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Title:	Physics and Algorithm Enhancements for a Validated MCNP/X Monte Carlo Simulation Tool, Phase VII
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Physics & Algorithm Enhancements for a Validated MCNP/X Monte Carlo Simulation Tool, Phase VII

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ABSTRACT

Currently the US lacks an end-to-end (i.e., source-to-detector) radiation transport simulation code with predictive capability for the broad range of DHS nuclear material detection applications. For example, gaps in the physics, along with inadequate analysis algorithms, make it difficult for Monte Carlo simulations to provide a comprehensive evaluation, design, and optimization of proposed interrogation systems. With the development and implementation of several key physics and algorithm enhancements, along with needed improvements in evaluated data and benchmark measurements, the MCNP/X Monte Carlo codes will provide designers, operators, and systems analysts with a validated tool for developing state-of-the-art active and passive detection systems. This project is currently in its seventh year (Phase VII). This presentation will review thirty enhancements that have been implemented in MCNPX over the last 3 years and were included in the 2011 release of version 2.7.0. These improvements include 12 physics enhancements, 4 source enhancements, 8 tally enhancements, and 6 other enhancements. Examples and results will be provided for each of these features. The presentation will also discuss the eight enhancements that will be migrated into MCNP6 over the upcoming year.

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Physics and Algorithm Enhancements for a Validated MCNP/X Monte Carlo Simulation Tool, Phase VII

Gregg W. McKinney

DNDO/NSF ARI Grantees Conference

Leesburg, VA, July 23-25, 2012

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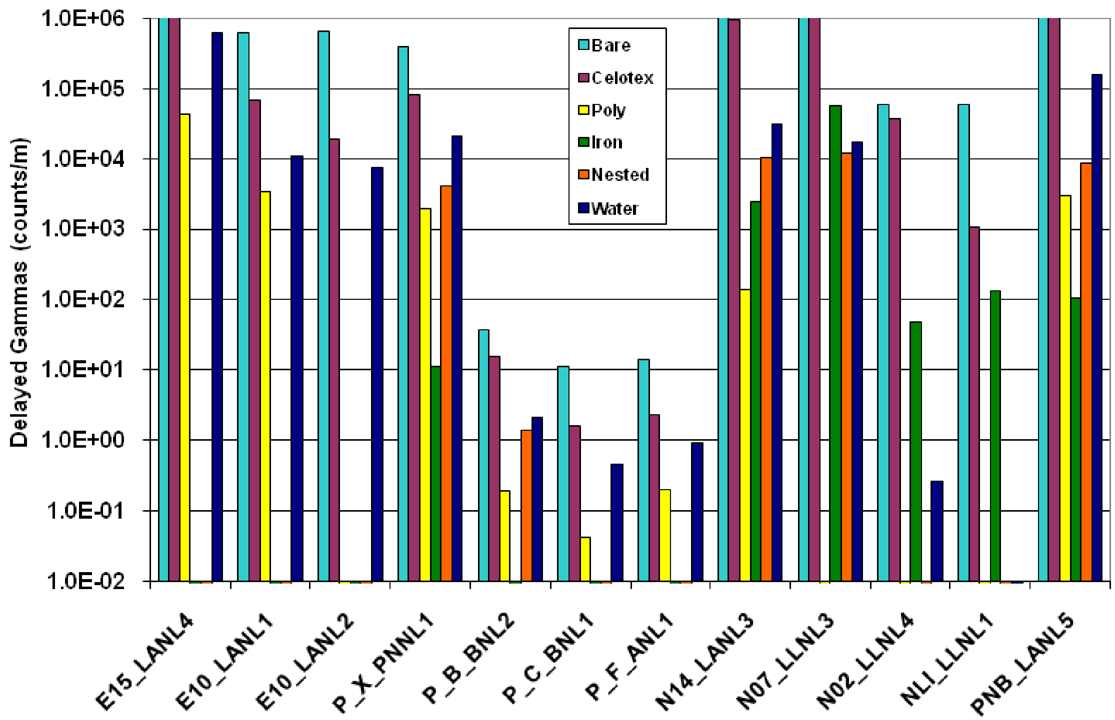
Outline

- MCNP overview
- DNDO MCNP project overview
- Highlights of various features

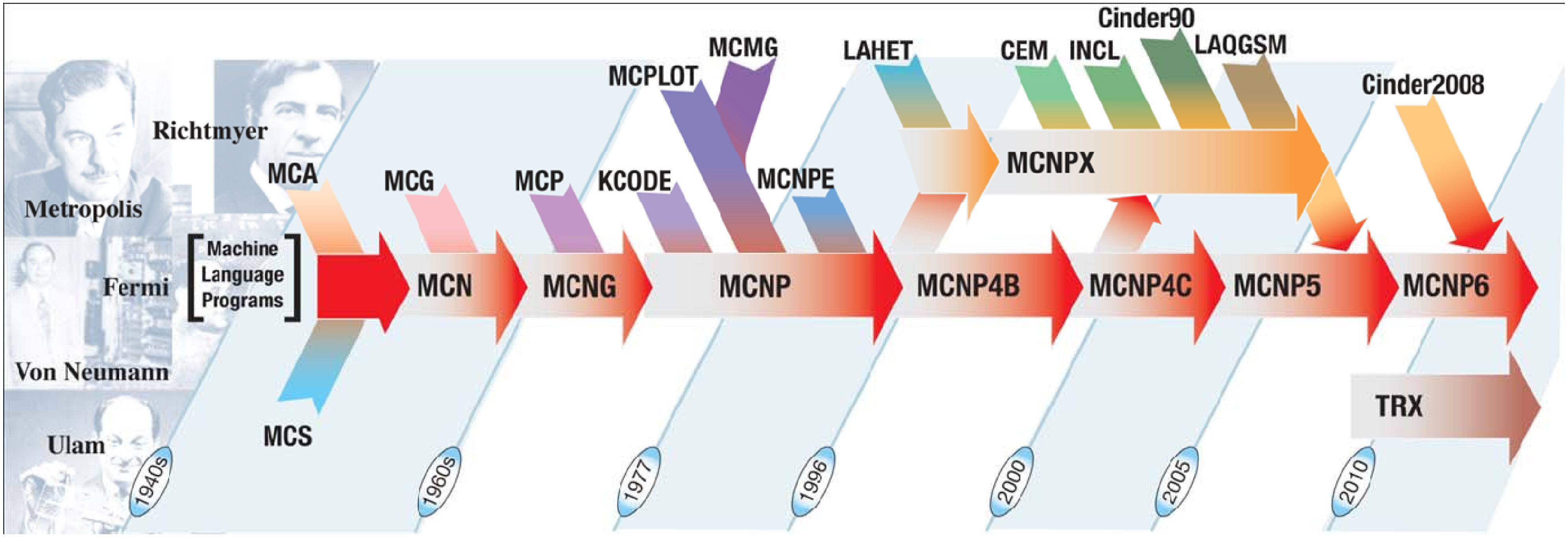
Simulation status as of June 2006:
- Results had large uncertainties
- Execution times were very long
- Lacked background contributions
- One-off delayed gamma treatment



MCNPX/MCNP6 are 3-D, all-particle, all-energy Monte Carlo transport codes

- **Monte Carlo radiation transport code**
  - Extends MCNP4C to virtually all particles and energies
  - 34 different particle types + 2205 heavy ions
    - Neutrons, photons, electrons, protons, pions, muons, light-ions, etc.
  - Continuous energy (~0 -1 TeV/n)
  - Data libraries below ~150 MeV (n,p,e,h) & models otherwise
- **General 3-D geometry**
  - 1st & 2nd degree surfaces, tori, 10 macrobodies, lattices
- **General sources and tallies**
  - Interdependent source variables, 7 tally types, many modifiers
- **Supported on virtually all computer platforms**
  - Unix, Linux, Windows, OS X (parallel with MPI)

MCNP has been under development for almost a century – and it wasn't always called MCNP!



MCNPX Public Versions

2.1.5, 1999

2.3.0 & 2.4.0, 2002

2.5.0, 2005

2.6.0, 2008

2.7.0, 2011

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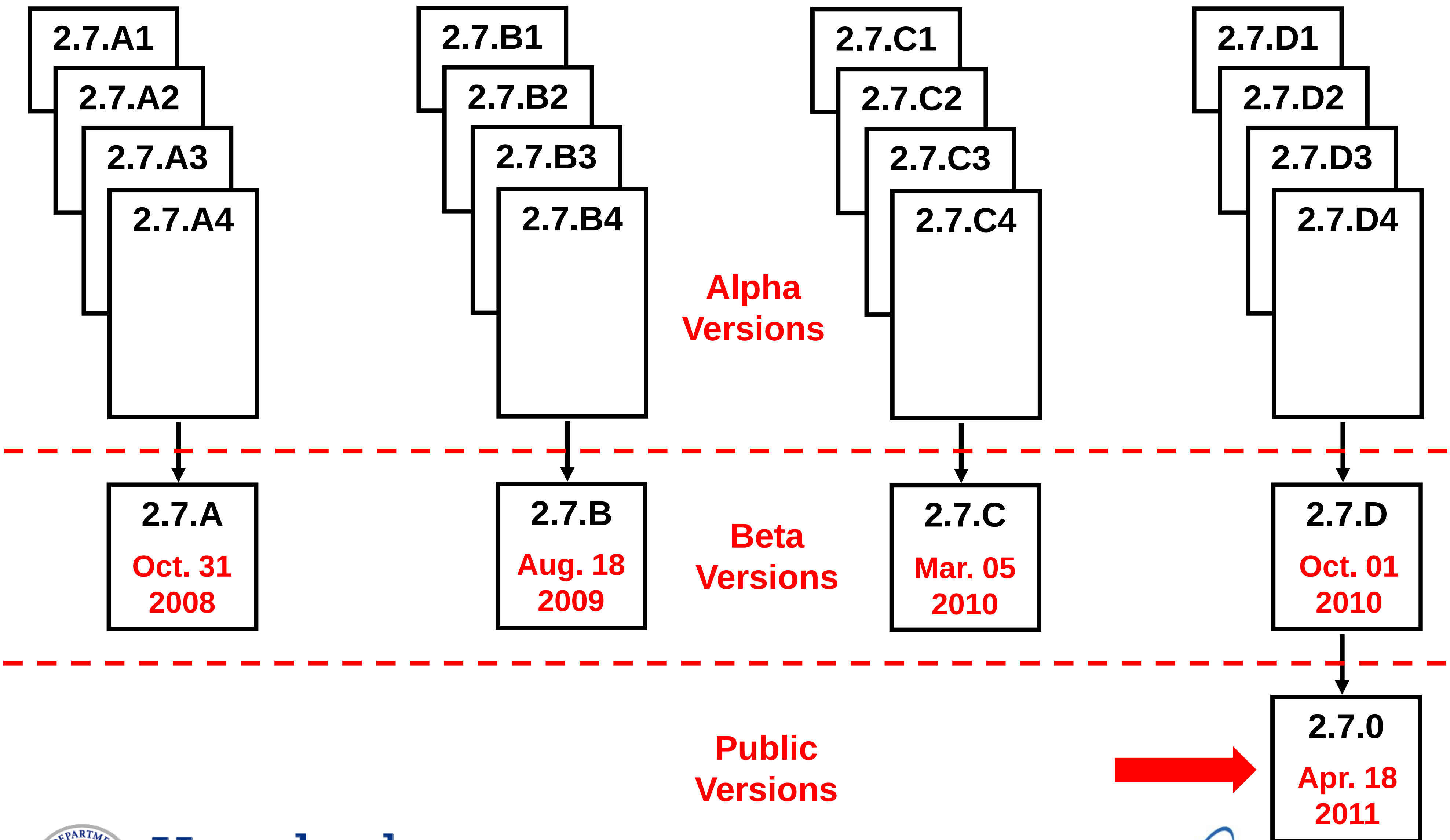
The current century of development – why so many versions of MCNPX?



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Resources for MCNP/X users

- **~3000 users world wide**
  - Provide ~6 workshops per year (~4 US, 2 international)
  - 1-2 workshops per year have a HS emphasis
  - Access to RSICC released versions only
    - http://www-rsicc.ornl.gov/ (BCC-004) 2.7.0
  - Limited access to MCNPX web site
    - http://mcnpx.lanl.gov (some documentation and data)
- **~2000 registered Beta Users**
  - Full access to MCNPX web site
  - Access to intermediate Beta versions
  - Increased user support

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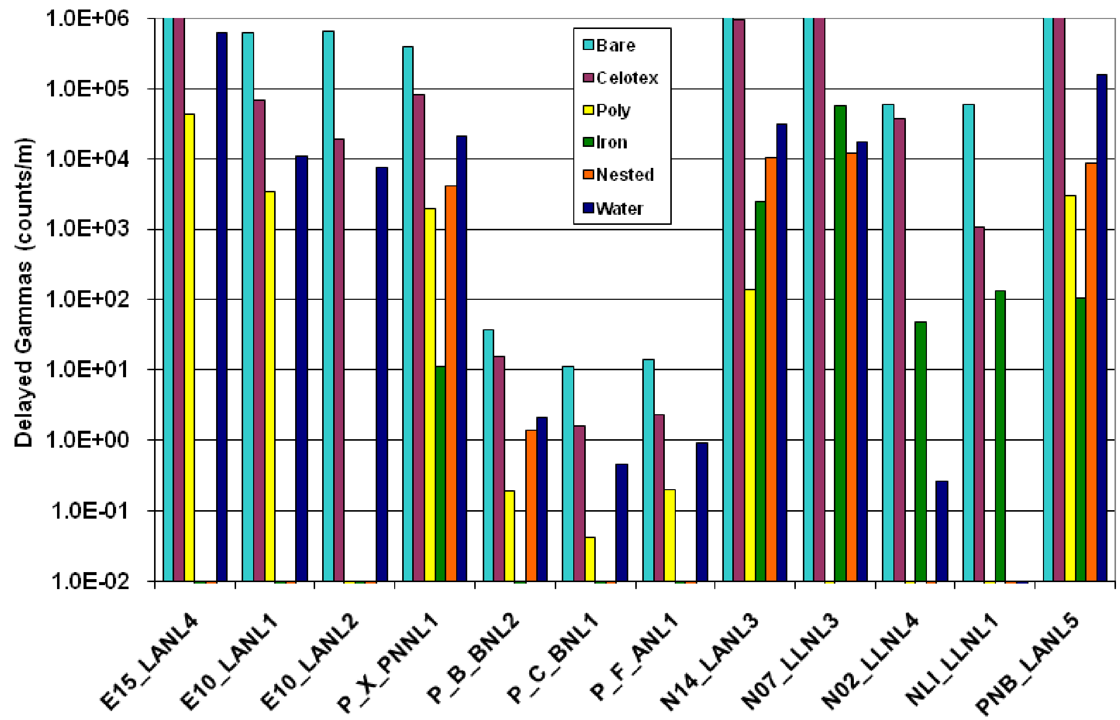

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MCNP/X is an essential tool for predicting radiation detector system performance

- U.S. needs a single end-to-end (i.e., source-to-detector) simulation tool to evaluate, design, and optimize SNM detection systems
- Physics and algorithm upgrades were identified to enable simulation of DHS detection systems
- Upgrades for the MCNP/X transport code are being developed to:
  - Incorporate all signal and background signatures
  - Span the range of DHS design and analysis needs
  - Predict and optimize receiver-operator characteristic (ROC) curves

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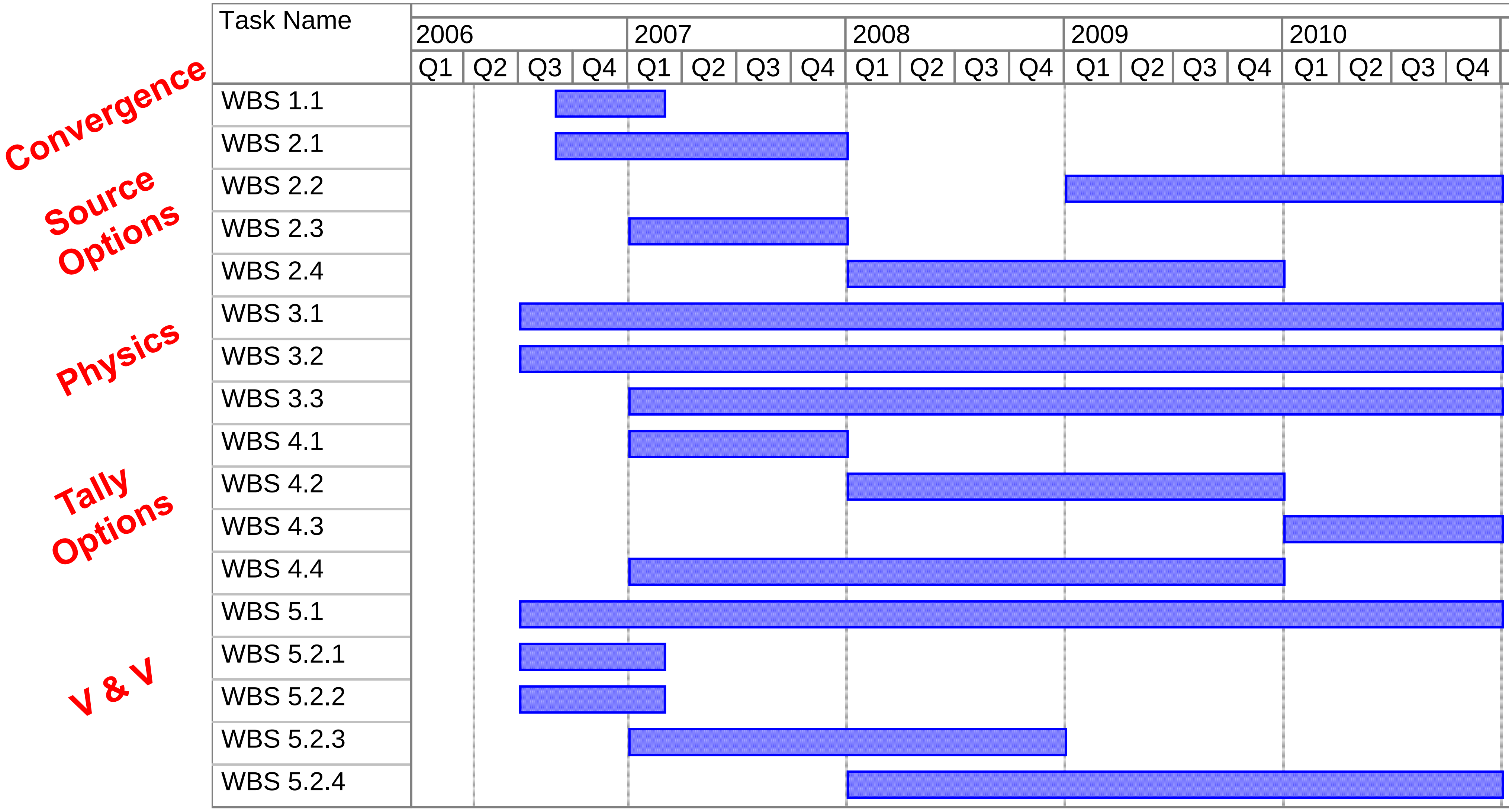
Project plan includes a prioritized approach with a commitment to verification and validation

- Created a prioritized list of capabilities to address gaps
  - Includes ~~~12~~ 18 features implemented over ~~5~~ 7 years
  - Important physics upgrades developed first
  - Algorithm and data refinements primarily in the out years
- Accomplish objectives by:
  - Following standard SQA procedures (verification)
  - V~~alidating new physics with benchmark measurements~~ Eliminated
  - Releasing new MCNP versions to DHS users
- Project contributors
  - MCNPX code development team (NEN-5)
  - Nuclear data and modeling team (T-2)

Project Gantt chart – top level tasks separated into five categories



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Plans and Schedule – Top level FY11 tasks

- Automatic production of background activation (6 of 6 yr)
- Neutron & gamma background sources (2 of 2 yr)
- Time dependent pulse-height tallies (2 of 2 yr)
- Test suite improvements to provide verification (6 of 6 yr)
- Correlated secondary particle production (5 of 5 yr)
- Improvements in photonuclear data (6 of 6 yr)
- Directional photon tallies (1 of 2 yr)
- Vulnerability analysis (2 of 2 yr)

Plans and Schedule – Top level FY12 tasks

- Migrate delayed beta feature from MCNPX to MCNP6
- Migrate pulse-height trigger feature from MCNPX to MCNP6
- Update cosmic source feature to MCNP6 main trunk
- Update background source feature to MCNP6 main trunk
- Migrate other features to MCNP6
  - Low-energy secondary particle correlations (CGM Link)
  - Compton image tally option
  - Scintillator response curves
  - Fixed-source eigenvalue

MCNPX public version 2.6.0 – DNDO sponsored features account for ~40% of new capabilities

Physics Enhancements

Muon capture physics
Integration of the LAQGSM event generator
Heavy-ion transport
Integration of the Cinder code
Photo-fission yield data
Delayed particles from activation
Upgrade of the CEM event generator
Ion production from library neutron capture
Gravity effects for neutrons
Updated photon de-excitation data

Source Enhancements

Transmutation with KCODE
Acceleration of KCODE source convergence
Spontaneous decay photon sources

Tally Enhancements

Termination based on precision
Spherical mesh tally plots
Differential tallies extended to library events

Variance Reduction Enhancements

Spherical mesh WW (weight windows)
Coupled space-energy-time WW
Additional WW controls

Other Enhancements

Long file names
Proton step size control
Output for induced-fission multiplicity
Several graphics enhancements

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MCNPX public version 2.7.0 – DNDO sponsored features account for ~60% of new capabilities

Physics Enhancements

CEM upgrade to 03.02
Adjustable stopping-power grid
LLNL photofission multiplicities
Delayed gamma exact sampling
LLNL neutron fission multiplicities
Muonic x-ray enhancements
Delayed neutron spectra
NRF data in ACE libraries
Improved photoatomic form factors
DG algorithm improvements
GEF photofission yields
LAQGSM upgrade to 03.03

Source Enhancements

Burnup enhancements
Pulsed sources
Beam source options
Natural background sources

Tally Enhancements

Tally tagging*
LET tally option
Quality factor tally option
Cyclic tally binning
ROC curve tally option
Residual tally upgrades
Triple & quadruple coincidences
Time-dependent pulse-height tallies

Other Enhancements

MCPLOT graphics enhancements
Activation options (ACT card)
MCPLOT tally manipulations
Nested READ cards
Feature-based memory reduction
M & MX card extensions

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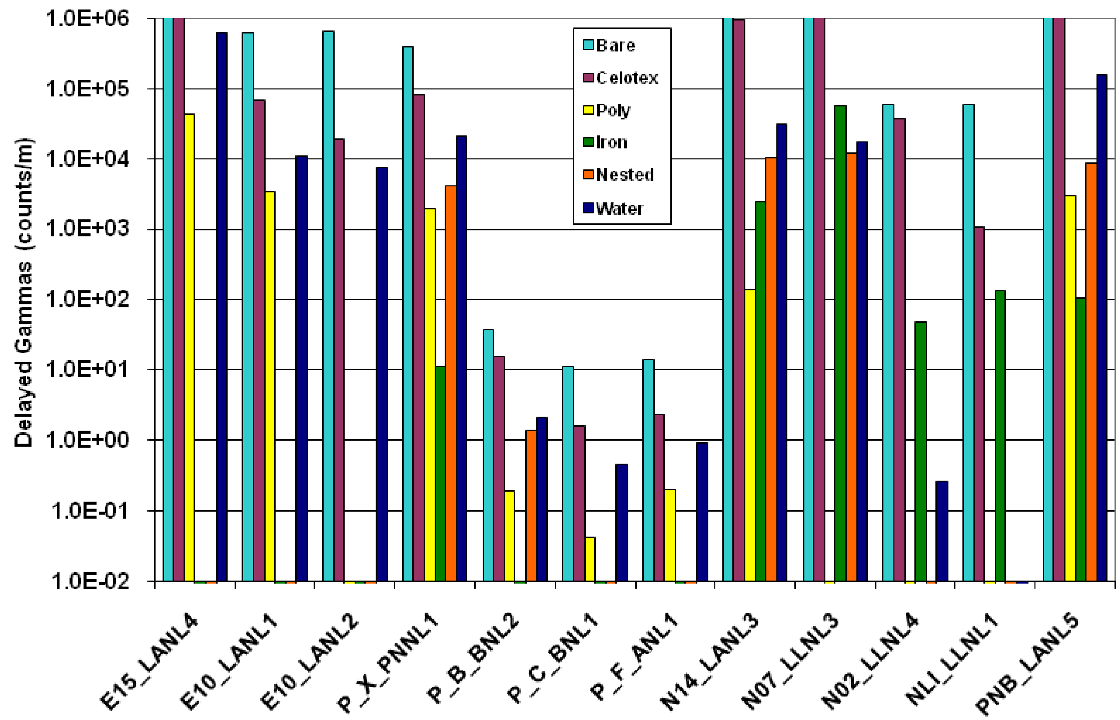

Physics: LLNL fission multiplicity – benchmarking of neutron multiplicity from thermal neutron induced fission

Comparison to Measured Data (Holden, 1986)

	U-233	U-235	Pu-239	[illegible]41
P0	1.33%	7.11%	0.[illegible]	[illegible].99%
P1	3.60%	7.41%	[illegible]	0.30%
P2	1.67%	0.90[illegible]	[illegible]%	0.66%
P3	3.50%	[illegible]	0.03%	1.04%
P4	5.44%	[illegible]	0.21%	2.25%
P5	17.[illegible]	[illegible]31%	0.10%	1.69%
P6	[illegible]	19.70%	1.23%	13.37%
P7	[illegible]%	45.90%	1.69%	30.89%
1st mome[illegible]	[illegible].46%	0.94%	0.10%	0.45%
2nd [illegible]	1.93%	1.58%	0.28%	0.89%
3rd m[illegible]t	4.96%	0.43%	0.71%	1.17%

T. A. Wilcox et al., "MCNP6 Fission Multiplicity," Proceedings of the ANS Annual Meeting, Chicago, IL, June 24-28 (2012)

Physics: LLNL fission multiplicity – benchmarking of neutron multiplicity from spontaneous fission

Comparison to Measured Data (Holden, 1986)

	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%	
1st moment	0.00%	1.04%	0.00%	0.00%	0.00%	0.00%
2nd moment	0.00%	2.10%	0.00%	2.01%	0.00%	0.00%
3rd moment	0.00%	3.20%	0.00%	6.52%	0.00%	0.00%

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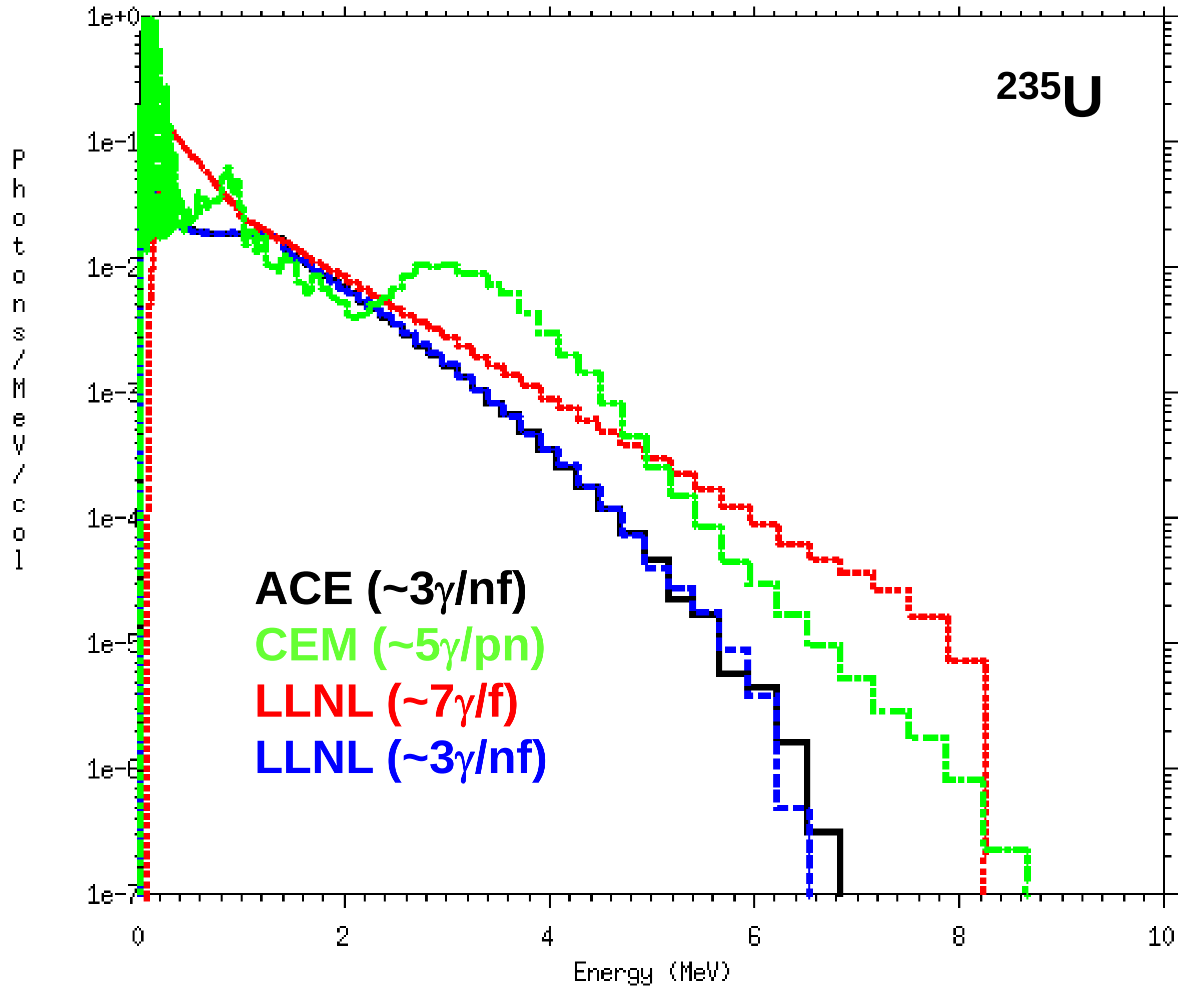
Physics: LLNL fission multiplicity – provides prompt gammas from photofission (physics gap in ACE libraries)

```
12-MeV photons into U-235
1  1  -19.0     -1  imp:n=1
2  0             1  imp:n=0

1  so  1.0

mode n p
m1   92235 1  pnlib=.70u
PHYS:P j 1 j 1 2j 1 $ LLNL model
sdef par=p erg=12
LCA  7j -2
f1:n  1
e1    1e-6 199log 12
f11:p 1
e11   1e-3 199log 12
ft11  tag 3
fu11  -1 0.00004 92000.00003
     92235.00005 92000.00005
     92235.00018 1e10
nps   1000000
print
```



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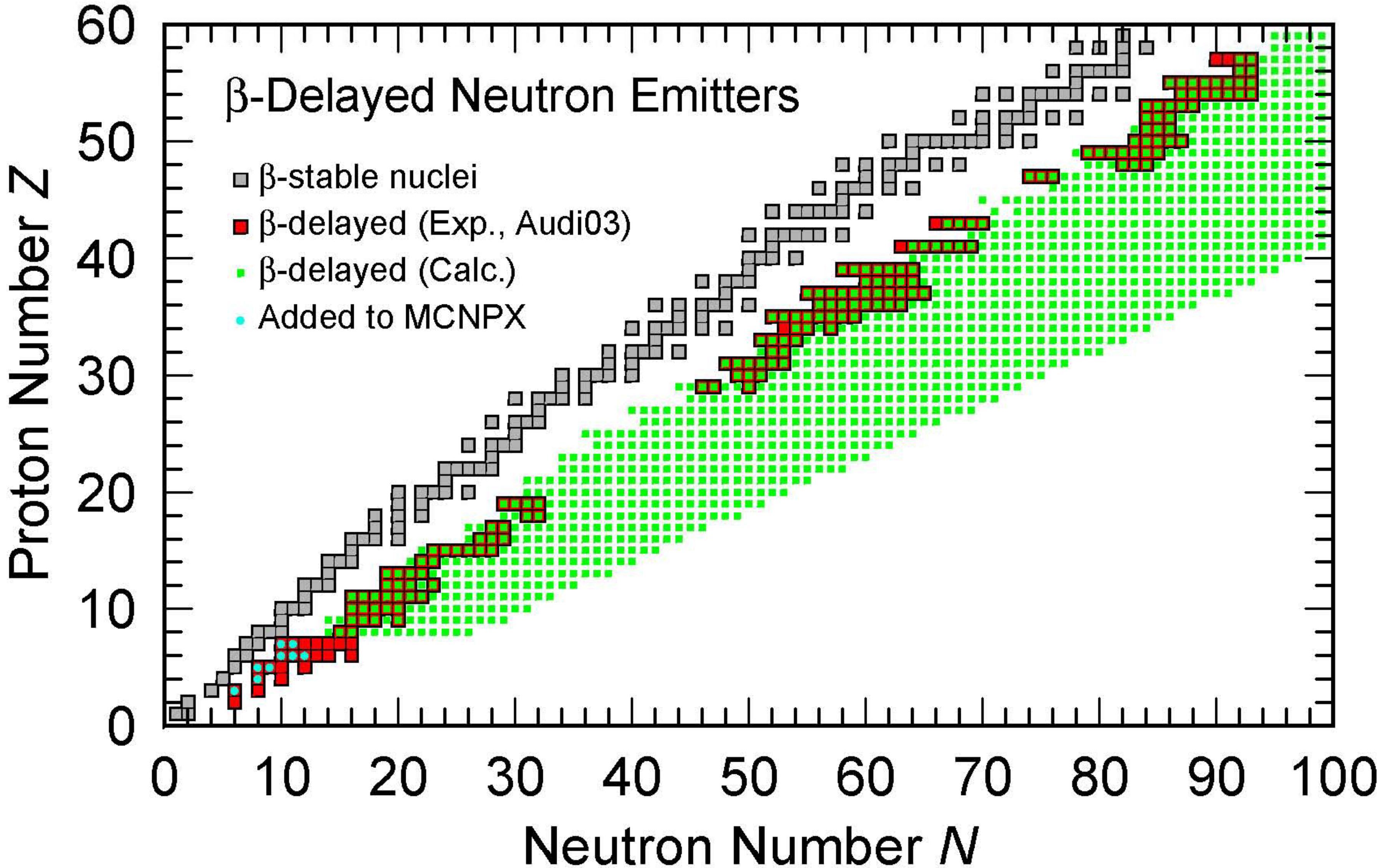
Physics: delayed particle production – delayed neutron spectra calculated for nearly all beta-unstable nuclei



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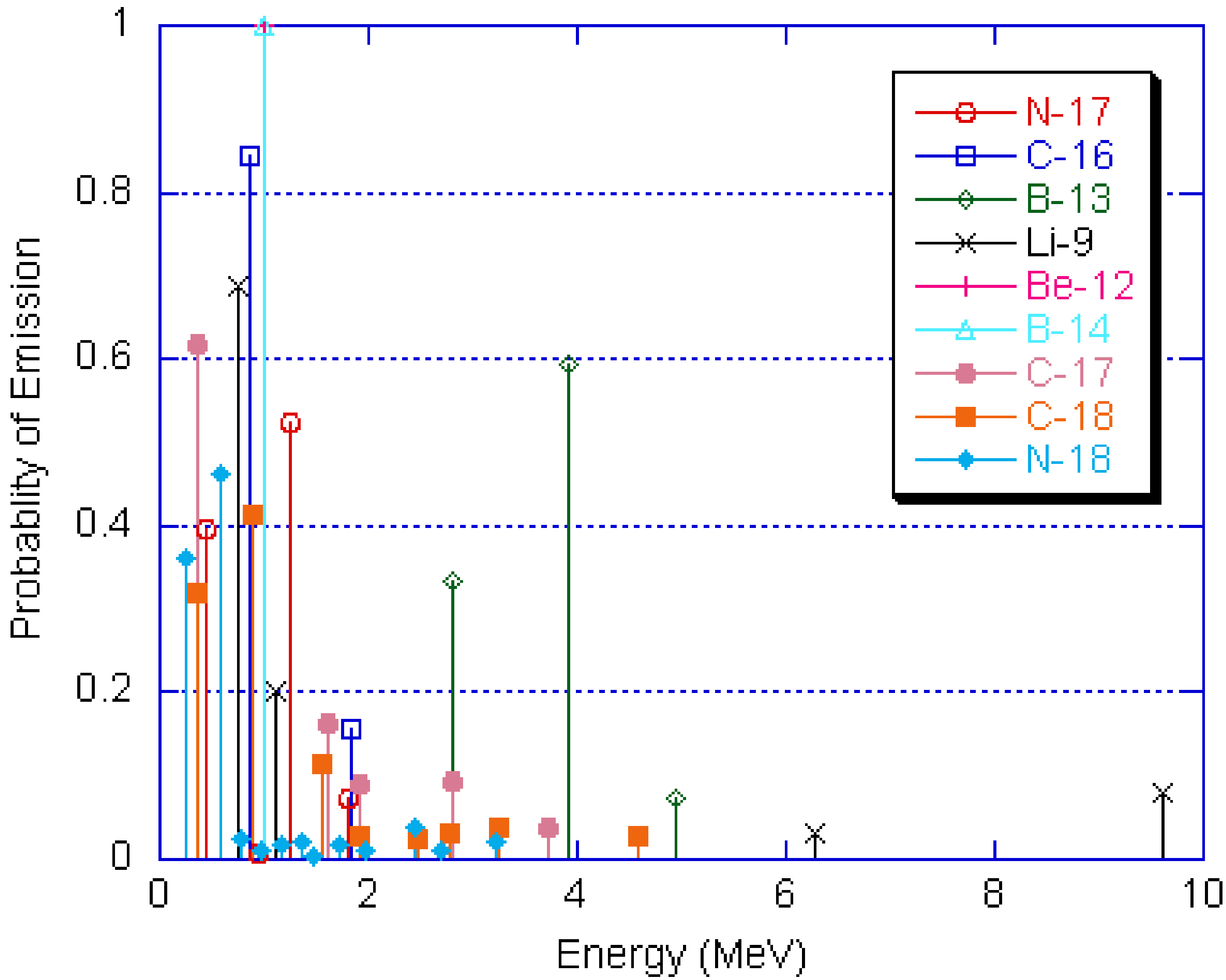
Physics: delayed particle production – using measured delayed neutron spectra for low-Z nuclei



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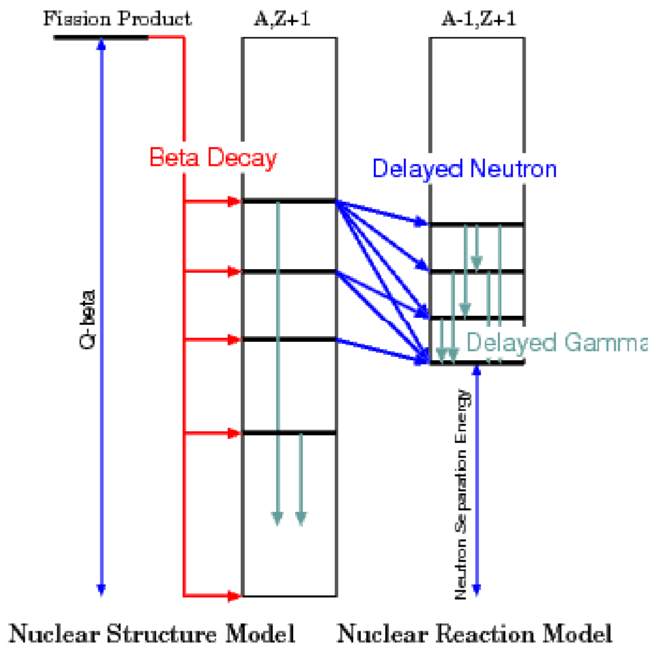
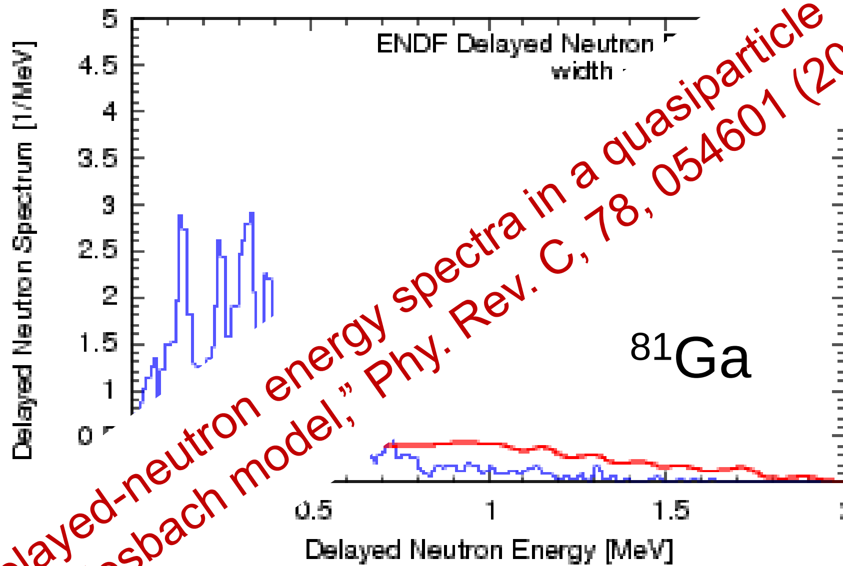
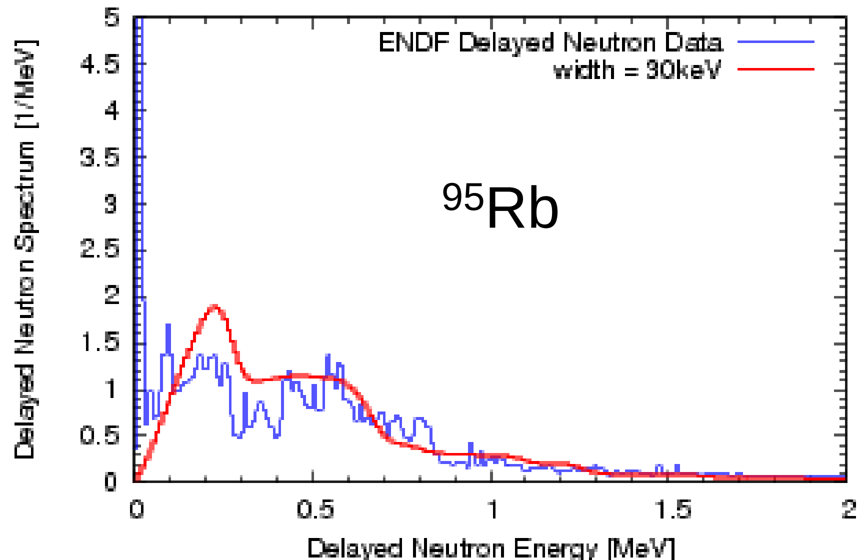
Physics: delayed particle production – using calculated delayed neutron spectra for 270 fission products





T. Kawano et al., “Calculation of delayed-neutron energy spectra in a quasiparticle random-phase approximation - Hauser-Fesbach model,” Phy. Rev. C, 78, 054601 (2008)

34 of the 270 ENDF DN... are based on meas... while the others use si... ions. We have update... a based on a LANL n... ure model and a statistic... er-Feshbach model.



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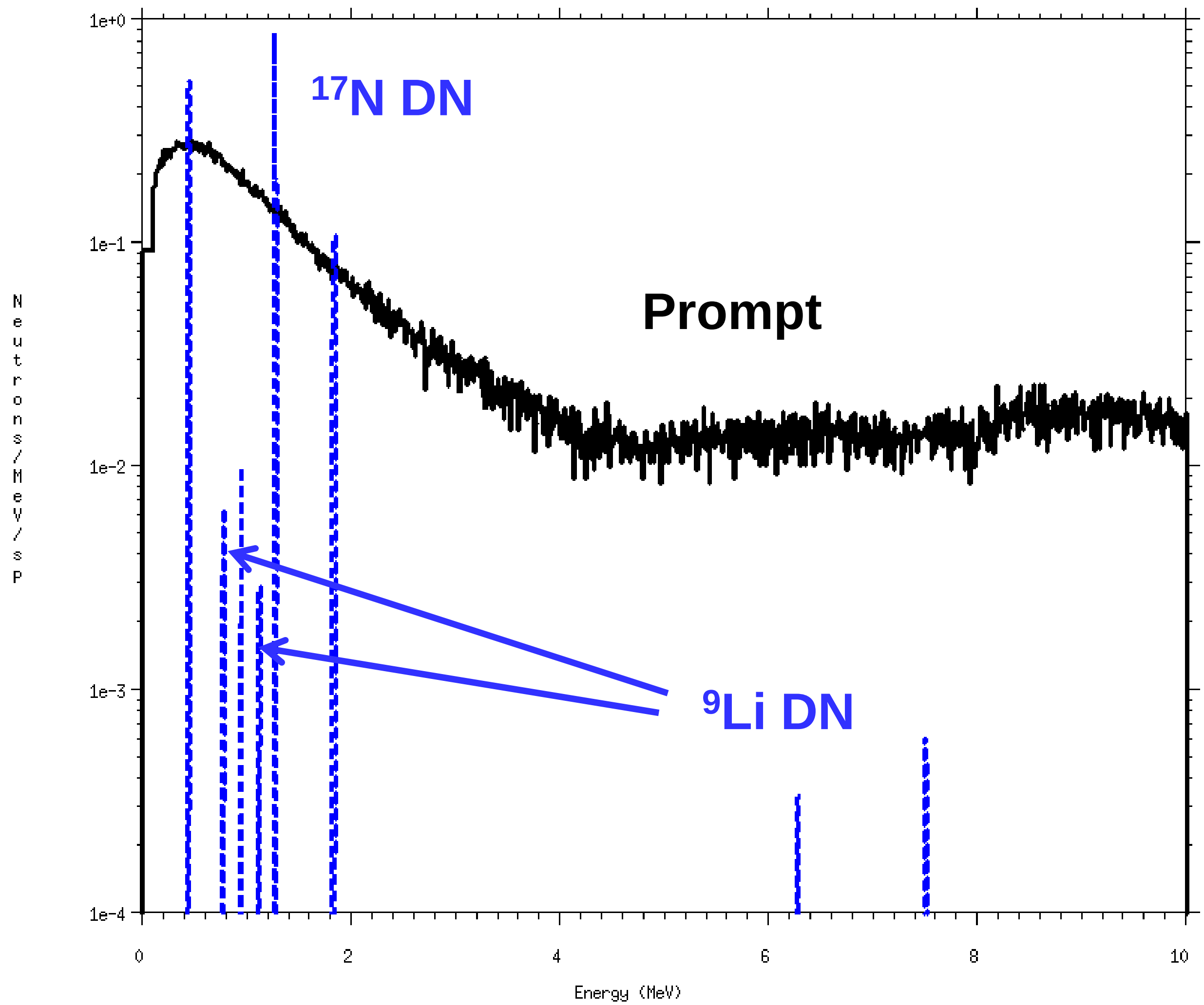
Physics: delayed particle production – a simple delayed neutron activation example

```
16-MeV neutrons into BeO
1   1   -1.0     -1     imp:n=1
2   0             1     imp:n=0

1 so   1.0

m1       4009 1 8017 1
sdef     par=n  erg=16
ACT      NONFISS=all DN=model
         DNBIAS=5
lca      7j -2
f1:n     1
e1       .1 999i 10.
t1       0.001000e8  1e30
nps      1000000
print
```

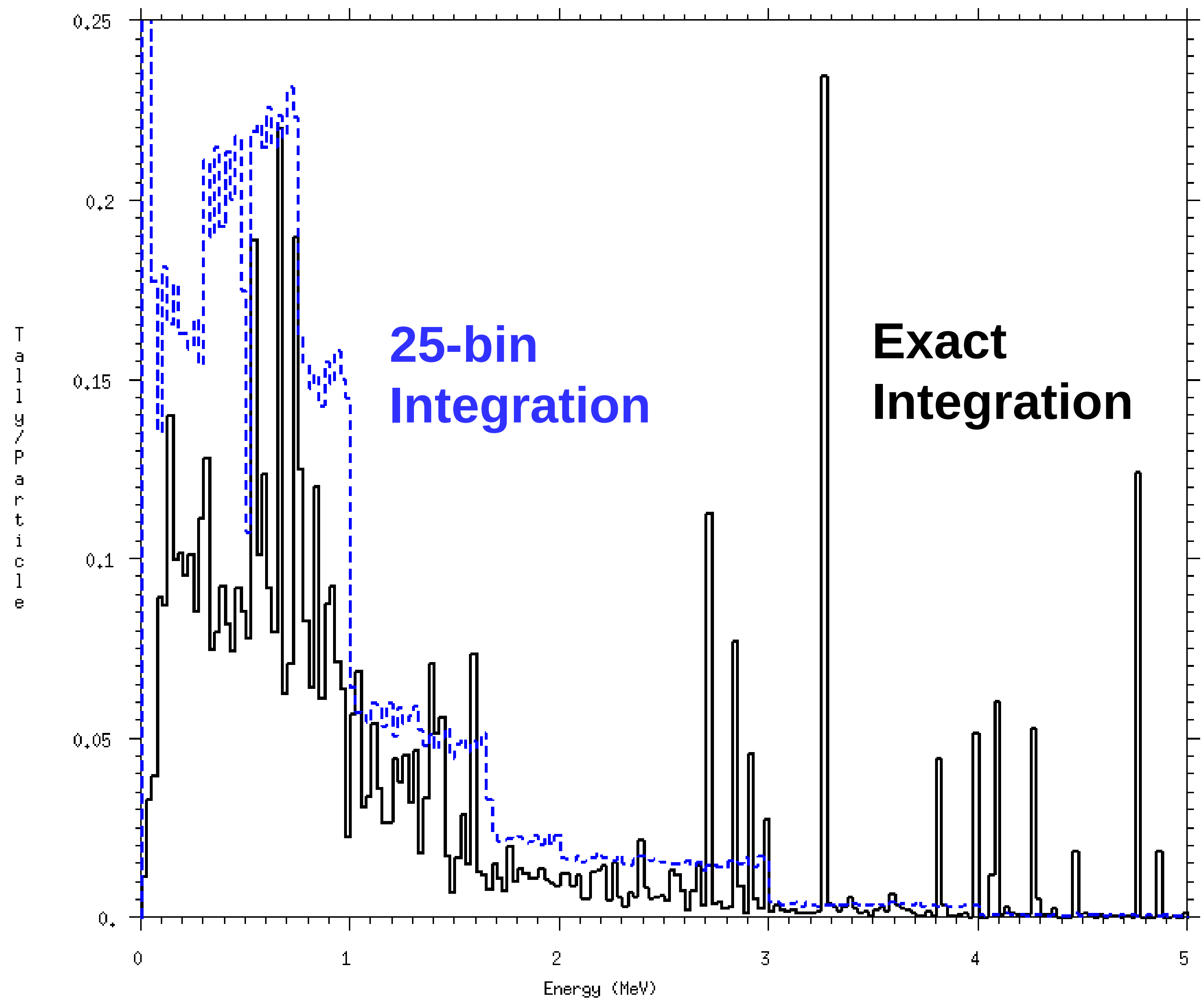


Physics: delayed particle production – new delayed gamma library with improved algorithms provide high fidelity

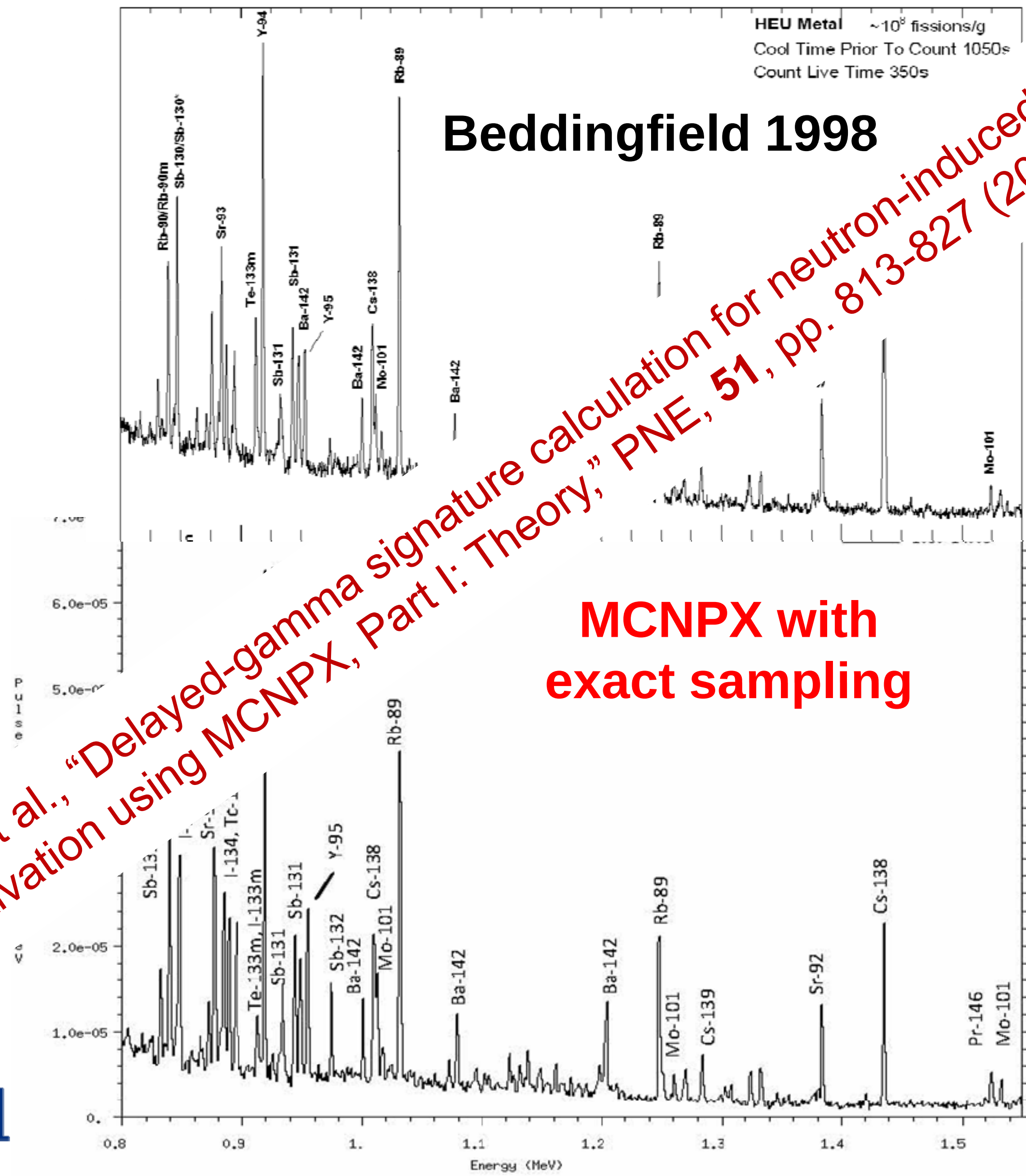
```
Thermal neutrons into U-235
1     1 -8.9     -1    imp:n=1
2     0           1    imp:n=0

1     so  1.0

m1      92235.70c  1.0
mode    n p
ACT     DG=lines $ Use line data
cut:n   j j 0 0
lca 7j -2
sdef    par=n erg=2.54e-8
f1:p    1
e1      0.0 399i 10
sd1     1
t1      1e4  1e30
tf1     7j 2
nps     25000
print
```

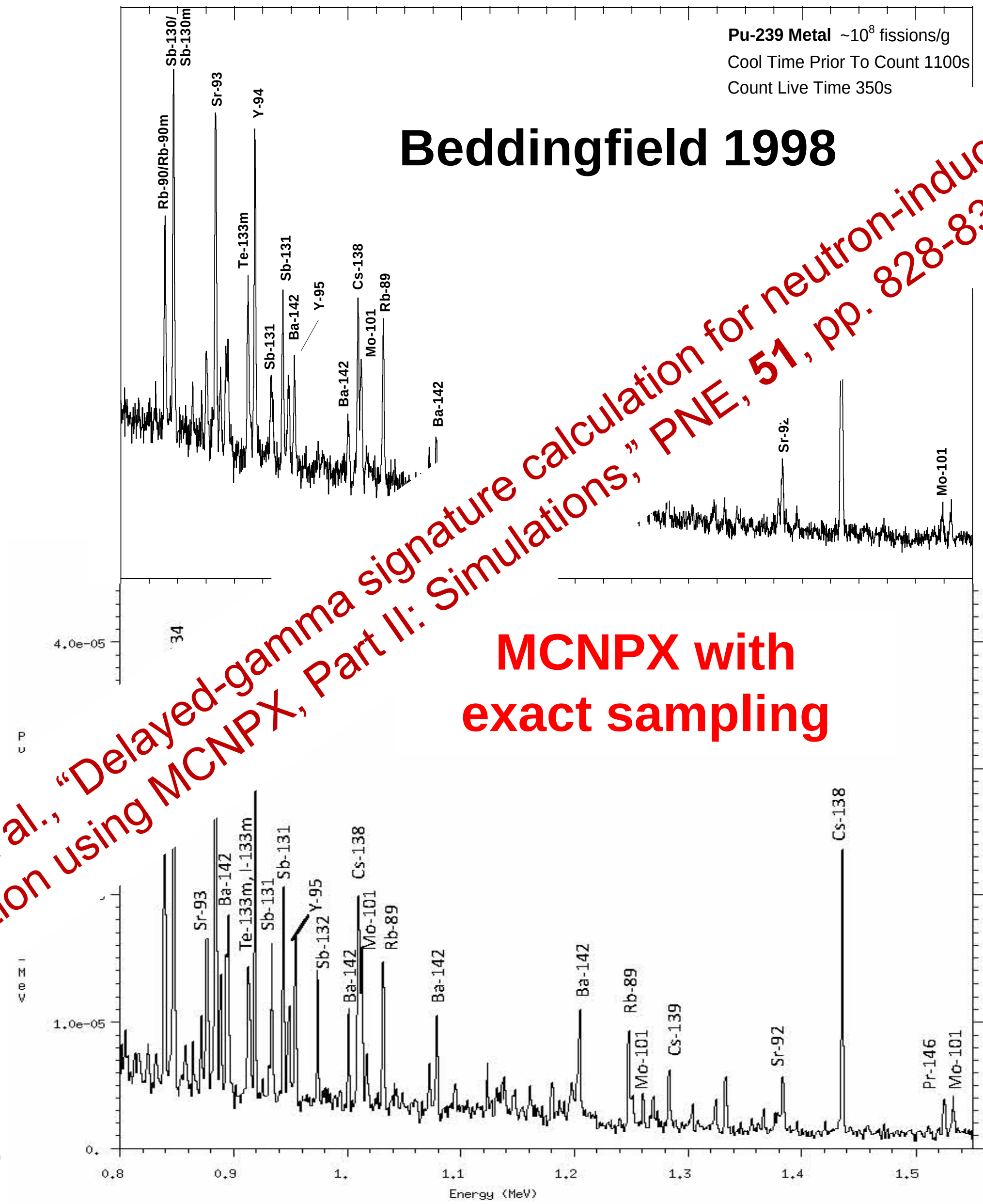


Physics: delayed particle production - spectroscopic results from HEU fission agree with measured data



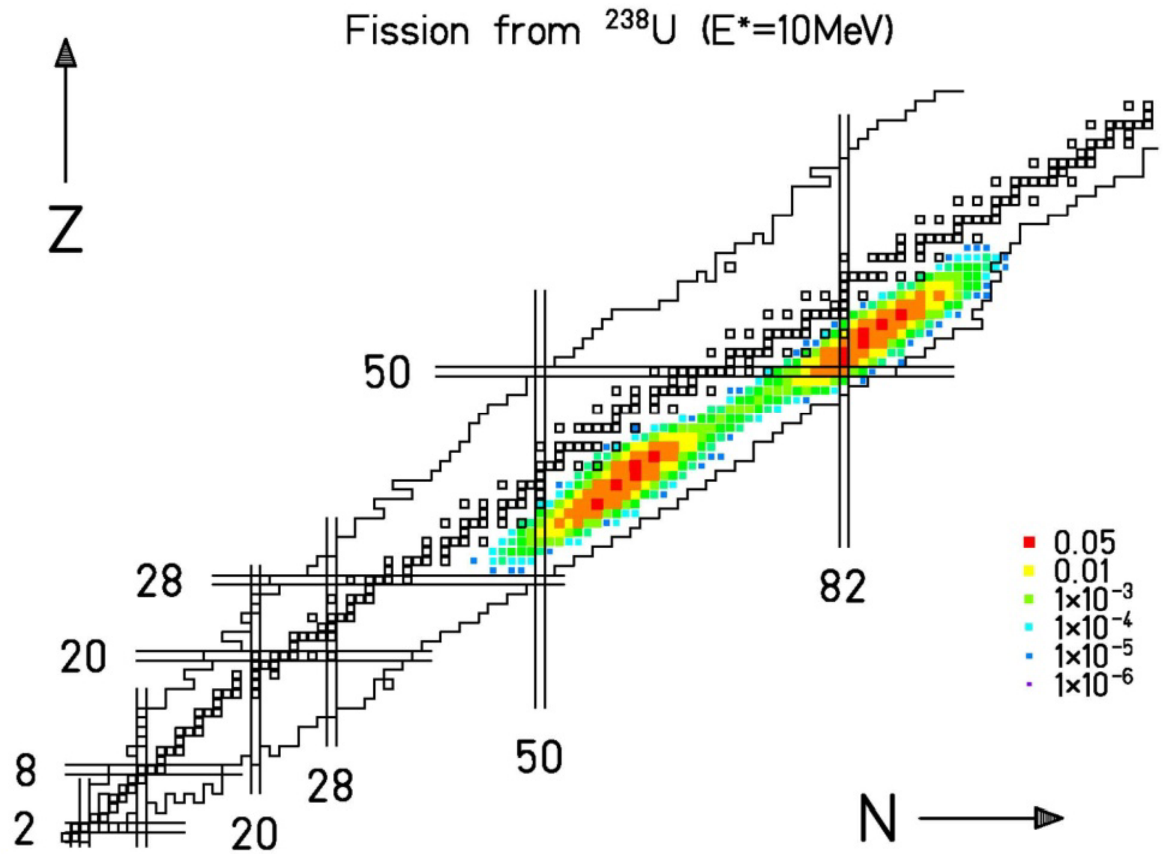
J. W. Durkee et al., "Delayed-gamma signature calculation for neutron-induced fission and activation using MCNPX, Part I: Theory," PNE, **51**, pp. 813-827 (2009)

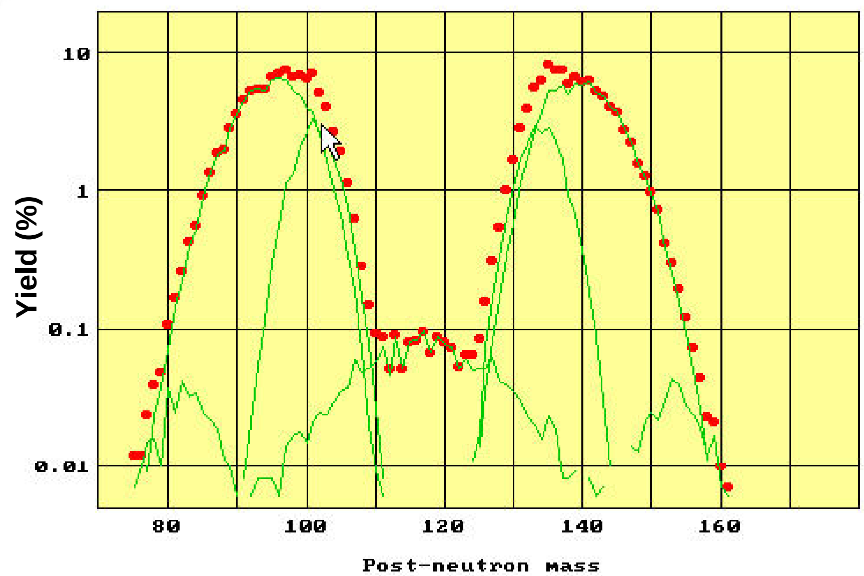
Physics: delayed particle production - spectroscopic results from ^{239}Pu fission agree with measured data



J. W. Durkee et al., “Delayed-gamma signature calculation for neutron-induced fission and activation using MCNPX, Part II: Simulations,” PNE, **51**, pp. 828-836 (2009)

Physics: photofission fission-product yields – French GEF code used to generate new actinide yield curves





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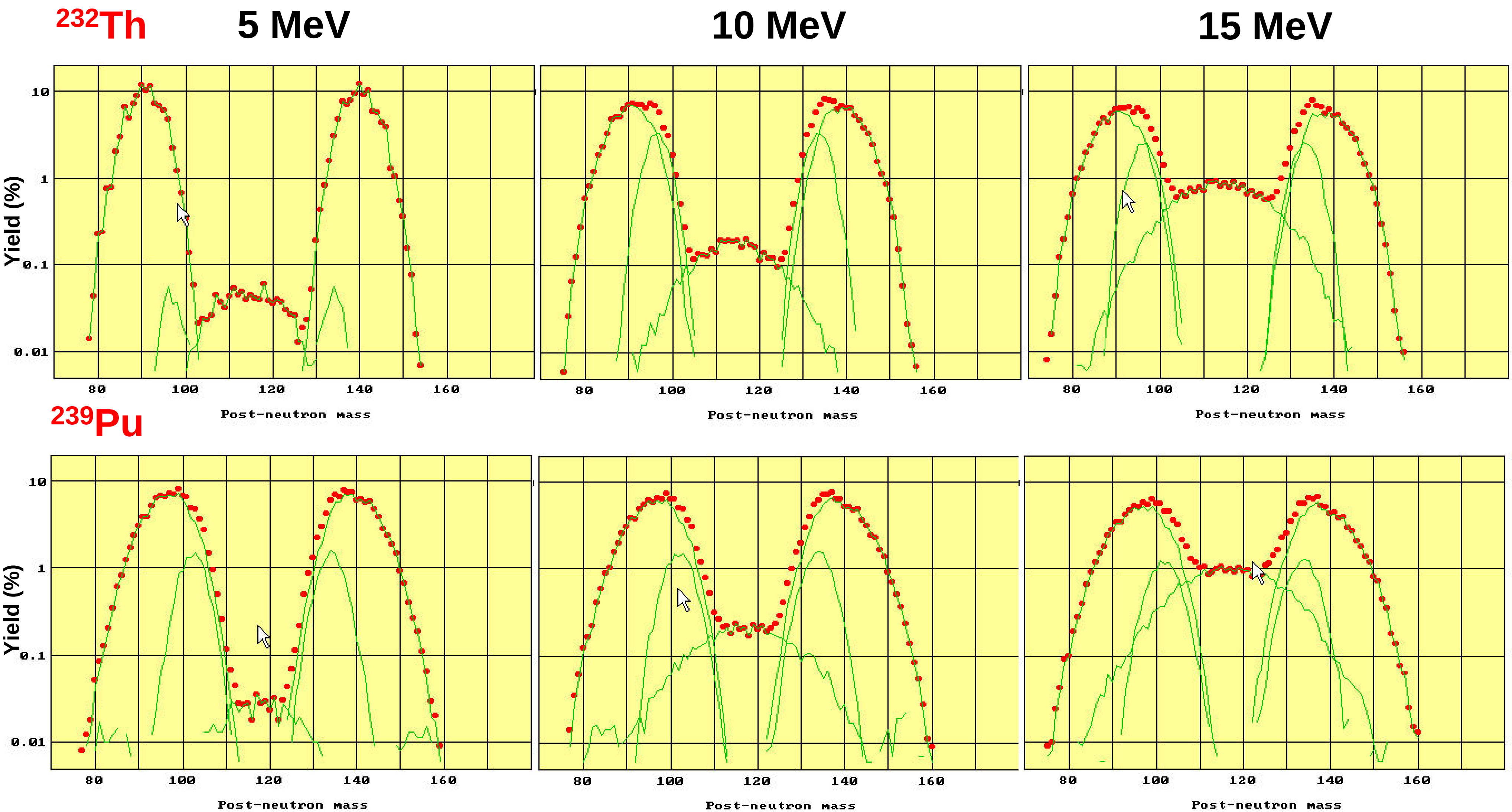

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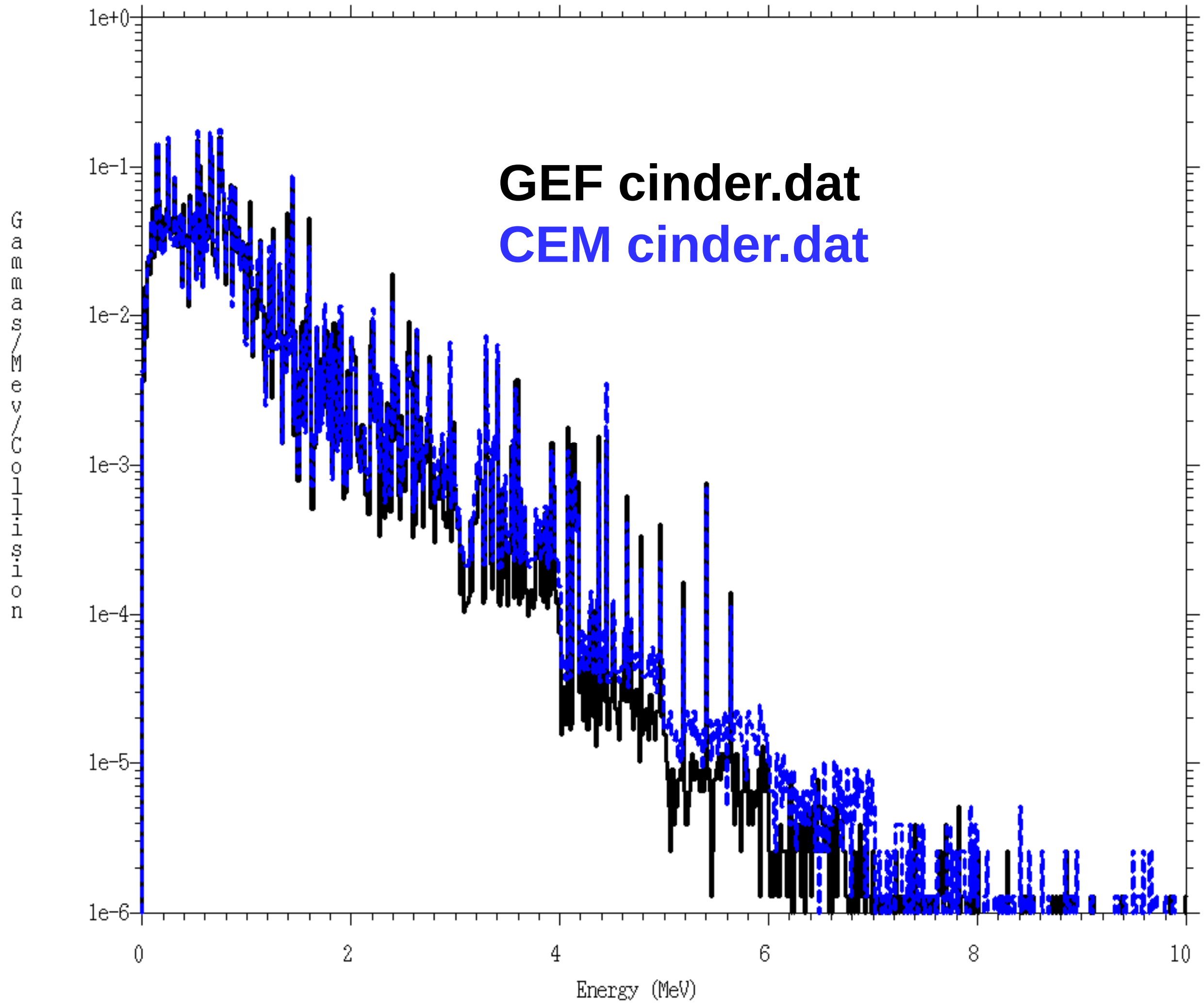
Physics: photofission fission-product yields – a simple photofission example of delayed gamma production

```
12-MeV photons into U-235
1  1  -19.0   -1  imp:n=1
2  0           1  imp:n=0

1  so 1.0

mode n p
m1  92235 1
phys:n  3j 105
phys:p  3j   1 j -102 $ Line data
sdef par=p erg=12.0
lca  7j -2
f1:n 1
e1   1.e-3 999i 15.0
t1   100  1e37
f11:p 1
e11  1.e-3 999i 15.0
t11  100  1e37
print
nps 1000000
```



Physics: muonic x-ray production – MUON/RURP codes used to generate new library with 295 isotopes

Nuclide		L - Energy Levels			K - Energy [illegible]	
		Energy (MeV)	Probability		Energy (MeV[illegible]	[illegible]ty
He-3					[illegible]	[illegible]000
He-4					[illegible]	1.00000
Li-6					[illegible]	1.00000
Li-7					[illegible]78	1.00000
Be-9		0.00619	1.00000		[illegible].03973	1.00000
B-10		0.00970	0.33373		0.06223	0.33327
		0.00970	0.66[illegible]		0.06223	0.66673
B-11		0.00971	[illegible]		0.06228	0.33327
		0.00971	[illegible]		0.06229	0.66673
C-12		0.013[illegible]	[illegible]		0.07587	0.35847
		[illegible]	[illegible]894		0.07589	0.07160
		[illegible]	0.04989		0.08984	0.18988
		[illegible]	0.09955		0.08984	0.37989
					0.08985	0.00014
C-13		[illegible].01397	0.14162		0.07591	0.35847
		0.01398	0.70890		0.07592	0.07161
		0.01402	0.04990		0.08989	0.18987
		0.01402	0.09957		0.08989	0.37989
					0.08989	0.00014

A. B. McKinney et al., "MCNPX Updated Muonic X-ray Library," Proceedings of the ANS Winter Meeting, Washington, DC, Nov. 15-19 (2009)

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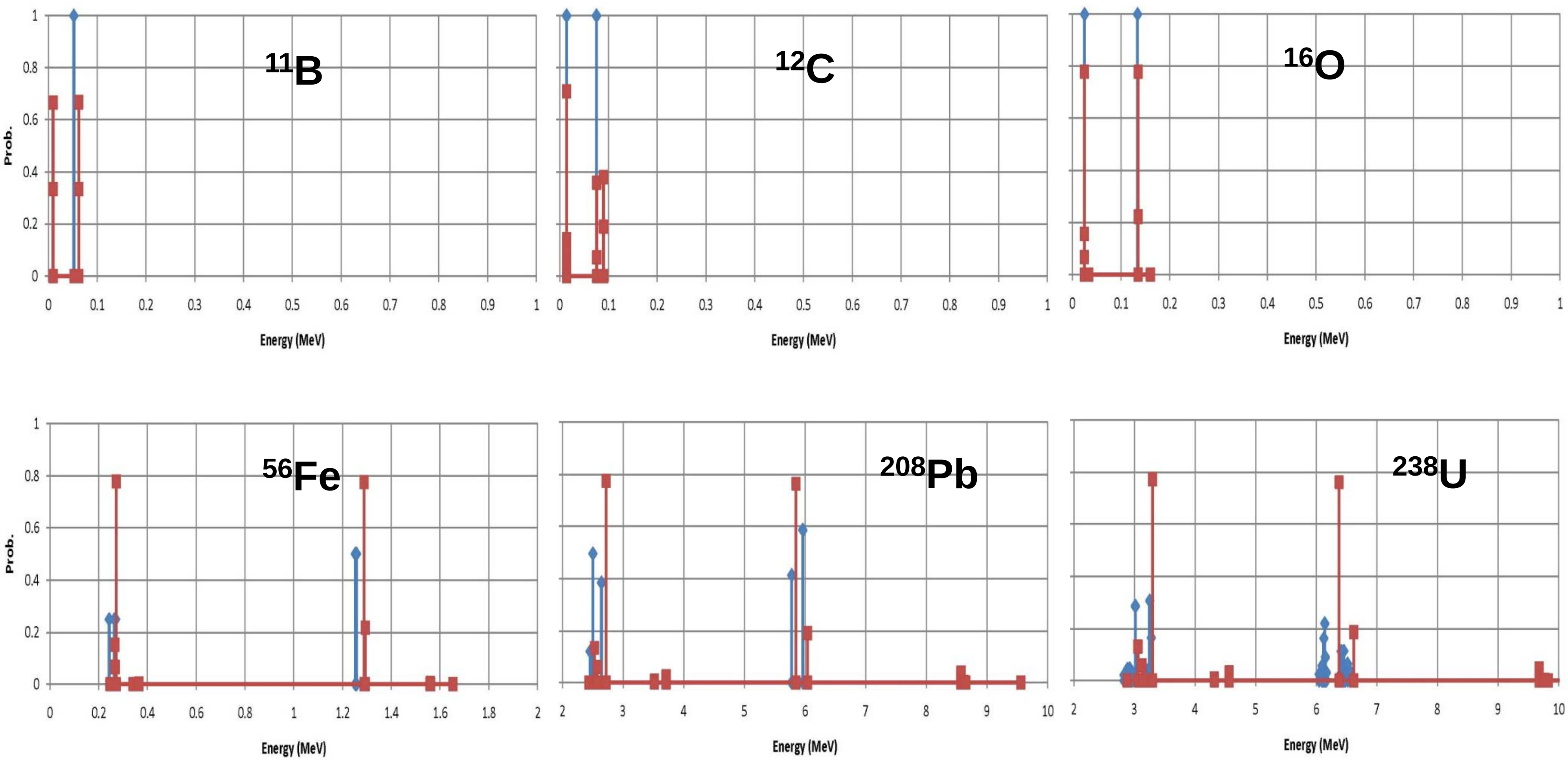
Physics: muonic x-ray production – good agreement with previous data and measured data

New Data vs. **Previous Data**



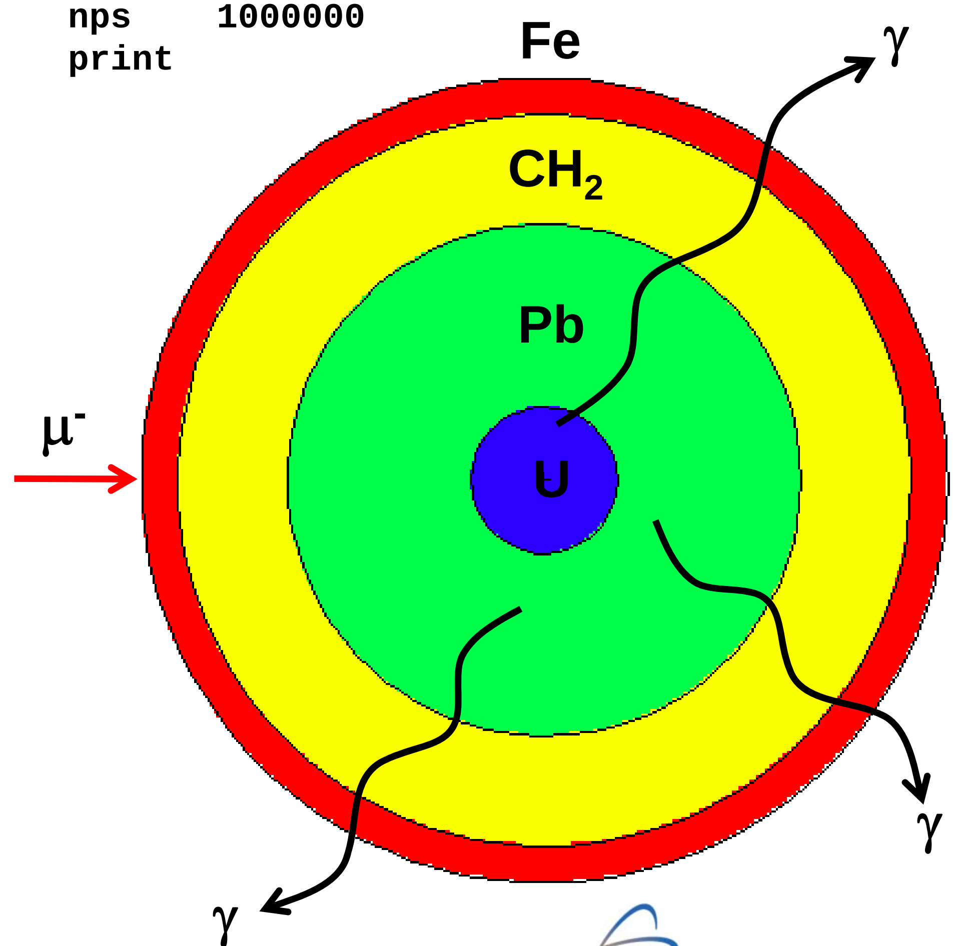
Physics: muonic x-ray production – a simple example of shielded HEU

```
200 MeV muons into shielded HEU
1  1   -19.0     -1      imp:p=1
2  2   -11.35     1  -2  imp:p=1
3  3    -1.0      2  -3  imp:p=1
4  4    -7.9      3  -4  imp:p=1
5  0              4      imp:p=0

1  so 2.0
2  so 7.0
3  so 10.0
4  so 11.0

m1   92235 .5    92238 .5
m2   82204 .0140 82206 .2410 82207 .2210
     82208 .5240
m3   26054 .0585 26056 .9175 26057 .0212
     26058 .0028
m4   1001 2.00   6012 .99    6013 .01
mode  n p h d t s a / z |
phys:n 210
phys:| 6j  1 $ new data
sdef  par=| erg=200 pos=-10.999 0 0
      vec=1 0 0 dir=1
f1:p  4
e1    .001 999log 10
tmesh
```

```
rmesh11:| flux
cora11  -11.1 199i 11.1
corb11  -11.1      11.1
corc11  -11.1 199i 11.1
endmd
nps    1000000
print
```



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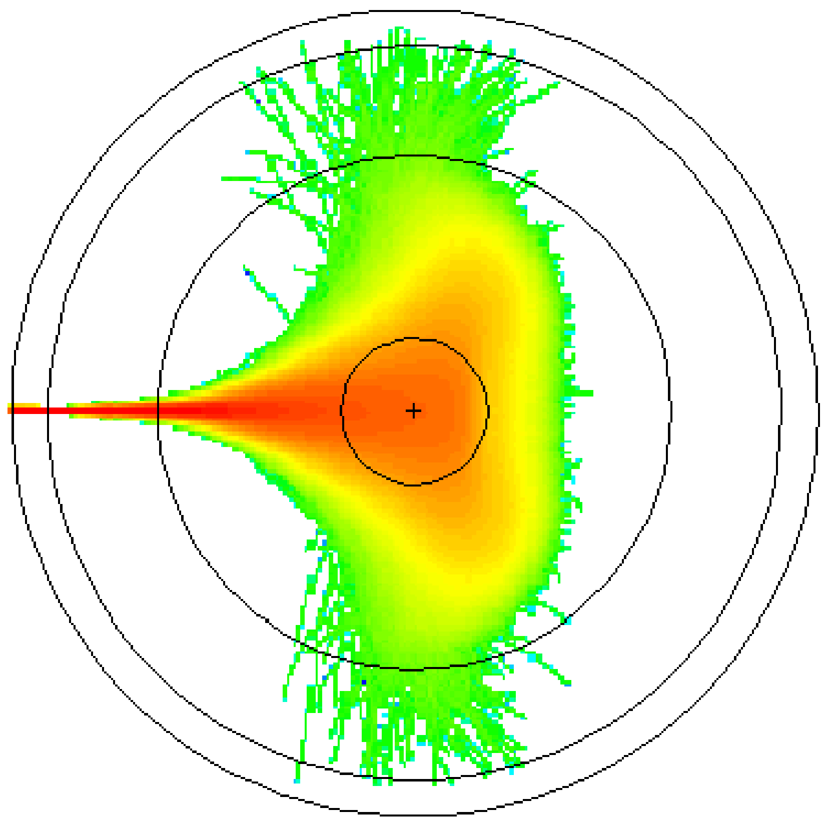
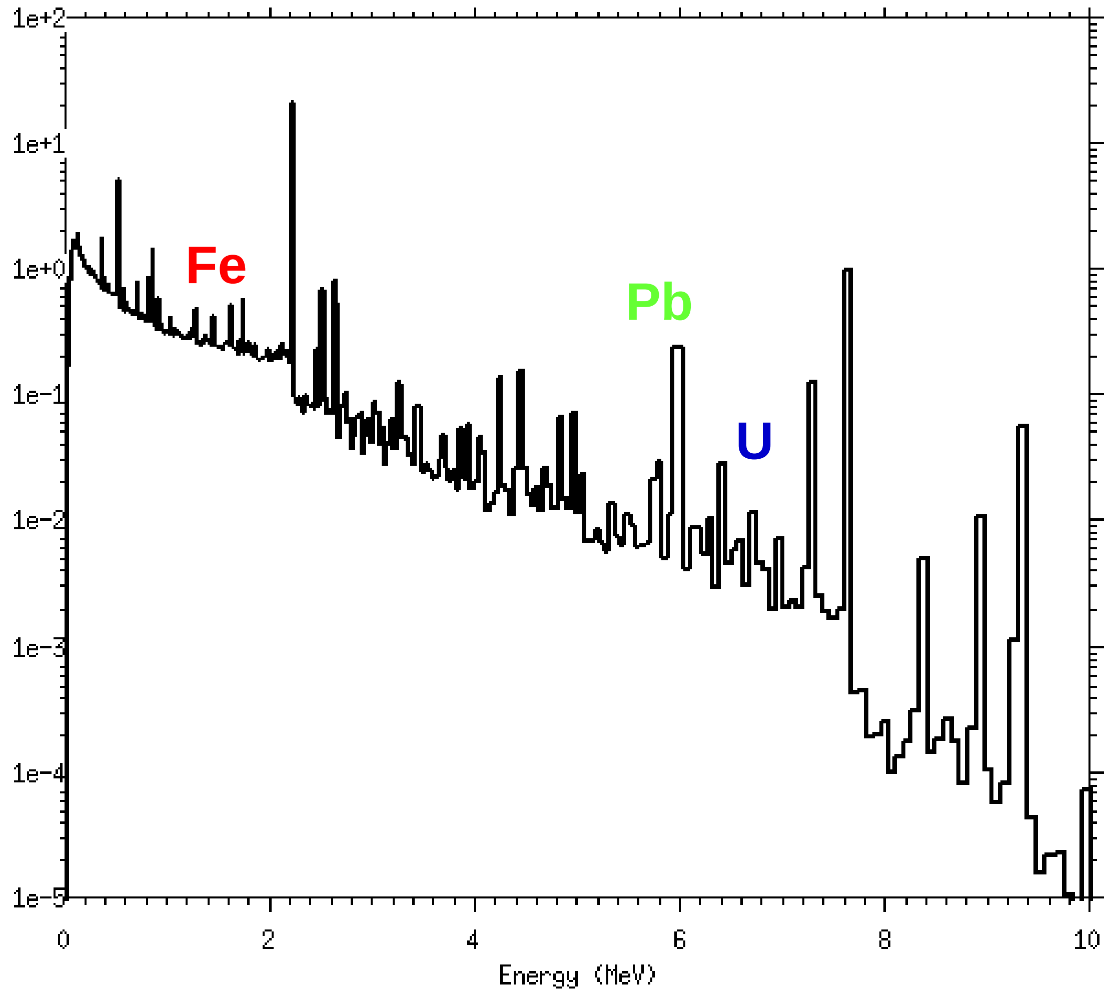
Physics: muonic x-ray production – a simple example of shielded HEU



Muon flux within the stack

Photons escaping the shield



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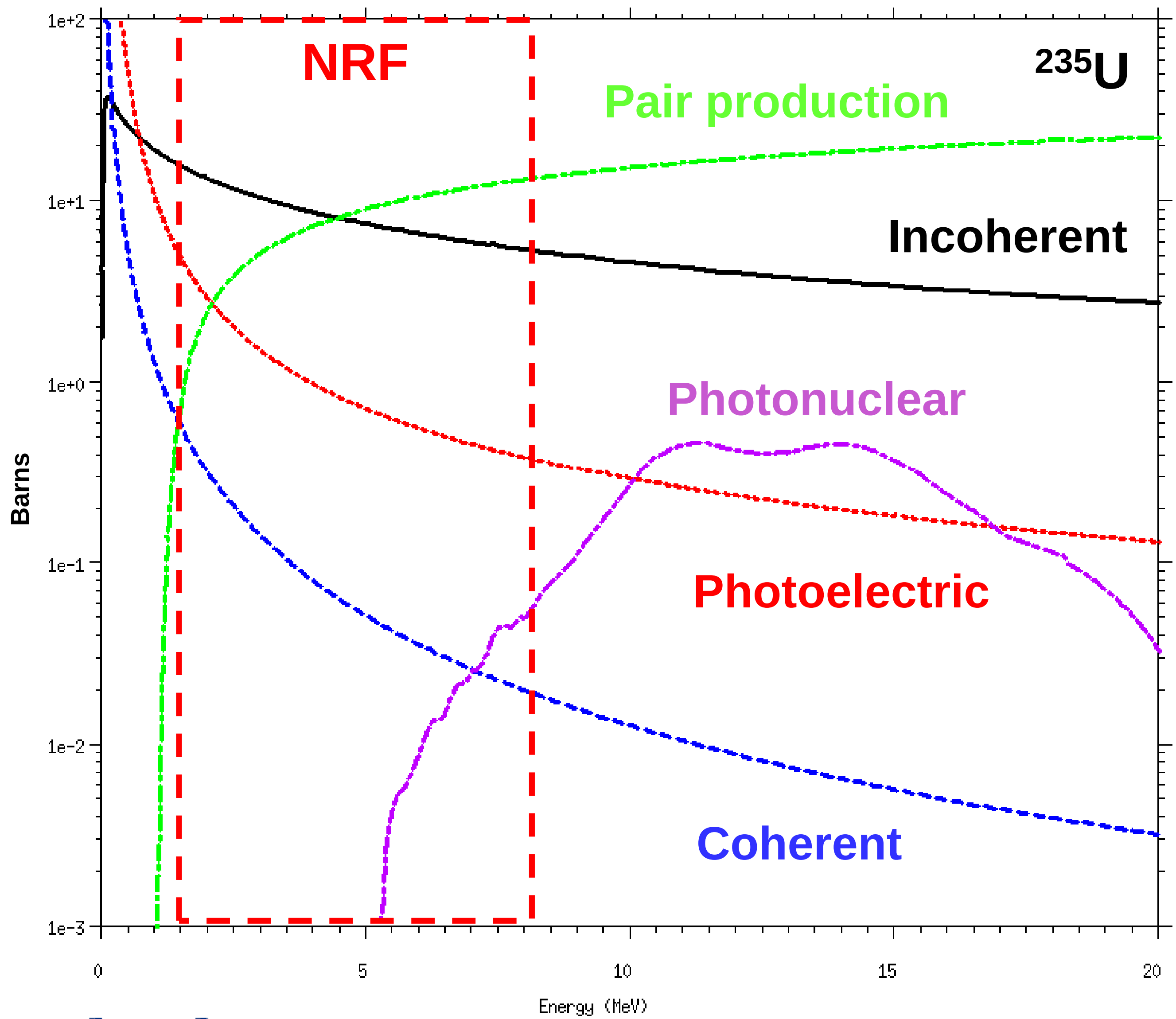
Physics: nuclear resonance fluorescence – improvements in photoatomic & photonuclear data libraries were needed



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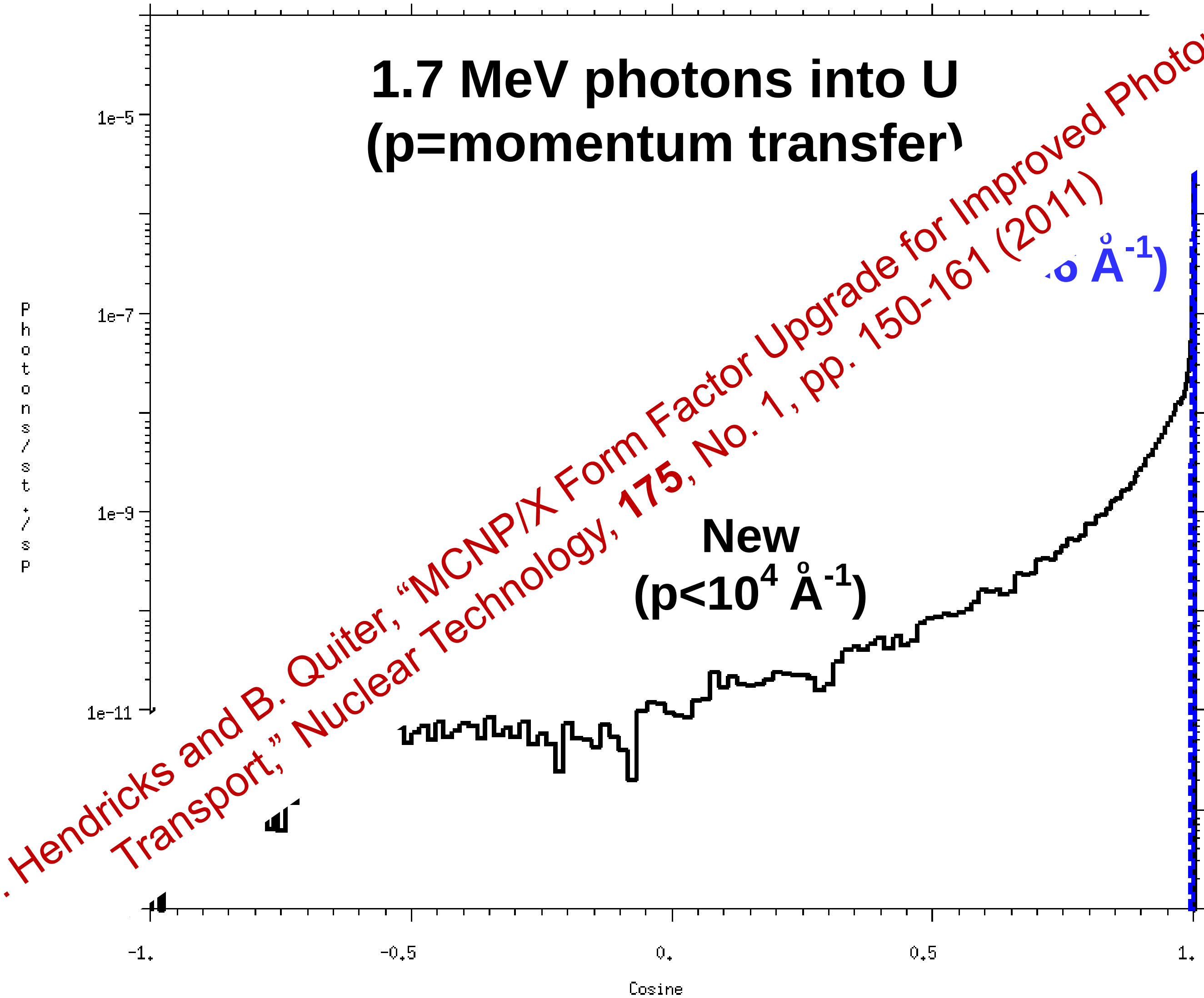
Physics: nuclear resonance fluorescence – coherent & incoherent form-factors were improved for all elements

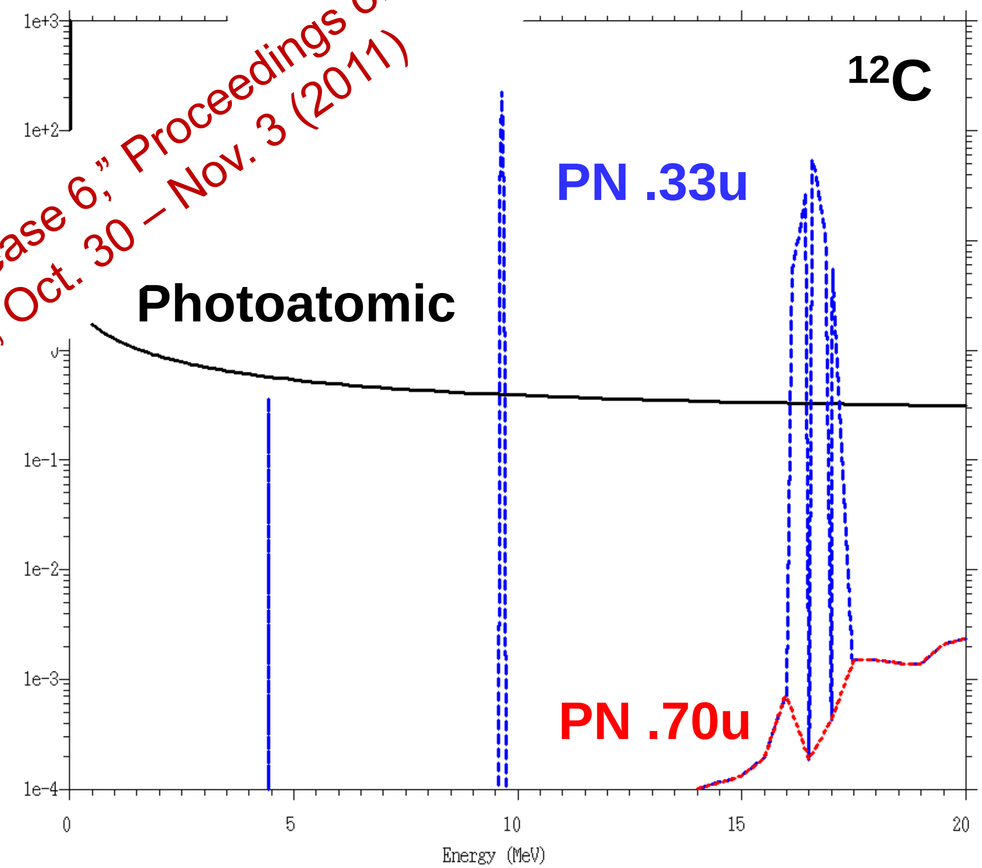


J. S. Hendricks and B. Quiter, "MCNP/X Form Factor Upgrade for Improved Photon Transport," Nuclear Technology, **175**, No. 1, pp. 150-161 (2011)

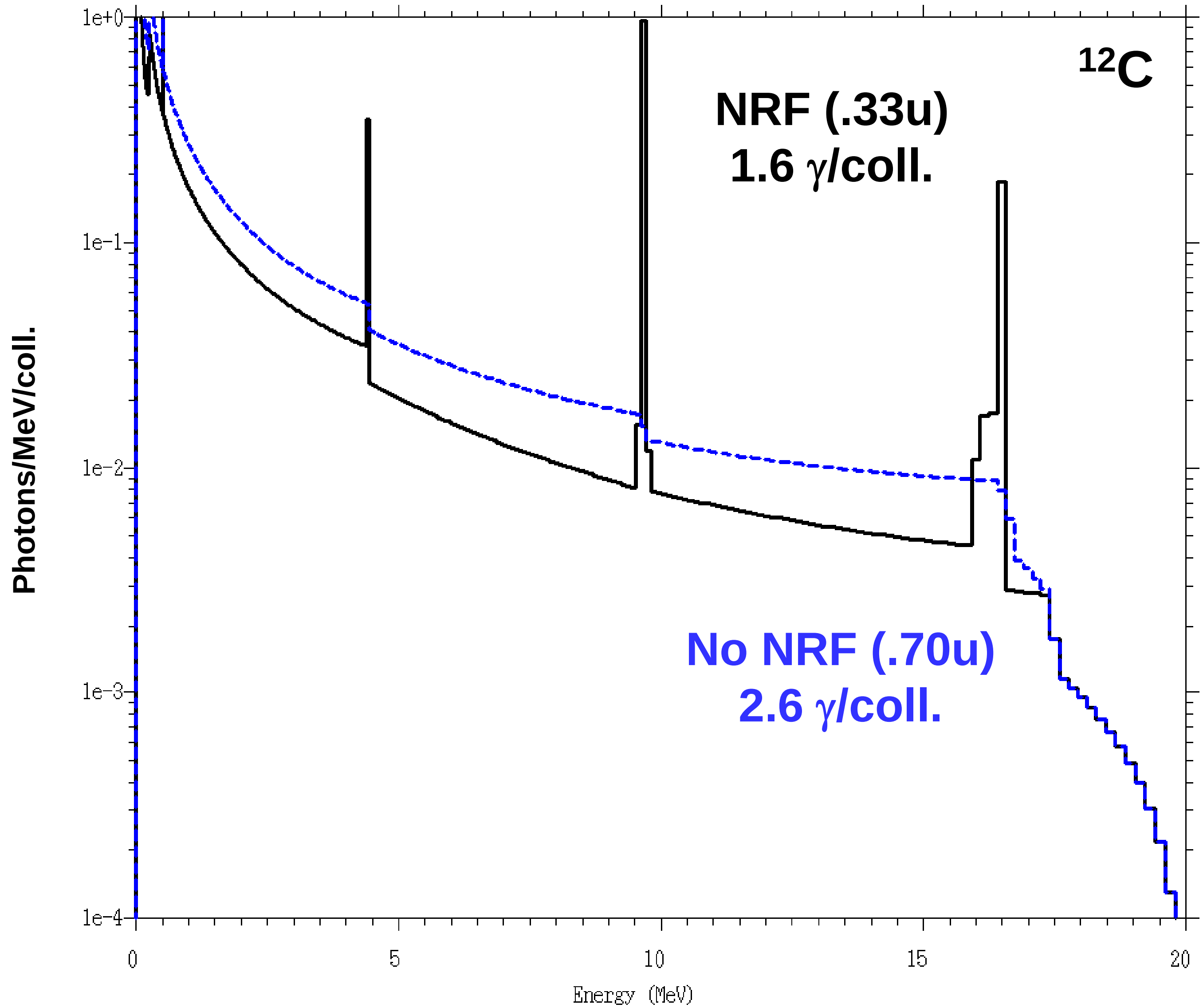
Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei

```
Test of 6012.33u NRF data
1  1  -1.0    -1   imp:p=1
2  0            1   imp:p=0

1  so  1.0

mode p
m1  6012 1  pnlib=.33u
lca  7j -2
phys:p 3j 1
sdef   par=p erg=d1
si1 H  0.000000000000000 &
4.438830000000000 4.439030000000000 &
9.657920000000001 9.658120000000000 &
10.00000000000000
sp1    0 1 4r
print
nps  1000000000
f1:p 1
e1   1e-3 999log 12
```

T. Wilcox, et al., "MCNPX NRF Library – Release 6," Proceedings of the ANS Winter Meeting, Washington, DC, Oct. 30 – Nov. 3 (2011)



Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei



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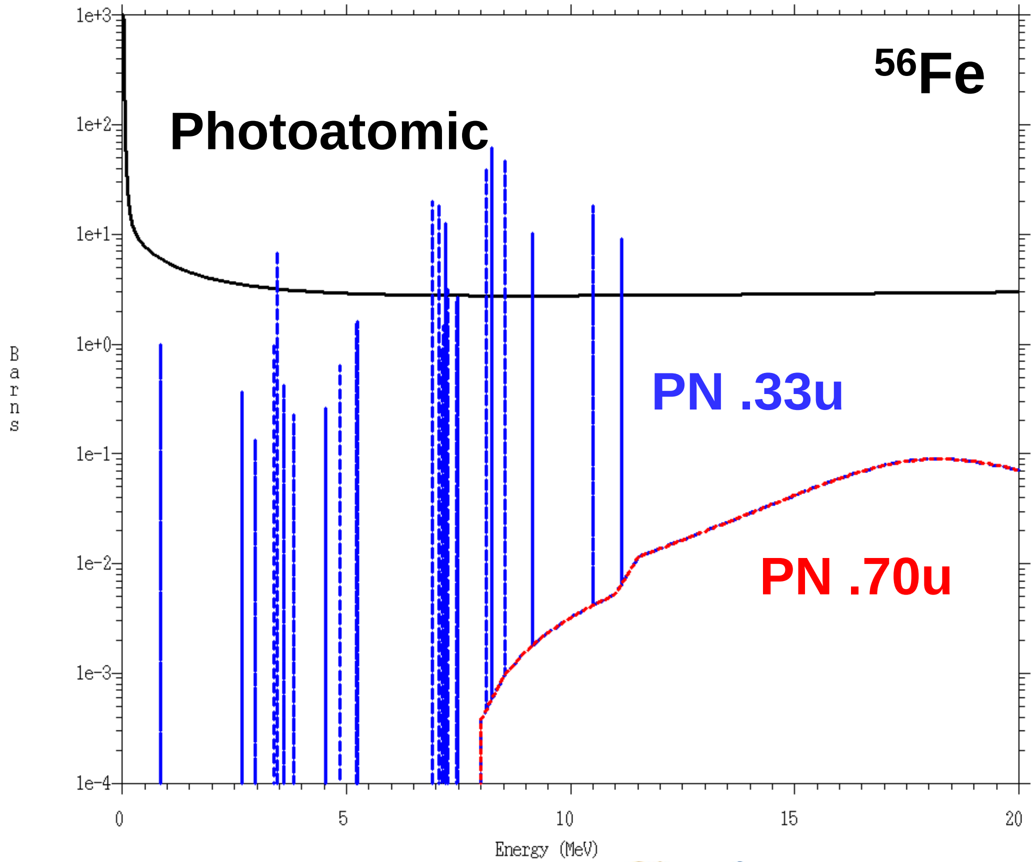
Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei

```
Test of 26056.33u NRF data
1  1  -1.0    -1   imp:p=1
2  0           1   imp:p=0

1  so  1.0

mode p
m1  26056 1  pnlib=.33u
lca  7j -2
phys:p 3j 1
sdef   par=p erg=d1
si1 H    0.000000000000000 &
0.846680000000000  0.846880000000000 &
2.657460000000000  2.657660000000000 &
2.959820000000000  2.960020000000000 &
3.369640000000000  3.369840000000000 &
3.449200000000000  3.449400000000000 &
3.601910000000000  3.602110000000000 &
3.831910000000000  3.832110000000000 &
4.539410000000000  4.539610000000000 &
4.846910000000000  4.847110000000000 &
5.227210000000000  5.227410000000000 &
5.256910000000000  5.257110000000000 &
6.926410000000001  6.926610000000000 &
7.065910000000001  7.066110000000000 &
7.134910000000001  7.135110000000000 &
7.166910000000001  7.167110000000000 &
7.211410000000000  7.211609999999999 &
7.248410000000000  7.248609999999999 &
7.446410000000000  7.446610000000000 &
7.468410000000000  7.468610000000000 &
```

```
8.128510000000000  8.128710000000000 &
8.239610000000001  8.239810000000000 &
8.536610000000000  8.536809999999999 &
9.140210000000000  9.140409999999999 &
10.000000000000000
sp1  0 1 46r
nps  1000000000
f1:p 1
e1   1e-3 999log 12
```



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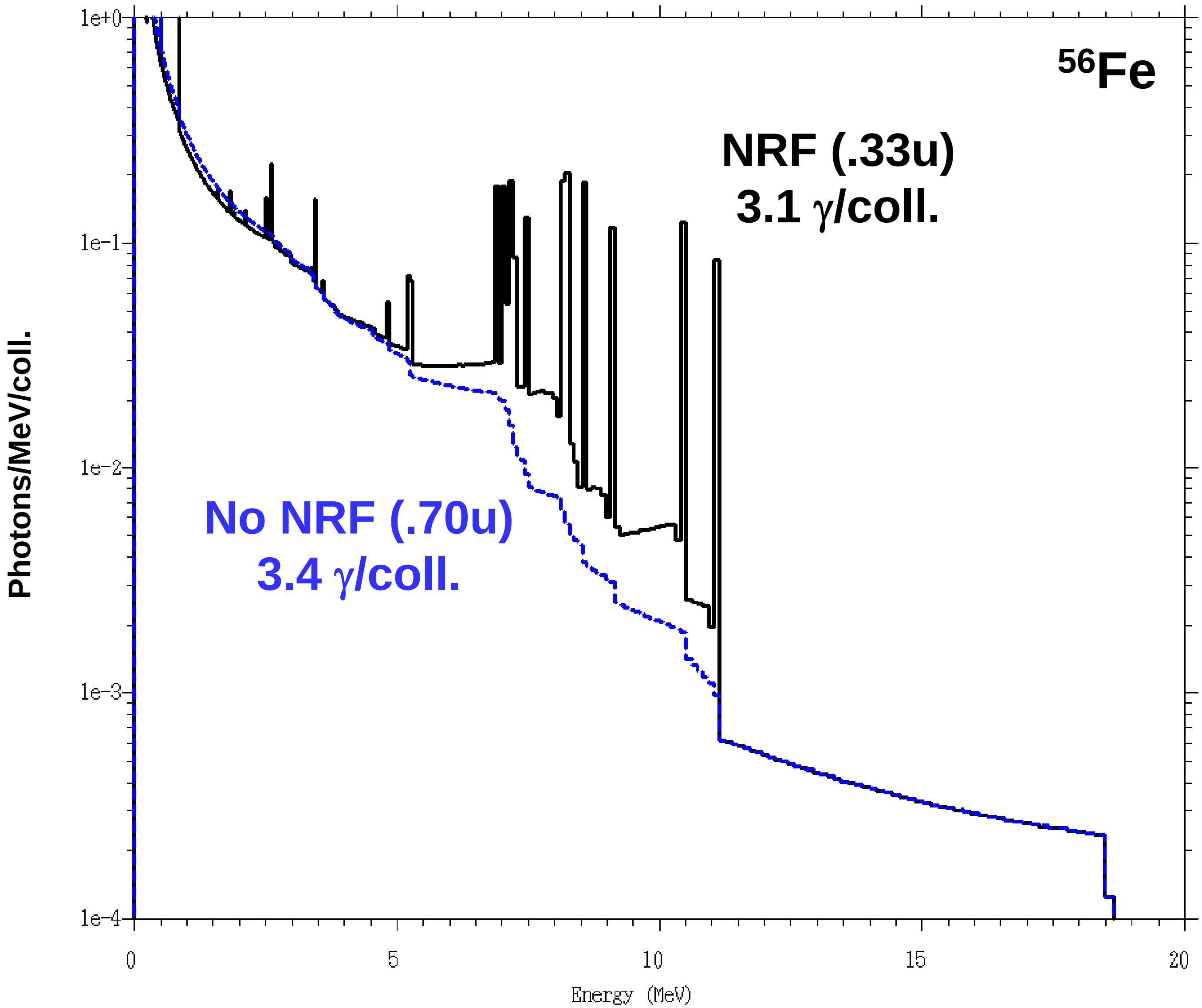
Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei



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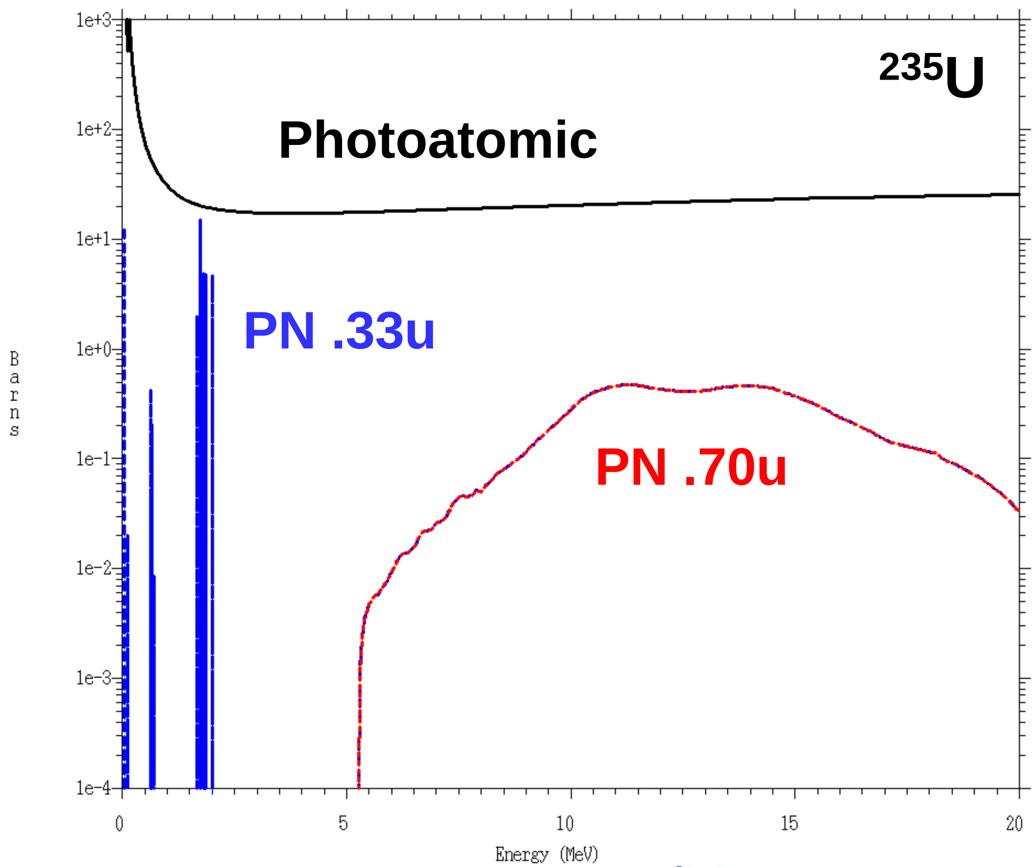
Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei

```
Test of 92238.33u NRF data
1  1  -1.0    -1   imp:p=1
2  0           1   imp:p=0

1  so  1.0

mode p
m1  92238 1  pnlib=.33u
lca  7j -2
phys:p 3j 1
sdef   par=p erg=d1
si1 H    0.000000000000000 &
0.044820000000000  0.045020000000000 &
0.680010000000000  0.680210000000000 &
0.967200000000000  0.967400000000000 &
1.037200000000000  1.037400000000000 &
1.060200000000000  1.060400000000000 &
1.224100000000000  1.224300000000000 &
1.781900000000000  1.782100000000000 &
1.792900000000000  1.793100000000000 &
1.845900000000000  1.846100000000000 &
2.175900000000000  2.176100000000000 &
2.208900000000000  2.209100000000000 &
2.244900000000000  2.245100000000000 &
2.294900000000000  2.295100000000000 &
2.409900000000000  2.410100000000000 &
2.467900000000000  2.468100000000000 &
2.753900000000000  2.754100000000000 &
3.253300000000000  3.253500000000000 &
4.806500000000001  4.806700000000000 &
6.299900000000000  6.300100000000000 &
6.499900000000000  6.500100000000000 &
10.000000000000000
sp1   0 1 40r
print
nps  1000000000
f1:p 1
e1   1e-3 999log 12
```



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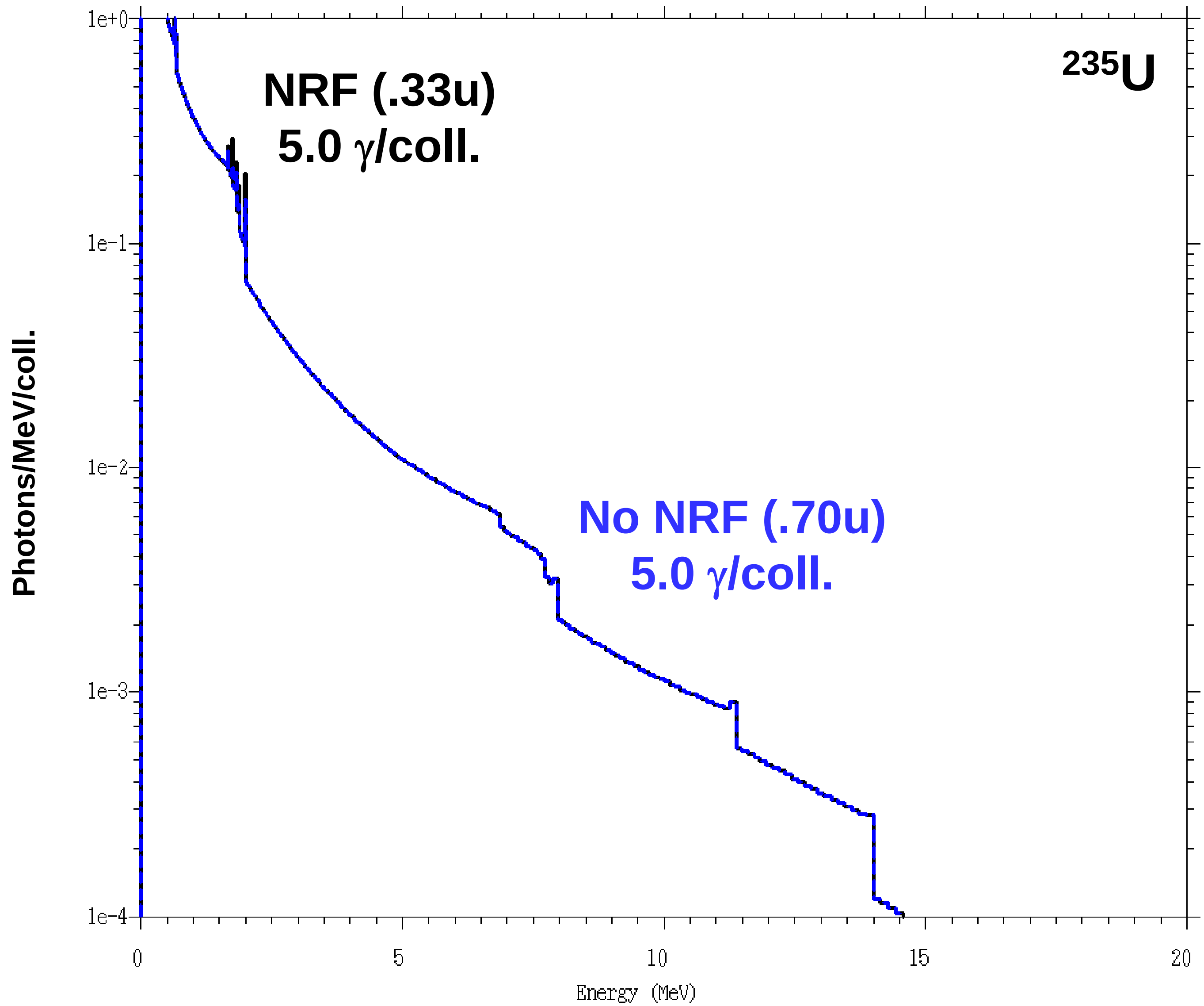
Physics: nuclear resonance fluorescence – new NRF photonuclear library (PN6-NRF) consists of 154 nuclei



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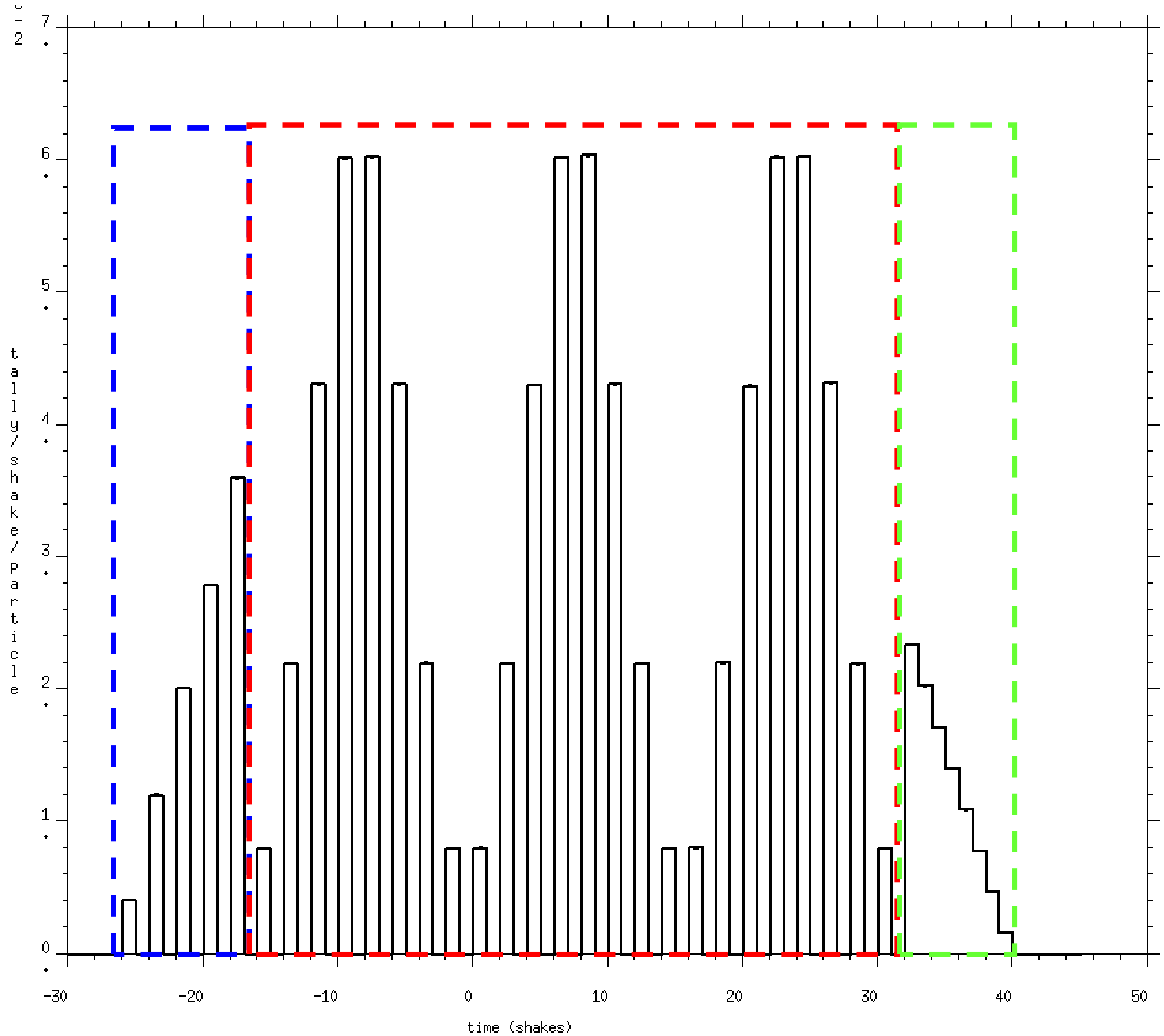
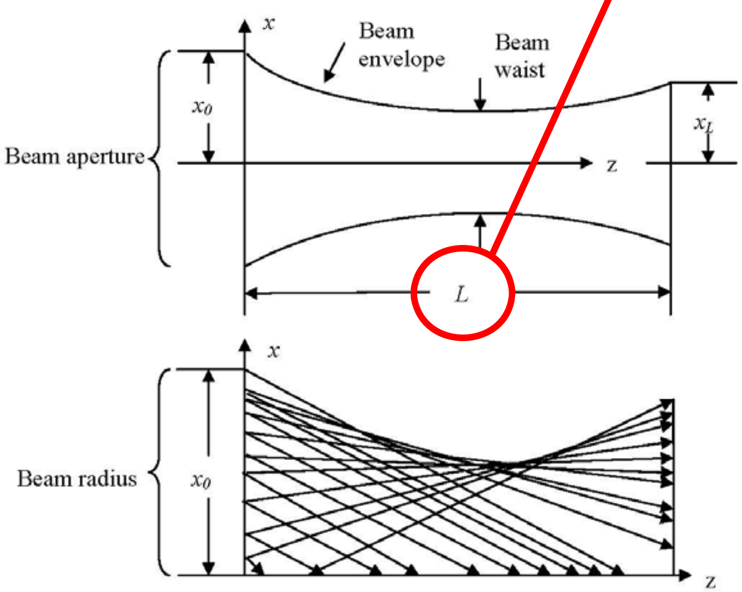
Sources: micro/macro beam pulse option – nesting of time distributions provides accurate beam modeling

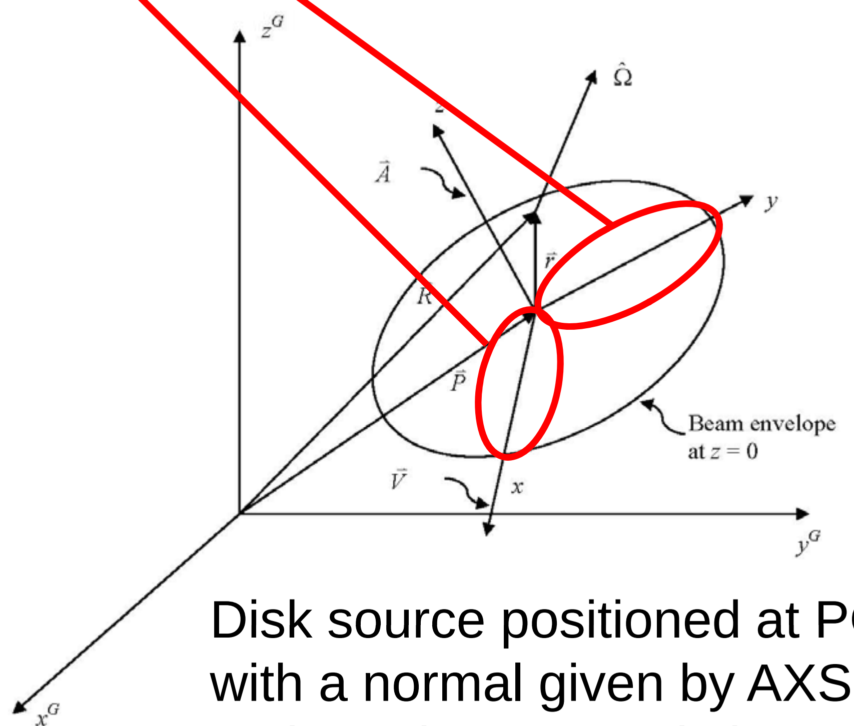
```
…
SDEF TME=D41
#        si41        sp41
            S           D
         51<52         .1
      (31<32<33)       .8
           61          .1
si51 H    0    1    2
sp51      0    1    0
si52 A -26  -16
sp52      0    1
si31      0    1    2
sp31      0    1    0
si32      0   16
sp32    -41    8    8
si33    -16   32
sp33      0    1
si61 A   32   40
sp61      1    0
```



Sources: beam profile source option – new user interface increases fidelity of spatial profiles

```
SDEF  PAR=| ERG=100 POS=0 0 0 AXS=0 0 1 VEC=1 0 0
      BEM=9.776e-3 9.776e-3 100 BAP=1.0 1.0 0
```





Disk source positioned at POS, with a normal given by AXS and a orthogonal axis by VEC

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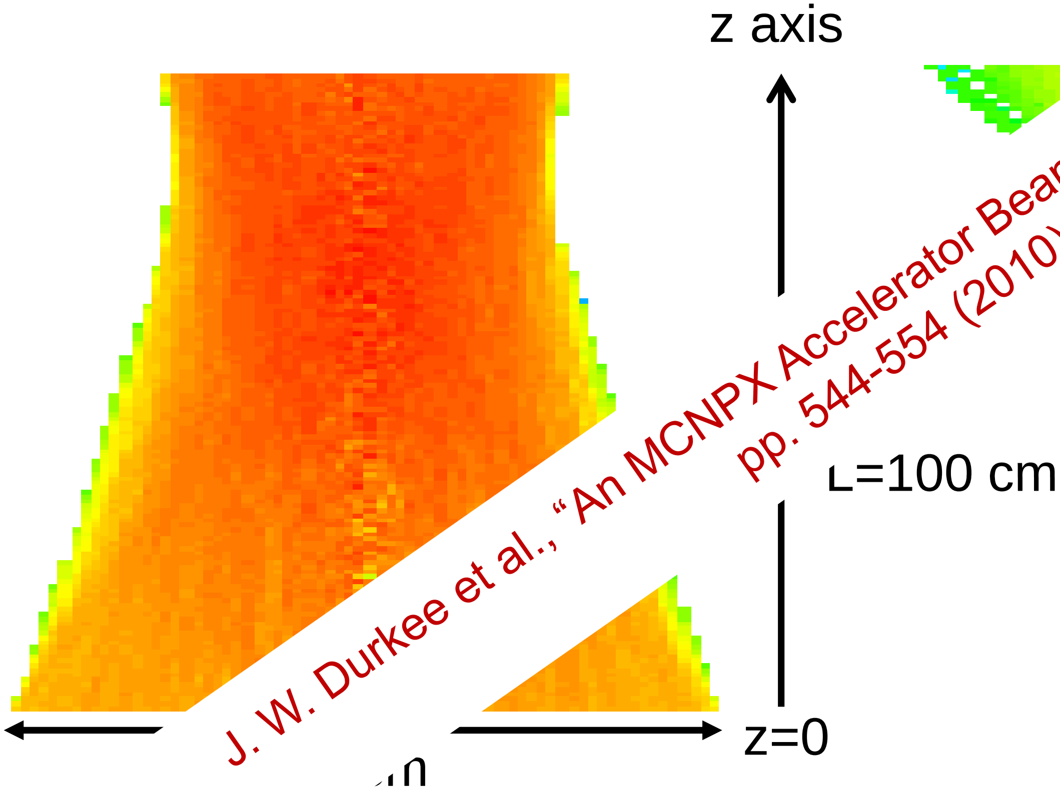
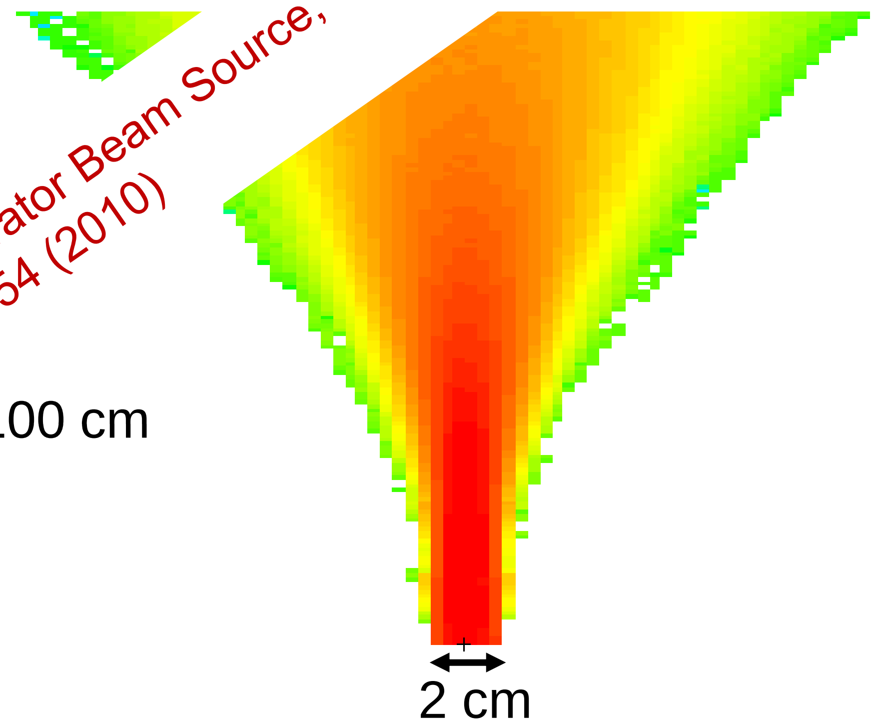
Sources: beam profile source option – new user interface increases fidelity of spatial profiles

Beam transport in vacuum



Beam tra… ir



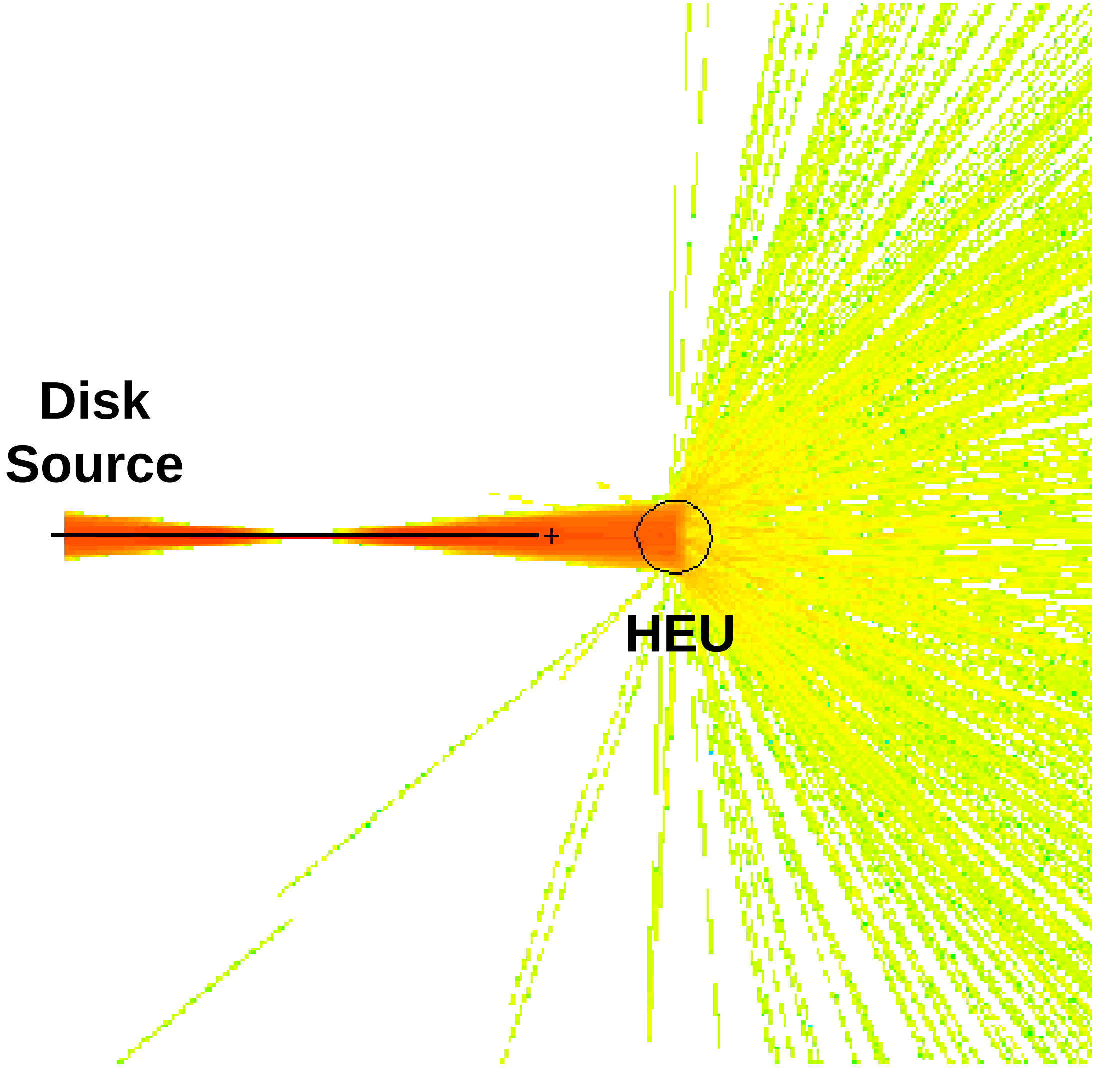
J. W. Durkee et al., "An MCNPX Accelerator Beam Source," PNE, **52**, No. 6, pp. 544-554 (2010)

Sources: beam profile source option – a simple example for a 100-MeV muon beam

```
100 MeV muons in air
1  1 -0.0013  -1 2 3 imp:n=1
2  2 -19.0    -2     imp:n=1
3  1 -0.0013  -3     imp:n=1
4  0           1     imp:n=0

1  so  200
2  sph 50 0 0  3.0
3  rcc -1 0 0 40 0 0 .001

mode n p h |
m1   7014 .8  8016 .2
m2  92235 .5 92238 .5
phys:n 200
sdef par=| erg=100
     pos=0 0 0 axs=1 0 0 vec=0 1 0
     bem=9e-3 9e-3 20 bap=2.0 2.0 0
tmesh
rmesh1:|  flux
cora1 0 499i 100
corb1 -50 499i 50
corc1 -50 50
endmd
nps  1000000
print
```



Sources: natural background source option – new data file enables automatic sampling of background spectra

Routines from GADRAS, which implement the Goldhagen normalization technique for GCR neutron fluxes, were obtained and used to create integral flux values contained in the NBS file. A special flag indicates the existence of a specific spectrum for that location. Also shown is the generic photon spectrum currently provided.

```
Neutron flux from Goldhagen JEDEC No. 89A (2006)
              90.0              0.0              0.0          330
 flux (n/cm2/s)     0.1193E-01 flux (p/cm2/s)      0.1667E+00
      1.0593E-10     2.1270E+02      4.6400E-02     0.0000E+00
      1.1885E-10     2.3849E+02      4.6500E-02     1.4500E+01
      1.3335E-10     2.6743E+02      4.6600E-02     0.0000E+00
      1.4962E-10     3.0003E+02      5.0100E-02     0.0000E+00
      1.6788E-10     3.3624E+02      5.0200E-02     1.4900E-01
      1.8836E-10     3.7715E+02      5.0300E-02     0.0000E+00
      2.1135E-10     4.2306E+02      5.3100E-02     0.0000E+00
      2.3714E-10     4.7393E+02      5.3200E-02     1.2600E+00
      2.6607E-10     5.3131E+02      5.3300E-02     0.0000E+00
      2.9854E-10     5.9510E+02      6.3200E-02     0.0000E+00
      3.3497E-10     6.6707E+02      6.3300E-02     1.2500E+01
      3.7584E-10     7.4766E+02      6.3400E-02     0.0000E+00
                                 …
LB       Latitude       Longitude        Altitude    # lines
             30.0           120.0             0.0          0
 flux (n/cm2/s)     0.6866E-02 flux (p/cm2/s)      0.1667E+00
                                 …
NY       Latitude       Longitude        Altitude    # lines
             40.0            70.0             0.0          0
 flux (n/cm2/s)     0.8859E-02 flux (p/cm2/s)      0.1667E+00
                                 …
```

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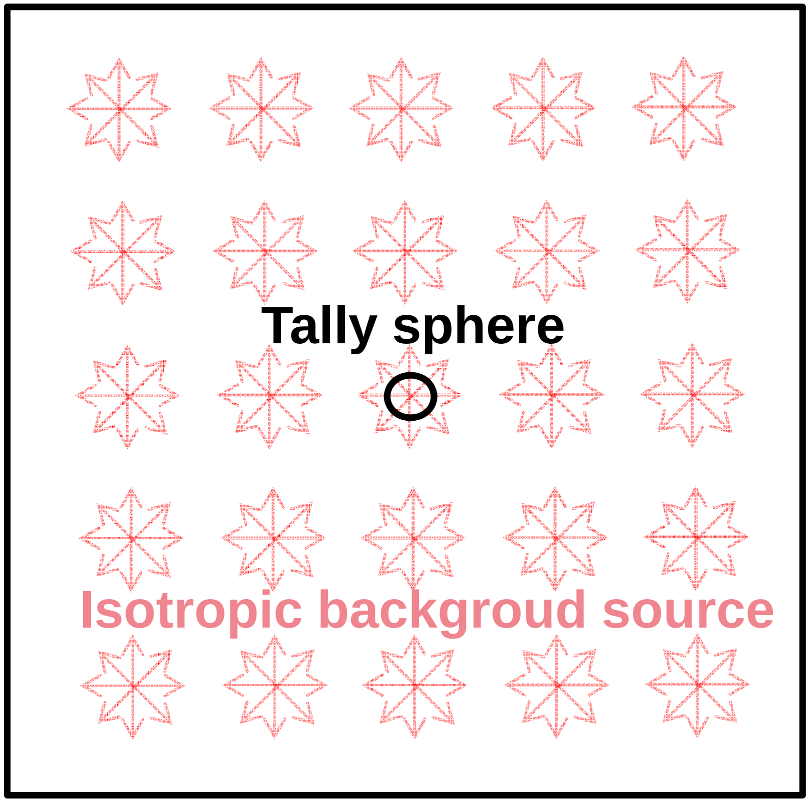
Sources: natural background source option – a simple example producing neutron spectra for NY and CA

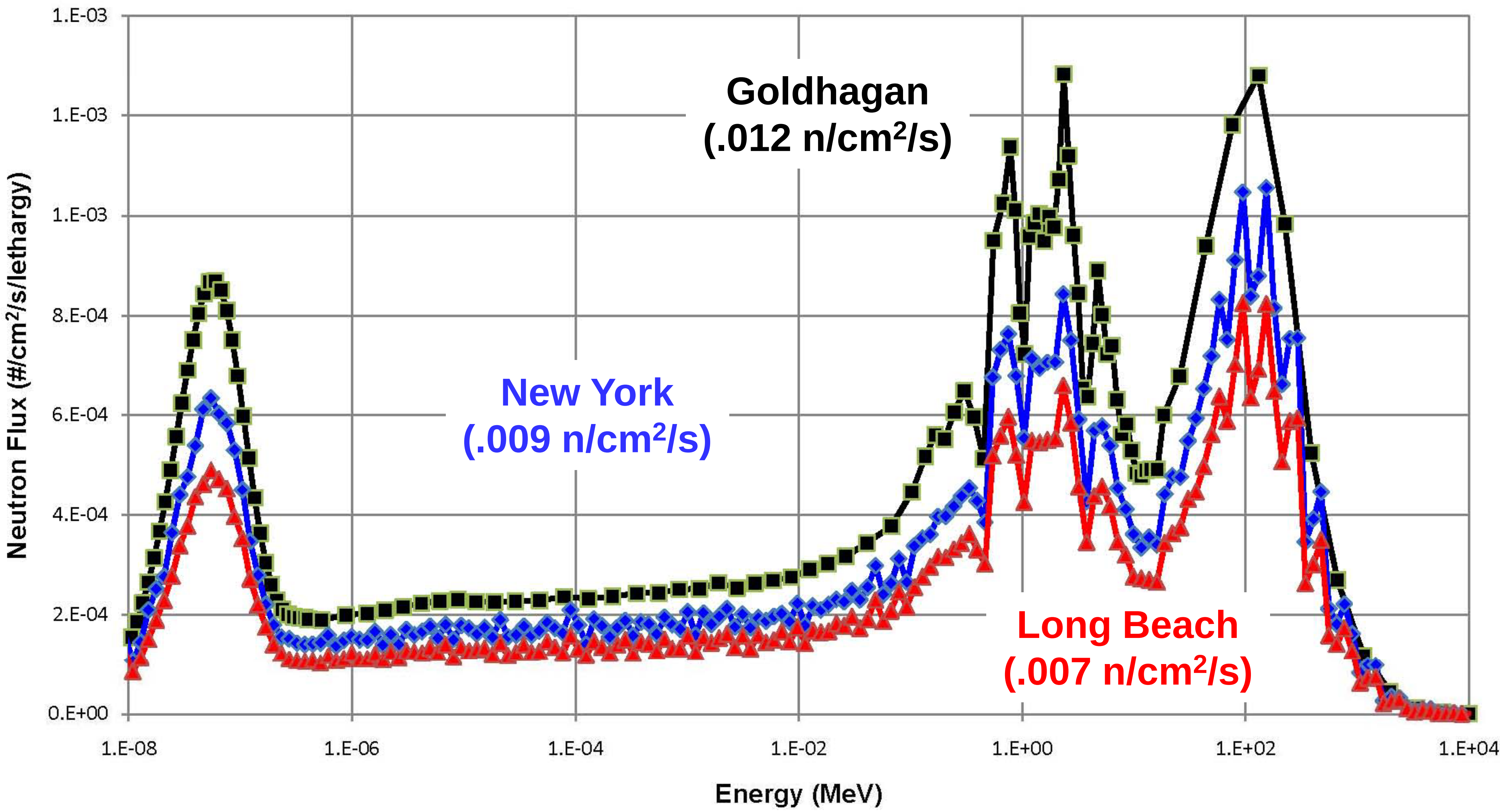
```
Background source for NY & LB
1   0   -1 5 imp:n=1
5   0    -5  imp:n=1
99  0    1   imp:n=0

1  rpp  -100 100 -100 100 -100 100
5   s    0  0  0  5

mode  n p
phys:n 5e5
phys:p 1e5
sdef  X=d1 Y=d2 Z=d3  PAR=bg
      WGT=578.93565 LOC=40.78  73.97 0 $ NY
c     WGT=448.69310 LOC=33.77 118.18 0 $ LB
si1   -100 100
sp1     0  1
si2   -100 100
sp2     0  1
si3   -100 100
sp3     0  1
f4:n 5
e4 1e-8 199log 1e6
f14:p 5
e14 0 299i 10
nps   1000000000
print
```



Sources: natural background source option – a simple example producing neutron spectra for NY and CA



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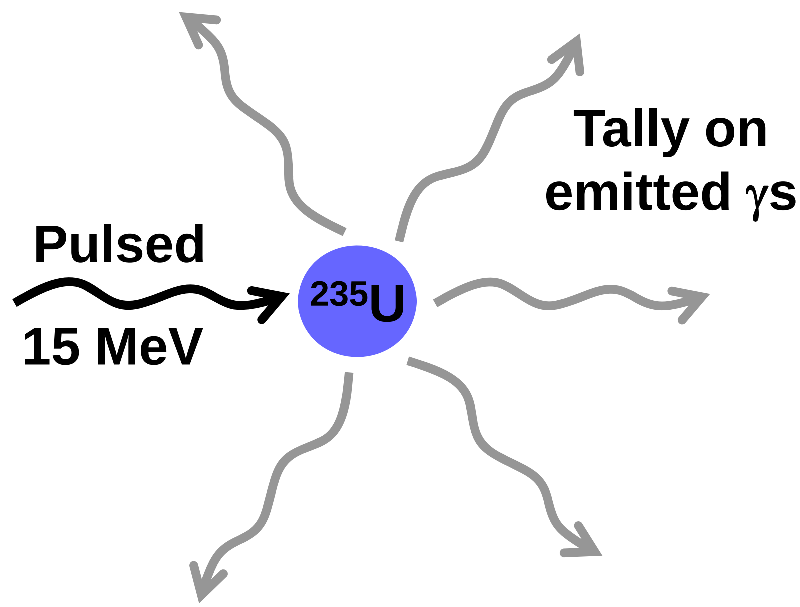
Tallies: cyclic-bin tally option – simplifies accumulation of tallies in pulsed applications

```
Pulsed 15-MeV gammas into U-235
1   1 -19.0    -1   imp:p=1
2   0           1   imp:p=0

1   so 10

m1    92235 1
mode p
phys:p 3j 1 j -101
lca   7j -2
sdef par=p erg=15 tme=d1<d2
si1   0 0.000001e8 .001e8
sp1   0           1      0
si2   0         1e8
sp2   0           1
f1:p 1
t1    CBEG=0.0 CFRQ=1000.e-8 COFI=0.000005e8
      CONI=0.0005e8 CSUB=5 $ CEND=1e8
ft1    tag 1
fu1    92235.99999 92000.0
nps    100000000
print
```

1 μs pulse every 1 ms out to 1s



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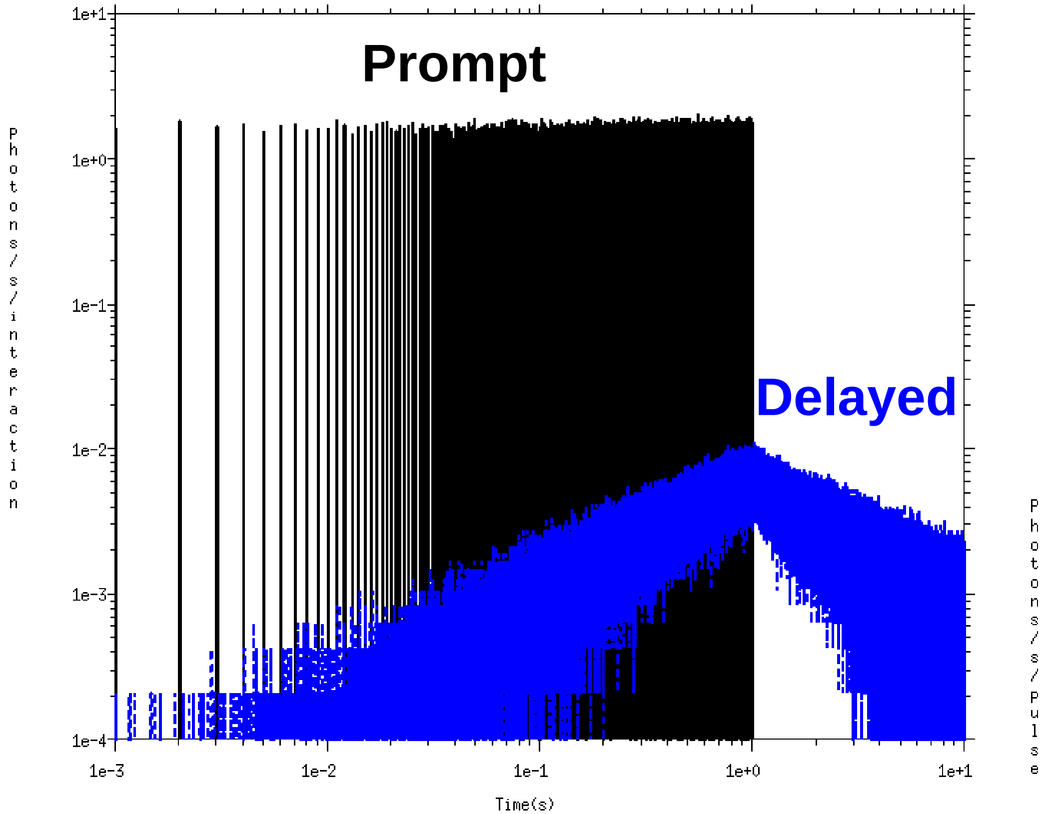
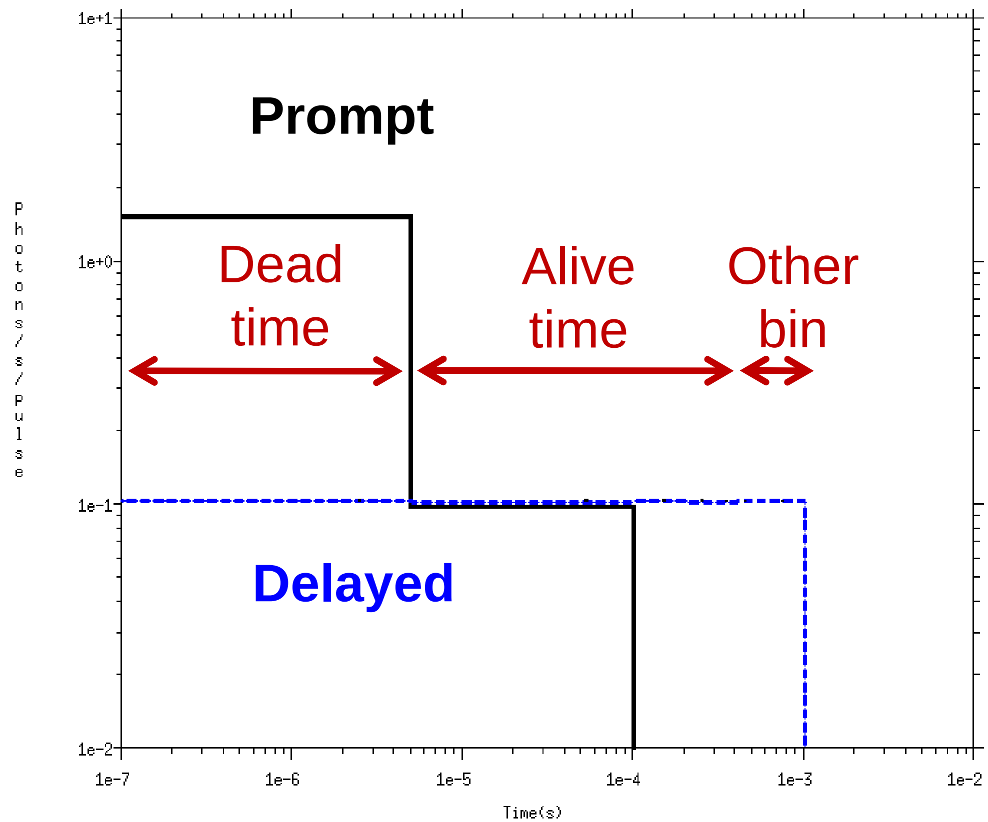
Tallies: cyclic-bin tally option – pulsed photon irradiation of ^{235}U



Full time-dependent behavior of 1000 pulses with dead/alive time bins repeated every 1 ms. Note decay after beam is turned off.

Cyclic time feature accumulates contributions across all 1000 repeated bins.



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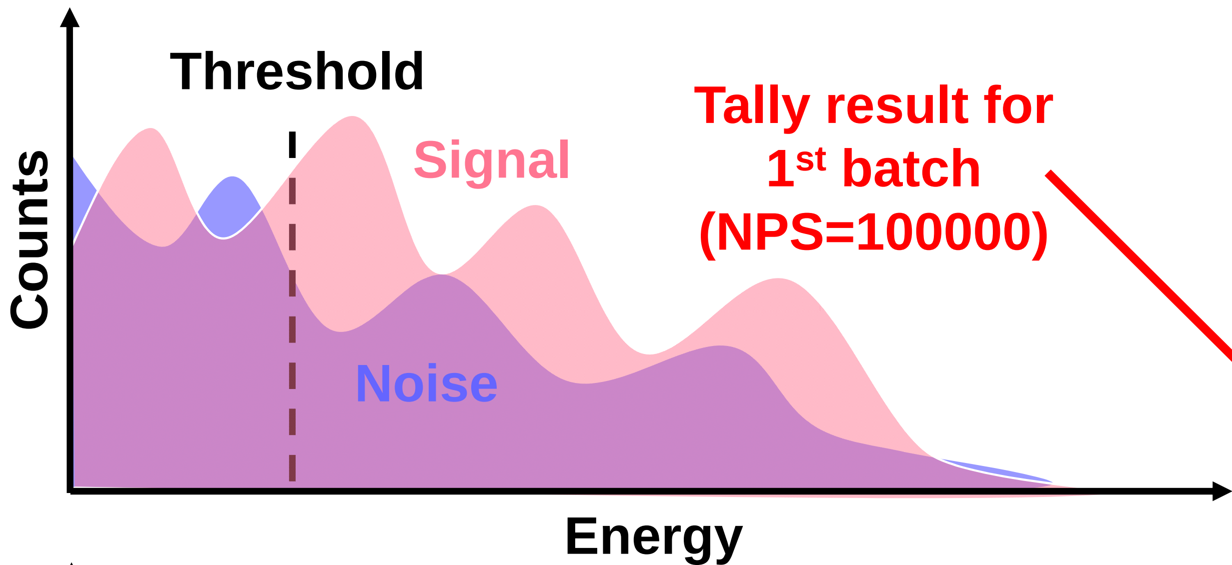
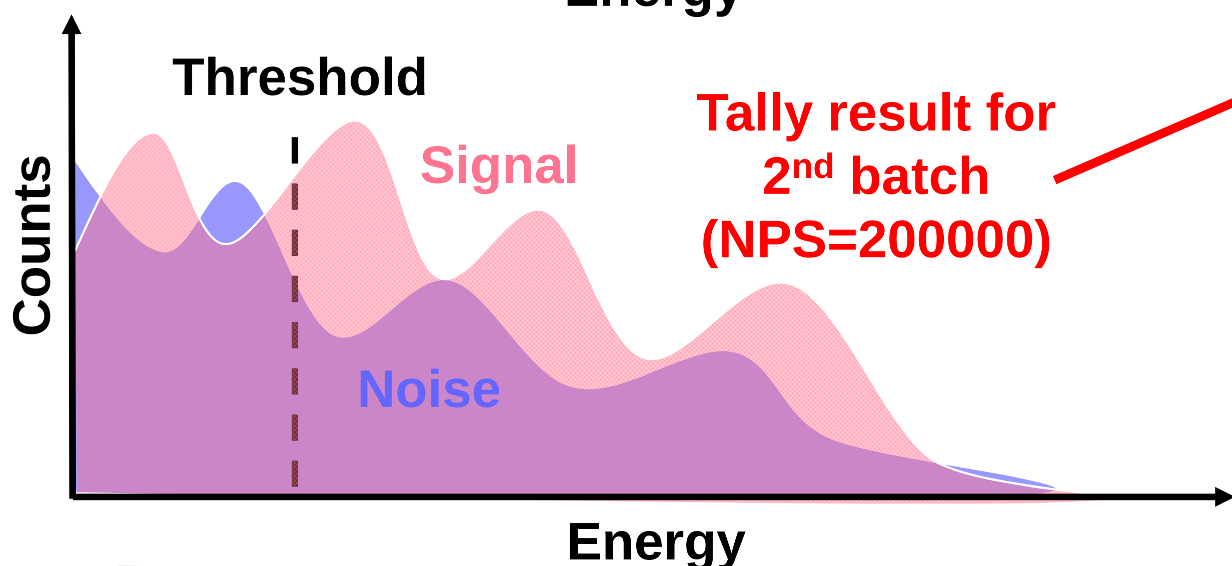
Tallies: ROC curve tally option – generates ROC curves from signal & noise tallies using batches of samples



Tally result for 1st batch (NPS=100000)



Tally result for 2nd batch (NPS=200000)

.
.
.

Tally Fluctuation Chart

NPS	Signal	Noise
100000	30.0	19.3
200000	32.1	25.1
300000	28.3	20.8

.
.
.

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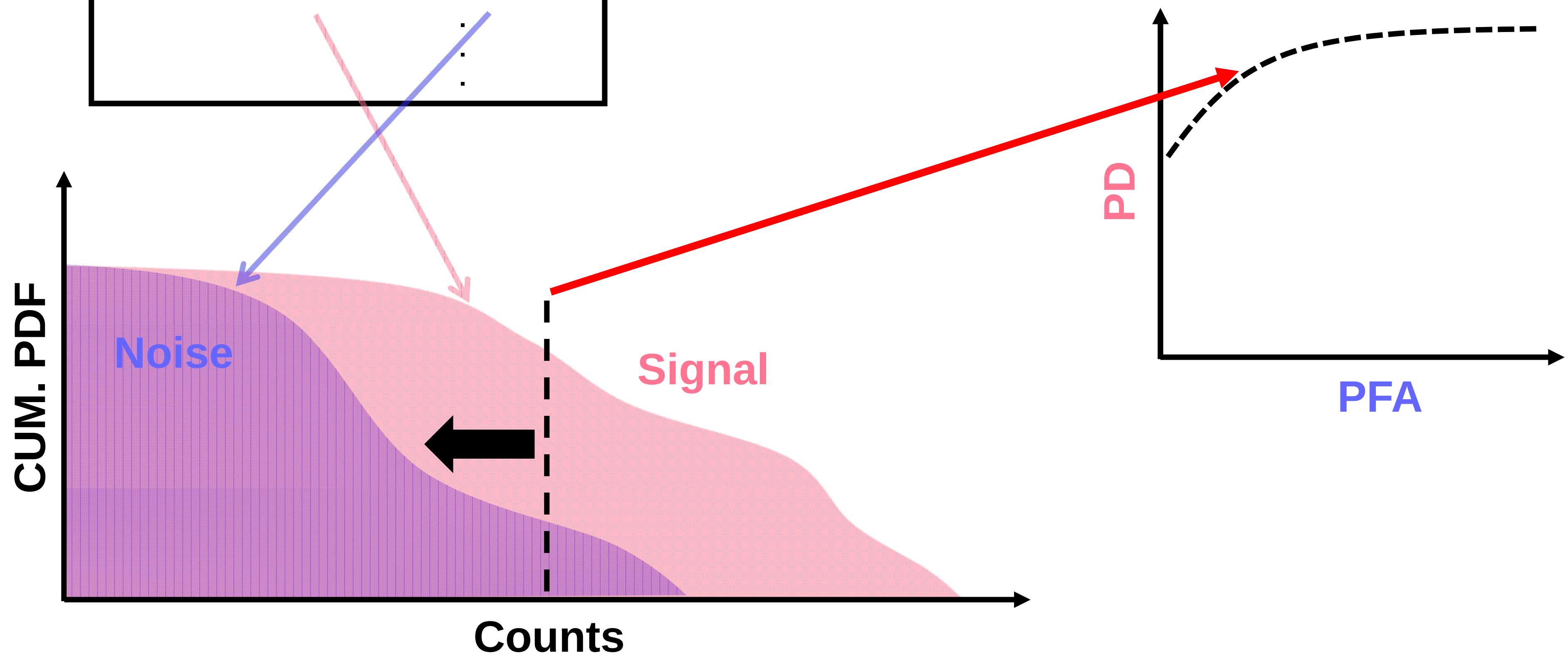
Tallies: ROC curve tally option – generates ROC curves from signal & noise tallies using batches of samples

Tally Fluctuation Chart

NPS	Signal	Noise
100000	30.0	19.3
200000	32.1	25.1
300000	28.3	20.8
.	.	.



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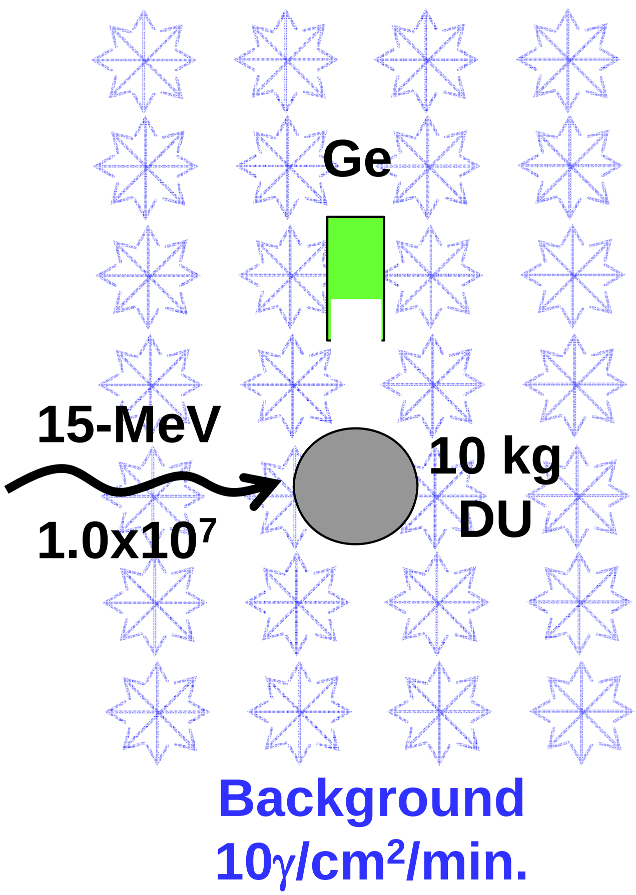
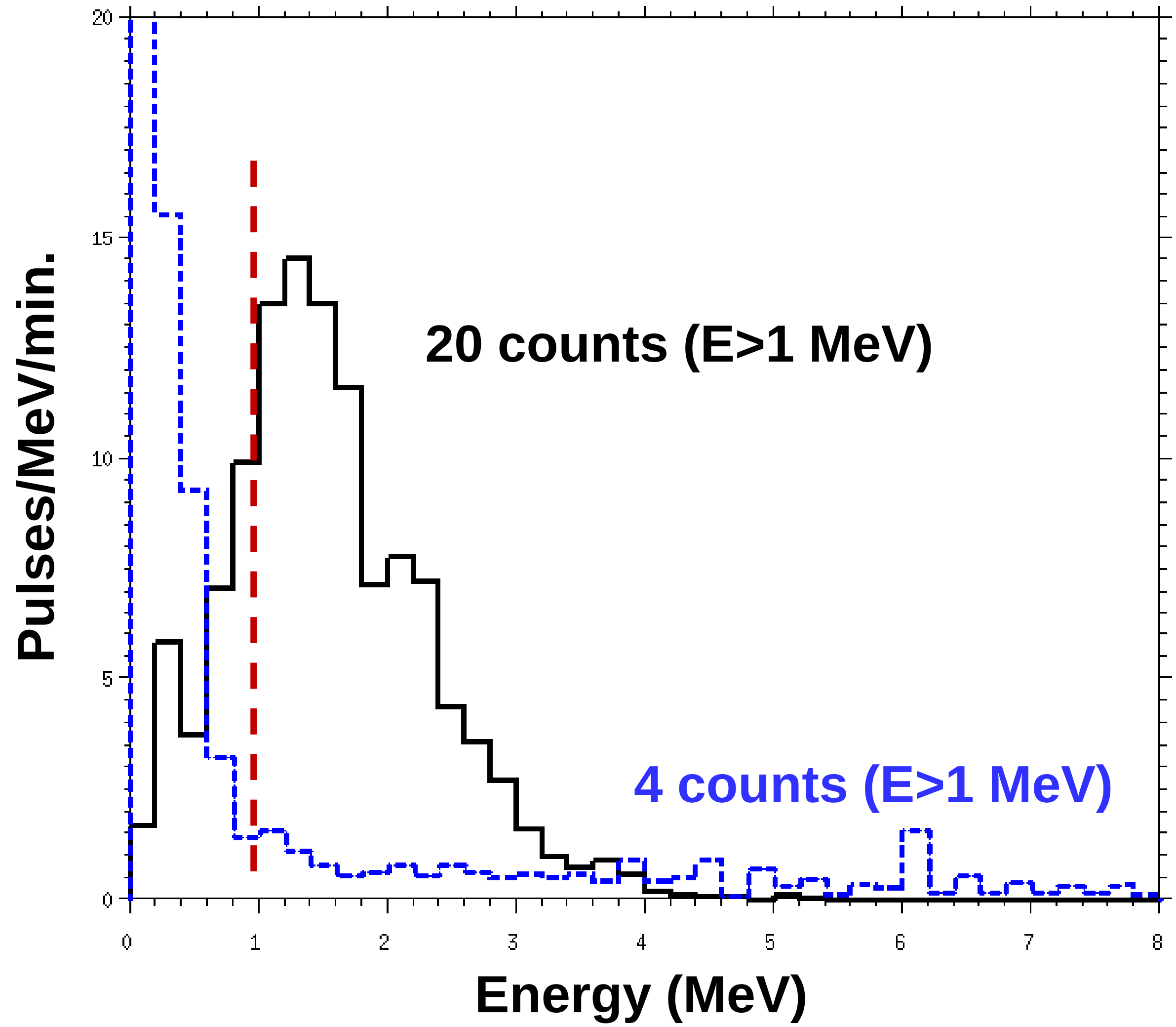
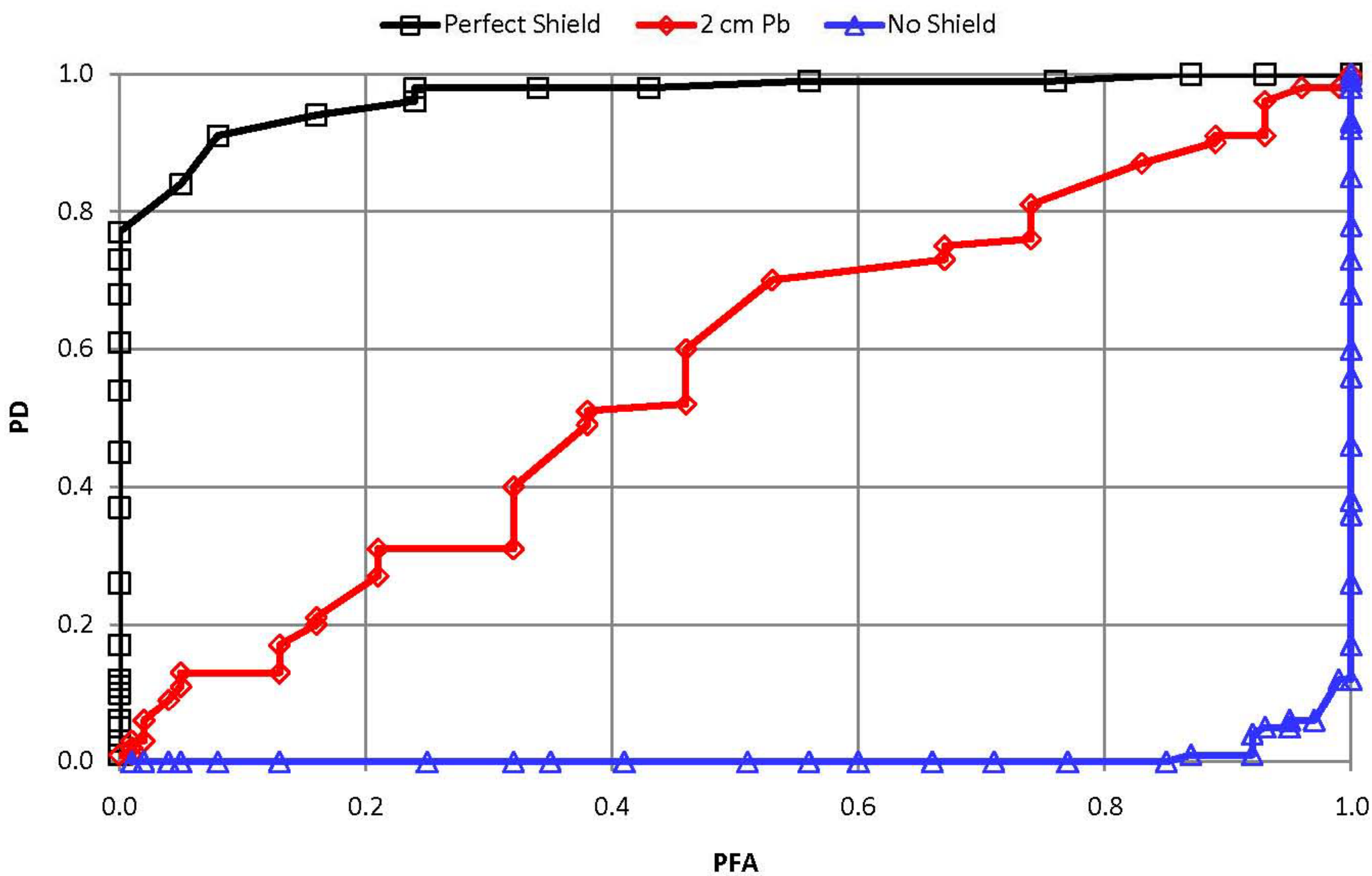
Tallies: ROC curve tally option – photon interrogation of DU with gamma background





Tallies: ROC curve tally option – photon interrogation of DU with gamma background



Tallies: triple & quadruple coincidences – extension of PHL tally option enables high-order coincidencing

- Format extended to add 3^{rd} and 4^{th} regions

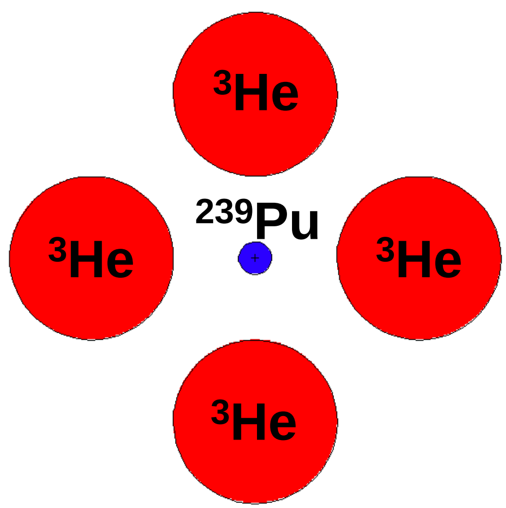
PHL	${}^1N\ {}^1T_1\ {}^1F_1\ {}^1T_2\ {}^1F_2\ \ldots\ {}^1T_{1N}\ {}^1F_{1N}$	1^{st} Region
	$[{}^2N\ {}^2T_1\ {}^2F_1\ {}^2T_2\ {}^2F_2\ \ldots\ {}^2T_{2N}\ {}^2F_{2N}]$	2^{nd} Region
	$[{}^3N\ {}^3T_1\ {}^3F_1\ {}^3T_2\ {}^3F_2\ \ldots\ {}^3T_{3N}\ {}^3F_{3N}]$	3^{rd} Region
	$[{}^4N\ {}^4T_1\ {}^4F_1\ {}^4T_2\ {}^4F_2\ \ldots\ {}^4T_{4N}\ {}^4F_{4N}]$	4^{th} Region

- Other tally cards now allowed to specify energy channels

E8	${}^1E_1\ {}^1E_2\ {}^1E_3\ {}^1E_4\ \ldots$	1^{st} Region
Fu8	${}^2E_1\ {}^2E_2\ {}^2E_3\ {}^2E_4\ \ldots$	2^{nd} Region
C8	${}^3E_1\ {}^3E_2\ {}^3E_3\ {}^3E_4\ \ldots$	3^{rd} Region
Fs8	${}^4E_1\ {}^4E_2\ {}^4E_3\ {}^4E_4\ \ldots$	4^{th} Region

Tallies: triple & quadruple coincidences – a simple fission example with ^{3}He detectors surrounding ^{239}Pu

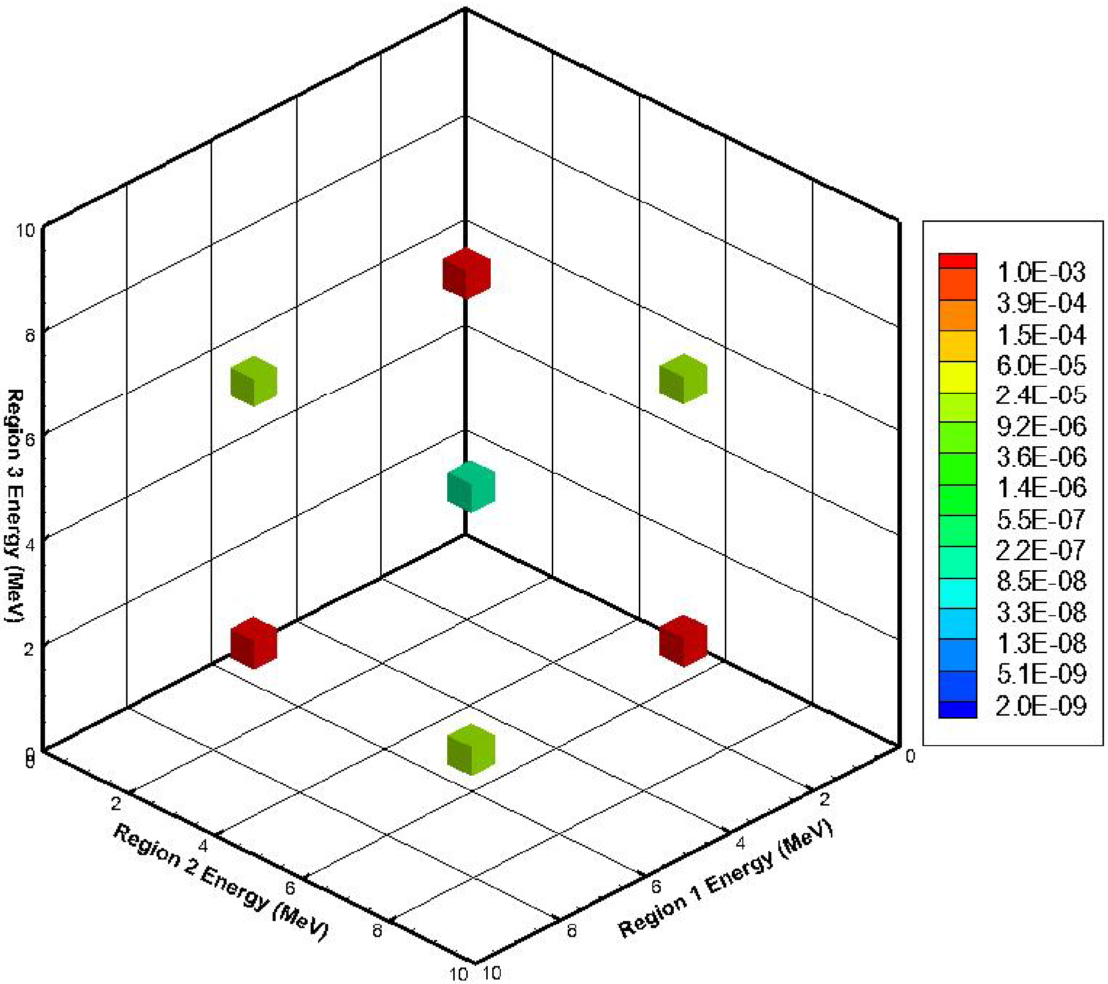
```
Thermal neutrons into Pu-239
1  1  -10.0   -1   imp:n=1
2  2  -1e-3   -2   imp:n=1
3  2  -1e-3   -3   imp:n=1
4  2  -1e-3   -4   imp:n=1
5  2  -1e-3   -5   imp:n=1
6  0           1 2 3 4 5 -6  imp:n=1
7  0                      6  imp:n=0

1  sph    0   0  0  1.0
2  rcc  -10   0 -10  0 0 20  5.0
3  rcc   10   0 -10  0 0 20  5.0
4  rcc    0 -10 -10  0 0 20  5.0
5  rcc    0  10 -10  0 0 20  5.0
6  sph    0   0  0  100.0

mode n h t s
m1   94239 1
m2    2003 1
phys:n 5j 1 2
cut:n  2j 0 0
cut:h,t,s j 0.001
sdef  par=n  erg=1e-8
f06:h  2 3 4 5
f16:t  2 3 4 5
f26:s  2 3 4 5
```

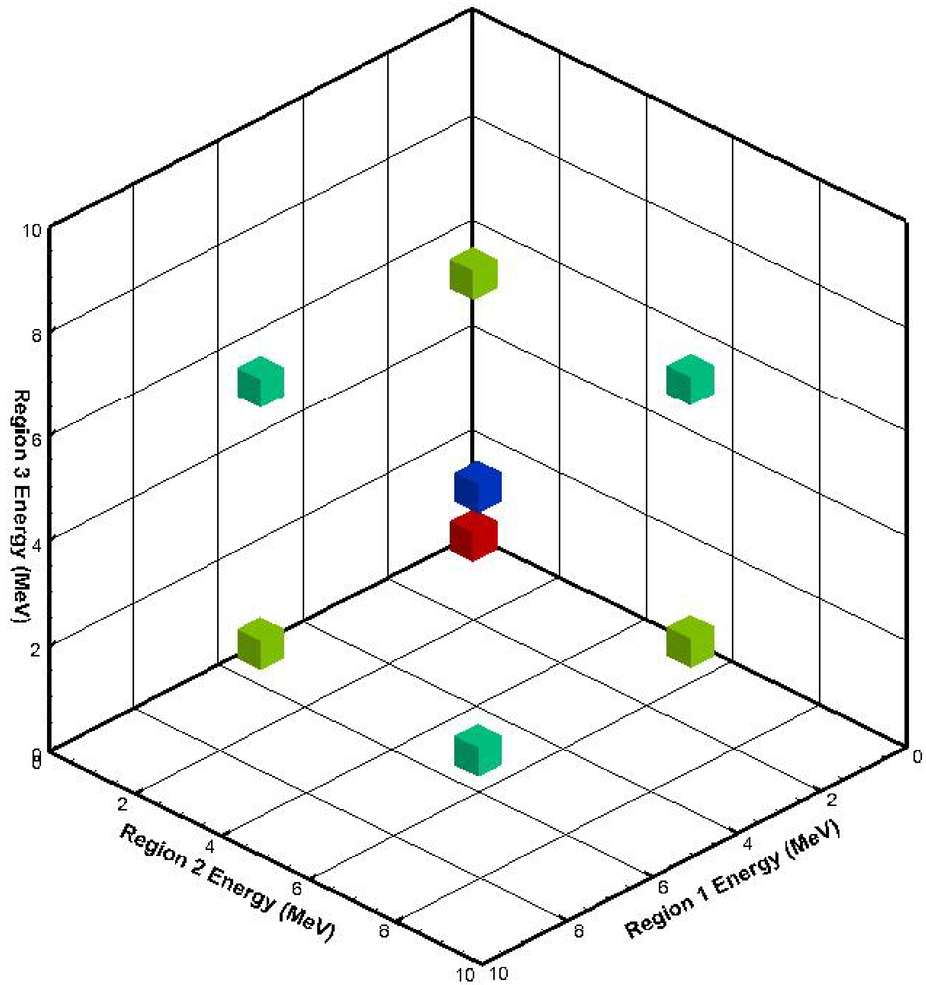



```
fc8  Integrated Pulse Spectrum
f8:h,t,s (2 3 4 5)
ft8    PHL 3 6 1 16 1 26 1
           3 6 2 16 2 26 2
           3 6 3 16 3 26 3
           3 6 4 16 4 26 4
e8  0 10 NT
fu8 0 10 NT
c8  0 10 NT
fs8 0 10 NT
fq8 s c e u
fc28  Full Pulse Spectrum
f28:h,t,s (2 3 4 5)
ft28   PHL 3 6 1 16 1 26 1
           3 6 2 16 2 26 2
           3 6 3 16 3 26 3
           3 6 4 16 4 26 4
e28  0 1 2 3 4 5 6 7 8 9 10 NT
fu28 0 1 2 3 4 5 6 7 8 9 10 NT
c28  0 1 2 3 4 5 6 7 8 9 10 NT
fs28 0 1 2 3 4 5 6 7 8 9 10 NT
fq28 s c e u
nps  10000000000
```

Tallies: triple & quadruple coincidences – a simple fission example with ^{3}He detectors surrounding ^{239}Pu

No Counts in 4th Detector | **With Counts in 4th Detector**





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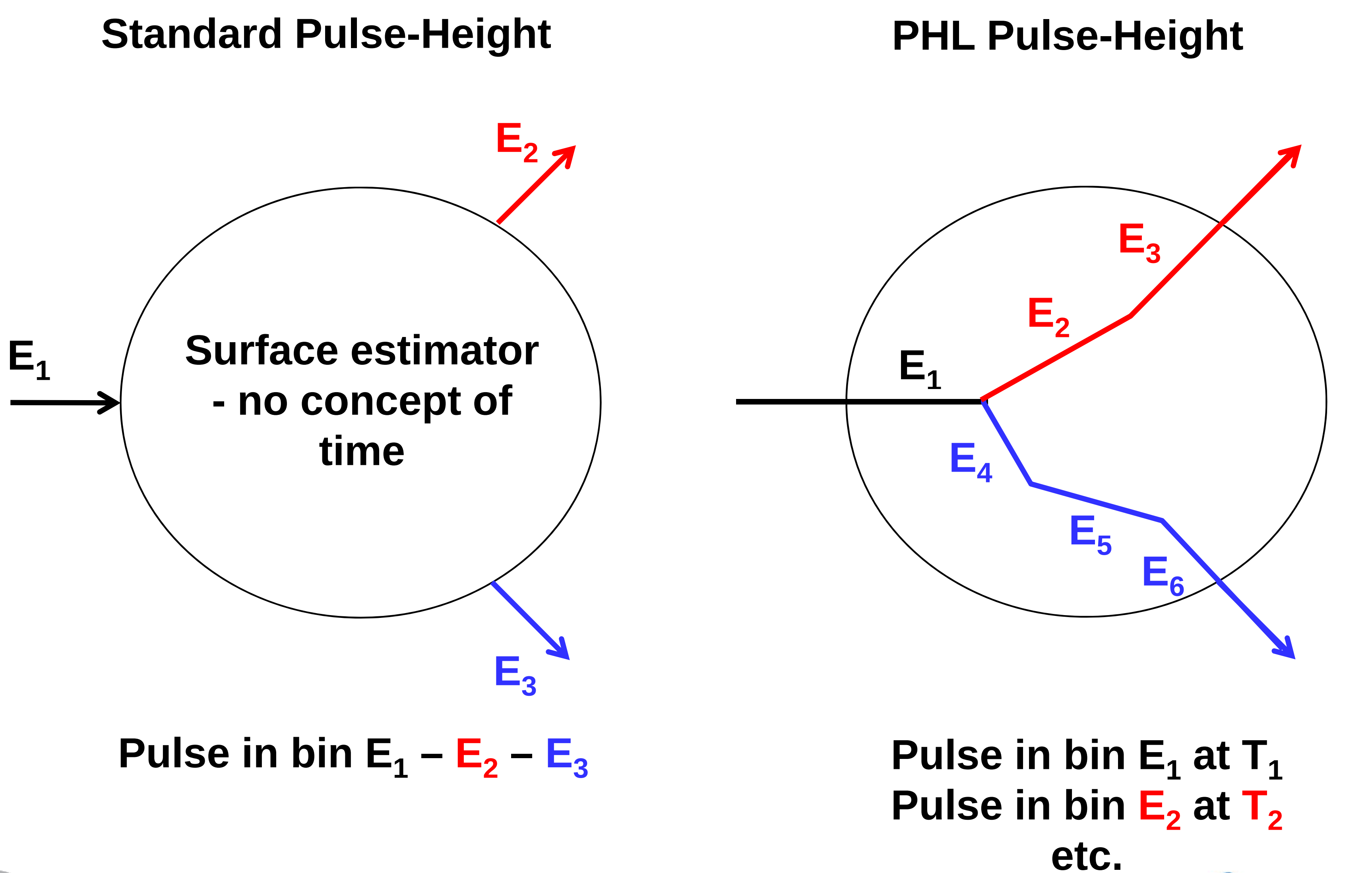
Tallies: time-dependent pulse-height tallies – extension of the PHL tally option enables pulse-shape discrimination



Tallies: time-dependent pulse-height tallies – a simple model of a ^{3}He detector

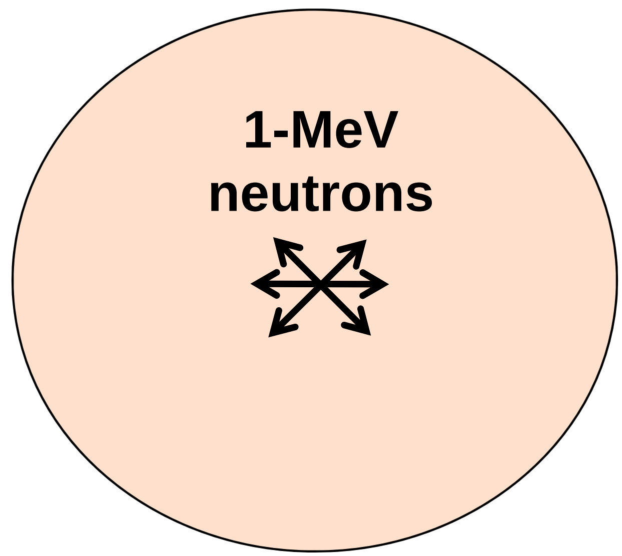
```
1-MeV Neutrons into He-3
1  1  -1e-3   -1    imp:n=1
2  0           1 -2 imp:n=1
3  0              2 imp:n=0

1  so  100.
2  so  1000

mode n h t s
m1    2003 1
phys:n 5j 1 2
cut:h,t,s j 1e-3
sdef   par=n  erg=1
f16:h  1
f26:t  1
f36:s  1
f8:h   1
ft8    phl 1 16 1  0
e8     .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
t8     05 10 15 20 25 30 35 40 45 50 55 60
f18:t   1
ft18    phl 1 26 1  0
e18    .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
t18    05 10 15 20 25 30 35 40 45 50 55 60
f28:s   1
ft28    phl 1 36 1  0
e28    .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
t28    05 10 15 20 25 30 35 40 45 50 55 60
```

```
f38:h,t,s   1
ft38     phl 3 16 1 26 1 36 1  0
e38      .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0
t38      05 10 15 20 25 30 35 40 45 50 55 60
nps  100000000
print
```

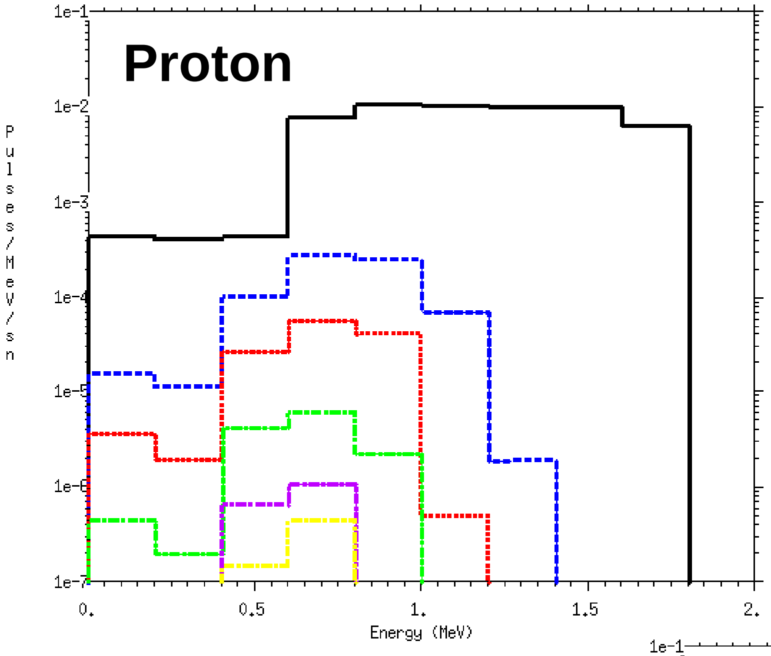
1-m Sphere of ^{3}He



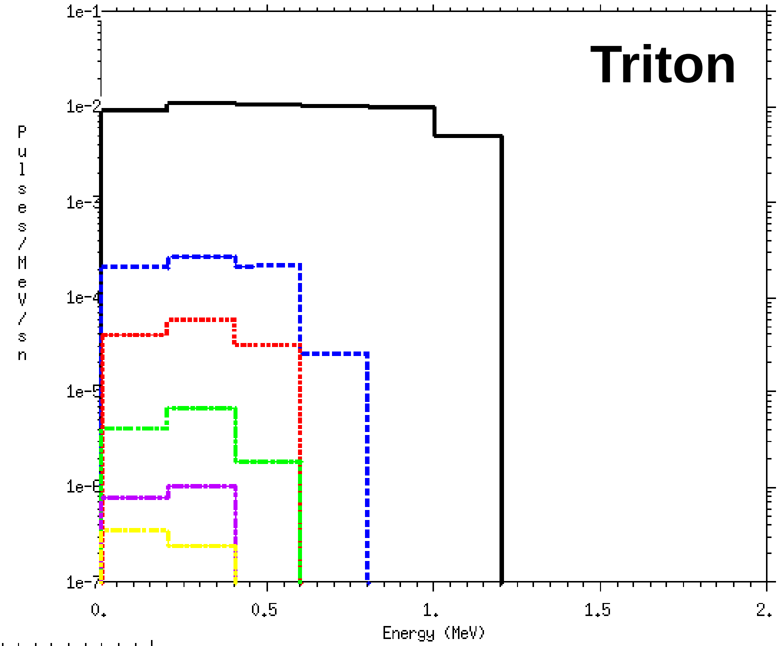
$^3He + n \rightarrow p + t$

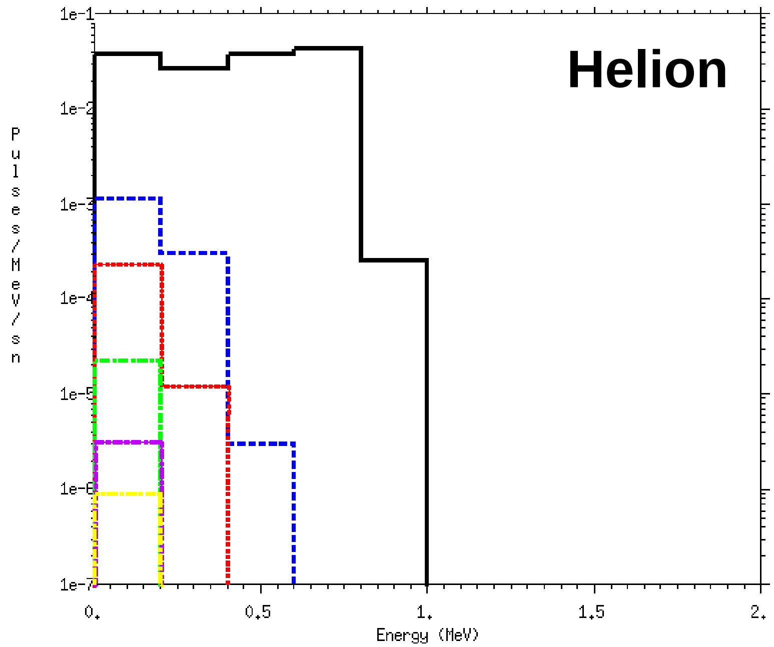
$^3He + n \rightarrow {}^3He^+ + n'$

Tallies: time-dependent pulse-height tallies – particle-dependent & time-dependent pulse spectra



.05 µs
.15 µs
.25 µs
.35 µs
.45 µs
.55 µs





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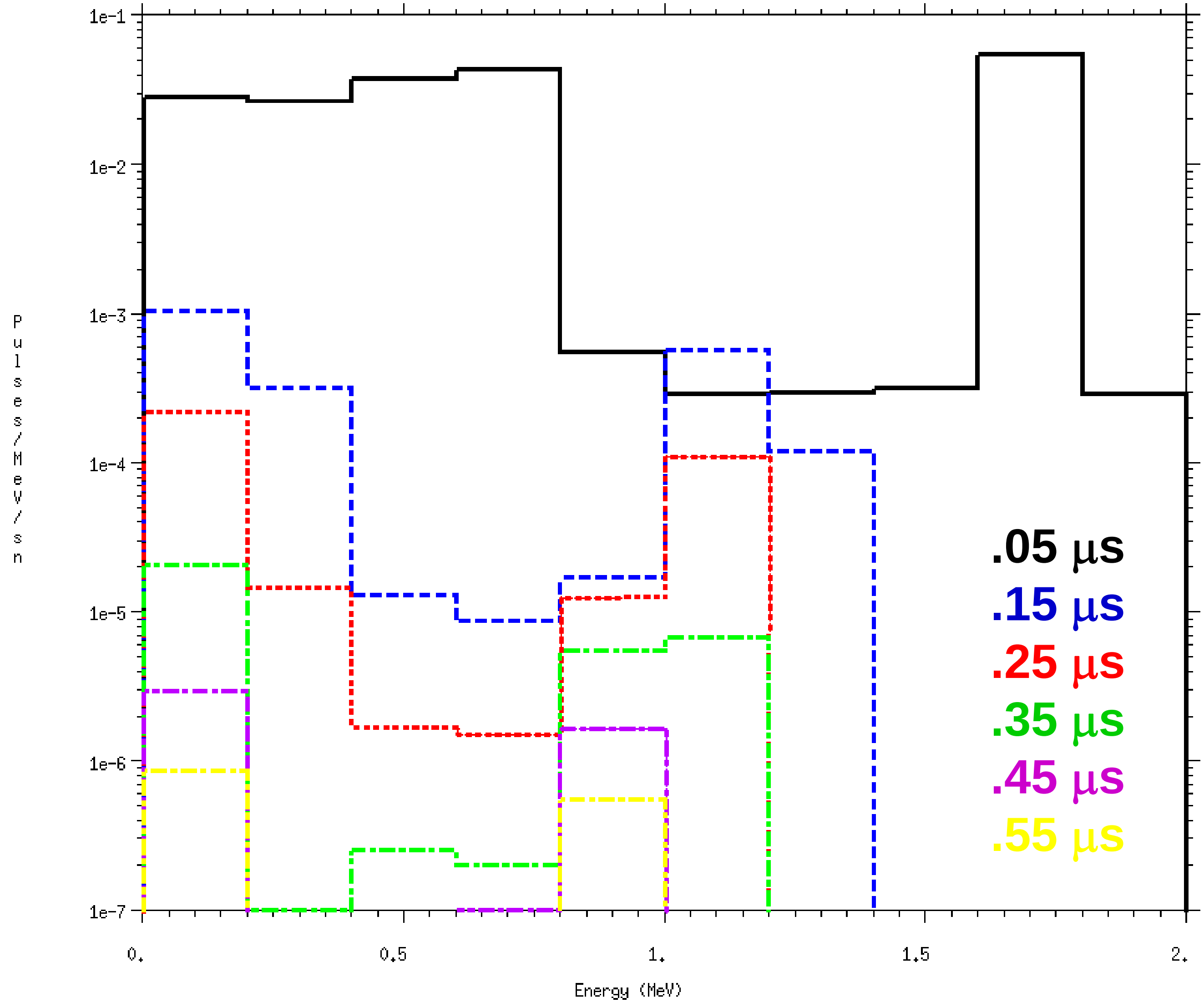
Tallies: time-dependent pulse-height tallies – combined time-dependent pulse spectra



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