Time Encoded Imaging for Nuclear Non-Proliferation

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Objective

Develop a dual particle imaging system for non-proliferation and radiological search applications

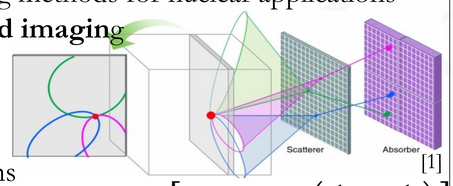
- Sensitive to both neutrons and gammas
- High intrinsic detection efficiency for count starved scenarios
- Cost effective and robust for large scale use

Neutral Particle Imaging

There are two major imaging methods for nuclear applications

1. Scattering physics based imaging

- Create source cone from interaction positions and energy deposited.
- Need multiple interactions => low efficiency
- PSF is dependent on energy resolution, position sensitivity, and geometry.
- Polaris (UM), Dual Particle Imaging (UM), Neutron Scatter Camera (Sandia), Compton Gamma Ray Observatory (NASA)

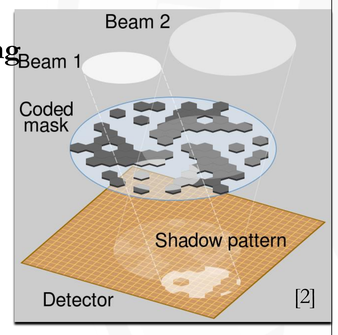


[1]

$$\theta_\gamma = \cos^{-1}\left[1 + m_0c^2\left(\frac{1}{E_\gamma} - \frac{1}{E'_\gamma}\right)\right]$$

2. Spatial modulation based imaging

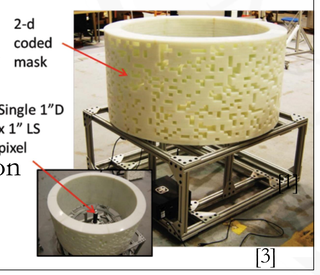
- Source shines on the mask creating a unique shadow pattern
- PSF limited by pixel size
- Requires 2-D positioning => complex electronics & expense
- HPGe Coded Aperture (ORNL) SWIFT (NASA)



[2]

Time encoded imaging

- Mask rotates around central detector
- Time dependent counting rate
- Requires non-position sensitive det.
- PSF decoupled from energy resolution only dependent on mask design
- RHESSI (NASA), 2-D TEI (Sandia)

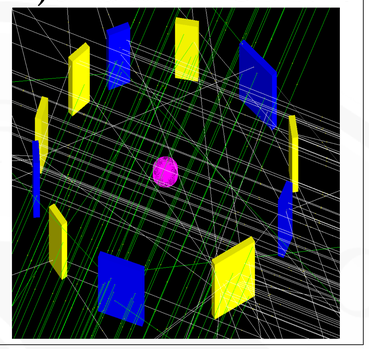


[3]

GEANT4 Simulation

Built a time encoded imaging (TEI) simulation in GEANT4

- Highly customizable simulation
  - Multiple source configurations
  - Mask generation function
  - Material/detector repository
  - Custom built physics list
- External bash script creates and executes simulations for different mask rotation angles.
- Parallelized in G4 v 10.2

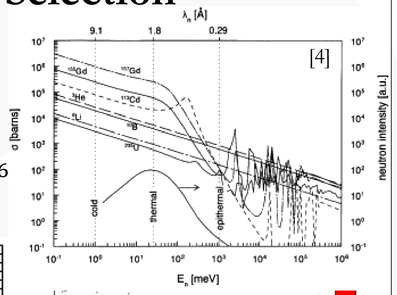


Detector Selection

Dual Particle Sensitivity

- Gammas: high ρ, high Z
- Fast neutrons: hydrogenous
- Thermal neutrons: absorption
- Gamma rejection ratio $< 10^{-6}$

Elpasolite Crystals



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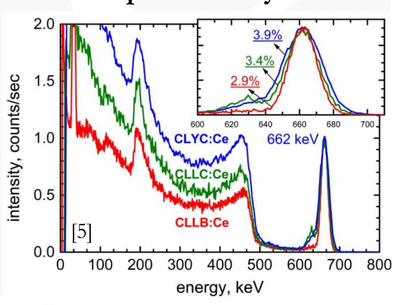

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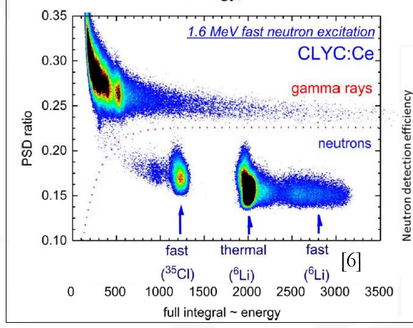

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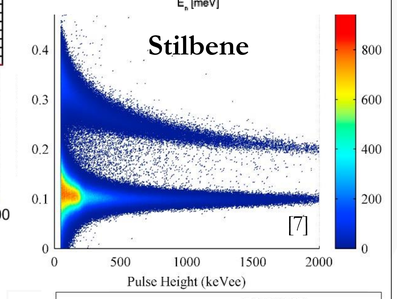

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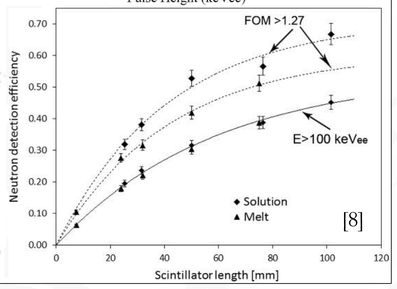

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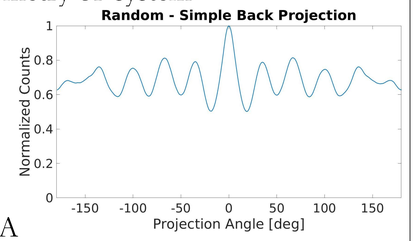
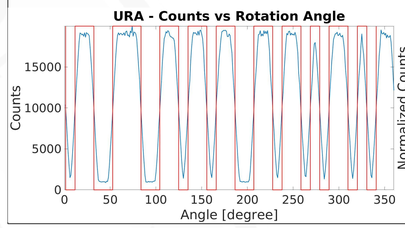
Mask Design

PSF is highly dependent on geometry of system

- Ideal PSF determined by autocorrelation of mask
- Convolved with detector shape: $MD * e^{-2\mu\left(r^2-x^2\right)^{\frac{1}{2}}}$
- Optimize PSF against SNR
- Mask: Random, URA, MURA





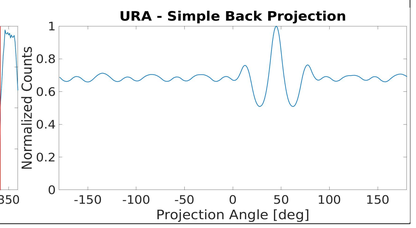


Image Reconstruction

Simple Backprojection

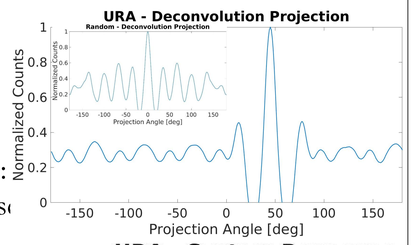
- Deconvolution method
- Include transmission prob.

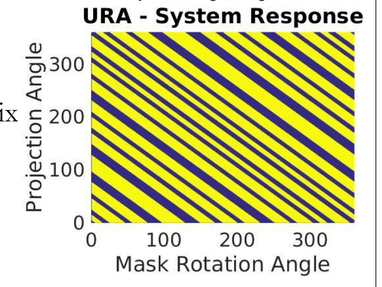
Filtered Backprojection

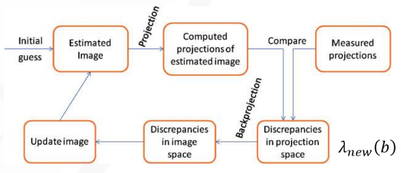
- Analytically calculate filter to:
  - Deconvolve detector response
  - Deconvolve mask autocorrelation broadening

MLEM

- Calculate system response matrix
- Maximize $P(n^*|\lambda)$







$$\lambda_{new}(b) = \lambda_{old}(b)\sum_{d=1}^{D}\frac{n^*(d)p(b,d)}{\sum_{b'=1}^{B}\lambda_{old}(b')p(b',d)} \quad b = 1,2,\ldots,B$$

Use phase change in CR to determine source location

- Matched Filter

References

[1] S. M. Kim, et al, Phys. Med. Biol. Vol. 58 2823 2013 [2] INTEGRAL, NASA [3] J. Brennan, et al, SAND2014-18023 2014 [4] C. W. E. van Eijk, Rad. Meas. Vol 38 2004 [5] J. Glodo, et al, IEEE Trans on Nucl. Sci. Vol 58 No 1 2011 [6] J. Glodo, et al, IEEE Trans. on Nucl. Sci. Vol. 60 2013 [7] M. L. Ruch, et al, NIM Phys. A Vol 793 No 1 2015 [8] N. Zaitseva, et al, NIM Phys. A, Vol 789 No. 21 2015

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