Experimental Campaign at the Device Assembly Facility

[1]Jack Linkous, [2]Michael Hamel, [2]David Goodman, et al.

[1]North Carolina State University
[2]University of Michigan

Objective

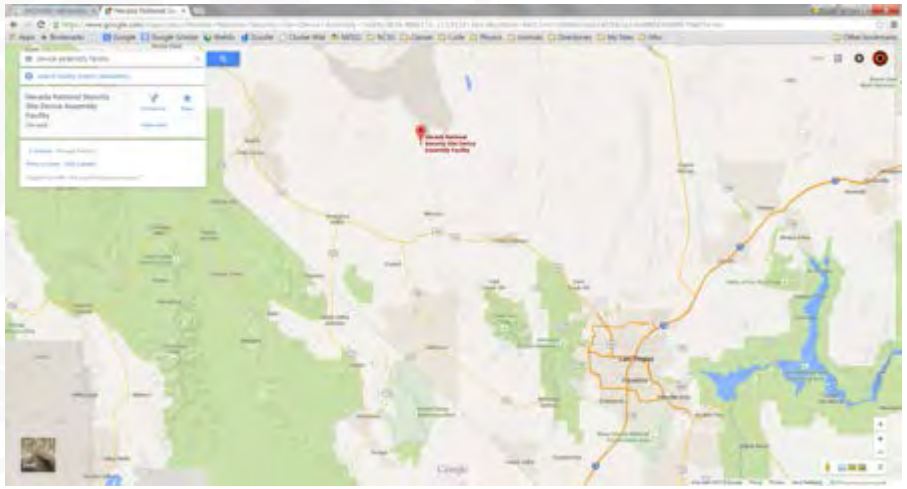
- **Objective:** provide CVT students, post-docs, and faculty with the opportunity to conduct hands-on experiments with Category I (weapons usable) special nuclear material (SNM)

- CVT worked with LANL to plan and execute Cat-I SNM experiments at the NNSS Device Assembly Facility (DAF) in Summer 2015

- July 6 – 9, 2015, CVT conducted some of the first-ever university-led experiments with Cat-I SNM at DAF

Device Assembly Facility (DAF)

- Located about 90 minutes northwest of Las Vegas
- Operated by NSTec for NNSA
- DAF can support critical and subcritical measurements of
  - Highly-enriched uranium (HEU) metal and oxide
  - Weapons-grade plutonium (WGPu) metal and oxide
  - Neptunium metal



Fissionable and Reflector Materials Allowed in Construction of Multiplying Assembly

Fissionable Material	Mass Limit
Pu in metal /compounds /dry residues	≤ 3,000 g
^{233}U in metal /compounds /dry residues	≤ 3,000 g
Pu in oxide	≤ 4,400 g
^{233}U in oxide	≤ 4,400 g
^{235}U in hydride	≤ 3,000 g
^{235}U in metal /compounds (excluding hydride) /dry residues	≤ 10,000 g
^{237}Np Sphere	~6 kg Np
BeRP Ball	~4.5 kg Pu
Rocky Flats Shells (1-24)	~13.7 kg HEU
One Thor Core Piece	~2-4 kg Pu

Reflector Material	Type	Thickness Restriction
Copper	A	Total thickness of these reflectors shall not exceed 1 inch
Nickel		
Stainless Steel 304		
Tungsten		
Natural Uranium		
Depleted Uranium		
Cadmium		
Carbon Steel	B	The total combined thickness of Type A and B reflectors shall not exceed 1 inch if Type A reflectors are present. If no Type A reflectors are used, an unlimited thickness of Type B reflectors may be used.
Iron		
Lead		
Lucite		
Polyethylene		
Borated Polyethylene		
Manganese		
Boroflex		
Aluminum	C	Unlimited thickness of these materials in any combination may be used.
Thorium		
Mock HE1		
Mock HE2		
Mock HE3		

Participants

NC State

- John Mattingly (faculty, lead) and Jonathan Mueller (post-doc)

Michigan

- Zhong He (faculty), David Goodman (student), Michael Streicher (student), Sara Pozzi (faculty), Kyle Polack (student), Michael Hamel (student)

ORNL

- Jason Newby

LANL

- Jesson Hutchinson (PIC, lead), Derek Dinwiddie (PIC), Donnette Lewis, Kenny Valdez, Lenny Trujillo, Clemente Garcia, Mark Mitchell, Scott Gardner, and Jeff Favorite (POC)

Left to right: Jonathan Mueller, Michael Hamel, Sara Pozzi, Kyle Polack, John Mattingly, David Goodman, Jason Newby, Zhong He, and Michael Streicher

Experiments

SNM sources:

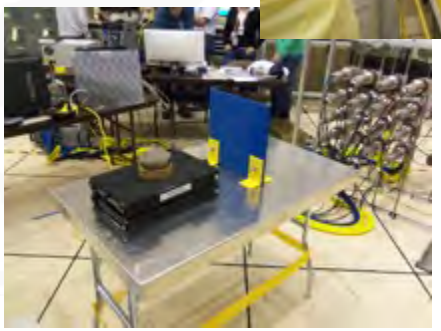
- BeRP ball: 4.5 kg WGPu metal sphere
- Rocky Flats shells: 13 kg HEU metal shells
- Thor core (central piece): 4 kg WGPu metal "disk"

Reflectors/shielding:

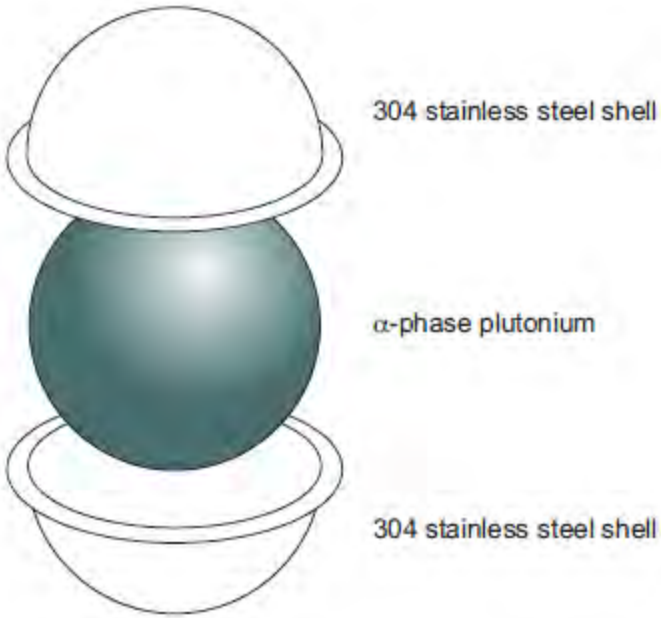
- Bare (none)
- Polyethylene
- Iron
- Tungsten

Instruments:

- Fast neutron coded aperture imager (ORNL/SNL)
- Dual particle scatter imager (U of M)
- Polaris/Orion Compton scatter gamma imagers (U of M)

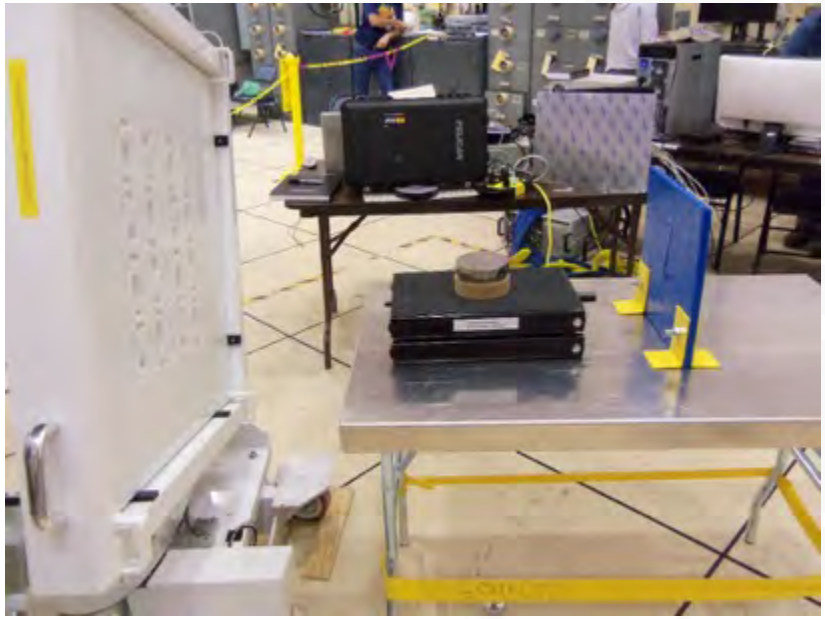


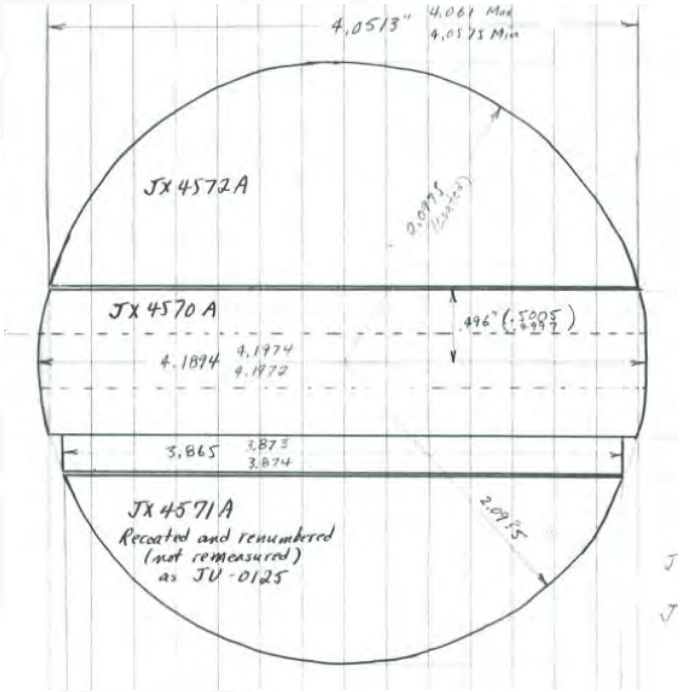
BeRP ball


304 stainless steel shell
α-phase plutonium
304 stainless steel shell

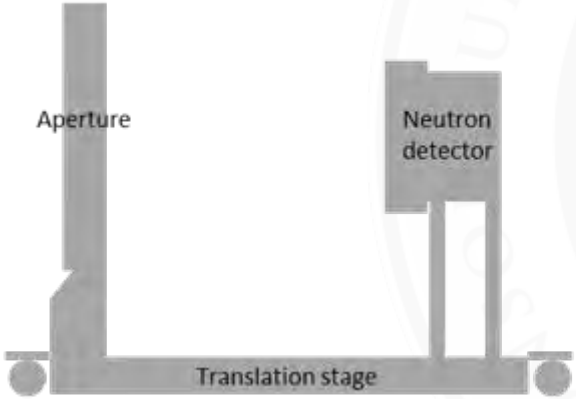
Rocky Flats shells

Thor core




4.0513"
4.061 Max
4.0513 Min
JX 4572A
JX 4570 A
.496" (.5005 / .4997)
4.1894
4.1974
4.1972
3.865
3.873
3.874
JX 4571A
Recoated and renumbered
(not remeasured)
as JU-0125

Coded Aperture Imager



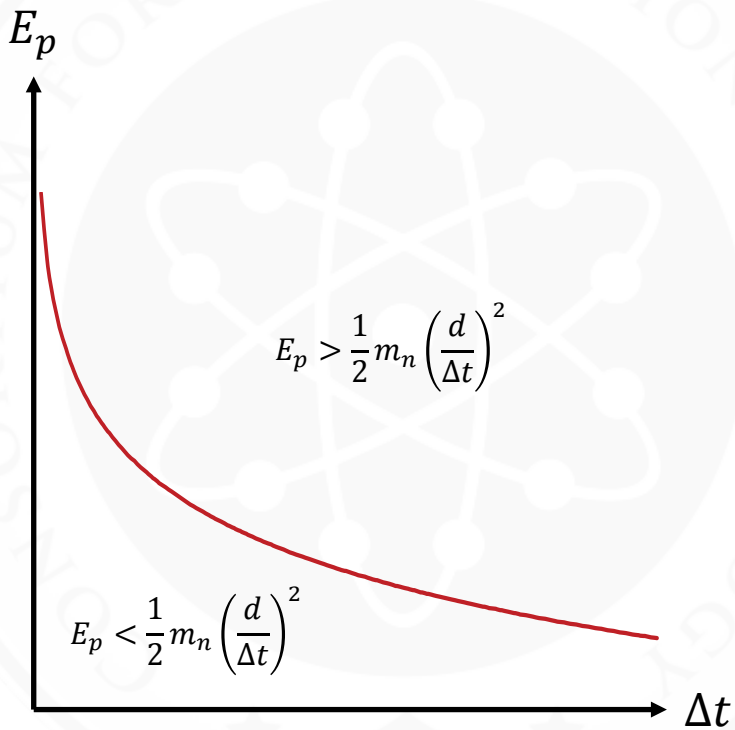
Exploiting fission chain-reaction dynamics

$$E_p > \frac{1}{2} m_n \left(\frac{d}{\Delta t}\right)^2$$

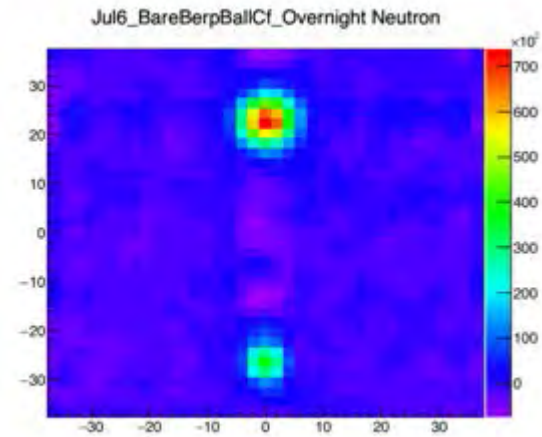
$$E_p \leq \frac{1}{2} m_n \left(\frac{d}{\Delta t}\right)^2$$

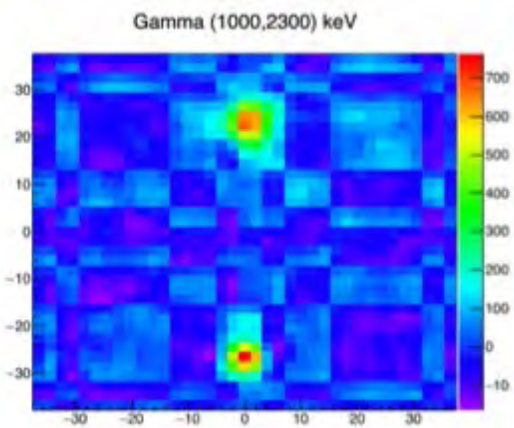
$$t_\gamma - \frac{d}{c} \longrightarrow \Delta t = t_n - \left(t_\gamma - \frac{d}{c}\right)$$

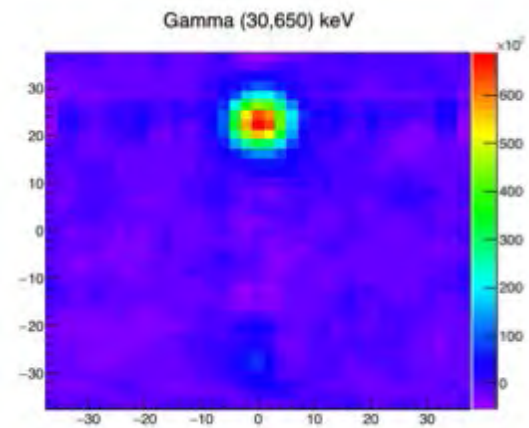
Detecting fission chain-reaction neutrons

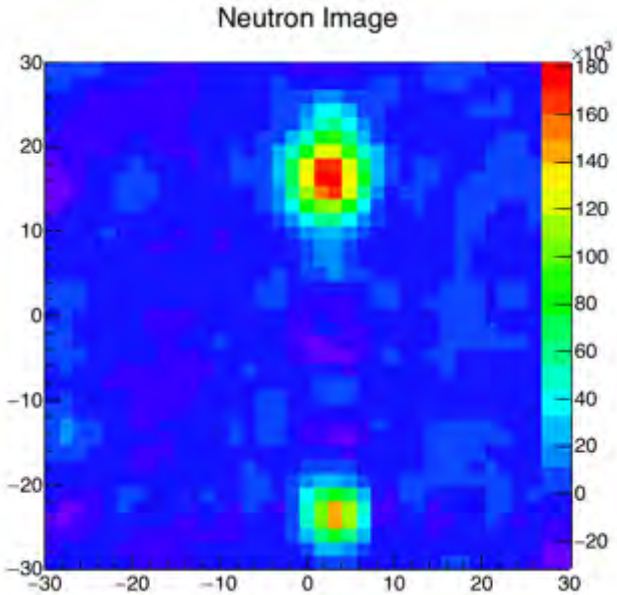


BeRP Ball and Cf-252








Neutron Image
×10³
180
160
140
120
100
80
60
40
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0
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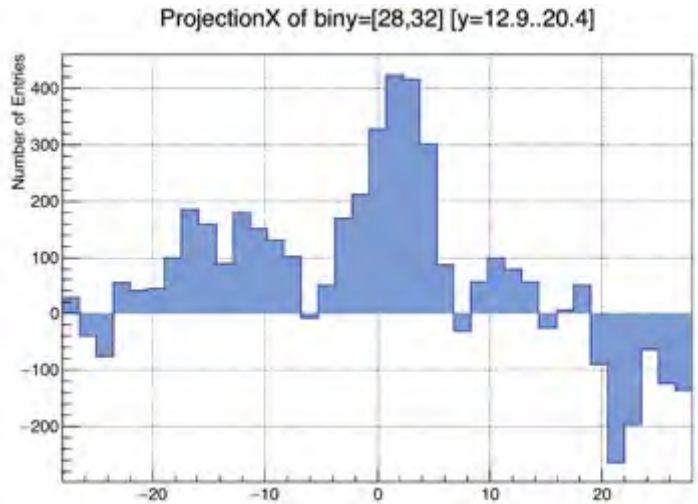
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Number of Entries
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200
100
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−100
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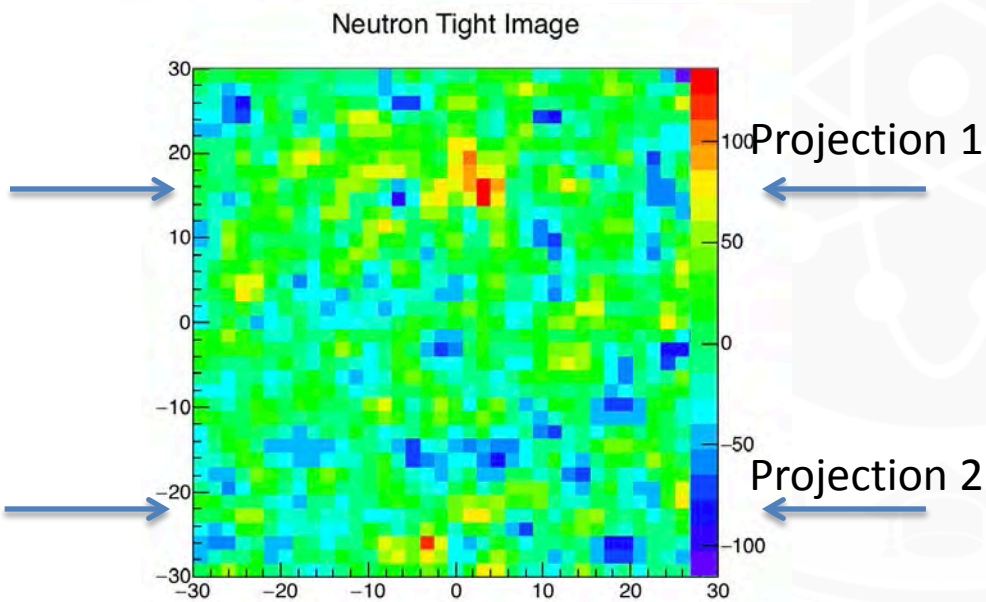
Neutron Tight Image
Projection 1
Projection 2
100
50
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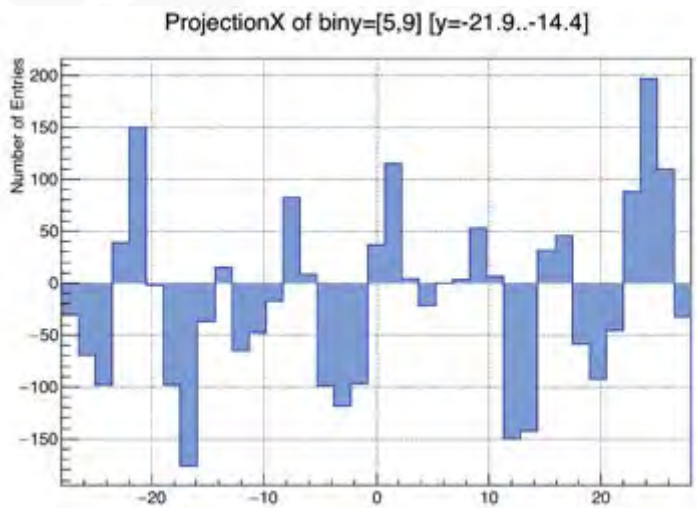
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Number of Entries
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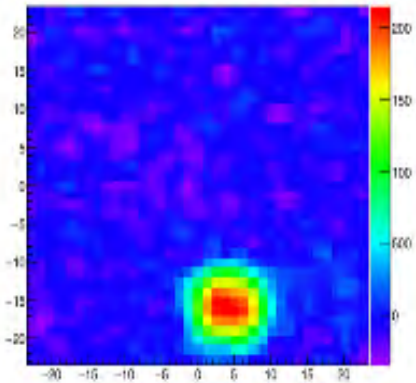
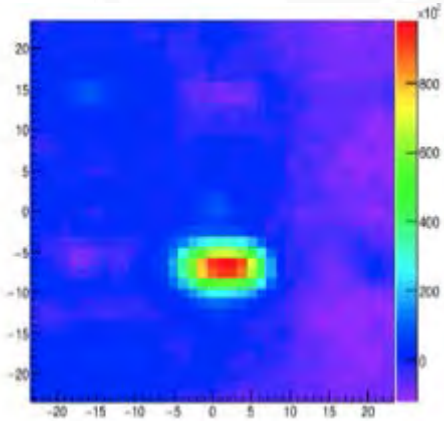
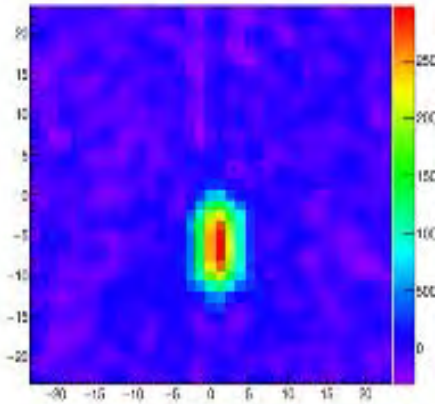
20

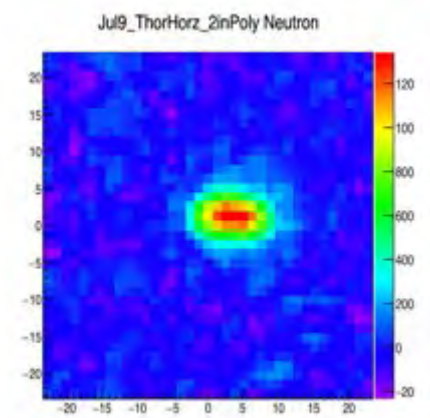
Thor Core

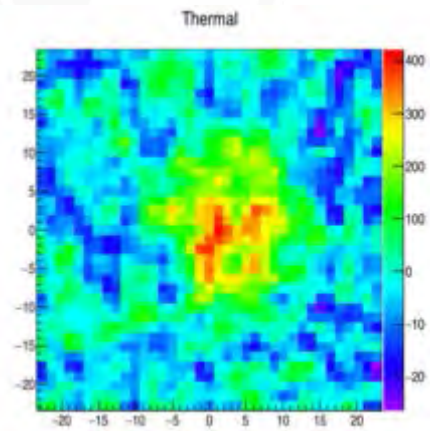






Thor Core in Polyethylene





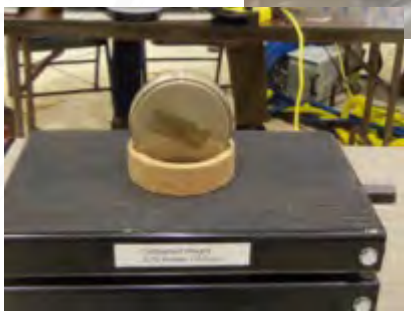
Dual-Particle Imager

Goals and Objectives

- Evaluate system performance in presence of category-I SNM for disarmament treaties and Non-proliferation Treaty verification
- Acquire benchmark data for continued development of the Dual-Particle Imager
- Identify SNM in the presence of multiple neutron and gamma-ray sources

BeRP Ball

Rocky Flats Shells

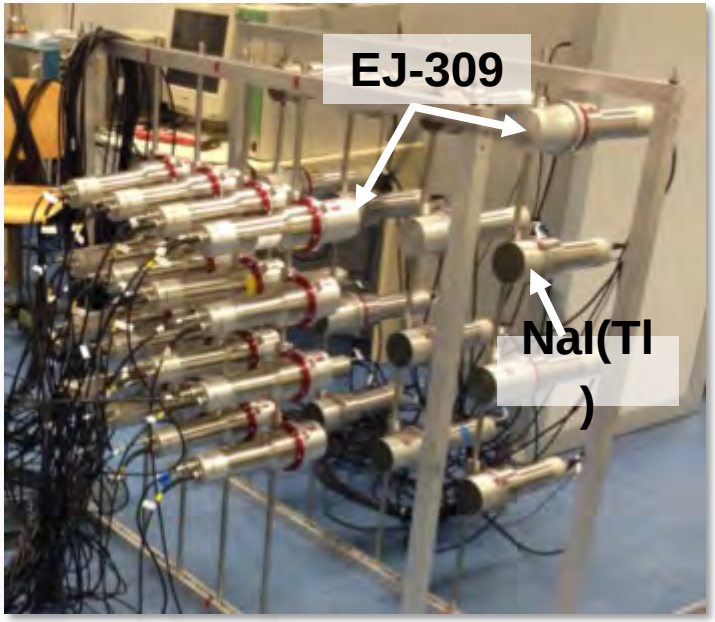


Thor Core

Dual-Particle Imager

System Design

- EJ-309 organic liquid scintillators
  - Pulse shape discrimination
  - ~15% energy resolution
  - ~1.2 ns time resolution
- NaI(Tl) scintillators
  - ~6% energy resolution
  - ~8 ns time resolution
- CAEN V1720 Digitizers
  - 250 MHz
  - 12-bit resolution
- Custom algorithms
  - Pulse shape discrimination
  - Data acquisition and on-line processing
  - Event correlation
  - Advanced imaging and spectroscopy

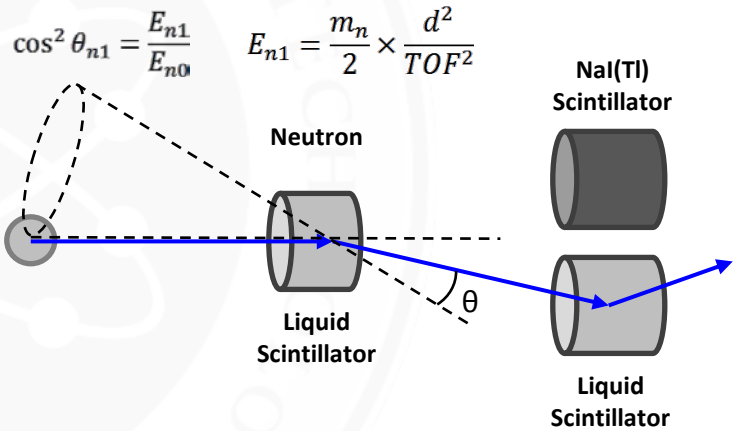


Combined Compton and neutron scatter camera with two 4 x 4 detector arrays

Detector purchase funded by DOE-NEUP Award #DE-NE0000324

Dual-Particle Imager

- Possible source location is defined by a cone for each correlated event
- The superposition of many cones creates a hot-spot at the source location
- Photon events assumes a full-energy deposition in the NaI(Tl)
- The energy of neutron events is obtained through time of flight



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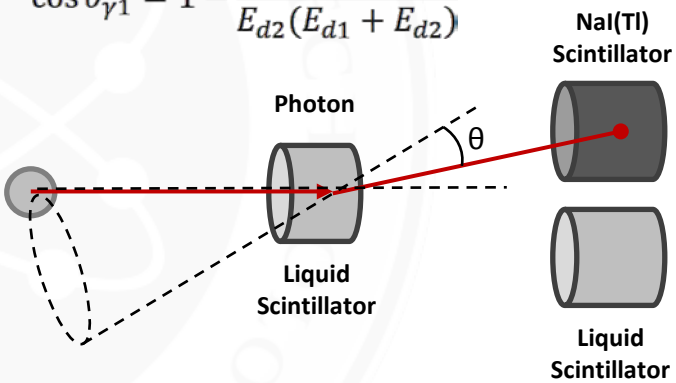
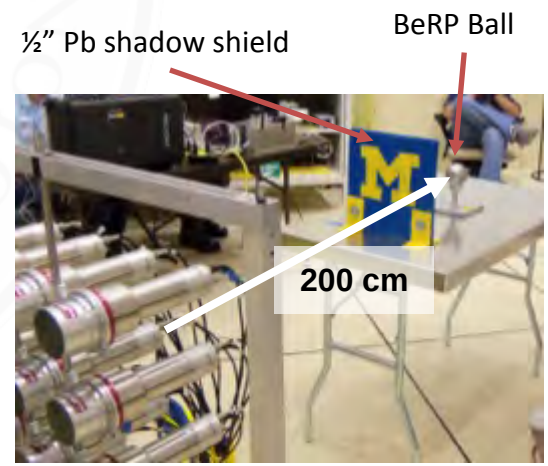
$$\cos\theta_{\gamma 1} = 1 - \frac{m_e c^2 \times E_{d1}}{E_{d2}(E_{d1} + E_{d2})}$$



Challenges

High Gamma-Ray Flux

- Low energy photons can overload digitizers and contribute to light production in the detectors
- 59.5 KeV photon from ^{241}Am was most problematic in BeRP ball
- Problem mitigated by using ½" lead shield and higher thresholds for NaI detectors



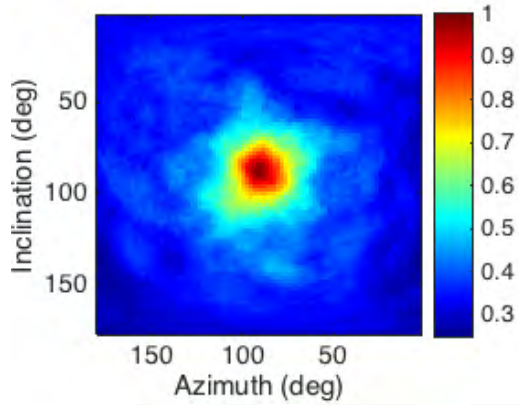
Preserved counts in this region

Table 8-2. Useful gamma rays in various energy regions

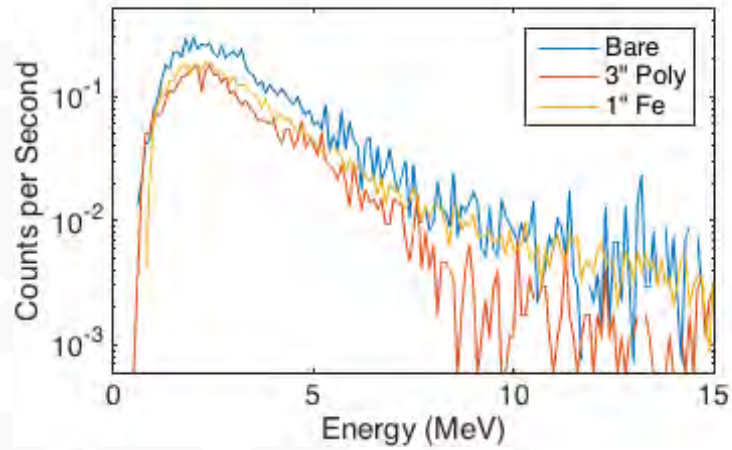
Dual-Particle Imager

BeRP Ball Results

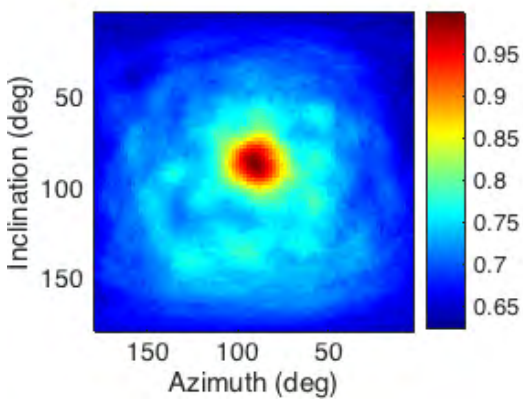
Bare BeRP Ball: Neutron Backprojection



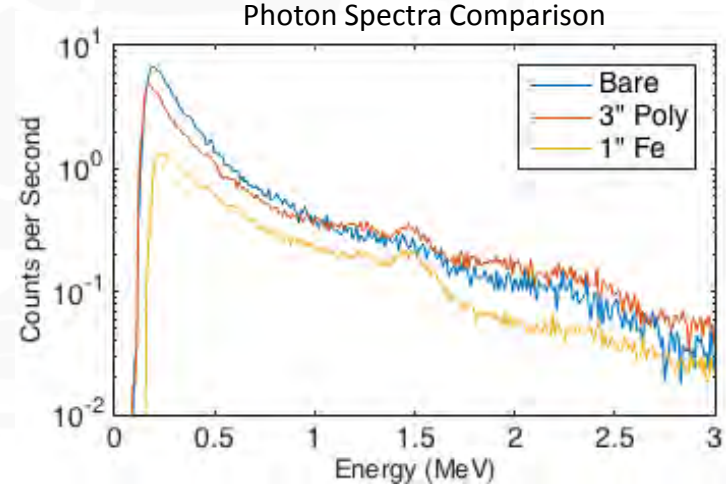
Neutron Spectra Comparison



Bare BeRP Ball: Photon Backprojection



Photon Spectra Comparison

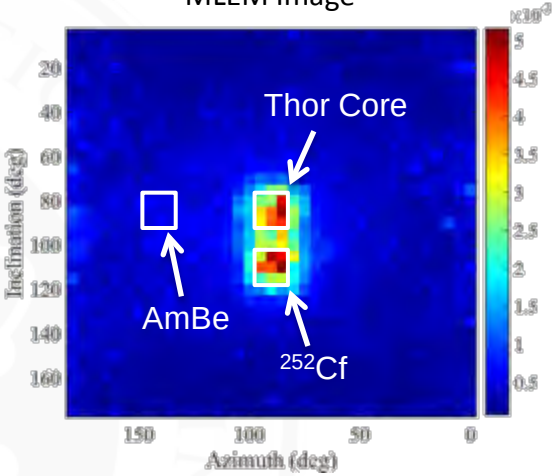


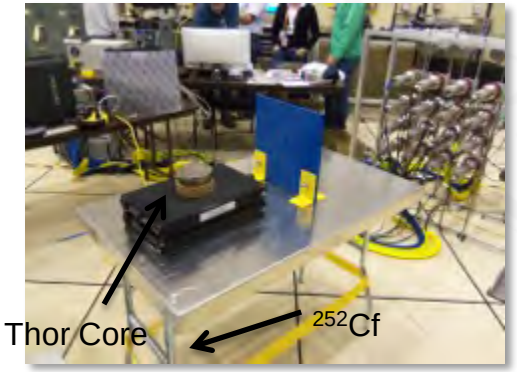
Dual-Particle Imager

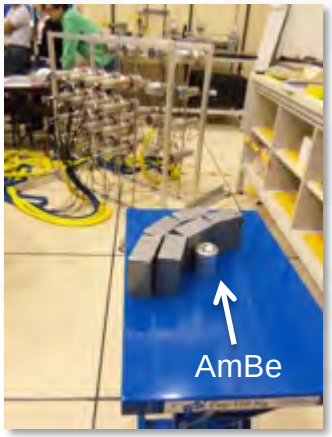
Multi-Source Measurement – Photons

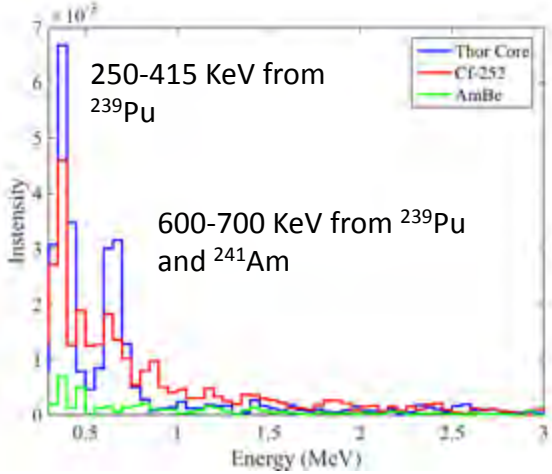
- 850-minute measurement of:
  - ~5.2×10^5 neutrons/second δ-phase plutonium sample shielded by 1.3 cm of lead located at (90°, 85°)
  - ~3×10^5 neutrons/second ^{252}Cf source unshielded located at (90°, 109°)
  - ~1×10^6 neutrons/second AmBe source shielded by 10 cm of lead located at (141°, 85°)
- ~2-meter standoff for all sources
- ~212,000 neutrons measured
- ~2,135,000 photons measured

MLEM Image









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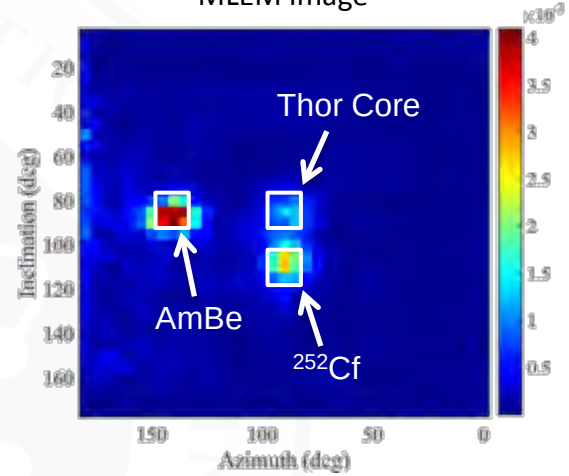
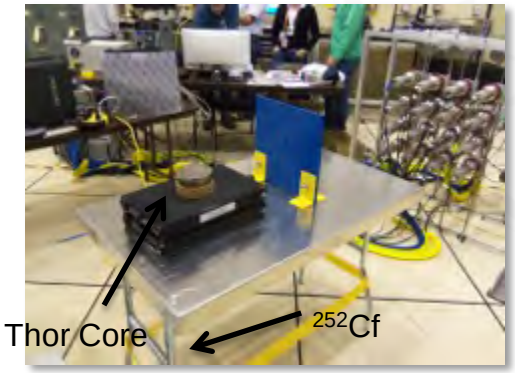
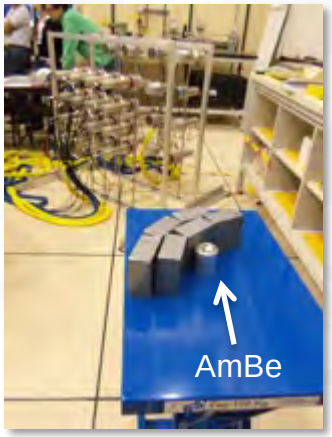
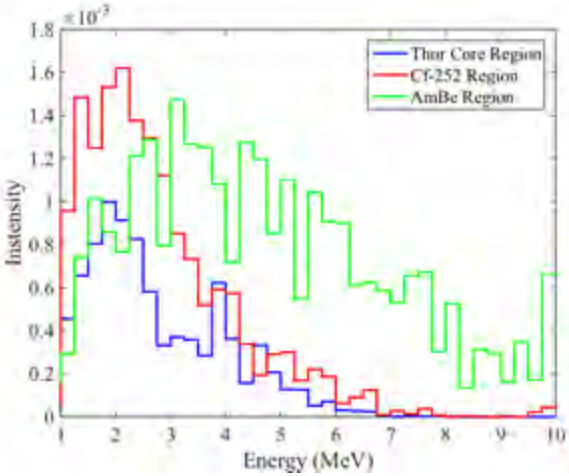
MLEM Image









Conclusions

- The Dual-Particle Imager provides images and energy spectra for neutron and gamma-rays from SNM
- Measurement of category-I SNM with the Dual-Particle Imager requires mitigation of high gamma-ray flux
- The Dual-Particle Imager can image and discriminate multiple neutron and gamma-ray sources including SNM

Publications

1. A. Poitrasson-Rivière, J. K. Polack, M. C. Hamel, D. D. Klemm, K. Ito, A. T. McSpaden, M. Flaska, S. D. Clarke, S. A. Pozzi, A. Tomanin, and P. Peerani, "Angular-Resolution and Material-Characterization Measurements for a Dual-Particle Imaging System with Mixed-Oxide Fuel," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 797, pp. 278-284, 2015.

2. A. Poitrasson-Rivière, B. A. Maestas, M. C. Hamel, S. D. Clarke, M. Flaska, S. A. Pozzi, G. Pausch, C.-M. Herbach, A. Gueorguiev, M. Ohmes, and J. Stein, "Monte Carlo Investigation of a High Efficiency Two-Plane Compton Camera for Long-Range Localization of Radioactive Material," Progress in Nuclear Energy, vol. 81, pp. 127-133, 2015.

3. A. Poitrasson-Rivère, M. C. Hamel, J. K. Polack, M. Flaska, S. D. Clarke, S. A. Pozzi, "Dual-Particle imaging system based on simultaneous detection of photon and neutron collision events," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 760, pp 40-45, 2014.

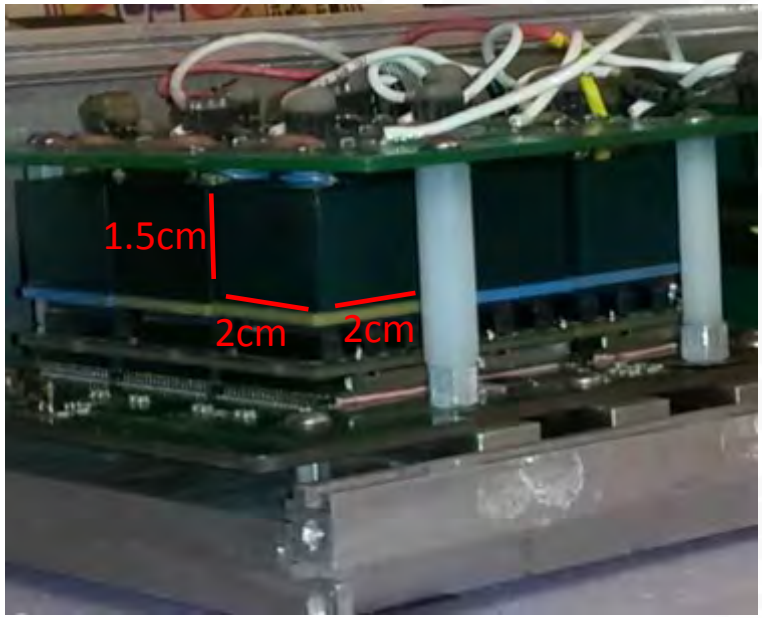
The Dual-Particle Imager is supported in-part by the National Nuclear Security Administration through NA-22 funding opportunity DE-FOA-0000568. It is also funded in-part by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534. M.C. Hamel and J.K. Polack are funded in-part by the Sandia National Laboratories Excellence in Engineering Research Fellowship. The prototype system is funded in-part by the Department of Energy, Nuclear Energy University Program, award number DE-NE0000324.

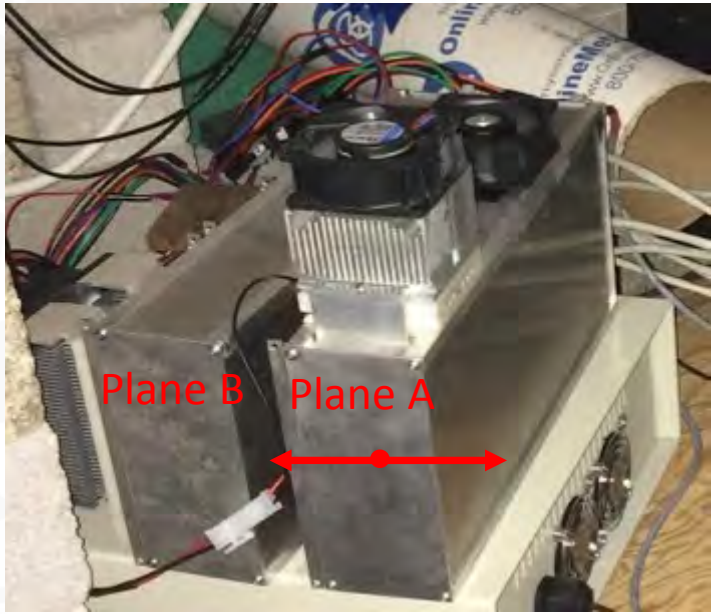
Orion Radiation Measurement Group

- Focus: Room temperature imaging spectrometers
- Research areas include:
  - Reconstruction algorithm development
    - Compton, coded aperture and time encoded imaging
  - Diagnosing semiconductor material imperfections
    - CdZnTe and TlBr
  - Digital readout and pulse processing
  - Practical applications of imaging systems
    - Safeguards, treaty verification and nuclear power

Campaign Systems

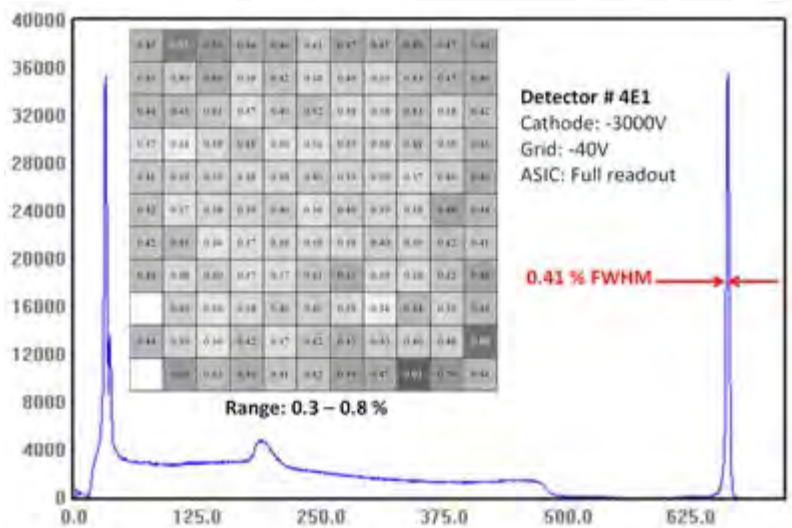
- Polaris Separable Plane (SP) System
  - 3 by 3 by 2 array of 2 x 2 x 1.5 cm^3 CdZnTe crystals
  - Each crystal further subdivided into 11x11x40 voxels

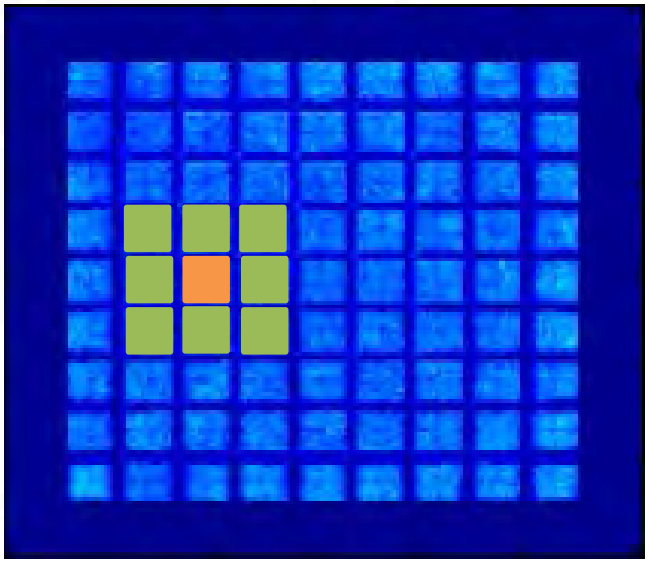




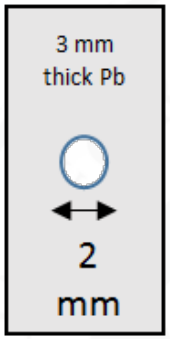
Campaign Systems Continued

- Digital Orion:
  - 2 by 2 array of (2cm x 2cm x 1.5cm) CdZnTe crystals
  - ASICs digitize triggered and neighboring pixel waveforms
  - Subpixel resolution via induced charge on neighboring pixels
    - $\sim 300 \mu m$ at 662keV
    - $\sim 700 \mu m$ at 122keV

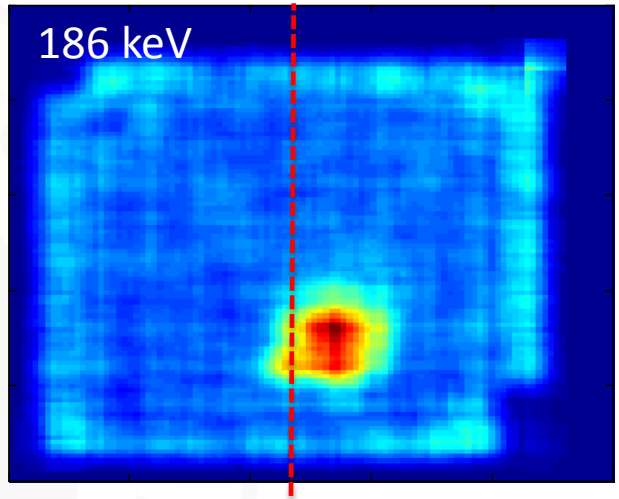


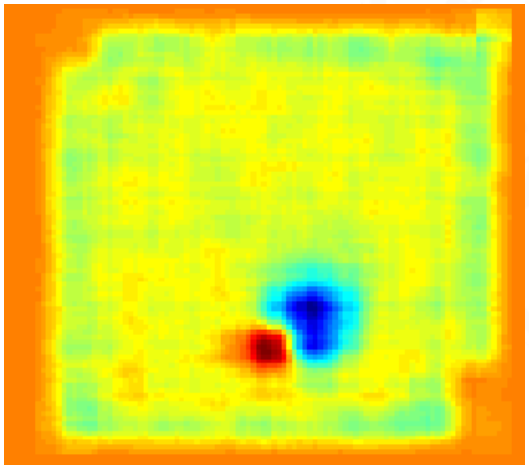


Rocky Flats Shells with AmBe Driver



Orion

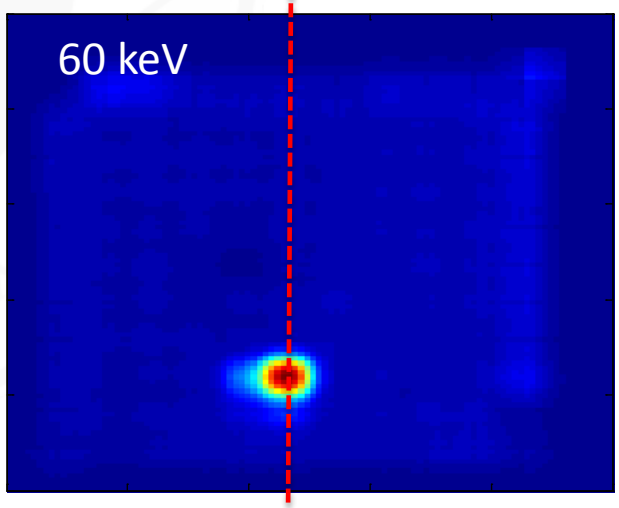




Only 60 keV signal in image pixel

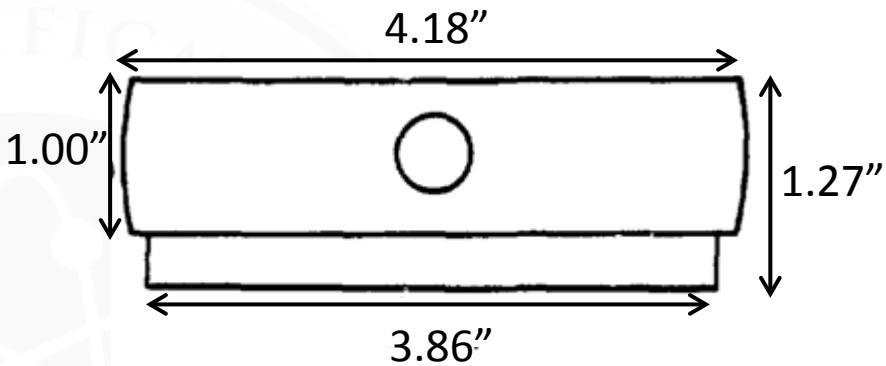
Equal contributions

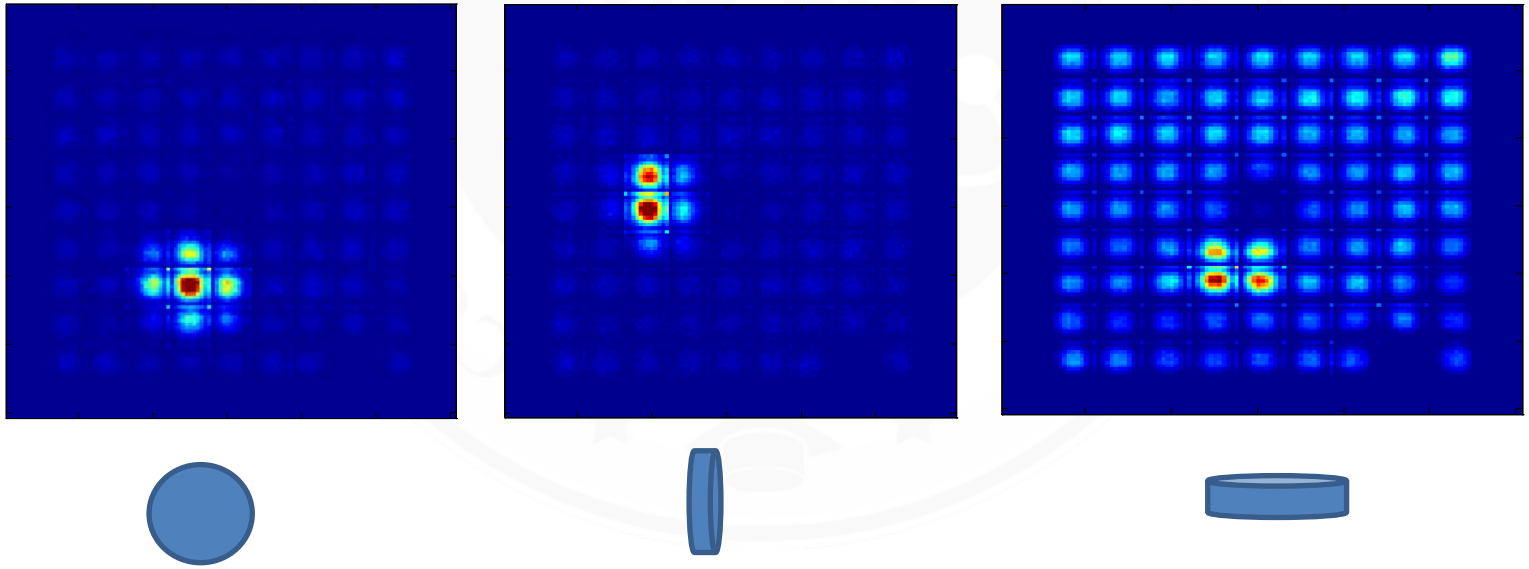
Only 186 keV signal in image pixel



THOR Core

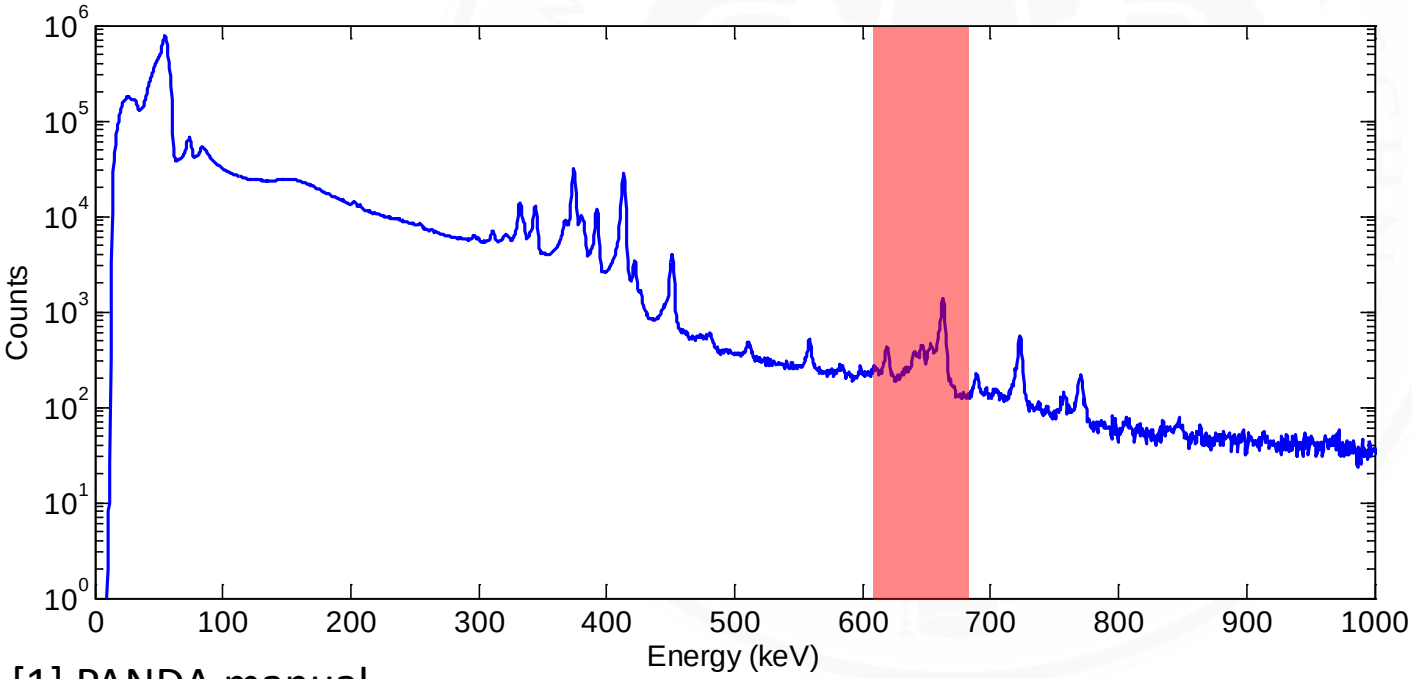
- Central slice of THOR core pinhole imaged in several geometries





THOR Core Continued

- Orion single pixel spectrum taken overnight
- ^{240}Pu content measured by 630-670keV spectrum



Plutonium Emissions

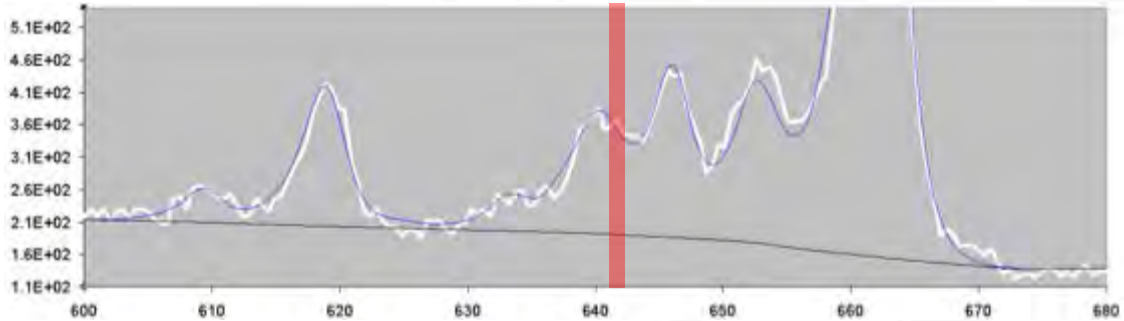
Isotope	Energy (keV)	Branching Ratio (photons/dis)
^{241}Am	633.000	1.260×10^{-8}
^{239}Pu	633.150	2.530×10^{-8}
^{239}Pu	637.837	2.560×10^{-8}
^{239}Pu	640.075	8.200×10^{-8}
^{241}Am	641.420	7.100×10^{-8}
^{240}Pu	642.480	1.245×10^{-7}
^{239}Pu	645.969	1.489×10^{-7}
^{239}Pu	649.321	7.120×10^{-9}
^{239}Pu	650.529	2.700×10^{-9}
^{239}Pu	652.074	6.550×10^{-8}
^{241}Am	652.960	3.770×10^{-7}
^{239}Pu	654.880	2.250×10^{-8}
^{239}Pu	658.929	9.690×10^{-8}
^{241}Am	662.420	3.640×10^{-6}
^{239}Pu	664.587	1.657×10^{-8}
^{239}Pu	668.200	3.930×10^{-10}

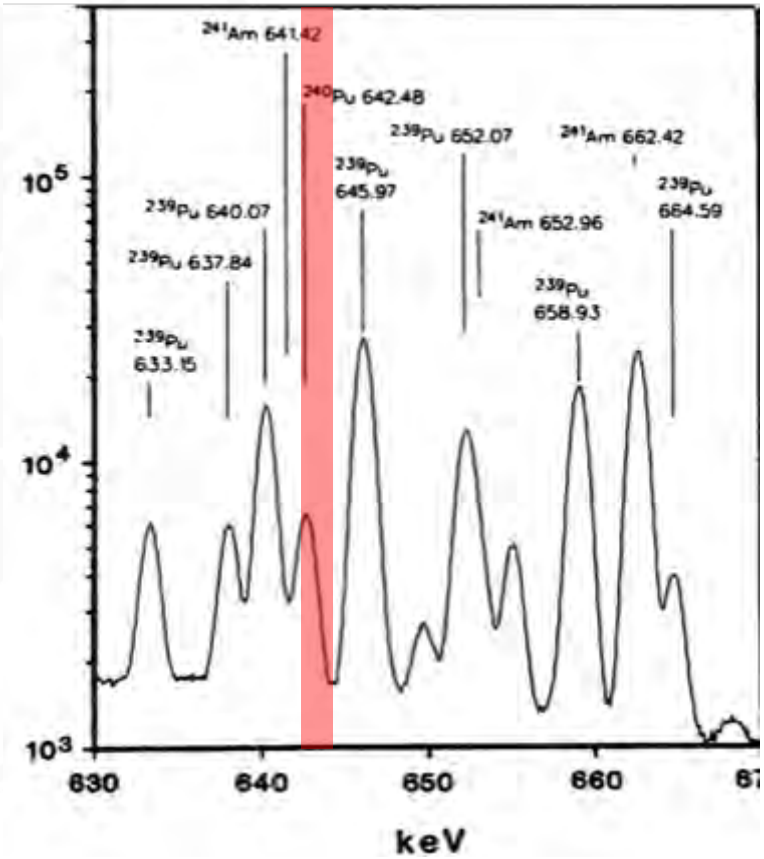
[1] PANDA manual

THOR Core Continued

- ^{240}Pu estimated as 3.63%, actual 5.02%
  - Within 2σ measurement uncertainty

	Initialize	Rel Act (Bq)			Iso Ratos		uncert.
Pu239	7.08071	V	Λ	Pu239	96.09	%	2.87
Pu240	0.26746	V	Λ	Pu240	3.63	%	1.02
Am241	0.02222	V	Λ	Am241	3015	ppm	60
Bi214	0.33272	V	Λ	Bi214	45.15	ppq	0.00





* Spectral analysis done by Scott Garner (LANL)

Campaign Successes

- Imaged HEU gamma-rays using pinhole camera and coded aperture
- Distinguished relative THOR core geometries using pinhole
- Measured THOR core ^{240}Pu content to within 2σ measurement uncertainty

2016 DAF Campaign Opportunity

- There will be a CVT one-week experimental campaign at the DAF again in 2016 (June-July timeframe)
- If you are interested in participating, the due date for applications is October 23, 2015
- Contact Prof. Sara Pozzi or Prof. John Mattingly for the application or more information

Acknowledgements

Thank you to Jesson Hutchinson and Karen Miller for helping us successfully access the DAF and implement our measurements.