X-ray Detectors

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NX School
Outline

- Counting vs. integrating
- Indirect versus direct detection
  - Scintillation Counters
  - Area detectors using scintillators
    - Large area for diffraction (low spatial resolution, \(\sim 100\ \mu\text{m}\))
    - Small area for imaging (high spatial resolution, \(\sim 1\ \mu\text{m}\))
  - Ion Chambers
  - Pixel array detectors (e.g., Pilatus)
  - Energy resolving detectors (i.e., spectroscopic detectors)
    - Measuring the energy of photons
    - Silicon diodes
    - Superconducting detectors
How do you detect x-rays?

- Need to convert to something that you can measure
  - **Electrons**... \( Q = CV \)
    - Indirectly (x-rays \( \rightarrow \) optical photons \( \rightarrow \) electrons)
      - Scintillators + Optics + photomultiplier/CCDs
    - Directly (x-rays \( \rightarrow \) electrons)
      - Ion Chambers, Pixel Array detectors (e.g., Pilatus)
  - **Temperature**
    - \( \Delta T = E_\gamma / (\text{Heat Capacity}) \)
      - Superconducting calorimeters
Counting versus Integrating

Counting

Integrating

threshold

counter

ADC

dexposure current
Counting versus Integrating

- **Counting**
  - Single photon counting
    - Scintillator counting detectors (e.g., Cyberstar)
    - Pilatus (counting pixel array detectors)
    - Energy-resolving Detectors (Silicon or Germanium diode detectors)
  - Deadtime limitations!!!
  - Dark current rejected with a sufficiently high threshold.

- **Integrating**
  - Signal accumulates
  - CCDs, Ion chamber
  - No deadtime limitations
  - Read noise and dark current are issues to consider
Shaping time - counting detectors

- Response time of detector
- Gain is usually associated with longer shaping time.
- Longer shaping time improved the energy resolution
  - But reduced the total count rate throughput.
Deadtime limitations for counting detectors

Analog pulses

[Diagram showing the pulse shapes for different voltages (Vf) with labels: Vf = -0.15 V, Vf = -0.20 V, Vf = -0.30 V]

Discriminator output
Deadtime

- As you increase the input count rate (ICR), does the output count rate (OCR) follow linearly?
  - The longer the shaping time, the lower the ICR before deviating from linearity.

When to worry?
- Rate > $1 / (2 \times \tau)$
Deadtime for synchrotron (pulsed source)

- Depends on the fill pattern and speed of the detector

324 or 24 bunch mode

Hybrid Singlet

- 1.59 µs

Fast detector (shorter shaping time)

What fill pattern pattern will you be using???

- Hybrid singlet and 324 bunch mode each 2 weeks a run.
- Hybrid singlet useful for special timing experiments.
  - Not great for high count rate experiments.
Indirectly (x-rays $\rightarrow$ optical photons $\rightarrow$ electrons)

Scintillation Counters

NaI(Tl) is the most common scintillator and gives an energy resolution ($\Delta E/E$) of about 35% - 40%. Organic (plastic) scintillators are used for higher speed applications but energy resolution is sacrificed.
Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs)

- Optical detectors are everywhere in our lives... camera phones, etc.

CCDs are integrating detectors. No dead-time issues, but read noise and dark current
Indirectly (x-rays $\rightarrow$ optical photons $\rightarrow$ electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators
Indirectly (x-rays $\rightarrow$ optical photons $\rightarrow$ electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators

- With demagnification for large area detectors
  - Diffraction (< 30 keV)

<table>
<thead>
<tr>
<th>Fiber Optic Taper (Optical photons)</th>
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<tbody>
<tr>
<td>(1 – 3 De-Magnification)</td>
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- Spatial resolution ~ 100 $\mu$m
- No deadtime correction
- Calibrations
  - Dark Subtraction
  - Spatial Distortion
  - Spatial gain variations

- Scintillator (e.g., Gd$_2$O$_2$S)
Indirectly (x-rays $\rightarrow$ optical photons $\rightarrow$ electrons) Amorphous Silicon Flat Panel + x-ray scintillators

- Used at higher energies (> 50 keV)
- Thin film transistor (TFT) technology (a-Si photo-sensors) allows large area detectors
  - Cheaper than CCDs, but more noise!
Indirectly (x-rays → optical photons → electrons)
Charge Coupled Devices (CCDs) + x-ray scintillators

- Magnification → Microscopy
  - μm-scale spatial resolution with x-rays
Directly (x-rays $\rightarrow$ electrons)

**Ion Chambers**

- Integrating detectors... ion current $\sim$ x-ray flux
- Used to monitor beam intensity
- Used to normalize data to the beam intensity ("$I_0$")
- Also used for transmission XAS measurements.
Directly (x-rays → electrons)
Pixel Array Detectors (e.g., Pilatus)

**Diode Detection Layer**
- Fully depleted, high resistivity
- Direct x-ray conversion in Si

**Connecting Bumps**
- Solder, 1 per pixel

**CMOS Layer**
- Signal processing
- Signal storage & output

Sol Gruner et al
Directly (x-rays ➔ electrons)
Pixel Array Detectors (e.g., Pilatus)

Diode Layer (Sensor)

Photodiode layer ➔ high resistivity silicon
(3,000–10,000 ohm-cm).
Thick detector ➔ effective up to 20 keV x-rays.

Diode Cross Section

Sol Gruner et al
Directly (x-rays $\rightarrow$ electrons)
Pixel Array Detectors (e.g., Pilatus)

**CMOS readout chip** (i.e., Application Specific Integrated circuit, ASIC)

Pilatus is a *digital* PAD (photon counting)

*PSI/SLS Detector Group*
Directly (x-rays $\rightarrow$ electrons)

Integrating Pixel Array Detectors

- You can design the CMOS readout in anyway you like.
  - e.g., with an integrating front end.

**Figure 1**: Simplified pixel schematic. The hybridized detector will have the bump-bonding connections between the detector diode and CMOS electronics at the node labeled "IN". All pixels have a switched capacitor charge injection circuit for testing pixel functionality and secondary verification of the calibrated gain profile.

**Figure 1**

Simplified pixel schematic that differentiates the front-end stage and the sampling stage. The reversed biased diode represents the high-resitivity detector layer.

CSPAD at LCLS

Gruner et al.,
Directly (x-rays $\rightarrow$ electrons)

Pixel Array Detectors (e.g., Pilatus)

- Each pixel is a single photon counting detectors!
- Thus has count rate limitations

- 487 x 195 pixels (172 $\mu$m)
- 8.3 cm x 3.3 cm Area
- Count Rate $\sim$ 1 MHz/pixel
- 20-bit counter/pixel
- 5ms readout (Frame Rate = 200 Hz !!)
- 320 micron thick Silicon sensor
- Gateable & electronic shutter

Lower Level Discriminator only

Brönnimann et al. @ PSI in Switzerland (Dectris)
Directly (x-rays $\rightarrow$ electrons)

Pixel Array Detectors - Pilatus Threshold

- Where to set the threshold?
- Is there an “optimal” threshold?
Pilatus Threshold - pixel charge sharing

X-rays

500 μm

X-ray absorption and conversion to photocurrent

Pixels
If threshold is too high, then you under count events (effectively a small pixel).
If threshold is too low, then you double count events.
“Optimal” threshold is 50% of beam energy.
Unless you need to reject fluorescent background.
Energy Resolving Detectors

(aka Energy Dispersive Detectors)
(aka Spectroscopic Detectors)
(aka XRF detector)
Fluorescence (XRF) Measures...

- Abundance (ppm level) and spatial correlations of heavy elements

**Elemental Compositions of Comet 81P/Wild 2 Samples Collected by Stardust** (Flynn et al. 2006)

**Solid-phases and desorption processes of arsenic within Bangladesh sediments** (Polizzotto et al. 2006)

**A link between copper and dental caries in human teeth identified by X-ray fluorescence elemental mapping** (Harris et al. 2008)

**Levels of Zinc, Selenium, Calcium, and Iron in Benign Breast Tissue and Risk of Subsequent Breast Cancer** (Cui et al. 2007)
Spectroscopic Detectors

Diode

( Silicon or Germanium )

X-ray

X-Ray Energy $\sim$ # of e-h pair

( 3.67 eV are need to produce 1 e-h pair for Silicon!!)
In reality, we use *Silicon Drift Diodes* ...
Spectroscopic Detectors – Signal Chain

x-ray → diode → Preamp → Shaping Amp → Digitizer

Pulse Height Analyzer
Multi-Channel Analyzer
Histogram

Energy ~ P.H. ~ channel #

Pulse Height

1 V

3 µs
Spectroscopic Detectors – Pulses to Histograms

Fe-55 Source

Pulse Height

3 µs

1 V

MCA = histogram (e.g., 2048 channels)

SCA = Single Channels (i.e., ROIs)
4-element Silicon Drift Diode

Peak-to-Background Important!!!

- Usually signal is buried here!
- Recombination, incomplete charge capture, etc.

Best Energy Resolution ~ 150eV
Trade-off between count rate and energy resolution!!!

- Shorter shaping time (length of pulse) means more count rate, but less energy resolution.
  - Depends on your experiment.

![Resolution vs. Peaking Time for Amptek Si-PIN and SDD Detectors](image)
Beyond Silicon ... Superconducting sensors

**Thermal sensors**

- energy (calorimeter) or power (bolometer)

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<tr>
<td>Heat Capacity</td>
<td>Thermal Conductance</td>
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- Transition-Edge Sensor (TES) = thin-film biased in superconducting-normal transition
- Use strong $dR/dT$ in transition as thermometer

- molybdenum-copper: robust and temperature stable
  - $T_c \sim 0.92$ K normal

Kent Irvin et al, NIST-Boulder

1/e response time = 100 $\mu$s - 1 ms
Transition Edge Sensors

High resolution, low count rates $\rightarrow$ Need to make arrays

- Optimized TES: energy resolution = 2.4 eV FWHM at 5.9 keV
- NSLS U7A: soft-X-ray (200–800 eV) spectroscopy beamline.

Note:
- useful device:
  - integrated into close-packed array
  - 1.5 μm Bi absorber $\rightarrow$ QE ~ 55% at 5.9 keV
  - 260 μs decay time

Best resolution of any energy-dispersive detector at 6 keV.
Microwave Kinetic Inductance Detectors

‘Microwave’ refers to the readout frequency!
Why use Low Temperature Superconductors?

Energy Gap
- Silicon: 1.10000 eV
- Aluminum: 0.00018 eV

Energy resolution:
\[ R = \frac{1}{2.355} \sqrt{\frac{\eta \hbar \nu}{F \Delta}} \]
Microwave Kinetic Inductance Detectors

- Excess quasiparticles or $\Delta T$ generated by x-ray causes an inductance increase (i.e., “kinetic inductance”)
  - Measure inductance change in a LC resonating circuit

**Multiplexing:** Lithographically vary geometric inductance/resonant frequency...

**Observables...**

- $\Delta L_s$
- $\Delta R_s$
- $\delta \theta$
- $\delta P$
Cryogenic Detector R&D at APS

- The goal is energy resolution < 5eV with good count rate capabilities (> 100kcps)
- Three Main Aspects:
  1. **Device Fabrication**
     - Completely in-house with dedicated deposition chamber
  2. **Cryogenics and Device Characterization**
     - Turnkey 100 mK cryostat (cryogen-free)
  3. **Readout electronics**
     - Multi-pixel implementation in progress
Anatomy of a thermal MKID (i.e., calorimeter)

- **Feedline**
- **Capacitor**
- **Inductor**
- **Absorber**
- **Empty Space**

- 0.5 μm thick SiN
- 300 μm
- 0.5 x 300 x 300 μm Tantalum Absorber
- 100 nm WSi₂ resonator
Microfabration Fabrication Process

1. 0.5 µm SiN + 300 µm Silicon wafer
2. Resonator deposition (@ APS)
3. Resonator Lithography (MA-6, CNM)
4. Resonator Etch (Oxford RIE, CNM)
5. Resist strip (1165 remover, CNM)
6. Absorber Lithography (MA-6, CNM)
7. Absorber deposition (@ APS, CNM)
8. Absorber liftoff (1165 remover, CNM)
9. SiN bridge lithography(MA-6, CNM)
10. Backside SiN membrane lithography (MA-6, CNM)
11. Backside SiN etch (March etcher, CNM)
12. Bulk Si etch (KOH, CNM)
13. Backside protective Al depositions (@ APS)
14. SiN bridge etch (March etcher, CNM)
15. Al wet etch (CNM)
16. Resist strip (1165 remover, CNM)
Conclusions

- Take a moment to analyze what kind of detector you are using!
  - Counting or Integrating?
    - Counting: Deadtime limitations (what’s the fill pattern during my experiment?)
    - Integrating: Dark Subtraction?
  - Pilatus detector (counting pixel array detectors)
    - What threshold should use?
  - Energy resolving detectors?
    - What shaping time to use?
      - Speed versus resolution
  - Interested in detector physics? Come talk to me!
    - Looking for some young minds to develop new detectors!