Correlations in Prompt Neutrons and Gamma Rays from Fission

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Detection for Nuclear Nonproliferation Group

Motivation

- Nuclear nonproliferation and safeguards applications require improved models for physics of nuclear fission and detector response.
- Specifically, the correlated neutron and gamma ray emission properties of important nuclear isotopes such as ^{235}U and ^{239}Pu are not well known. These data are important in nuclear safeguards and nonproliferation.
- A past DOE – NEUP project has led to a successful measurement campaign at LANSCE (2010) for the measurement of the ^{235}U fission neutron spectrum (without information on angular distribution or multiplicity).
- The present work builds on that experience and includes *correlated* information.

The MCNPX-PoliMi Code System

- MCNP-PoliMi was developed to simulate correlation measurements with neutrons and gamma rays
  1. Physics of particle transport (MCNPX-PoliMi code)
     - Built-in correlated sources (^{252}Cf, ^{240}Pu etc.)
       - Multiplicity-dependent energy distribution
       - Light fission fragment direction-dependent neutron flight direction
     - Energy is conserved in each individual collision
     - Prompt neutrons and gamma rays associated with **each event** are modeled explicitly

  ➡ Improved simulation of correlation and multiplicity distributions

  2. Physics of detection (MCNPX-PoliMi Post-Processor, MPPost)
     - MPPost treats **each collision** in the detector individually
     - Transport must be **completely analog**

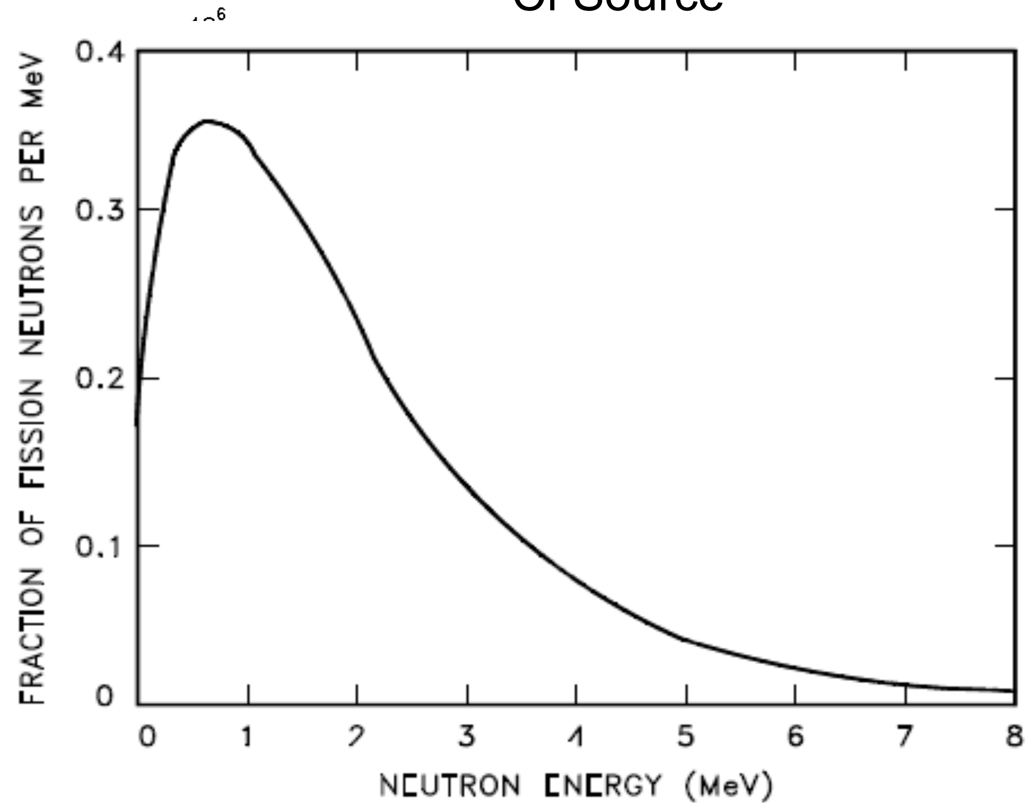
  ➡ Improved simulation of detector response

Spontaneous Fission Sources

Energy Distributions

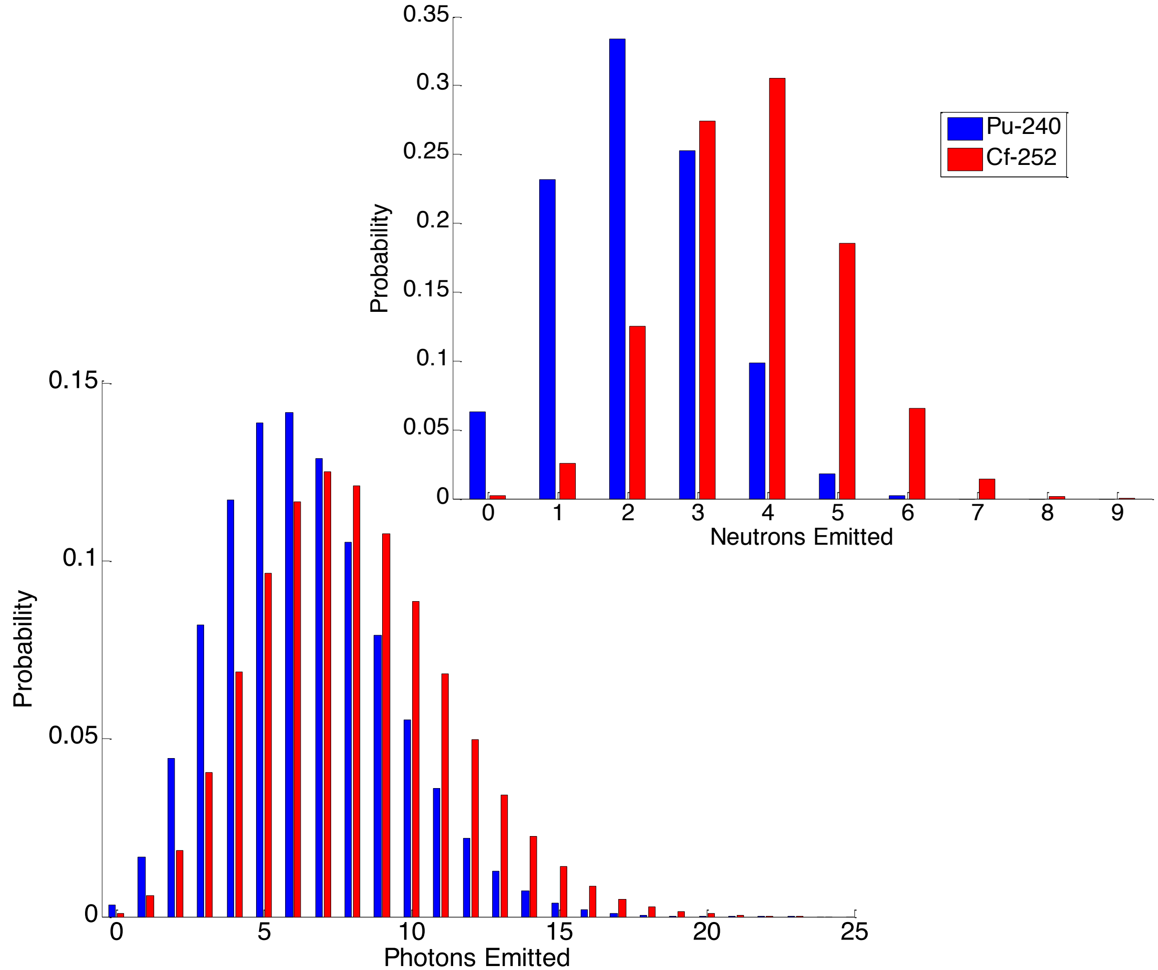
- The energy distributions of spontaneous-fission neutrons and gamma rays are independently sampled
- The data contained in MCNPX-PoliMi are based on results from the literatures. Lemaire, P. Talou, T. Kawano, M.B. Chadwick and D. G. Madland. *Monte-Carlo approach to sequential neutron emission from fission fragments*. Phys. Rev. C 72, 024601 (2005)

^{252}Cf Source



Spontaneous Fission Sources
Multiplicity Distributions

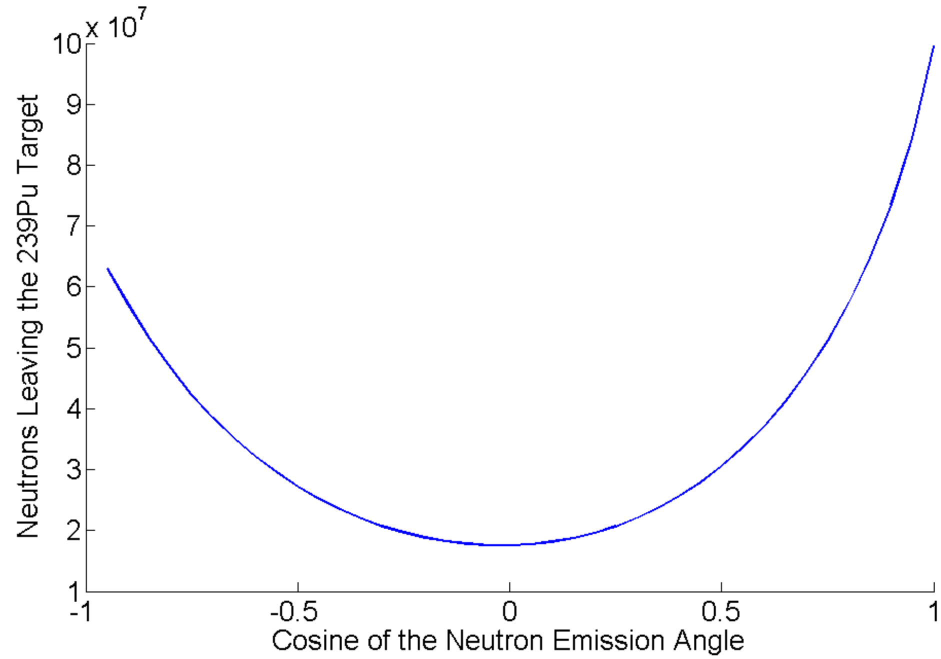
- MCNPX-PoliMi contains complete neutron and gamma-ray multiplicity distributions for each source
- The number of neutrons and gamma rays from each fission event is independently sampled from these distributions



Spontaneous Fission Sources

Angular Distributions

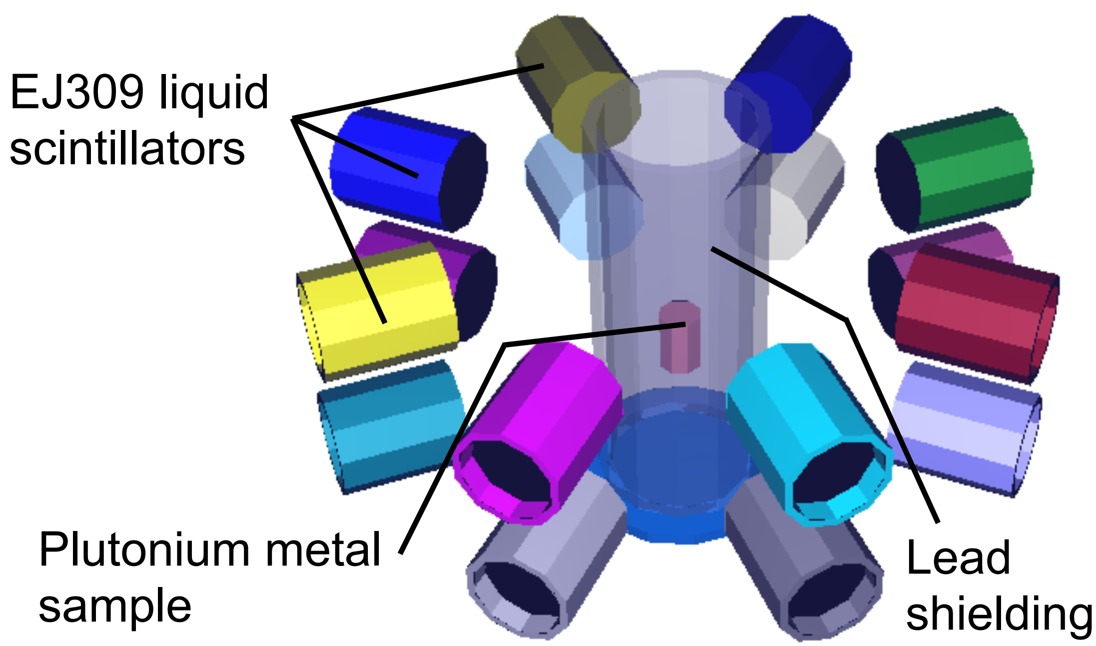
- Anisotropic angular emission of neutrons is available, and recommended for each spontaneous fission source*
- The direction of each particle is sampled independently from any other parameters
- A completely isotropic distribution is available for debugging purposes

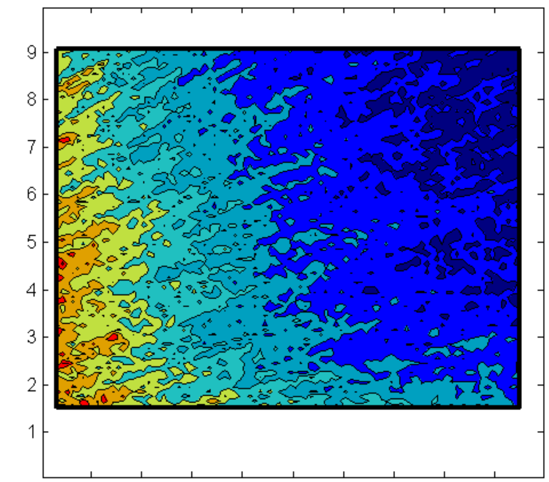


**T. Valentine, "MCNP-DSP Users Manual," ORNL/TM-13334,R2 (2001).*

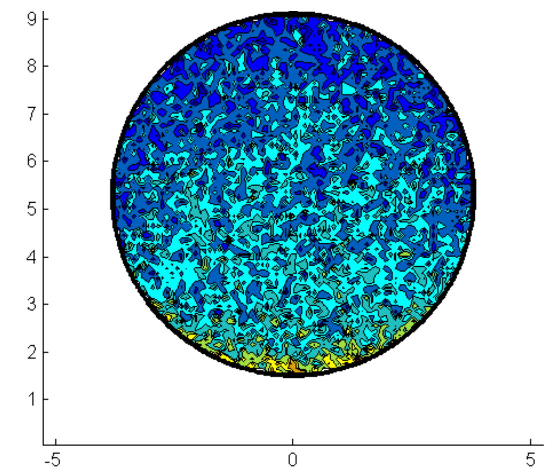
Spontaneous Fission Measurements
Pu Metal Samples at JRC, Ispra

- A prototype fast-neutron multiplicity counter was tested at JRC, Ispra in 2013
- 1.63 g of $^{240}Pu_{eff}$ was measured with 1-cm of lead shielding and a 70 keVee threshold



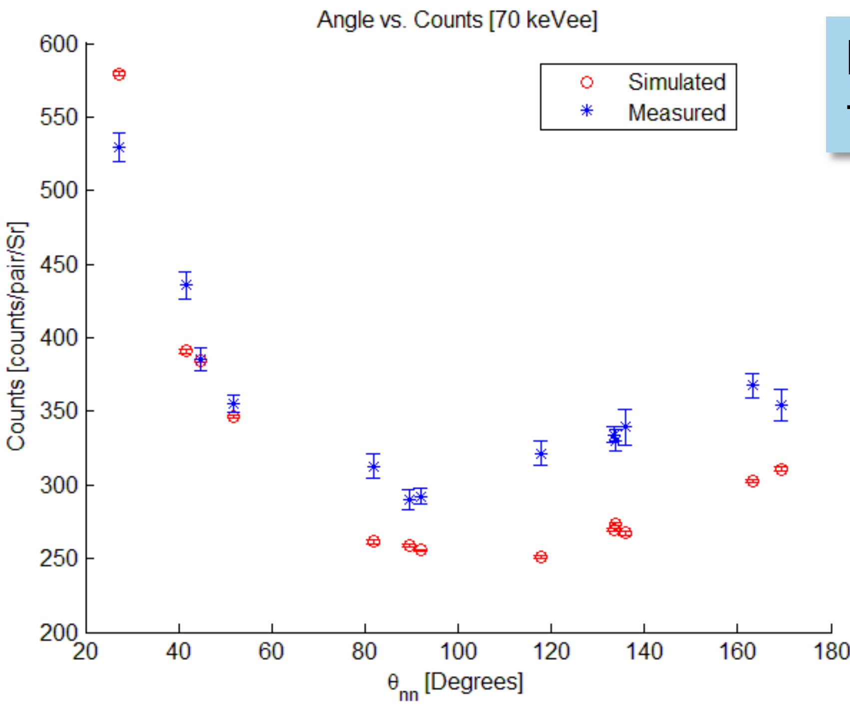


Neutron flux in the detectors

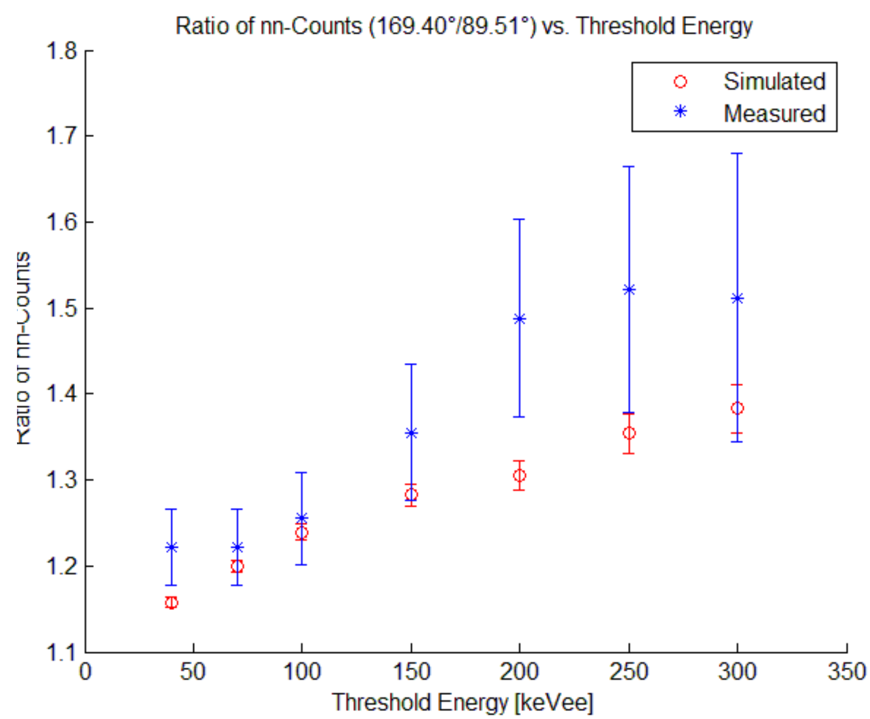


Pu Measurements at JRC-Ispra

Comparison of Results



Fission-source anisotropy is clearly visible in the simulation and the measurement

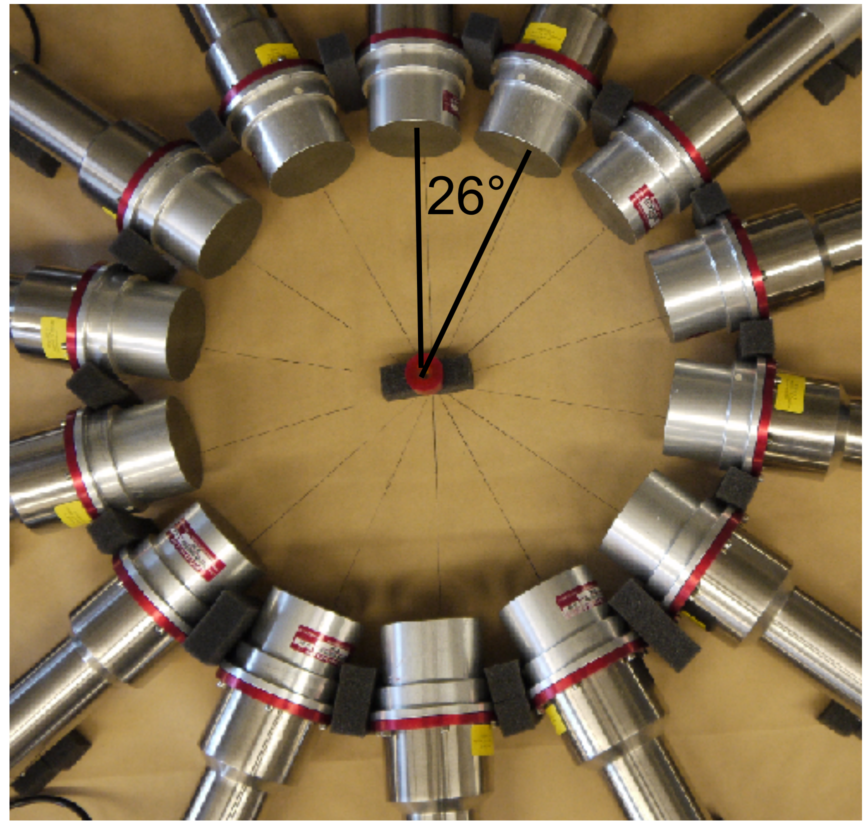


Increasing the detection threshold increases the observed anisotropy

Spontaneous Fission Measurements

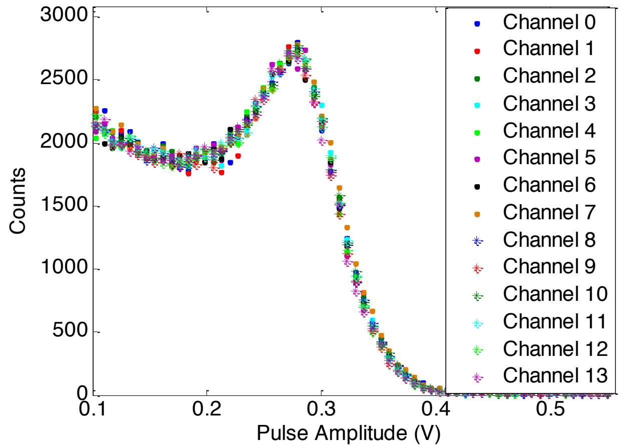
^{252}Cf at University of Michigan

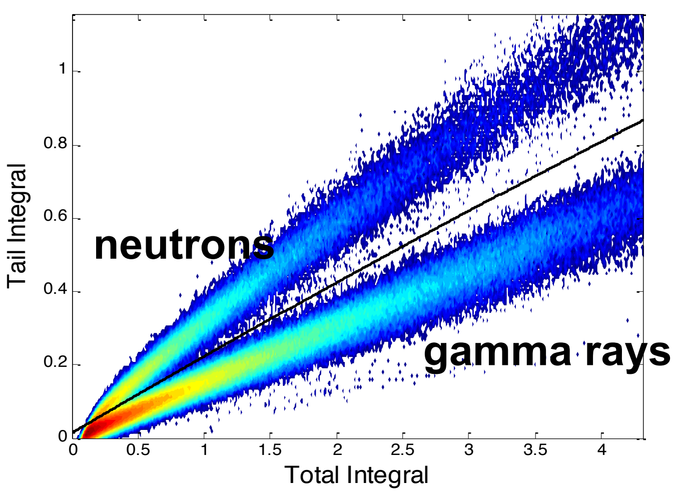
- 14 3x2 inch EJ309 liquid scintillation detectors at a distance of 20 cm, separated by ~26° with a detection threshold of 40 keVee
- A 47 µCi (54000 fissions/sec) ^{252}Cf source was used
- 2 CAEN V1720 12-bit, 250-MHz waveform digitizers



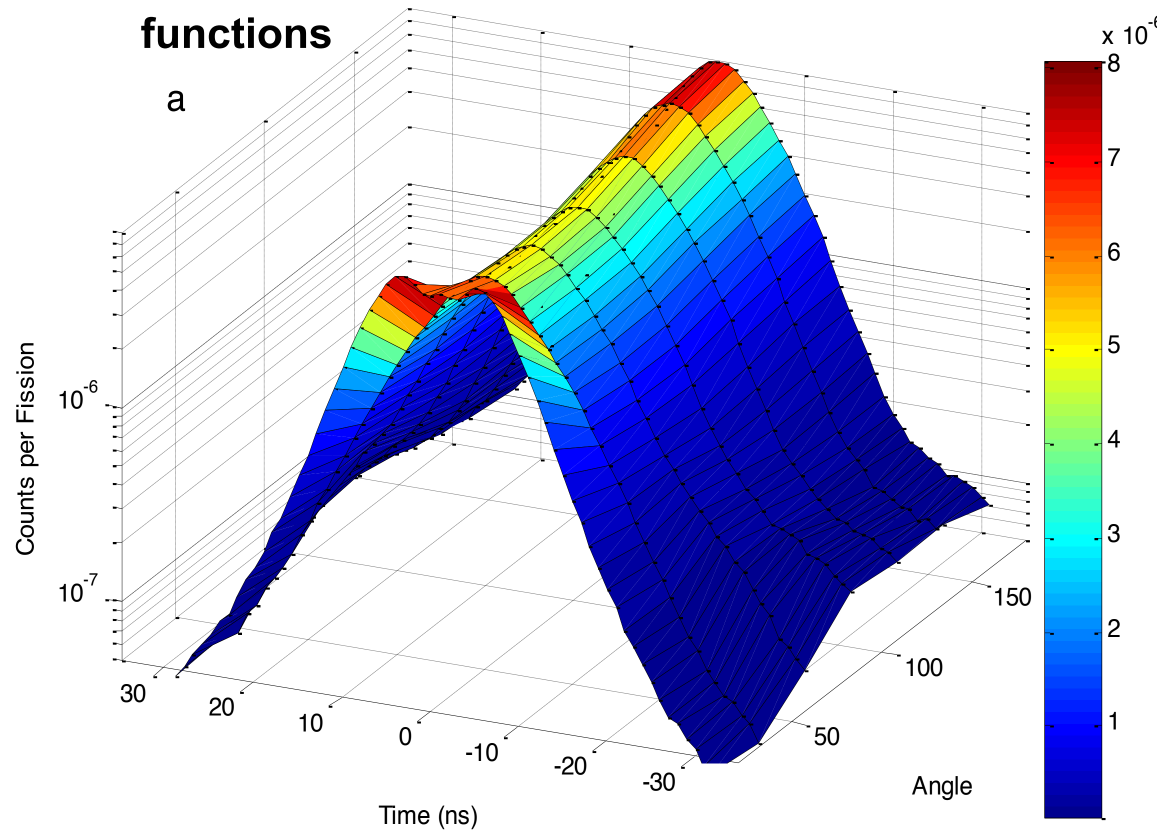
^{252}Cf Measurements at UM

Results





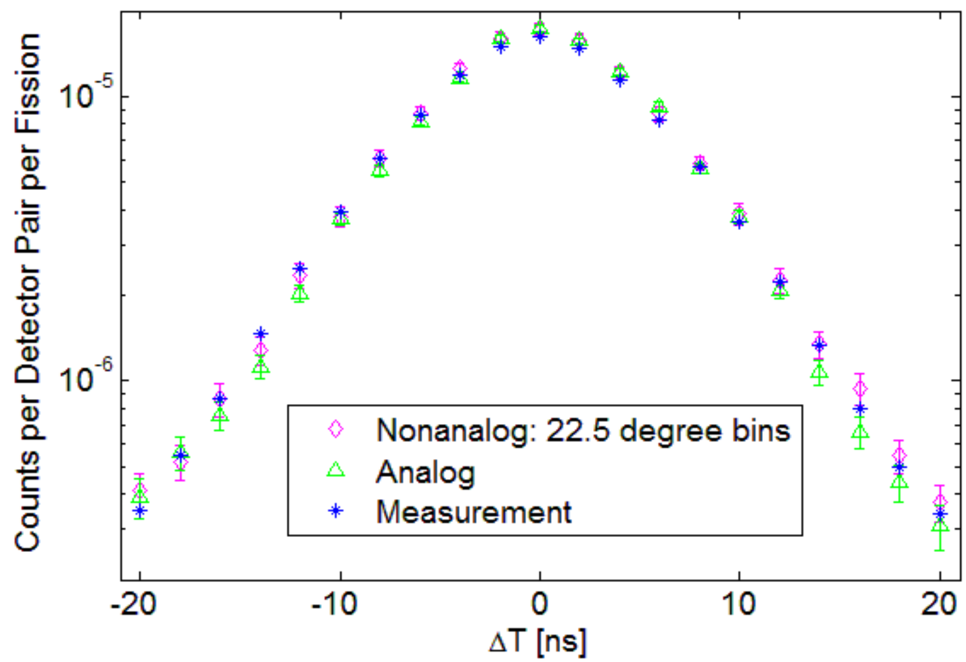
- **Neutron-neutron cross-correlation functions**



S. A. Pozzi, B. Wieger, A. Enqvist, S. D. Clarke, M. Flaska, M. Marcath, E. Larsen, R. C. Haight, and E. Padovani, Correlated Neutron Emissions from Cf-252, accepted for publication on *Nuclear Science and Engineering*

^{252}Cf Measurements at UM
Neutron-neutron Correlations at 180 deg.

- Very good agreement between measurement and simulation.
- Non-analog treatment improves simulation efficiency.



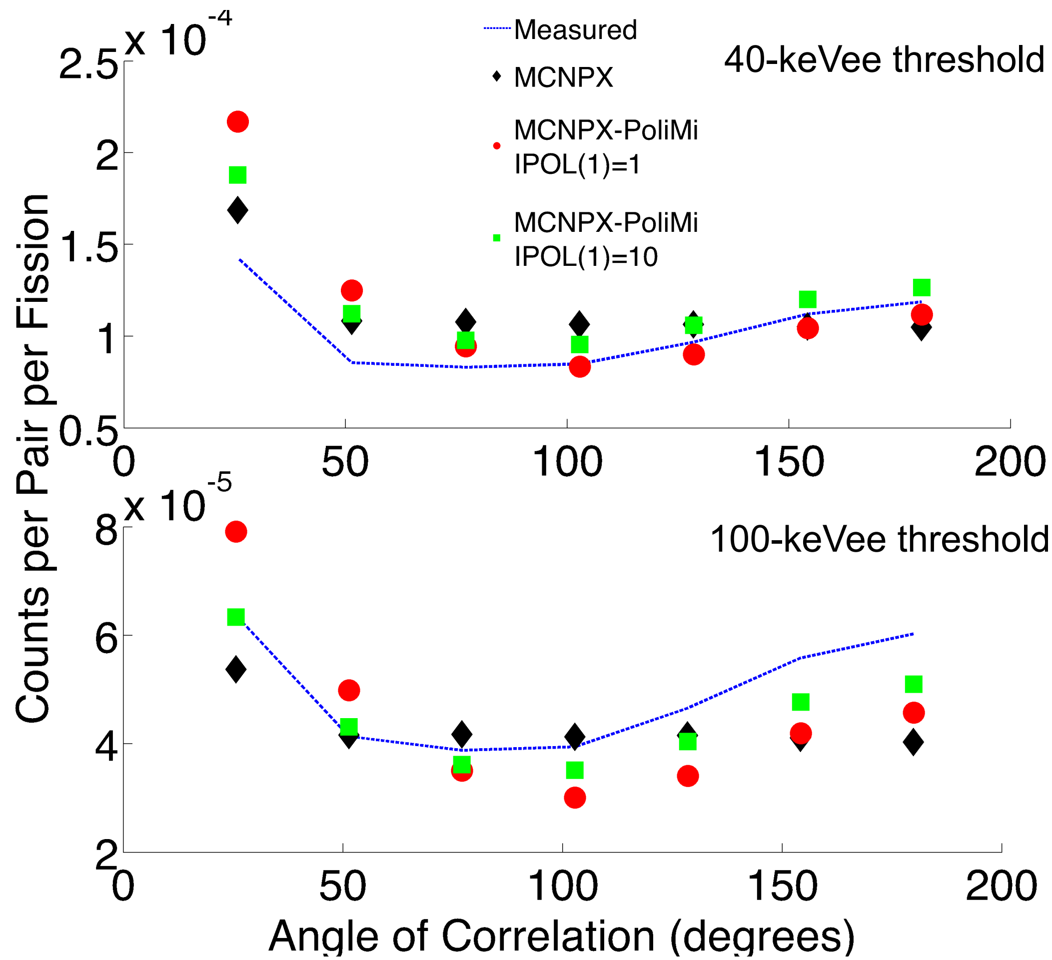
M. J. Marcath, S. D. Clarke, B. M. Weiger, E. W. Larsen, S. A. Pozzi, "An Implicit Correlation Method for Cross-Correlation Sampling, with MCNPX-PoliMi Validation," *Nuclear Science and Engineering*, submitted July 2014.

^{252}Cf Measurements at UM

Number-angle Correlations

- All MCNPX-PoliMi treatments more physical than the standard MCNPX treatment

IPOL(1)	Energy Distribution
1	Neutron multiplicity-dependent spectrum
10	Watt spectrum

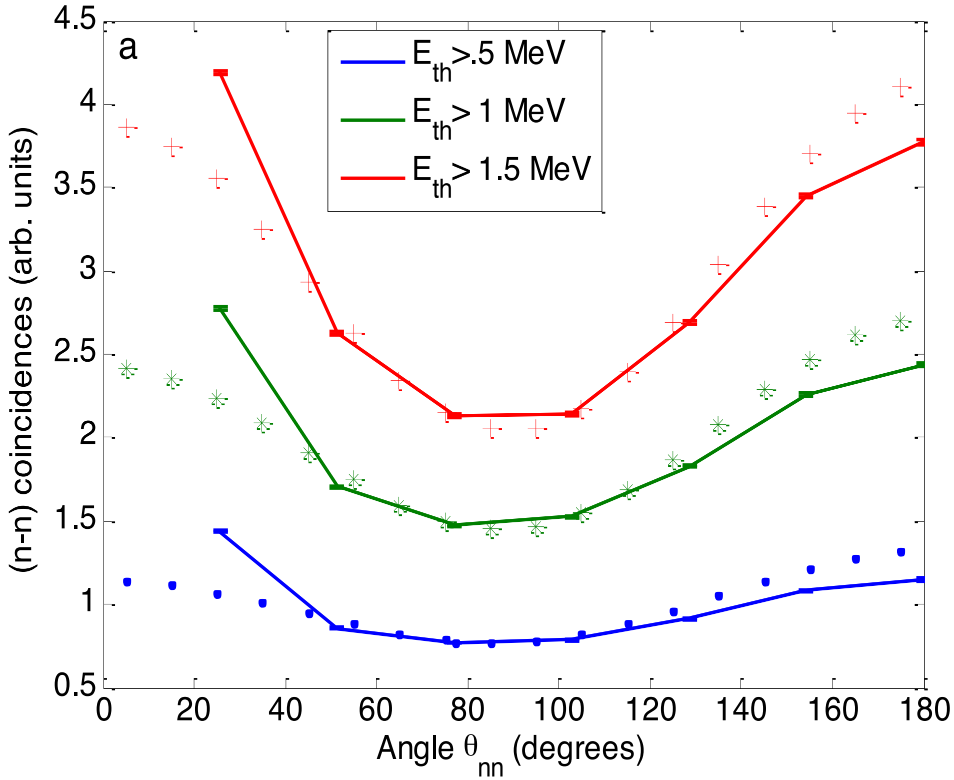


^{252}Cf Measurements at UM

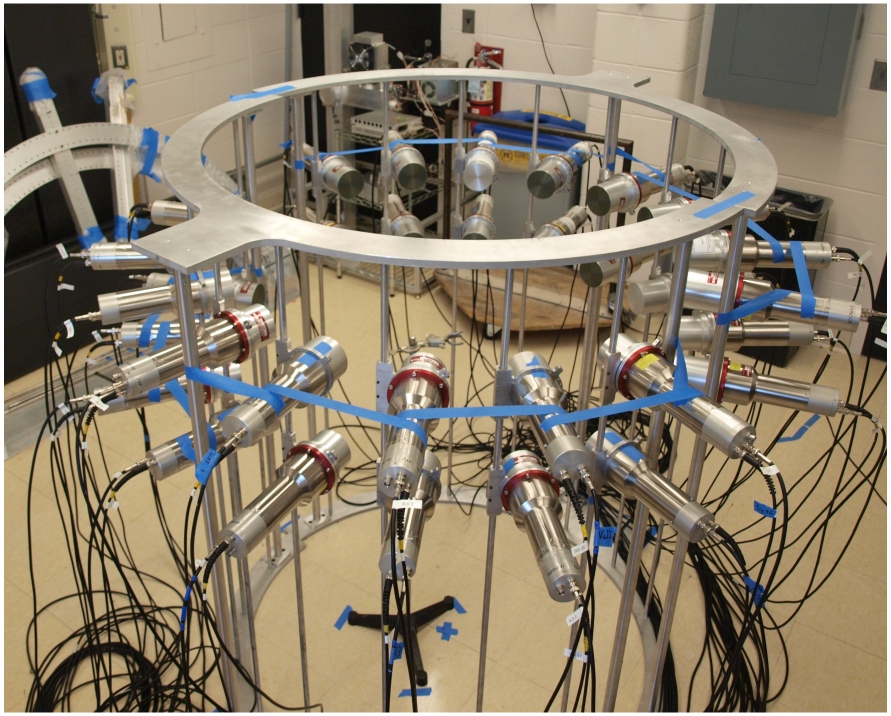
Comparison with Theory

- Measured – this work – (solid line) neutron-neutron correlated counts as a function of angle between detectors

- Compared to theory results from LLNL/LBNL using FREYA (symbols) (Vogt and Randrup)



Neutron-Gamma-ray Correlations
Scintillator Array at University of Michigan

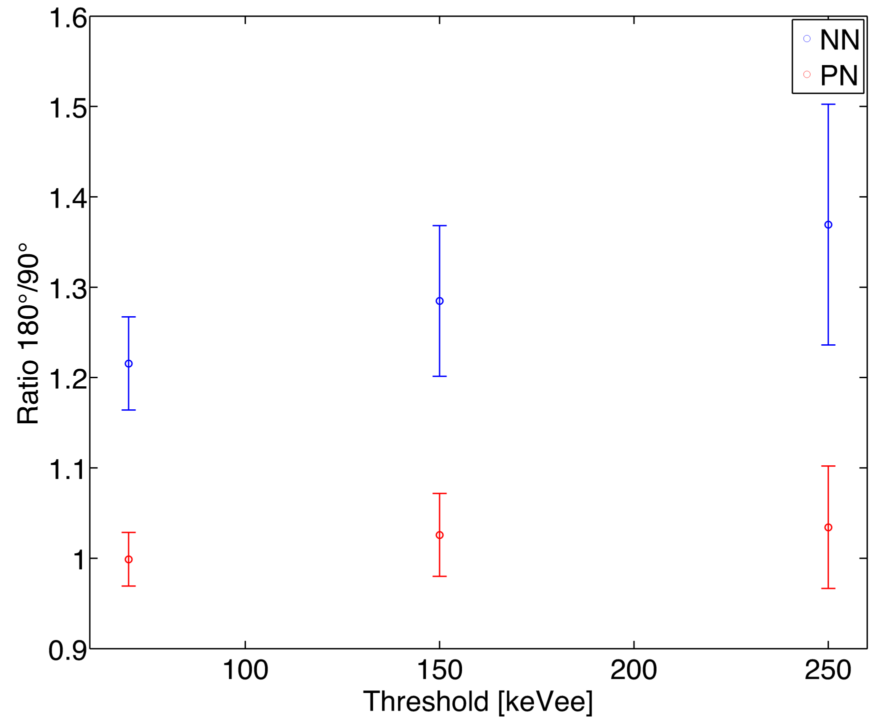


Neutron-Gamma-ray Correlations

Results

- Neutron-neutron correlations show an increasing trend with detection threhold
- Photon-neutron correlations show no trend with detection threshold
- Approximately 3 hrs of data have been processed

Detectors	EJ309 7.62x7.62cm EJ309 7.62x7.62cm	
Detector angle [degrees]	97	141
n-n [cts/pair]	1472	1789
n-γ [cts/pair]	3374	3316
γ−n [cts/pair]	3407	3404
γ-γ[cts/pair]	8666	8177



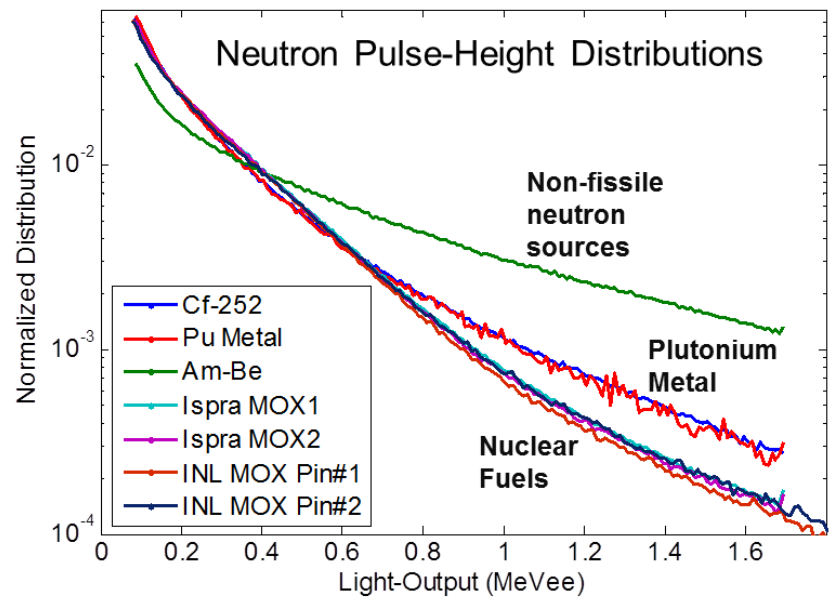
Summary and Conclusions

- New measurements of correlated, prompt emissions from ^{252}Cf and ^{240}Pu have been performed
  - Neutron-neutron, neutron-gamma ray correlations
  - Experimental results used to validate codes: MCNPX-PoliMi treatments are more physical than the standard MCNPX treatment
- New fission models have been implemented in MCNPX PoliMi
  - Anisotropic neutron emission from fission
  - Multiplicity-dependent neutron energy spectra
- Further development is underway to develop a comprehensive model that is more physical
  - MCNPX-PoliMi Short Course at IEEE-NSS on November 9

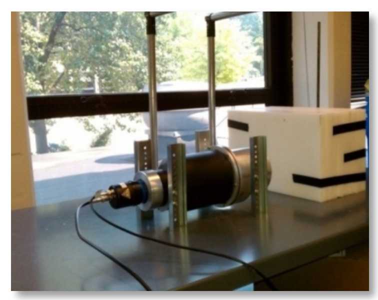
Extra slides

Detecting SNM Signatures
Organic Scintillation Detectors

- Organic scintillators have several advantages for detecting SNM signatures
  - Nanosecond-scale response times
  - Response is proportional to the energy deposited
  - Good intrinsic efficiency
  - Pulse shape discrimination
  - Good scalability and low cost
- Light is produced as incident particles interact with the scintillation material
  - Compton scattering on electrons
  - Elastic scattering on hydrogen and carbon

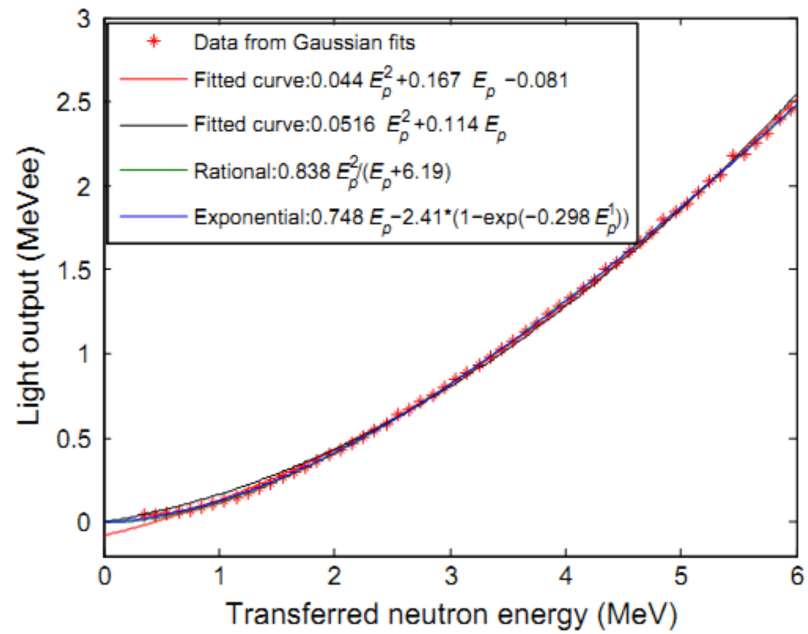


* Measurements performed by Jennifer Dolan at INL(2009) and ISPRA (2010)



Detector Response Simulation
Organic Scintillation Detectors

- The energy deposited by a particle, T, must be calculated for *each individual collision*
- The energy deposited in each collision is converted into light output, L, using measured relationships
- Energy deposition to light conversion is a *nonlinear* process for neutrons and must take place individually for all collisions
  - Order of collision matters: carbon-hydrogen or hydrogen-carbon
- A light pulses is a sum of several light flashes produced within a pulse generation time



A. Enqvist, C. C. Lawrence, B. M. Wieger, S. A. Pozzi, T. N. Massey. *Neutron Light Output Response and Resolution Functions in EJ-309 Liquid Scintillation Detectors*, Nucl. Instr. Meth. A 715, 79 (2013).