Simulation study of CdTe detectors for astrophysics with Geant4

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The CSIC is a Public Research Organism with a multi-sectorial and multi-disciplinary character, made up of a network of 120 institutes distributed throughout Spain.

As an institute of the CSIC the Institute of Space Sciences aims to contribute significantly to the scientific and technological research, doing science of and from space. By this, the institute is putting special emphasis on instrumentation on board satellites as well as all the technical aspects involved in such projects. Within this framework, the ICE is active in the following disciplines:

• Astrophysics and Cosmology  
• Earth Science  
• Fundamental Physics
Observations of the X- and gamma-ray sky reveal the most powerful sources and the most violent events in the Universe

The gamma-ray sky provides us with a view on the non-thermal Universe

- **Cosmic explosions:** supernovae, novae, GRB,… Nuclear reactions take place in all these scenarios and synthesized all the elements in the Cosmos (e.g., $^7\text{Be}$ at 0.478 MeV, $^{56}\text{Co}$ at 0.847 MeV, $^{44}\text{Ti}$ at 1.157 MeV, $^{22}\text{Na}$ at 1.275 MeV),

- **Cosmic accelerators:** compact objects, pulsars, supernova remnants, Sun. In this object particles are accelerated to extreme relativistic energies by mechanisms which are still poorly understood
The aims of ICE is not only to contribute significantly to the space science, but also to the technological research of the instrumental design of the future gamma-ray missions.

Since 2005 we have been participating in an European consortium, which has as goal the definition of a future gamma-ray mission (Gamma-Ray Imager, GRI) which should represent a significant step forward in the post-INTEGRAL era. We are also involved in other prospective missions, based on the Compton telescope technique, such as ACT and GRASP, in the scientific committees.

The Gamma-Ray Imager mission was submitted on June, 2007 to the ESA’s Cosmic Vision 2015-2025 program.

Even though the GRI proposal was not selected by ESA in this call, the R&D activity begun at the ICE about CdTe detectors is still under way.
R&D at the ICE

A research and development project was approved by the National Plan for Space Research in Spain (2008).

The goal of this project is the design and development of a CdTe calorimeter for a Compton Camera prototype in the MeV region.

State of the art

In order to have a good calorimeter for a Compton Camera in the MeV gamma-ray region we will follow the idea of stacked CdTe detector:

- Stacked together thin and large CdTe diode and operated them as a single detector

- Prototype Si/CdTe Compton telescope
  - T.Tanaka, S.Watanabe, et al., NIM A, 568, pp. 375-381, 2005

- CdTe Pixel gamma-ray detector
R&D at the ICE

Tracker
- Double-sided Si strip detector

Compton Camera

Calorimeter
- Pixelated CdTe detector
- Layers of 2.0 and 5.0mm thick
Simulations with Geant4

**CdTe calorimeter**
- Modeling of a pixelated CdTe detector
- A CdTe diode detector
  - Pulse height spectra: tailing effect
  - Photo peak detection efficiency

**Compton camera**
- First simulations of a Compton Camera with Geant4.
- Compton reconstruction with MEGAlib tool
Simulation with Geant4

**GEANT4:**
Monte Carlo simulation of the interactions inside the CdTe substrate.

**Hit position:** (x,y,z)
**Energy:** E (keV)

**Tracking code**
To track the electron and the hole through the detector. Determine the induced signals on anode/cathode as function of time.

**Modelling of pixelated CdTe detectors**

**FEMLAB:**
Determination of the electric field inside the pixelated CdTe detector with the finite-difference method.

**Electric potential**
**Weighting potential**

**Modelling of read-out electronics**

**Full detector simulations**

**Comparison with a measured spectra**
Simulations with Geant4

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A CdTe diode detector

Pulse height spectra: tailing effect

Pulse Height spectra for various thicknesses of CdTe (5mm, 2mm, and 0.5mm).

Hecht equation: \[ PH(z) \propto n_0 \left[ \bar{\epsilon}_e \left( 1 - \exp\left( -\frac{d - z}{\bar{\epsilon}_e} \right) \right) + \bar{\epsilon}_h \left( 1 - \exp\left( -\frac{z}{\bar{\epsilon}_h} \right) \right) \right] \]

Uniform electric field: \( E = \frac{V}{d} \)

\[ \bar{\epsilon}_e = \hat{i}_e \hat{\epsilon}_e E \quad , \quad \bar{\epsilon}_h = \hat{i}_h \hat{\epsilon}_h E \]
Pulse height spectra for CdTe detector of 2 mm thickness for various applied bias voltage (800V, 1400V and 2400V).

For a certain detector thickness (2mm) the charge collection efficiency improves as the applied bias voltage increase.
Simulation with Geant4
A CdTe diode detectors

High stopping power for high energy photons

CdTe & Ge: Photo peak detection efficiency for 0.5MeV photon at different thickness

- CdTe
- Ge

Efficiency [%]

2  4  6  8  10  12  14  16  18  20
Thickness [mm]
Simulation with Geant4

A CdTe diode detectors

Photo peak detection efficiency: monolithic CdTe detector
Simulations with Geant4

- **CdTe calorimeter**
  - Modeling of a pixelated CdTe detector
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    - Photo peak detection efficiency

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Simulations with Geant4

Compton Camera

Photo peak detection efficiency: Si/CdTe stacked detector

Geant4 Geometry
10 layers of Si + 5 layers of CdTe
Simulation with Geant4

pre-Compton reconstruction with MEGAlib toolkit


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Summary

- The R&D of a CdTe calorimeter for a Compton camera is in progress at the ICE.

- First simulations with Geant4 have been done. A model for the pixelated CdTe detector will be available soon.

- The MEGAlib toolkit will be use for the data analysis and Compton reconstruction of our Compton Camera with a pixelated CdTe calorimeter.
Thank you for your attention!