Electron-Tracking Compton Telescope
Based on a Gaseous TPC and a Scintillation Camera (SMILE)

A. Takada (ISAS/JAXA),
T. Tanimori, H. Kubo, K. Miuchi, S. Kabuki, H. Nishimura,
(Kyoto Univ.)

- Motivation
- Electron-Tracking Compton Telescope
- 1st Flight of SMILE
- Preparation for next step
- summary

Joint Gamma-ray Mission Meeting 2009
ISAS/JAXA, Sagamihara, Japan, March 10-11, 2009.
Motivation

Observation of MeV gamma-ray will provide us...

- **Nucleosynthesis**
  - SNR: Radio-isotopes
  - Galactic plane: $^{26}\text{Al},^{60}\text{Fe}$
  - Annihilation

- **Acceleration**
  - Jet (AGN): Synchrotron + Inverse Compton

- **Strong Gravitational Potential**
  - Black Hole: accretion disk, $\pi^0$

- **Etc.**
  - Gamma-ray Pulsar, solar flare

- Line gamma
- Continuum
- Continuum + Line

- The observation of continuum component is also important.
- Where are MeV gamma-ray objects?
- There are many background events which obstruct the observations.

Requirements for the next-generation detectors are...

- Wide-band detection
- Large Field of View
- Background rejection
Electron-Tracking Compton Imaging

- **Gaseous TPC**: Tracker track and energy of recoil electron
- **Scintillator**: Absorber position and energy of scattered gamma

Reconstruct Compton scattering event by event

- 1 photon \(\Rightarrow\) direction + energy
- Large FOV \((\sim 3\text{str})\)
- Kinematical background rejection

\[
\begin{align*}
\cos \alpha_{\text{geo}} &= \vec{g} \cdot \vec{e} \\
\cos \alpha_{\text{kin}} &= \left(1 - \frac{m_e c^2}{E_\gamma}\right) \sqrt{\frac{K_e}{K_e + 2m_e c^2}}
\end{align*}
\]

- \(g\): unit vector of scattering direction
- \(e\): unit vector of recoil direction
- \(E_\gamma\): Energy of scattered gamma-ray
- \(K_e\): Kinematic energy of recoil electron
- \(m_e c^2\): Rest mass of electron
Sub-MeV gamma-ray Imaging Loaded-on-balloon Experiment

10cm cube camera @ Sanriku (Sep. 1st 2006)
- Operation test @ balloon altitude
- Observation of diffuse cosmic/atmospheric gamma
  ~400 photons during 3 hours (100 keV~1MeV)

30cm cube camera
- Observation of Crab/Crg X-1

40cm cube camera Sub-MeV ~ MeV
- Long duration observation with super pressure balloon
- Adding pair-creation mode

50cm cube camera
- All sky survey (load on a satellite)
SMILE-I gondola

- Plastic scinti.
- TPC
- GSO scinti.
- preamplifier
- NIM module
  - Shaper
  - DAC
- VME module
  - CPU
  - ADC
  - telemetry
  - scaler
- FPGA encoding board
- Regulator
- Bessel
- Battery
- Ballast

Size: 1.45x1.2x1.55m³
Weight: 397 kg
Power: ~250 W
No posture control!!
Gas: Xe 80% + Ar 18% + C$_2$H$_6$ 2%
1 atm, sealed

Gain: ~35000

Drift velocity (V$_d$=400V/cm):
- measured: 2.5 cm/$\mu$s
c- simulation: 2.48 cm/$\mu$s

Volume: 10 × 10 × 14 cm$^3$

Energy resolution:
- ~45% (22.2 keV, FWHM)

Position resolution: ~500 $\mu$m
Gaseous-TPC (Time Projection Chamber)

- Cosmic muon
- Recoil electron
Scintillation Camera

- Scintillator: GSO(Ce)
- Pixel size: 6×6×13 mm³
- Photo readout: H8500 (HPK)
- DC/HV: EMCO Q12N-5
- A unit consists of 192 pixels, 3 PMTs, 3 DC/HV and 4 preamplifier
- 4 channels readout with resistive chain
- Bottom: 3×3 PMTs
- Side: 3×2 PMTs × 4
- Energy resolution: ~11% (662 keV, FWHM)

137Cs Position imaging map

Absorber Unit
• Detection Efficiency: $3 \times 10^{-4}$ for 150-1500 keV
• Effective area: $2 \times 10^{-2}$ cm$^2$ for 150-1500 keV, 0-60°
• The simulated effective area was roughly consistent with that obtained by experiments.
• Effective area has a maximum at $\sim 25°$ <- caused by the geometry
Energy/Angular Resolution

Energy resolution

- TPC: 45% @ 22keV  Scint.: 11% @ 662keV -> 12% @ 662keV
- ARM 22°  SPD 165° @ 662keV
- Energy resolution of ETCC was almost equal to that of scintillation camera.
- ARM was limited by the energy resolution of Absorber and the accuracy of Compton point.
- SPD was limited by the accuracy of recoil direction and that of Compton point.

Angular resolution

- Theoretical limit of ARM by Doppler broadening
1st Flight

- Sanriku Balloon Center (JAXA)
- Launch at Sep. 1st 2006

There was no serious trouble during this flight!
1st Flight
Compton event rate & spectrum

Rate of Compton event
- 100~900 keV
- All direction ~2000
- in FOV (3 str) ~940

Energy Spectrum
- 32~35 km level flight
- 3.5 hours (live ~3h)
- in FOV event
  ~420 events
  GEANT4 ⇒ ~400 events
Background simulation with QARM
QinetiQ Atmospheric Radiation Model
http://qarm.space.qinetiq.com

Differential flux of background particles
@ 7g/cm²
- Black: QARM (downward)
- Grey: QARM (upward)

Proton
Electron
Neutron

Flux [ph/sec/cm²]
Differential flux of background particles
Atmospheric depth dependence

2006/09/01, 39.16N, 141.82E,
Source: Galactic Cosmic Rays, Kp=3
Majority of BG was gamma produced in the gondola (BG-gamma).

Simulator expected:
- Obtained Compton events at level flight
- Gamma-ray ~78%
- BG-gamma ~20%
- Neutron 1.5%
- Charged particle < 0.25%

Particles incoming to TPC @ 7 g/cm²

Spectrum of Background gamma @ 7 g/cm²
Dependence of gamma-ray flux on Atmospheric depth

- **Cosmic:** $\phi_C = \phi_d + \phi_s$
  - directory incoming component: Gamma-rays are attenuated by atmosphere
    \[ \phi_d = A \times \exp \left( - \frac{z}{\tau_{\text{tot}}} \right) \]
  - scattered component: Gamma-rays are scattered in atmosphere before reaching the detector
    \[ \phi_s = p(E, z) \times \phi_d \]

- **Atmospheric:** $\phi_A$
  The component of the interaction of charged particle and atmosphere
  \[ \phi_A = B \times z \]

$z$: atmospheric depth
$\tau_{\text{tot}}$: mean free path
$p(E, z)$: correction factor
$A, B$: free parameter
Our results were consistent with those of past observations!!!
**Toward Next Step**

- **SMILE-I** : 1<sup>st</sup> Sep. 2006 launched
  - Observation of diffuse cosmic/atmospheric gamma-rays
    -> detection by integration in a large FOV
  - Electron Tracker : 10x10x15 cm<sup>3</sup>, Xe+Ar 1atm
  - Absorber : 15x15x1.3 cm<sup>3</sup> @ Bottom
    15x10x1.3 cm<sup>3</sup> x4 @ Side
  - Effective area : ~2x10<sup>-2</sup> cm<sup>2</sup>

- **SMILE-II**
  - Observation of a Bright object (Crab nebula or Cyg X-1)
    3.0 hours, 40 km
  - Requirement : ~1 cm<sup>2</sup>
  - Electron Tracker : 30x30x30 cm<sup>3</sup>, Ar/CF<sub>4</sub> 2atm
  - Absorber : 30x30x1.3 cm<sup>3</sup> @ Bottom
    30x15x1.3 cm<sup>3</sup> x4 @ Side
  - Improvement of Angular resolution
Improvement of Angular resolution

LaBr₃ array

MAPMT HPK H8500

4.1 ±0.1 % @ 356 keV

GSO

LaBr₃

limited by energy resolution of absorber and the accuracy of Compton point

Xe + GSO(Ce) => Ar + LaBr₃

22° => 4.2° @662 keV

FWHM

Counts (arb. units)

0 0.2 0.4 0.6 0.8 1

Energy [keV]

250 300 350 400 450

10² 10³

Energy [keV]

SMILE-I 2006

(Xe + GSO)

Ar TPC + GSO (2008)

Ar TPC + LaBr₃ (2008)
We are developing a larger ETCC based on the 30cm $\times$ 30cm $\times$ 30cm TPC and 6 $\times$ 6 scintillation cameras.

- **Gaseous TPC**
  - volume: 30 $\times$ 30 $\times$ 30 cm$^3$
  - gas: Ar 90% + C$_2$H$_6$ 10% (1atm)
  - drift velocity: 4 cm/μsec
  - gain: $\sim$30000
  - energy resolution: 46%@32keV
  - position resolution: 400 μm

- **Scintillation Camera**
  - number of pixels: 2304 pixels
  - Crystal: GSO(Ce)
  - pixel size: 6 $\times$ 6 $\times$ 13mm$^3$
  - energy resolution: 10.9% (@662keV, FWHM)
  - position resolution: 6mm
Gaseous TPC

40cm

40cm

Encoder (FPGA board)

60cm

ASD (PreAmp)

Scintillation camera

Setup

source

Z

Y

Gaseous TPC

X

Center of μPIC : (0, 0, 0)

Center of Scinti. : (-3.3, 0.2, 5.7)
Gamma-ray imaging (preliminary)

All range

$^{137}$Cs: 662 keV

$^{54}$Mn: 835 keV

580-740 keV

$^{137}$Cs: 662 keV

‘W’ (364 keV)

760-910 keV

$^{54}$Mn: 835 keV
**Summary**

- We develop an Electron-Tracking Compton Camera.
- The flight model detector for SMILE-I
  - Energy resolution: ~12% for 662keV @ FWHM
  - Detection efficiency: ~2×10⁻⁴ for 356 keV
  - Field Of View: ~3str
- The first balloon was launched on September 1st, 2006 from Sanriku-Balloon-Center (ISAS/JAXA).
- The balloon flight lasted 7 hours, and the level flight continued during 4 hours at the altitude of 32-35 km.
- Our detector was stable at the balloon altitude.
- The experiment is the first observation using ETCC at the balloon altitude.
- There were ~2000 gamma-ray events in this flight, and ~420 gamma-ray events in FOV during the level flight.
- We confirmed the past observations of the fluxes of diffuse cosmic and atmospheric gamma-rays.
- Our detector realized a large FOV and a high S/N at the balloon altitude.
- Now, we are developing a larger volume detector for the next step.
Sensitivity of X/Gamma-ray observations

- Photo Absorption
- Compton
- Pair Creation

Erg / (cm² sec)

- SMILE-I
- SMILE-II
- COMPTEL
- EGRET
- AIR Cherenkov
- FERMI

Obs. Time: $10^6$ sec

- NeXT
- ASCA
- JEM-X
- CHANDRA, NEWTON
- Δθ: 1'' ~ 1'
- ΔΩ: All Sky
- All Sky
- All Sky
- All Sky
- Pointing
- < 0.1°
- < 0.1°
Thank you!