Compton Gamma-ray Camera Using a Gaseous TPC and GSO(Ce)-LaBr$_3$(Ce) Scintillator Pixel Arrays for Astronomy and Medical Imaging

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• **Astronomy**
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  – Animal imaging
  – Proton Therapy

• **Summary**
Observation of MeV gamma-ray

All sky survey: Astro-H

1m Crab

EGRET

Sensitivity gap in the MeV gamma-ray region
Medical Imaging (functional image)

- PET : $E = 511\text{keV}$
- SPECT : $E < 360\text{keV}$

- **New radioactive tracer with new radioisotopes**
- It is possible that we obtain various images: anti-body, enzyme, protein reaction
- **Multi-radioisotope Imaging**
  - With wide energy range
  - Simultaneous observation of some metabolisms and interactions

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Electron-Tracking Compton Camera (ETCC)

Reconstruct incident gamma ray event by event

gaseous TPC
(time projection chamber):
[containing $\mu$-PIC (MPGD), GEM (Sauli (1997), Inuzuka et al. (2004))]
--- energy and 3-D track of Compton-recoil electron

Scintillation camera:
[Pixel array Scintillator]
--- energy and position of scattered gamma ray

- Large FOV (~3str)
- Kinematical background rejection by comparison of two $\alpha$ angles

Energy dynamic range: from 0.1 to ~10 MeV
Imaging with ETCC

- **Target**
- **Error region (arc)**
- **Incident Gamma rays**
- **Gaseous TPC**
- **Recoil electron (Electron cloud)**
- **Scattered gamma rays**

Event number 1
Event number 2
Event number 3
Event number 5
Event number 10
Event number 50
Event number 100
Vs. Conventional Compton Camera

Advanced
Measure
the 3-D track of a Recoil electron
• Reconstruction: point
• Direction error region: arc

Conventional
DO NOT measure
the track of a Recoil electron
• Reconstruction: circle
• Direction error region: donut

Our ETCC

COMPTEL

150 events

137Cs(1MBq)x2, Advanced Compton

600 events

137Cs(1MBq)x2, Classical Compton
Gaseous Time Projection Chamber (TPC)

Gas gain: ~30,000

Position Resolution (FWHM): ~0.4 mm (3-D)

2-D gaseous detector: ~ 65,000 pixels
400 μm pitch

Position resolution: 120 μm

μ-PIC (micro pixel chamber)

X-ray image with μ-PIC
Position-Sensitive Scintillation Camera

GSO(Ce) 8x8 pixels
Pixel size: 6x6x13mm³
Reflector: ESR™ (3M) 65μm thickness

Multi-anode
Photo Multiplier Tube (PMT)
HPK H8500 8x8 anodes

Dynamic energy range: 0.08 - 1 MeV
Eng. Resolution: 10.5 % @ 662 keV

2-D image in flood-field irradiation

137Cs

500
400
300
200
100

Counts (a. u.)

-0.8
-0.4
0
0.4
0.8

X-position (a. u.)
Astronomy

SMILE Project

Sub-MeV gamma-ray Imaging

Loaded-on-balloons Experiment
Schedule

(10cm)$^3$ ETCC (2006) → SMILE-1
- Operation test of ETCC @ 35km
- Measurement of Diffuse cosmic and atmospheric gamma rays ~ 4 hours

(30cm)$^3$ ETCC (2011)
- Observation of Crab or Cyg X-1 ~ 3 hours

(40cm)$^3$ ETCC
- Long duration balloon ~ 10 days

(50cm)$^3$ ETCC All sky survey
- Orbiting balloon (~30 days) or satellite
SMILE-1 Flight Model

- **GSO scintillator**
  - 3x3 PMTs at bottom
  - 4x(3x2) PMTs at side

- **(10cm)^3-size TPC**
  - Gas: Xe(80%) + Ar(18%) + C\textsubscript{2}H\textsubscript{6}(2%)
  - 1 atm, sealed

- **Electronics**

- **Dynamic energy Range:** 0.1 – 1 MeV
- **Field of view (FOV):** 3 str (FWHM) (0.15 - 1 MeV)
- **Efficiency:** \(\sim 10^{-4}\) @ 0.1-1 MeV
- **Energy resolution (ETCC):** \(\sim 12\%\) @ 662 keV, FWHM
- **Angular resolution**
  - **ARM:** 22 deg.
  - **SPD:** 165 deg.
  @ 662 keV, FWHM
The balloon was launched on Sep. 1, 2006 @ Sanriku Balloon Center, JAXA / ISAS, Japan.
Energy spectrum

diffuse cosmic \( \gamma \) rays

atmospheric \( \gamma \) rays

Previous results

SMILE-1

We detected 420 photons (Total) @0.15-1 MeV, 32-35 km for 4 hours
(30cm)$^3$ ETCC for SMILE-2 to launch in 2011

Scintillator (GSO(Ce))

TPC

40cm

60cm

Two source image

$^{137}$Cs (662 keV)

$^{54}$Mn (835 keV)

Energy[keV]
We detected 10 MeV gamma rays with our camera as pair creation detector using AIST laser-Compton gamma-ray beam.

Collaborator: H. Toyokawa (Advanced Industrial Science and Technology: AIST, Japan)
Medical imaging

Our Camera

- diagnostic tool
  - Function imaging
    - Animal imaging
- Treatment: monitor tool
  - Proton therapy
  - Water phantom test
To obtain a higher angular resolution / spatial resolution (≤ 1 cm)
Angular resolution of the Compton camera depends on the energy resolution of scintillator

LaBr$_3$(Ce) : $\Delta E/E \approx 3\%$
@ 662 keV (FWHM) Loef et al. (2001)
Using our technique, we assembled an 8×8 array.

LaBr₃ (Ce) array

6.1 mm pitch
(=multi-anode PMT H8500 anode pitch)

54mm

20mm

LaBr₃: hygroscopic

Hermetic package

GSO monolithic

LaBr₃ monolithic

$\Delta E/E = 4.1 \pm 0.1 \%$
@ 356 keV (FWHM)

LaBr₃ FWHM(%) =

$(5.7 \pm 0.4) \times (E/662\text{keV})^{-0.53 \pm 0.01}$

GSO FWHM(%) =

$(10.4 \pm 0.3) \times (E/662\text{keV})^{-0.51 \pm 0.01}$
Setup of ETCC

LaBr$_3$(Ce) arrays (576 pixels)

Angular resolution [deg.] @662 keV (FWHM)
GSO : 6.4 ± 0.2
LaBr$_3$ : 4.2 ± 0.3

Spatial resolution : ~1cm
Mouse (small animal) imaging

$^{131}\text{I}}$-MIBG (365keV)
Imaging (ETCC & CT)

$^{65}\text{Zn}^2+$ (1116keV)
Imaging (ETCC & photo)

Collaborator:
H. Kimura, H. Amano,
H. Saji, (Kyoto Univ., Japan)
$^{131}$I-MIBG (365keV) & $^{18}$F-FDG (511keV) simultaneous imaging

Collaborator:
H. Kimura, H. Amano, H. Saji, (Kyoto Univ., Japan)
Rabbit (medium-sized) imaging

Collaborator:
H. Kimura, H. Amano, H. Saji, (Kyoto Univ., Japan)
Dual head Compton Camera

Scintillator

TPC

Target

TPC

Scintillator

3-D image: $^{133}$Ba source

20 cm
Proton Therapy

Attack on Cancerous cells

Monitoring
Before treatment: ionization chamber
After treatment: PET technique (PET: positron emission tomography)
Real time: none

ETCC:
- ability to detect Prompt gamma rays as the monitor
  - Wide energy range (0.1-10 MeV)
- Rejection of Neutron
- Wide field of view (~3 str.)

Simulation study:
- Gamma rays
- Proton
- Neutron Water phantom

Graph showing Depth in Tissue (water) [mm] with 150 MeV proton and 200 MeV proton.

Table of Depth in Tissue (water) [mm] with 150 MeV proton and 200 MeV proton.
Proton Therapy

Attack on Cancerous cells

Monitoring
Before treatment: ionization chamber
After treatment: PET technique
  (PET: positron emission tomography)
Real time: none

ETCC:
- ability to detect Prompt gamma rays as the monitor
  - Wide energy range (0.1-10 MeV)
- Rejection of Neutron
- Wide field of view (~3 str.)
We are developing a monitor for Proton Therapy

160 MeV Proton

ETCC (10cm)$^3$ TPC

Water Phantom

30cm

Experiment in Osaka Univ. Research Center for Nuclear Physics (RCNP)

collaborator: J. Kim
(Research Institute and Hospital, National Cancer Center, Korea)
Summary

• We have developed Electron-Tracking Compton Camera

• For Astronomy:
  – SMILE-1 (10cm)$^3$ TPC + GSO(Ce) array
    We measured the cosmic / atmospheric gamma rays
  – SMILE-2 (30cm)$^3$ TPC + GSO(Ce) array
    We are optimizing the gas mixture and pressure, and developing the detector for SMILE-2 (2011, launch !)
    – Pair creation mode at ~ 10 MeV

• For Medical Imaging:
  – animal imaging
    (10cm)$^3$ TPC (Ar(90%) C$_2$H$_6$(10%) 1atm) + LaBr$_3$(Ce)array
    FWHM angular resolution 4.2±0.3 deg. at 662 keV
  – Proton therapy
    Real time monitor of prompt gamma rays to measure the Bragg-peak position
Thank you for your attention