Detectors, Electronics, and Algorithms for Nuclear Nonproliferation, Safeguards, and Homeland Security Applications

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Detection for Nuclear Nonproliferation Group

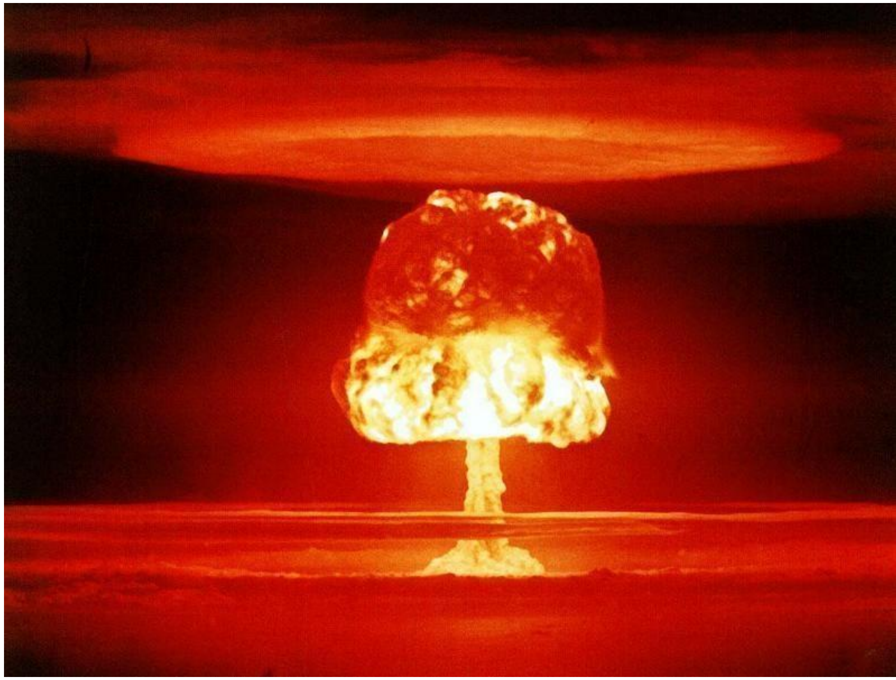
Outline

- Motivation
- MCNP-PoliMi Code System
- Scintillation Detectors
- Scalable-Platform Electronics
- Analysis Algorithms for SNM Identification
- Conclusions
- Upcoming Events

Preventing Nuclear Terrorism

Grand Challenge - National Academy of Engineering

"It should not be assumed," write physicists Richard Garwin and Georges Charpak, "that terrorists or other groups wishing to make nuclear weapons cannot read." Consequently, the main obstacle to a terrorist planning a nuclear nightmare would be acquiring fissile material — plutonium or highly enriched uranium capable of rapid nuclear fission. Nearly 2 million kilograms of each have already been produced and exist in the world today. It takes less than ten kilograms of plutonium, or a few tens of kilograms of highly enriched uranium, to build a bomb.



Source: National Academy of Engineering website

Resurgence of Nuclear Power

Challenge # 2 – Safeguarding Nuclear Fuel

- The resurgence of nuclear power requires advanced materials control and accounting techniques for nuclear fuel reprocessing in order to prevent diversions, ensure safety, and reassure the international community
- Near real-time accountability measurements are needed for material at all stages of the fuel cycle
- Quantification of Pu-239 and other fissile isotopes

Detection Technology

Challenge # 3 – Replacement Technology for He-3 Neutron Detection

- ^{3}He counters are widely deployed in radiation portal monitors
  - They are a common choice for detecting neutrons
    - Energy information is lost
    - ^{3}He is currently in short supply
- Candidates for ^{3}He replacement should have:
  1. High efficiency
  2. Reliable neutron/gamma-ray discrimination
  3. Neutron spectroscopic capabilities

Description of Simulation Tools
MCNP-PoliMi Monte Carlo Code

- MCNP-PoliMi was developed to simulate correlation measurements with neutrons and gamma rays
- Unique features:

1. Physics of particle transport (MCNP-PoliMi code)
   - Prompt neutrons and gamma rays associated with **each event** are modeled explicitly; neutron and photon-induced **fission multiplicity** distributions have been implemented

→ Improved simulation of correlation and multiplicity distributions

2. Physics of detection (Detector Response Module)
   - **Each collision** in the detector is treated individually

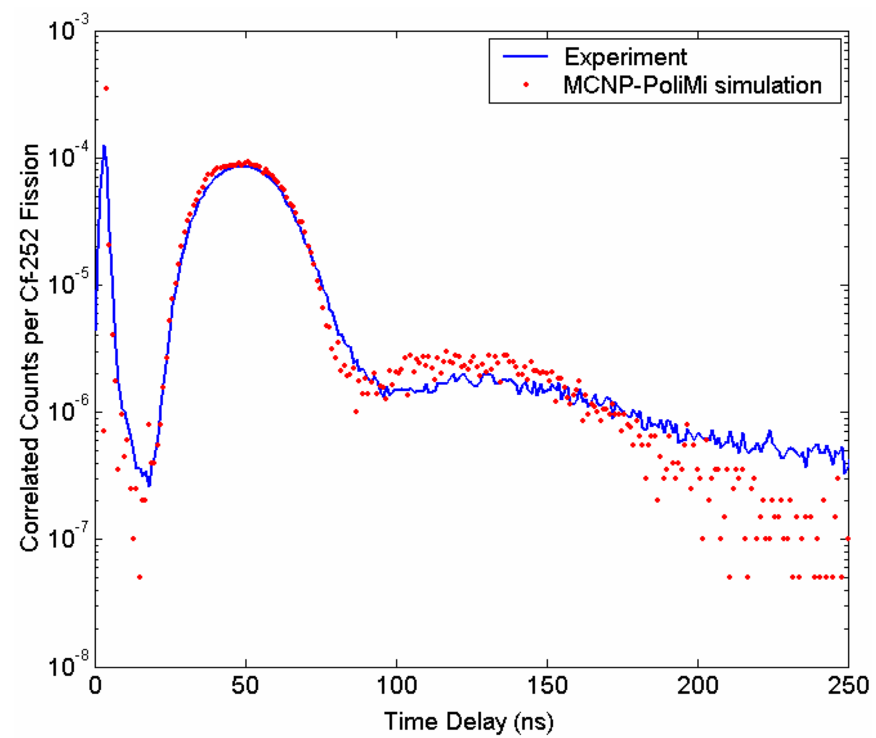
→ Improved simulation of detector response

MCNP-PoliMi Code System

Detector Response Simulation Capabilities

- MCNP-PoliMi was developed to simulate correlated particle interactions on an event-by-event basis
- The code allows for high-fidelity detector response simulation:
  1. Nonlinearity in the light output from neutron collisions
  2. Varying light output from carbon and hydrogen collisions
  3. Pulse generation time within the scintillator
  4. Detector dead time
  5. Detector resolution is being implemented

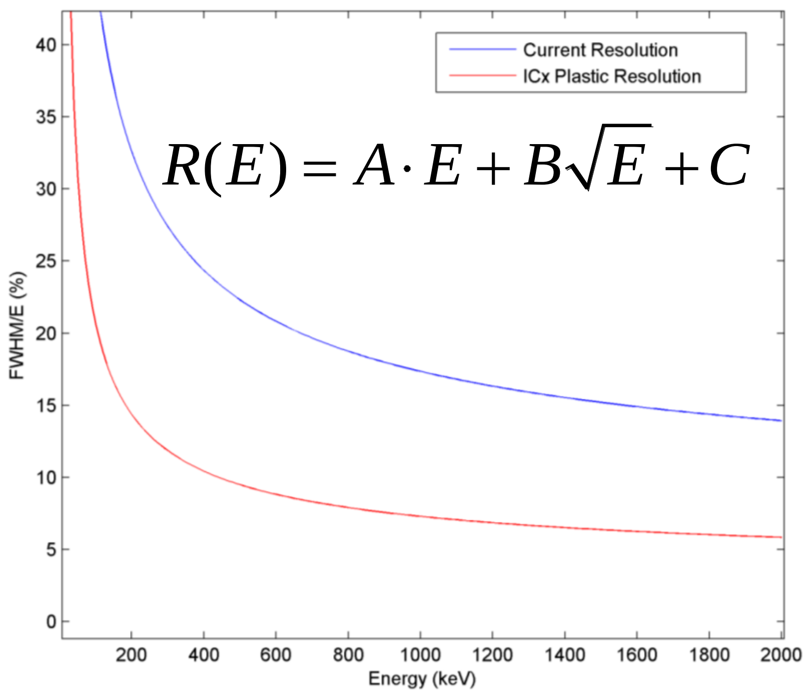
<u>^{252}Cf time-of-flight with a liquid scintillator</u>

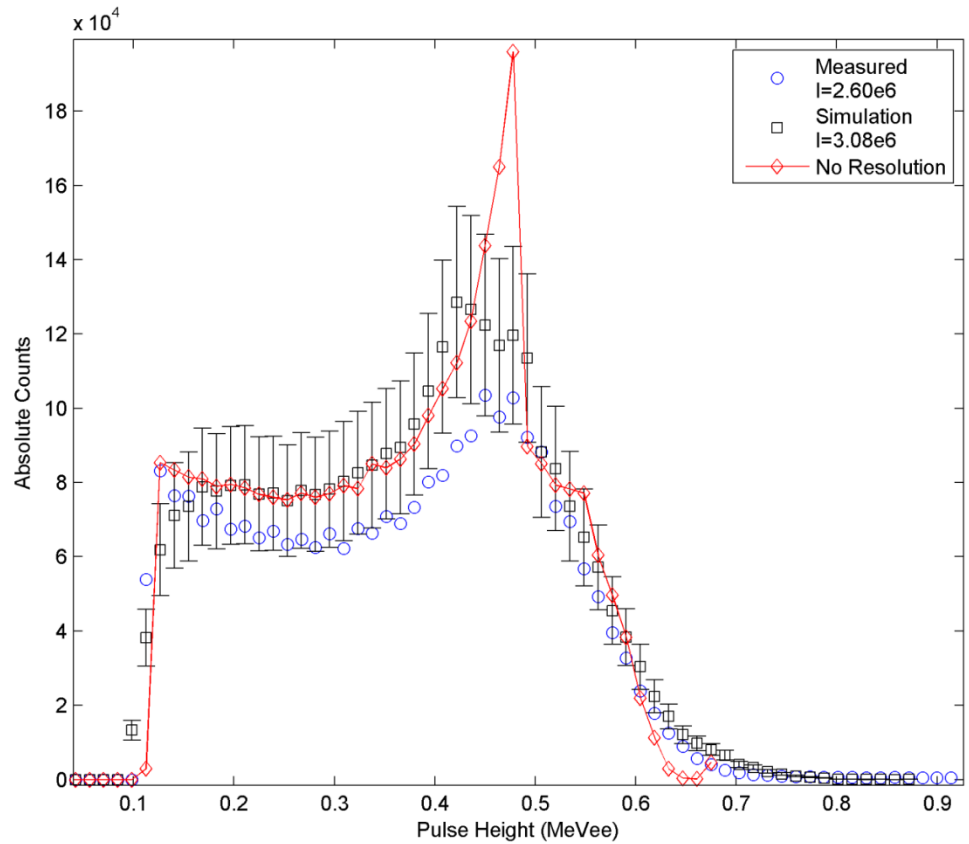


MCNP-PoliMi Code System

Scintillator Resolution Implementation

- The resolution functions are based on measured plastic-scintillator data





Passive Measurements in Ispra, Italy

Cross-Correlations of Plutonium Oxide

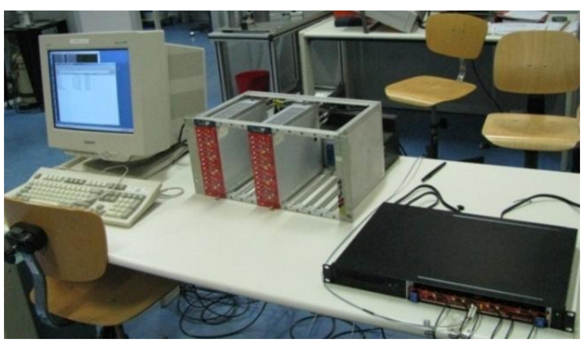
- Measurements of PuO_2 standards were performed in August, 2008 at the JRC in Ispra, Italy
- Passive cross-correlation data was acquired using six cylindrical EJ-309 liquid scintillation detectors
  - Offline pulse shape discrimination (PSD) was used to separate the neutron and gamma contributions

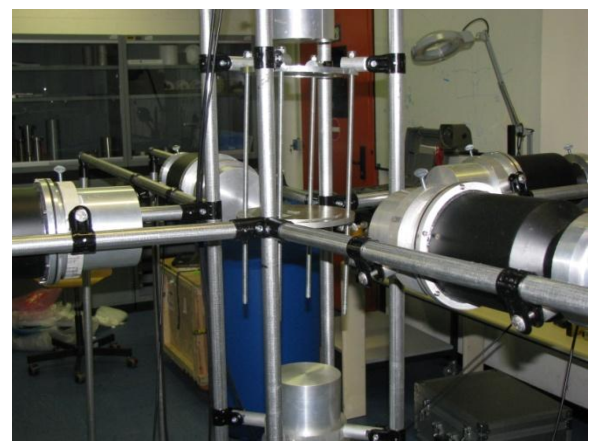
Passive Measurements in Ispra, Italy
Measurement Summary

- We collected approximately 10k correlations for each of five different samples:
  1. Low burnup, 100 g
  2. Low burnup, 300 g
  3. Low burnup, 500 g
  4. High burnup, 50 g
  5. High burnup, 100 g

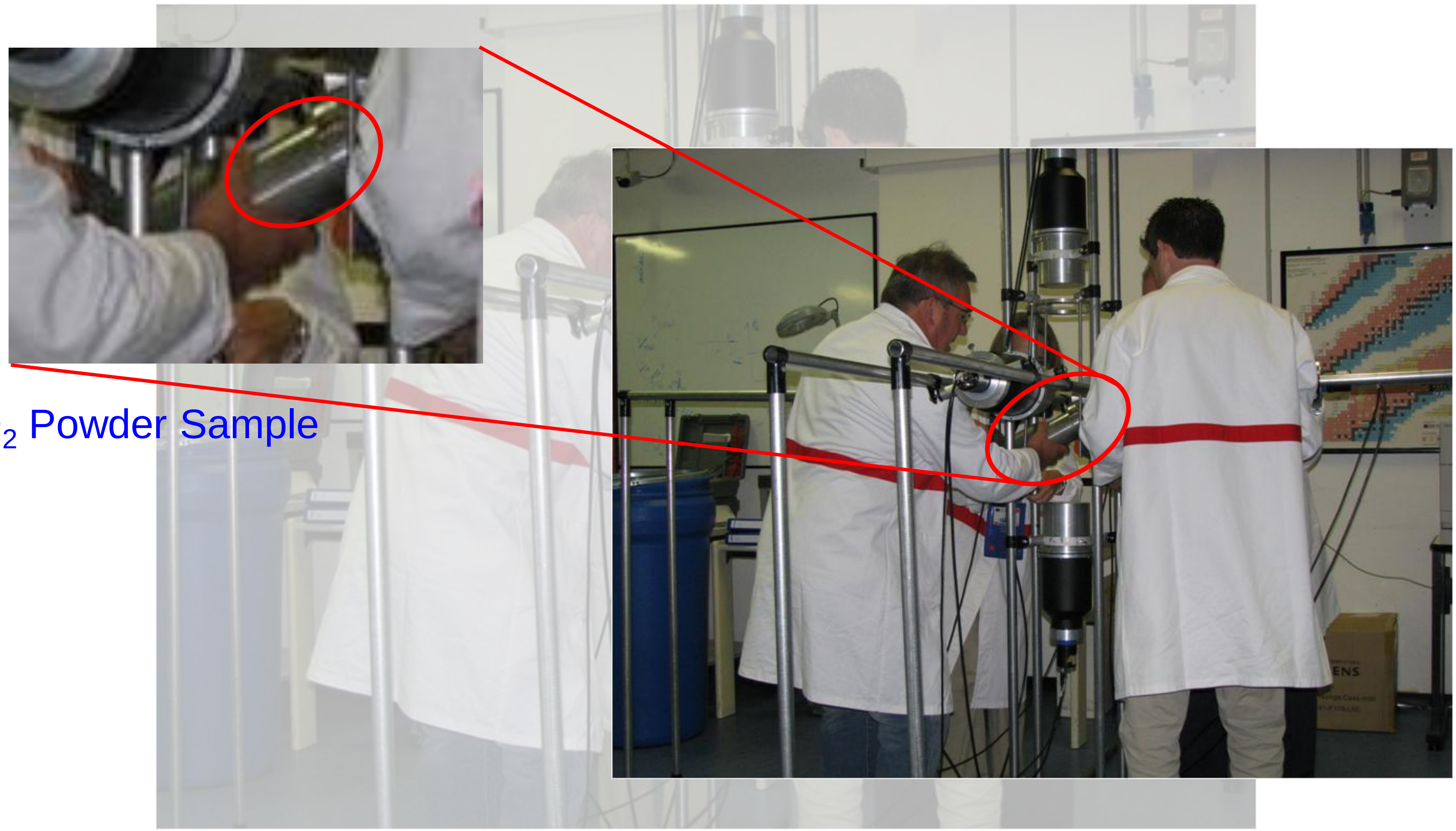
<u>Sample Isotopics (mass percent)</u>

Isotope	Low Burnup	High Burnup
Pu-238	0.20%	1.72%
Pu-239	70.96%	58.10%
Pu-240	24.58%	24.77%
Pu-241	3.29%	9.77%
Pu-242	0.98%	5.65%



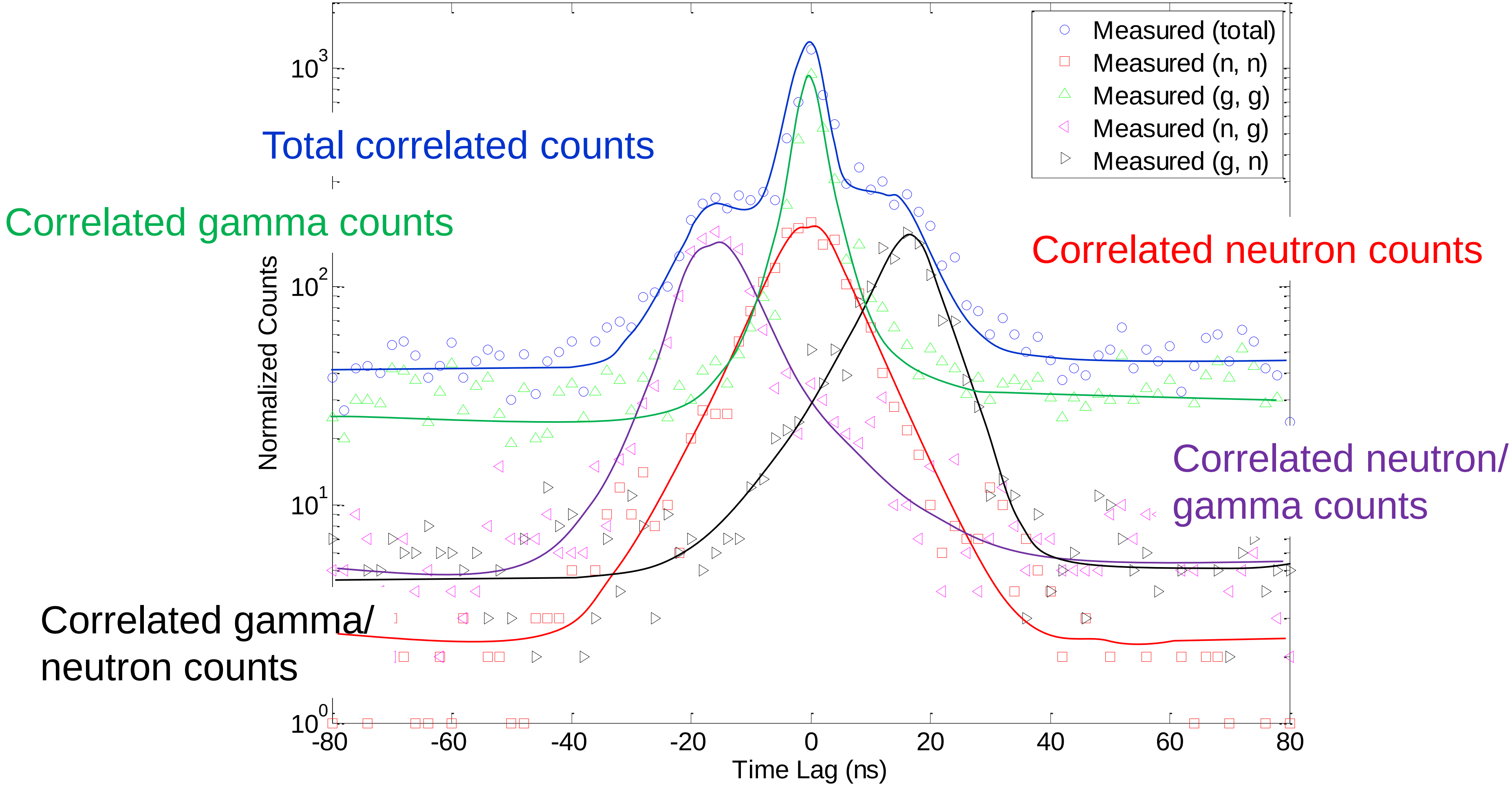


Passive Measurements in Ispra, Italy



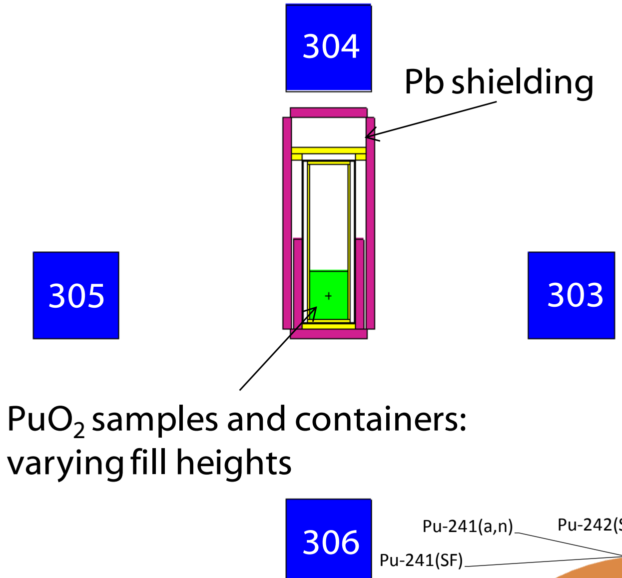
Measured Data

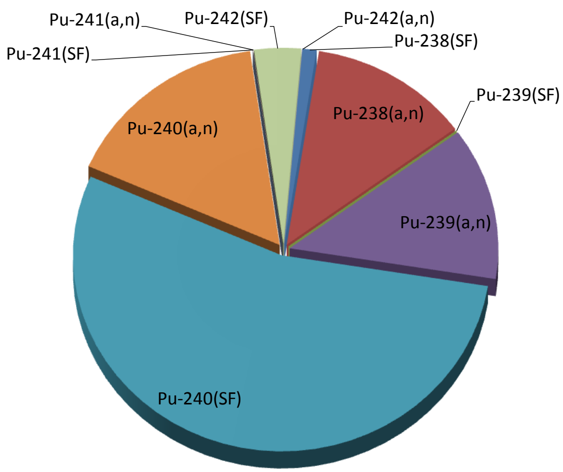
Low-Burnup PuO_2, 500 g

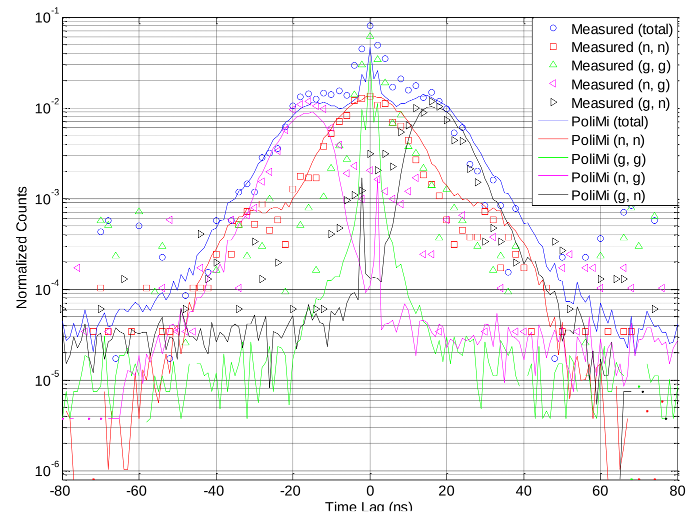


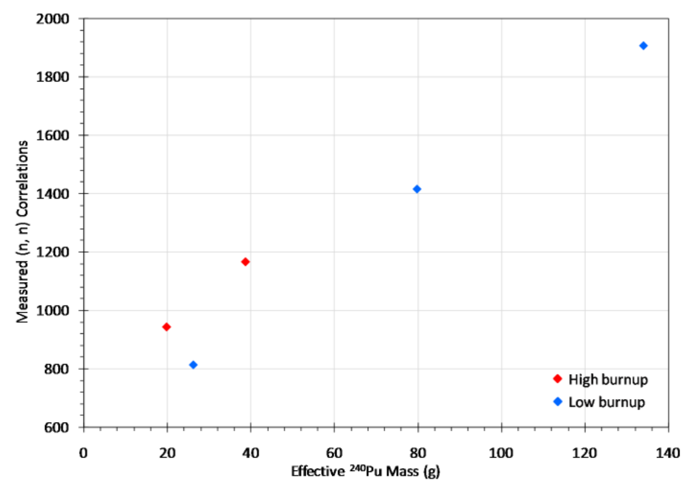
Passive Detection Results

Simulated and Measured





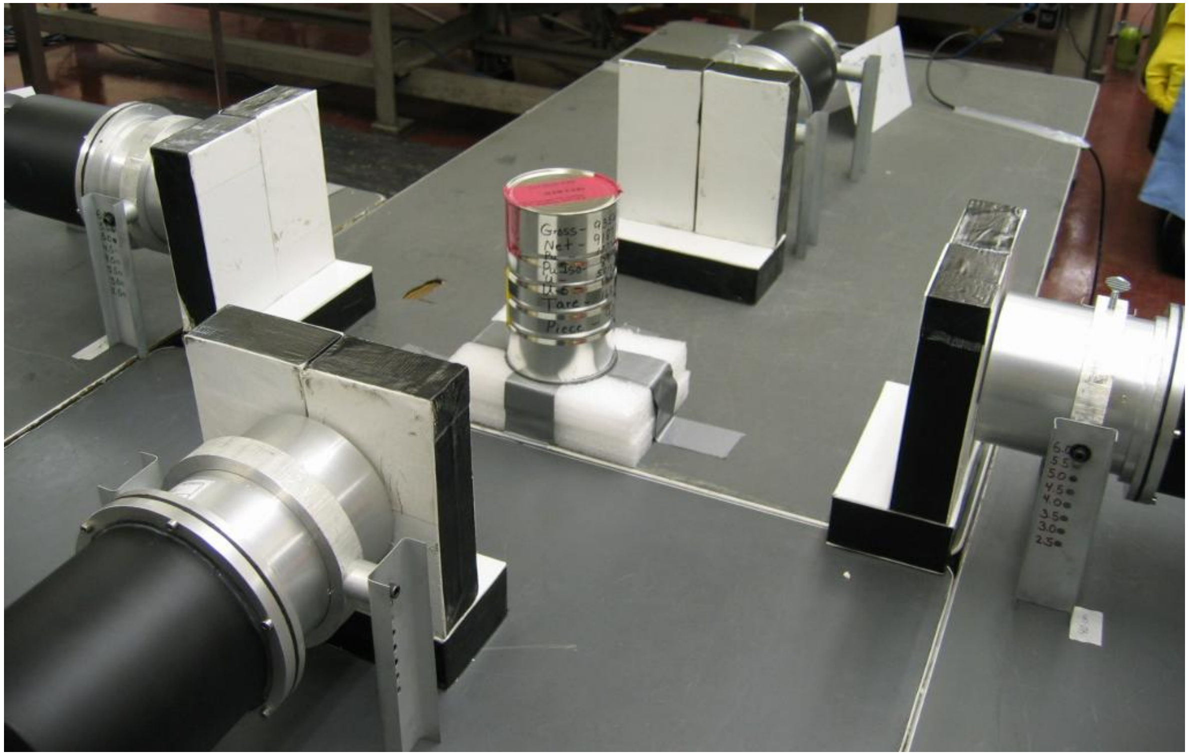




Passive Measurements of MOX

Experimental Geometry

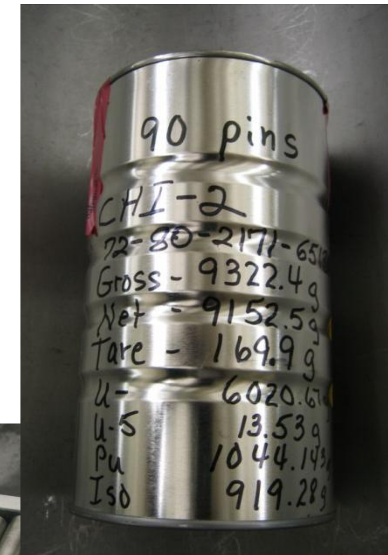
- Idaho National Laboratory
- Zero-Power Physics Reactor Facility (ZPPR)
- Measurement of Mixed-Oxide Fuel pins (MOX)

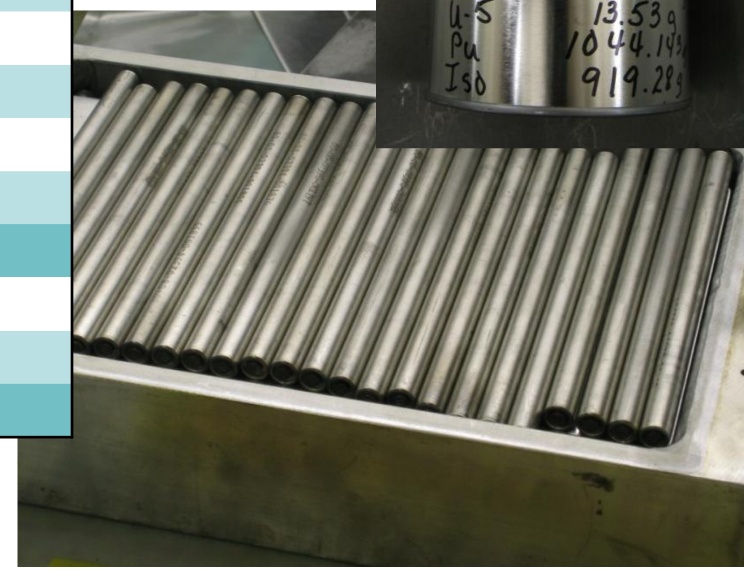


Passive Measurements of MOX

Material Composition

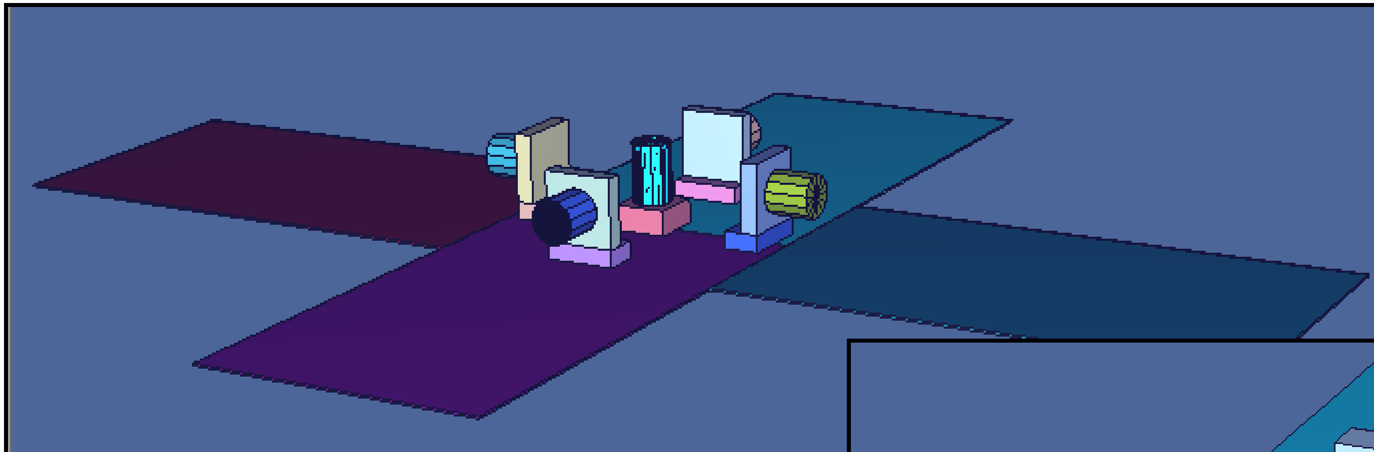
	Pin #1	Pin #2
Diameter [cm]	0.97	0.97
Length [cm]	15.24	15.24
MOX weight [g]	**89.55**	**89.78**
Total Pu weight [g]	**11.74**	**14.01**
Pu-238	0.01	0.01
Pu-239	10.19	9.81
Pu-240	1.36	3.66
Pu-241	0.04	0.15
Pu-242	0.02	0.02
Am-241	0.16	0.51
Total U weight [g]	**66.90**	**64.58**
U-235	0.15	0.14
U-238	66.75	64.45
O-16	10.57	10.59





Monte Carlo Simulation

MCNP-PoliMi Model



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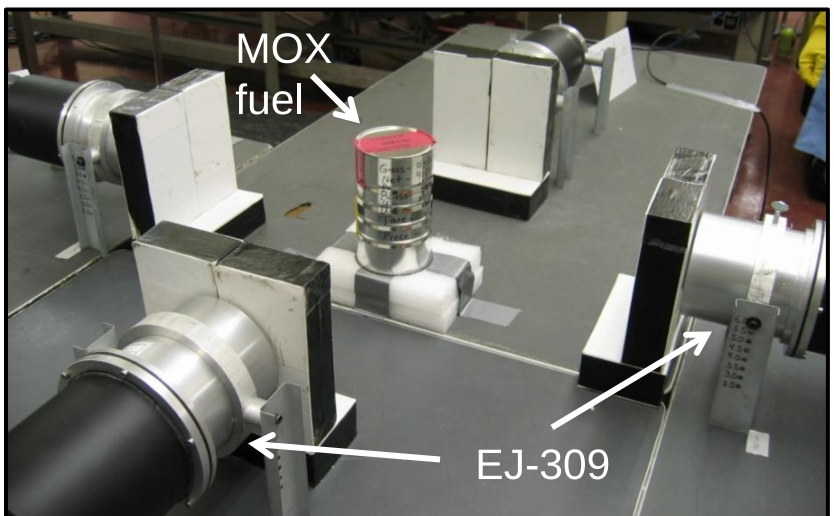
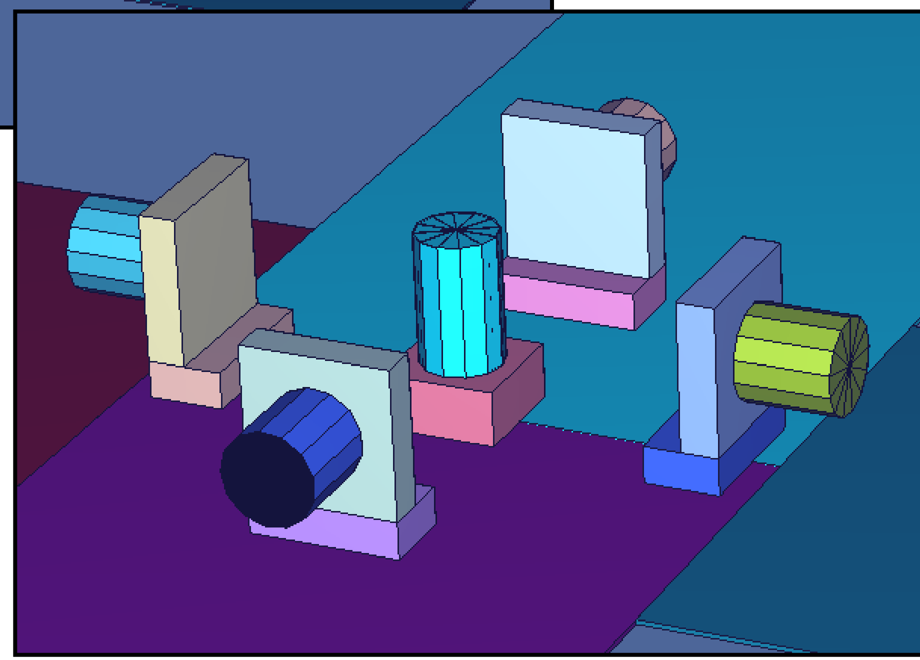
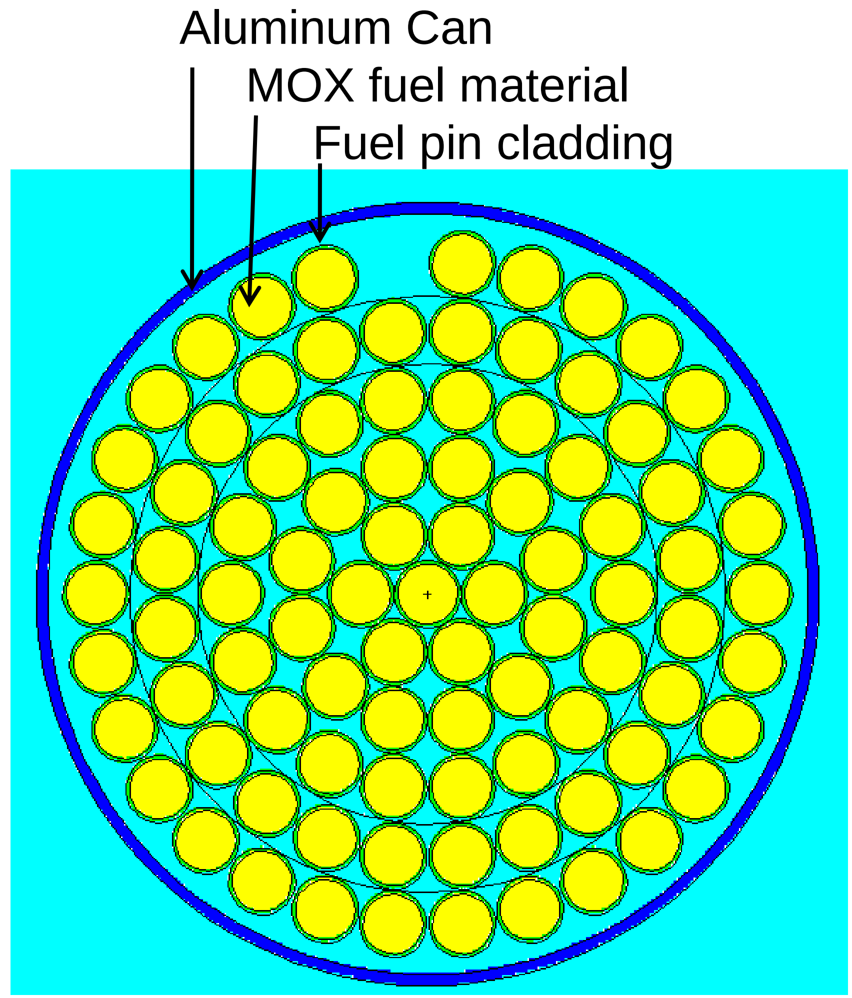




Monte Carlo Simulation

MCNP-PoliMi Model

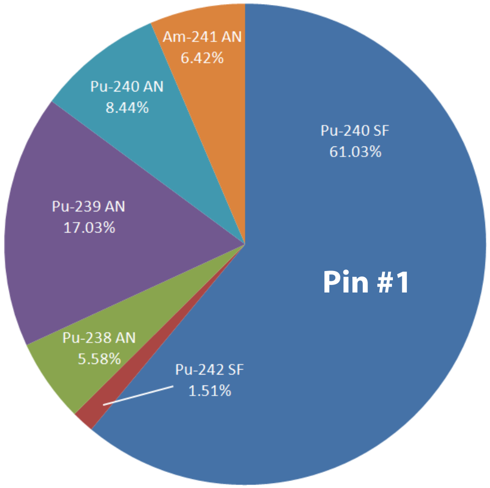


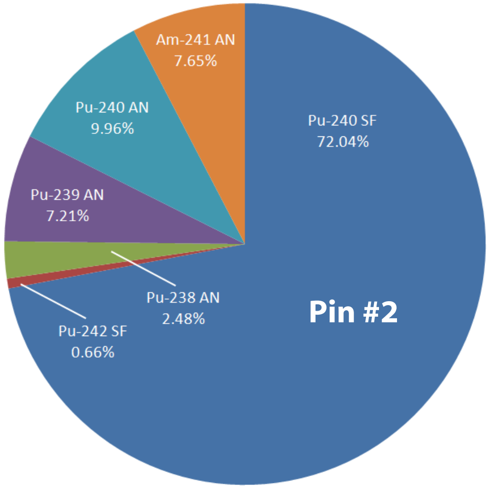
Material Characterization

pin type #1 vs. pin type #2 (100 pin arrays)

Neutron Creation Data	**Pin #1**	**Pin #2**
Neutrons/sec from Spontaneous Fission	1426.1	3767.9
Neutrons/sec from (alpha,n) Reactions	854.3	1414.7
Neutrons/sec from Induced Fission	278.6	665.7
Average Energy of Neutrons from Spontaneous Fissions	1.98	1.98
Average Energy of Neutrons from (alpha,n) Reactions [MeV]	2.30	2.31
Average Energy of Neutrons from Induced Fission [MeV]	1.69	1.69

Photon Creation Data	**Pin #1**	**Pin #2**
Photons/sec from Spontaneous Fission	4261.1	11258.4
Photons/sec from (alpha,n) Reactions	645.7	1132.1
Average Energy of Photons from Spontaneous Fissions	0.94	0.94
Average Energy of Photons from (alpha,n) Reactions [MeV]	0.76	0.74

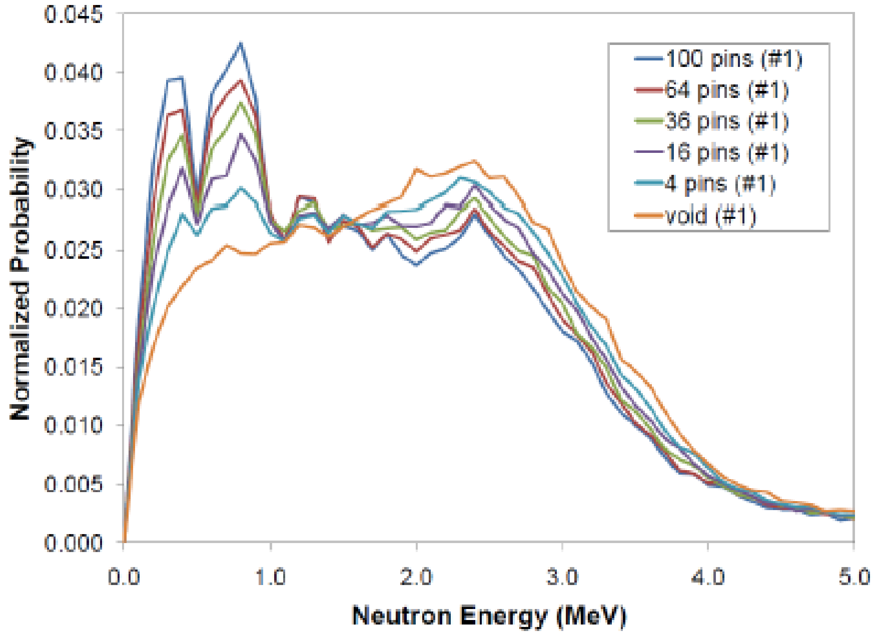


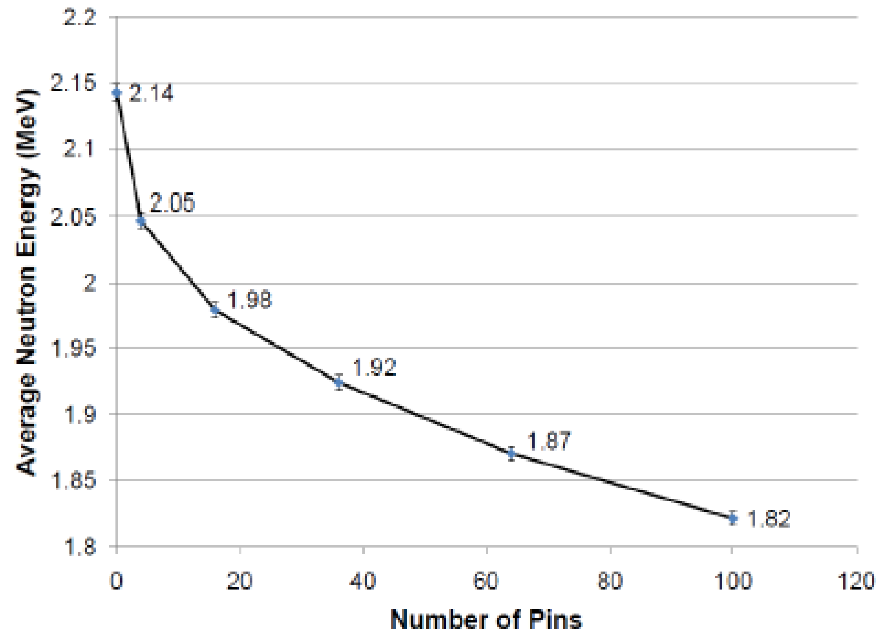


Simulation Results and Comparison

Neutron Energy Spectra and Average Energy

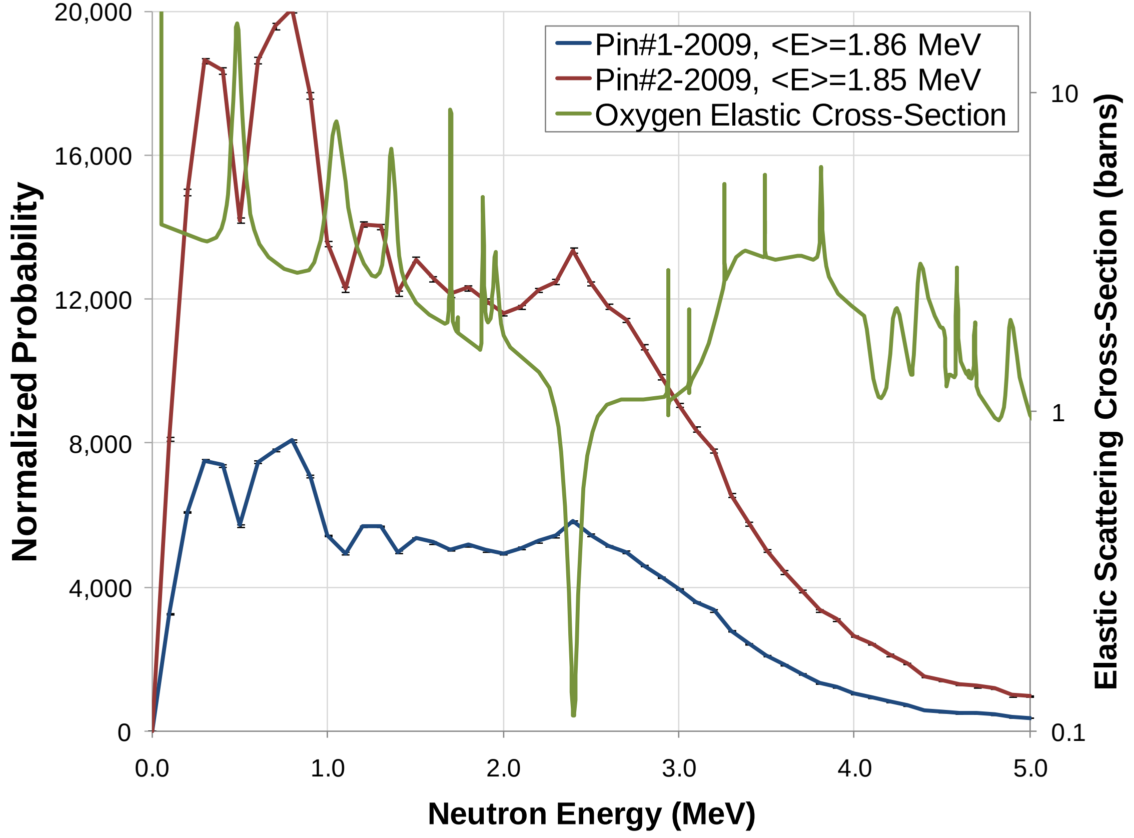
- The quantity of MOX fuel material effects the emitted neutron energy distribution
- As the number of fuel pins increases the average neutron energy decreases





Simulation Results and Comparison
Neutron Energy Spectra

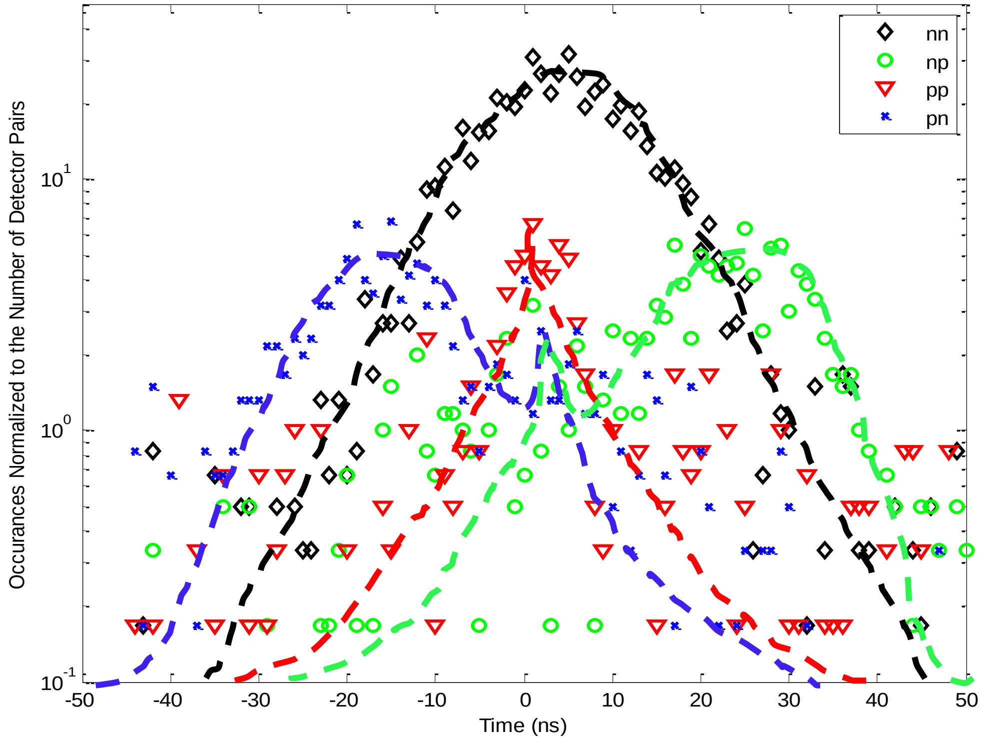
- The combination of six MCNP-PoliMi sources provide the anticipated neutron energy distributions for the 90 fuel pin can
- Neutron energy tally on the exterior of the fuel pin can

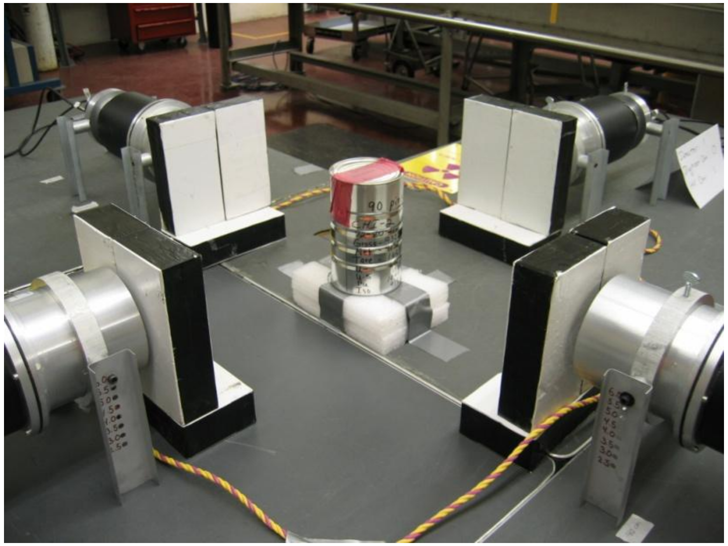


ENDF/B-VII.0 (USA, 2006)

Measurement Results

Cross-Correlation Functions





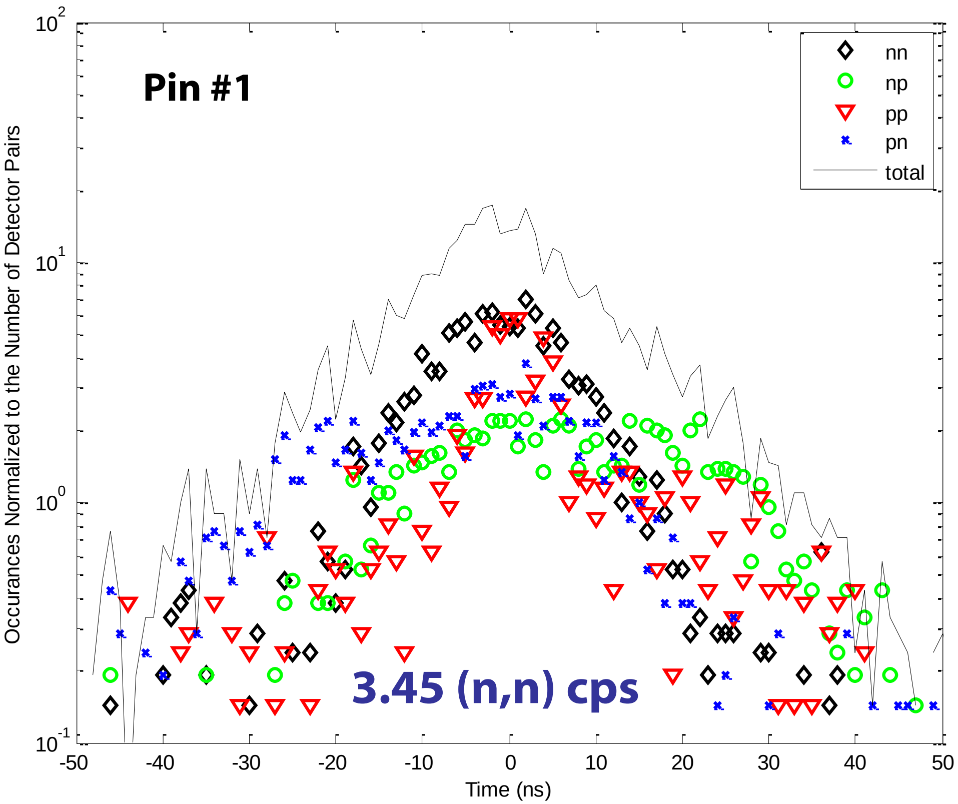
12 minute acquisition, 90 pins of #2, 40 cm detector distance, 70 keVee threshold, 2 in lead shielding

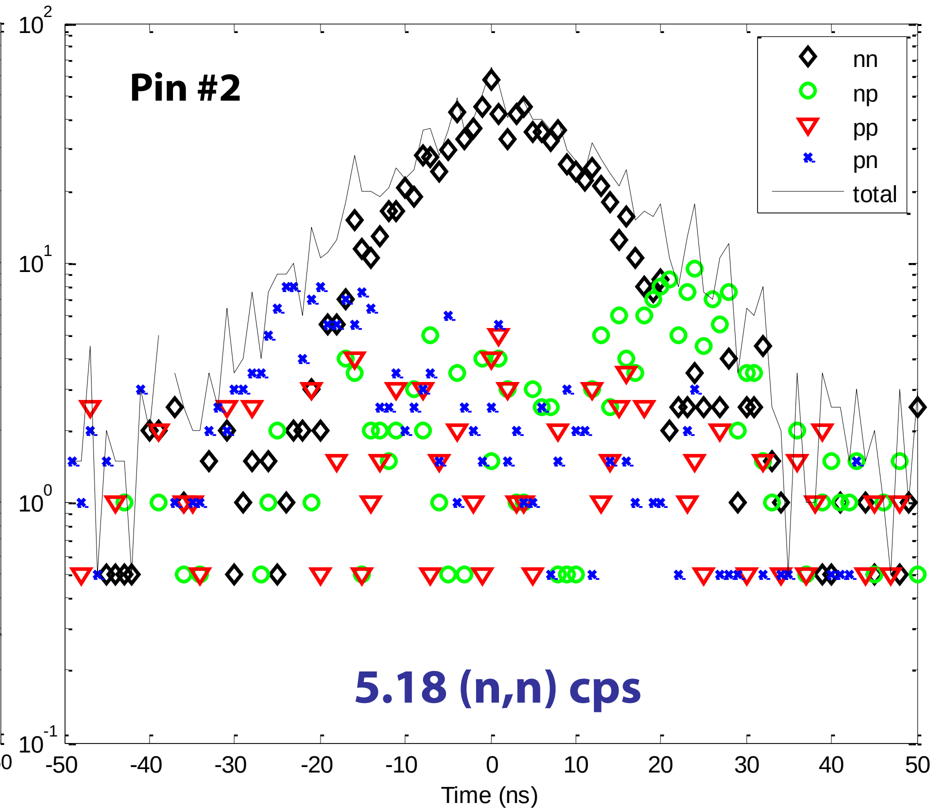
- PSD allows for study of individual components of the cross-correlation curve
- **neutron-neutron correlations** provide information on **fission** events

Measurement Results

Cross-Correlation Functions

- Comparison of (n,n) to (n,p) and (p,n) correlations:
  - Pin #1—0.74
  - Pin #2—2.34

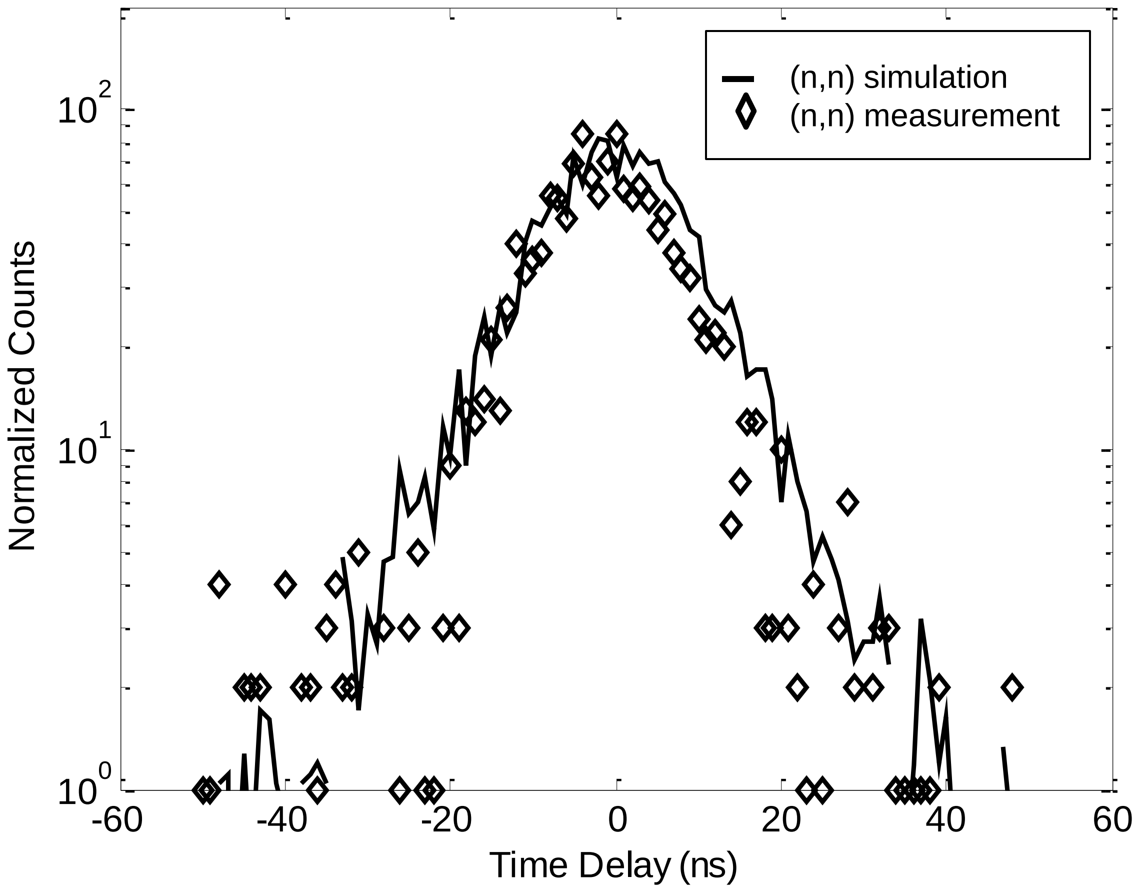




Measurement vs. Simulation

Cross-Correlation Functions

- Good agreement in neutron-neutron correlations
- High gamma-ray background from radioactive decay of fuel elements hinders good photon related correlations

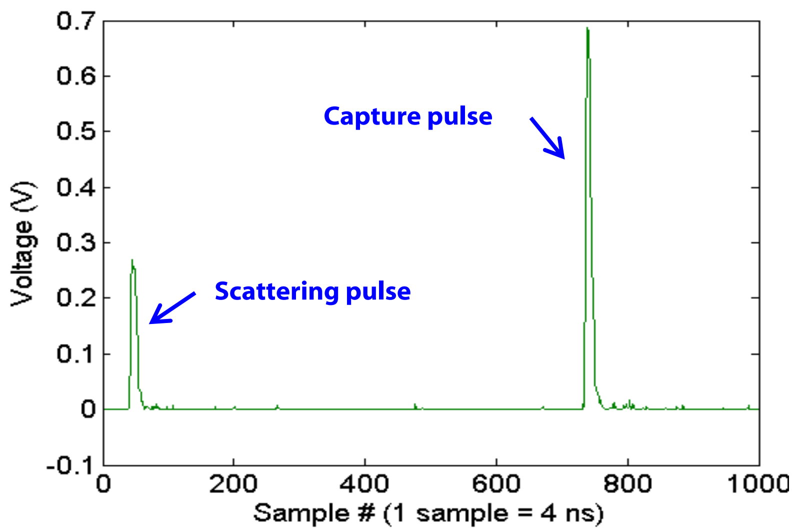


Capture-Gated Detectors
Working Concept

Capture-gated detectors* provide **enhanced neutron spectroscopic information**

- Initial neutron scattering pulses is followed by capture pulse
- Size of the scattering pulse is directly related to the initial neutron energy

Capture-gated neutron spectroscopy can be performed by adding material(s) with high σ_a for thermal neutrons (^{10}B, ^{6}Li, ^{nat}Gd, Cd, etc.)

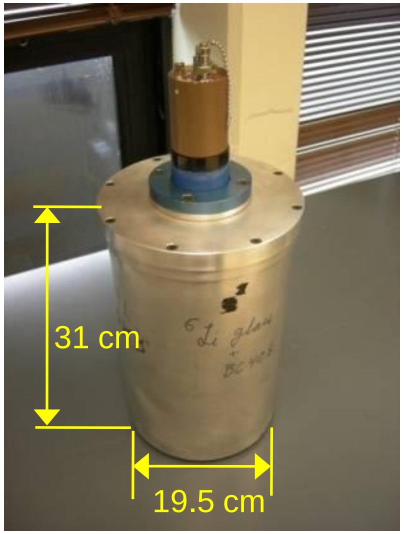


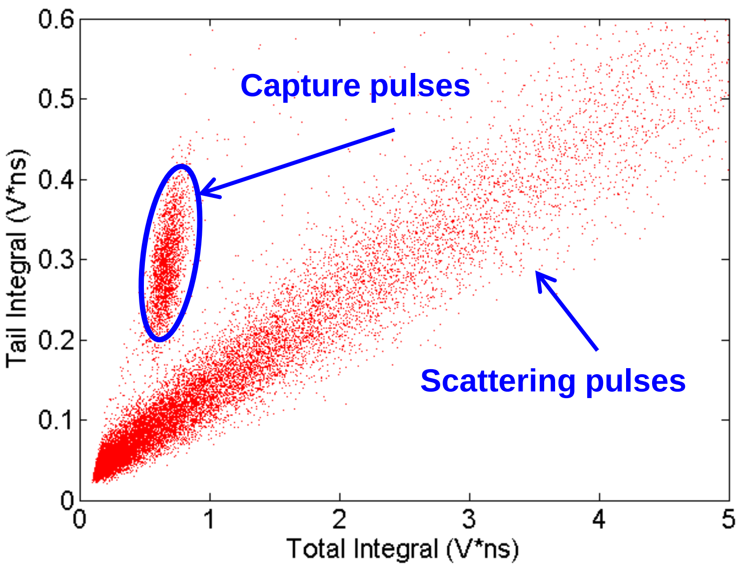
*G.F. Knoll, Radiation Detection and Measurement, third Ed., Wiley, New York, 2000, p. 570.

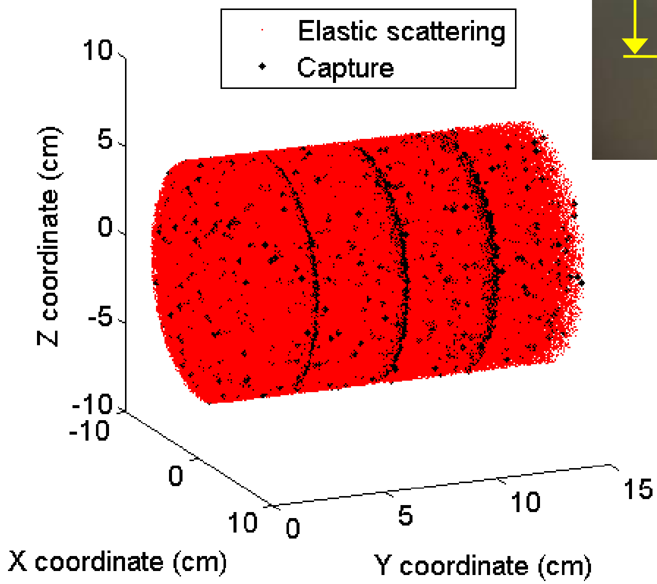
Passive Measurements, ^{6}Li Detector

Heterogeneous, ^{6}*Li Glass/Plastic Scintillator*

- The detector consists of 7 slabs (4 BC-408 and 3 GS20 slabs)
- 1 Ci ^{239}Pu-Be source shielded by 2 in. of lead
- The source was placed 30 cm from the detector
- Ratio of neutron captures from all neutron collisions: 2.5%







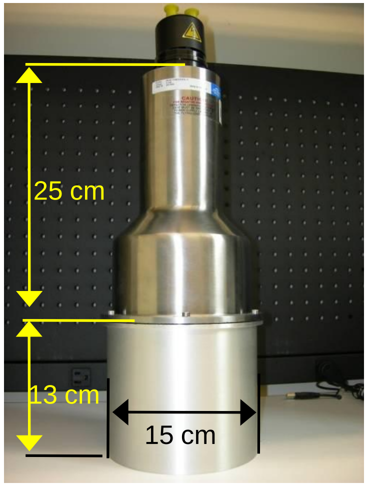
Scintillation Detectors: ^{10}B-Liquid

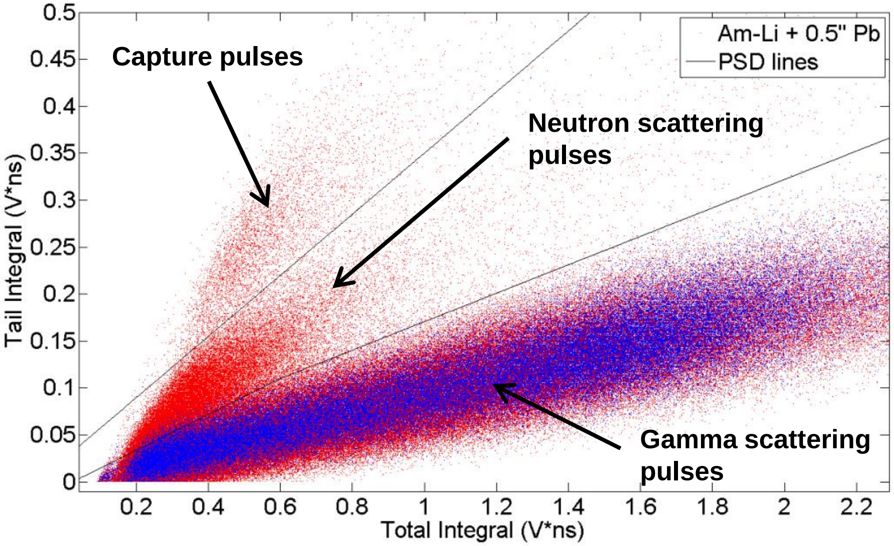
Measurement Results

- Saint-Gobain BC-523A homogeneous detector based on liquid scintillator BC-501A
- The detector is loaded with 4.41%wt. of ^{10}B
- Large thermal-neutron capture cross section (3858 barns) is utilized to produce capture pulses

$$^{10}_{5}B+^{1}_{0}n \rightarrow ^{11*}_{5}B \rightarrow ^{4}_{2}\alpha+^{7}_{3}Li+\gamma$$

$E_{\alpha} = 1.47$ MeV
$E_{Li} = 0.84$ MeV
$E\gamma = 0.48$ MeV (94%)

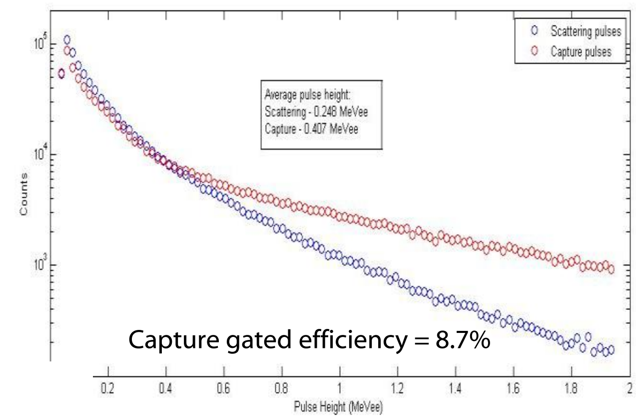


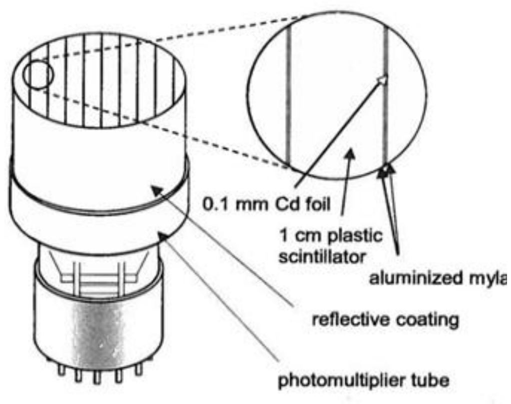


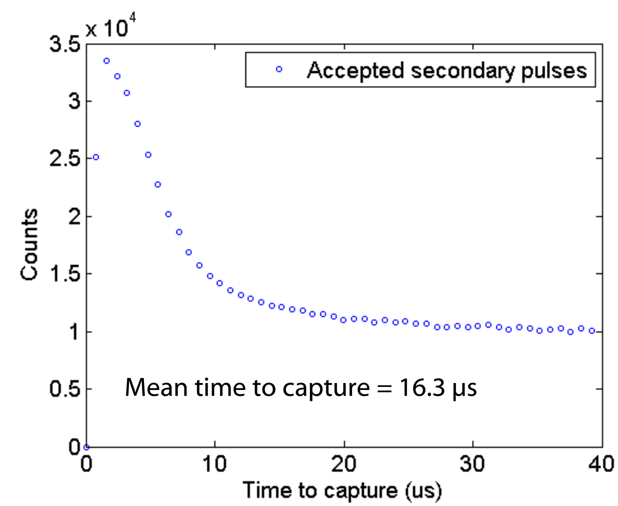
Scintillation Detectors: Cd-Plastic *Measurement Results*

- CAEN V1720 waveform digitizer
  - 12-bit vertical resolution
  - 250-MHz sapling rate (4-ns step)
  - DNNG data-acquisition software

- Cadmium detector at 15 cm from a ^{252}Cf source
  - U = 1350 V
  - ~ 62000 neutrons/s from the source
  - ~ 3300 neutrons/s at the face of the detector
- Binary data files obtained
  - Measurement time 300 s, 8 files
  - ~740,000 pulses/file
  - 100 points/pulse
- Thresholds
  - Measurement threshold = 75 keVee
  - Coincidence (capture-gated) window = 40 μs



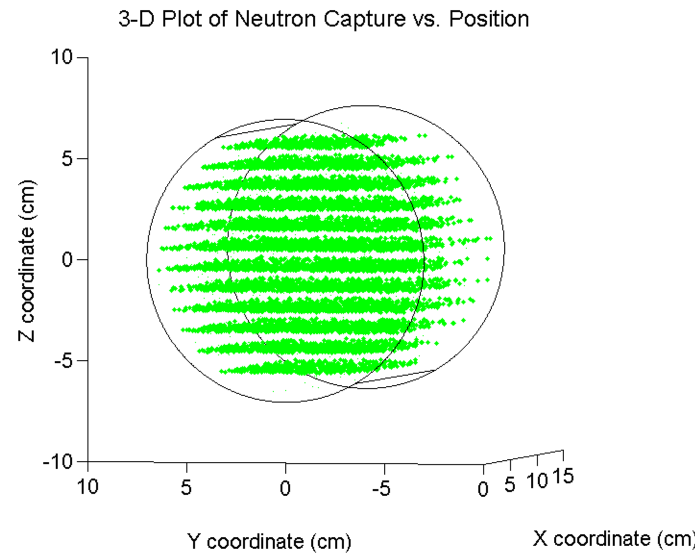


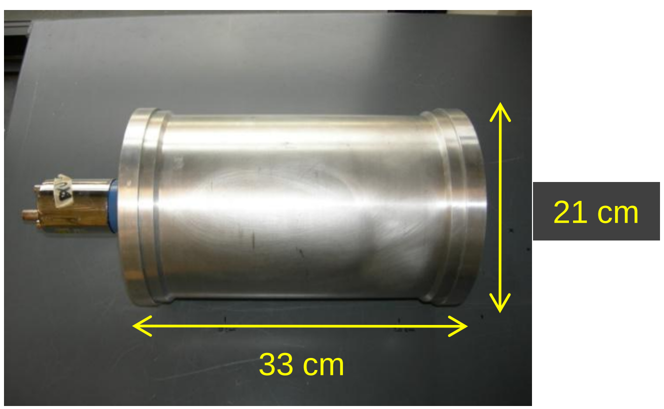


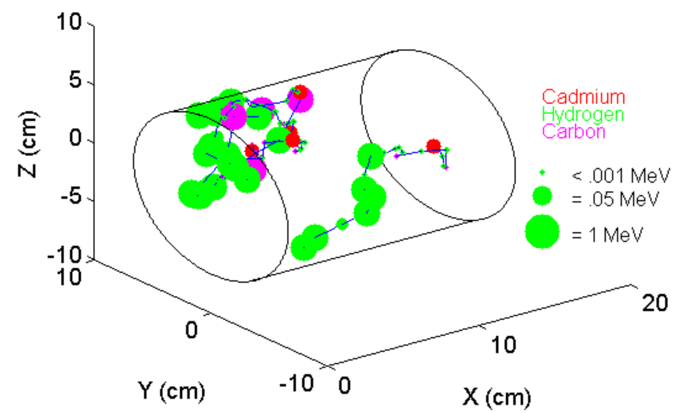
Scintillation Detectors: Cd-Plastic

MCNP-PoliMi Simulation Results

- The MCNP-PoliMi code produces a specialized output file detailing all collisions within a detector
- DNNG-developed algorithms analyze the information in this file to predict detector response
- Result Examples
  - Positions of a specific collision type in detector
  - Track histories with description of collision types



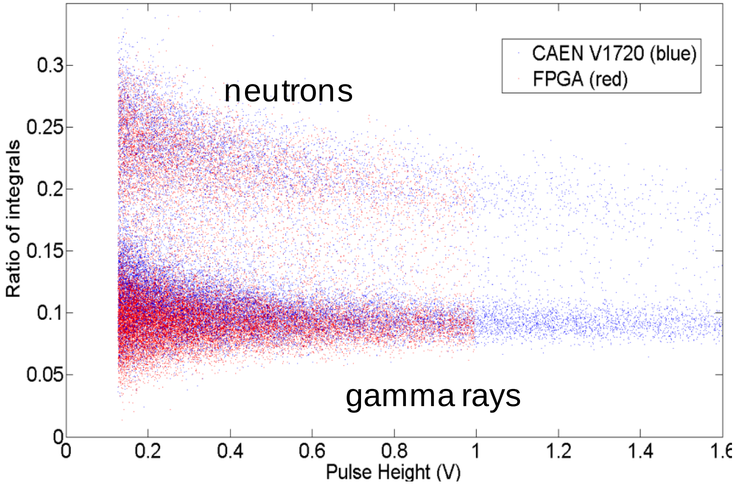




Scalable-Platform Electronics

Digitizer Development

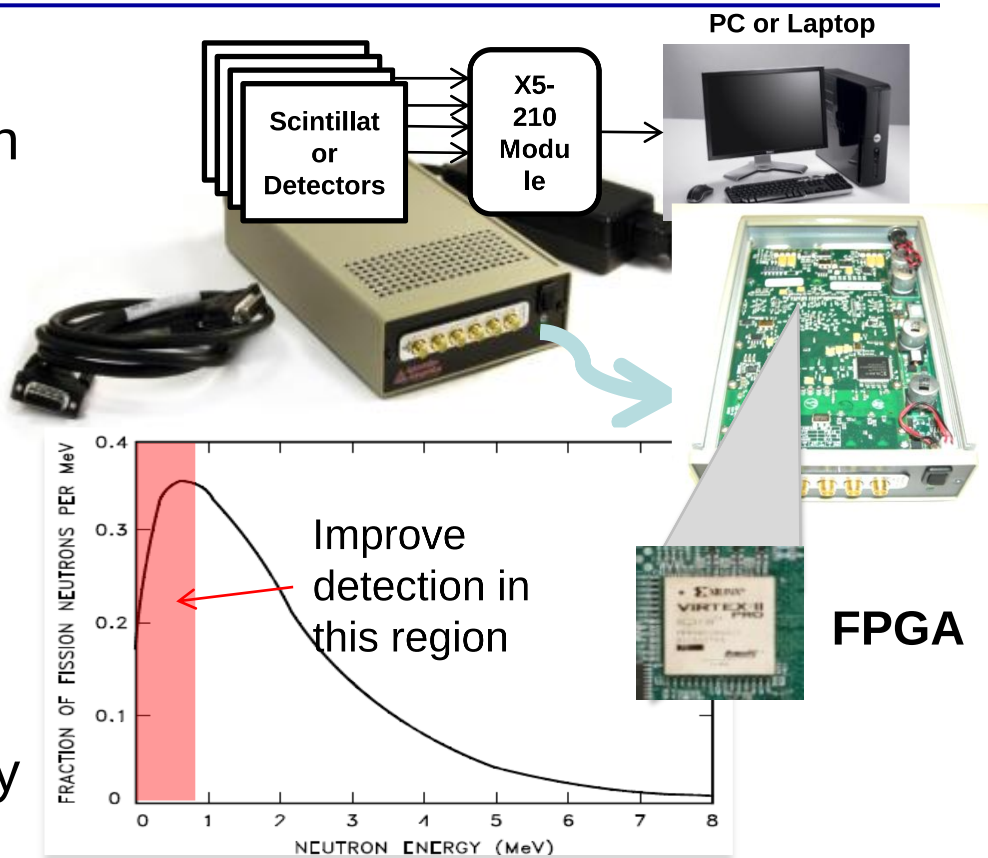
- **CAEN V1720 waveform digitizer**
  - 12-bit vertical resolution
  - 250-MHz sampling rate (4-ns step)
  - 8 channels
  - 2-V dynamic range
  - One motherboard FPGA
  - 8-channel FPGAs
  - DNNG custom-made data-acquisition software
  - Optimized for offline mode
- **FPGA waveform digitizer**
  - 14-bit vertical resolution
  - 250-MHz sampling rate
  - 4 channels
  - 2-V dynamic range
  - One FPGA
  - DNNG custom-made data-acquisition software
  - Optimized for online mode



Scalable-Platform Electronics

Platform Description

- The electronics developed in this project will allow extraction of very low-energy pulses
- Such pulses are generated from neutrons depositing very little energy within the scintillators
- Accurately measured low-energy portion of the fission spectrum will lead to more accurate neutron spectroscopy

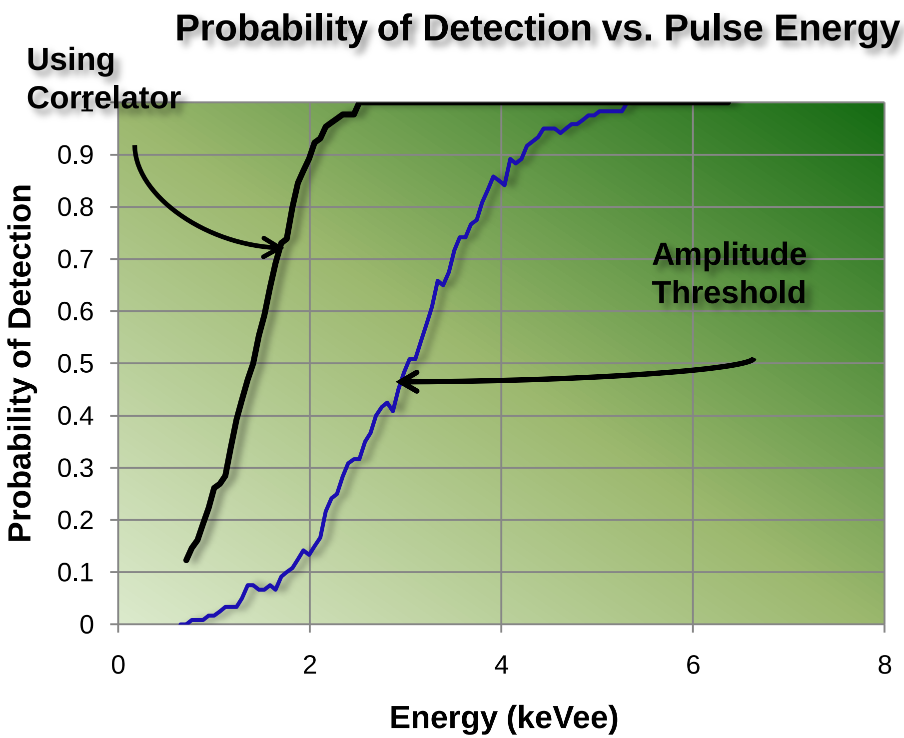


Fast, robust identification and characterization

Scalable-Platform Electronics

Platform Analysis Algorithms

- Normalized Cross Correlation
- Widely used in template matching for image processing, wireless communication etc
- 2x improvements in probability of detection
- Real-time detection
- Simulations show lowest detectable energy to be 3 keVee
- Eventually real-time PSD on FPGA

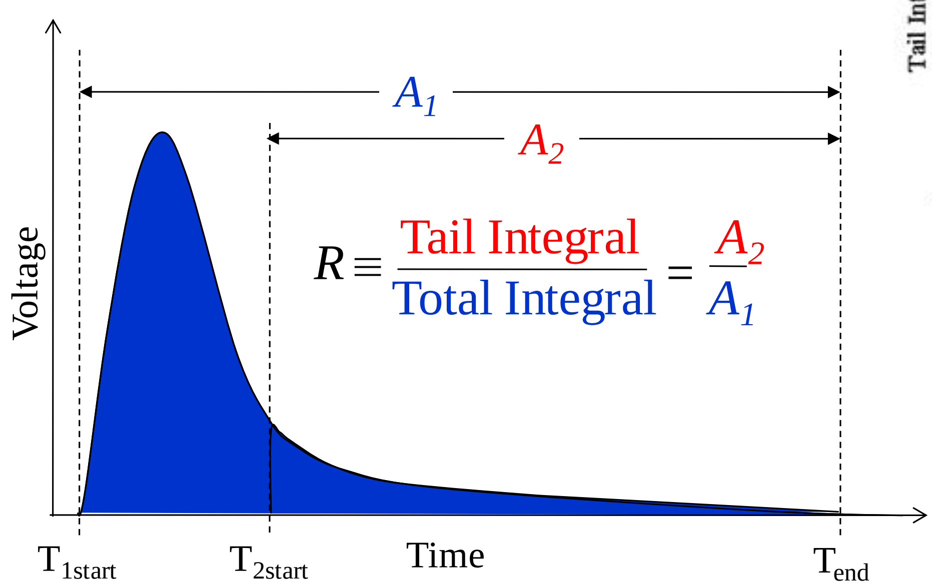


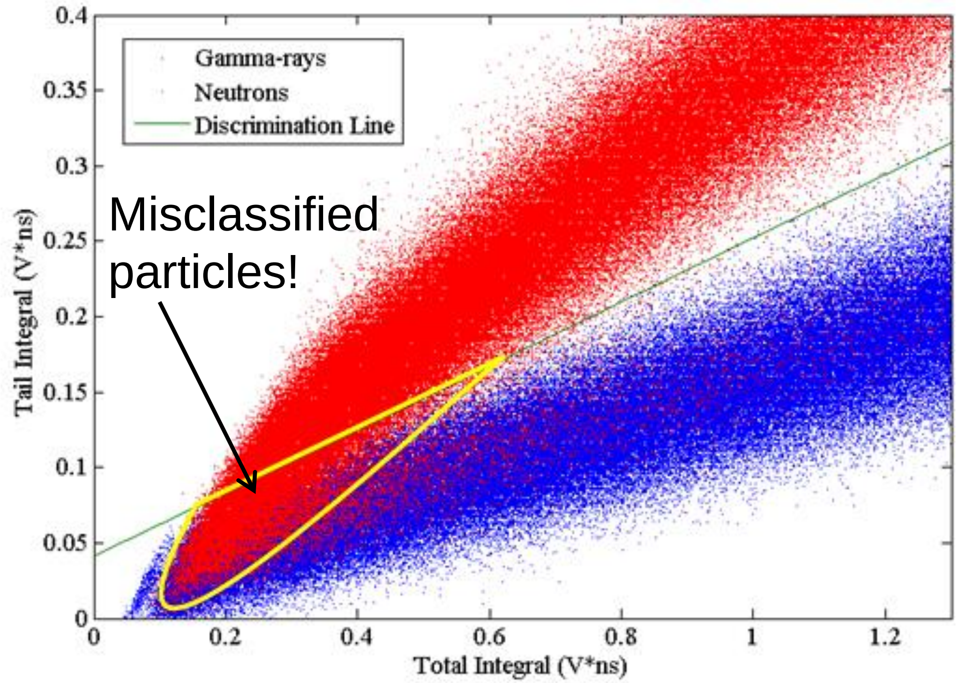
Correlation threshold can be varied to tolerate different error rates

Analysis Algorithms

Digital Pulse Shape Discrimination (PSD)

- Detector pulses are digitized at 250 MHz
- Each pulse is integrated offline and classified by comparison to a discrimination line

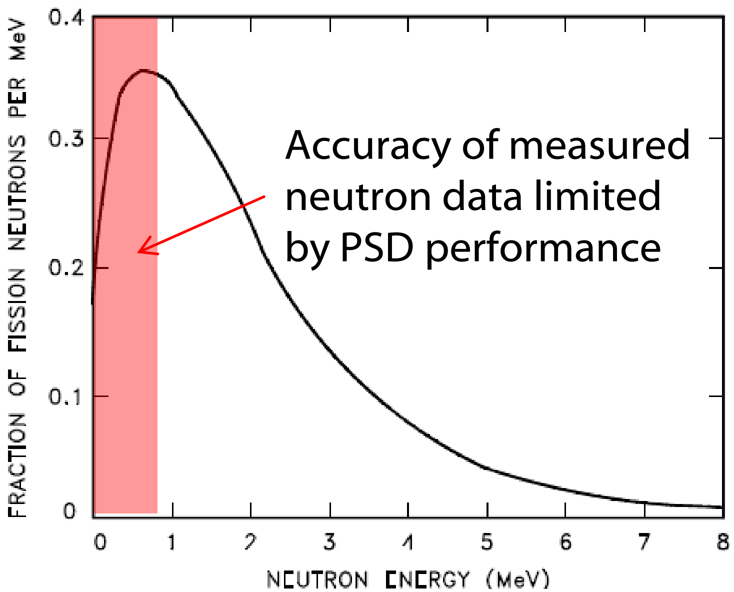


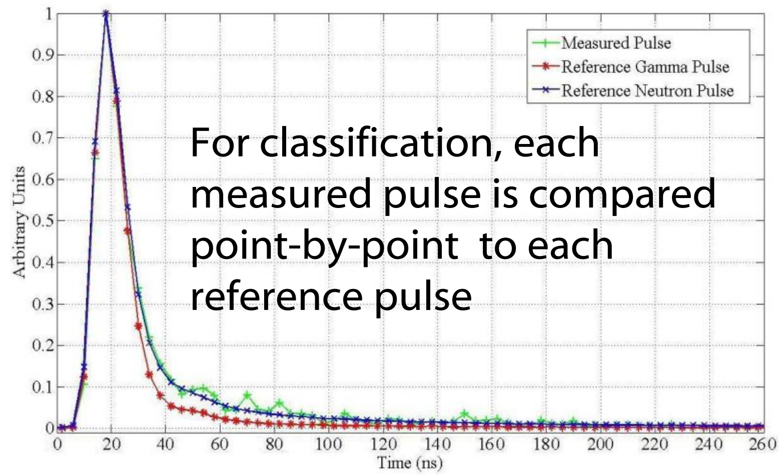


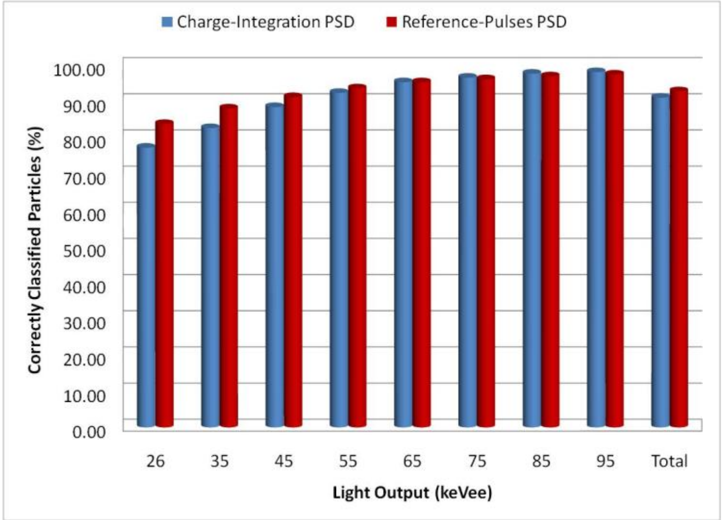
This technique breaks down at low detection thresholds (200-keV neutron energy deposited)

Analysis Algorithms
Reference-Pulses PSD

- To improve low-energy PSD, neutron and gamma-ray reference pulses have been created
- This allows for higher-fidelity measurements of fission spectra





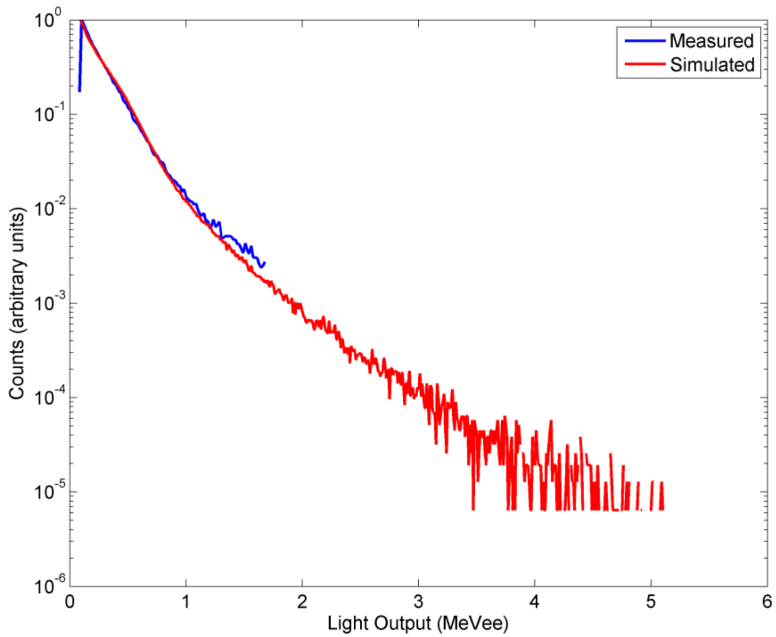


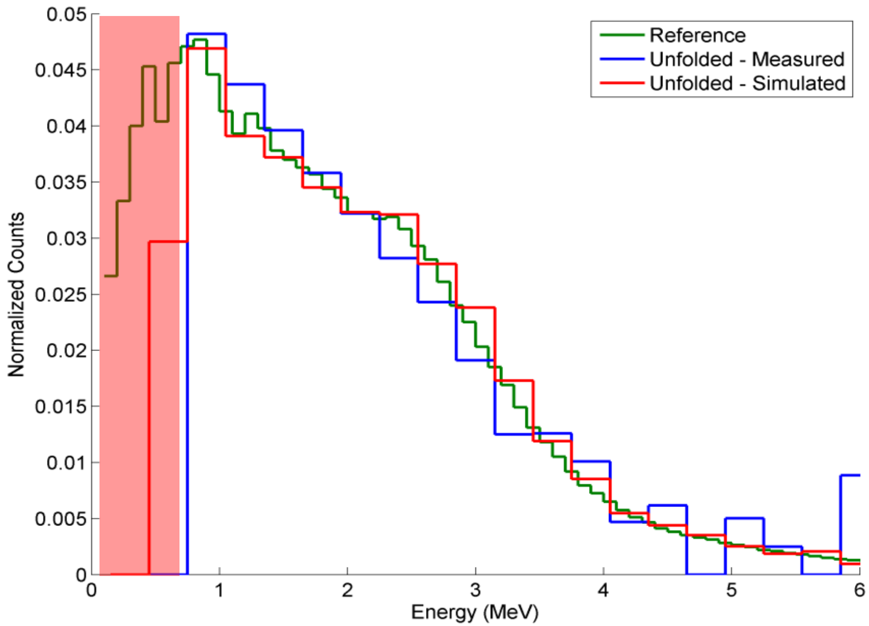
Analysis Algorithms
Neutron Spectrum Unfolding

- Neutron pulse height distributions are related to the neutron energy spectra

$$N(L) = \int R(E_n, L)\Phi(E_n)dE_n$$

- Advanced algorithms are needed to "unfold" the energy spectra

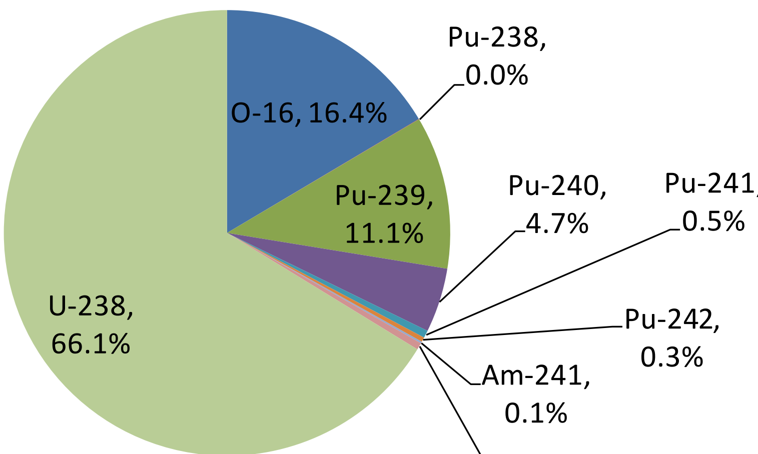




Upcoming Measurement Campaign

Fissile Samples in Ispra, Italy, June 2010

- Measurements of MOX powder (2 kg total mass) will be performed using capture-gated and traditional scintillators as well as ^{3}He tubes
- Cross-correlation, pulse height, and multiplicity data will be acquired

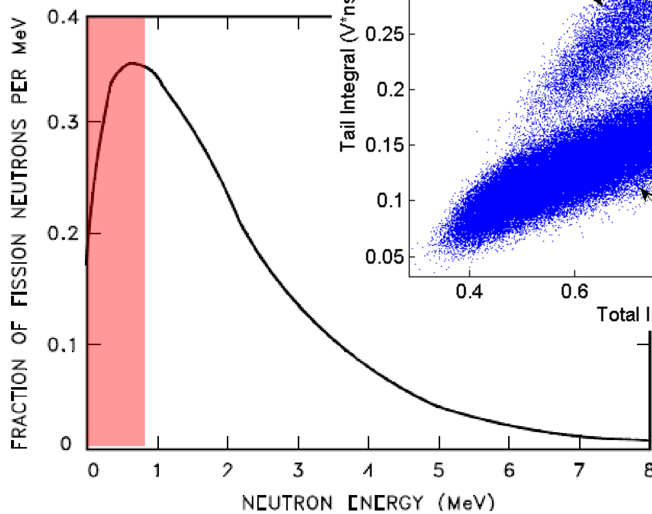


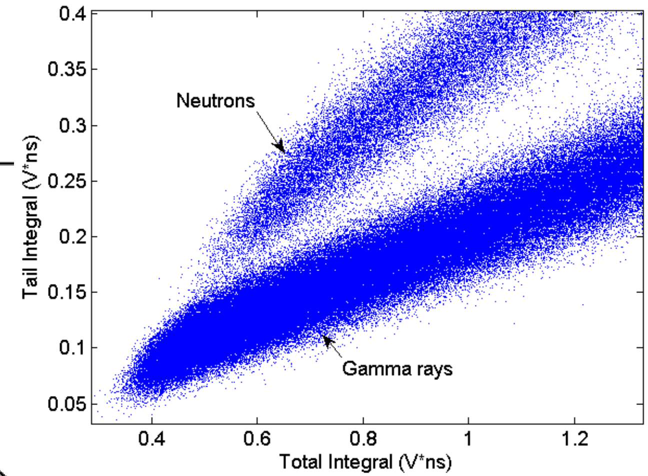
Mass fractions of MOX samples

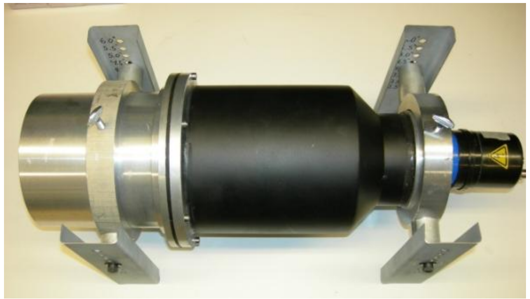
Upcoming Measurement Campaign

Los Alamos LANSCE Facility, July/August 2010

- Previous experiments at LANSCE have measured the fission neutron energy spectrum of ^{235}U and ^{239}Pu above 1 MeV
- A significant fraction of the neutrons from fission lies below 1 MeV – these measurements will extend the data down to approximately 100 keV
- Measurements will be performed using a DNNG-developed digital data-acquisition and pulse-shape-discrimination system







New Courses Available in NERS

- **Detection Techniques for Nuclear Nonproliferation**
  - Nuclear nonproliferation; homeland security
  - Introduction to the physics of nuclear fission
  - Monte Carlo simulations for nuclear nonproliferation applications
  - Passive and active inspection of SNM
  - Detectors and safeguards instruments
- Winter 2008 – 17 students
- Fall 2009 – 19 students

- **Nuclear Safeguards**
- Collaboration with the Oak Ridge National Lab Safeguards Lab user facility
  - History of nuclear safeguards
  - International safeguards policy
  - Nondestructive assay techniques
  - Typical safeguards instruments for neutron and gamma-ray detection
  - Data analysis for nuclear material identification and characterization
- Fall 2009 – 17 students

Summary and Conclusions

- Nuclear nonproliferation and homeland security challenges require the development of new detectors, electronics, and algorithms for SNM detection and characterization
- Our effort at UM is a three-pronged approach to identifying suitable technology: new detectors, new electronics, and new algorithms
  - Several new scintillation detectors have been developed and evaluation is currently underway
  - A scalable electronics platform is being developed: initial tests indicate two-fold improvement in SNM detection probability
  - Cutting-edge analysis algorithms are under development to allow reliable fast neutron spectroscopy for SNM identification and classification

Detection for Nuclear Nonproliferation Group

Department of Nuclear Engineering and Radiological Sciences - University of Michigan
Group Leader: Sara Pozzi

Group Members

- Marek Flaska, Assistant Research Scientist
- Shaun Clarke, Assistant Research Scientist
- Andreas Enqvist, Postdoctoral Researcher
- Eric Miller, Graduate Student
- Jennifer Dolan , Graduate Student
- Shikha Prasad, Graduate Student
- Jeff Katalenich, Graduate Student
- Christopher Lawrence, Graduate Student
- Alexis Poitrasson-Riviere, Graduate Student
- Mark Bourne , Graduate Student
- Bill Walsh, Graduate Student
- 8 Undergraduate Students

Collaborators – National

- Robert Haight, Los Alamos National Laboratory
- Alan Hunt, Idaho Accelerator Center
- Donald Umstadter, University of Nebraska
- Peter Vanier, Brookhaven National Laboratory
- John Mattingly, Sandia National Laboratory
- Andrey Gueorgueiv, ICx Radiation

Collaborators – International

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- Paul Scoullar, Southern Innovation, Australia
- Peter Schillebeeckx, JRC Geel Belgium
- Senada Avdic, University of Tulsa, Bosnia