Detection of X-Rays

- Solid state detectors
- Proportional counters
- Microcalorimeters
- Detector characteristics
Solid State X-ray Detectors

X-ray interacts in material to produce photoelectrons which are collected by applying a drift field.
Charge Coupled Devices
Charge Coupled Devices
Charge Transfer in CCDs

Time-slice shown in diagram
Pixelated Detectors

CCDs have small pixel sizes, good energy resolution, and a single readout electronics channel, but are slow, thin (< 300 microns), and only made in Si.

Pixelated detectors have larger pixel sizes, require many electronics channels, but are fast and can be made thick and of various materials – therefore can be efficient up to higher energies.
Microcalorimeters

X-ray Photon

absorber

thermometer

temperature

time

$\Delta E = 6 \text{ eV}$

@ 6 keV

$< 0.1 \text{ K}$
Proportional Counter

- X-ray enters counter, interacts with gas emitting photoelectrons which drift toward anode
- E field near anode is high, electrons are accelerated and ionized additional atoms, original charge is multiplied
- Output is one electrical pulse per interacting X-ray

Gas fills volume
Position Sensing

- Need to have drift E field which is parallel.
- Need segmented readout.
- Resolution is limited by diffusion of electron cloud.
- Time resolution is limited by drift time.
Detector Characteristics

- Sensitivity
- Quantum efficiency
- Energy resolution
- Time resolution
- Position resolution
Poisson Process

\[ P(k \text{ events in interval}) = \frac{\lambda^k e^{-\lambda}}{k!} \]

- Detection of individual X-rays are random events described by a Poisson process.
- For an expected number of events \( \lambda \), the Poisson distribution gives the probability of detecting \( k \) events.
- For large \( k \), the Poisson distribution looks like a Gaussian distribution with mean = \( \lambda \) and standard deviation = \( \sqrt{\lambda} \).
- X-ray and gamma-ray detectors are 'photon counting', there are always fluctuations in photon counts.
Source Counts

- Fluctuations in background signal:
  \[ N = S A t \]
  - \( t \) is integration time
  - \( S \) is source flux (counts cm\(^{-2}\) s\(^{-1}\))
  - \( A \) is detector “effective” area
    \[ = \text{geometric area} \times \text{quantum efficiency} \times \text{window transmission} \]

- Can also measure flux in energy units, multiply photon flux by average photon energy.
Sensitivity

• Fluctuations in background signal:

\[ \Delta N = \sqrt{t\left( B_1 + \Omega AB_2 \right)} \]

• \( B_1 \) is particle background
• \( \Omega \) is detector solid angle
• \( A \) is detector effective area
• \( \Omega AB_2 \) is rate of X-ray background
• \( t \) is integration time
• \( S \) is source flux (counts cm\(^{-2}\) s\(^{-1}\))
Sensitivity

• Signal to noise ratio of source detection

\[ \sigma_n = \frac{\text{signal}}{\text{noise}} = \frac{SA \tau}{\sqrt{B_1 \tau + \Omega AB_2 \tau}} \]

• Limiting sensitivity

\[ S_{\text{min}} = \sigma_n \sqrt{\frac{B_1 / A + \Omega B_2}{At}} \]
Energy Resolution

Generation of photoelectrons is also a random process and is subject to Poisson fluctuations.
Energy Resolution

Number of initial photoelectrons \( N = E/w \), where \( E \) = energy of X-ray, \( w \) = average ionization energy (3.62 eV for Si, 21.5 eV for Xe)

Creation of photoelectrons is a random process, number fluctuates

Variance of \( N \): \( \sigma_N^2 = FN \), where \( F \) is the “Fano” factor, fluctuations are lower than expected from Poisson statistics (\( F = 0.17 \) for Ar, Xe)

Energy resolution (FWHM) is

\[
\frac{\Delta E}{E} = 2.35 \frac{\sigma_N}{N} = 2.35 \sqrt{\frac{wF}{E}}
\]

This is a fundamental limit. Energy resolution can be worse due to other factors, e.g. electronic noise, variations in amplification.
Energy Resolution

Energy resolution obeys same equation as for proportional counters, but average ionization energy is much smaller than for gases.

<table>
<thead>
<tr>
<th>Material</th>
<th>$w$ (eV)</th>
<th>Fano factor</th>
<th>$\Delta E @ 6$ keV (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>26.2</td>
<td>0.17</td>
<td>600-1200</td>
</tr>
<tr>
<td>Xe</td>
<td>21.5</td>
<td>0.17</td>
<td>600-1200</td>
</tr>
<tr>
<td>Si</td>
<td>3.62</td>
<td>0.115</td>
<td>120-250</td>
</tr>
<tr>
<td>Ge</td>
<td>2.96</td>
<td>0.13</td>
<td>112</td>
</tr>
<tr>
<td>CdTe</td>
<td>4.4</td>
<td>0.11</td>
<td>130-2000</td>
</tr>
</tbody>
</table>
Quantum Efficiency

To be detected, X-ray must pass through window without being absorbed and then be absorbed in gas

\[ Q = T_w \exp\left(-\frac{t}{\lambda_w}\right) \left[1 - \exp\left(-\frac{d}{\lambda_g}\right)\right] \]

\( T_w \) is geometric open fraction of window, \( t \) is window thickness, \( d \) is gas depth, \( \lambda \)'s are absorption length for window/gas (energy dependent)
Efficiency versus Energy

The graph illustrates the transmission through a window as a function of energy for different materials. The x-axis represents energy (in keV), and the y-axis represents the transmission through the window. The curves are labeled as follows:

- C2 (not light tight)
- C1 (light tight)
- 8 μm Be (0.3 mil)
- 13 μm Be (0.5 mil)
X-Ray Reflectivity

Reflectivity Data at 8.03 keV: H6 Production

- Experimental Results
- Theory

1024-1370-C1
Sample S19
25 July 1995
Grazing Incidence Optics
Scientific Gains from Imaging

• Increase S/N and thus sensitivity
  – Reduce source area and thus the associated background

• Allow more accurate background estimation
  – Take background events from the immediate vicinity of a source

• Enable the study of extended objects
  – Structures of SNR, clusters of galaxies, galaxies, diffuse emission, jets, …

• Minimize source confusion
  – E.g., source distribution in galaxies

• Provide precise positions of sources
  – Identify counterparts at other wavelengths
Gratings

\[ \sin \alpha + \sin \beta = -\frac{m\lambda}{d} \]

\( \alpha \) = incidence angle, \( \beta \) = diffraction angle, \( \lambda \) = wavelength, \( m \) = diffraction order (1, 2, …), \( d \) = groove spacing

For X-ray diffraction need \( d \sim 0.1 \text{–} 1 \mu\text{m} \)
Hands on Data Analysis

• Next Wednesday, we will do a hands on data analysis exercise.
• Please look at the lecture for 8/31 on “Hands on data analysis” and try downloading and installing the software over the next few days.
• Matt will be available in 607 VAN to help.

• Note that home work #1 is on the web site and is due on Wednesday, 8/31.