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Prompt Neutron and Gamma-ray Correlations from Cf-252 Spontaneous Fission

Matthew J. Marcath, Angela Di Fulvio, Tony H. Shin, Shaun D. Clarke, Edward W. Larsen, Enrico Padovani, Robert C. Haight, and Sara A. Pozzi

Abstract— New event-by-event fission models have prompt neutron and gamma-rays that are correlated in time, energy, and multiplicity, however there is limited measurement data available to validate these models. Measurement of high-order fission neutron and gamma-ray coincidences is difficult and there has previously been little motivation to measure properties of both particle types simultaneously. High-order Cf-252 spontaneous fission neutron and gamma-ray coincidences were measured with an array of 24 liquid organic and eight sodium iodide scintillation detectors. Measured coincidence data including neutron time-of-flight energy and measured gamma-ray pulse height distributions are compared with MCNPX-PoliMi simulation results from built-in and event-by-event fission models.

I. BACKGROUND

THE physics community is motivated to improve the theory of prompt neutron and gamma-ray emission, particularly to characterize correlation between those particles. Improved understanding of prompt fission emissions could lead to new safeguards and verification measurement techniques. Many studies of prompt emissions have already been done, exclusive to one particle type; however this work seeks to characterize the correlation between Cf-252 spontaneous fission neutrons and gamma-rays.

II. METHODS

An array of 14 - 7.62x7.62 cm EJ-309's, 8 - 7.62x5.08 cm EJ-309's, and 8 - 7.62x7.62 cm sodium iodide (NaI(Tl)) scintillators coupled to photomultiplier tubes were used to measure neutrons and gamma-rays from Cf-252 spontaneous fission. The array in Figure 1 had a flightpath of 51 cm for all detectors with the spontaneous fission source at the center axis of the array between the detector planes.

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Figure 1: A model of the detector holder and 32 detectors.

Approximately 70 billion fissions were observed from a 38,000 fission/s Cf-252 source and approximately half of the collected data is analyzed to date. Pulses from the detectors were digitized using four CAEN V1720 waveform digitizers with 250 MHz sampling and 12 bit amplitude resolution over a 2 V range. The detectors were gain matched to 478 keVee at 0.3 V with a threshold of 40 keVee. All digitized waveforms were recorded for post-processing. Pulse shape discrimination was used to discriminate between neutron and gamma-ray detection in the liquid organic scintillators [1]. A quadratic line is used to discriminate particle type, shown in Figure 2. At low pulse heights, pulse shape discrimination becomes challenging and is subject to misclassification.

Figure 2: Pulse tail integral to total pulse integral heat map with neutron-gamma-ray discrimination line. Approximately 200,000 waveforms are represented in the figure.

After post-processing of waveforms including pulse shape discrimination, coincident detections using a 200 ns window

were collected. The coincident detections were analyzed to produce pulse height, cross-correlation, multiplicity, and time-of-flight neutron energy distributions. The distributions can be compared to simulated results with various fission models.

MCNPX-PoliMi was used to simulate the measurement and MPPost was used to analyze data to replicate detector response [2]. Simulated MCNPX-PoliMi results using the built-in Cf-252 spontaneous fission model, the CGMF model [4], and the FREYA model [5] are compared to measured results.

III. RESULTS

Figure 3 shows MCNPX-PoliMi simulated pulse height histograms for each fission model compared with the measured result for . The neutron pulse height distributions in Figure 3a compare well with the measured distribution. Differences between the distributions are most prominent pulse heights above 1500 keVee (equivalent to a single neutron scatter on a proton depositing 4.1 MeV). The measured gamma-ray pulse height histogram does not agree well with the simulated distributions in Figure 3b. The simulated source only included Cf-252 spontaneous fission gamma-rays; all other gamma-ray sources are uncorrelated with the neutron source component and were thus ignored. A Compton recoil edge is visible near 300 keVee from a 388 keV Cf-249 characteristic gamma-ray.

Figure 3: Pulse height histograms from both measured and MCNPX-PoliMi simulated results are shown for neutrons (a) and gamma-rays (b).

Figure 4 shows MCNPX-PoliMi simulated cross-correlation distributions that agree well with measured distributions. Agreement in the cross-correlation distribution demonstrates basic validation of the simulation detector array model and post-processing methods.

Figure 4: Cross-correlation distributions of neutron-neutron, neutron-gamma, gamma-neutron, and gamma-gamma coincidences for both measured (stars) and simulated (lines). One standard deviation statistical uncertainty error bars are smaller than the markers in the peak of the distributions.

The average number of gamma-rays observed in coincidence with zero through four neutrons is shown in Figure 5 for simulated and measured results. The detector array has a poor solid angle relative to the source resulting in low average observed coincidences. Simulation and measurement results agree up to two neutrons in coincidence. At four neutron coincidences the average detected number of gamma-rays the measured and built-in PoliMi models agree and the CGMF and FREYA models under-predict measurement.

Figure 5: Average gamma-ray coincidences as a function of neutron coincidences for measured and MCNPX-PoliMi simulated results.

In Figure 6, the average number of neutrons detected in coincidence as a function of gamma-ray coincidences shows that the measured and simulated results agree only up to one neutron in coincidence. All models over-predict above a one gamma-ray coincidence event. The pulse height histogram shows that the simulated results over-predict at high energy and this may manifest in the coincidence data as well.

Figure 6: Average neutron coincidences as a function of gamma-ray coincidences for measured and MCNPX-PoliMi simulated results.

Neutron energy was estimated from time-of-flight where the start signal was a gamma-ray detection. This time-of-flight method assumes that the detected gamma-ray was a prompt emission from fission. The measurement system was sensitive to and able to resolve approximately 1 to 7 MeV neutrons. The

time-of-flight neutron energy and coincidence data were used to compute the average neutron energy in Tables I and II.

In Table I, as the number of coincidences increases, the measured average neutron energy remains constant within uncertainty in the measured data set. The CGMF and FREYA models show a slight increase in average neutron energy with an increase in the number of gamma-rays observed in coincidence. The built-in PoliMi models under-predict neutron energy whereas the CGMF and FREYA models over-predict neutron energies.

Table I: Average measured neutron energy over the sensitive range of the detectors, 1.1-6.6 MeV, as a function of gamma-rays detected in coincidence. Omitted entries had insufficient data.

γ Coincidences			Fission Model		CGMF	FREYA
	Energy [MeV]	Measured	PoliMi 1	PoliMi 10		
0		2.475(2)	2.344(2)	2.359(2)	3.27(7)	3.2(1)
1		2.48(1)	2.411(9)	2.42(1)	3.7(2)	3.6(3)
2		2.49(6)	2.45(4)	2.46(5)	3.5(8)	-
3		2.4(4)	2.5(3)	2.3(2)	-	-

In Table II, as the number of neutrons observed in coincidence increases the measured and simulated average neutron energy remain constant within uncertainty. Again, the built-in PoliMi models under-predict neutron energy whereas the CGMF and FREYA models over-predict neutron energies.

Table II: Average measured neutron energy over the sensitive range of the detectors, 1.1-6.6 MeV, as a function of neutrons detected in coincidence. Omitted entries had insufficient data.

n Coincidences			Fission Model		CGMF	FREYA
	Energy [MeV]	Measured	PoliMi 1	PoliMi 10		
1		2.475(2)	2.347(2)	2.361(2)	3.31(7)	3.2(1)
2		2.52(1)	2.359(9)	2.40(1)	3.4(2)	3.5(3)
3		2.51(9)	2.34(6)	2.41(6)	-	-
4		2.4(9)	2.3(5)	2.4(5)	-	-

IV. CONCLUSION

Increasingly detailed and complex event-by-event fission treatments are being developed to more accurately represent the fission process, including neutron and gamma-ray correlations. The liquid organic and NaI(Tl) array successfully measured high-order Cf-252 spontaneous fission prompt neutron and gamma-ray correlated quantities. Neutron time-of-flight data was analyzed to find average neutron energy correlated data distributions and other correlated quantities. With MCNPX-PoliMi simulations, these fission model neutron and gamma-ray correlations are compared with measured Cf-252 spontaneous fission data.

Cross-correlation and pulse height distributions for measured and simulated results agree well, except for gamma-ray pulse height distributions due to non-fission gamma-ray sources present in measurement that were not modeled. Trends in the number of particles detected in coincidence compare well with measured data, however all models over-predicted the average number of neutrons detected in coincidence with more than one gamma-ray. No significant trend in neutron energy was observed with the number of particles detected in coincidence. Built-in PoliMi models under-predict neutron energy whereas the CGMF and FREYA models over-predict neutron energies for this measurement geometry. Future work should seek to increase sensitivity to high order correlations while maintaining neutron time-of-flight ability to better discriminate between fission models.

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