CdTe Hybrid Pixel Detector for Imaging with Thermal Neutrons

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Outline

- Motivation: Neutron radiography
- Medipix2 device as a neutron imager
- CdTe Simulations
- Measurements
- Sample objects
- Comparison with other detectors
- Conclusions
Why neutron radiography?

• While X-rays are attenuated more effectively by heavier materials like metals, neutrons allow to image some light materials such as hydrogenous substances with high contrast.
• Neutron radiography can serve as complementary technique to X-ray radiography

X-rays

Neutrons

In the X-ray image, the metal parts of the photo camera are seen clearly, while the neutron radiogram shows details of the plastic parts.
## X-rays

### Attenuation coefficients with X-ray [cm⁻¹]

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<th>3a</th>
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### Lanthanides

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### Legend

Attenuation coefficient [cm⁻¹] = sp.gr. * µ/δ

Thermal neutrons

Attenuation coefficients with neutrons [cm\(^{-1}\)]

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* Lanthanides

* Actinides

Legend

\[ \sigma\text{-total} \times \text{sp.gr.} \times 0.6023 = \text{att.wt.} \]


Medipix device

- Planar semiconductor pixel detector (Si, GaAs, CdTe, ...)
- Bump-bonded to Medipix readout chip containing amplifier, double discriminator and counter in each pixel cell.

**Medipix-1**
- Pixels: 64 x 64
- Pixel size: 170 x 170 μm²

**Medipix-2**
- Pixels: 256 x 256
- Pixel size: 55 x 55 μm²
Adaptation of the Medipix device for slow neutron detection

**Principle:**
Semiconductor pixel detector can barely detect slow neutrons directly.
⇒ Conversion of thermal neutrons to detectable radiation in a suitable material is needed.

**Placement of a converter:**
- on the sensor surface (coated detector),
- inside of the sensor volume (stuffed detector),
- converter is a component of the sensing material.

**Converter materials:**

<table>
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<tr>
<th>Material</th>
<th>Reaction</th>
<th>Emission</th>
<th>Cross section</th>
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</thead>
<tbody>
<tr>
<td>$^6$Li</td>
<td>$^6$Li + n → α (2.05 MeV) + $^3$H (2.72 MeV)</td>
<td></td>
<td>940 barns</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>$^{10}$B + n → α (1.47 MeV) + $^7$Li (0.84 MeV) + γ (0.48 MeV) (93.7%)</td>
<td>(0.48 MeV) (93.7%)</td>
<td>3 840 barns</td>
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<tr>
<td>$^{10}$B</td>
<td>$^{10}$B + n → α (1.78 MeV) + $^7$Li (1.01 MeV) (6.3%)</td>
<td>(1.01 MeV) (6.3%)</td>
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<tr>
<td>$^{113}$Cd</td>
<td>$^{113}$Cd + n → $^{114}$Cd + γ (0.56 MeV) + conversion electrons</td>
<td></td>
<td>26 000 barns</td>
</tr>
<tr>
<td>$^{155}$Gd</td>
<td>$^{155}$Gd + n → $^{156}$Gd + γ (0.09, 0.20, 0.30 MeV) + conversion electrons</td>
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<tr>
<td>$^{157}$Gd</td>
<td>$^{157}$Gd + n → $^{158}$Gd + γ (0.08, 0.18, 0.28 MeV) + conversion electrons</td>
<td></td>
<td>~60 000 barns</td>
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Promising candidate: CdTe sensor

- 1mm thick CdTe bonded on Medipix2 chip
- Opaque for slow neutrons => almost all neutrons are captured
- Secondary radiation to be detected:
  - 558 keV photons
  - 558 keV electrons of internal conversion (about 3%)

What imaging properties would have such neutron detector?
Monte-Carlo Simulations: Gamma Ray Interactions

10,000 tracks of 560 keV photons in CdTe crystal have been simulated in MCNP.

Range of 560 keV gamma photons exceeds Medipix size
=> background signal in images
Point and Line Spread Functions

Simulated point spread function caused by gamma detection

Simulated Line Spread Function caused by gammas

⇒ Spatial resolution in terms of FWHM of LSF via detection of gamma photons would be \( \sim 480 \mu m \)

⇒ Background signal is generated in whole image

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Monte-Carlo Simulations: Electron Interactions

⇒ Expected spatial resolution via electron detection is ~200 µm
Combination

Expected behavior of CdTe as a slow neutron detector is given by combination of previous results:

⇒ Estimated spatial resolution is ~ 6 pixels which is 320 µm.
⇒ Estimated detection efficiency is ~ 20% but only 8% is usable for imaging.
Tests with Thermal Neutrons

- Horizontal channel of the LVR-15 nuclear research reactor at Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague.
  - Intensity is about $10^7$ neutrons/cm$^2$s (at reactor power of 8MW)
  - Beam Cross section: 4 mm (height) x 60 mm (width)
  - The divergence of the neutron beam is < 0.5°

- Detector setting:
  - Bias voltage = 250V
  - Variable threshold level

Beam profile

Single events (1ms)
CdTe detector properties

Edge Response Function

Projection of the straight edge of 1mm thick cadmium plate used.

Flat Field correction by beam profile performed.
Comparison with simulation

Comparison of simulated and measured
Edge response function

- Rel. signal vs X [mm]

Simulation
Measurement

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Real spatial resolution

LSF can be obtained by numerical differentiation of measured edge response function:

FWHM of LSF: 
= 8.1 pixels 
= 445 µm
Sample objects

- Blank cartridge
- CdTe
- LiF

- Head of fish
- CdTe
- LiF + Medipix1
### Comparison with other neutron converters

<table>
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<tr>
<th>Placement</th>
<th>Converter type</th>
<th>Spatial resolution</th>
<th>Detection efficiency</th>
<th>Remarks</th>
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<tr>
<td>Surface layer</td>
<td>$^6$LiF</td>
<td>100 µm</td>
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<td>$^{10}$B</td>
<td>50 µm</td>
<td>1.5 %</td>
<td>-</td>
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<td>$^{113}$Cd</td>
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<td>5 %</td>
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<td>$^{155,157}$Gd</td>
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<td>Mixed</td>
<td>Cd in CdTe detector</td>
<td>445 µm</td>
<td>8 %</td>
<td>High background</td>
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Conclusions

- The simulations and measurements of CdTe sensor as neutron imager has been done.

- CdTe sensor in combination with Medipix2 chip can be used for direct neutron imaging but its imaging performance is not good. Particularly:
  - Spatial resolution is 450 µm
  - Detection efficiency is about 8%

- Other converter types can offer better results
Thanks a lot for your attention