X-Ray Polarimetry and Cadmium Zinc Telluride (CZT) Detectors

M. Beilicke, Q. Guo, F. Kislat, K. Lee, J. Martin, H. Krawczynski (Wash. Univ.), A. Burger, M. Groza (Fisk Univ.), J. Matteson (UCSD)

Plan of Talk:

- Motivation: X-Ray Polarimetry.
- CZT Detectors:
  - Development.
  - Exemplary architectures.
- Summary.
X-Ray Observations

Chandra & XMM Newton
(1999-present, 0.1-12 keV)

Tycho Super Nova Remnant

- Few polarimetric results, except Crab Nebula, Cyg X-1 with OSO-8 (Weisskopf et al. 1978) and Integral (Dean et al. 2008, Laurent et al. 2011).

- Polarization measurements:
  - Statistics
    (5% pol. degree: ~10,000 γ’s for 99% confidence level detection)
  - Systematics
    (~10% systematic errors on Integral results)

X-Ray Polarimetry

GEMS Gravity and Extreme Magnetism SMEX (2-10 keV)

- 4 Time Projection Chambers, each 30 cm demethyl ether at 0.25 atm.

Swank et al., GSFC

X-Calibur (5-70 keV, 20-70 keV):

- 14cm scintillator rod surrounded by 32 CZT detectors.

Krawczynski, Beilicke, Guo, Kislat et al.
Hard X-Ray Polarimetry with X-Calibur

- 1.6 ton payload,
- 40 km flight altitude,
- Pointing accuracy: 0.015°

- 255 shell Al mirror;
- 50 cm² area at 30 keV;
- (Pt/C coating).
Hard X-Ray Polarimetry with X-Calibur

Tueller et al.

Kunieda et al.

Rotation: cancel systematics.
Results with Polarized Beam

One-Day Balloon Flight (Fort Sumner, NM, 2013): Observe Cyg X-1, GRS 1915, Crab, Her X-1, Mrk 421 with 4% MDP for Crab.

Reconstructed polarization fraction: 52%.
Science Driver: X-ray Polarimetric Observations of Black Holes

Cygnus X-1:

19 M\(_\odot\) O-star orbits
“invisible” 15 M\(_\odot\) companion with 5.6 day period.

Stellar mass black hole in X-ray binary:

- Energy resolved (non-imaging) polarimetry \(\Rightarrow\) map accretion flow and spacetime!
Science Driver: X-ray Polarimetric Observations of Black Holes

Guo et al. (2011):

\[
a_* = \frac{cJ}{GM^2} > 0.97 \ (3\sigma)
\]

X-ray polarimetry (0.5-100 keV):
- Test Accretion Disk Models.
- Test No-Hair Theorem of GR.
- Constrain corona geometry.
Simulation Results

Example photon trajectory:

\[ M = 10 \, M_\text{sun} \]
\[ L_{\text{Disk}} = 0.1 \, L_{\text{edd}} \]
\[ i = 75^\circ \]

Simulation Results

Rightarrow Measure Black Hole Spin and some (but rather limited) sensitivity to test No Hair Theorem (HK 2012).

Also: Connors et al. (1980), Schnittman & Krolik (2010).
Cadmium Zinc Telluride X-Ray and Gamma-Ray Detectors

- **Cd\((1-x)\) Zn\(x\) Te; \(x\sim 0.1\).**

- **Large direct band-gap:**
  - \(E_g = 1.57\) eV; \(E_i = 4.64\) eV
  - Room-temp operation!

- **High stopping power:**
  - High \(<Z>\): 49.1,
  - High-density: 5.78 g cm
  - Detector thickness: 0.2...1.5 cm.

- **Detector Units (Endicott, Orbotech, Redlen, Creative Electron, Qickpak):**
  - Standard: 0.5x2x2 cm\(^3\);
  - Large: 0.5x4x4 cm\(^3\) & 1.5x2x2 cm\(^3\).

- **Electronic properties:**
  - \(\mu\tau|_e = 5 \times 10^{-3} \) cm\(^2\) V\(^{-1}\);
  - \(\mu\tau|_h = 5 \times 10^{-5} \) cm\(^2\) V\(^{-1}\).
Planar Detectors vs. Small Pixel Detectors

Si, Ge Detectors

Planar CZT Detector

Pixel CZT Detector

δq ∝ δφ

Barret et al., Luke et al. 1995
Applications for CZT Detectors

2-100 keV X-rays (vs. Si):
- Energy thresholds ≥2 keV.
- Energy res. 0.5-2 keV FWHM.
- Spatial resolutions ~ 1mm.
- Better stopping than Si.
- Higher $\sigma_{PE}/\sigma_{C}$.

>100 keV gamma-rays (vs. Scint. & Germanium):
- Better energy (<1% FWHM @ 662 keV) and spatial resolutions than the best scintillators.
- No need for cryogenic cooling.

Material of choice for many spectroscopic photon detection in
Detector Fabrication:
- Polish with abrasive.
- 5% Br, 95% Methanol wet etch;
- Photolithography;
- Contact deposition with e-Beam evaporator.
Optimization of Detector Contacts

- Au on cathode: blocking contact on n-type CZT ⇒ reduced dark current.
- In & Ti on anode: ohmic contact on n-type CZT ⇒ reduced noise.
Good yield for detectors with pixels at ~100 micron pixel pitch.
Pixelated Detectors
Cross-strip CZT detector: 0.5 $\times$ 4 $\times$ 4 cm$^3$.

Dual-anode CZT detectors: 1 $\times$ 2 $\times$ 2 cm$^3$.

Limited energy resolutions (>~3%) and modest detection efficiency owing to modest small pixel effect and weak cathode signals.
Detector Systems

ASIC board:

ASIC developed by G. de Geronimo (Brookhaven):
- 32 channel;
- 1-2 keV noise (FWHM).

CZT on ceramic substrate:

Tower with 8 detectors:
Towards Smaller Pixels

- CZT with 4096 pixels at 350 μm pitch, footprint 2.24 x 2.24 cm²;
- ASIC: 2048 channels ASIC (L. J. Meng, UIUC);
- Wash. Univ. readout system:

- CdTe detector (2mm).
- Energy res. 4 keV FWHM.
• Infrared imaging (1.1 µm) reveals non-uniformities correlated with underperforming pixels.
Pockels effect can be used to measure E-field.

E-field from Pockels (CZT: 0.5x0.9x0.9 cm³):

Groza et al. 2010

E-field from Simulations:
Pockels image of 0.5x1.9x1.7 cm³ CZT detector suggests “layered E-field” inside detector.

Transient analysis confirms results from Pockels imaging.
Detector Simulations

- $\mu_e = 700 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\tau_e = 5.9 \times 10^{-6} \text{ s}$;
- $\mu_h = 50 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\tau_h = 10^{-6} \text{ s}$. 

Potential from 2-D Laplace solver: 0.5 cm thick CZT, -1000 V bias:
Results: $^{57}$Co spectrum after threshold minimization.

Orbotech CZT, 0.5x2x2 cm$^3$

Beilicke et al. 2012
Energy Resolutions (1x2x2 cm$^3$ eV-Products CZT)

Li et al. 2010
Direct Comparison of Different Anode Patterns

Steering grids improve performance!

Beilicke et al. 2012
## CZT Based Astroparticle Physics Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Start</th>
<th>Number of Detectors</th>
<th>Volume of Detectors</th>
<th>Pixels per Detector</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swift (BAT)</td>
<td>2004</td>
<td>32,768</td>
<td>0.2x0.4x0.4 cm³</td>
<td>1</td>
<td>15-150 keV</td>
</tr>
<tr>
<td>NuSTAR</td>
<td>2012</td>
<td>4</td>
<td>0.2x1.9 x1.9 cm³</td>
<td>1024</td>
<td>5-80 keV</td>
</tr>
<tr>
<td>X-Calibur</td>
<td>2013</td>
<td>32</td>
<td>0.2x2x2cm³ 0.5x2x2cm³</td>
<td>64</td>
<td>20-70 keV</td>
</tr>
<tr>
<td>COBRA</td>
<td>tbd</td>
<td>9,556</td>
<td>0.5x4x4cm³</td>
<td>256</td>
<td>2-3 MeV</td>
</tr>
</tbody>
</table>
The SWIFT Burst Alert Telescope

Launch Nov. 2004

Barthelmy et al. 2005

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>Coded mask</td>
</tr>
<tr>
<td>Detecting Area</td>
<td>5200 cm²</td>
</tr>
<tr>
<td>Detector</td>
<td>CdZnTe</td>
</tr>
<tr>
<td>Detector Operation</td>
<td>Photon counting</td>
</tr>
<tr>
<td>Field of View</td>
<td>1.4 sr (partially-coded)</td>
</tr>
<tr>
<td>Detection Elements</td>
<td>256 modules of 128 elements</td>
</tr>
<tr>
<td>Detector Size</td>
<td>4 mm x 4 mm x 2mm</td>
</tr>
<tr>
<td>Telescope PSF</td>
<td>17 arcmin</td>
</tr>
<tr>
<td>Energy Range</td>
<td>15-150 keV</td>
</tr>
</tbody>
</table>
The SWIFT Burst Alert Telescope

Soto et al. 2003

Map of MuTau Electron

Soto et al. 2003

7 keV FWHM
The Nuclear Spectroscopic Telescope Array NuSTAR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>0.6 mm/12.3''</td>
<td>Max processing rate</td>
<td>400 evt/s</td>
</tr>
<tr>
<td>Focal plane size</td>
<td>13' × 13'</td>
<td>Max flux meas. rate</td>
<td>10^4/s</td>
</tr>
<tr>
<td>Pixel format</td>
<td>32 × 32</td>
<td>time resolution</td>
<td>2 μsec</td>
</tr>
<tr>
<td>Threshold</td>
<td>2.5 keV (each pixel)</td>
<td>Dead time fraction (weak source)</td>
<td>2%</td>
</tr>
</tbody>
</table>

Harrison et al. 2010
The Nuclear Spectroscopic Telescope Array NuSTAR

Electronic Noise.

Rana et al. 2009

Detector resolution.
Summary

❖ In Astrophysics CZT has become the material of choice for the detection of hard X-rays (5 keV - 1 MeV) with excellent spatial and energy resolutions.

❖ Infrared imaging and Pockels studies show that CZT crystals exhibit a wide range of non-uniformities. Even some good detectors show horizontal E-field variations.

❖ Thick (>2mm) detectors work best with small pixels.

❖ Main effect of steering grids: improvement of detection efficiency by ~20%.

❖ Excellent energy resolutions require small pixels, and thus a considerable number of readout channels.

❖ Not covered here: COBRA (Zuber et al.), protoEXIST (Grindley et al.) and 3-D CZT time projection detectors (He et al.).