X-ray detector development at Washington University in St. Louis

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Collaborators: GSFC, BNL

X-ray Science Analysis Group meeting
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X-ray (semiconductor) detectors: Overview

Cadmium Zinc Telluride (CZT):
- Z \sim 50, \ \rho = 5.78 \text{ g/cm}^3,
- X-ray photons: photo effect & Compton scattering
- Operation at room temperature (band gap: \sim 1.6eV)
- Limits in energy resolution: charge fraction => phonons
- Alternatives: Measure $\Delta T$ of absorber

Application of CZT:
- Medical & homeland security
- Astrophysics (Swift: 32,768, INTEGRAL: 16,384)
  + present and future missions

X-ray mirror technology:
- Major improvements in fabrication/cost/accuracy
- Focusing (compared to coded mask):
  larger effective area, better imaging, higher S/N
CZT on board the NuSTAR satellite

NuSTAR mission (SMEX):
- Harrison et al., arXiv 1301.7307 (2013)
- Kitaguchi et al., SPIE, 8145, 814507 (2011)
- Wolter X-ray mirror (large effective area)
- launched in 2012

Focal plane instrument:
- 2x2x0.2 cm³ CZT detectors (32x32 pixels, 605 μm pitch)
- Energy resolution: 0.5keV@14keV, 0.9keV@122keV
- Readout: Caltech NuCIT ASIC (0.4keV readout noise)
  e-/h readout -> determine depth-of-interaction
ProtoEXIST flight:
- Hong et al., NIMA, 654, 361 (2011)
- Coded mask instrument (balloon)

Instrument:
- 8x8 detectors (64 pixels each, p=2.5mm)
- RadNET ASIC (power: ~150 µW/pixel)

3D position sensitive detectors:
- Z.He, et al, IEEE, 54, 843 (20107)
- expertise in thick CZT detectors/readout
- 3D position sensitive: depth-of-interaction
  (<1% energy resolution @ 662keV)
- High-energy Compton imaging
CZT X-ray detectors: fabrication & optimization @ Washington Univ.

Clean room (class-100):  
- Photo-lithography masks & E-beam evaporation  
- Readout electronics: BNL & Washington University

Detector characterization:  
- Energy resolution & threshold, effect of steering grid  
- Comparison to simulations (charge sharing/transport)

- Energy resolution: <1% @ 662keV  
- threshold: down to ~15 keV
Variable size pixels (2mm detector)

Findings:
- Big pixels: better energy resolution & rate
- Steering grid improves energy resolution
- Steering grid improves rates (esp. HE)

Rapid prototyping:
(1) quick configuration scan on one detector
(2) reduces uncertainties of re-fabrication
Variable pitch pixels (5 mm detector)

N=1

N=2

rate

resolution

Increasing StGrid voltage

N=2

N=1

N=2
Small (sub-mm) pixels

- Fabricate/test: pixel pitches 350, 600, & 700 um
- Direct bonding to ASIC broad
- Collaboration with L.J. Meng (UIUC): AJAT ASIC readout
- Collaboration with G. Jernigan (Berkeley) & Black Forest: testing 600 um pixel detectors

Readout board for 2048-channel AJAT ASIC.
Future goal: 150 um pixel detectors

Motivation:
- New X-ray mirrors: improved point spread function

Project goals:
- Detectors with 150 um pixel pitch (5-10 arc sec)
- Low energy threshold (<5keV)
- Optimized readout electronics: BNL

Astrophysical applications:
- Black hole vicinity (Fe K band absorption lines)
- Supernova remnants: element emission (C to Ni), relative line power: mechanisms of explosion
- Velocity distribution of rotating gas


See also differential deposition: Weisskopf et al.
Bump-bonding Si detector to small-pixel ASIC
Preliminary ASIC layout overlapping the silicon sensor:
16 by 16 array, 250-µm pitch, 0.6mW/pixel, ENC<10 electrons

Si sensors (16 by 16 arrays)
X-ray astronomy:
- Spectral/morphology studies well established (non-thermal astrophysical sources)
- Spectro-polarimetric observations: access fraction & angle of polarization

Processes resulting in polarized radiation:
Synchrotron radiation (linear, \( ^\) to \( B \)), curvature radiation (circular), Thomson scattering (perpendicular to scattering plane)

X-ray polarimetry: Mission Status
- INTEGRAL: Crab polarization (0.1-1MeV): ~46% [Science, 321, 1183, 2008]

Astrophysics (extract):
- Accreting black holes (BHs): testing accretion disk & BH mass/spin
- Pulsars/PWN: constrain magnetic field & particle populations
- Active galactic nuclei: testing magnetic jet structure

X-ray polarimetry: Possible/future missions:
- Gravity and Extreme Magnetism SMEX (GEMS): 2-10 keV (100 x OSO-8) [Swank]
- Astro-H: E>10 keV, Compton Polarimetry (systematics) [SPIE, 7732, 34, 2010]
X-Calibur design (PI: H.Krawczynski)
measure polarization of 20-80keV X-rays

1: Compton scattering in low-Z scintillator:
   more likely \( \perp \) to \( E \) field vector of photon
   EJ-200, \( \rho \sim 1 \text{g/cm}^3 \), read by Hamamatsu R7600U PMT
2: photo-absorption in high-Z CZT
   8x8 pixels each, read by BNL ASIC (DeGeronimo & Wulf)
3: signature in azimuthal scattering distribution
X-Calibur: Polarized X-rays @ CHESS
Cornell high-energy synchrotron sources (CHESS)

1. CHESS beam
2. scintillator
3. Compton spectrum
4. Azimuth scatter distribution

CZT detectors
Polarized X-ray beam
X-Calibur: Polarized X-rays @ CHESS
Cornell high-energy synchrotron sources (CHESS)

1. CHESS beam
2. Scintillator
3. CZT detectors
4. Azimuth scatter distribution

Agreement with expectations

Compton spectrum
X-Calibur flight: InFOCuS X-ray telescope
8m focal length, 1.4t, grazing incidence Wolter X-ray mirror

X-Calibur/InFOCuS:
1: High detection efficiency (80%)
2: low background (low volume)
3: control/reduction of systematics

Flight: 2013 (1 day, New Mexico)

Crab, Her X-1, Cyg X-1, GRS 1915, Mrk 421, EXO 0331

Rotation: Reduction of systematic effects
Summary & Conclusion

Cadmium-Zinc-Telluride:
→ Material of choice for hard X-ray detectors

Future CZT detector/ASIC development:
→ Smaller pixels (~200 um pitch)
→ Low threshold (<5 keV) ASIC

Hard X-ray polarimeter X-Calibur:
→ Detector fully assembled, calibrated & tested at CHESS
→ 2013-day X-Calibur/InFOCuS balloon flight (Crab, Her X-1, Cyg X-1, GRS 1915, EXO 0331, Mrk 421)
→ Applied for long-duration flight (goal: 2keV threshold)

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