Event-by-Event Neutron and Photon Multiplicity Correlations in Nuclear Fission

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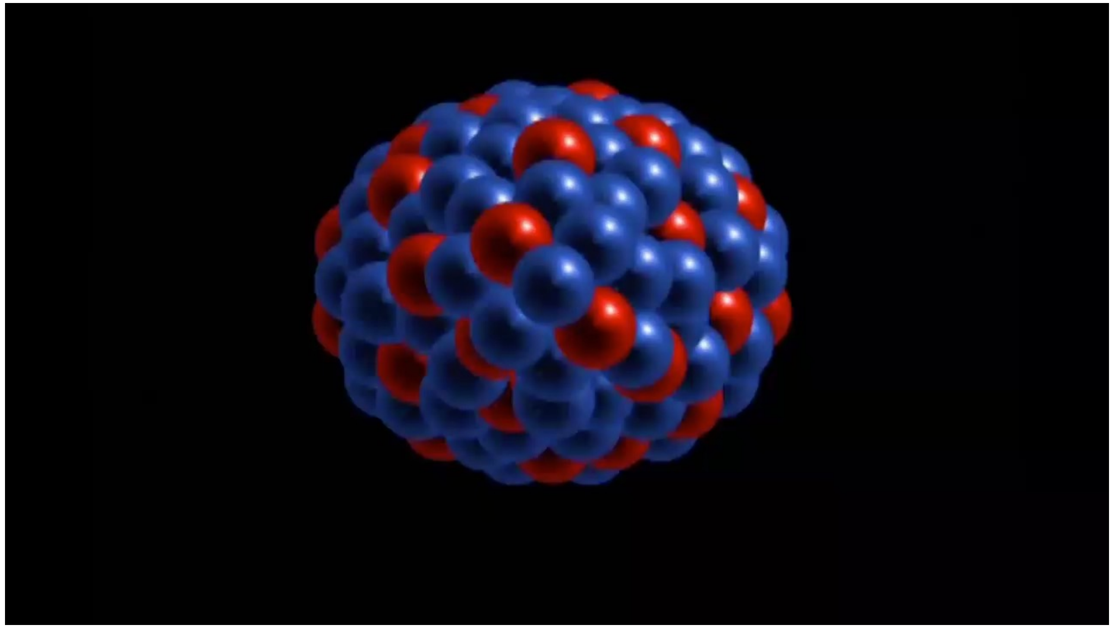
Introduction and Motivation

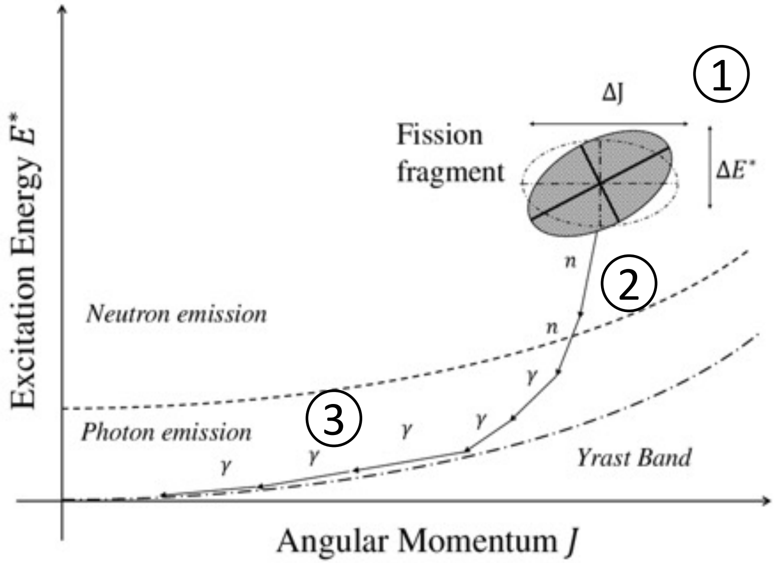
- We investigate the physics of fission fragment formation and excitation; these processes lead to the observed correlated neutron-gamma emission

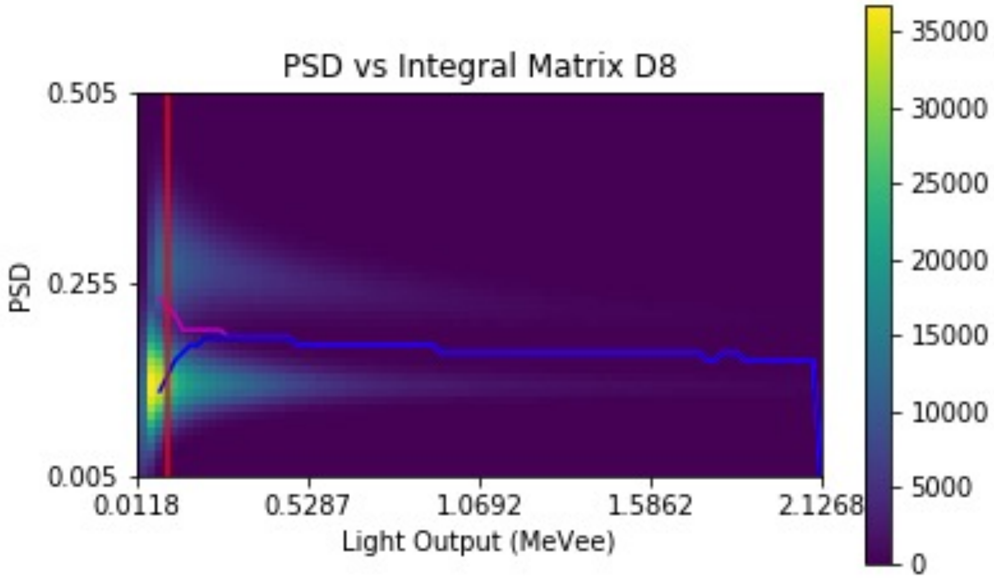
- Development and improvement of theoretical models of fission for scientific and technical applications



Technical Approach

- Organic scintillators provide neutron-gamma detection capability, and excellent discrimination
- Analyze neutron-gamma correlations, and their dependence on the full space of the problem
- We employ theoretical models and radiation transport codes to quantify the results of our measurements

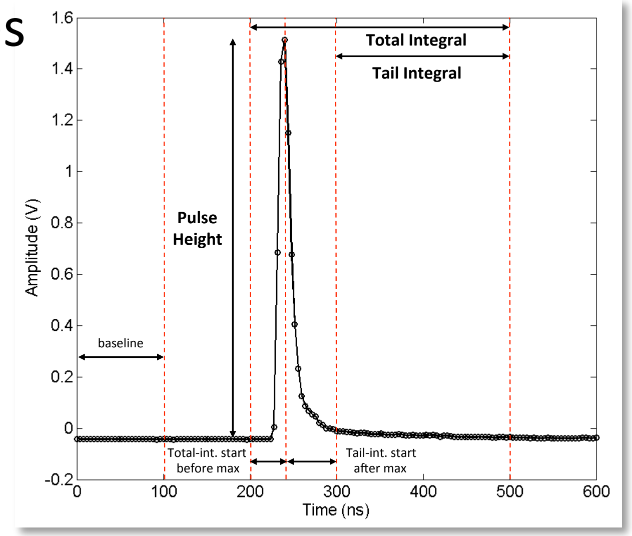




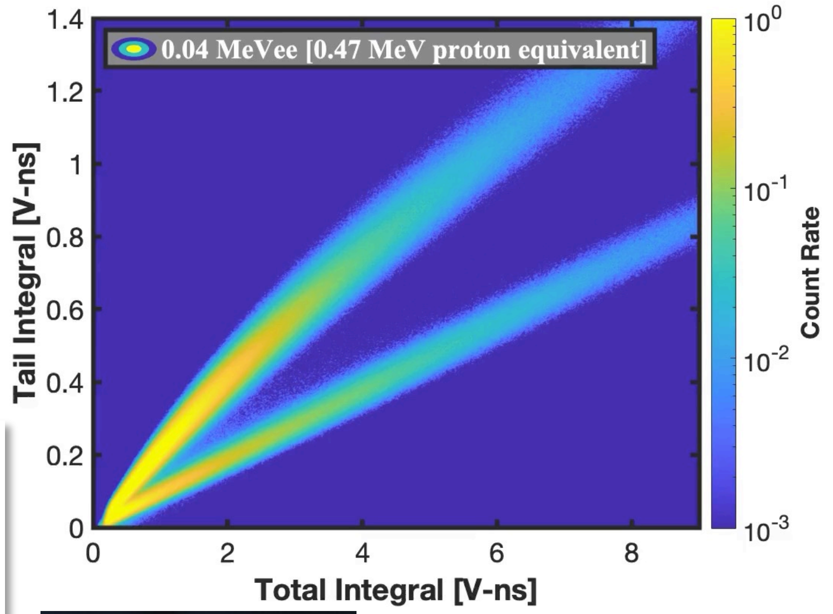
Organic Scintillation Detectors

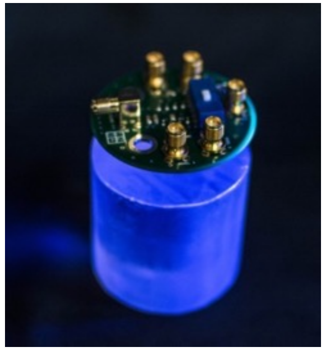
General Characteristics

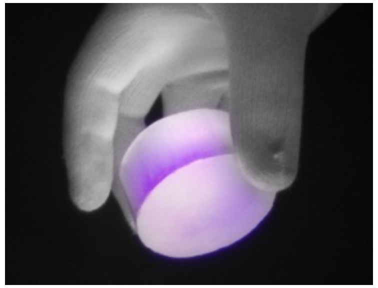
- Benchmark experiments based on organic scintillator systems could provide data in an expanded energy range
- Organic scintillators have several advantages for detecting neutrons and gamma rays
  - Nanosecond-scale response times
  - Response is proportional to the energy deposited
  - Good intrinsic efficiency
  - Pulse shape discrimination
  - Good scalability and low cost



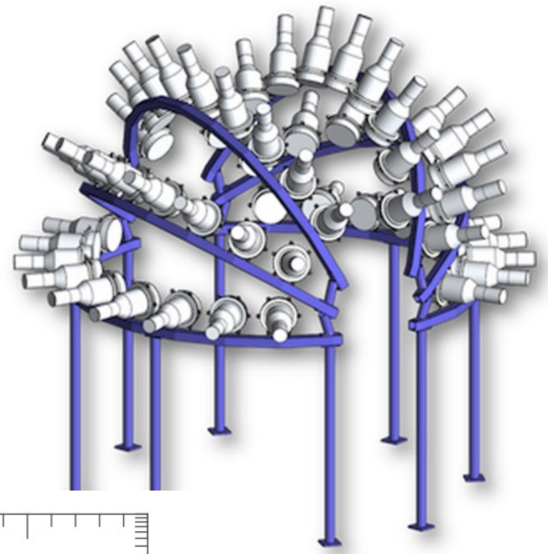
Shielded ^{252}Cf source measured with a 5 cm x 5 cm stilbene cylinder detector



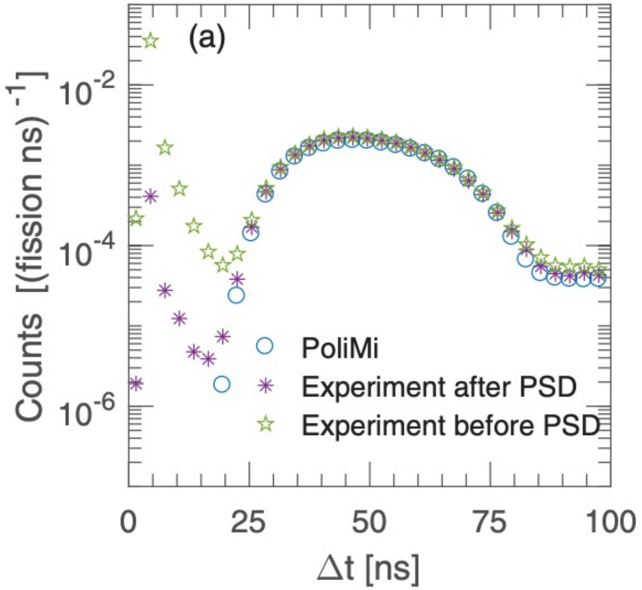




Chi-Nu ^{252}Cf(sf) Experiment at Los Alamos National Lab, LANSCE



- The Chi-Nu array at LANSCE consists of 54 liquid organic scintillation detectors
- An ionization chamber was used to create coincidences between the measured radiation and fission reactions
- We have used the large flight path from source to detector to determine the spectra of neutrons
- We have analyzed the data to understand the impact of the system response on observables



M. J. Marcath et al. “Measured and simulated ^{252}Cf(sf) prompt neutron-photon competition”, Phys. Rev. C **97**, 044622 (2018)

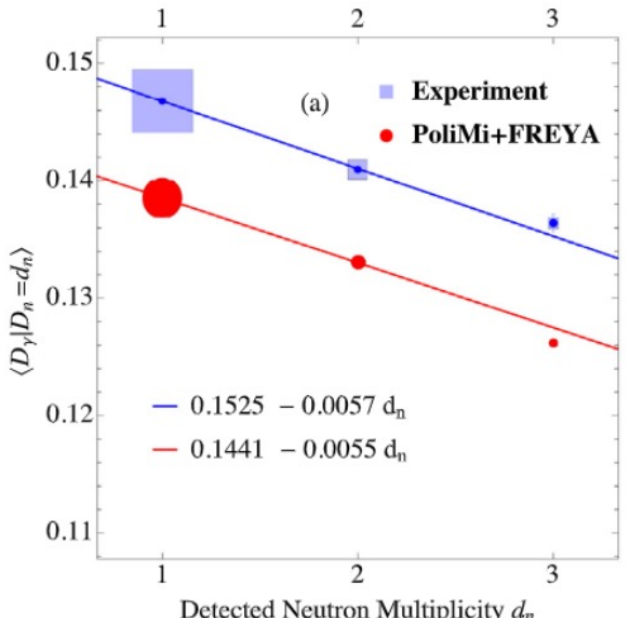
Neutron-Photon Correlations

- Analytic unfolding techniques were developed to address systematic biases in the experimental data
- We have surveyed and resolved inconsistencies in the literature regarding neutron-photon correlations in fission
- Experimental data shows that, averaged over all energies and directions, neutron-photon emission is negatively correlated

Table 2
Summary of the discussion of Section 4. For each of the reported values, both model based calculations and experimental determinations, we provide our determination of the corrected covariance.

Determination	$cov(N_n, N_\gamma)$
CGMF [7,8]	-0.839 ± 0.004
FREYA [9–13]	-0.8200 ± 0.0004
Glässel et al. [4,14]	-0.71 ± 0.17
Bleuel et al. [5]	-0.69 ± 0.10
Marcath et al. [6]	-0.58 ± 0.06[a]

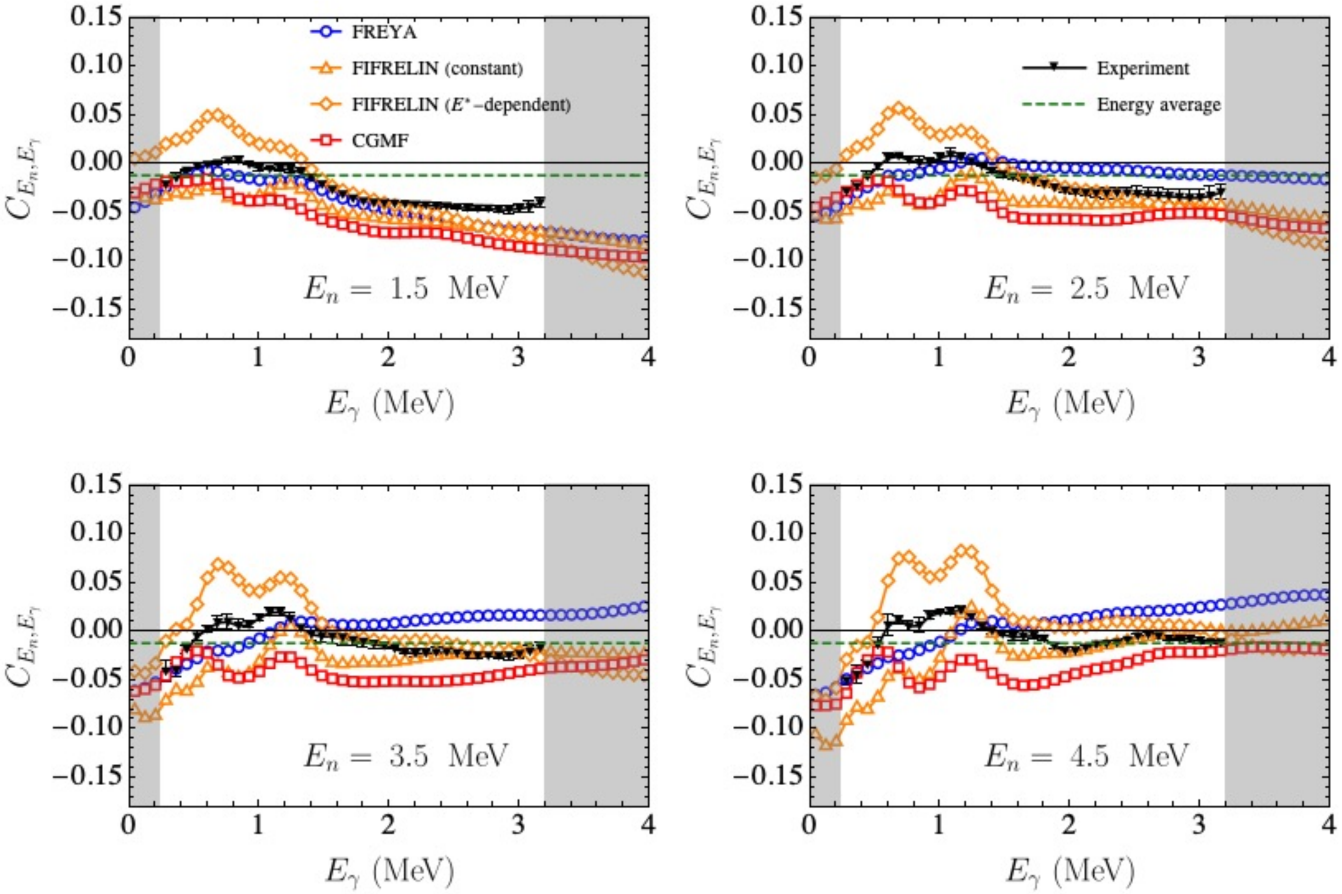
[a]Energy sensitivity considerations show that this result is also in quantitative agreement with FREYA.



S. Marin *et al.* "Event-by-Event Neutron-Photon Multiplicity Correlations in 252Cf(sf)", NIM-A **968**, 163907 (2020).

Energy-Dependent Neutron-Photon Correlations

- The normalized neutron-gamma covariance C_{E_n,E_γ} quantifies multiplicity correlations
- We observe structure with respect to C_{E_n,E_γ} averaged over all energies (green dashed line)
- The experimental data (black markers) feature positive correlation enhancements at gamma energies of 0.7 and 1.2 MeV

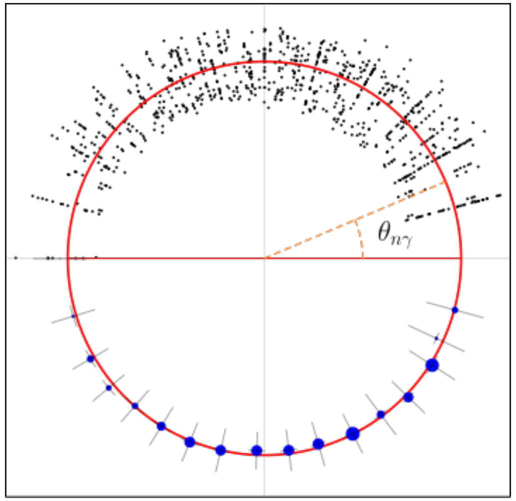


S. Marin *et al.* "Structure in the Event-by-Event Energy-Dependent Neutron-Gamma Multiplicity Correlations in 252Cf(sf)", *submitted to Phys. Rev. C* (2021) available at arxiv.org/abs/2104.06166

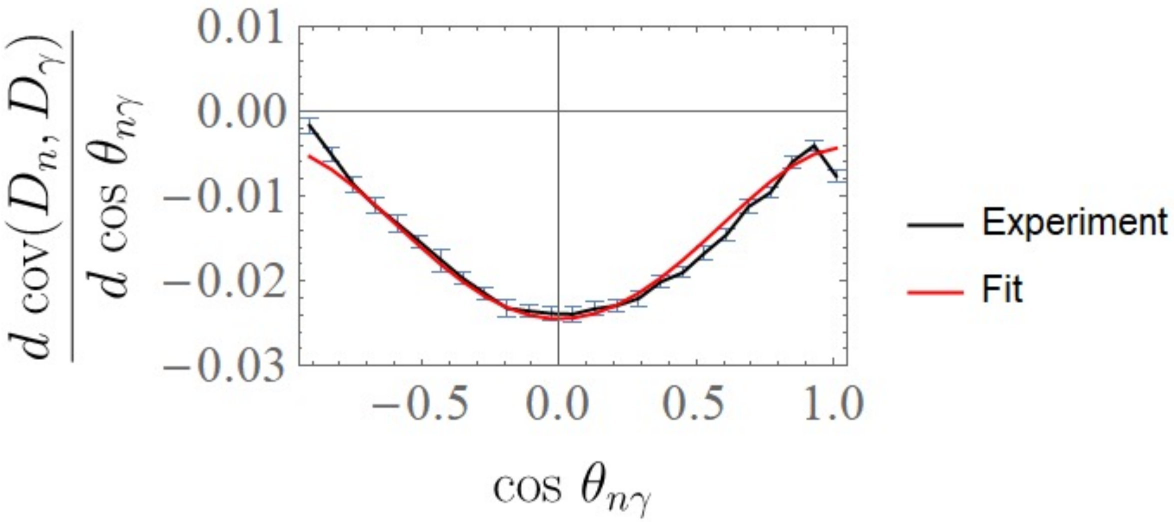
Momentum-Dependent Neutron-Photon Correlations

- Dependence of the neutron-photon multiplicity covariance on the particle energies and the angle between particles

- Overall multiplicity covariance is negative and strongest when the neutron and photon make 90° with each other



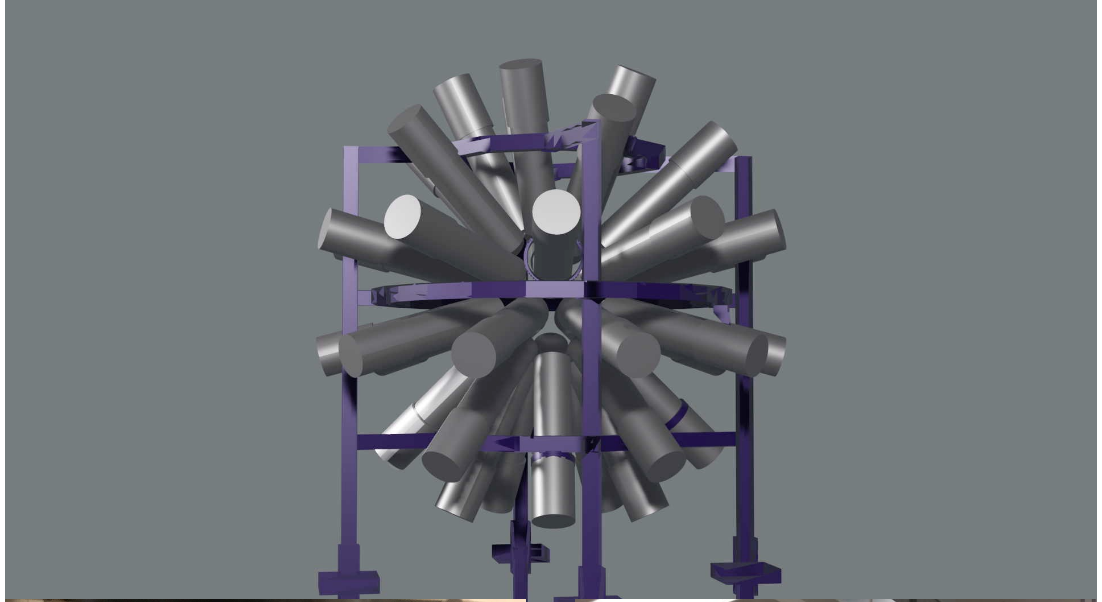
Detector doubles efficiencies at various neutron photon angles

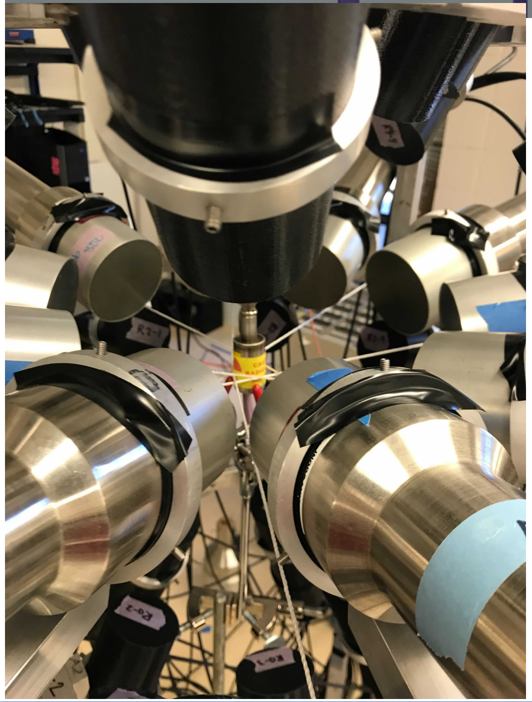


Dependence of neutron-photon multiplicity covariance on the NP-angle

Fission Sphere 3 (FS3) Detection Array

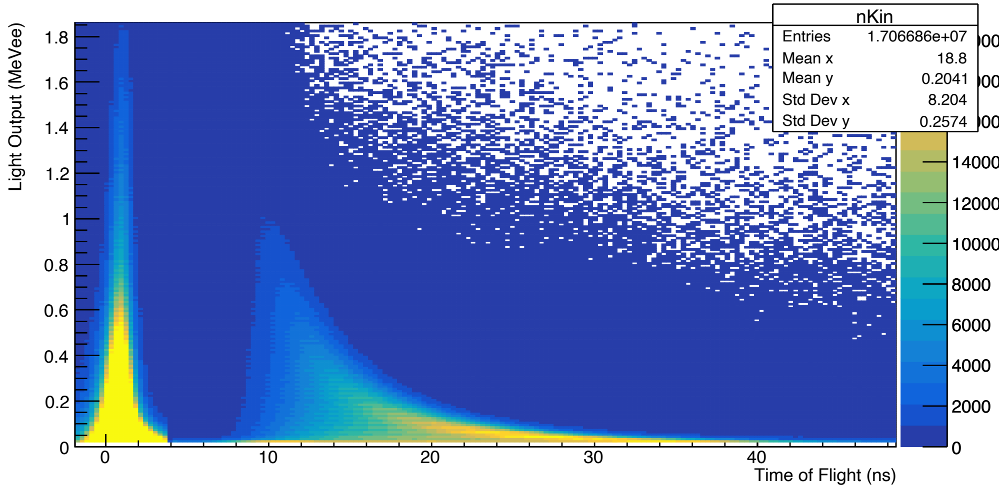
- 40 stilbene 2″Ø×2″ stilbene organic scintillation detectors, in spherical configuration
- Variable distance to source, 12 cm to 25cm
  Efficiency 15% to 4%
- Sensitive to neutrons > 0.3 MeV and gamma rays through Compton interaction
- Experiments in coincidence with ionization chambers for fission fragment trigger





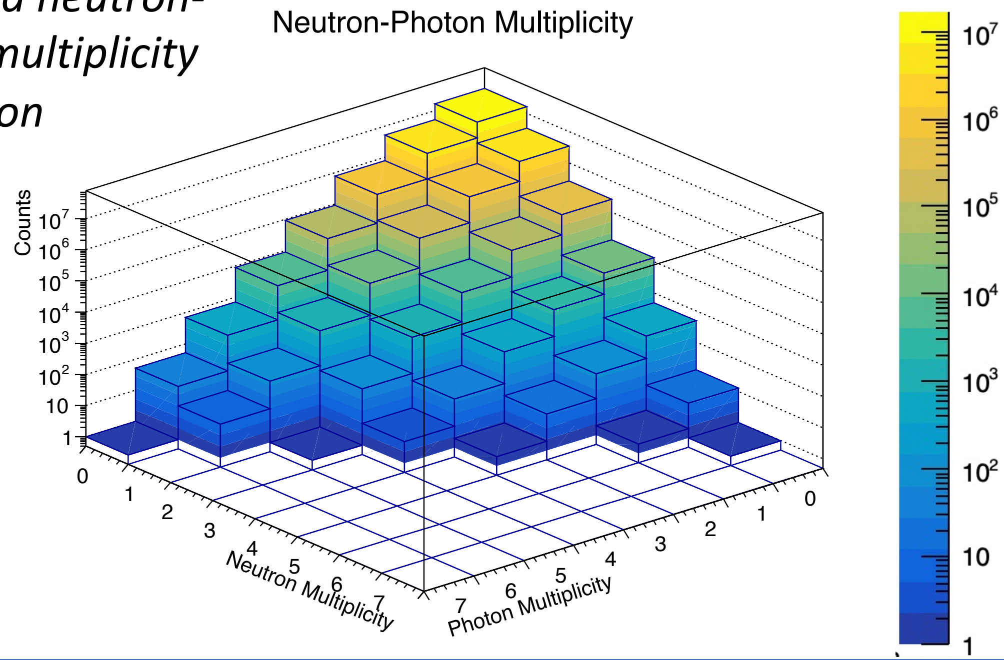
Neutron Detection Using FS3

Kinematic plots for neutron-gamma detection



- The excellent timing capabilities of the FS-3 stilbene detectors allow us to perform ToF spectroscopy and neutron-gamma separation

Correlated neutron-gamma multiplicity distribution



- We determine the correlated event-by-event neutron-gamma multiplicity distribution to understand emission competitions in fission

- We are assessing systematic biases and plan to combine this system with gamma-ray spectrometers and ion detectors

Expected Impact

- We continuously interact with theoretical groups in the United States and abroad to ensure that the experimental results improve our understanding of the fission process
- The signatures we have inspected are sometimes unique to the fission process and can be used to identify SNM
- Application involving induced fission will help us understand the propagation of these correlations in macroscopic objects

Conclusion and Next Steps

- The characteristic emission of neutrons and gamma rays accompanying fission is important for scientific and technological goals

- We are collaborating with Argonne National Laboratory to measure the neutron-gamma emission in coincidence with the kinematic properties of fission fragment

- We are always looking for ways to collaborate on the analysis or experimental side of the research

Acknowledgements

The Consortium for Monitoring, Technology, and Verification would like to thank the NNSA and DOE 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