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Spectrum Isolation in Multi-Source Image Reconstruction Using a Dual-Particle Imager

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Institute of Nuclear Materials Management, 56th Annual Meeting

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Motivation
The Need for Versatile Imaging Systems

- Localization and characterization of special nuclear material is a cross-cutting global need
  - Hidden special nuclear material within large-scale containers
  - International safeguards
  - Treaty verification (disarmament, warhead counting)
  - Build-up within nuclear facilities
  - Medical treatment planning and dose monitoring
- Passive special nuclear material signatures can be obtained by:
  - Particle counting
  - Spectroscopy
  - Multiplicity and coincidence counting
  - Imaging
- **Our research aims to develop versatile systems able to obtain the most information possible from these signatures**

Dual-Particle Imager
A Versatile Imaging System

- One system capable of localizing and characterizing both neutron and photon sources
- The use of commercially-available components yields a fully scalable and relatively inexpensive system, adaptable to any need or facility
- The strength of the system is its versatility which enables it to image heavily shielded material as well as characterize diverse nuclear materials, from fission sources to single-decay gamma sources
- Potential end users: emergency response, DTRA, DNDO, IAEA

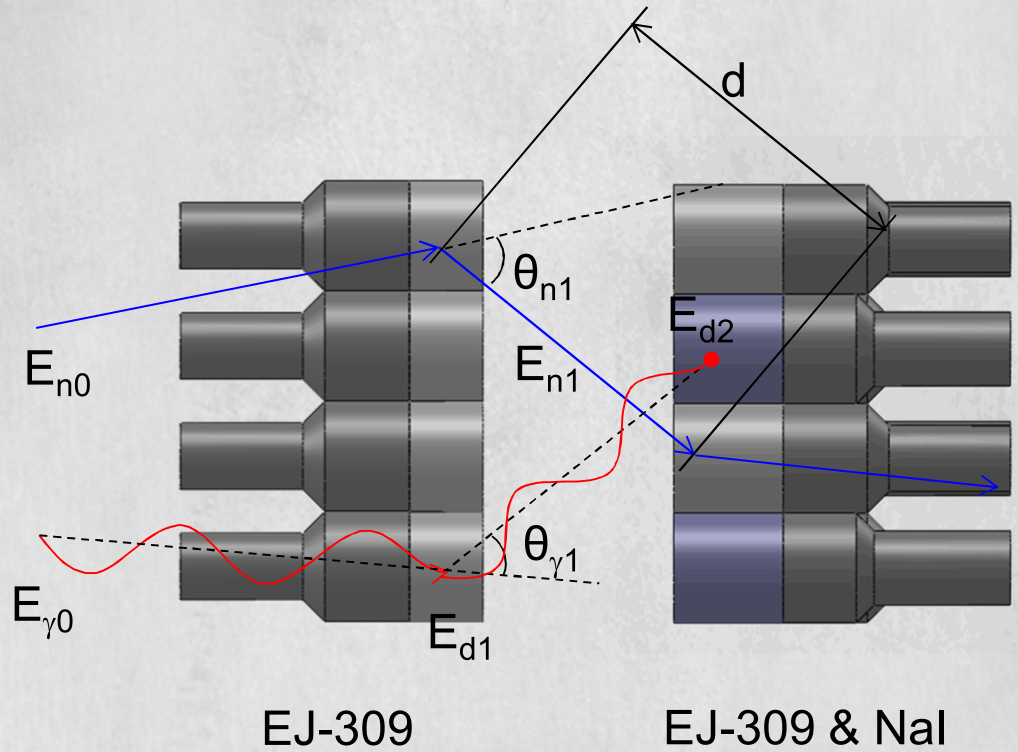
Dual-Particle Imager

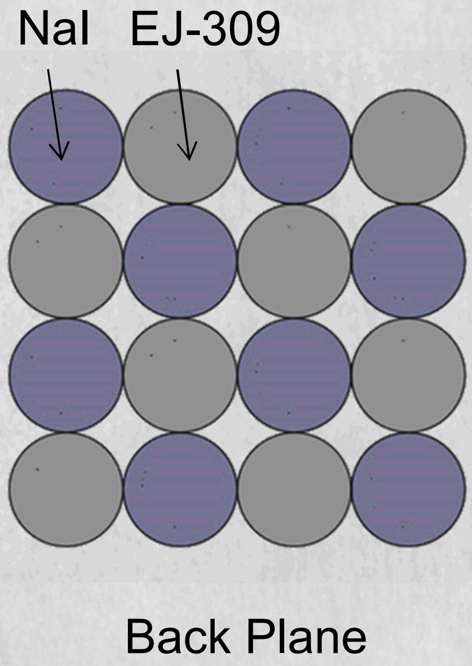
Design & Principle

$$\cos^2\theta_{n1} = \frac{E_{n1}}{E_{n0}}$$

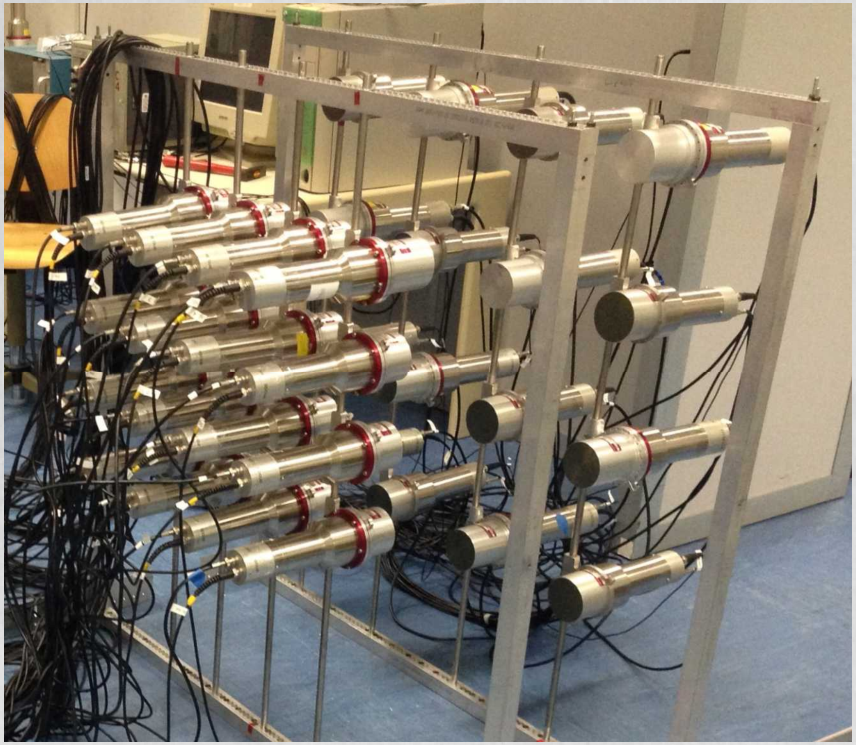
$$E_{n1} = \frac{m_n}{2} \times \frac{d^2}{TOF^2}$$

$$\cos\theta_{\gamma 1} = 1 - \frac{m_e c^2 \times E_{d1}}{E_{d2}(E_{d1} + E_{d2})}$$





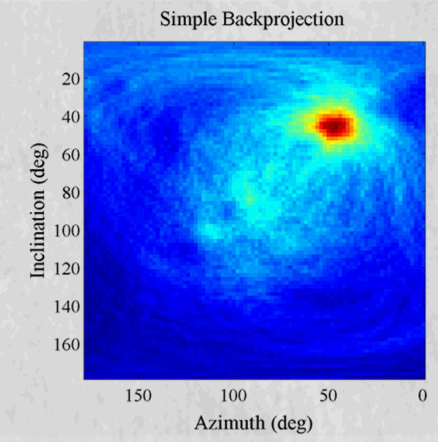
Dual-Particle Imager
Prototype Geometry

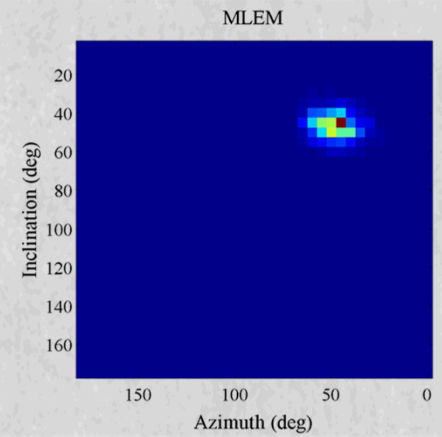


- 30-cm separation between planes
- 15 cm between detector centers in the front plane
  - 7.38-cm gap between detectors
- 25 cm between detector centers in the back plane
  - 17.38-cm gap between detectors

Image Reconstruction
Advanced Algorithms

- Simple backprojection reconstruction is easy to implement but results in blurry images
- Advanced reconstruction algorithms can improve signal-to-noise ratio
  - Filtered backprojection
  - Maximum-likelihood expectation-maximization (MLEM)
  - Stochastic origin ensembles (SOE)
- Ability to estimate individual energy spectra when multiple sources are present

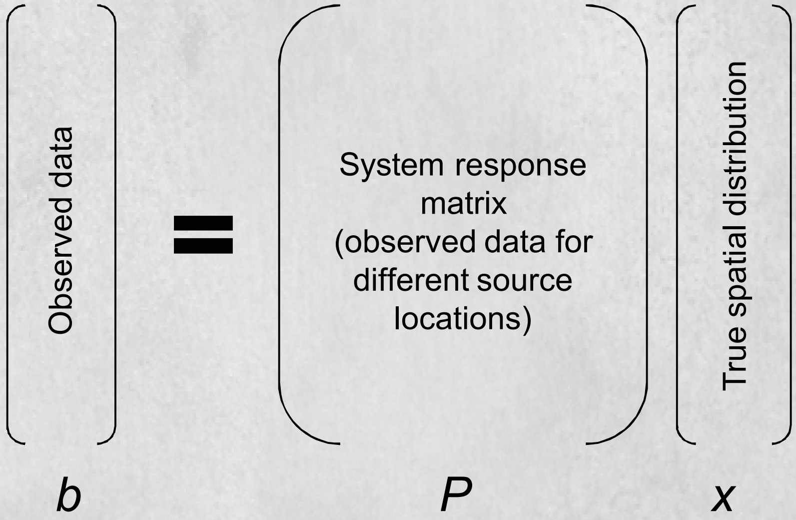




Neutron images for a simulated 26 hour measurement of a 170k neutrons/second ^{252}Cf source at 5 meters.

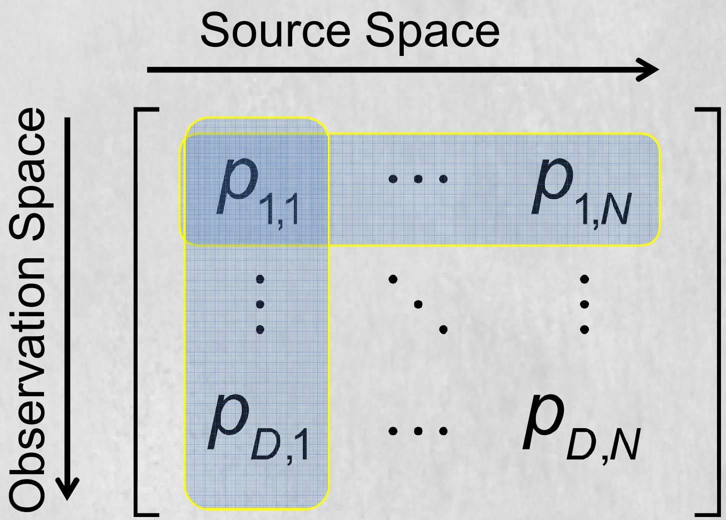
MLEM
Algorithm

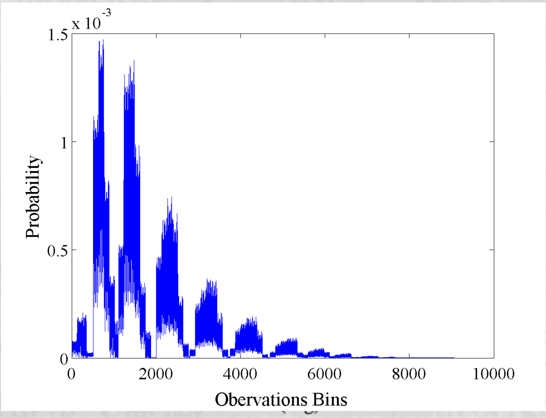
- The MLEM algorithm is used to estimate the true spatial distribution using the observed data
- The system matrix, *P*, maps the system response to the spatial distribution of a source



MLEM
System Matrix

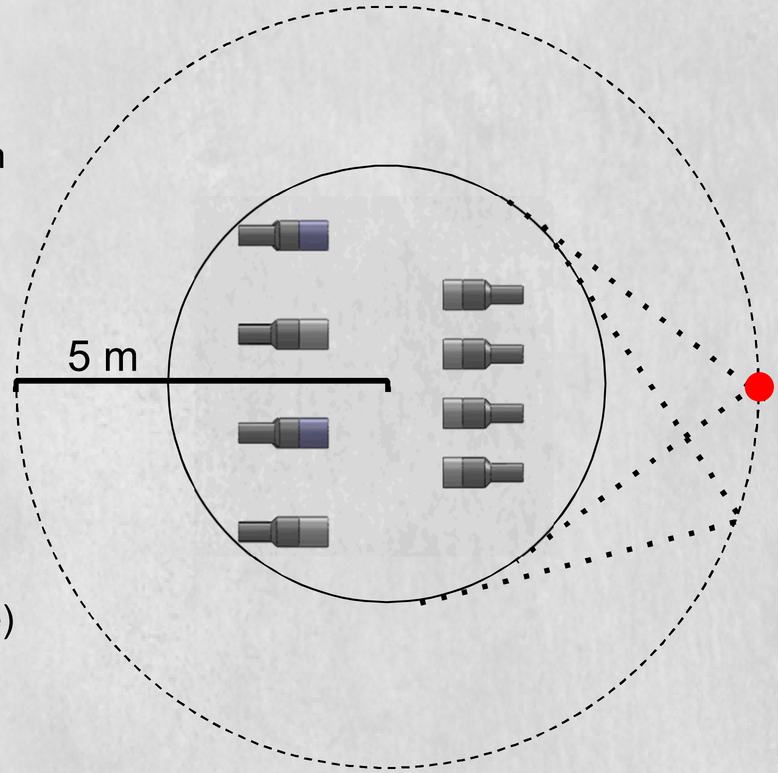
- $p_{d,n}$ is the probability that an emission from the n^{th} source position is recorded in the d^{th} observation bin
- Observation space can be binned by detector pair, reconstructed energy and reconstructed scattering angle
- Source space is binned by location (on an angular mesh), as well as by energy
- Energy bins along source space allow for reconstruction of emitted energy spectra at each location





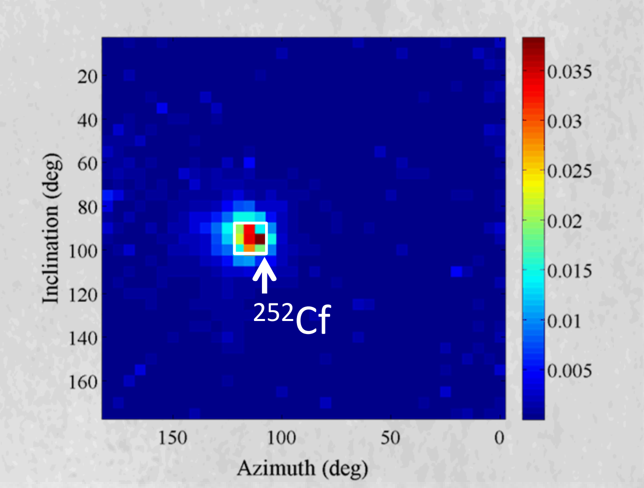
MLEM
System Matrix Creation

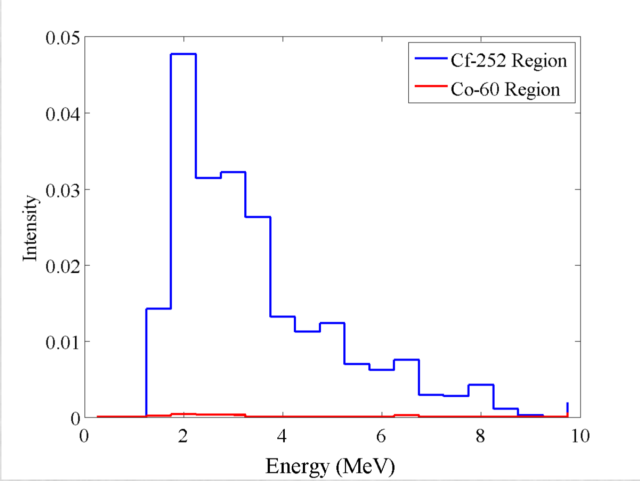
- System matrix calculated by simulating the response from a source in each spatial bin around the system
  - 5° bins are used in both the azimuthal and inclination (1295 locations for 2π hemisphere)
  - Particles are emitted in a cone directed toward a sphere surrounding the system
- Neutrons
  - Source is distributed from 0-10 MeV
  - ~18 hours to simulate 3×10^8 neutrons at each spatial bin
  - Typical system matrix size might be 138,240×51,800 (when energy binning source space)
- Photons
  - Source is distributed from 0-5 MeV
  - ~15 hours to simulate 3×10^8 photons at each spatial bin
  - Typical system matrix size might be 207,360×64,750 (when energy binning source space)

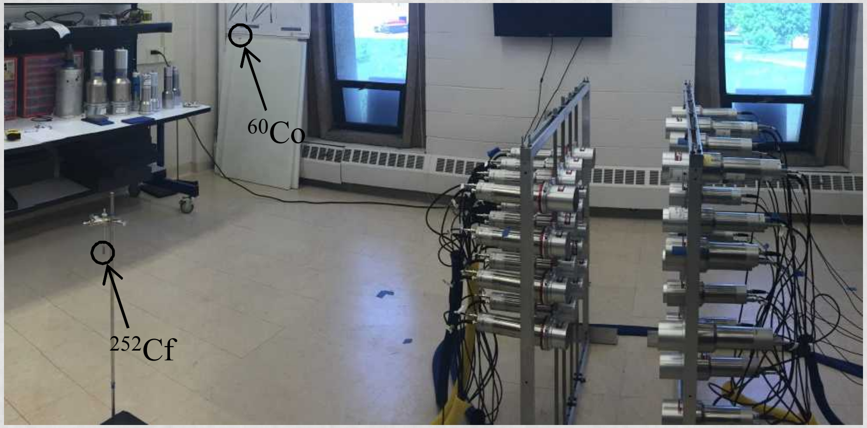


Spectrum Isolation
Neutrons

- 350-minute measurement of:
  - ~3.3×10[4] fissions per second ^{252}Cf located 175 cm from the system at (114°, 93°)
  - ~68 μCi ^{60}Co source located 390 cm from the system at (58°, 84°)
- ~11,500 neutrons measured
- ~1,440,000 photons measured

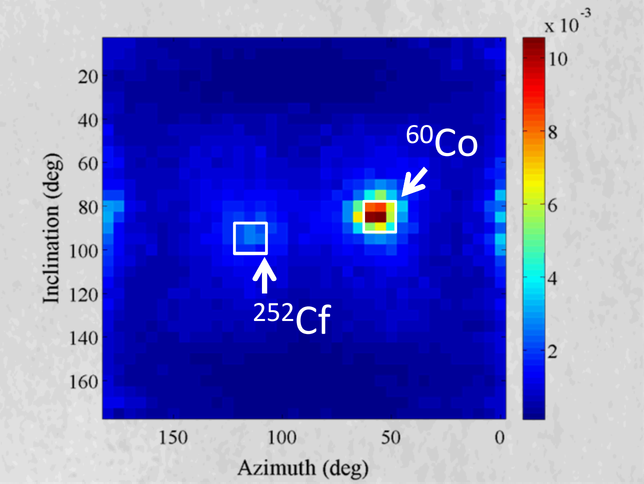


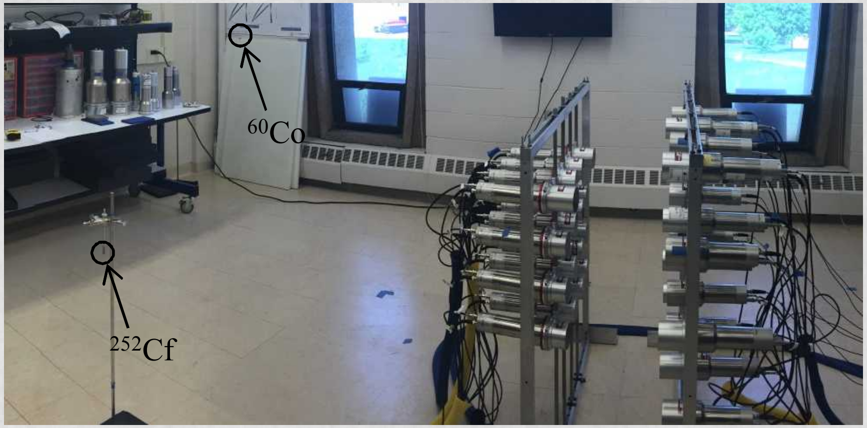


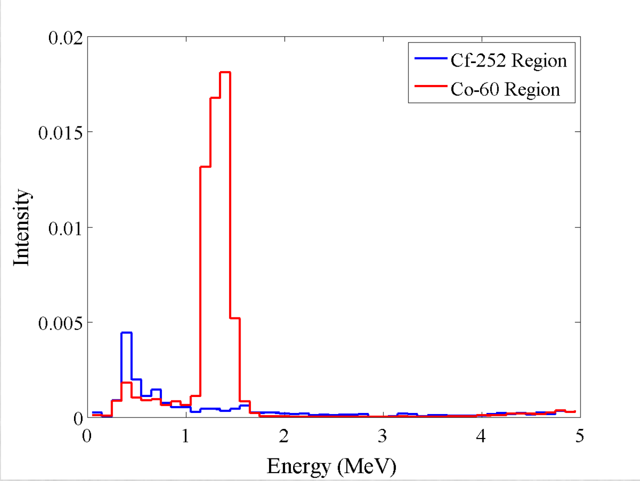


Spectrum Isolation
Photons

- 350-minute measurement of:
  - ~3.3×10^4 fissions per second ^{252}Cf located 175 cm from the system at (114°, 93°)
  - ~68 μCi ^{60}Co source located 390 cm from the system at (58°, 84°)
- ~11,500 neutrons measured
- ~1,440,000 photons measured

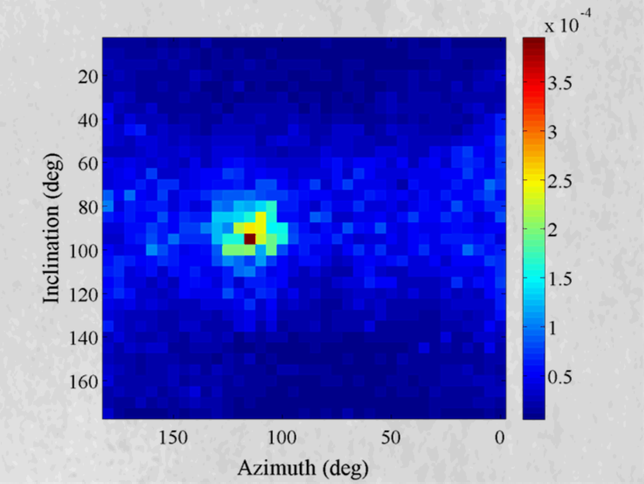


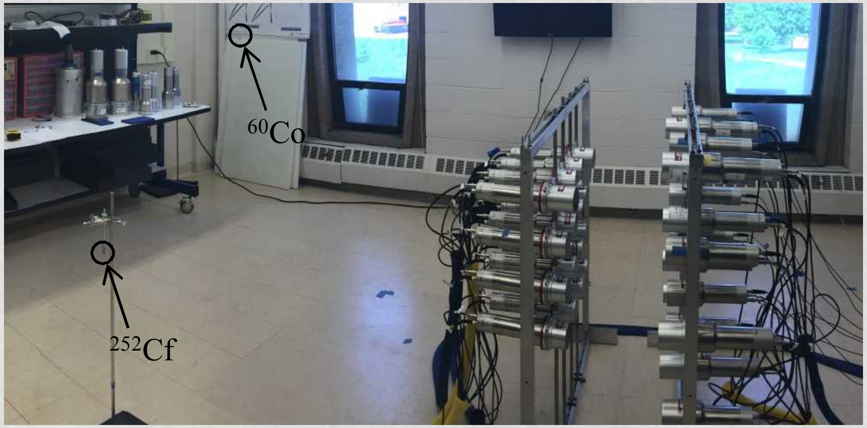


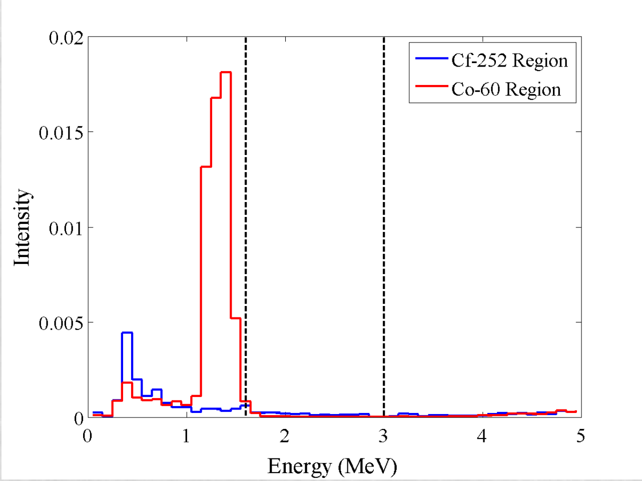


Spectrum Isolation
High-Energy Window

- 350-minute measurement of:
  - ~3.3×10^4 fissions per second ^{252}Cf located 175 cm from the system at (114°, 93°)
  - ~68 μCi ^{60}Co source located 390 cm from the system at (58°, 84°)
- ~11,500 neutrons measured
- ~1,440,000 photons measured

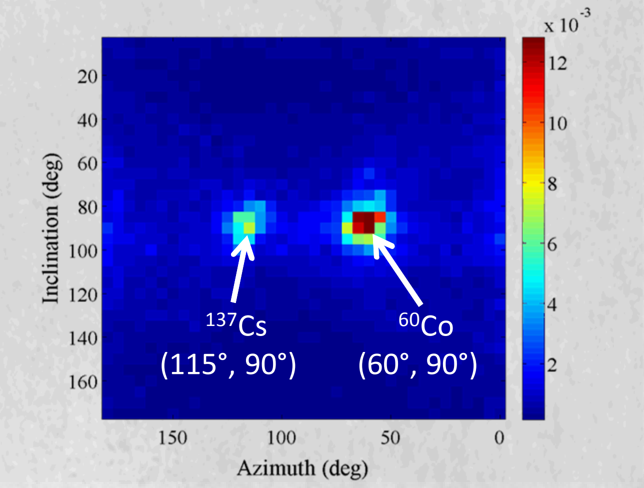


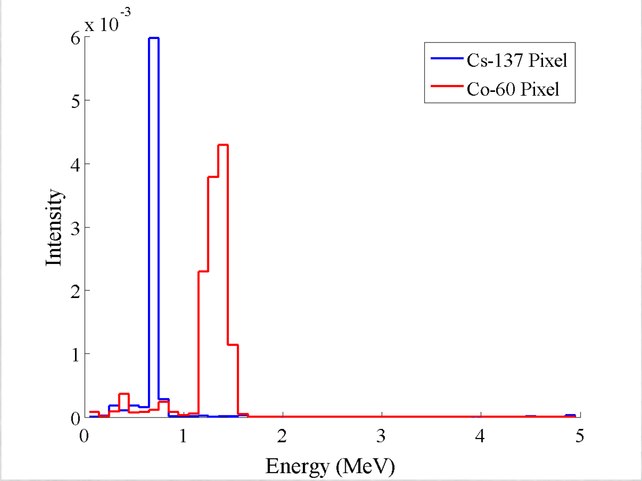




Spectrum Isolation
Gamma-ray Check Sources

- 15-minute measurement of:
  - ~89 μCi ^{137}Cs source located at (117°, 90°)
  - ~68 μCi ^{60}Co source loacted at (61°, 90°)
- 3.8-meter standoff for both sources
- ~58,000 photons measured

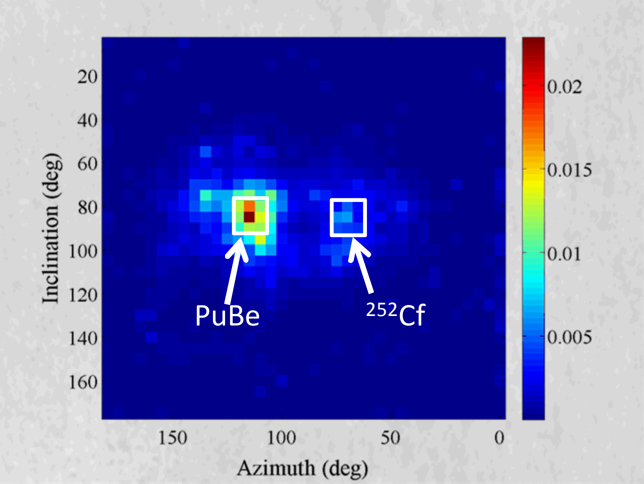




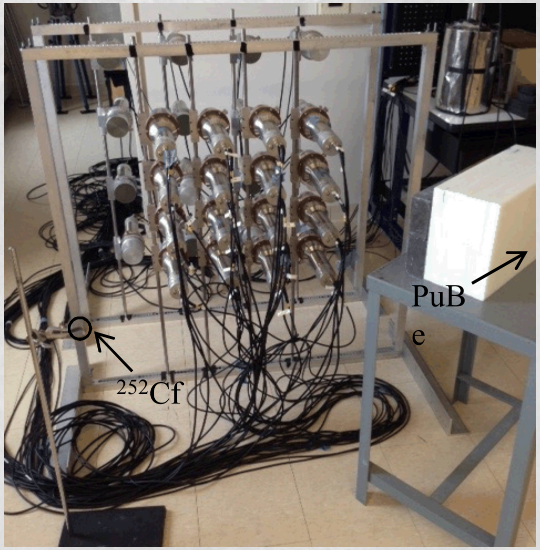
Add photo if possible

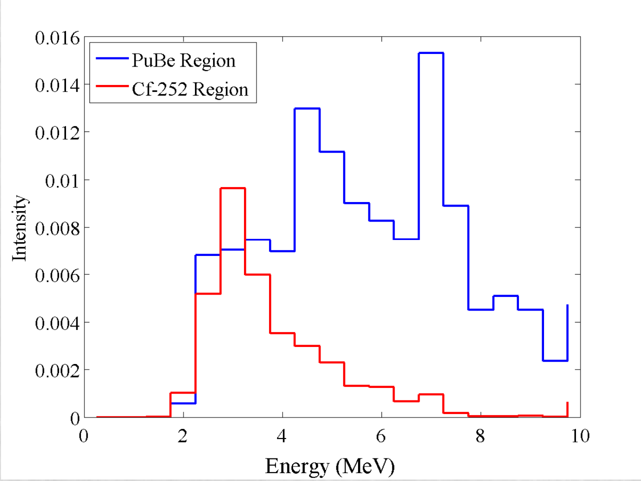
Spectrum Isolation
Neutron Sources

- 480-minute measurement of:
  - ~1.75×10^6 neutrons/second PuBe source shielded by 15.5 cm of poly and 5 cm of lead located at (120°, 98°)
  - ~1.35×10^5 neutrons/second ^{252}Cf source unshielded located at (60°, 90°)



- 1-meter standoff for both sources
- ~103,000 neutrons measured





Summary and Conclusions

- MLEM allows for reconstruction of of the energy spectrum at each spatial location
- The DPI was able to successfully locate photon and neutron sources and reasonably estimate their corresponding energy spectra
- Energy windowing can be used to improve localization and identification capabilities
- The DPI is a viable tool when locating and identifying multiple sources is important: hold-up measurements, cargo screening, warhead verification, etc.

References

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[8] M. Flaska and S. A. Pozzi, “Identification of shielded neutron sources with the liquid scintillator BC-501A using a digital pulse shape discrimination method,” Nuclear Instruments and Methods in Physics Research A, vol. 577, no. 3, p. 654-663, 11 July 2007.

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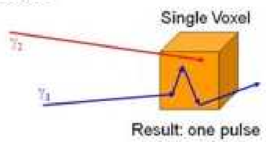
Data Analysis

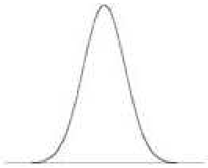
MPPost

MCNPX-PoliMi Data
- Interaction data

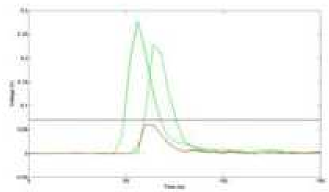
Create Pulses
- Combine interactions in one detector within the pulse generation time



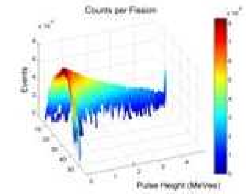
Apply Resolutions
- Energy resolution
- Time resolution



Apply Detector Thresholds
- Lower and upper thresholds



Simulated Detector Response
- Pulse list sorted by time



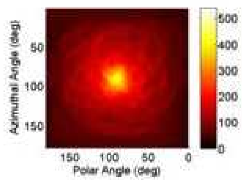
Detector Response
- Simulated or measured

Correlation Algorithm
- Time window applied to correlate pulses

Correlated Counts
- List of accepted pulse pairs

Imaging Algorithm
- Energy window implemented
- Back-projection
- Maximum likelihood expectation maximization (MLEM)

Source location
- Image of the surroundings with a hotspot at the source location



MLEM Algorithm

$$\hat{x}_s^{(k+1)} = \hat{x}_s^{(k)} \sum_{d=1}^{D} \left[\frac{b_d}{\sum_{s'=1}^{S} P_{ds'} \hat{x}_{s'}^{(k)}} P_{ds} \right], \; s = 1, \ldots, S$$

Calculation performed at each iteration of the MLEM algorithm

x – true source distribution

$\hat{x}$ – estimated spatial distribution

b – Observed data vector

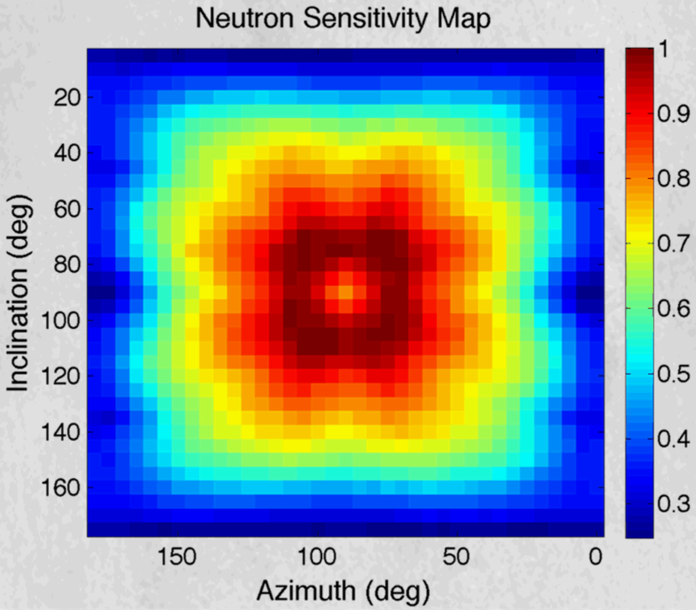
P – System response matrix

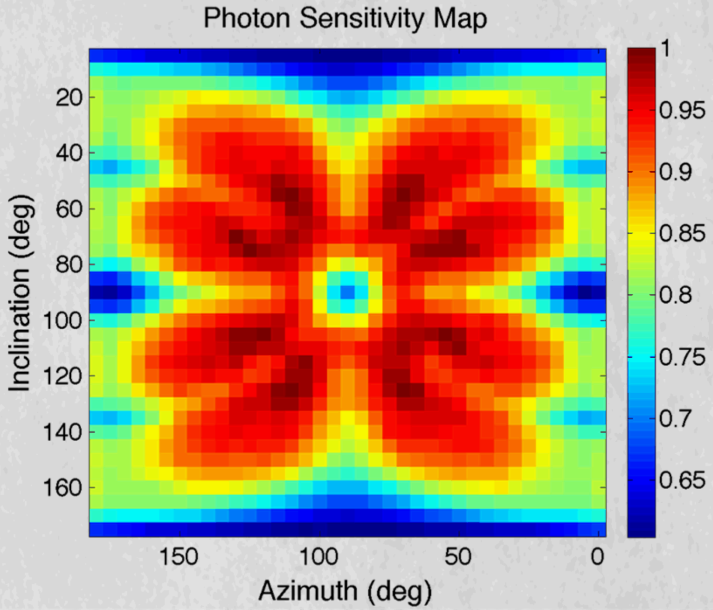
k – Iteration number

D – Number of observation bins

S – Number of spatial bins

^{252}Cf Sensitivity Maps





Relative sensitivity as a function of source location based on simulations of ^{252}Cf

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