Applications in Security and Environmental Imaging

PSD 13 Keynote
September 8, 2023

Prof. Sara A. Pozzi
University Diversity and Social Transformation Professor
Director, Consortium for Monitoring, Technology, and Verification
Director, Diversity, Equity, and Inclusion, College of Engineering
University of Michigan

Motivation

- Preventing the further spread of nuclear weapons and related technology is paramount to our national security
- Recent world events have significant impact on the nonproliferation landscape
  - North Korea nuclear weapons program and recent rocket tests
  - Possible revival of the Joint Comprehensive Plan of Action with Iran
  - Russia/Ukraine war putting nuclear facilities and nonproliferation at risk
- Timely detection of nuclear proliferation requires a deep understanding of the associated signatures and technology

The New York Times

ASIA PACIFIC

North Korean Nuclear Test Draws U.S. Warning of 'Massive Military Response'

查看简体中文版 | 查看繁體中文版

By DAVID E. SANGER and CHOE SANG-HUN SEPT. 2, 2017

329

Dual Use Technology

Enrico Fermi Nuclear Power Plant, Michigan, USA

Ivy Mike, the first successful hydrogen bomb, USA, 1952

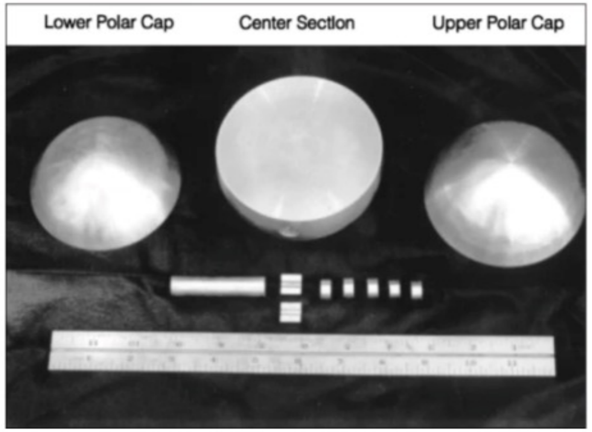
A tension exists between the pursuit of nuclear energy and the effort to prevent the spread of nuclear weapons.

Special Nuclear Material (SNM)

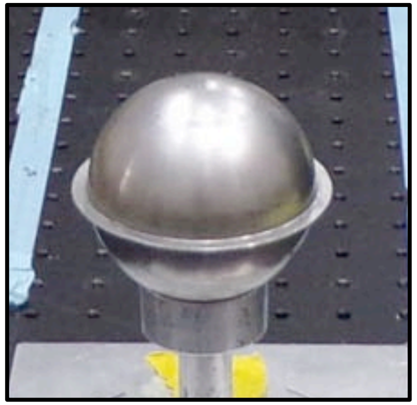
- plutonium
- uranium-233
- uranium enriched in the isotope 235 by more than 20%

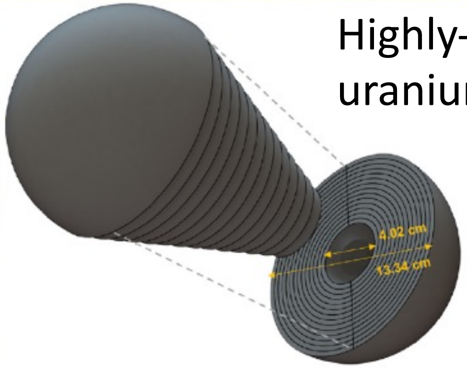
Necessary component of nuclear weapons

Plutonium assembly



Plutonium sphere





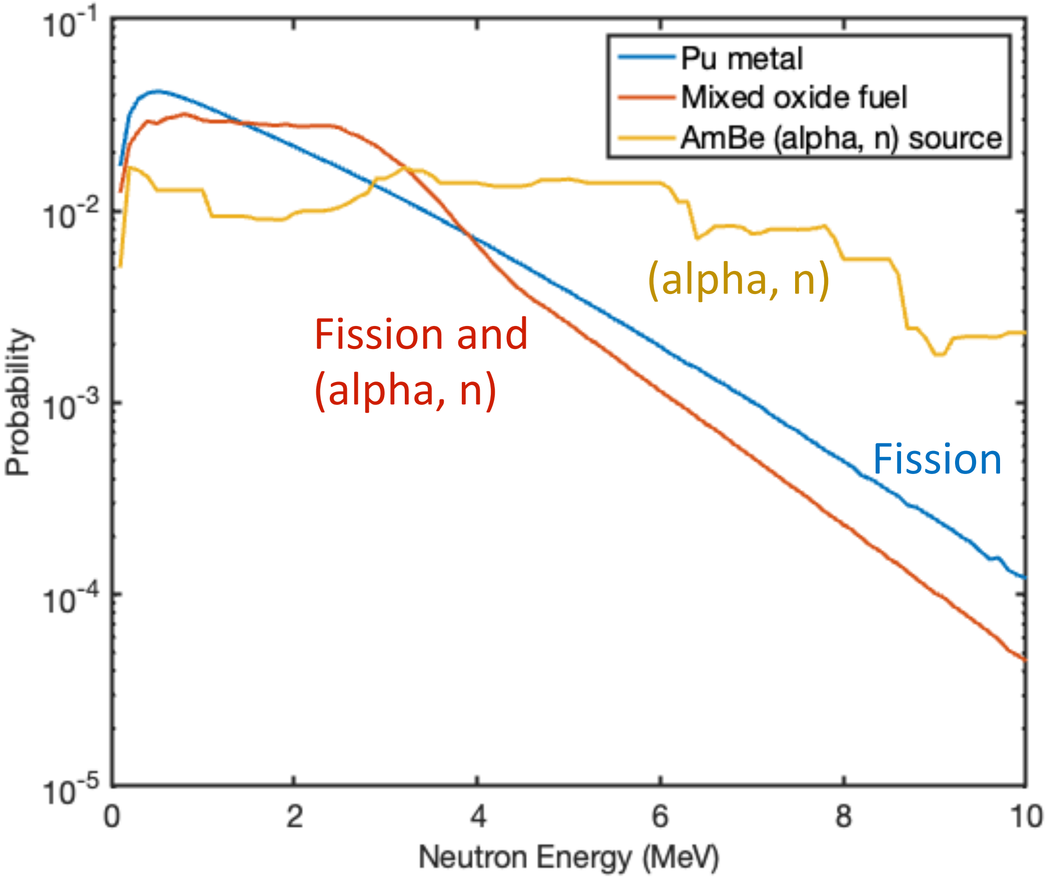
Highly-enriched uranium shells

Neutron Energy Spectra

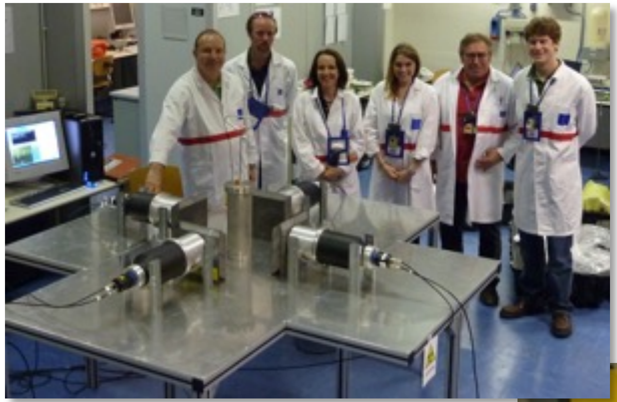
- Various nuclear material forms can be distinguished by their neutron energy spectra

- Neutron emitted from industrial sources such as AmBe or PuBe (alpha, n) reactions have a higher average energy than those from fission

Emitted neutron energy spectra



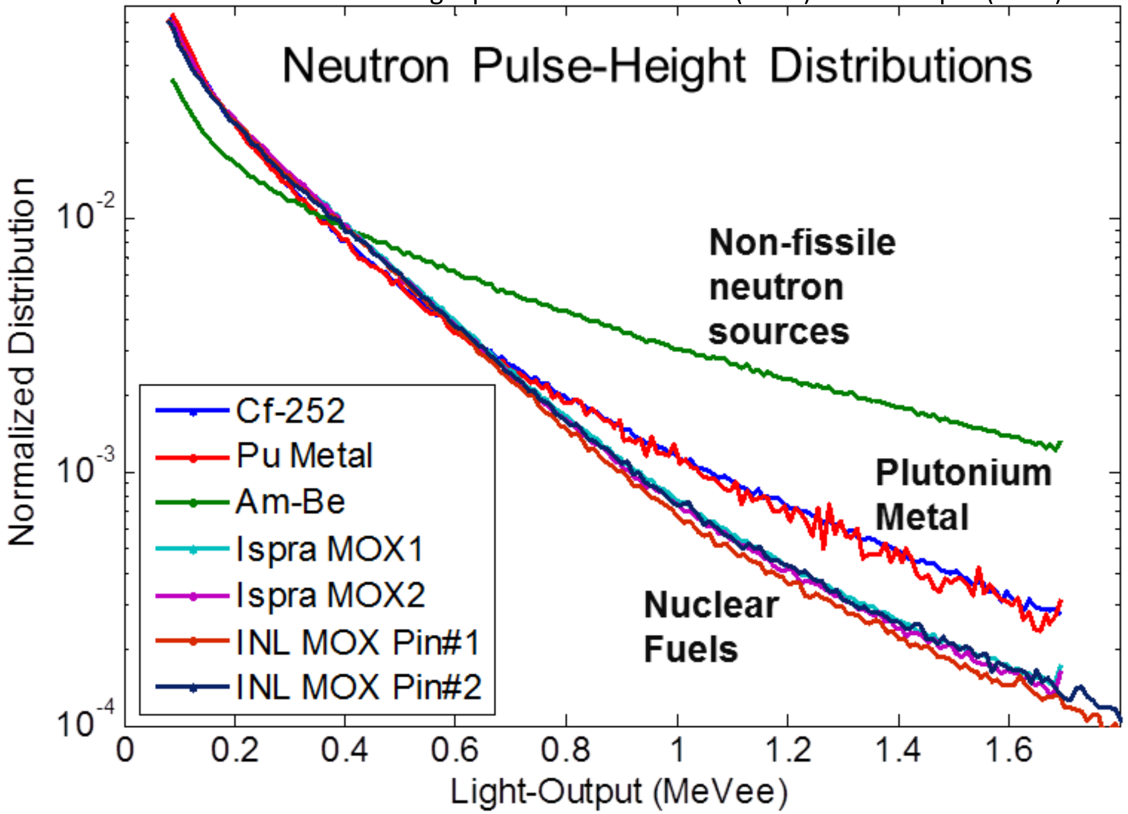
Detecting SNM Signatures
Distinguishing Pu Metal from Other Neutron Sources



Joint Research Centre, Ispra Italy

Idaho National Laboratory

* Measurements using liquid scintillators at INL(2009) and JRC-Ispra (2010)



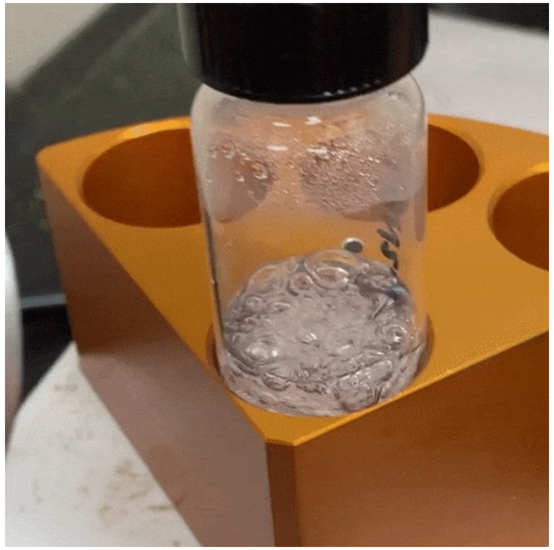
J. L. Dolan, M. Flaska, A. Poitrasson-Riviere, A. Enqvist, P. Peerani, D. L. Chichester, S. A. Pozzi, "Plutonium measurements with a fast-neutron multiplicity counter for nuclear safeguards applications", *Nucl. Instr. Meth. A* 763, 565-574 (2014).

Organic Glass Scintillators for Radiation Detection

- Novel organic glass (OGS) compound recently developed by Sandia National Labs and a casting facility has been developed at UM
- This OGS has demonstrated high light-output and excellent detection efficiency relative to other organic scintillators, such is stilbene
- The OGS can be melt-cast into a variety of shapes and sizes, making it suitable for a wide variety of applications
- A prototype neutron and gamma-ray imaging system has been developed and tested

Sandia National Laboratories

Glass heating and degassing

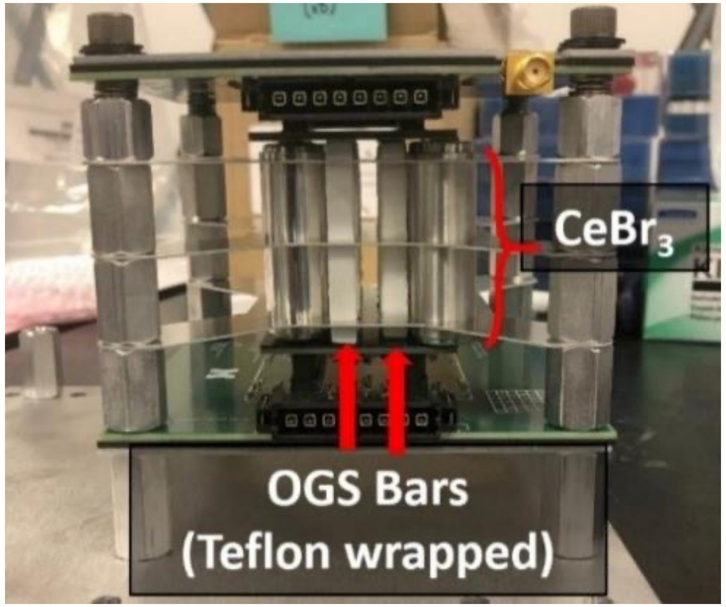


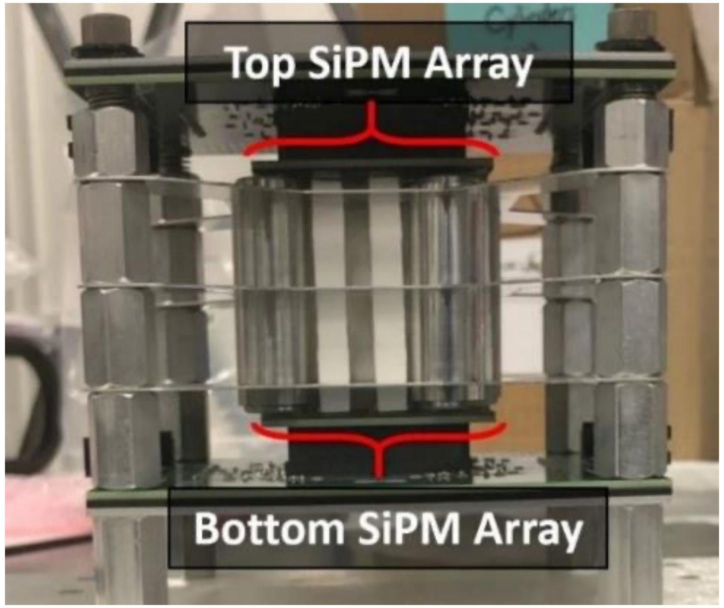
Glass bars used in out imaging system

N. P. Giha, W. M. Steinberger, L. Q. Nguyen, J. S. Carlson, P. L. Feng, S. D. Clarke, S. A. Pozzi, "Organic glass scintillator bars with dual-ended readout", *Nucl. Instr. Meth. A* 1014, 165676, ISSN 0168-9002 (2021).

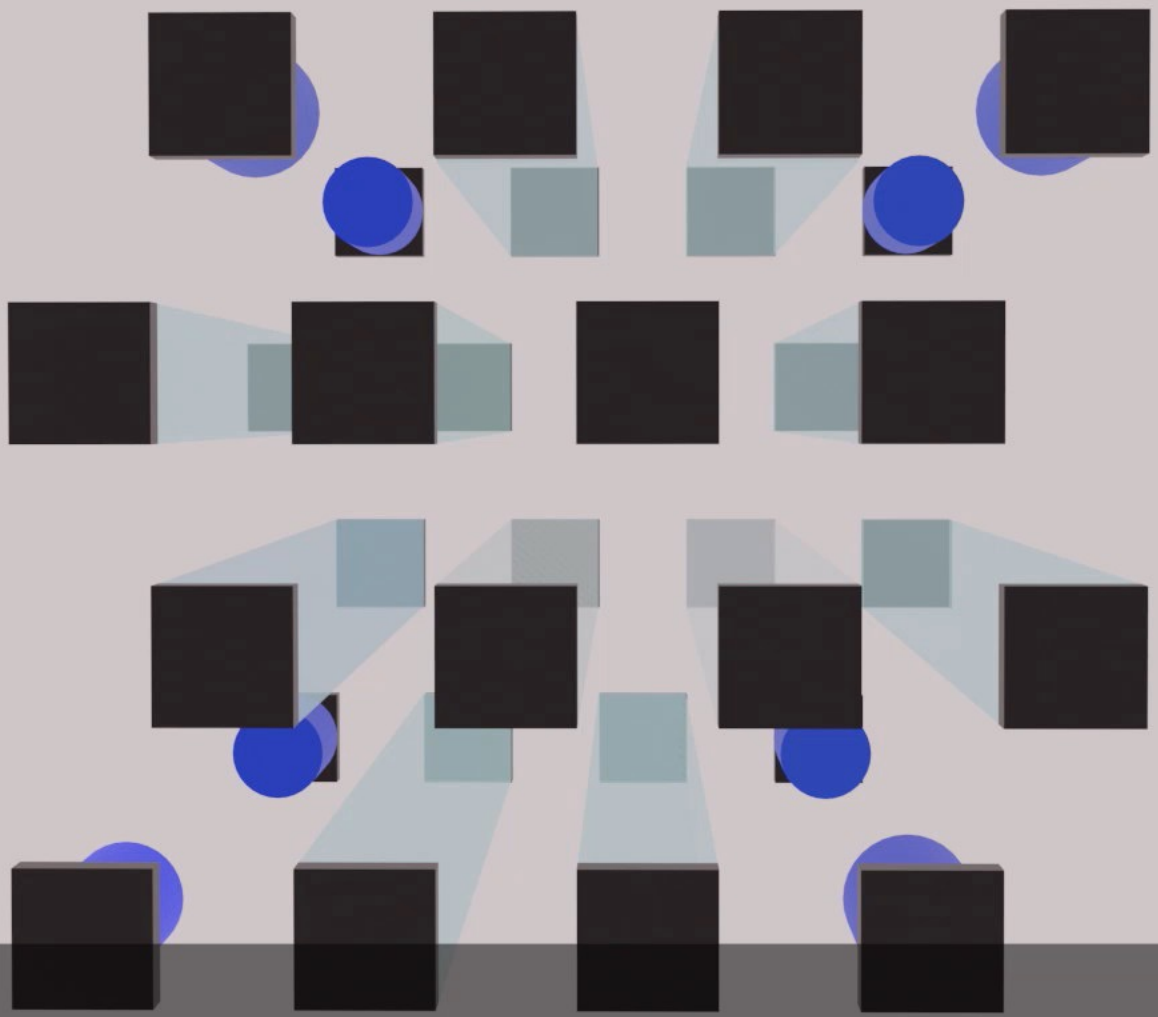
Handheld Dual-Particle Imaging System

- Handheld system to detect, localize, characterize neutrons and gamma rays from special nuclear material (SNM)
- Detectors are solid scintillation pillars coupled to silicon photomultipliers (SiPMs)
  - Combination of inorganic (CeBr) and organic (stilbene or organic glass) scintillators





W. M. Steinberger, M. L. Ruch, N. P. Giha, A. Di Fulvio, P. Marleau, S. D. Clarke, S. A. Pozzi, “Imaging of special nuclear material using a handheld dual particle imager”, *Sci. Rep. 10*, 1855 (2020).



Consortium for Monitoring ,Technology, and Verification

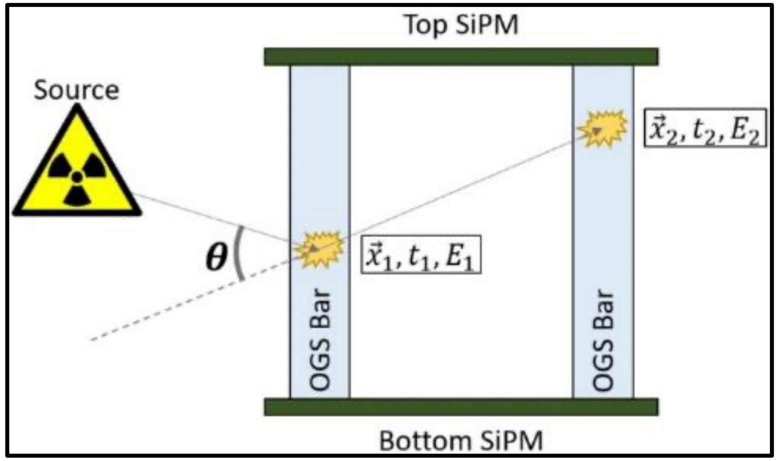
Technical Approach – Imaging

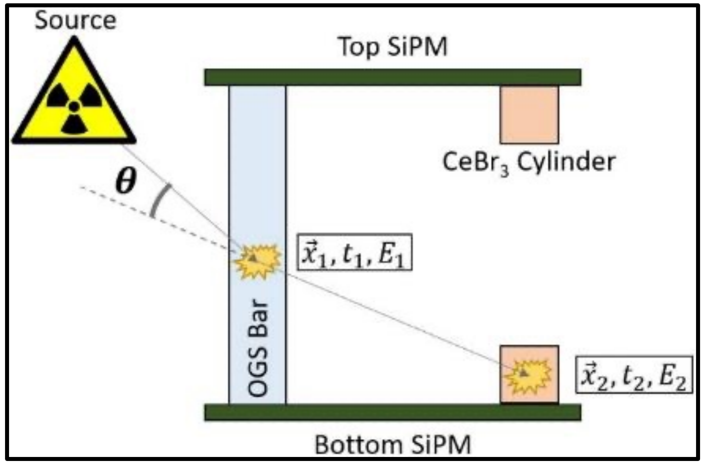
- Scatter-based OGS imager consists of:
  - 12 OGS bars (6x6x50 mm^3) w/ diffuse reflector
  - 8 $CeBr_3$ (6 mm height, 6 mm Ø) cylinders
  - Silicon photomultiplier arrays for output
- Reconstruct double scatter events using simple backprojection (SBP) then apply converging algorithm (LM-MLEM)

R. Lopez, W. M. Steinberger, N. Giha, P. Marleau, S. D. Clarke, S. A. Pozzi, "Neutron and gamma imaging using an organic glass scintillator handheld dual particle imager", *Nucl. Instr. Meth. A* 1042, 167407 (2022).

Neutron Imaging

(Elastic scattering)





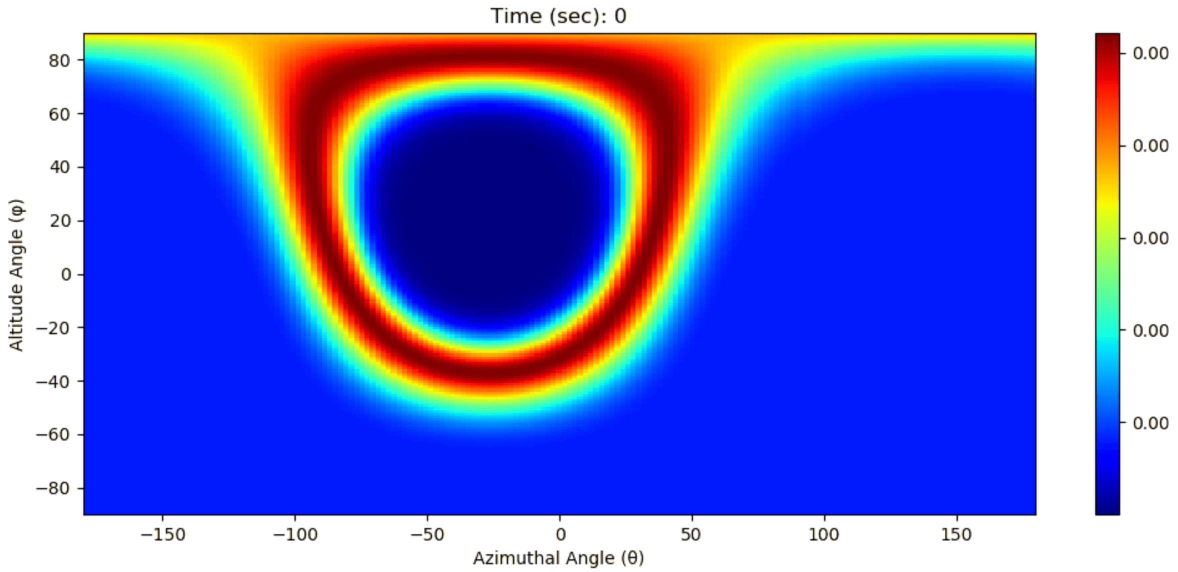
Gamma Imaging

(Compton scattering)

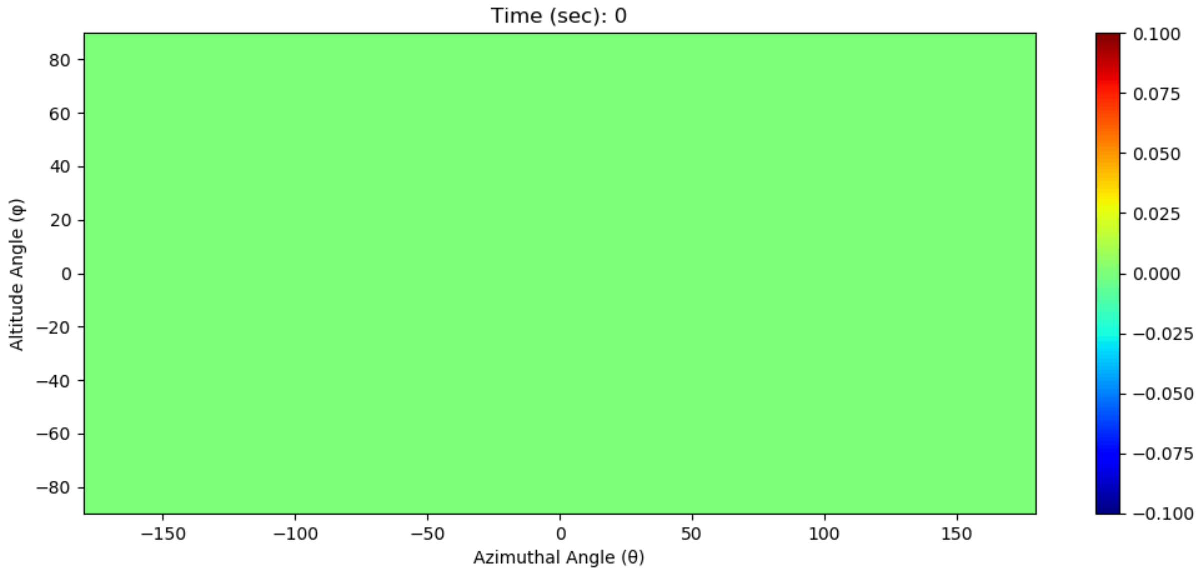
Neutron Imaging – Simple Backprojection

- Cone projections are summed to produce a simple backprojection (SBP) image

Measurement of a 6x10^6 n/s ^{252}Cf source at 58.4 cm, 10 cone projections in 4.3 seconds

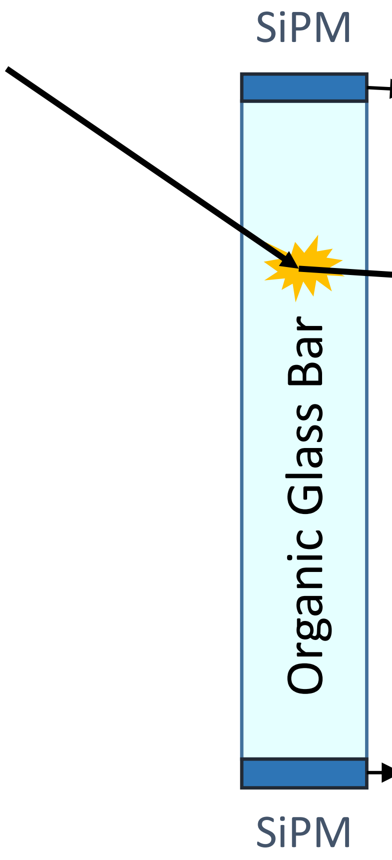


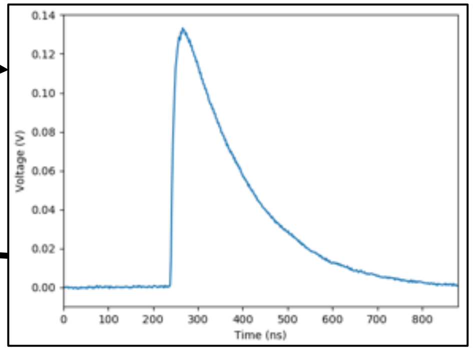
Background neutron measurement



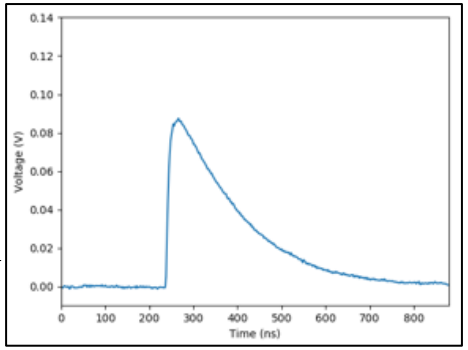
Technical Approach – Data Acquisition

Particle interactions create pulses from each SiPM

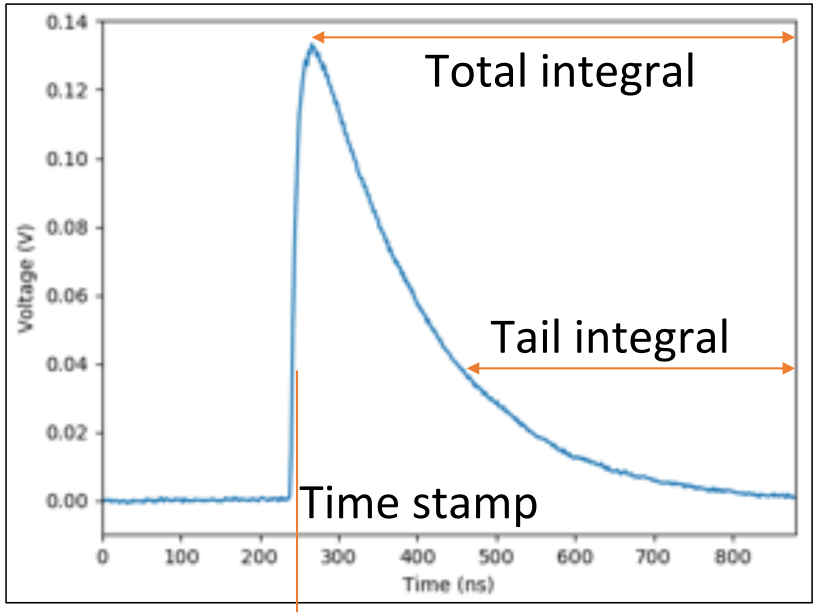




Particle integral ratio determines axial position



Pulse analysis (example)



Time stamps are calculated using digital constant fraction discrimination

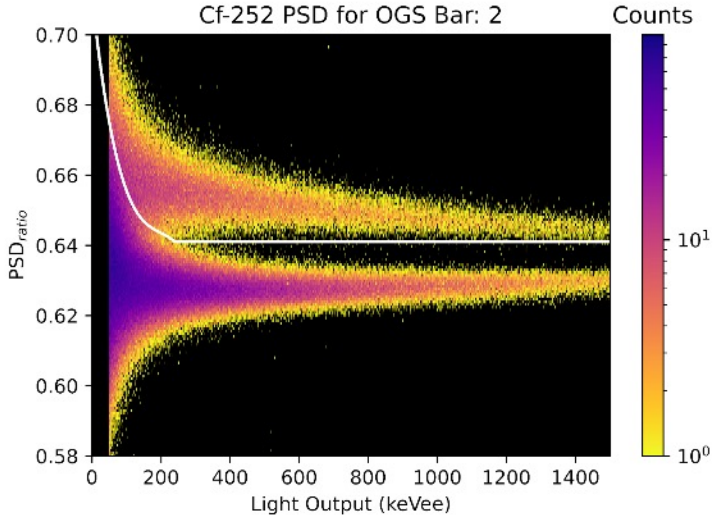
Differences in these time stamps are used to form coincident detections

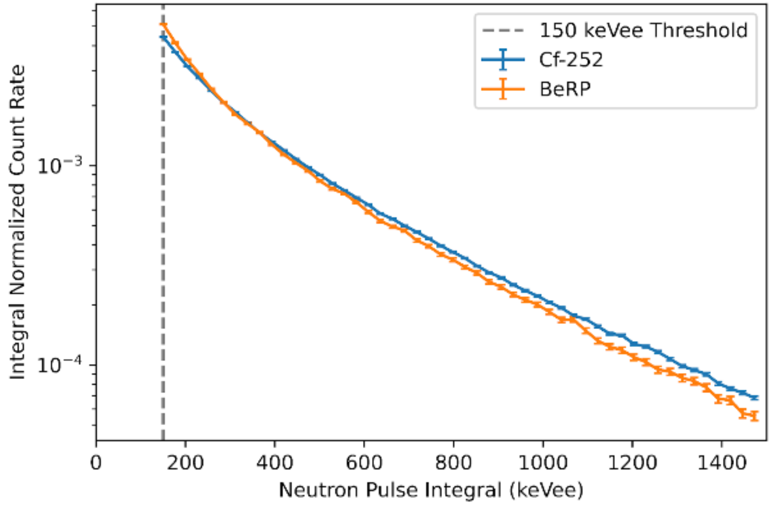
Detecting Neutrons and Gamma Rays

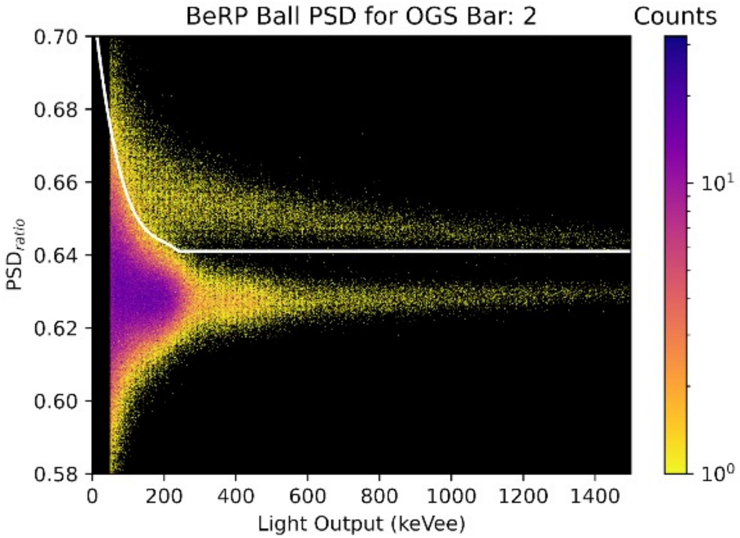
- Tail and total integrals are calculated for each of the two SiPM pulses collected for each detected event

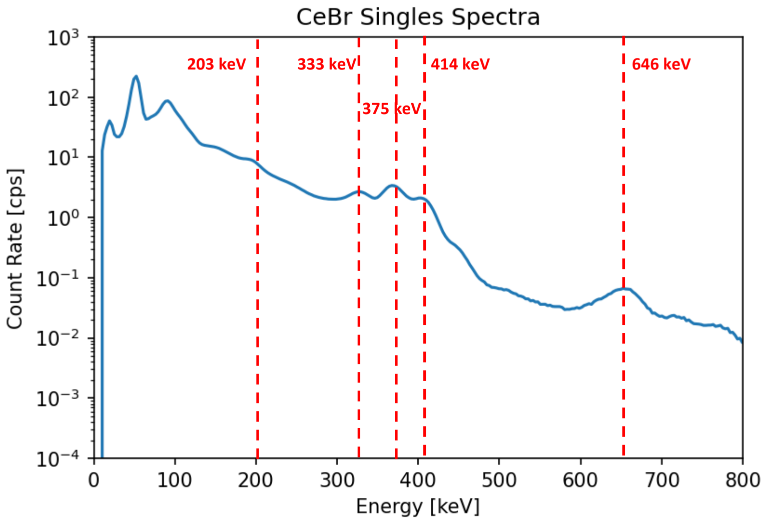
- A pulse shape discrimination (PSD) ratio is calculated for each detected event

$$Ratio_{quad} = \frac{\sqrt{Tail_1^2 + Tail_2^2}}{\sqrt{Total_1^2 + Total_2^2}}$$

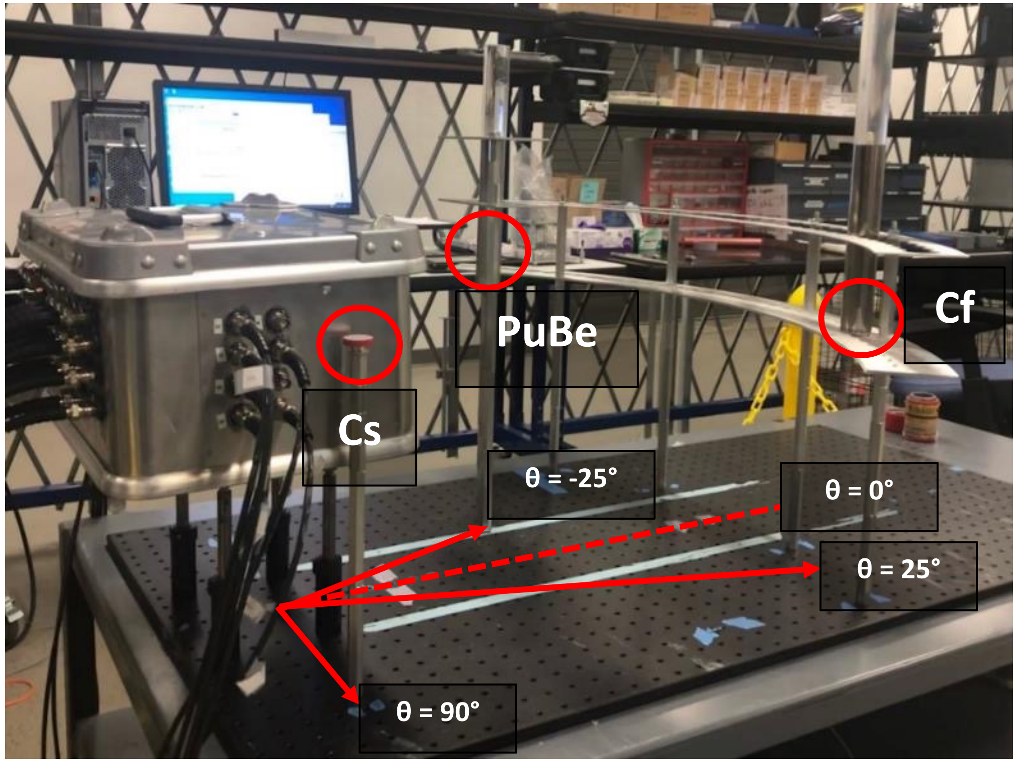


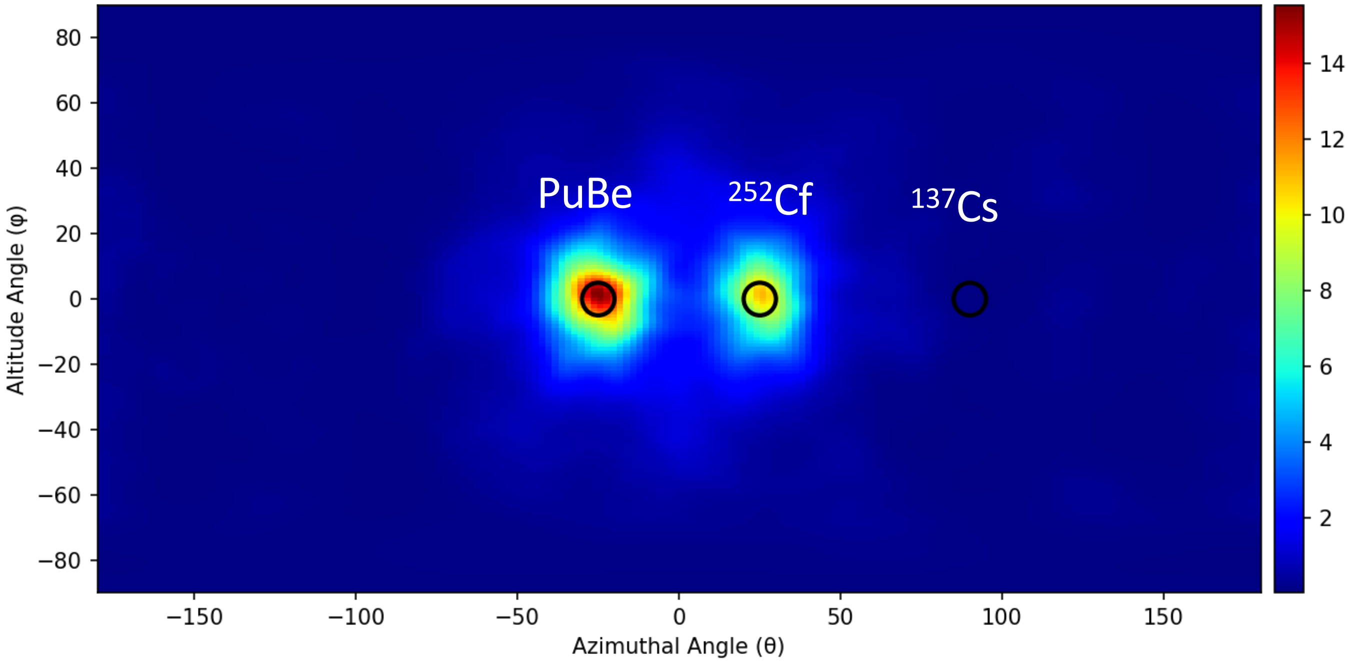






Imaging Multiple Neutron Sources





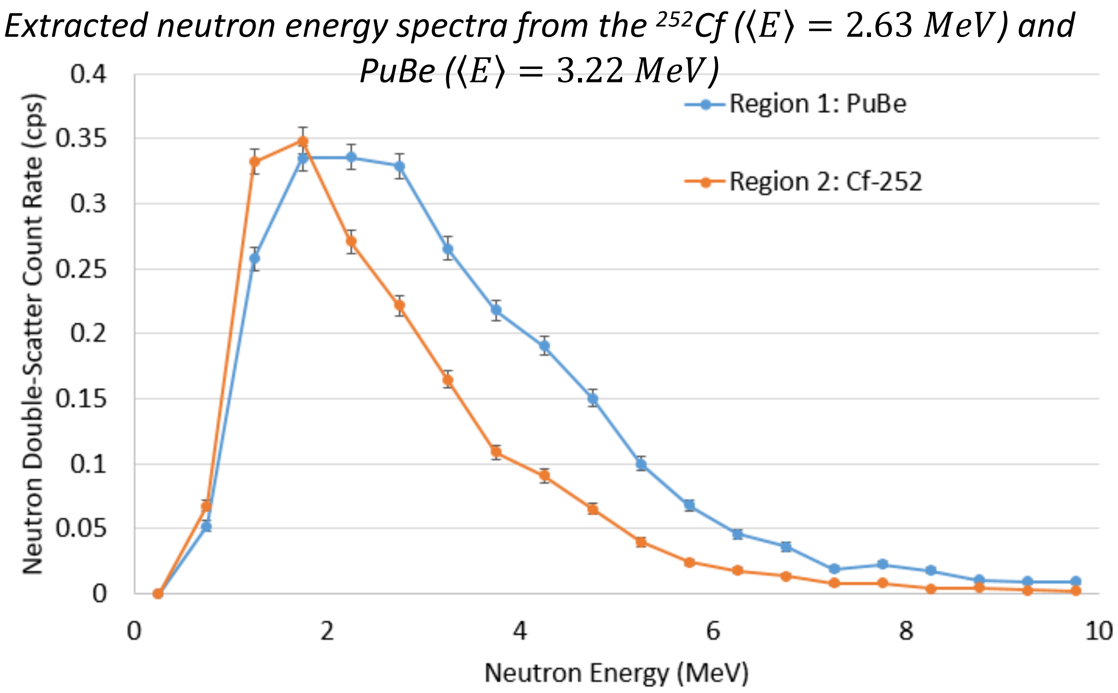
<u>Source Location</u>

Actual: (-25°, 0°) & (25°, 0°)

Converged: (-25.14°, 1.51°) & (25.14°, 1.51°)

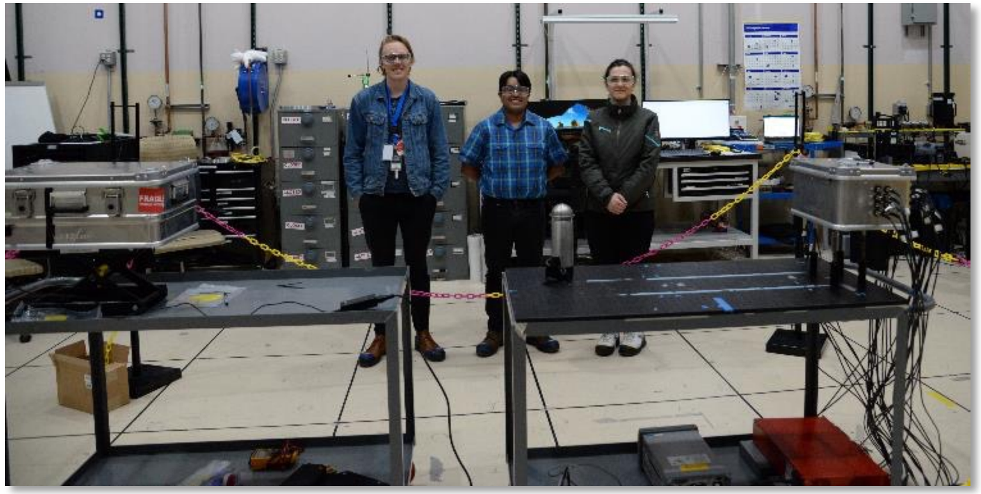
Neutron Spectrometry

- H2DPI imaging methodology allows for neutron spectrometry capabilities
- Measurement of a 200 µCi ^{137}Cs source, 6x10^{6} n/s ^{252}Cf source and a 1x10^{6} n/s PuBe source in the same field of view



Experiments with Special Nuclear Material
National Criticality Experiments Research Center

- The National Criticality Experiments Research Center (NCERC) was founded in 2011 and is located inside the Device Assembly Facility (DAF) at the Nevada National Security Site (NNSS)
- The only general-purpose critical experiments facility in the U.S.
- Houses a variety of kilogram-quantity, unclassified special nuclear material objects
- Annual experiments made possible through our DOE/NNSA-funded consortia



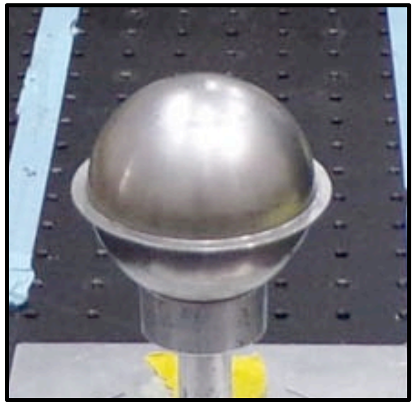
S. A. Pozzi, Z. He, J. Hutchinson, I. Jovanovic, R. Lopez, K. Ogren, J. Nattress, D. Shy, S. D. Clarke, "Detecting and characterizing special nuclear material for nuclear nonproliferation applications", *Nat. Sci. Rep.* 13, 10432, (2023).

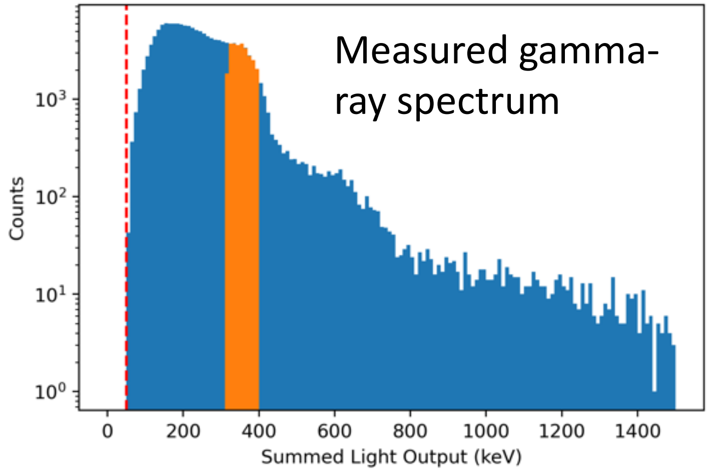
Imaging Special Nuclear Material – Plutonium

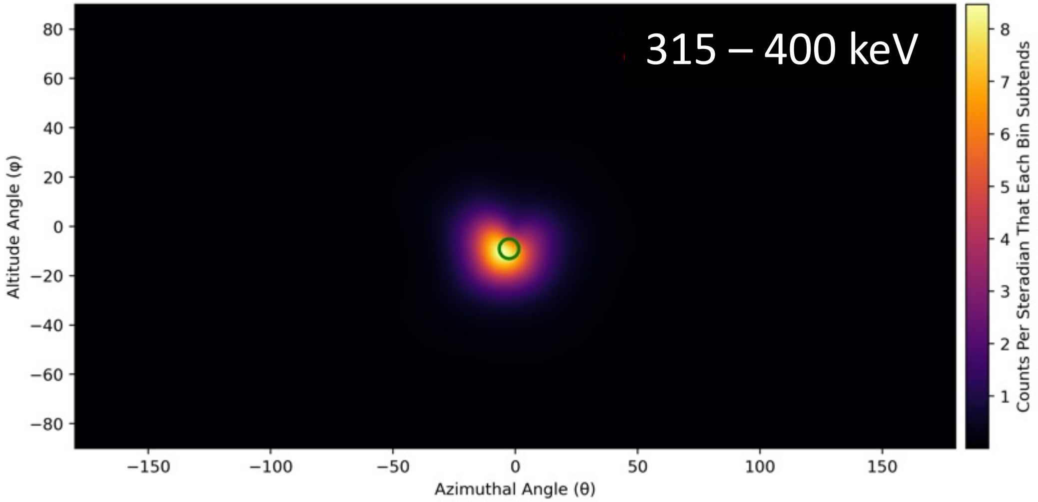
BeRP Ball

- ~4.5 kg sphere of α-phase Pu metal
  - ρ = 19.86 g/cm^3
- 93.3 wt% ^{239}Pu and 6 wt% ^{240}Pu
- Distance: 57 cm

- Neutron signature possible to image
- Gamma emissions of interest for imaging:
  - 375/414 keV
  - 646 keV

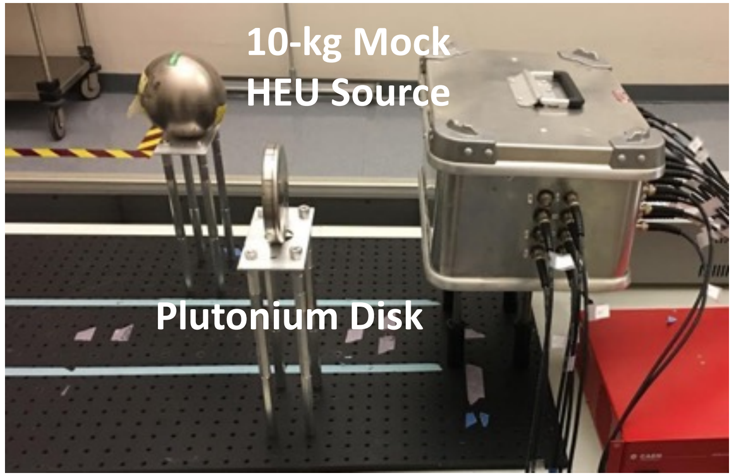


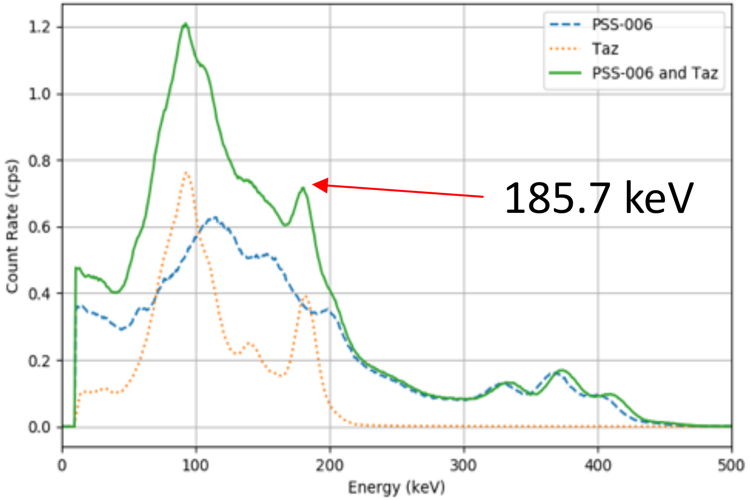


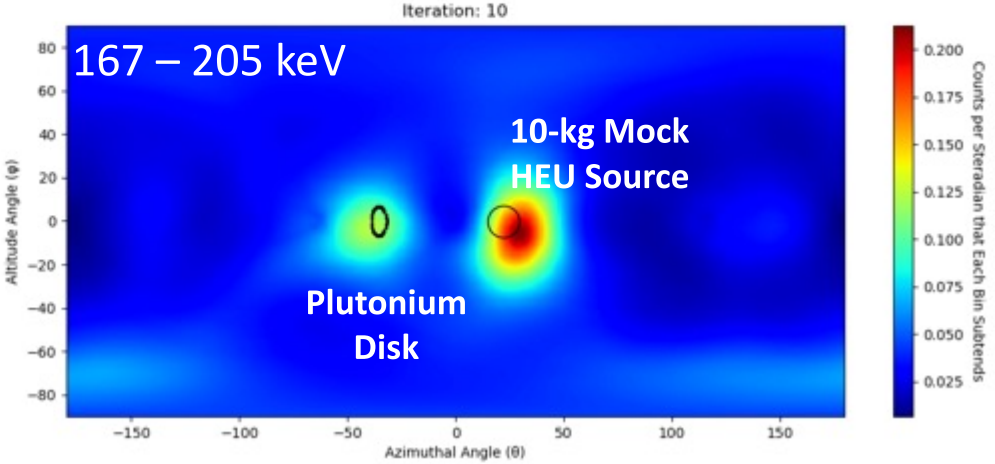


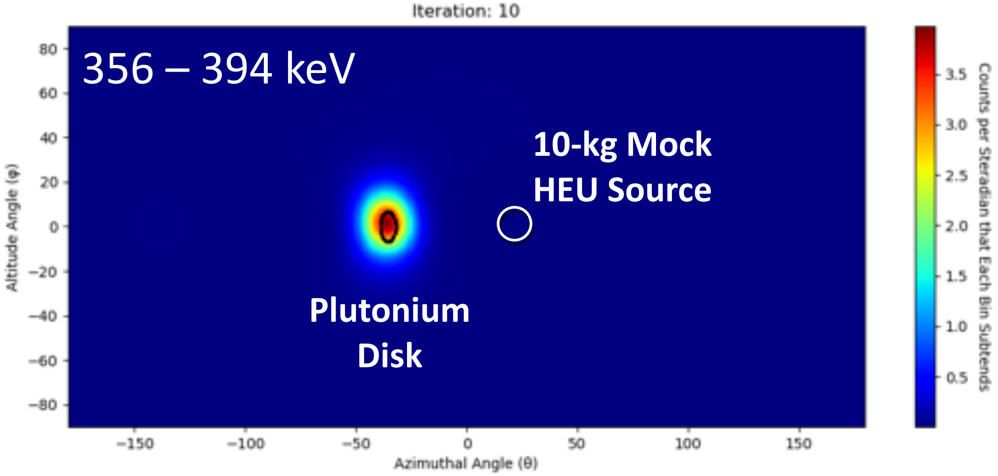
Characterizing SNM: Plutonium vs. Uranium

- The 185.7 keV gamma ray emitted by ^{235}U is present in the measured spectrum from both sources
- The plutonium region of the image is isolated when the energy window is increased



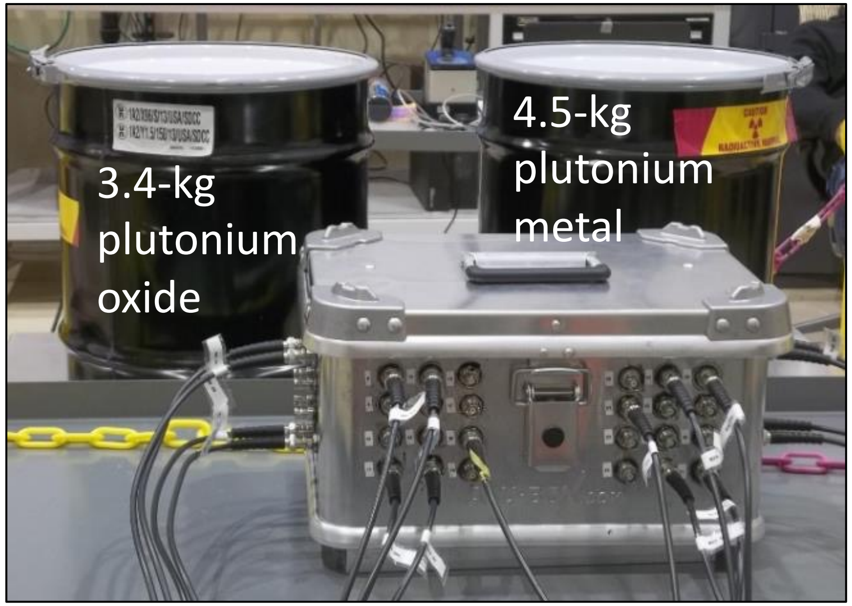


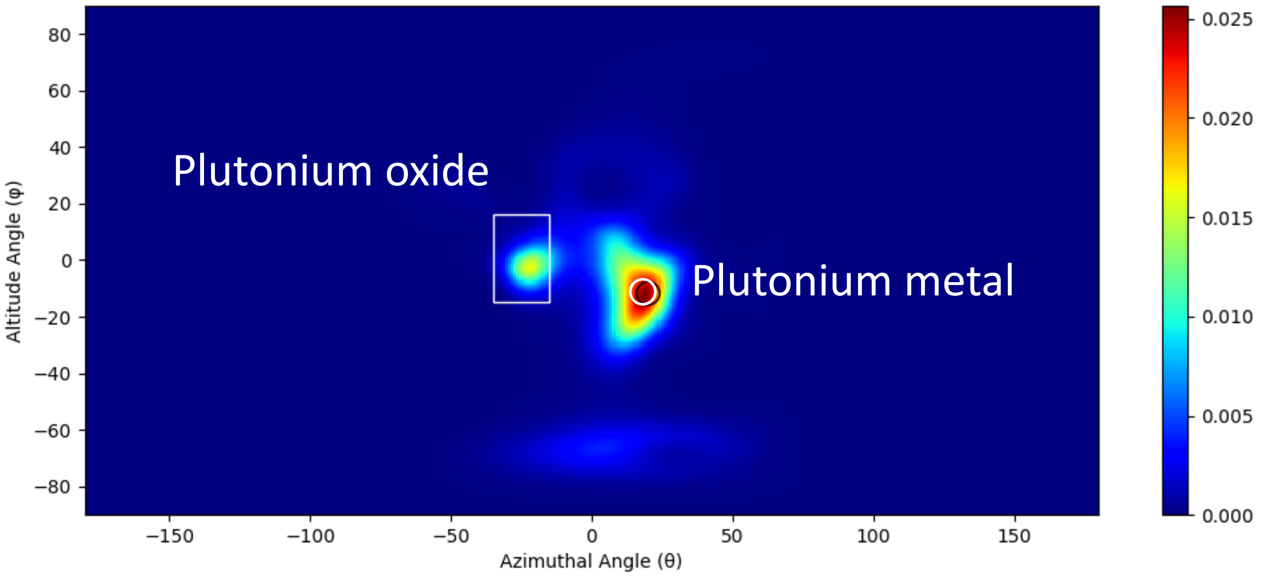




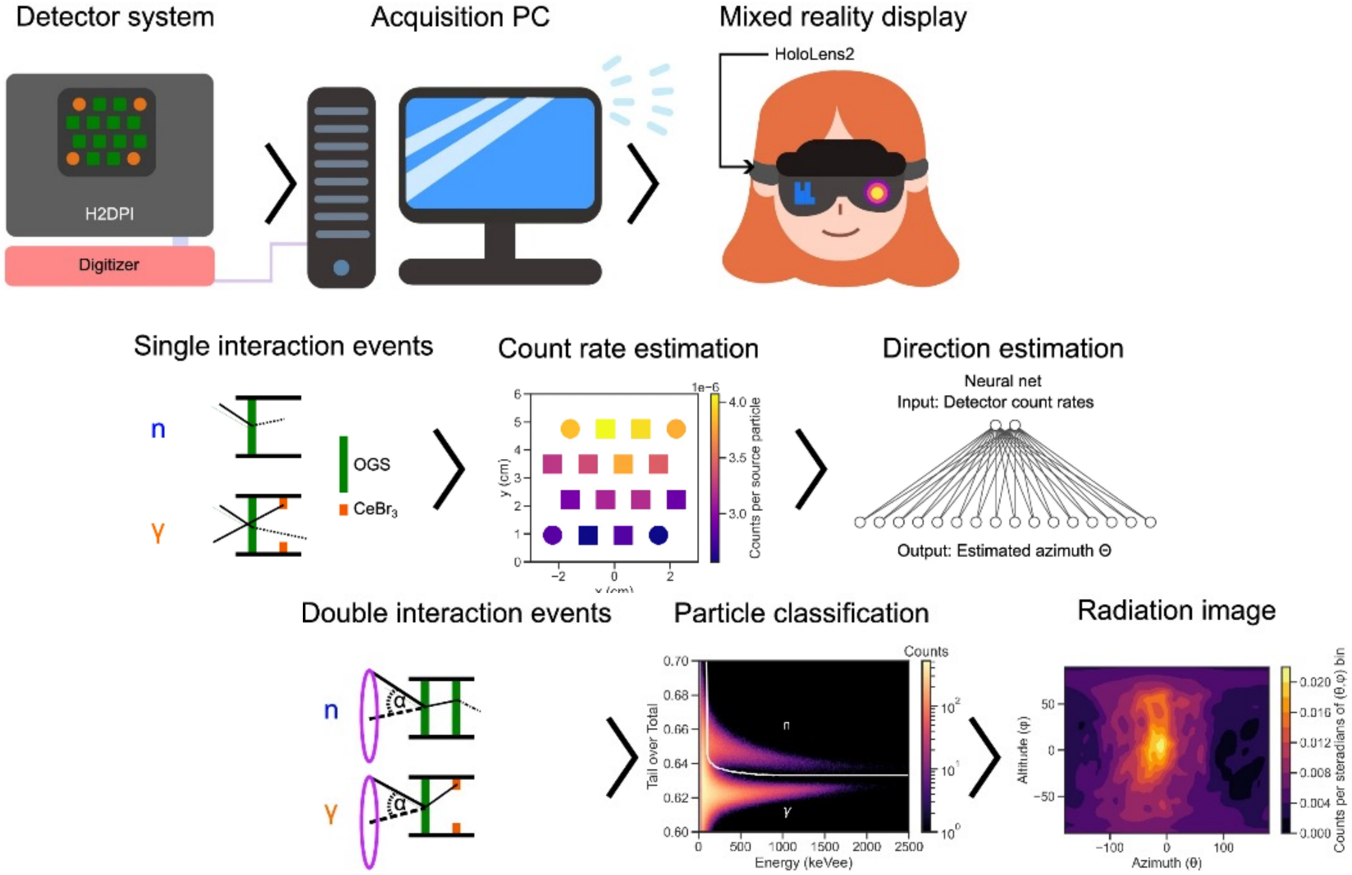
Characterizing SNM
Multiple Plutonium Objects

- Plutonium oxide and metal samples were placed 50 cm from the H2DPI
- The measured neutron image was processed using a list-mode maximum-likelihood expectation algorithm





Imaging into Augmented Reality



O. Pakari, R. Lopez, et al., "Real-time mixed reality display of dual particle radiation detector data", Sci Rep 13, 362 (2023).


Mixed Reality
Radiation Visualization
Using HoloLens 2
UNIVERSITY OF
MICHIGAN

Areas of Impact

- A handheld dual-particle imaging system has been developed based on organic-glass and cerium-bromide scintillators
- Results demonstrate the capability of a compact dual particle imager based on an active volume of OGS
  - Localized kg quantities of plutonium using neutrons imaging
  - Performed simultaneous gamma-ray imaging and spectroscopy to distinguish HEU from plutonium
- A real-time augmented reality interface has been developed for dual-particle imaging and spectroscopy
- Applications include treaty monitoring and verification

Acknowledgements

The Consortium for Monitoring, Technology, and Verification would like to thank the DOE/NNSA for the continued support of these research activities.

This work was funded by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920