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Title: Correlated Fission Multiplicity Model Verification Efforts in MCNP6

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Correlated Fission Multiplicity Model Verification Efforts in MCNP6

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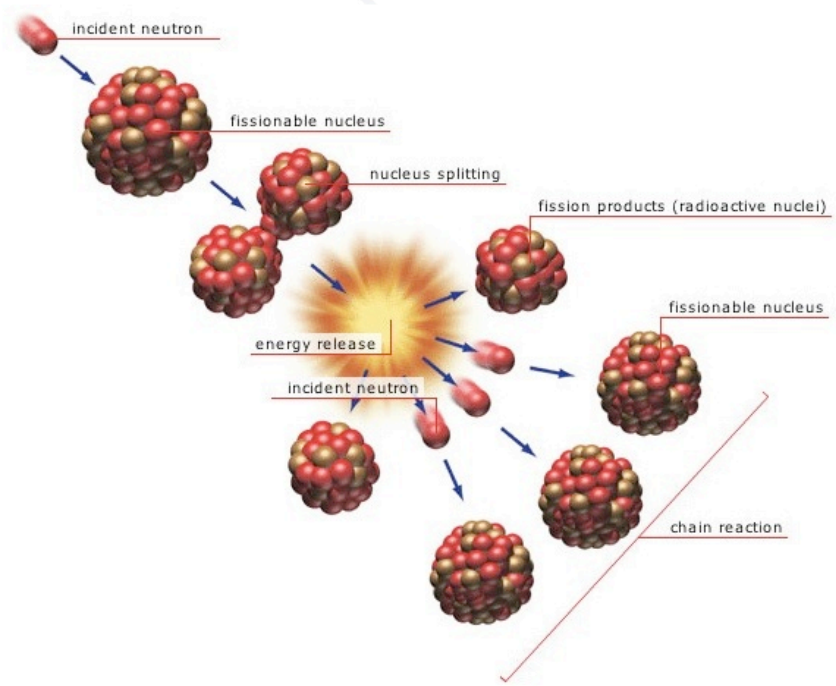


Introduction

- Application of interest
  - Global security and nuclear nonproliferation
  - Detection of special nuclear material (SNM)
  - Warhead measurement campaign (WMC)
  - Passive and active interrogation techniques
  - Coincident neutron and photon leakage

- Key issues
  - Average nuclear data quantities are insufficient
  - Cannot predict correlated signatures of shielded SNM
- Approach to obtain predictive capability
  - Use transport code MCNP for modeling neutrons and photons
  - Need microscopic fission event information
  - Fission event generators are under development
  - Implement in MCNP and compare to experiments

Background

- In tabulated nuclear data libraries (i.e. ENDF/B-VII.1):
  - Average secondary neutron and photon information can be available
    - Average multiplicity, $\bar{\nu}$
    - Average spectrum, $\chi(E)$
    - Average energy-angle spectrum, $\chi(E,\theta)$
  - Generally, high-dimensional distributions of secondary particles are unavailable
    - Multiplicity distribution, $P(\nu)$
    - Multiplicity-dependent emission spectra, $\chi(\nu,E)$
    - Multiplicity-dependent energy-angle emission spectra, $\chi(\nu,E,\theta)$
    - Neutron-neutron, neutron-photon and photon-photon correlations
    - Too much data to measure, evaluate and tabulate!
- Default MCNP uses average quantities
  - In some cases, consider this a nuclear data “variance reduction” technique
  - Good for integral quantities, like flux and effective multiplication
  - Bad for studying detailed particle emission physics

Multiplicity Options

- MCNP6.1.1 contains two (low-energy) event generators:
- LLNL Fission Library[1]
  - Spontaneous, neutron-induced and photo-fission
  - Fission Reaction Event Yield Algorithm (FREYA)[2] isotopes:
    - Spontaneous: ^{238}U, ^{240}Pu, ^{244}Cm and ^{252}Cf
    - Neutron-induced: ^{233}U, ^{235}U and ^{239}Pu
  - When available, FREYA generates secondary neutrons and photons
- Cascading Gamma-ray Multiplicity (CGM)[3] - LANL
  - Generates secondary particles from a variety of reactions
  - No fission! (CGMF under active development)

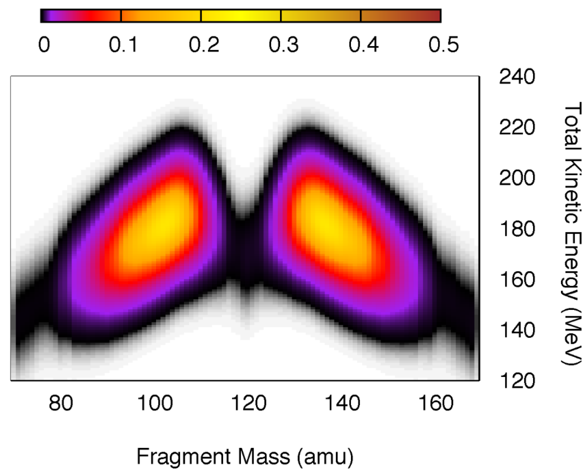
[1]J.M. Verbeke, C. Hagmann, and D. Wright, Lawrence Livermore National Laboratory, UCRL-AR-228518 (2014).

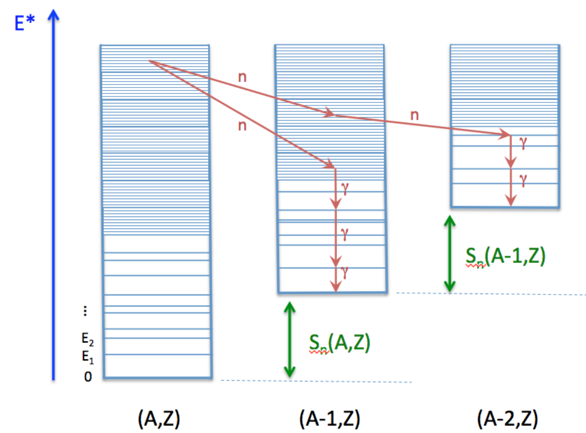
[2]R. Vogt and J. Randrup, *Phys. Rev. C*, vol. 84, pp. 044612-1-14 (2011).

[3]T. Kawano, P. Talou, M.B. Chadwick, and T. Watanabe, *J. Nucl. Sci. Tech.*, 47 (5), 462-69 (2010).

CGM and CGMF

- CGMF is a superset of CGM with an added fission reaction capability
- Fission fragments are sampled from a joint probability distribution function of mass (A), charge (Z) and total kinetic energy (TKE)
- Uses Hauser-Feshbach statistical theory of nuclear reactions
- Neutron / photon competition is treated during evaporation from fission fragments
- Monte Carlo is used to sample each step in the de-excitation process

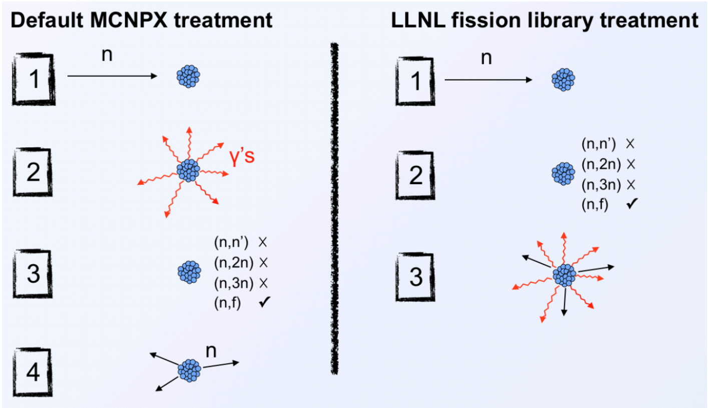


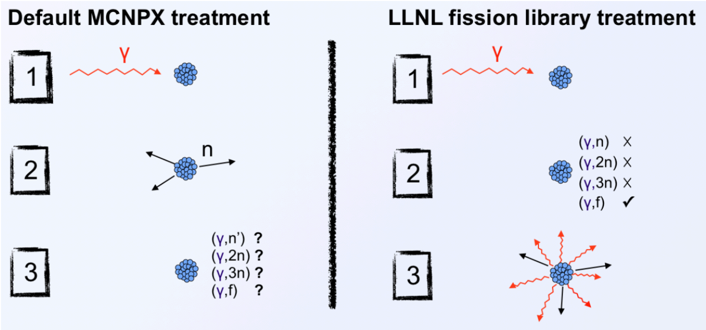


[4]B. Becker, P. Talou, T. Kawano, Y. Danon, and I. Stetcu, *Phys. Rev. C*, 87, 014617 (2013).

LLNL Fission Library and FREYA

- FREYA is LLNL's fission event generator
- In MCNP6, it is accessible through LLNL Fission Package
- The LLNL Fission Package includes more tabulated and fitted data used for lesser known isotopes FREYA can't presently handle
- FREYA uses a Monte Carlo Weisskopf approach
  - Neutrons emitted by sampling from Weisskopf spectrum
  - After neutrons are done emitting, gamma rays are emitted from residual energy
- Computationally more efficient than Monte Carlo Hauser-Feshbach



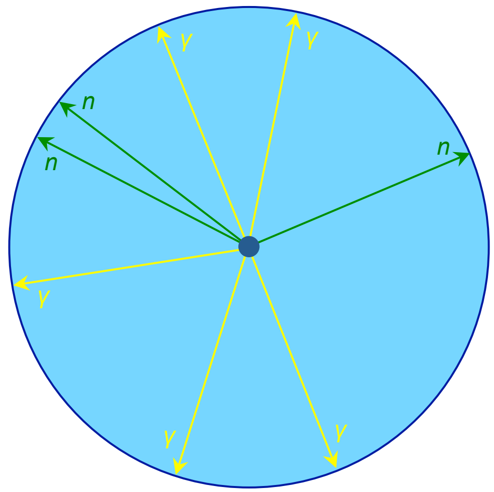


Verification Strategy

- Prove the models are implemented as intended
  - Assume models are verified against theory
- Check secondary neutron and photon emission quantities
  - Averages
    - Multiplicity: $\bar{\nu}_n$, $\bar{\nu}_\gamma$
    - Energy: $\bar{\chi}_n$, $\bar{\chi}_\gamma$
  - Distributions
    - Multiplicity: $P(\nu_n)$, $P(\nu_\gamma)$
    - Energy: $\chi_n(E)$, $\chi_\gamma(E)$
  - Correlations
    - Multiplicity: $P(\nu_n, \nu_\gamma)$
    - Angular: $n(\vec{\Omega}) \cdot n(\vec{\Omega})$
- Standalone code versus MCNP integrated code results

Numerical Results

- Compare standalone against MCNP6 integrated
  - CGMF and FREYA
  - Spontaneous and neutron-induced fission
  - Roughly 1E6 fission events
- Simple test problem description
  - Force collision at source location
  - Secondary particles stream without collision
  - Use PTRAC to calculate results
- Quantities for comparison
  - Averages
  - Distributions
  - Correlations
- Secondary photons bug fixed



Averages

- Standalone versus integrated results are in agreement within statistics!

CGMF

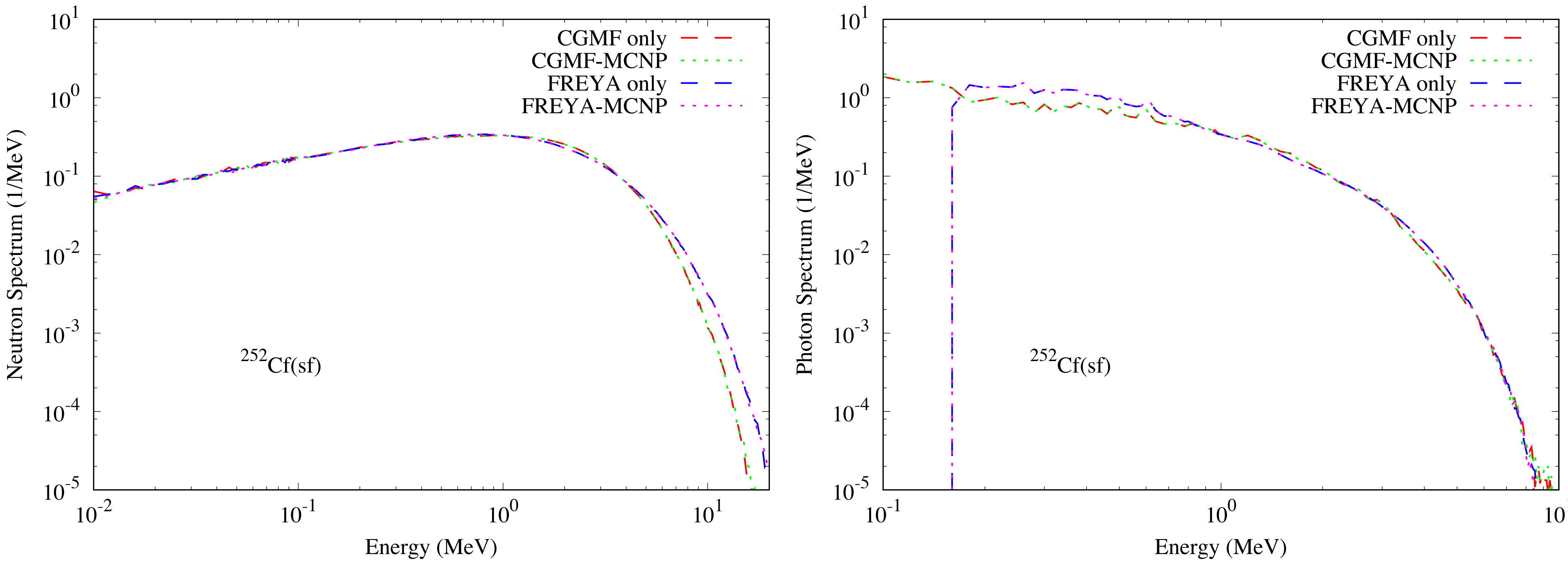
	^{252}Cf(sf)		n(1.0273 MeV)+^{239}Pu		n(thermal)+^{235}U	
Quantity	Standalone	MCNP	Standalone	MCNP	Standalone	MCNP
$\bar{\nu}_N$	3.7415(13)	3.7439(16)	3.0512(11)	3.0481(11)	2.4315(11)	2.4305(11)
$\bar{\chi}_N$	2.0927(8)	2.0920(10)	2.0322(9)	2.0329(9)	1.9726(9)	1.9740(9)
$\bar{\nu}_\gamma$	8.2721(32)	8.2680(37)	7.9039(31)	7.9053(31)	7.4328(30)	7.4425(30)
$\bar{\chi}_\gamma$	0.8561(3)	0.8558(3)	0.9287(3)	0.9293(3)	0.9139(3)	0.9131(3)

FREYA

	^{252}Cf(sf)		n(1.0273 MeV)+^{239}Pu		n(thermal)+^{235}U	
Quantity	Standalone	MCNP	Standalone	MCNP	Standalone	MCNP
$\bar{\nu}_N$	3.7415(12)	3.7402(12)	2.7745(10)	2.7753(10)	2.2014(10)	2.2011(10)
$\bar{\chi}_N$	2.2491(10)	2.2483(10)	2.0272(10)	2.0276(10)	1.8692(10)	1.8689(10)
$\bar{\nu}_\gamma$	8.0961(30)	8.1055(30)	7.1463(26)	7.1453(26)	6.7010(25)	6.7034(25)
$\bar{\chi}_\gamma$	0.8929(3)	0.8924(3)	0.9922(3)	0.9918(3)	0.9770(3)	0.9774(3)

Distributions

- Energy spectrum of neutrons and photons
  - Cf-252 (sf), Pu-239 (n,f) and U-235 (n,f)



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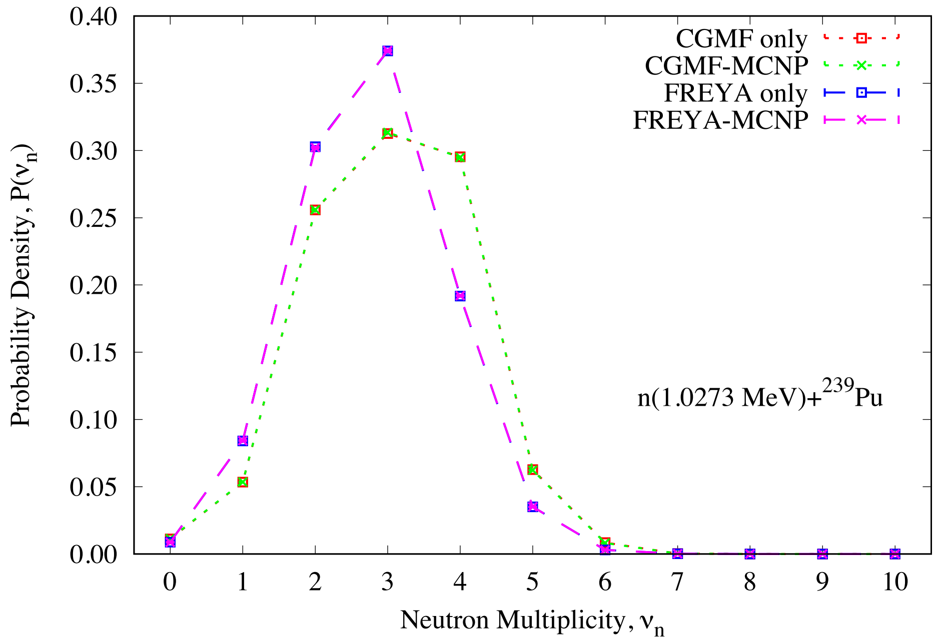
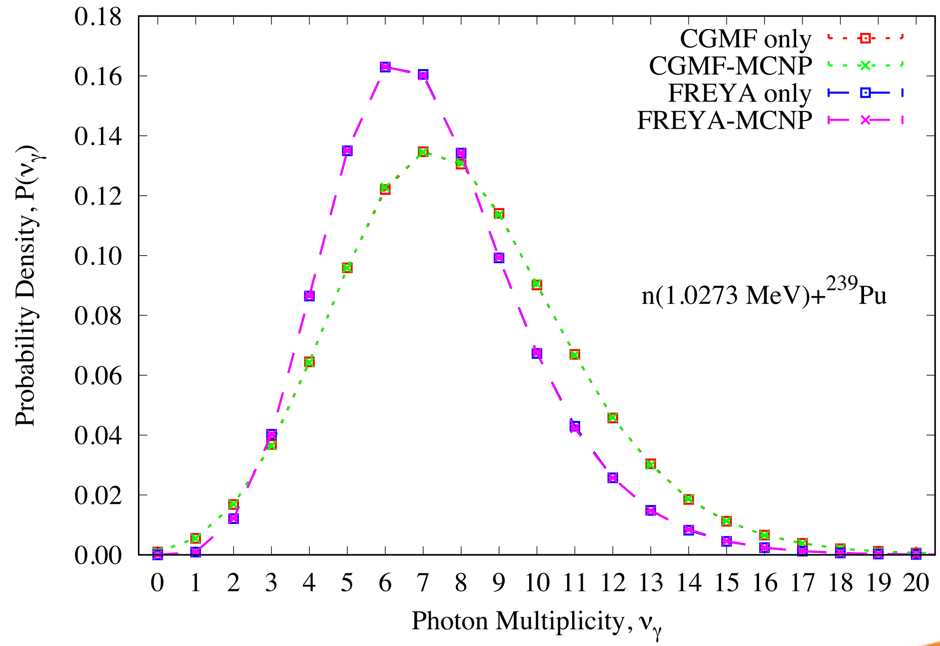
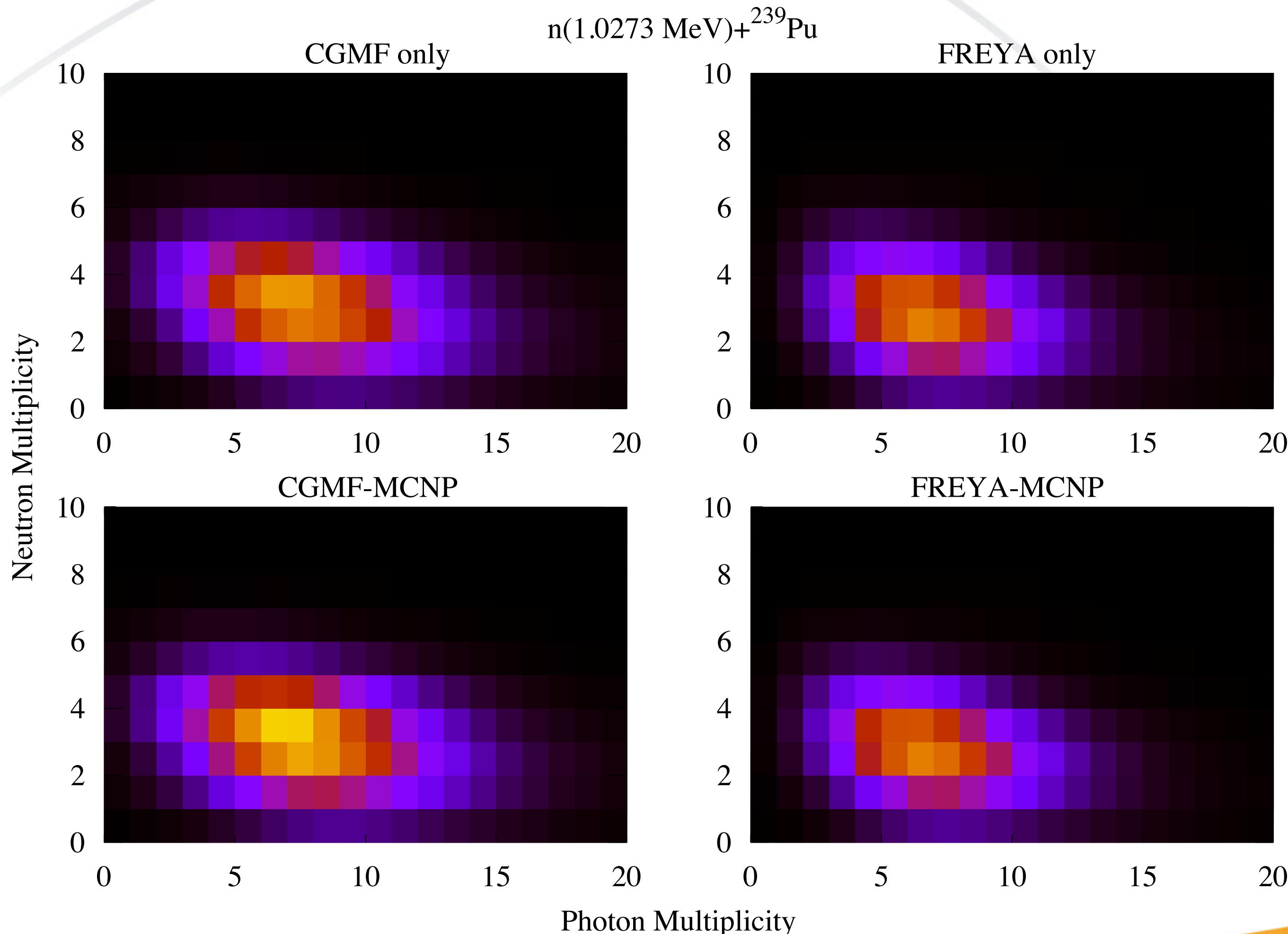
Distributions

- Multiplicity of neutrons and photons
  - Cf-252 (sf), Pu-239 (n,f) and U-235 (n,f)





Distributions



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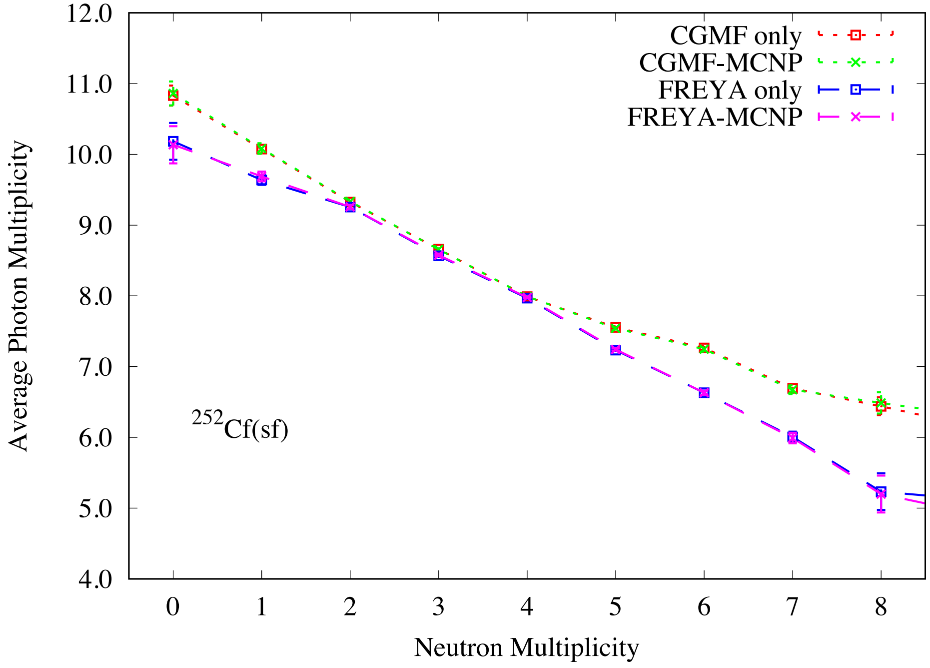
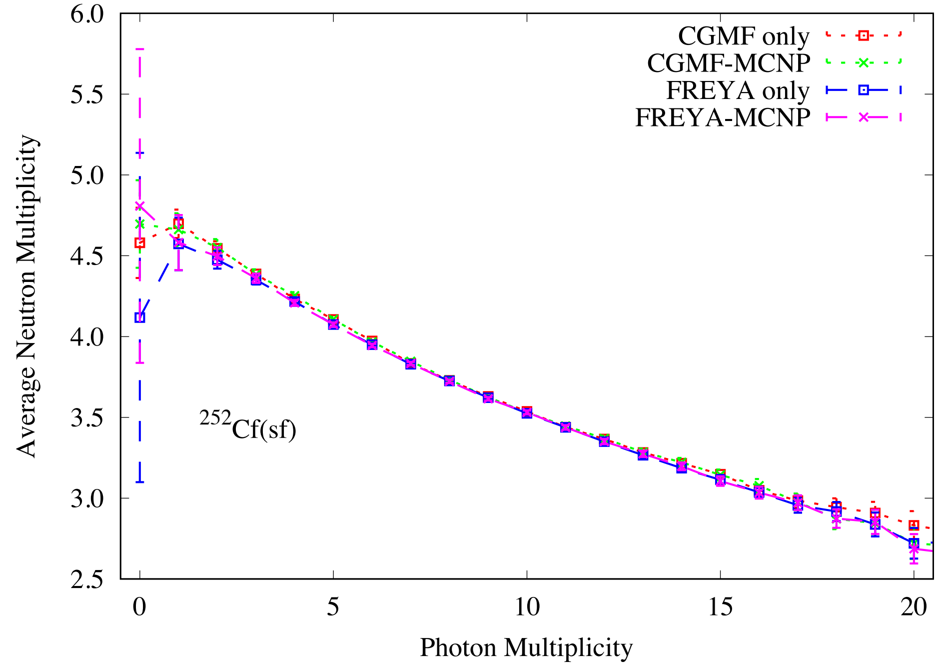
Correlations

- Multiplicity correlations
  - Tagging on number of neutrons or photons observed

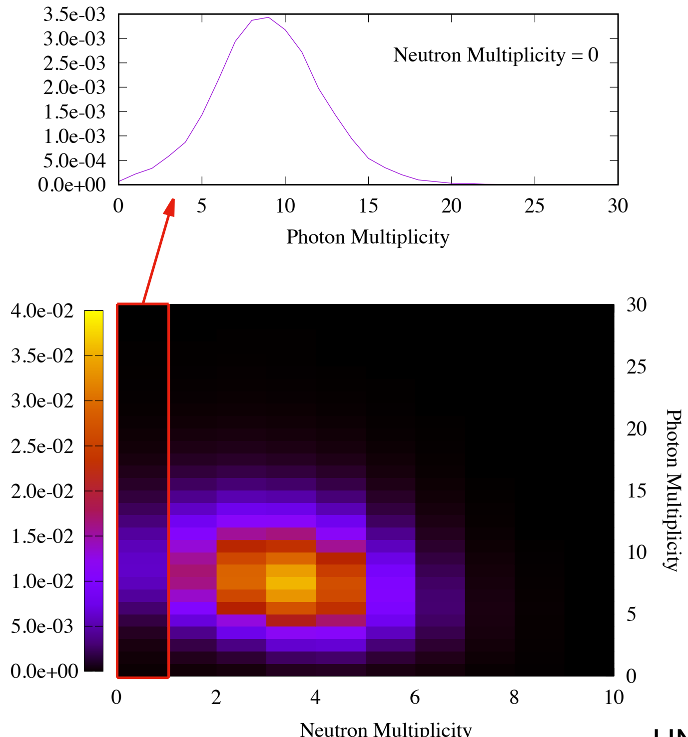




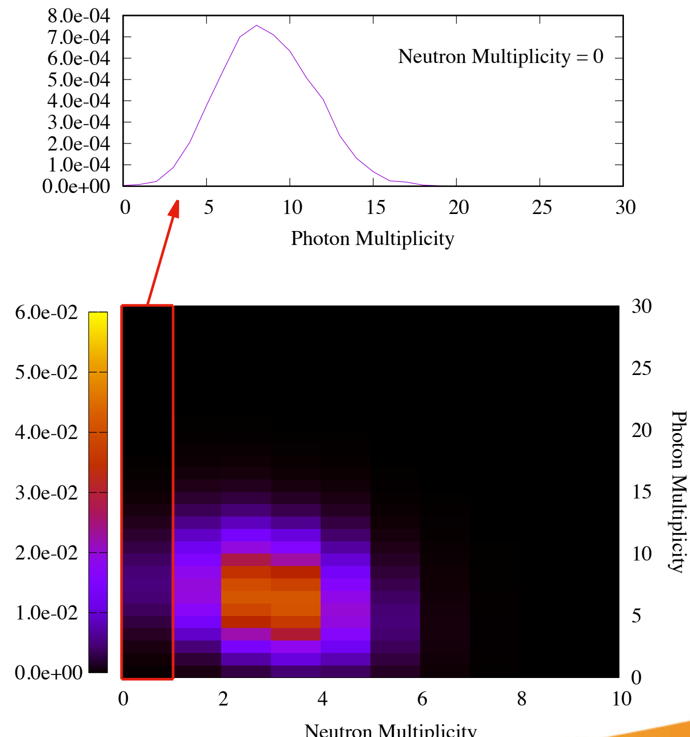
Secondary Photon Bug Fixed

- Previously when zero neutrons emitted ➔ zero photons emitted
- MCNP6.2 includes this bug fix

CGMF

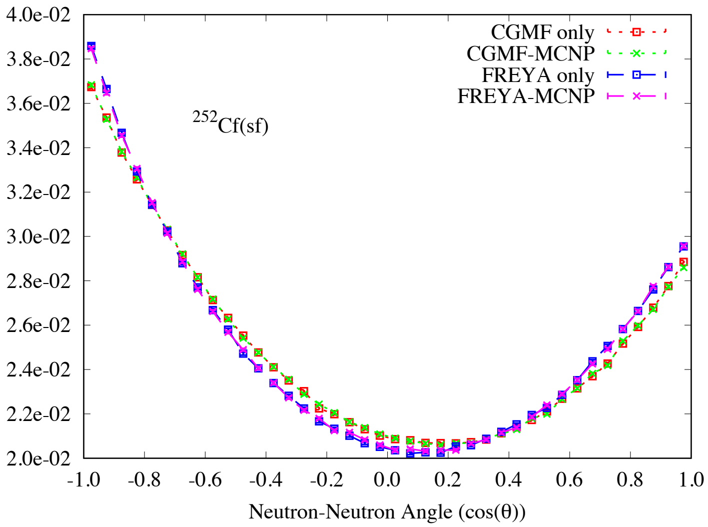


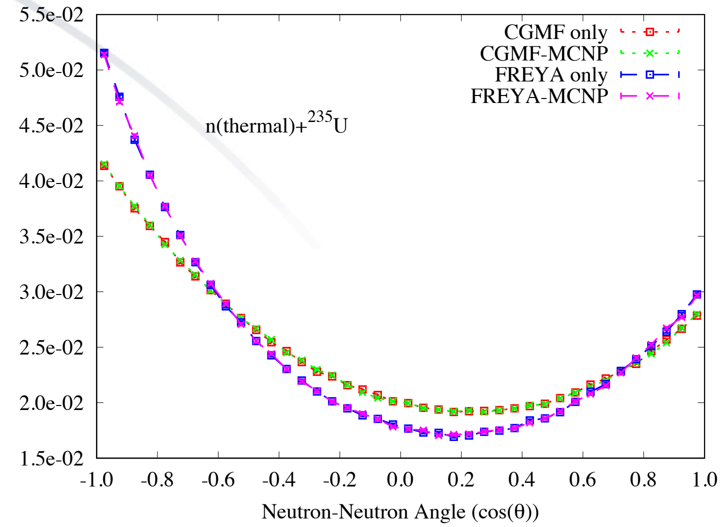
FREYA

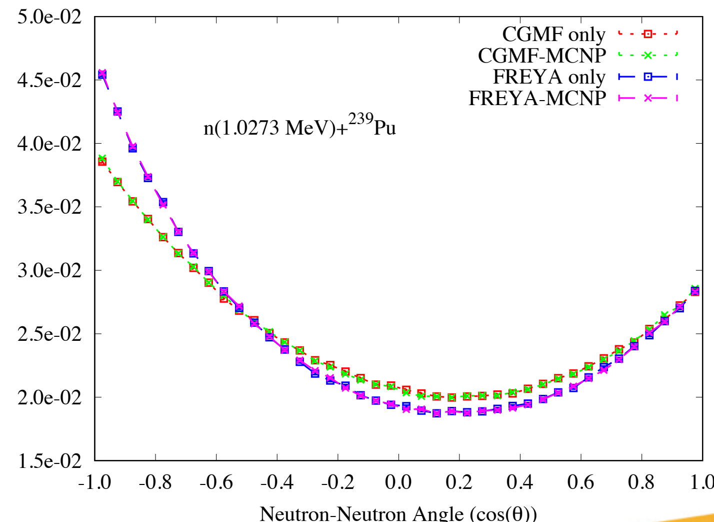


Correlations

- Angular neutron-neutron correlations
  - Cf-252 (sf), Pu-239 (n,f) and U-235 (n,f)







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Conclusions

- Integrated fission event generator models appear to be implemented correctly!
- Next version of MCNP 6.2 will contain two new fission event generators
  - CGMF from LANL
  - FREYA from LLNL/LBNL

THANK YOU!