETCC fits for the MeV gamma-ray astronomy, whose serious problem is the obstruction by background.

High contrast image by decision of scatter plane



3. Performance of Current ETCC

Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment

For the future observations with loading on a satellite, we have a plan of balloon experiments. As the first step, we launched a small ETCC using a 10 cm cube TPC in 2006 (SMILE-I). By the background rejection power of ETCC, it was successful to observe diffuse cosmic and atmospheric gamma rays. The next step (SMILE-II) is an observation of the Crab nebula using a middle size ETCC.

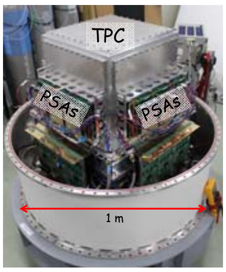
Requirements for SMILE-II
- Effective area : > 0.5 cm² (< 300 keV)
- Angular resolution : < 10° (662 keV)

Gaseous Electron Tracker

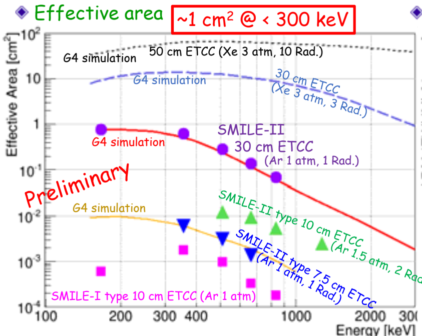
Effective volume	30 x 30 x 30 cm³
Gas	Ar:iso-C_4H_{10}:CF_4 (95:2:3), 1 atm.
Spatial resolution	~0.5 mm
Energy resolution (FWHM)	22 % (@ 22 keV)

Pixel scintillator arrays

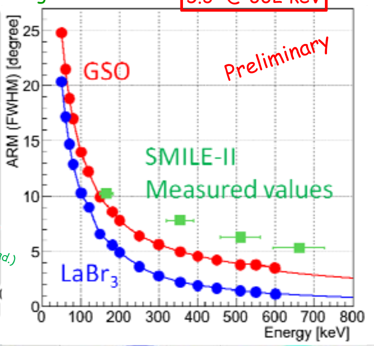
Scintillator	GSO:Ce (6.71 g/cm³)
Pixel size	6 x 6 x 13 mm³
# of pixels	6912
Dynamic range	80 keV—1.3 MeV
Energy resolution (FWHM)	10 % (@ 662 keV)



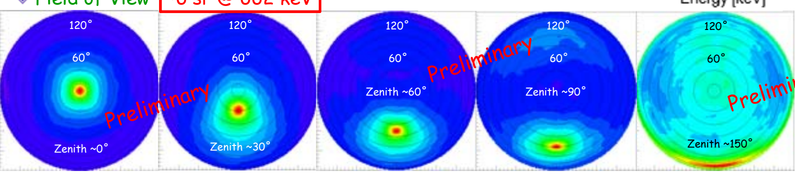
Effective area ~1 cm² @ < 300 keV



Angular resolution 5.3° @ 662 keV



Field of View ~6 sr @ 662 keV

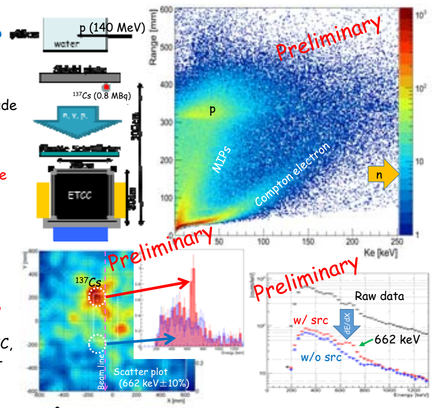


4. Observation in Intense Radiation Field

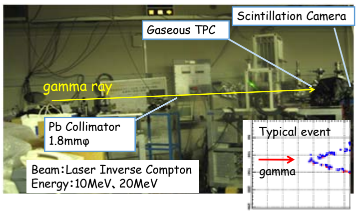
Can our ETCC detect gamma-ray checking source in intense radiation field?

- Irradiation proton beam to water target
  -> produced gamma, neutrons, protons, …
- gamma : neutron = 3 : 1 @ ETCC
  -> similar to background at the balloon altitude
- Observation ^{137}Cs under this situation

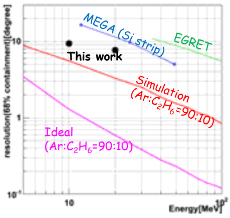
- Our ETCC can be operated in 5 times more intense background than the expectation at the balloon altitude in middle latitude.
- Utilizing the particle identification by dE/dx, the events of fully-contained electron is clearly separated from other components.
- The effective area, which is calculated using the energy spectrum obtained by this experiment, is nearly equal to the effective area obtained at low background observation.
- By the efficient background rejection of our ETCC, we can obtain the background-suppressed energy-spectra and images.



5. Pair Tracking Imaging



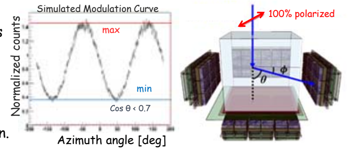
We had a proof of principle experiment of Pair tracking mode using the laser inverse Compton beam on 13-14, Oct., 2009 at AIST. We obtained angular resolutions of 9.4 and 7.7 degrees (68% containment) at 10 and 20 MeV, respectively. These resolutions are better by factor of about 1.4 than those of the silicon strip detector.

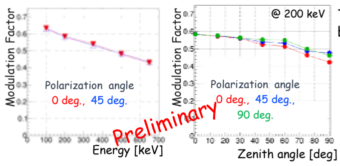


6. Ability of Polarization Measurement

Simulation study by Geant4

For astronomical polarimetry, the requirements for detectors are a large modulation factor, a large effective area, a efficient background rejection, and a clear imaging. Because the azimuthal angle distribution of Compton scattering has asymmetry for polarization of incident gamma ray, our ETCC has a sensitivity for gamma-ray polarization. Therefore, we studied the current ETCC (SMILE-II) using Geant4 simulation.



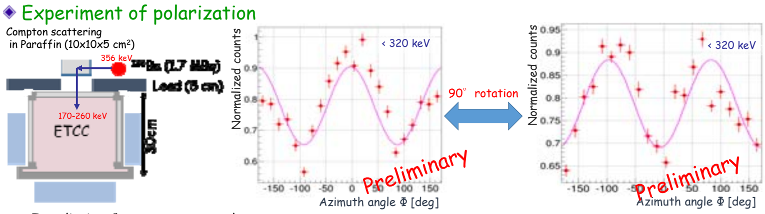


The low-energy gamma-ray polarimetry will be realized with balloon experiments, if our ETCC has a effective area of ~10 cm².

3σ Minimum Detectable Polarization of SMILE-III

- mid-latitude, 40 km, 10 hours flights
  - Crab : ~ 20% Cyg X-1 : ~ 30%
- polar region, 40 km, 1 month flights
  - GRBs : 10^{-6} erg/cm²/s (2-3 GRBs/month) ~ 8%
  - 10^{-7} erg/cm²/s (~10 GRBs/month) ~ 30%

Experiment of polarization

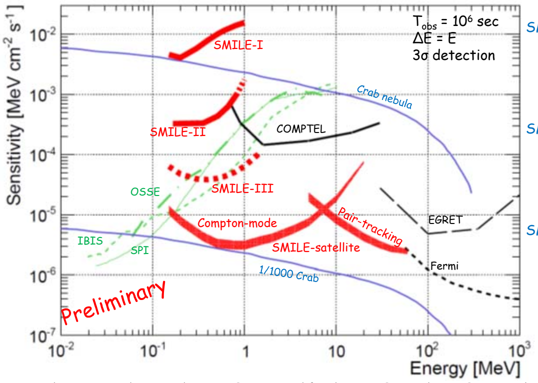


- Irradiation Compton-scattered gamma ray
  - scattering angle : 50-130°
  - energy : 170-260 keV
  - fraction of polarization : ~40%
- Background dominated observation
  - Signal : BG = 0.17 : 1 (trigger rate)

- It was successful to obtain clear modulation curves.
- ETCC can observe polarization of faint sources.

For more detail study, SMILE-II ETCC will be tested at SPring-8, in Jan. 2015.

7. Expected Detection Sensitivity



SMILE-II (current ETCC) :
30 cm-cubic TPC (Ar 1 atm)
GSO (1 Radiation length)
detectable Crab nebula with 3 h at 40 km

SMILE-III :
30 cm-cubic TPC (Xe 3 atm)
GSO (3 Rad. length)
detectable polarization of Crab nebula with balloon

SMILE-Satellite :
50 cm-cubic TPC (Xe 3 atm) × 4
$LaBr_3$ (10 Rad. length)
reach to 1 mCrab
×100 higher sensitivity than COMPTEL

The background observed in SMILE-I was used for the SMILE-II and SMILE-III simulations, and an extra diffuse gamma flux in 0.1-5 MeV reported by SMM and COMPTEL were included for the Satellite-ETCC. Also 2D-Lorentzian distribution was used as a response function of the ETCC for the point source, and thus 1/4 of detected gamma rays from the point source concentrated in FWHM was used for the calculation of expected flux based on the formula of 2D-Lorentian. A duty factor of 0.5 in the operation of the Satellite-ETCC was assumed.

SMILE will become a new pioneer of MeV astronomy.
Let's join the SMILE project !!

http://www-cr.scphys.kyoto-u.ac.jp/research/MeV-gamma/index_e.html