Using the MCNP6.2 Correlated Fission Multiplicity Models, CGMF and FREYA

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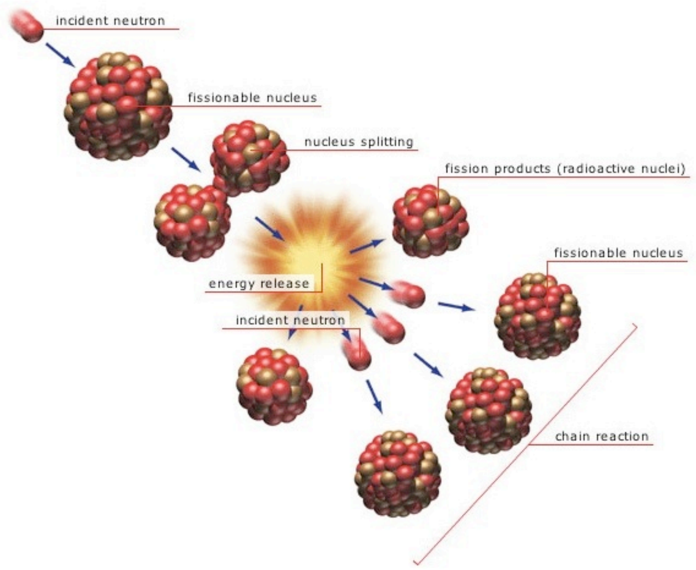
Outline

- **Introduction**
- **Motivation for different fission multiplicity treatments**
- **Background**
  - MCNP default behavior
  - FMULT input card
  - LLNL Fission Library
  - FREYA – LBNL/LLNL
  - CGMF – LANL
  - Other Monte Carlo transport codes
- **Guidance with numerical results**
- **Preview of works in progress**
- **Conclusions & future work**



Introduction

- **MCNP is a general purpose Monte Carlo transport code**
  - Many choices must be made by users to run the code properly for their applications
  - Example: *What kind of variance reduction techniques are needed for my shielding application?*

- **Applications include:**
  - Criticality safety
  - Nuclear safeguards and non-proliferation
  - Nuclear energy
  - Nuclear threat reduction and response
  - Radiation detection and measurement
  - Radiation health protection
  - Stockpile stewardship

Motivation

What results do I want to obtain from my Monte Carlo calculation?

- **Fixed-source**
  - current, flux, charge and energy deposition, dose
- **Criticality**
  - k_{eff}, current, flux, reaction rates, power distributions, burnup

All of the above can be computed using default MCNP fission treatment

- **Fixed-source**
  - time-coincident detector pulses (e.g. multiplicity counters)

Need fission multiplicity treatment - not default in MCNP

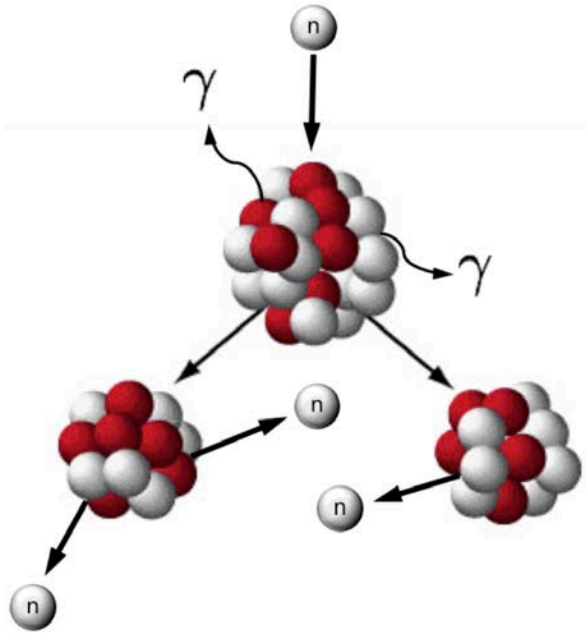
Motivation

- **Warhead Measurement Campaign (WMC) meant to passively and actively measure nuclear warheads for treaty verification**
  - New measurements of neutron and photon coincidence data of shielded special nuclear materials (SNM)
  - At the time, the transport simulation tools available were limited in their ability to fully predict WMC-like measurements
  - This was due to the type of nuclear fission data available
  - To address these shortcomings, more detailed behavior of nuclear fission physics was needed
  - Making the transport simulations more predictive in SNM detection applications

- **Key Issues**
  - Average nuclear data quantities are insufficient
  - Need better ways to compare to experiment

Background

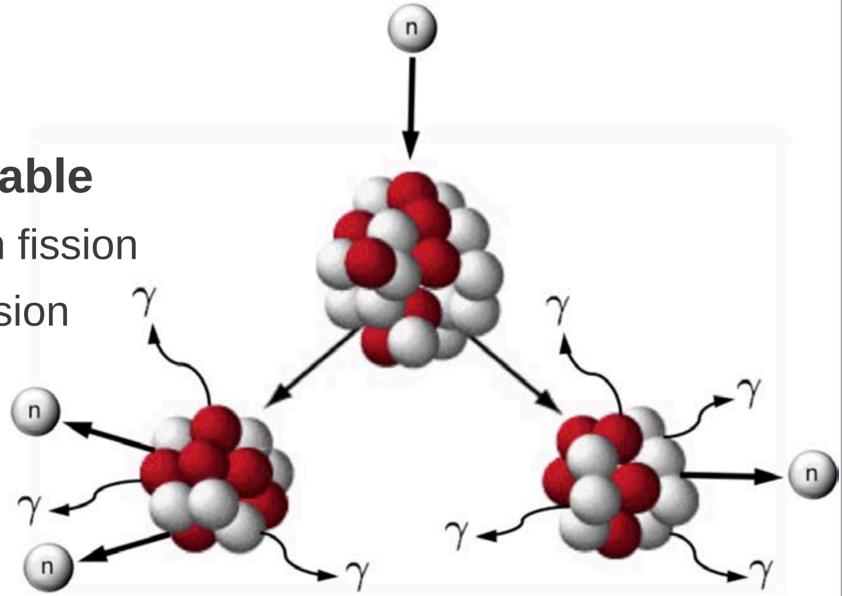
- **MCNP6 default nuclear fission physics**
  - Average photon production for each collision
  - Average neutron production for each fission
  - Average energy spectra for neutrons and gamma rays
  - Isotropic angular emission
  - No correlations!



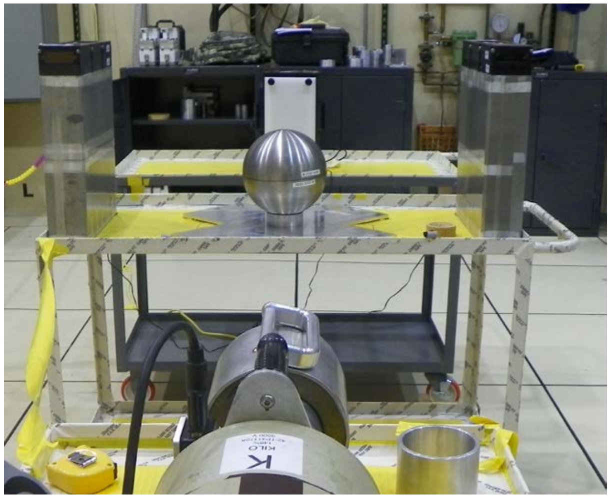
- **Applications**
  - Shielding: current, flux, energy deposition, dose
  - Subcritical / Critical Systems: k_{eff}, flux, reaction rates
  - Reactor Physics: k_{eff}, current, flux, power distributions, burnup
  - Radiation Detection: charge and energy deposition, pulse-height spectra, bulk counting rates

Background

- **MCNP6.2 – nuclear fission physics available**
  - Multiplicity distribution of gamma rays for each fission
  - Multiplicity distribution of neutrons for each fission
  - Multiplicity dependent energy spectra (energy correlations)
  - Angular emission from fission fragments (angular correlations)
  - Full correlations!



- **Applications**
  - In addition to MCNP6 default applications …
  - Subcritical Systems: singles, doubles, etc. counting rates, leakage multiplication, probability of initiation/extinction
  - Reactor Physics: higher-order power distribution fluctuations
  - Radiation Detection: n-n, n-γ, γ-γ time coincidence



Background
MCNP Default Behavior

- **In nature, a fission event will emit a number of neutrons and gamma rays with some probability distribution, $P(E,\nu)$**

- **In MCNP, by default**
  - The average neutrons emitted is used, $\bar{\nu}(E)$
  - Bounded integer sampling scheme:
    - If $\bar{\nu} = 2.2$,
    - Then, $P(\nu = 2) = 80\%$ and, $P(\nu = 3) = 20\%$
  - Preserves expected value

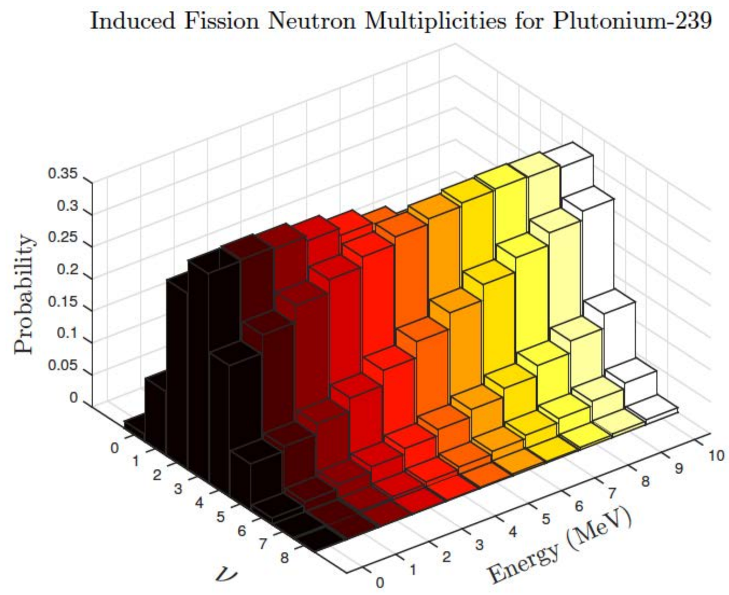


Figure take from: M. Ortega, M.S. Thesis, University of New Mexico, NM.

Background
FMULT Input Card

- **Original FMULT options within MCNP turns on neutron multiplicity sampling and allows the user to,**
  - Modify spontaneous fission average multiplicity and yield rate
  - Change Watt energy spectrum parameters for spontaneous fission
  - Provide Gaussian FWHM width for spontaneous and induced fission multiplicity distributions
  - Select a sampling algorithm and data source
- **Does not handle fission gamma ray emission**
- **Each neutron emitted,**
  - Direction is isotropic and independently sampled
  - Energy is sampled independently from the same energy distribution (uncorrelated)

MCNP output file, print table 38

1fission multiplicity data.

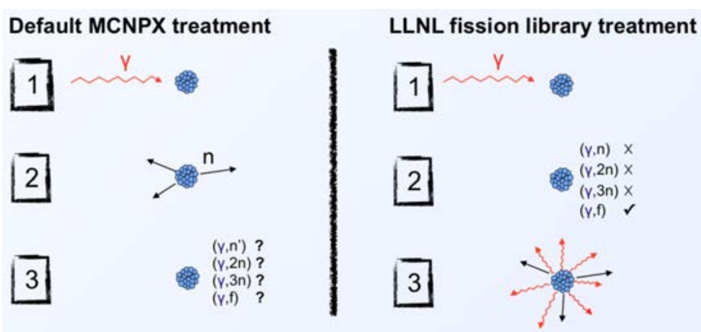
	zaid	width	watt1	watt2	yield	sfnu
	90232	1.079	.800000	4.00000	6.00E-08	2.140
	92232	1.079	.892204	3.72278	1.30E+00	1.710
	92233	1.041	.854803	4.03210	8.60E-04	1.760
	92234	1.079	.771241	4.92449	5.02E-03	1.810
	92235	1.072	.774713	4.85231	2.99E-04	1.860
	92236	1.079	.735166	5.35746	5.49E-03	1.910
	92238	1.230	.648318	6.81057	1.36E-02	0.048
	93237	1.079	.833438	4.24147	1.14E-04	2.050
	94236	0.000	.000000	0.00000	0.00E+00	0.080
	94238	1.115	.847833	4.16933	2.59E+03	0.056
	94239	1.140	.885247	3.80269	2.18E-02	2.160
	94240	1.109	.794930	4.68927	1.02E+03	0.063
	94241	1.079	.842472	4.15150	5.00E-02	2.250
	94242	1.069	.819150	4.36668	1.72E+03	0.068
	95241	1.079	.933020	3.46195	1.18E+00	3.220
*	96242	1.053	.887353	3.89176	2.10E+07	0.021
	96244	1.036	.902523	3.72033	1.08E+07	0.015
	96246	0.000	.000000	0.00000	0.00E+00	0.015
	96248	0.000	.000000	0.00000	0.00E+00	0.007
	97249	1.079	.891281	3.79405	1.00E+05	3.400
	98246	0.000	.000000	0.00000	0.00E+00	0.001
	98250	0.000	.000000	0.00000	0.00E+00	0.004
	98252	1.207	1.180000	1.03419	2.34E+12	0.002
	98254	0.000	.000000	0.00000	0.00E+00	0.000
	100257	0.000	.000000	0.00000	0.00E+00	0.021
	102252	0.000	.000000	0.00000	0.00E+00	0.057

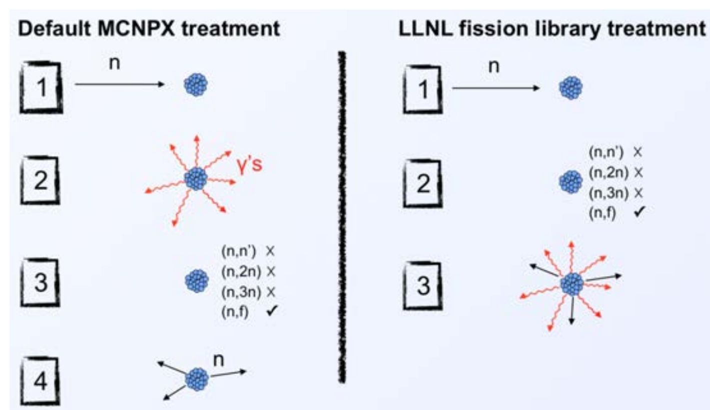
* = used in problem.

See MCNP6 User's Manual, Los Alamos National Laboratory, LA-CP-14-00745 (2014).

Background
LLNL Fission Library

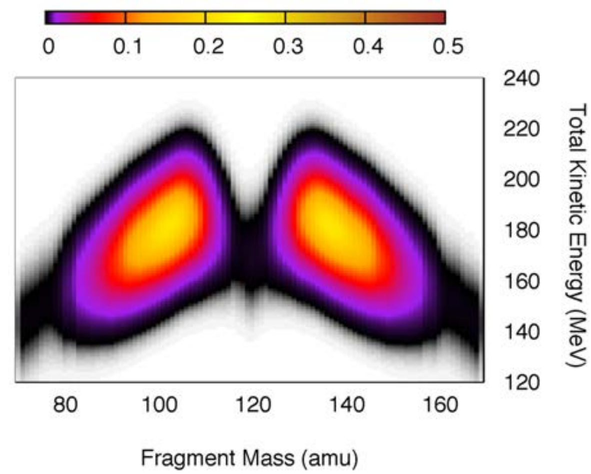
- **In MCNP6.1 (and 6.1.1), the LLNL Fission Library is one of two (low-energy) event generators:**
  - Spontaneous, neutron-induced and photo-fission for most fissionable systems
  - MCNP6.2 version produces same results from previous versions
  - Input card: `FMULT method=5`
  - Now includes FREYA 2.0
- **The LLNL Fission Library includes more tabulated and fitted data used for lesser known isotopes FREYA can't presently handle**
- **If the LLNL Fission Library cannot handle a particular isotope, the FMULT default parameters are used instead**





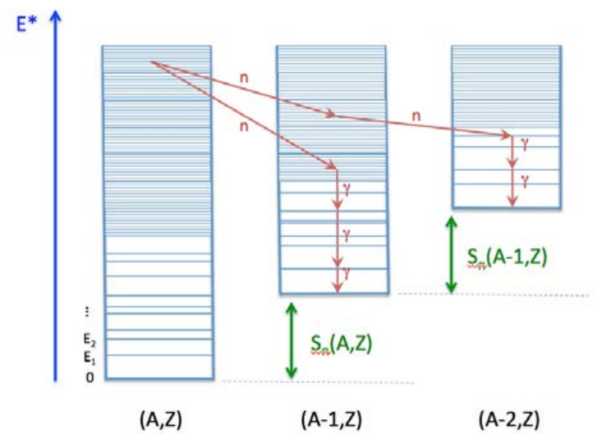
Background
FREYA – LBNL/LLNL

- **The FREYA is developed by LBNL/LLNL**
- **In MCNP6, it is accessible through LLNL Fission Package with different `FMULT` card option**
  - Input card: `FMULT method=6`
- **Spontaneous fission: ^{238}U, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{244}Cm, and ^{252}Cf**
- **Neutron-induced fission: ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu**
- **If FREYA cannot handle particular isotope, LLNL Fission Library is used**
- **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 (CGMF)**



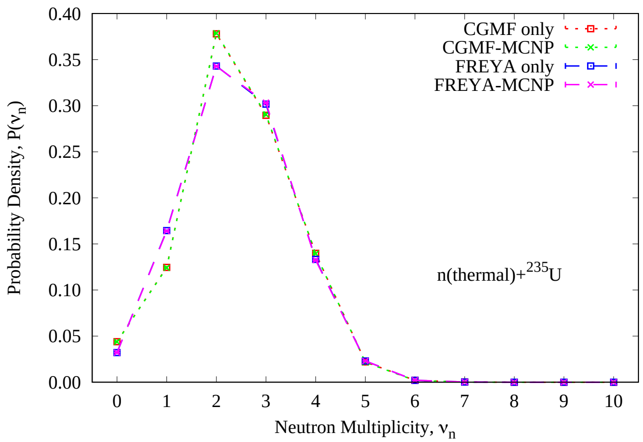
Background
CGMF – LANL

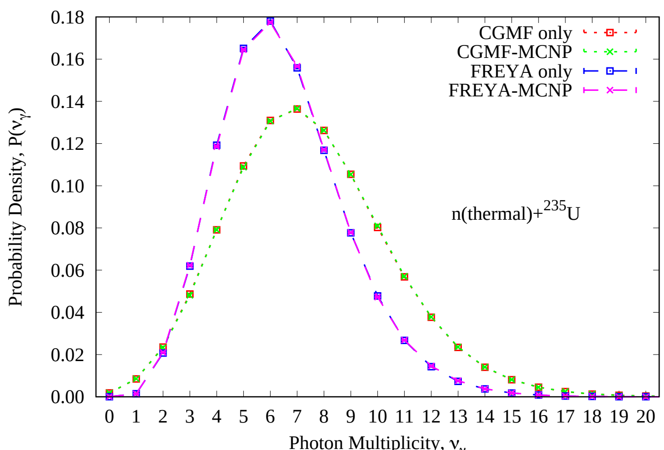
- **CGMF is a superset of CGM with an added fission reaction capability**
  - Input card: `FMULT method=7`
- **Fission fragments are sampled from a joint probability distribution function of mass (A), charge (Z) and total kinetic energy (TKE)**
- **Uses Hauser-Feshbach statistical theory of nuclear reactions treating neutron / photon competition de-excitation of fission fragments**
- **Monte Carlo is used to sample each step in the de-excitation process**
- **Spontaneous fission: ^{240}Pu, ^{242}Pu, and ^{252}Cf**
- **Neutron-induced fission: ^{235}U, ^{238}U, and ^{239}Pu**
- **If CGMF cannot handle a particular isotope, the LLNL Fission Library is used instead**

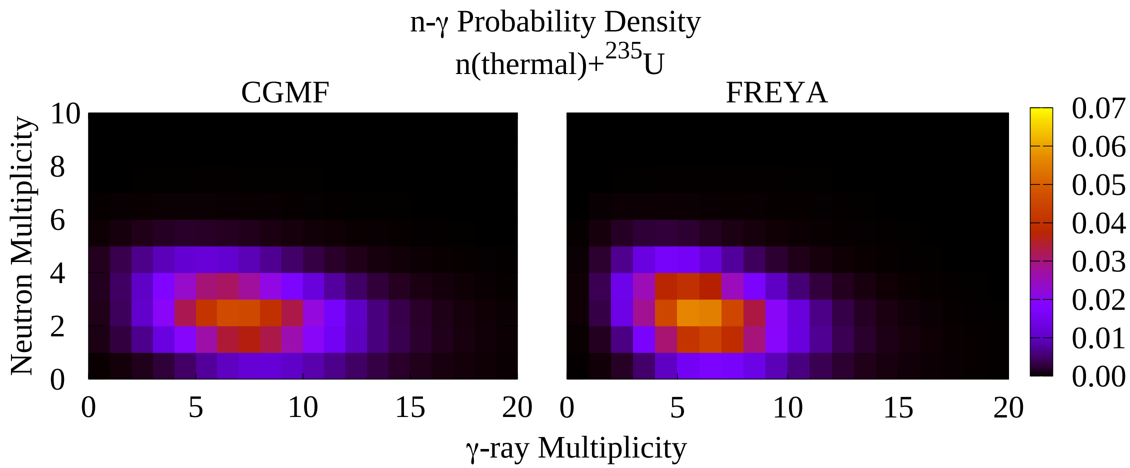


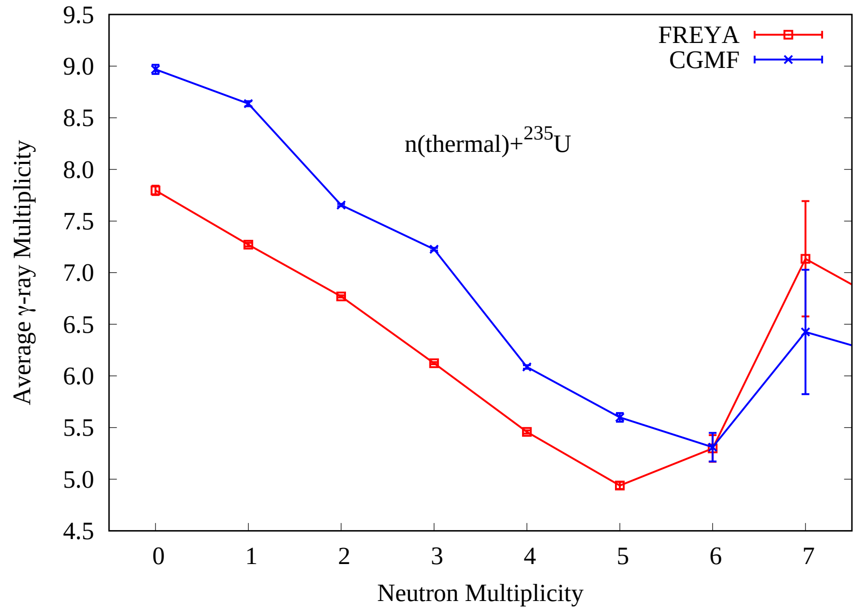
Background
FREYA & CGMF

- **Neutron & gamma-ray multiplicity**



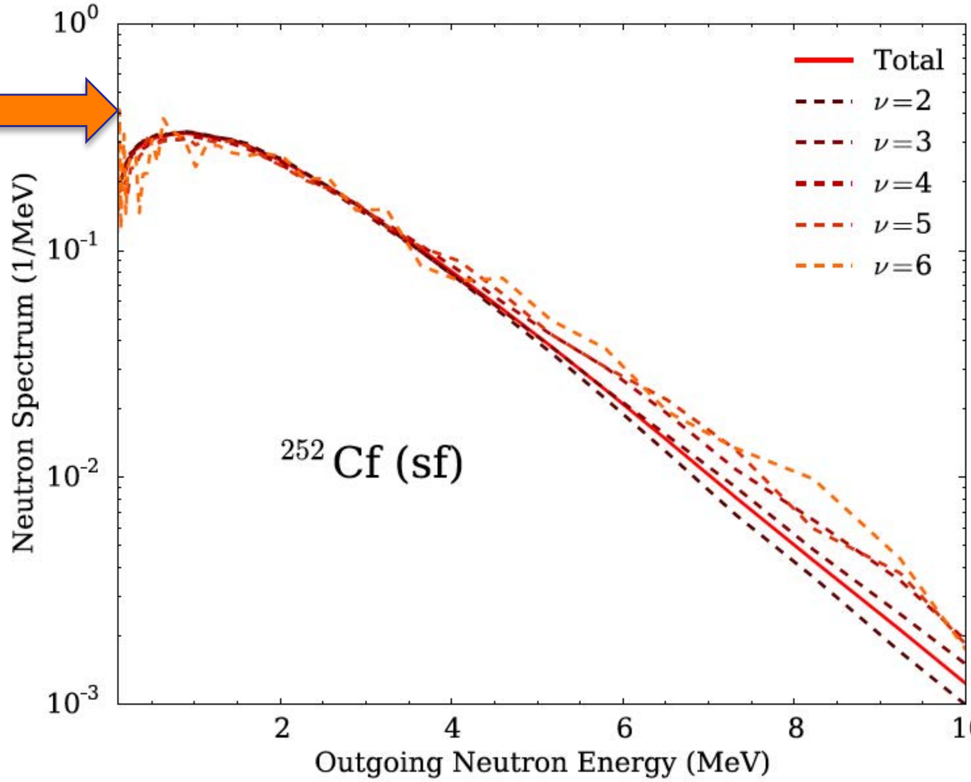


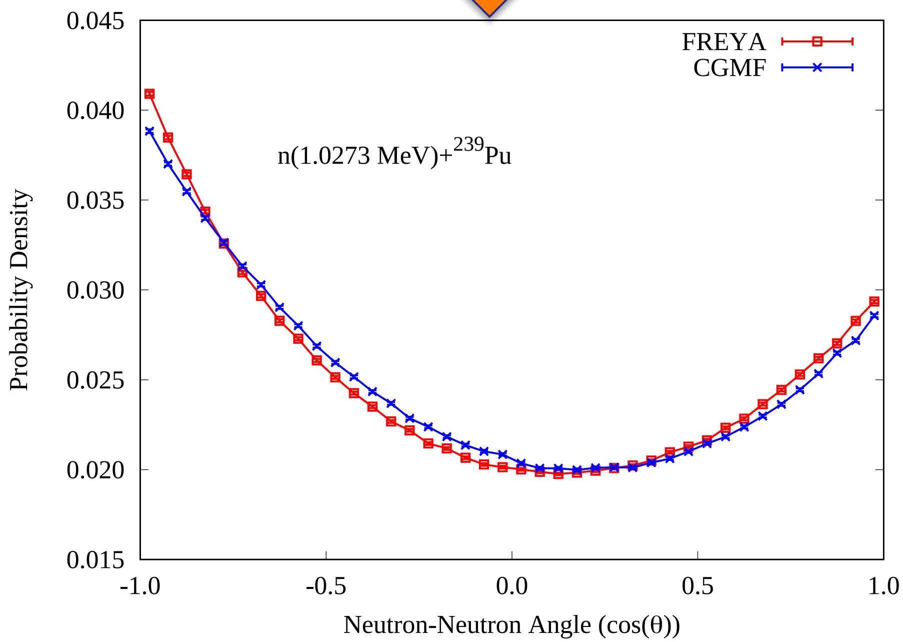




Background
FREYA & CGMF

- **Multiplicity-dependent spectra**
- **Neutron emission angular correlations**





Background
Other Monte Carlo Codes

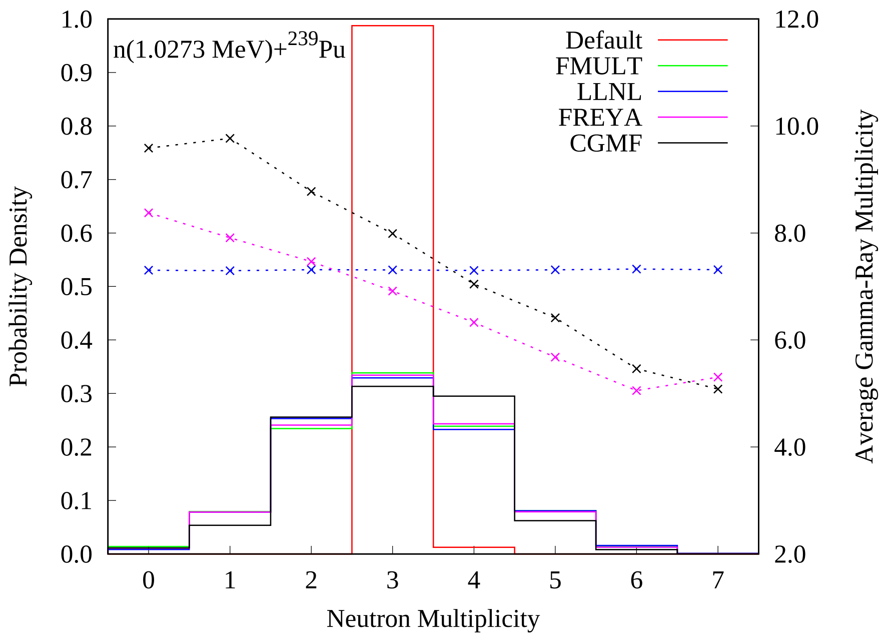
- **MCNPX-PoliMi:**
  - Implemented some correlated models (IPOL(1)=1, IPOL(1)=10) for Cf-252 systems
  - Integrated CGMF and FREYA into local research version
- **MCNPX (and now MCNP6)**
  - Implemented LLNL Fission Library
- **TRIPOLI (CEA)**
  - LLNL Fission Library & FREYA integration supported by J. Verbeke
- **MORET (IRSN)**
  - LLNL Fission Library & FREYA
- **GEANT**
  - LLNL Fission Library & FREYA (only locally integrated, not in the open community)

Guidance with Numerical Results

- **Brief summary of options**
  - Default: no neutron multiplicity, no gamma-ray multiplicity*, uncorrelated**
  - FMULT: neutron multiplicity, no gamma-ray multiplicity*, uncorrelated**
  - LLNL: neutron multiplicity, gamma-ray multiplicity, uncorrelated**
  - FREYA: neutron multiplicity, gamma-ray multiplicity, correlated
  - CGMF: neutron multiplicity, gamma-ray multiplicity, correlated

n(1.0273 MeV)+^{239}Pu fission reaction

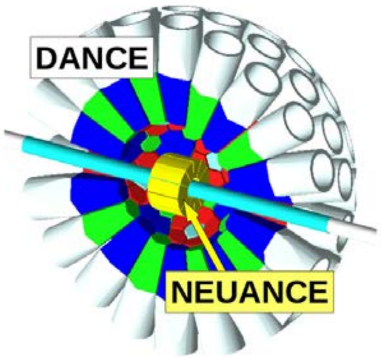
Model	$\bar{\nu}_n$	$\bar{\chi}_n$	$\bar{\nu}_\gamma$	$\bar{\chi}_\gamma$
Default	3.0126(1)	2.139(1)	*	*
FMULT	3.012(1)	2.137(1)	*	*
LLNL	3.014(1)	2.036(1)	7.307(3)	0.8985(3)
FREYA	3.012(1)	2.153(1)	6.876(2)	1.0098(4)
CGMF	3.048(1)	2.033(1)	7.905(3)	0.9293(3)

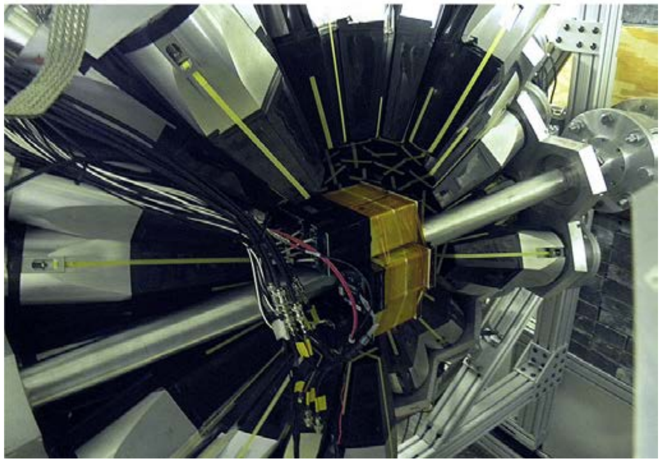


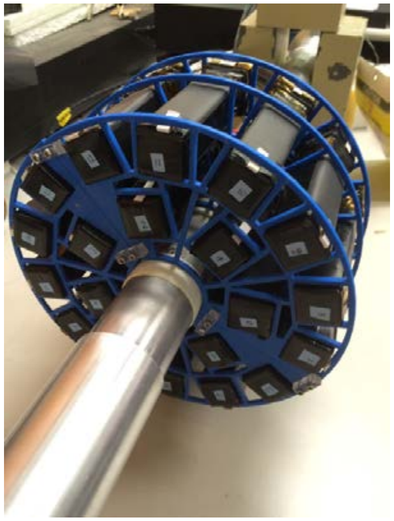
*gamma-rays can be present, but may not be fission reaction specific
**neutrons and gamma-rays are uncorrelated from each other

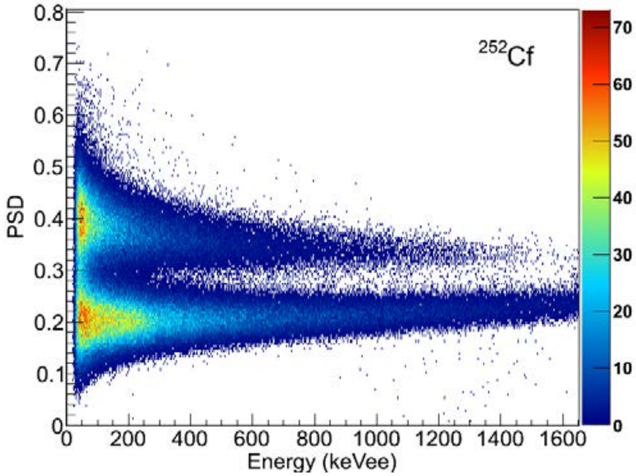
Guidance with Numerical Results

- **Differential Experiment Validation**
  - Using differential measurements to validate event-by-event predictions of CGMF/FREYA
  - CNEC student at LANL working on modeling detailed detectors in NEUANCE (M. Pinilla)
  - Using PTRAC and DRiFT to model stilbene
- **To make sure CGMF & FREYA are a reflection of reality**



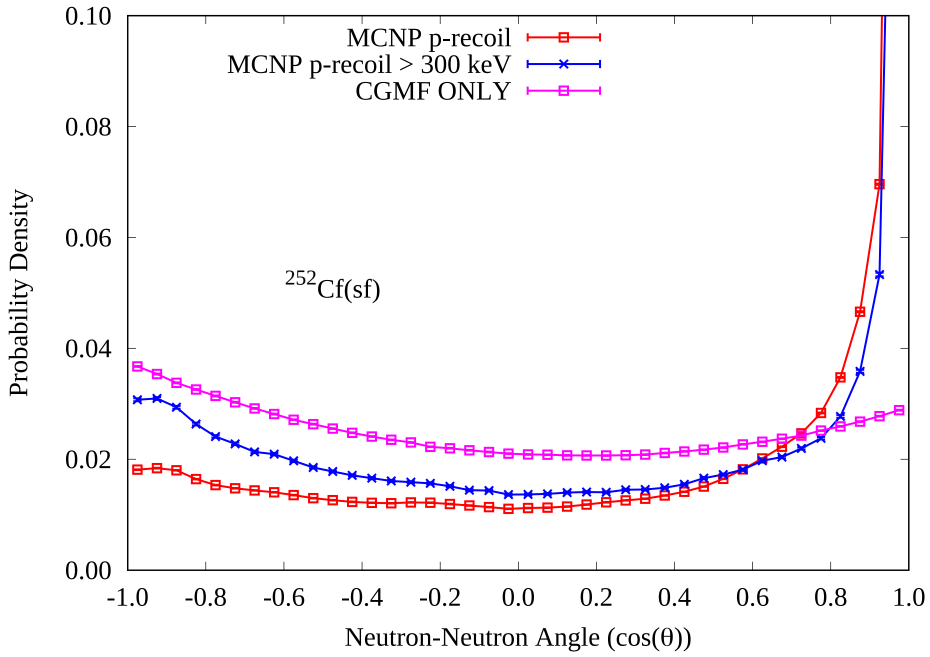


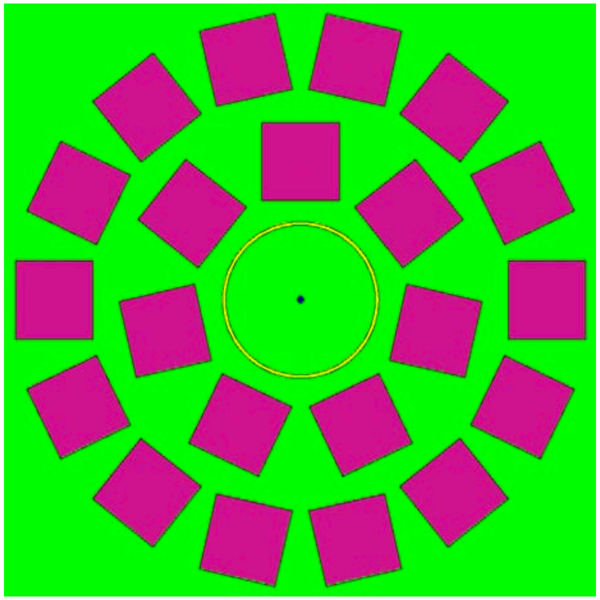




Guidance with Numerical Results

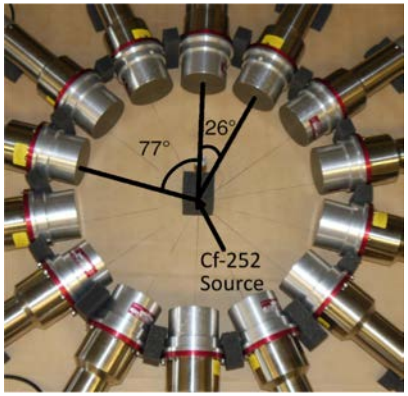
- **Simplified MCNP model of NEUANCE**
  - 21 stilbene detectors in array
  - ^{252}Cf spontaneous fission source

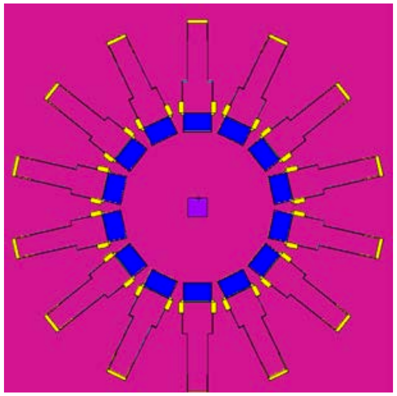




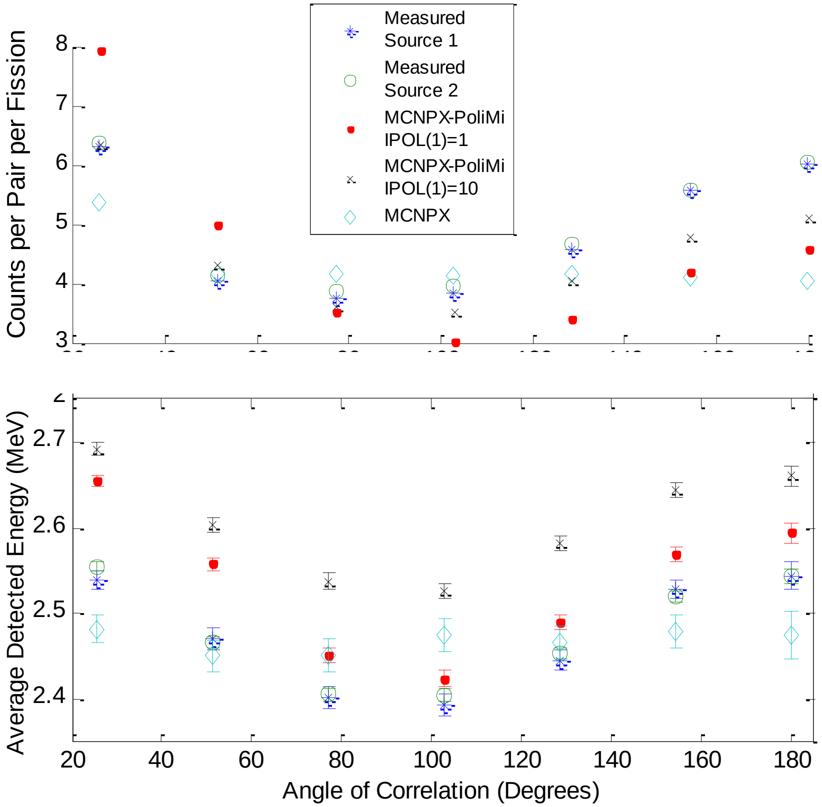
- **Using `mcnptools` (included with MCNP6.2 release) to analyze PTRAC results**
- **Need to add detector response using DRiFT (in progress)**

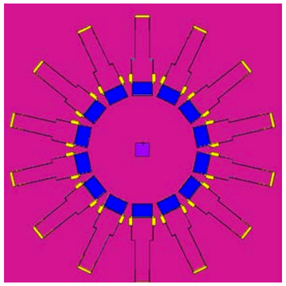
Preview of Works in Progress





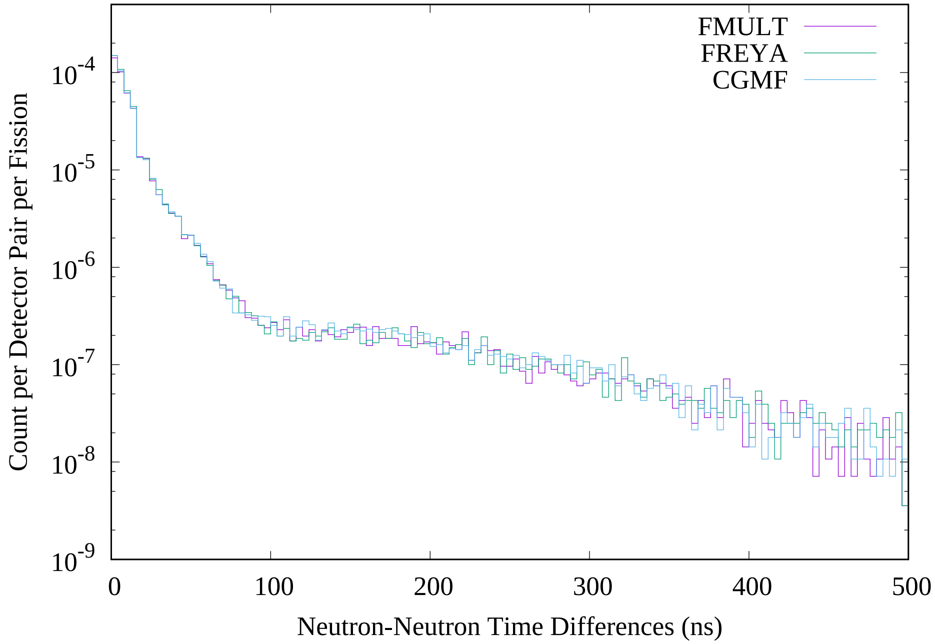
- **University of Michigan differential measurements of angular correlations**
- **Priority is to compare against experimental measurements**
- **Follow-up of 2014 NSE paper by S.A. Pozzi *et al*.**
- **Submitted an abstract to IRRMA X meeting in Chicago, IL, July 9-13**
- **Transport and post-processing code comparisons**
  - MCNP6 / DRiFT
  - MCNP6 / MPPost
  - MCNPX-PoliMi / MPPost
  - MCNPX-PoliMi / DRiFT

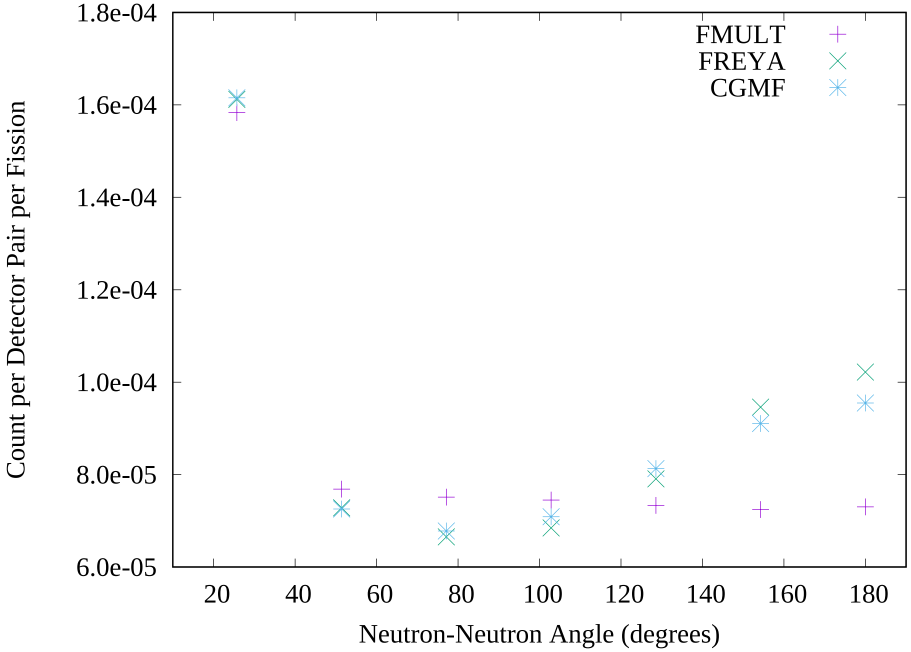




Preview of Works in Progress

- **MCNP6.2 simulation of correlated counts**

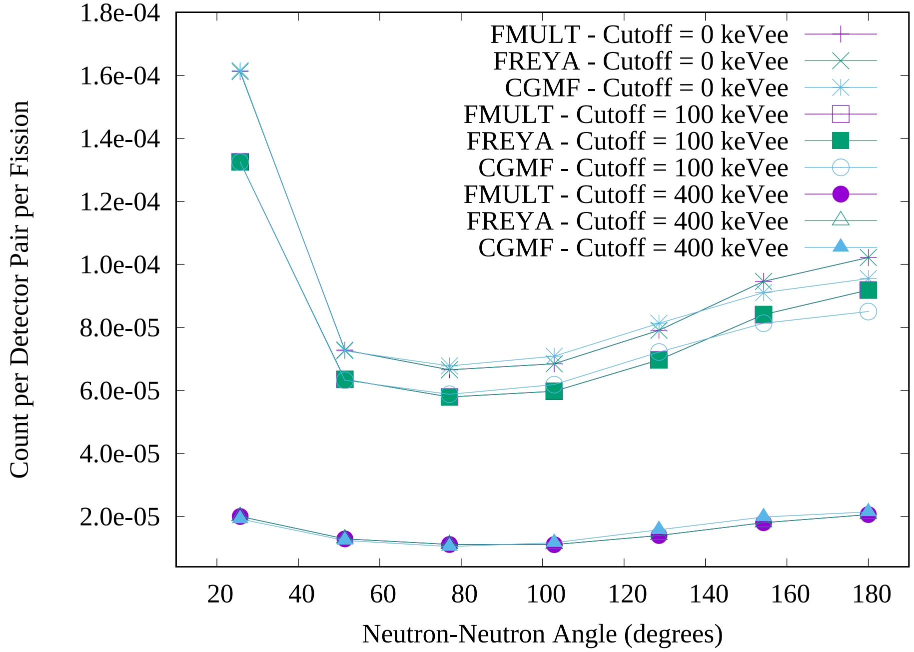




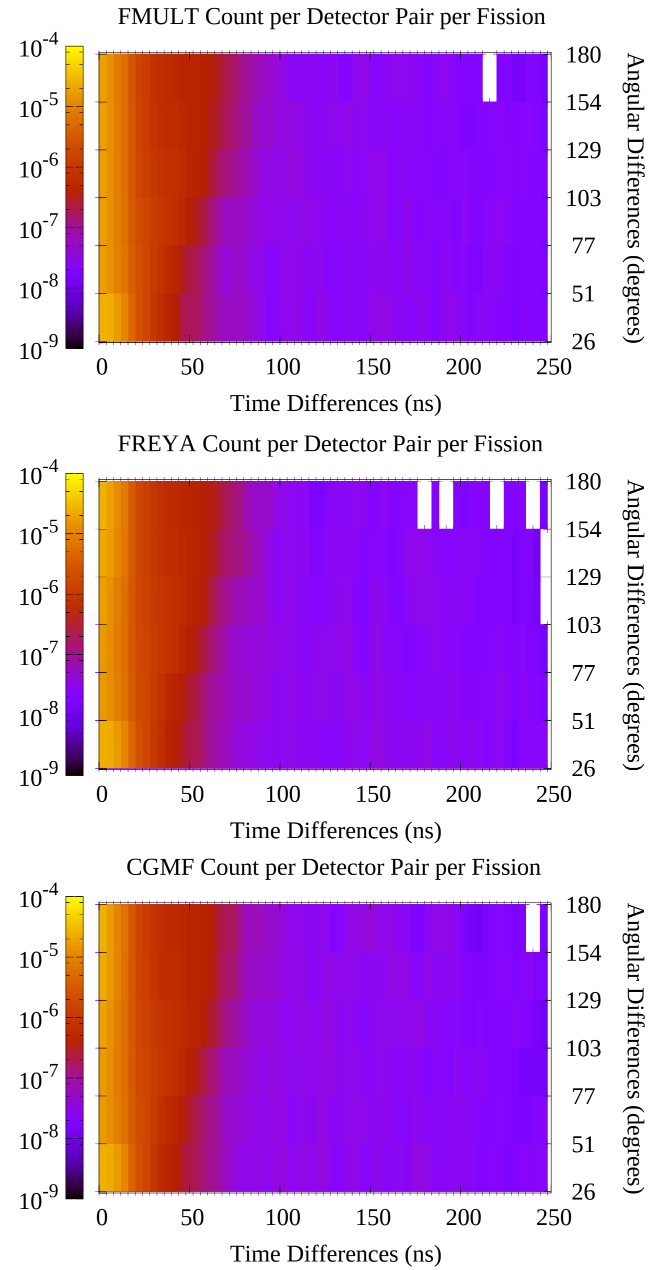
- **Time-stamp differences are small**
- **Angular differences are significant!**
  - Lots of cross-talk between detectors at small angles

Preview of Works in Progress

- **Correlated counts**



- **Changing pulse height thresholds changes:**
  - Overall count rates
  - Removes some of the cross-talk effect
- **Time stamp differences change w.r.t angle**



Conclusions & Future Work

Conclusions

- **MCNP6.2 manual is updated with new information on the fission multiplicity treatment options within `FMULT` and how they work**
- **When correlated fission multiplicity models are needed, MCNP6.2 now contains two such models:**
  - FREYA from LBNL/LLNL
  - CGMF from LANL
- **New post-processing capabilities distributed with MCNP6.2 for users in many application areas (see `mcnptools` for PTRAC processing)**

Future Work

- **Improvements to FREYA and CGMF**
  - More isotopes/energies, photofission, time-dependent gamma-ray emission, etc.
  - Computational speed improvements (CGMF)
- **Validation – more simulation vs. experiment**

Acknowledgements

Other members of our NA-22 collaboration project:

- Madison T. Andrews, LANL XCP-3
- Patrick Talou, Toshihiko Kawano, and Ionel Stetcu, LANL T-2
- Marian Jandel, Gencho Rusev, and Carrie Walker, LANL C-NR
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- Jorgen Randrup, LBNL
- Ramona Vogt and Jerome Verbeke, LLNL
- Sara Pozzi, Shaune D. Clarke, and Matthew J. Marcath, Univ. of Michigan

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Thank you!

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