Gamma-ray Imaging with a Large micro-TPC and a Scintillation Camera

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Detection Sensitivity in the X/gamma-ray band

MeV band
✓ COMPTEL (CGRO)
✓ INTEGRAL

Sensitivity (ergs cm\(^{-2}\) s\(^{-1}\))

- COMPTEL (CGRO)
- INTEGRAL
- GLAST (2007)
- EGRET
- AIR CHERENKOV
- JEM-X
- COMPTEL
- Integral IBIS
- Integral IBIS
- ASCA
- CHANDRA, NEWTON
- ASCA
- CHANDRA, NEWTON
- ASCA
- CHANDRA, NEWTON
- ASCA
- CHANDRA, NEWTON

Our Goal

10 times as high sensitivity as that of COMPTEL

MeV band

All-sky survey

\(\Delta \theta \sim 1'' - 1'\)
\(\Delta \Omega \sim 1^\circ\)

\(\Delta \theta \sim 1^\circ\)
\(\Delta \Omega < 0.1^\circ\)
Principle of Classical Compton Imaging

Photon · · · · · main interaction in MeV band

Compton scattering

incident gamma-ray

liquid scintillator

Recoil electron
energy loss, location, time

NaI(Tl) scintillator
Scattered gamma-ray
Energy loss, location, time

Distribution of TOF (time-of-flight)


Recoil electrons are not tracked

The origin of a single event can be restricted by the “event circle”
The gamma-ray originated at the point of overlap
low background rejection power
Principle of Advanced Compton Camera based on Micro Pixel Chamber (μ-PIC)

- **2-dimensional imaging gaseous detector**
  - **micro-TPC** (gas detector)
  - **energy and track** of a recoil electron
  - **Anger camera scintillation detector**
    - NaI(Tl) (surrounding micro-TPC)
    - energy and position of a scattered gamma-ray

Having tracks of recoil electrons...

- **1 photon:** reconstructed completely energy and direction

**High background rejection power**

Unnecessary to use a TOF value and a collimator.
2-dimensional imaging
gaseous detector
electrode pitch 400 μ m

prototype of Compton camera based on a μ -PIC
with a detection area of 10 cm × 10 cm

Max gas gain ~ 15000

Stable operation
@gas gain ~ 6000

position resolution ~120 μ m

Electric field
Development of large $\mu$-PIC

Goal 10 times as high sensitivity as that of COMPTEL
To attain goal.....
prototype (10 cm $\times$ 10 cm) is not enough

large $\mu$-PIC with a detection area of 30 cm $\times$ 30 cm
- gain max : 7,000
- stable gas gain : 2,000

To detect Compton events · · · · · detection of recoil electrons
using the micro-TPC
Energy loss of recoil electrons $\sim$ 2 ~ 3 $\times$ MIPs (Minimum Ionizing Particle)
required gas gain $2 \times 10^4$
(We have not achieved because of discharge)
Another electron multiplier is necessary

GEM (Gas Electron Multiplier)
F.Sauli(1997)
operated @ low gas gain(\textasciitilde10)
Micro-TPC based on $\mu$-PIC and GEM

- segmented GEM (8 segments)
- to reduce capacitance and thus damage caused by discharge
- 23 cm $\times$ 28 cm (limited by material size)
- Scienergy Co. Ltd, Japan

GEM was installed just above the $\mu$-PIC

A charged particle runs in the micro-TPC and makes electron clouds, and then electron clouds are pre-amplified by the GEM and then the $\mu$-PIC.
Performance of $\mu$-PIC and GEM

Maximum gas gain of $5 \times 10^4$

Stable gas gain
$2 \times 10^4$

$\mu$-PIC $2 \times 10^3$

GEM 10

using Ar-C2H6(90:10) gas
1 atm

$\Delta$GEM = 260V
$\Delta$GEM = 240V
$\Delta$GEM = 220V

without GEM

$\mu$-PIC and GEM
The micro-TPC was set in a aluminum vessel filled with Ar-C$_2$H$_6$(90:10) gas to a pressure of 1 atm sealed for the duration of the measurements.

Anode: 768ch + cathode: 768ch
→ Signals from the $\mu$-PIC are sent via the printed boards

from $\mu$-PIC

256ch per board

to pre-amplifiers
DAQ system

**micro-TPC**

**ASD** (amplifier-shaper-discriminator)

1536 ch digital

21 cm

11 cm

anode 768 ch

cathode 768h

summed analog (8ch)

**VME Memory Board**

Recording anode and Cathode coincident position and the timing

**VME FADC**

100MHz 8ch × 3

Recording summed analog signals

**Position encoding module (100MHz FPGA)**
Performance of the micro-TPC (1)

Gain uniformity rms 13.9 %
10cm × 10cm $\mu$-PIC 5%

Energy resolution

- Gain uniformity rms 13.9 %
- 10cm × 10cm $\mu$-PIC 5%
- Energy resolution: gain $2.3 \times 10^4$
- Direct X-ray (31 keV)
- Irradiation of $^{133}$Ba with the whole detector
gain $2.3 \times 10^4$
- The peak of copper fluorescent X-rays at 8.0 keV,
generated at the GEM and the $\mu$-PIC
by the original X-rays from 133Ba
- The energy resolution was worse at 59.5 keV
  It might be due to the saturation of the ASD chips
Two plastic scintillators were used in coincidence for cosmic muon trigger.

Position resolution

\[ \sigma(l) = \sigma_{\text{detector}}^2 + \sigma_{\text{diffusion}}^2 \]

\[ = \sigma_{\text{detector}}^2 + (D\sqrt{l})^2 \]

\[ \sigma_{\text{detector}} = 0.51 \text{ mm}, \quad D = 0.37 \text{ mm} \]

Total gas gain of $5 \times 10^4$
Compton Camera

Anger camera scintillation detector for scattered gamma-rays
A large NaI(Tl) crystal and $6 \times 6$ PMTs

- Position resolution < 11mm (FWHM)
- Effective Area (No image distortion) \(\sim 30 \times 30 \text{cm}^2\)
- Energy Resolution $7.4\%$ (FWHM)@662keV, $11.2\%$ (FWHM)@80keV
- Dynamic range 80keV - 1.5 MeV
Prototype of Advanced Compton Camera

Imaging Quality (662keV two sources)

Electron-tracking telescope
SPD~40°

Event Arc
150 events (smoothing)

Classical Compton telescope

Event Circle
1625 events (smoothing)

We have developed Prototype of Compton Camera based on 10cm × 10cm μ-PIC Line source I-131 (364 keV)
Performance of Compton Camera (1)

based on 23 cm × 28 cm × 15 cm micro-TPC

Typical recoil electron tracks
Irradiating $^{137}$Cs (662 keV)

Typical Compton event
$^{137}$Cs (662 keV)

$E_{\mu -PIC}$ : 78.02 keV
$E_{scinti}$ : 615.9 keV
Performance of Compton Camera (2)

$^{137}\text{Cs} 662 \text{ keV}$ using data with reconstructed energy 610 keV ~ 760 keV

137Cs (1 MBq) × 2

Point source ~45 cm from micro-TPC
Error concerned with the reconstructed direction of a Incident gamma is determined event by event

✓ ARM (Angular Resolution Measure)
Concerned with the angle between the scattered gamma-ray and the recoil electron

✓ SPD (Scatter Plane Deviation)
Determination accuracy of the plane formed by the scattered gamma-ray and the recoil electron

$^{137}$Cs (662 keV)

ARM = 9.95° (FWHM)

SPD = 159° (FWHM)

Well fitted by Lorentzian

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Summary & Future Works

Micro-TPC based on 23cm $\times$ 28cm GEM and 30cm $\times$ 30cm $\mu$-PIC

effective volume 23cm $\times$ 28cm $\times$ 15cm

Gain uniformity rms 13.9%
energy resolution FWHM 37.5% (31.0 keV)

Large Compton camera
recoil electron tracks were successfully obtained
point source imaging
using $^{137}$Cs (662 keV)
ARM 9.96$^\circ$ (FWHM)
SPD 159$^\circ$ (FWHM)

Future Works
Imaging using source with various energy (350 keV ~ a few MeV)
To obtain better position resolution of scattered gamma-rays.....
Anger camera ( < 11mm FWHM ) $\rightarrow$ Pixel scintillator ( < 3mm FWHM)

Goal FWHM
500 keV ARM 7$^\circ$ SPD 40$^\circ$
1 MeV 5$^\circ$ 20$^\circ$
MeV gamma-ray Astronomy

✓ Nucleosynthesis
  Supernova: nuclear line from radioisotope
  Galactic disk: long-time decay radioisotope

✓ Particle Acceleration
  AGN Jet, Gamma-ray pulsar
  Gamma-ray burst, Solar flare

✓ Strong Gravity
  Black hole:
    accretion disk • \(\pi^0\) decay • Primordial

✓ Structure and Evolution of Universe
  Extragalactic diffuse background

✓ Origin and Propagation of cosmic-ray
  Galactic diffuse emission