An Advanced Compton Telescope based on Thick, Position-sensitive Solid-state Detectors

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Outline

Germanium Strip Detectors
Thick silicon Strip Detectors
   Si(Li)
   Intrinsic silicon
Simulations
ACT Instrument Design
Instrument Options
Directions for Improvement

Increased Efficiency
- More Compact Design
- Monolithic, Position-sensitive detectors

Energy Resolution
- Solid State Detectors

Angular Resolution
- Position-sensitive detectors
- Energy resolution

Background Reduction
- Electron tracking
- Event reconstruction
- Choice of orbit
  Note: No time of flight discrimination possible

50 times higher sensitivity through
1. Higher efficiency
2. Better angular and energy resolution

NRL concept using solid-state strip detectors
Position-sensitive Germanium Detectors

- Orthogonal Strip Planar Germanium Detector
- $5 \times 5 \times 1$ cm detector; 2mm strip width
- Detector cooled to 80K in cryostat
- Room temperature electronics

Note: currently testing 80mm x 80mm x 2mm LBNL detector with amGe contacts
Depth Measurement

Depth of interaction affects time of charge collection

Depth is proportional to the time difference between charge collection on the front and back face of the detector.

An interaction occurring at the front face will have the charge on that face collected ~100ns before the other face of the detector.

Achieve 0.5mm depth resolution

From Momayezi, Warburton and Kroeger (SPIE, 1999)
Single Detector Imaging

\[ \cos \varphi_1 = 1 - m_e c^2 \left( \frac{1}{E_2} - \frac{1}{E_1} \right) \]

- First Demonstration of Compton Imaging in a single position-sensitive solid-state detector
- Use 50mm x 50mm x 10mm Ge detector
- Na-22 and Cs-137 at 40 cm from detector
- Point Spread Function at 662 keV is \(~5\) cm or \(7^\circ\) angular resolution
- Impossible in a single detector without depth information
3-Compton Imaging with two Germanium detectors

Experiment set-up with two orthogonal Ge strip detectors---2mm position resolution with depth sensing (0.5mm)

Image of $^{22}\text{Na}$ source in 511 keV positron annihilation gamma rays.
Three Gamma Interaction Technique

\[ \cos \Theta_2 = 1 - m_e c^2 \left( \frac{1}{E_3} - \frac{1}{E_2} \right); \quad L_2 = E_2 - E_3 \]

\[ E_1 = L_1 + \frac{L_2^2 + \frac{4m_e c^2 L_2}{1 - \cos \Theta_2}}{2} \]

- Unknown source: 3 interactions required to determine energy, \( E_1 \)
- Known source: 2 interactions required to determine energy, \( E_1 \)
- Does *not* require total energy absorption
- Efficient Compton telescope, even if using *silicon* detectors
Advantages of silicon detectors

Operating Temperature: -20 to –50 C

Reduced cost

Lower Doppler Broadening effects on angular and energy resolutions compared to Ge, CZT

Silicon detectors

Lithium-drifted silicon
  • Can drift to 6-10mm thick
  • 125mm dia. wafers available

High Resistivity Silicon
  • 2-3mm thickness
  • 150mm wafers available

ASICs for many analog channels (Power)
LBNL Si(Li) Detector (54mm x 54mm x 3.5mm thick)

N-contacts: am-silicon
P-contacts: boron implants
Strip pitch: 2mm

Figure 4: Photo of double-sided Si(Li) strip detector fabricated at LBNL. The boron-contact side is seen in the mirror.

$^{57}$Co spectrum from the $\alpha$-Si contact side of the LBNL orthogonal strip detector.
SINTEF intrinsic Si detectors/ ASICs

Four VAS3/TAT3 chip sets mounted on an "L" shaped test board. A silicon detector is shown in relation to the board.

63mm x 63mmx 2mm inSilicon detector
We plan to pursue 95mm x 95mm x 2-3mm thick detectors
**Compton Imaging with 3-layer silicon stack**

3-Layer silicon stack. Each detector is 30 x 5 strips. Strip pitch is 890 microns.

Room temperature spectrum with $^{241}$Am source. FWHM=2.8 keV

Image of a 662 keV source using 3-layer intrinsic Si detector stack. Red contours are from a simulated image using the same geometry and source.
Tracks of two events in a simulation of a large Compton Imager
Doppler Broadening

Silicon: \( E_{\text{inc}} = 800 \text{ keV} \)

Germanium: \( E_{\text{inc}} = 800 \text{ keV} \)
Event reconstruction

What is the correct sequence of interactions?

- Consider events with 3 interactions
- There are six possible sequences
- Let’s just try them all and see which ones work

1  2  3  4  5  6
Study all possible sequences

Easy to generalize to any number of interactions:

<table>
<thead>
<tr>
<th>Number of interactions</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sequences</td>
<td>6</td>
<td>24</td>
<td>120</td>
<td>720</td>
<td>5040</td>
</tr>
</tbody>
</table>

1. Consider all possible sequences
2. Determine FOM for each sequence

FOM weighting derived from some combinations of the following terms:

\[
\begin{align*}
   p_1 &= e^{-\sigma} r_1 \\
   p_2 &= e^{-\sigma} r_2 \\
   p_3 &= \frac{\partial \sigma_1}{\partial \theta} \\
   p_4 &= \frac{\partial \sigma_2}{\partial \theta}
\end{align*}
\]

\[ fom = p_1 p_2 p_3 p_4 \]

3. Select kinematically possible sequence with highest FOM
3-Interaction Sequencing

Sequence picked

40% right out of 6 possibilities

Reconstructed energy

185 keV
Small shelf above peak

414 keV

80% right

2615 keV
3-Compton Efficiency

Tracking
- Recover many partial-E events, albeit with degraded energy resolution (expect 50-80% recovery)
- Improve position resolution (order ~2 cm to ~2 mm)
- Reject Compton shelf (background)
- Reject some good photo-peak events (small loss of efficiency)

Efficiency includes 1-10 interactions
Red curves: continuous passive approximation
Tracking efficiency (i.e. correct sequence) not included
42.6 g/cm² thick (8 cm Ge), 1 m² area
Prototype Unit

- 8 identical trays held in a stack by side-walls
- Side-walls provide structural support and cooling
Si Compton Imager Tray

- 4x4 array of detectors edge bonded to each other with epoxy
- Silicon array held on frame around perimeter
- Electrically daisy-chained to each other in opposite directions on opposite faces
- Readout on both faces (2 sides)
- Front-end electronics attached to frame
Tray Design Concept

- Brazed Aluminum Frame
- Split Corner Blocks
- Shape Memory Alloy (SMA) Clamps
Instrument Design Concept

- External Supports:
  - rigid egg-crate base grid
  - shear panels on all sides
- Internal Supports:
  - towers tied together
- Sealed Container (not shown)
  - Dry N$_2$ (or vacuum if req’d)
- 4x4 Array of identical towers
  - Each tower = stack of 24 identical trays
Tower Structural Analysis

- Vibration Modes
  - Fundamental = 116 Hz (goal > 50 Hz)
- Pseudo-Static Deformations (20g)
  - Max in-plane deformation < 500 µm
  - Max out-of-plane deformation < 140 µm
- Stresses (20g)
  - Frame < 50% \( \sigma_{\text{yield}} \)
  - Silicon < 2% \( \sigma_{\text{ult}} \)
  - Tubes < 63% \( \sigma_{\text{yield}} \)
Instrument Options

- Combine Si and CZT in low-temperature detector (e.g. –20 C)
- Addition of scintillator scatter detector/anticoincidence shield
- Addition of a wide field-of-view coded-aperture system around the Compton Telescope to extend the energy range down to 5-10 keV. Use thin W, Ta or Pb coded mask effective to ~100-150 keV.
SUMMARY

• NRL is pursuing 3-D position-sensitive Ge and Si detectors for an Advanced Compton Telescope

• 3-Compton scatter concept is attractive for a high efficiency, high sensitivity instrument.

• Potential for dramatic background reduction using event reconstruction. Places premium on energy and position resolution.

• GEANT4 simulations will be used to validate performance capabilities/guide instrument design.