Fast Neutron Detection and Imaging

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Neutron Imaging
**Special Nuclear Material - detection/imaging**

**SNM detection applications**
- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

**SNM imaging applications**
- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

Standoff detection

Cargo screening

Arms control treaty verification

Emergency response
### Special Nuclear Material – why neutrons?

#### The Passive Gamma-Ray Signatures

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Energy (keV)</th>
<th>Activity (γ/g·s)</th>
<th>Mean Free Path (mm) (High-Z, ρ)</th>
<th>Mean Free Path (mm) (Low-Z, ρ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}$U</td>
<td>120.9</td>
<td>$9.35 \times 10^4$</td>
<td>0.23</td>
<td>69</td>
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<tr>
<td>$^{235}$U</td>
<td>143.8</td>
<td>$8.40 \times 10^3$</td>
<td>0.36</td>
<td>73</td>
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<td>185.7</td>
<td>$4.32 \times 10^4$</td>
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<tr>
<td>$^{238}$U</td>
<td>766.4</td>
<td>$2.57 \times 10^1$</td>
<td>10.0</td>
<td>139</td>
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<td>1001.0</td>
<td>$7.34 \times 10^1$</td>
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<td>159</td>
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<tr>
<td>$^{238}$Pu</td>
<td>152.7</td>
<td>$5.90 \times 10^6$</td>
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<td>75</td>
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<td>766.4</td>
<td>$1.387 \times 10^5$</td>
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<tr>
<td>$^{239}$Pu</td>
<td>129.3</td>
<td>$1.436 \times 10^5$</td>
<td>0.27</td>
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<td>413.7</td>
<td>$3.416 \times 10^4$</td>
<td>3.7</td>
<td>106</td>
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<tr>
<td>$^{240}$Pu</td>
<td>45.2</td>
<td>$3.80 \times 10^6$</td>
<td>0.07</td>
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<td>0.45</td>
<td>76</td>
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<td>642.5</td>
<td>$1.044 \times 10^3$</td>
<td>7.4</td>
<td>127</td>
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<tr>
<td>$^{241}$Pu</td>
<td>148.6</td>
<td>$7.15 \times 10^6$</td>
<td>0.37</td>
<td>74</td>
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<td>208.0</td>
<td>$2.041 \times 10^7$</td>
<td>0.86</td>
<td>83</td>
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<td>$^{241}$Am</td>
<td>59.5</td>
<td>$4.54 \times 10^{10}$</td>
<td>0.14</td>
<td>38</td>
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<tr>
<td></td>
<td>125.3</td>
<td>$5.16 \times 10^6$</td>
<td>0.26</td>
<td>70</td>
</tr>
</tbody>
</table>

*These materials are dense; self-shielding is not negligible.*

Ref: “Panda Book”
### The Passive Neutron Signatures

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life</th>
<th>Spontaneous Fission Yield (n/s·kg)</th>
<th>Spontaneous Fission Multiplicity $\nu$</th>
<th>Induced Thermal Fission Multiplicity $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{U}$</td>
<td>71.7 yr</td>
<td>1,300</td>
<td>1.71</td>
<td>3.13</td>
</tr>
<tr>
<td>$^{233}\text{U}$</td>
<td>$1.59 \times 10^5$ yr</td>
<td>0.86</td>
<td>1.76</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>$2.45 \times 10^5$ yr</td>
<td>5.02</td>
<td>1.81</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$7.04 \times 10^8$ yr</td>
<td>0.299</td>
<td>1.86</td>
<td>2.41</td>
</tr>
<tr>
<td>$^{236}\text{U}$</td>
<td>$2.34 \times 10^6$ yr</td>
<td>5.49</td>
<td>1.91</td>
<td>2.2</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$4.47 \times 10^9$ yr</td>
<td>13.6</td>
<td>2.01</td>
<td>2.3</td>
</tr>
<tr>
<td>$^{237}\text{Np}$</td>
<td>$2.14 \times 10^6$ yr</td>
<td>0.114</td>
<td>2.05</td>
<td>2.70</td>
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<tr>
<td>$^{238}\text{Pu}$</td>
<td>87.7 yr</td>
<td>$2.59 \times 10^8$</td>
<td>2.21</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>$2.41 \times 10^4$ yr</td>
<td>21.8</td>
<td>2.16</td>
<td>2.88</td>
</tr>
<tr>
<td>$^{240}\text{Pu}$</td>
<td>$6.56 \times 10^3$ yr</td>
<td>$1.02 \times 10^8$</td>
<td>2.16</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>14.35 yr</td>
<td>50 ±</td>
<td>2.25</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{242}\text{Pu}$</td>
<td>$3.76 \times 10^5$ yr</td>
<td>$1.72 \times 10^8$</td>
<td>2.15</td>
<td>2.81</td>
</tr>
<tr>
<td>$^{244}\text{Cm}$</td>
<td>18.1 yr</td>
<td>$1.08 \times 10^{10}$</td>
<td>2.72</td>
<td>3.46</td>
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<tr>
<td>$^{252}\text{Cf}$</td>
<td>2.65 yr</td>
<td>$2.34 \times 10^{15}$</td>
<td>3.757</td>
<td>4.06</td>
</tr>
</tbody>
</table>

Ref: "Panda Book", values with ± have significant uncertainty.
**Why neutrons?**

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.

### WGPu vs. HEU

- WGPu:
  - ~5.5e4 n/s/kg
  - IAEA sig = 8 kg
- HEU:
  - ~1.5 n/s/kg
  - IAEA sig = 20 kg

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Diagram showing the penetration of different types of radiation through various materials. Alpha, beta, and gamma rays are shown interacting with paper, thin aluminum plate, lead plate, and water and paraffin. Neutrons interact differently, leading to the emission of gamma rays.
By the way …

The Neutron Fission Cross Sections

Slide courtesy of David Chichester, INL
Backgrounds

- **Gammas**
- **Neutrons**
Backgrounds

- **Gammas**
  - Terrestrial (U, Th, K, etc)
  - Cosmic
  - Radon
  - Granite
  - Coal
  - Tobacco
  - Ceramics
  - Kitty litter
  - Bananas
  - People (medical)

- **Neutrons**
  - Cosmic
  - Few Commercial Products (Smoke Detectors)
  - Industrial Radiography (Cf252, AmBe)
  - Terrestrial (cosmic generated)
Cosmic Rays?

http://apod.nasa.gov/apod/image/0711/cr_auger_big.jpg
Cosmic Rays?

http://apod.nasa.gov/apod/image/0711/cr_auger_big.jpg
Cosmic Background

Taken from Particle Data Group

http://www.fisica.unlp.edu.ar/~veiga/experiments.html
Cosmic Background (variation - altitude)

Taken from Particle Data Group

Cosmic Background (variation - location)

Figure: Graphs showing the variation of cosmic background with altitude and atmospheric depth. 

From Gordon, Goldhagen, et.al. - 2004

Taken from Particle Data Group
Cosmic Background (Magnetosphere)

Cosmic Background (variation - Rigidity)

Cosmic Background (variation - Rigidity)

Neutron Integral Flux (0.5-10 MeV) vs Rigidity (Voyages 17 and 18)
Detection

- Gammas
- Neutrons
Neutron Detection

Hydrogen

Helium-3

Taken from ENDF database

Sandia National Laboratories
Slow Neutron Detection

- High thermal cross section
- High Q-value

\[
\begin{align*}
n + ^3\text{He} & \rightarrow ^3\text{H} + ^1\text{H} + 0.764 \text{ MeV} \\
n + ^{10}\text{B} & \rightarrow ^7\text{Li} + ^4\text{He} + 2.31 \text{ MeV} \\
n + ^6\text{Li} & \rightarrow ^3\text{H} + \alpha + 4.78 \text{ MeV}
\end{align*}
\]
### Neutron Detection - Elastic

\[ Q_{\text{max}} = \frac{4mME_n}{(M + m)^2} \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>( Q_{\text{max}}/E_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H})</td>
<td>1.000</td>
</tr>
<tr>
<td>(^2\text{H})</td>
<td>0.889</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>0.640</td>
</tr>
<tr>
<td>(^9\text{Be})</td>
<td>0.360</td>
</tr>
<tr>
<td>(^{12}\text{C})</td>
<td>0.284</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>0.221</td>
</tr>
<tr>
<td>(^{56}\text{Fe})</td>
<td>0.069</td>
</tr>
<tr>
<td>(^{118}\text{Sn})</td>
<td>0.033</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>0.017</td>
</tr>
</tbody>
</table>

![Graph showing cross section vs. incident energy](image_url)

[Graph showing cross section vs. incident energy]
Discrimination – It’s all about $dE/dx$

$-dE/dx \sim M Z^2/E$

$Me = 511\text{ keV}$

$Mp = 938\text{ MeV}$
**Discrimination – It's all about $dE/dx$**

- **He3 Tube**
  
  $$n + ^3\text{He} \rightarrow ^3\text{H} + ^1\text{H} + 0.764 \text{ MeV}$$

- **BF3 Tube**
  
  $$n + ^{10}\text{B} \rightarrow ^7\text{Li} + ^4\text{He} + 2.31 \text{ MeV}$$
Discrimination – It’s all about $dE/dx$

$-dE/dx \sim M Z^2/E$

Discrimination – It’s all about $dE/dx$

$-dE/dx \sim M Z^2/E$

http://www.bubbletech.ca/radiation_detectors_files/Bubble%20Detectors.html
Neutron Detection – Scintillator

- Luminescence - When a material is excited and it subsequently gives off light.
- How it is excited determines the type of luminescence.
- Scintillation – luminescence produced by ionizing radiation excitation.
- Fluorescence – photoluminescence or scintillation that has a fast decay time (ns to μs).
- Phosphorescence – same as fluorescence, but with much slower decay time (ms to seconds)
Neutron Detection – Organic Scintillator

\[ T_1 + T_1 = S_0 + S_1 \]

http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html
Neutron Detection – Quenching, Birk’s Law

- start with linearity at low ionization density 
  \( \frac{dL}{dx} = A \frac{dE}{dx} \)
- let the density of excited molecules be proportional to the ionization density 
  \( B \frac{dE}{dx} \)
- let \( k \) be the fraction that is quenched 
  \( \frac{dL}{dx} = \frac{A \frac{dE}{dx}}{1 + kB \frac{dE}{dx}} \)
- for small \( \frac{dE}{dx} \), approaches linearity
- for large \( \frac{dE}{dx} \), approaches saturation 
  \( \frac{dL}{dx} = \frac{A}{kB} \)
Neutron Detection – Quenching, $dE/dx$
Neutron Detection – Slow Component

- Triplet: 512 nm
- Singlet: 405 nm

Graph showing counts over time with a logarithmic scale.
Pulse Shape Discrimination

What are we doing again?

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.
- Low and fairly well understood background.

---

Background
~5e-3 n/s/cm²

WGPu
~5.5e4 n/s/kg
IAEA sig = 8 kg

HEU
~1.5 n/s/kg
IAEA sig = 20 kg
Oh yeah ...

Example: Large stand-off application (100 meters)

- 8 kg WGPu = $\approx 4.4 \times 10^5$ n/s → $4.4 \times 10^5 \times \exp(-R/100)/4\pi R^2 \approx 1.3 \text{ n/s/m}^2$
- Background = $\approx 50 \text{ n/s/m}^2$ (at sea level)

- 100% efficient, 1 m$^2$ detector → $5\sigma$ det in $\approx 13$ minutes
- 10% efficient, 1 m$^2$ detector → $5\sigma$ det in $\approx 2$ hours

\[ WGPu \sim 5.5 \times 10^4 \text{ n/s/kg} \]

IAEA sig = 8 kg

Background

$\sim 5 \times 10^{-3} \text{ n/s/cm}^2$

WGPy

~5.5e4 n/s/kg

IAEA sig = 8 kg
\( \delta \theta = \text{angular resolution (solid angle)} \)

\[
\text{Signal} = S A_{\text{eff}} \\
\text{Background} = B A_{\text{eff}} \frac{1 - \cos(\delta \theta)}{2}
\]
4 $\pi$ Counter

Signal = $\sum n ((A/n) \varepsilon S t)$

Background = $\sum n ((A/n) \varepsilon f B t)$

$\sigma_{det}$ = Signal/$\sqrt{Background}$
  = $S \sqrt{(A \varepsilon t/(f B))}$
  = $S \sqrt{(A \varepsilon t/(B))}$

A = physical area
$\varepsilon$ = efficiency
S = signal flux
B = background flux ($4\pi$)
t = time
n = number of pixels
f = FOV fraction per pixel = 1
Collimated Counter

Signal \(= \sum n ((A/n) \varepsilon S t)\)
Background \(= \sum n ((A/n) \varepsilon f B t)\)

\[\sigma_{det} = \frac{\text{Signal}}{\sqrt{\text{Background}}}\]
\[= S \sqrt{\left(\frac{A \varepsilon t}{f B}\right)}\]
\[= S \sqrt{\left(\frac{A \varepsilon t}{B (1-\cos(\theta))/2}\right)}\]
\[= \text{Counter} / \sqrt{(1-\cos(\theta))/2}\]

> Counter

A = physical area
\(\varepsilon = \) efficiency
S = signal flux
B = background flux \((4\pi)\)
t = time
n = number of pixels
f = FOV fraction per pixel
\[= \frac{(1-\cos(\theta))/2}{2}\]
Pinhole Imager

\[ \text{Signal} = (A/n) \varepsilon S t \quad (1 \text{ pixel}) \]
\[ \text{Background} = (A/n) \varepsilon f B t \quad (1 \text{ pixel}) \]

\[ \sigma_{\text{det}} = \frac{\text{Signal}}{\sqrt{\text{Background}}} \]
\[ = S \sqrt{(A \varepsilon t/(n f B))} \]
\[ = S \sqrt{(A \varepsilon t/(n B (1-\cos(\theta/n))/2))} \]
\[ = \text{Counter} / \sqrt{(n/2 (1-\cos(\theta/n)))} \]
\[ < \text{Counter} \quad (n > 1) \]
\[ = \text{Collimator} \quad (n = 1) \]

A = physical area
\( \varepsilon = \text{efficiency} \)
S = signal flux
B = background flux \((4\pi)\)
t = time
n = number of pixels
f = FOV fraction per pixel
\[ \alpha = q/\sqrt{n} \quad (for \ 2-D) \]
Signal $= (A/n) \varepsilon S \ t$ (only 1 pixel)

Background $= (A/n) \varepsilon f B \ t$ (only 1 pixel)

Background uncertainty estimate
$= \sqrt{(A/n) \varepsilon f B \ t/(n-1))$ (others)

$\sigma_{\text{det}} = \frac{\text{Signal}}{\text{Background} + \text{uncertainty}^2}$
$= S \sqrt{(A \varepsilon t/(f B n^2/(n-1)))}$
$= S \sqrt{(A \varepsilon t/(n^2/(2(n-1)) B (1-\cos(\theta/n)))}$

**Counter** - cannot estimate uncertainty without conditions allowing a “no source” data set to be taken.

**Collimator** - cannot estimate uncertainty unless its FOV can change (ie rotation).

$\alpha = \theta / \sqrt{n}$ (for 2-D)
**Pinhole imager**

- Just like a pinhole camera—detect neutrons streaming through a single hole in a thick mask.
- Simplest possible directional detector.
- But low effective area.
Coded aperture imaging

- Extension of pinhole imaging with higher mask open fraction to improve the throughput of neutrons

Pinhole
High Resolution, Low Throughput

Coded aperture
High Resolution, High Throughput
Coded aperture imaging

- Aperture is used to modulate the flux emitted by an unknown source distribution
  - Modulated flux intensity is measured at the detector plane by a position sensitive detector

![Diagram of coded aperture imaging]

Carolli et al, Space Science Reviews 45 (1987), 349-403
Aperture types

- **Uniformly redundant array (URA)**
  - Arrays with constant sidelobes of their periodic autocorrelation function
  - URAs can be generated in any length $L$ that is prime and of the form $L = 4m + 3, m = 1, 2, 3, \ldots$
  - Throughput equal to $(L – 1)/2L$
Coded Aperture Imager

\[ \alpha = \frac{\theta}{\sqrt{n}} \quad \text{(for 2-D)} \]

\[ \sigma_{\text{det}} = \frac{\text{Signal}}{\sqrt{\text{Background}}} \]

\[ = \frac{S}{\sqrt{(A \varepsilon t/(2 f B))}} \]

\[ = \frac{S}{\sqrt{(A \varepsilon t/(2 B (1-\cos(\theta/2))/2))}} \]

\[ = \text{Counter} / \sqrt{(1-\cos(\theta/2))} \]

\[ = \text{Pinhole} \times \sqrt{(n/2)} \]

\[ \times \sqrt{(1-\cos(\theta/n)) / (1-\cos(\theta/2))} \]

\[ < \text{Counter}, \]

\[ > \text{Pinhole} \quad (n > 2) \]

\[ \alpha = \frac{\theta}{\sqrt{n}} \]

\[ A = \text{physical area} \]

\[ \varepsilon = \text{efficiency} \]

\[ S = \text{signal flux} \]

\[ B = \text{background flux} \quad (4\pi) \]

\[ t = \text{time} \]

\[ n = \text{number of pixels} \]

\[ f = \text{FOV fraction per pixel} \]

\[ = (1-\cos(\theta/2))/2 \]
Coded Aperture Imager
(unknown background)

Signal \( = \frac{A}{2} \varepsilon S t \) (1/2 the pixels)

Background \( = \frac{A}{2} \varepsilon f B t \) (1/2 the pixels)

Background uncertainty estimate
\( = \sqrt{\left(\frac{A}{2} \varepsilon f B t\right)} \) (other 1/2)

\( \sigma_{\text{det}} = \frac{\text{Signal}}{\sqrt{\text{Background} + \text{uncertainty}^2}} \)
\( = S \sqrt{\frac{A \varepsilon t}{4 f B}} \)
\( = S \sqrt{\frac{A \varepsilon t}{2 B (1 - \cos(q/2))}} \)
\( = \text{Pinhole} \ast \sqrt{\frac{n^2}{(n-1)}} \ast \sqrt{\frac{(1 - \cos(q/n))}{(1 - \cos(q/2))}} \)
\( > \text{Pinhole} \) (n > 2)

\( \alpha = \theta/n \)

\( \alpha = \theta/\sqrt{(n)} \) (for 2-D)

A = physical area
\( \varepsilon = \) efficiency
S = signal flux
B = background flux (4\pi)
t = time
n = number of pixels
f = FOV fraction per pixel
\( = (1 - \cos(q/2))/2 \)
Coded aperture imagers

- Extension of pinhole with much higher effective area: signal modulated in unique patterns.
- Excellent imaging resolution.
- Potential problems with multiple/extended sources.

Each source equivalent to IAEA significant quantity (1 hour dwell)
Switch spatial modulation for time modulation.
- Simple and robust, low-channel-count detectors.
- Can scale to large effective area.
S/N vs. Angular Resolution
Rotational Self Modulation Concept

- Portable Rotating Imager using Self Modulation (PRISM).
- Rotating Collimator minus passive shielding material.
- More compact and easily scalable at the cost of intrinsic angular resolution.
Rotational Self Modulation

- More compact and more easily scalable at the cost of lower S/N
Neutron scatter camera

Fast neutron directions and energies constrained by double scatter geometry

\[ \theta = \left[ \sin^{-1}\left(\frac{E_p}{E_n}\right) \right]^{1/2} \]

Multimode capability includes
- Neutron energy spectrum.
- Compton imaging.
Algorithms matter

Single neutron scatter camera dataset:

- Backprojection
- MLEM
\( A = \) physical area  
\( \varepsilon_{\text{pair}} = \) efficiency for a pair  
\( S = \) signal flux  
\( B = \) background flux \((4\pi)\)  
\( t = \) time  
\( n = \) number of pixels  
\( m = \) number of pairs = \((n/2)^2\)  
\( f = \) FOV fraction per pair  
\( \Omega_{\text{fractional}} = \)  

**Signal**  
\[ \text{Signal} = \frac{A}{n} \varepsilon_{\text{pair}} S m t \approx \frac{A}{4} \varepsilon^2 \Omega S n t \]

**Background**  
\[ \text{Background} = \frac{A}{n} \varepsilon_{\text{pair}} f B m t \approx \frac{A}{4} \varepsilon^2 \Omega f B n t \]

**\( \sigma_{\text{det}} \) for Double Scatter Imager**  
\[ \sigma_{\text{det}} = \frac{\text{Signal}}{\sqrt{\text{Background}}} \approx \text{Counter} \times \sqrt{\frac{\varepsilon \Omega \text{(rear plane}}}{4 f}} \]

\( \varepsilon_{\text{pair}} = \varepsilon^2 \Omega_{\text{fractional}} \)
The detector zoo

**GOALS**
- Detectors
- Upgrade paths

High-res imaging for treaties, emergencies

Imaging Resolution

- Pinhole
- Scatter Camera
- Coded Aperture
- Time-encoded imaging
- Anisotropy-based

Effective Area

Standoff/Screening (low S:B)

* But confused by multiple/extended sources
** But compact
Conclusions

- Because of their penetrating nature and low, well behaved, relatively well understood background, fast neutron detection is well motivated in the search and characterization of SNM.
- Low signals and backgrounds motivate large imaging detectors.
- Detection and imaging have different motivations.
- Pick the right detector for your application.
Extra Slides
Generate observation probability distribution for all possible source positions.

Use detector response to generate an observation assuming a source distribution and calculate the likelihood that this represents the data.

Maximum Likelihood Expectation Maximization iteratively adjusts the source distribution to increase the likelihood.
Use the right detector!

- Extended source imaging: 20” line source.
- Sizeable source at 3 m – S:B not an issue.
- Pinhole camera outperforms the scatter camera.

**Neutron scatter camera**

**Pinhole imaging system**
Aperture types

**Random**
- Not limited by a mathematical formula
- Can be built for any mask size or open fraction
Motivation for using random masks

- URAs only exist for a limited number of aperture sizes and open fractions
  - Aperture size may be constrained by the available detector size and resolution and cannot always be chosen arbitrarily

- Under non-ideal conditions (which typically exist), tiling the URA pattern to increase the field of view (FOV) of the imager introduces ambiguities in the reconstructed image
Extended source optimization

- Ring, block, point source arrangement

True

Source Distribution (true) zy projection

URA

Source Distribution (mlem) zy projection

Random (50% open fraction)

Source Distribution (mlem) zy projection
Extended source optimization

- **Optimal open fraction**
  - Red line represents URA performance
  - Blue line represents pinhole performance

![Image of graph showing image quality vs. open fraction]
**Extended source optimization**

- Ring, block, point source arrangement

---

**True**

**URA**

**Random (30% open fraction)**