Development and Characterization of CdZnTe Detectors for Neutrino Physics Research

Thomas Kutter, Jun Miyamoto
LSU

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Outline

• Introduction
  – Physics motivation
  – Why CdZnTe?

• Performance of
  – Coplanar detector
  – Pixelated detector

• Summary + Outlook
Physics Motivation

- Search for neutrino-less double beta decay
  - Physics beyond ‘standard model’
  - Nature of neutrino
- Requirement:
  - Excellent energy resolution
  - Efficient background rejection
    - High Q-value (choice of source)
    - Shielding
    - tracking, particle ID (detector capabilities)
  - Multiple isotopes

[Diagram showing a spectrum with labeled isotopes and energy values]

TI-208 E_γ = 2.6 MeV

figure: S. Pirro
Why CdZnTe detectors?

- CdZnTe crystals contain 9 double beta decay isotopes
  
<table>
<thead>
<tr>
<th>isotope</th>
<th>Natural abundance [%]</th>
<th>Q value [keV]</th>
<th>Decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd – 116</td>
<td>7.5</td>
<td>2805</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>Te – 130</td>
<td>33.8</td>
<td>2529</td>
<td>$\beta^-\beta^-$</td>
</tr>
<tr>
<td>Cd – 106</td>
<td>1.21</td>
<td>2771</td>
<td>$\beta^+\beta^+$</td>
</tr>
</tbody>
</table>

- Source = detector
- Good energy resolution
- Room temperature operation
- Modular design (coincidence studies, scalability)
- Potential for tracking (solid state TPC) → background reduction
- Industrial development of (clean) CdZnTe crystals

Above all U and Th chain gamma lines (2614 keV from Tl-208)

Co-Planar Detectors

- Idea based on gas ionization chambers: electrons and ions have different drift speeds (few orders of magnitudes)
- In large volume, depending on the location of ionization, a combined induced charge by electrons and ions varies greatly → worse energy resolution.

→ Frisch Grid is used to suppress charge induction from ions
→ single carrier detector

- In CdZnTe: remove the hole contribution to the signal
  - by alternating collecting/non-collecting electrodes biased at different potentials

E-field in a coplanar CZT

**Mechanism**
1. Electrons and holes drift in opposite directions
2. Once the electrons come near the surface, they are preferentially collected by the positively biased electrode
3. Charge is induced on the two coplanar electrodes according to the Ramo theorem in different ways
1. Inversion and addition are done in the analog stage of the pre-amp
2. Shaping is done after the two signals are added: equivalent to subtracting two signals from coplanar electrodes.
Charge Induction

**on collecting electrode:**

- Slow rise due to induced charge by drifting electrons and holes in bulk crystal.
- Fast rise caused by fast moving electrons near the coplanar E-field.

**on NON-collecting electrode:**

- Quick dip due to electrons drifting away from non-collecting electrode.

**Combined signal:**

- Removed part
- Extra amplitude due to compensation
- Newly created part as a result of hole cancelation

➤ Coplanar electrodes can correct for severe amplitude loss due to hole trapping.
Experimental setup at LSU

Cd$_{0.9}$ Zn$_{0.1}$ Te$_{1.0}$ crystal:
- weight: ~5.9 g
- Dimension: 10 x 10 x 10 mm$^3$
- clear passivation coating

Coplanar grid dimensions:
- Width: 200 micron
- gap: 300 micron

Guard ring:
- guard ring to edge: 250 micron
- active area to edge: 600 micron.
Observed signals (Cs-137 source)

Collecting electrode

Non-Collecting electrode

Post subtraction by hardware

Collecting electrode (+V)

Non-Collecting electrode (0V)

Cathode (-V)

interaction near anode: non-collecting electrode amplitude is purely negative

interaction near cathode: non-collecting electrode amplitude remains positive
Optimization of Coplanar Operation

Because of the small gap ($\approx 300 \mu$m), even a small bias voltage of 30 V (or more) is sufficient to make the coplanar field effective.

- Cathode biased at $\sim -2000$ V
Inherent electronics noise

Tests with pulse generator:
1. Used shaping time of 2 \( \mu \text{sec} \)
2. Width due to electronic noise remains constant
3. FWHM/Centroid (%) approaches sub percent levels
Gamma Source Spectra

**Ba-133**
- 356, 383 keV
- 276, 302 keV

**Na-22**
- 551 keV
- 1275 keV

**Cs-137**
- 662 keV

**Co-60**
- 1173 keV
- 1332 keV
Th-228

120 hr, Total counts=3,259,487

Th-228

Energy (keV)

Counts

2.68% @ 1621 keV

2614 keV starts appearing
### Energy Resolution Summary

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( E_\gamma ) [keV]</th>
<th>( \Delta E_{\text{FWHM}}/E ) [%]</th>
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<th>( E_\gamma ) [keV]</th>
<th>( \Delta E_{\text{FWHM}}/E ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba-133</td>
<td>276, 302</td>
<td>12.97</td>
<td>Na-22</td>
<td>511</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>355, 383</td>
<td>7.02</td>
<td></td>
<td>1274</td>
<td>5.9</td>
</tr>
<tr>
<td>Cs-137</td>
<td>662</td>
<td>7.0</td>
<td>Co-60</td>
<td>1173.2</td>
<td>3.95</td>
</tr>
<tr>
<td>Th-228</td>
<td>1621</td>
<td>2.68</td>
<td></td>
<td>1332.5</td>
<td>3.89</td>
</tr>
</tbody>
</table>

**Graph:**

- **Linearity check**
  - Equation: \( y = 0.2157x - 2.7416 \)
  - \( R^2 = 0.9998 \)
Beta Source Spectra

Counts near endpoint energies

Sr-90 : 2.28 MeV
Ru-106 : 3.54 MeV

→ Detector shows good dynamic range
Coplanar and Pixel Detector

Co – 60 source spectra

Coplanar detector: $10 \times 10 \times 10$ mm$^3$
$\Delta E/E \sim 3.89 \%$ FWHM@ 1332 keV

Pixel detector: $11 \times 11 \times 5$ mm$^3$
$4 \times 4$ pixels, size: $2.0 \times 2.0$ mm
pitch: 2.1 mm
$\Delta E/E$ (FWHM) $\sim 1.5\%$ @ 1332 keV

Note:
1. “small pixel” $\rightarrow$ superior energy resolution.
2. 5 mm thickness $\rightarrow$ reduced effect from charge trapping
Summary and Outlook

• Motivated CdZnTe detector R&D
• Demonstrated signal cancelation from hole contribution
• Presented results for energy resolution of coplanar and pixilated detector
• Linearity and dynamic range of detector response

Outlook:
• Study correlation between DOI and energy resolution
• Continue to develop sub millimeter pixel size detectors:
  – Study charge sharing effects
  – Possibility of particle tracking