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Testing the Lawrence Livermore National Laboratory Multiplicity Capability in MCNPX 2.7.0

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DHS HS-STEM Summer Internship Program

Overview

- **MCNP**
- **Fission**
- **Multiplicity and LLNL capability**
- **Motivation**
- **Initial Benchmarking using LLNL multiplicity**
- **Benchmarking distribution and correlation options in LLNL**
- **Conclusion**
- **Future Work**

Initial work with MCNP

- First time working with MCNP
- Spent first two weeks taking the MCNP class and working on the practice problems
 - Geometry, Sources, Tallies, Physics

```
source problem
c cell cards
1 1 -10.0 -1 imp:n 1
2 1 -10.0 -2 imp:n 1
3 0 1 2 imp:n 0

c surface cards
1 sph 0 1 0 4.001
2 sph 10 15 2 2.001

c data cards
m1 92238.70c 1.0
mode n | p h
sdef par=d1 erg=fpar=d2 pos=fpar=d7 rad=fpar=d8 cel=fpar=d11
si1 1 sf n | p h
sp1 .1 .9 .5 .3 .2
ds2 s 0 3 4 5 6 $further distribution no.
si3 1 1 2 3
sp3 .1 .85 .05
si4 1 10 20 25
sp4 .5 .2 .3
si5 1 7 8 9
sp5 10 30 60
si6 1 4 7 9
sp6 15 60 25
```

Fission

- **Fission is when a nucleus receives enough energy such that the nucleus can become energetic enough to split**
 - Neutron-induced – neutron gets absorbed into actinide
 - Radioactive decay by spontaneous fission
- **When the nucleus splits some of the mass is converted into energy**
 - $E=mc^2$
 - 2 to 3 fission products are created
 - Neutrons and gammas are released
 - U-235:

Form	Emitted Energy, Mev	Recoverable Energy, Mev
Fission fragments	168	168
Fission product decay		
Beta-rays	8	8
Gamma-rays	7	7
Neutrinos	12	
Prompt gamma rays	7	7
Fission neutrons (kinetic energy)	5	5
Capture gamma-rays		3--12
Total	207	198--207

Multiplicity

- Neutron multiplicity counting is a neutron detection technique that leverages the multiplicity emissions of neutrons from fission to identify various actinides in a lump of material
- Nubar is the average amount of neutrons released per fission event
 - Decimal number, different for spontaneous and neutron-induced
 - Unique for each isotope for a given incident neutron energy

U-235
 $f(< v >) = 2.41$ (thermal)
 $Sf(< v >) = 1.86$

Neutron Multiplicity
Counter

Multiplicity (continued)

- **Number of neutrons released per fission event is called ν**
 - Per fission event an integer number of neutrons is emitted
 - ν is different for spontaneous fission and induced fission
- **The neutron emission multiplicity distribution (P_ν) is the probability that a given fission will result in the emission of a discrete amount of neutrons.**
- **U-235:**

	Gwin 84	Boldeman 84	Consensus	Std. Dev
P0	0.0306776	0.032767	0.0317223	0.0015
P1	0.1707282	0.172686	0.1717071	0.0014
P2	0.3384084	0.3339897	0.3361991	0.0031
P3	0.3036614	0.3042775	0.3039695	0.0004
P4	0.1295224	0.1243698	0.1269459	0.0036
P5	0.0248181	0.0285404	0.0266793	0.0026
P6	0.0019968	0.0032675	0.0026322	0.0009
P7	0.0001872	0.0001026	0.0001449	0.00006
<nu>	2.414	2.414	2.414	0.007
<nu(nu-1)>/2!	2.3086	2.3296	2.3191	0.0297
<nu(n-1)(n-2)>/3!	1.116416667	1.1561	1.136266667	0.1683

Spontaneous

N-induced

Multiplicity in MCNP

- **Several multiplicity emission options from spontaneous and induced fission already existed in MCNPX 2.4.0.¹**
- **These options can be accessed through use of the 6th entry on the PHYS:N card**
- **MCNPX offers 5 different FISM options dealing with fission multiplicity control as laid out in the 2.7.0 manual²:**
 - If fism=0, use the MCNP treatment, samples the integer ceiling and floor of nubar
 - If fism=1, correct the sampled nubar to preserve the average
 - If fism=2, preserve the multiplicity by increasing the nubar threshold.
 - If fism=3, sample the Gaussian distribution without correction.
 - If fism=4, use the MCNP method in the presence of spontaneous fission or the FMULT card.
 - If fism=5, use the LLNL fission model for neutron-induced, spontaneous, and photonuclear fission

LLNL Multiplicity

- **LLNL's fission multiplicity physics model**
 - Neutron-induced and spontaneous fission – neutron/gamma multiplicity counting
 - Photofission – neutron/gamma multiplicity counting
- **Added to MCNPX 2.7.B⁴ and first documented in MCNPX 2.7.C⁵**
- **Features new to MCNP include:**
 - Prompt gamma emission/multiplicity from neutron-induced fission
 - Neutron multiplicity and gamma emission/multiplicity from photofission
 - An option to enforce energy correlation for gamma/neutron multiplicity emission

Motivation for Work

- Neutron multiplicity counting can give the ability to identify various actinides in a lump of material
- IAEA's mission – “verifying through inspection systems that States comply with their commitments, under the Non-Proliferation Treaty and other non-proliferation agreements, to use nuclear material and facilities only for peaceful purposes.”³
- The identification of individual actinide concentrations, especially U-235 and Pu-239, help meet this mission's goal

Motivation for DHS

- **These new capabilities allow correlated signal detection for identifying presence of special nuclear material (SNM)**
 - Provide new simulation capability for detection strategies
- **The capabilities help meet the missions of the Domestic Nuclear Detection Office (DNDO), which is tasked with developing nuclear detection strategies for identifying potential radiological and nuclear threats⁶**

Benchmarking Method

actinides n-induced fission mult data

c cell cards

1 1 -20.0 -1 imp:n,p 1

2 0 1 imp:n,p 0

c surface cards

1 so 0.001

c data cards

m1 92235.70c 1.0

f1:p 1

e1 0.001 1000log 20

phys:n 5j 5

mode p n

sdef par=n erg=2.53e-8

lca 7j -2

nps 1e9

print

The density for SF is dropped to
increase the mean free path
thereby avoiding another collision

source particles immediately
collide; all progeny escape

actinides sf mult data

c cell cards

1 1 -0.001 -1 imp:n 1

2 0 1 imp:n 0

c surface cards

1 so 0.001

c data cards

m1 92238.70c 1.0

f21:p 1

e21 0.001 1000log 20

mode p n

sdef rad=d1 pos 0 0 0 par=sf cel=1 erg=2.53e-8

si1 0 0.001

sp1 -21 2

phys:n 100 0.0 -1 -1 5.0

nps 1e9

print

Initial Multiplicity Work

- Used data collected by Zucker and Holden⁷
- Compared the data with LLNL multiplicity
- The tests gave accurate results when compared with experiment

Neutron Induced Fission % Difference

	U-233	U-235	Pu-239	Pu-241
P0	1.33%	7.11%	0.28%	9.99%
P1	3.60%	7.41%	0.25%	0.30%
P2	1.67%	0.90%	0.16%	0.66%
P3	3.50%	3.23%	0.03%	1.04%
P4	5.44%	4.58%	0.21%	2.25%
P5	17.99%	5.81%	0.10%	1.69%
P6	19.63%	19.70%	1.23%	13.37%
P7	220.44%	45.90%	1.69%	30.89%
<v>	0.46%	0.94%	0.10%	0.45%
<v(v-1)>/2!	1.93%	1.58%	0.28%	0.89%
<v(v-1)(v-2)>/3!	4.96%	0.43%	0.71%	1.17%

Spontaneous Fission % Difference

	U-238	Pu-238	Pu-240	Pu-242	Cm-242	Cm-244
P0	0.02%	4.14%	0.01%	1.55%	0.05%	0.05%
P1	0.00%	2.57%	0.00%	6.94%	0.01%	0.01%
P2	0.01%	0.13%	0.01%	3.03%	0.00%	0.00%
P3	0.01%	1.07%	0.01%	11.59%	0.00%	0.00%
P4	0.00%	2.94%	0.00%	49.57%	0.00%	0.00%
P5	0.05%	5.34%	0.03%	29.55%	0.01%	0.01%
P6			0.00%	99.92%	0.07%	0.07%
P7					0.07%	0.02%
P8					0.30%	
<v>	0.00%	1.04%	0.00%	0.00%	0.00%	0.00%
<v(v-1)>/2!	0.00%	2.10%	0.00%	2.01%	0.00%	0.00%
<v(v-1)(v-2)>/3!	0.00%	3.20%	0.00%	6.52%	0.00%	0.00%

N.E.Holden and M.S.Zucker, "A Reevaluation of the Average Prompt Neutron Emission Multiplicity (Nubar) Values from Fission of Uranium and Transuranium Nuclides," Brookhaven National Laboratory Report: BNL-NCS-35513 (1986).

Comparison of 5 FISM Options – N-Induced

- For n-induced fission isotopes the changes for the FISM options were evident.
- Results for U-235:

	Consensus	Std. Dev	LLNL	FISM 1	FISM 2	FISM 3	% Difference (LLNL, Consensus)	%Diff. (FISM 1, Cons.)	%Diff. (FISM 2, Cons.)	%Diff. (FISM 3, Cons.)
P0	0.0317223	0.0015	3.40E-02	4.09E-02	4.48E-02	0.040518	7.11%	28.80%	41.12%	27.73%
P1	0.1717071	0.0014	1.59E-01	1.60E-01	1.55E-01	0.158996	-7.41%	-6.97%	-9.88%	-7.40%
P2	0.3361991	0.0031	3.33E-01	3.24E-01	3.23E-01	0.323182	-0.90%	-3.74%	-3.87%	-3.87%
P3	0.3039695	0.0004	3.14E-01	3.08E-01	3.08E-01	0.308095	3.23%	1.17%	1.36%	1.36%
P4	0.1269459	0.0036	1.33E-01	1.37E-01	1.38E-01	0.137673	4.58%	7.90%	8.45%	8.45%
P5	0.0266793	0.0026	2.51E-02	2.84E-02	2.87E-02	0.028666	-5.81%	6.54%	7.45%	7.45%
P6	0.0026322	0.0009	2.11E-03	2.72E-03	2.75E-03	0.002748	-19.70%	3.16%	4.40%	4.40%
P7	0.0001449	0.00006	7.84E-05	1.17E-04	1.19E-04	0.000119	-45.90%	-18.92%	-17.68%	-17.68%
P8				2.26E-06	2.30E-06	2.3E-06				
P9				2.36E-08	2.46E-08	2.46E-08				
<nu>	2.414	0.007	2.44E+00	2.44E+00	2.44E+00	2.44101	0.94%	0.94%	0.94%	1.12%
<nu(nu-1)>/2!	2.3191	0.0297	2.36E+00	2.40E+00	2.40E+00	2.40396	1.58%	3.30%	3.66%	3.66%
<nu(n-1)(n-2)>/3!	1.1362667	0.1683	1.14E+00	1.20E+00	1.20E+00	1.20472	0.43%	5.45%	6.02%	6.02%

- The 4th FISM option is only applicable to spontaneous fission

Comparison of FISM Option - Spontaneous

- Only % differences of 0.05% or less between the first four FISM options and the consensus results in Zucker Holden.
- 5 FISM options appear to give the same results
- Results for U-238:

	Consensus	Std. Dev	LLNL	FISM 1	FISM 2	FISM 3	FISM 4	% Difference (LLNL, Consensus)	%Diff. (FISM 1, Cons.)	%Diff. (FISM 2, Cons.)	%Diff. (FISM 3, Cons.)	%Diff. (FISM 4, Cons.)
P0	0.0481677	0.0054	4.82E-02	4.82E-02	4.82E-02	4.82E-02	4.82E-02	0.02%	0.02%	0.02%	0.02%	0.02%
P1	0.2485215	0.0403	2.49E-01	2.49E-01	2.49E-01	2.49E-01	2.49E-01	0.00%	0.00%	0.00%	0.00%	0.00%
P2	0.4253044	0.0839	4.25E-01	4.25E-01	4.25E-01	4.25E-01	4.25E-01	-0.01%	-0.01%	-0.01%	-0.01%	-0.01%
P3	0.2284094	0.0263	2.28E-01	2.28E-01	2.28E-01	2.28E-01	2.28E-01	0.01%	0.01%	0.01%	0.01%	0.01%
P4	0.0423438	0.0108	4.23E-02	4.23E-02	4.23E-02	4.23E-02	4.23E-02	0.00%	0.00%	0.00%	0.00%	0.00%
P5	0.0072533	0.0011	7.25E-03	7.25E-03	7.25E-03	7.25E-03	7.25E-03	-0.05%	-0.05%	-0.05%	-0.05%	-0.05%
<nu>	1.99	1.99E+00	1.99E+00	1.99E+00	1.99E+00	1.99E+00	1.99E+00	0.00%	0.00%	0.00%	0.00%	0.00%
<nu(nu-1)>/2!	1.43715	1.44E+00	1.44E+00	1.44E+00	1.44E+00	1.44E+00	1.44E+00	0.00%	0.00%	0.00%	0.00%	0.00%
<nu(n-1)(n-2)>/3!	0.4703167	4.70E-01	4.70E-01	4.70E-01	4.70E-01	4.70E-01	4.70E-01	0.00%	0.00%	0.00%	0.00%	0.00%

Comparison of FISM options - Spontaneous

- Options 1 – 4 are exactly the same
- Option 5 (LLNL option) does vary slightly from the others

1problem summary				source particle weight for				50 -1.299E-04 9.709E-05 5.300E-04 1 0 -8.006E-01 4.905E-01				1problem summary				source particle weight for			
run terminated when 10000000 particle histories were done.								run terminated when 10000000 particle histories were done.											
+ actinides sf mult data								+ actinides sf mult data											
neutron creation	tracks	weight (per source particle)	energy	neutron loss				neutron creation	tracks	weight (per source particle)	energy	neutron loss							
source	19897991	1.0000E+00	1.6882E+00	escape				source	19897988	1.0000E+00	1.6879E+00	escape							
nucl. interaction	0	0.	0.	energy cutoff				nucl. interaction	0	0.	0.	energy cutoff							
particle decay	0	0.	0.	time cutoff				particle decay	0	0.	0.	time cutoff							
weight window	0	0.	0.	weight wind				weight window	0	0.	0.	weight wind							
cell importance	0	0.	0.	cell import.				cell importance	0	0.	0.	cell import.							
weight cutoff	0	0.	0.	weight cutoff				weight cutoff	0	0.	0.	weight cutoff							
energy importance	0	0.	0.	energy impor				energy importance	0	0.	0.	energy impor							
dxtran	0	0.	0.	dxtran				dxtran	0	0.	0.	dxtran							
forced collisions	0	0.	0.	forced coll				forced collisions	0	0.	0.	forced coll							
exp. transform	0	0.	0.	exp. transfo				exp. transform	0	0.	0.	exp. transfo							
upscattering	0	0.	0.	downscatter				upscattering	0	0.	0.	downscatter							
*photonuclear	0	0.	0.	capture				*photonuclear	0	0.	0.	capture							
(n,xn)	0	0.	0.	loss to (n,				(n,xn)	0	0.	0.	loss to (n,							
prompt fission	0	0.	0.	loss to fis				prompt fission	0	0.	0.	loss to fis							
delayed fission	0	0.	0.	nucl. inter.				delayed fission	0	0.	0.	nucl. inter.							
*prompt photofiss	0	0.	0.	particle de				*prompt photofiss	0	0.	0.	particle de							
tabular boundary	0	0.	0.	tabular bou				tabular boundary	0	0.	0.	tabular bou							
tabular sampling	0	0.	0.					tabular sampling	0	0.	0.								
total	19897991	1.0000E+00	1.6882E+00	total				total	19897988	1.0000E+00	1.6879E+00	total							
number of sources loaded				source particle weight for				number of sources loaded				source particle weight for				number of sources loaded			
----- by number -----				----- by number -----				----- by number -----				----- by number -----				----- by number -----			
fissions	neutrons	multiplicity	fraction	fissions	n-			fissions	neutrons	multiplicity	fraction	fissions	n-			fissions	neutrons	multiplicity	fraction
nu = 0	482690	0	4.82690E-02	2.42582E-02	0.00			nu = 0	482690	0	4.82690E-02	2.42582E-02	0.00			nu = 0	482690	0	4.82690E-02
nu = 1	2484410	2484410	2.48441E-01	1.24857E-01	1.24			nu = 1	2484410	2484410	2.48441E-01	1.24857E-01	1.24			nu = 1	2484410	2484410	2.48441E-01
nu = 2	4252273	8504546	4.25227E-01	2.13704E-01	4.27			nu = 2	4252275	8504550	4.25227E-01	2.13704E-01	4.27			nu = 2	4252275	8504550	4.25227E-01
nu = 3	2285586	6856758	2.28558E-01	1.14865E-01	3.44			nu = 3	2285584	6856752	2.28558E-01	1.14865E-01	3.44			nu = 3	2285584	6856752	2.28558E-01
nu = 4	422928	1691712	4.22928E-02	2.12548E-02	8.50			nu = 4	422929	1691716	4.22929E-02	2.12549E-02	8.50			nu = 4	422929	1691716	4.22929E-02
nu = 5	72113	360565	7.21130E-03	3.62413E-03	1.81			nu = 5	72112	360560	7.21120E-03	3.62409E-03	1.81			nu = 5	72112	360560	7.21120E-03
total	10000000	19897991	1.0000E+00	5.02563E-01	1.00			total	10000000	19897988	1.0000E+00	5.02563E-01	1.00			total	10000000	19897988	1.0000E+00

Print Table 38

- Neutron-induced fission uses width and watt parameters from print table 38; gets nubar from ENDF files
- Spontaneous fission will use width, watt, and sfnu unless the extra values exist

zaid	width	watt1	watt2	yield	sfnu
90232	1.079000	0.800000	4.000000	6.00E-08	2.140
92232	1.079000	0.892204	3.722780	1.30E+00	1.710
92233	1.041000	0.854803	4.032100	8.60E-04	1.760
92234	1.079000	0.771241	4.924490	5.02E-03	1.810
* 92235	1.072000	0.774713	4.852310	2.99E-04	1.860
92236	1.079000	0.735166	5.357460	5.49E-03	1.910
92238	1.230000	0.648318	6.810570	1.36E-02	0.048 0.297 0.722 0.950 0.993 1.000 1.000 1.000 1.000 1.000
93237	1.079000	0.833438	4.241470	1.14E-04	2.050
94236	0.000000	0.000000	0.000000	0.00E+00	0.080 0.293 0.670 0.905 0.980 1.000 1.000 1.000 1.000 1.000
94238	1.115000	0.847833	4.169330	2.59E+03	0.056 0.267 0.647 0.869 0.974 1.000 1.000 1.000 1.000 1.000
94239	1.140000	0.885247	3.802690	2.18E-02	2.160
94240	1.109000	0.794930	4.689270	1.02E+03	0.063 0.295 0.628 0.881 0.980 0.998 1.000 1.000 1.000 1.000
94241	1.079000	0.842472	4.151500	5.00E-02	2.250
94242	1.069000	0.819150	4.366680	1.72E+03	0.068 0.297 0.631 0.879 0.979 0.997 1.000 1.000 1.000 1.000
95241	1.079000	0.933020	3.461950	1.18E+00	3.220
96242	1.053000	0.887353	3.891760	2.10E+07	0.021 0.168 0.495 0.822 0.959 0.996 0.999 1.000 1.000 1.000
96244	1.036000	0.902523	3.720330	1.08E+07	0.015 0.131 0.431 0.764 0.948 0.991 1.000 1.000 1.000 1.000
96246	0.000000	0.000000	0.000000	0.00E+00	0.015 0.091 0.354 0.699 0.917 0.993 1.000 1.000 1.000 1.000
96248	0.000000	0.000000	0.000000	0.00E+00	0.007 0.066 0.287 0.638 0.892 0.982 0.998 1.000 1.000 1.000
97249	1.079000	0.891281	3.794050	1.00E+05	3.400
98246	0.000000	0.000000	0.000000	0.00E+00	0.001 0.114 0.349 0.623 0.844 0.970 1.000 1.000 1.000 1.000
98250	0.000000	0.000000	0.000000	0.00E+00	0.004 0.040 0.208 0.502 0.801 0.946 0.993 0.997 1.000 1.000
98252	1.207000	1.180000	1.034190	2.34E+12	0.002 0.028 0.153 0.427 0.733 0.918 0.984 0.998 1.000 1.000
98254	0.000000	0.000000	0.000000	0.00E+00	0.000 0.019 0.132 0.396 0.714 0.908 0.983 0.998 1.000 1.000
100257	0.000000	0.000000	0.000000	0.00E+00	0.021 0.073 0.190 0.390 0.652 0.853 0.959 0.993 1.000 1.000
102252	0.000000	0.000000	0.000000	0.00E+00	0.057 0.115 0.207 0.351 0.534 0.717 0.863 0.959 0.997 1.000

Options in LLNL Source Code

- **The source code allows data to be used from different sources for neutron-induced fission, spontaneous fission for Cf-252, and energy correlation between neutrons and gammas.**
- **The options are named and described as follows:**
 - `nudistoption` – provides four options for neutron multiplicity distributions
 - `ndistoption` – provides choice between one of two data sets for the neutron number distribution for the spontaneous fission of Cf-252
 - `correlationoption` – provides three options for neutron/gamma-ray energy correlation.
- **For the runs the options were changed and the source code was recompiled**
 - Print statements were added to the code to ensure that the changes were taking effect.

Nudist Runs

- The value for `nudistoption` was set from 0 to 3 and run for U-233, U-235, Pu-239, and Pu-241.
- An example of the input deck used is shown:
- For each of the isotopes runs were performed with `erg` set to 2.53e-8 MeV, 5 MeV, and 15MeV
 - For options 0 and 1 when `erg` > 10 MeV, 10 MeV is used to generate `Pv`

```
92235n_nudist - Notepad
File Edit Format View Help
actinides n-induced fission mult data
c cell cards
1 1 -20.0 -1 imp:n,p 1
2 0 1 imp:n,p 0

c surface cards
1 so 0.001

c data cards
m1 92235.70c 1.0
f1:p 1
e1 0.001 1000log 20
f21:n 1
e21 0.001 1000log 20
phys:n 5j 5
mode p n
sdef par=n erg=2.53e-8
lca 7j -2
nps 1e9
print
```

Nudist Results – U-235

- At 15 MeV for nudistoption 0 and 1 the nubar value for 10 MeV is used
- For options 2 and 3 the nubar value for 15 MeV is used.
- Described in Verbeke et al.²
- This is evident in the percent differences between 15 MeV and thermal with the nudist option set to 3 (bottom right table).
- The percent difference for options 0 and 1 are 59%, which is correct for 10 MeV, while the percent difference for option 2 and 3 are 86%, which is correct for 15 MeV.

	% Difference 5 MeV, Thermal				%Difference 15 MeV, Thermal			
	nudist=0	nudist=1	nudist=2	nudist=3	nudist=0	nudist=1	nudist=2	nudist=3
P0	-75.25%	-73.03%	-74.10%	-77.24%	-98.62%	-98.50%	-99.70%	-99.74%
P1	-53.29%	-51.69%	-52.89%	-50.07%	-95.34%	-95.18%	-98.61%	-98.52%
P2	-26.94%	-26.94%	-26.67%	-26.61%	-70.19%	-70.19%	-91.87%	-91.88%
P3	8.82%	7.63%	7.79%	5.42%	-8.56%	-9.59%	-54.79%	-55.82%
P4	80.50%	71.89%	76.34%	73.43%	163.32%	150.77%	142.99%	139.54%
P5	213.84%	223.25%	196.99%	235.91%	637.03%	659.14%	1051.02%	1203.93%
P6	609.99%	789.86%	587.97%	796.82%	2369.06%	2994.67%	5408.31%	7078.28%
P7	2410.48%	#DIV/0!	2117.75%	4960.30%	10846.89%	#DIV/0!	17214.10%	40010.73%
P8								220774.30%
P9								1153090.83%
<nu>	25.89%	24.75%	24.99%	24.98%	60.52%	59.08%	86.14%	86.22%
<nu(nu-1)>/2!	64.47%	62.35%	61.95%	62.59%	169.41%	166.05%	265.29%	267.17%
<nu(n-1)(n-2)>/3!	128.63%	127.39%	122.66%	129.04%	383.32%	381.27%	664.70%	688.20%

	%Difference 5 MeV, Thermal (nudist=3)				%Difference 15 MeV, Thermal (nudist=3)			
	nudist=0	nudist=1	nudist=2	nudist=3	nudist=0	nudist=1	nudist=2	nudist=3
P0	-76.90%	-76.90%	-77.25%	-77.24%	-98.72%	-98.72%	-99.74%	-99.74%
P1	-49.55%	-49.55%	-50.11%	-50.07%	-94.96%	-94.96%	-98.52%	-98.52%
P2	-26.27%	-26.27%	-26.73%	-26.61%	-69.92%	-69.92%	-91.88%	-91.88%
P3	5.41%	5.44%	5.34%	5.42%	-11.42%	-11.42%	-55.82%	-55.82%
P4	72.59%	72.59%	73.84%	73.43%	151.78%	151.78%	139.54%	139.54%
P5	233.15%	233.15%	236.45%	235.91%	682.38%	682.38%	1203.93%	1203.93%
P6	784.61%	784.59%	796.54%	796.82%	2976.32%	2976.32%	7078.28%	7078.28%
P7	5020.88%	4907.99%	5037.75%	4960.30%	22229.50%	22229.50%	40010.73%	40010.73%
P8								220774.30%
P9								1153090.83%
<nu>	24.73%	24.71%	25.05%	24.98%	59.03%	59.03%	86.22%	86.22%
<nu(nu-1)>/2!	61.93%	61.86%	62.78%	62.59%	165.25%	165.25%	267.17%	267.17%
<nu(n-1)(n-2)>/3!	127.74%	127.47%	129.50%	129.04%	381.44%	381.44%	688.20%	688.20%

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Nudist Results – U-235

Neutron

Nudist Results – U235

Ndist Runs

- The `ndistoption` allows the user to select between the use of experimental multiplicity data for Cf – 252 by Spencer et al.⁸ or Boldeman⁹.
- The results of the runs when compared to the experimental data is shown below.

	Spencer	Error	Boldeman	Error	ndist 0	Rel. Error	ndist 1	Rel. Error	% Difference (ndist 0, Spencer)	%Diff. (ndist 1, Boldeman)
P0	0.00217	0.00007	2.12E-03	8.00E-05	2.11E-03	7.00E-04	2.09E-03	7.00E-04	-2.66%	-1.31%
P1	0.0256	0.00129	2.60E-02	2.50E-04	2.47E-02	2.00E-04	2.62E-02	2.00E-04	-3.59%	0.92%
P2	0.12394	0.00138	1.27E-01	5.00E-04	1.23E-01	1.00E-04	1.26E-01	1.00E-04	-0.85%	-0.41%
P3	0.27146	0.00107	2.73E-01	8.00E-04	2.71E-01	1.00E-04	2.75E-01	1.00E-04	-0.01%	0.66%
P4	0.30463	0.00048	3.04E-01	1.00E-03	3.08E-01	1.00E-04	3.02E-01	1.00E-04	0.98%	-0.69%
P5	0.18662	0.00055	1.85E-01	7.00E-04	1.88E-01	1.00E-04	1.85E-01	1.00E-04	0.58%	-0.11%
P6	0.06812	0.00035	6.57E-02	6.00E-04	6.77E-02	1.00E-04	6.68E-02	1.00E-04	-0.61%	1.68%
P7	0.01516	0.00012	1.54E-02	3.00E-04	1.41E-02	3.00E-04	1.50E-02	3.00E-04	-7.29%	-2.63%
P8	0.0021	0.00003	2.00E-03	2.00E-04	1.67E-03	8.00E-04	2.10E-03	7.00E-04	-20.48%	5.01%
P9	0.00019	0.00001			1.21E-04	2.90E-03			-36.50%	
<nu>	3.773		3.76E+00		3.77E+00	0.00E+00	3.76E+00	0.00E+00	0.00%	0.00%

Correlation Runs

- **Correlationoption provides three different options for correlating the energy between the neutron and gamma-rays**
 - 0) (default) for no correlation between neutrons and photons
 - 1) total fission neutron energy and total fission gamma-ray energy are sampled from normal distributions of means given in Beck et al¹⁰.
 - 2) total fission neutron energy and total fission gamma-ray energy are sampled from normal distributions of means given in Vogt¹¹.
 - 3) total correlation – does not exist
- **For options 1 and 2 there is no correlation between the number of neutrons and the number of gamma-rays**

Correlation Results – U-235

- Correl 1 and 2 cut off at 10 MeV
- Correl 0 is not

Correlation Results – U-235

- Photon energy distribution
- Integral is total amount of gammas
- 7 gammas at 0.8 MeV each give a total of 5.6 MeV of energy

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Correlation Results – U-235

photon creation	tracks	weight (per source particle)	energy
source	0	0.	0.
nucl. interaction	0	0.	0.
particle decay	0	0.	0.
weight window	0	0.	0.
cell importance	0	0.	0.
weight cutoff	0	0.	0.
energy importance	0	0.	0.
dxtran	0	0.	0.
forced collisions	0	0.	0.
exp. transform	0	0.	0.
from neutrons	6532320613	5.9957E+00	5.8239E+00
bremsstrahlung	0	0.	0.
p-annihilation	0	0.	0.
*photonuclear	0	0.	0.
electron x-rays	0	0.	0.
1st fluorescence	0	0.	0.
2nd fluorescence	0	0.	0.
(gamma,xgamma)	0	0.	0.
tabular sampling	0	0.	0.
*prompt photofiss	0	0.	0.
total	6532320613	5.9957E+00	5.8239E+00

Conclusions

- **The results for the initial multiplicity testing:**
 - ANS paper show reasonable agreement for n-induce and spontaneous fission for most multiplicities and moments of nubar
- **The results for the FISM option tests:**
 - If there are columns > column 6 in print table 38, FISM options are not applicable for par=sf
 - FISM=5 is slightly different because of the cumulative distribution in LLNL which is slightly different from that in MCNPX 2.7.0
- **The results for the nudist option runs:**
 - Thermal not in agreement with other energies
- **The results for the correlation option runs:**
 - Agreement between Beck (option 1) and Vogt (option 2) for neutron plot
 - Option 0 (no correlation) results for photons are > than Beck (1) and Vogt (2)
 - There is no correlation option for number of neutrons and gammas

Future Work

■ Photofission option

- Collected several papers with experimental data on photofission neutron multiplicities to be used to compare with the LLNL multiplicity code
- This is the final feature of the LLNL multiplicity code that needs to be tested

■ Look into correlation option 3

- This 4th option was referenced in the Fission Library Interface section of the paper by Verbeke et al and is also partially in the source code but is not complete
- The option would correlate the number and energy between neutrons and photons

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Questions?