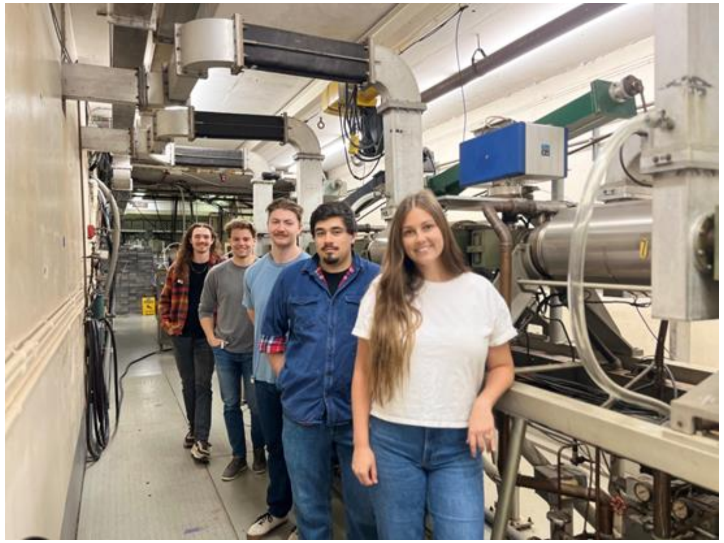
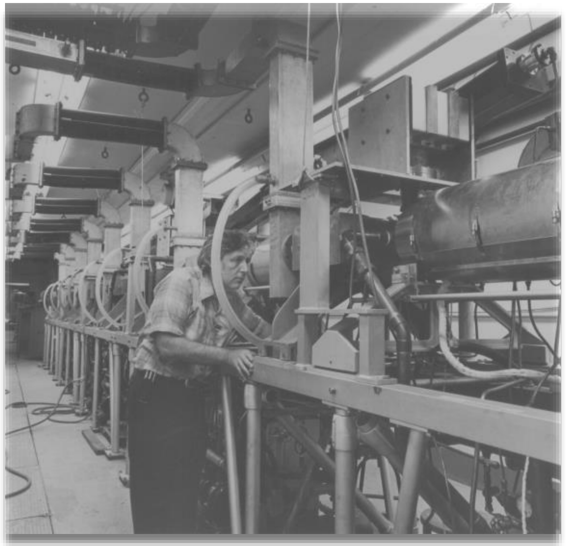
Development of Benchmark Measurements for Capture Gamma Cascades

Ian Parker, Yaron Danon, Katelyn Keparutis
Gaerttner Linear Accelerator (LINAC) Center, Rensselaer Polytechnic Institute, Troy, NY





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Project Overview:

Goal: Develop the methodology and provide data to test the accuracy of neutron capture gamma-ray production evaluations.

Objectives:

- Perform measurements using the RPI LINAC and Gamma-Ray Multiplicity Detector to collect neutron capture gamma-ray spectra.
- Accurately simulate gamma-ray emissions using cascade generators and Monte-Carlo codes.
- Assess the quality of neutron capture gamma-ray production evaluations by comparing measurement and simulation results.
- Provide benchmark methods, template, and examples, including experimental data, simulation inputs, and necessary tools.

Rensselaer Polytechnic Institute:
Yaron Danon – PI
Katelyn Keparutis – Graduate Student
Ian Parker – Graduate Student
Brookhaven National Laboratory:
David Brown
Emanuel Chimanski
Naval Nuclear Laboratory:
Devin Barry
Los Alamos National Lab:
Amanda Lewis



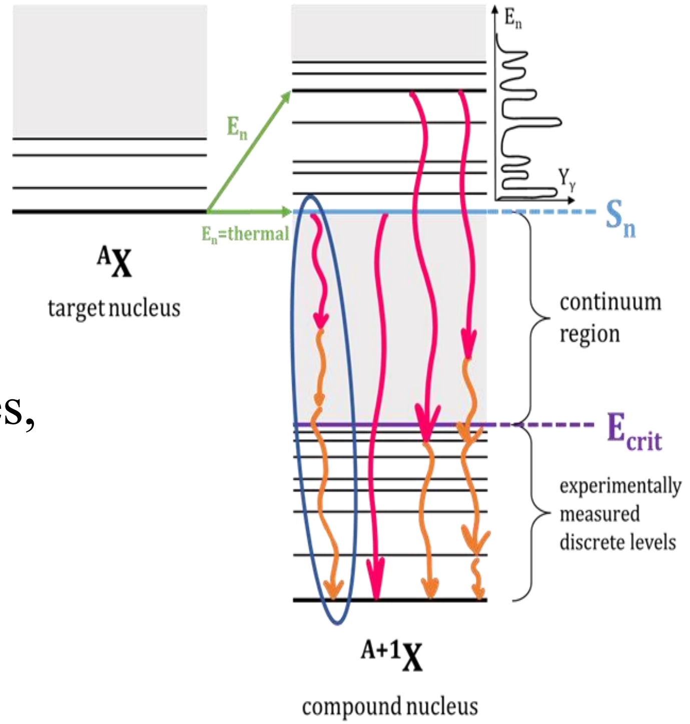




Motivation:

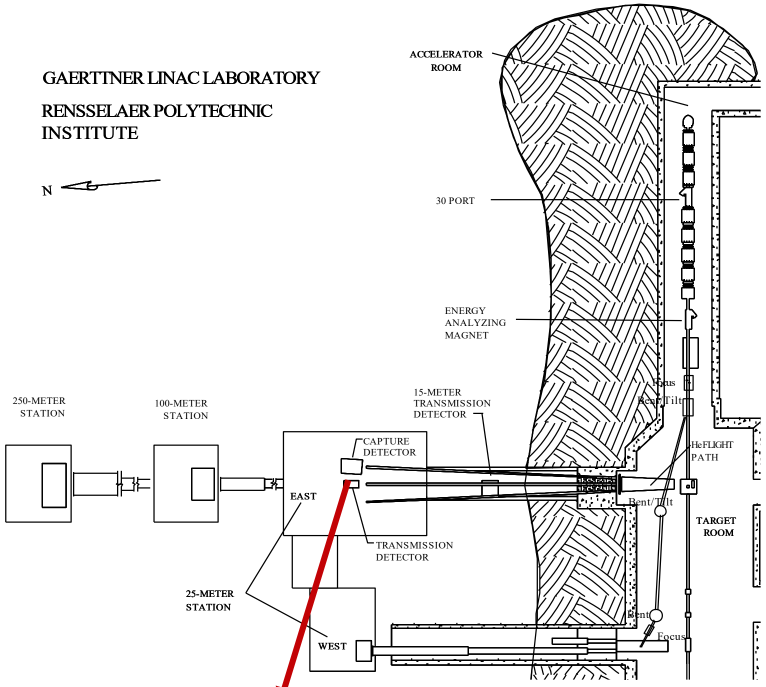
Currently, there is no benchmark or test suite available to test the accuracy of neutron capture gamma-ray production evaluations.

- Accurate gamma-ray production data is necessary for applications:
  - Reactor, shielding, and gamma-ray heating calculations.
  - Active neutron interrogation for material identification.
- **“Traditional” and “event-by-event” measurements are used[1]:**
  - **Traditional** – 1 detector, binned spectrum of gamma-ray counts per energy.
  - **Event-by-event** – Multiple detectors, coincidence measured, multiple observables/filters.
- Data needs to be well-known for individual gamma-ray energies and intensities, as well as level schemes and branching ratios for correlated gamma rays.
- Traditional simulation methods may accurately predict single detector spectra, but coincident gamma-rays can not be resolved.

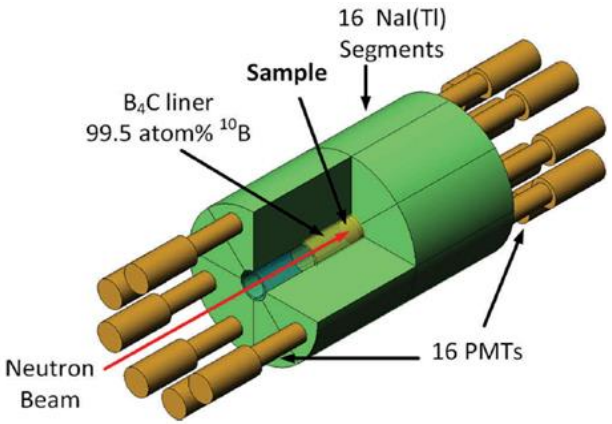


[1]S. McConchie et al.. Oak Ridge National Laboratory, ORNL/TM-2021/1900 (2001).

RPI Gamma-Ray Multiplicity Detector:



- ~4π 16 segment NaI(Tl) detector array – 20L total of NaI.
- Approximately 25m from the neutron production target.
- Contains a 1cm B_4C liner, 99.5 a/o ^{10}B enrichment – Used to limit false capture from scattered neutrons in the NaI.
- 6-inch lead shield surrounds the detector.
- Effective for incident neutron energies of 0.01 eV – 3 keV.
- 14-bit digitizer collects event timing and deposited energy.
- Time-of-flight method used to determine incident neutron energies.
- Used to measure both gamma-ray spectra and capture yield.



Completed Measurements: $0.01\ eV \leq E_n \leq 100.0\ eV$		
^{56}Fe	^{55}Mn/^{nat}Cu	^{59}Co
^{nat}Ta	^{nat}U	^{235}U
^{nat}Cd	**^{nat}Au**	**^{nat}In**
^{nat}Cu	**^{55}Mn**	**^{nat}Zr***

*Pilot Study

Process:

Measurement:
RPI γ-ray multiplicity detector

Experiment Processing:
Raw data to event-by-event table

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
82	48341	0	0	27009	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	4878	1709	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	2643	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	4179	0	3034	4039	0	0	0	0	0

Evaluated Data:
ENSDF, RIPL-3, ENDF

Cascade Generator:
ACE/DICEBOX/GIDI+

mod-MCNP6.2

Simulation Processing:
Read event list output

```
23 7 1.76999998092651
23 1 1.63999998569489
23 16 0.326371014768242
```

Event-by-Event Processing:
- Neutron capture γ-ray spectra
- Coincident γ-ray spectra
- Cascade Multiplicity Spectra
- Capture yield

Mod-MCNP6.2[1][2]:

- Uses Cascading γ-Ray Multiplicity (CGM) module to produce correlated secondary emissions.
- Implements ability to read externally made γ-ray cascade files in place of CGM generated reactions.
- Output contains energy deposited for each detector segment per neutron history.
- Cascade files can be generated with DICEBOX[3], GIDI+[4], or other cascade generation codes.

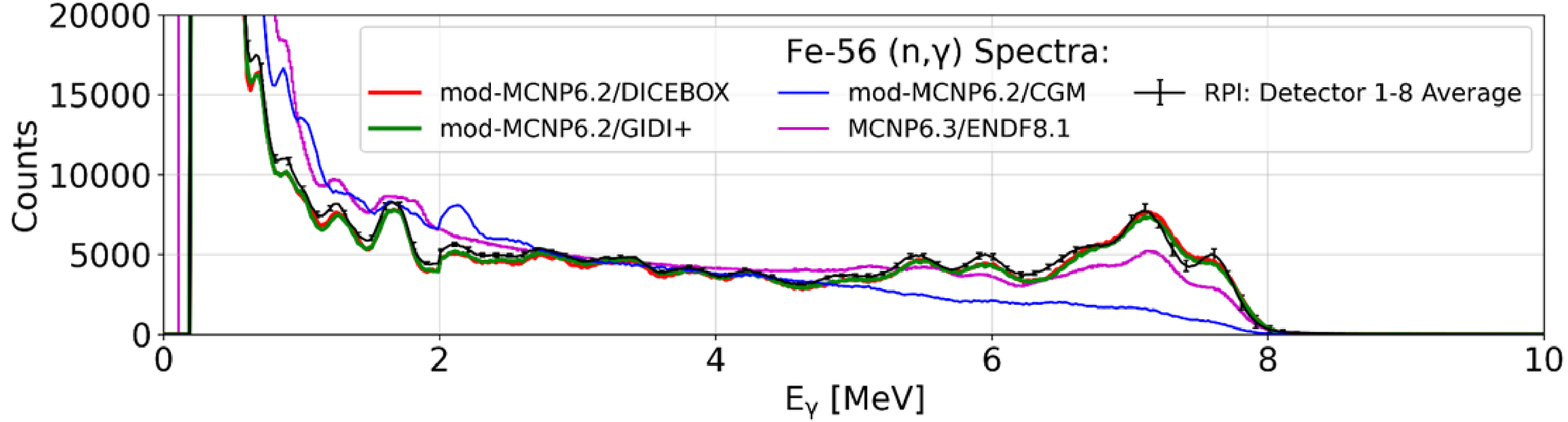
Cascade Generators:

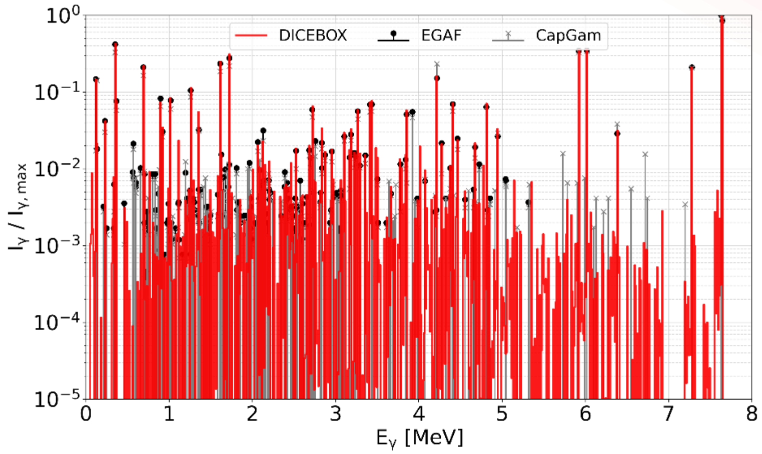
- ACE – Evaluator determines average gamma-ray multiplicity and spectra (discrete & continuum energies and intensities) – does not conserve binding energy when sampling individual gamma-ray energies.
- CGM – Pre-loaded ENSDF & RIPL data embedded in MCNP.
- DICEBOX – User defined input using ENSDF & RIPL data, simulates level scheme and determines de-excitation cascades.
- GIDI+ – Pre-determined level scheme and branching ratios, stored in a GNDS formatted file, realizations from GIDI+ API.

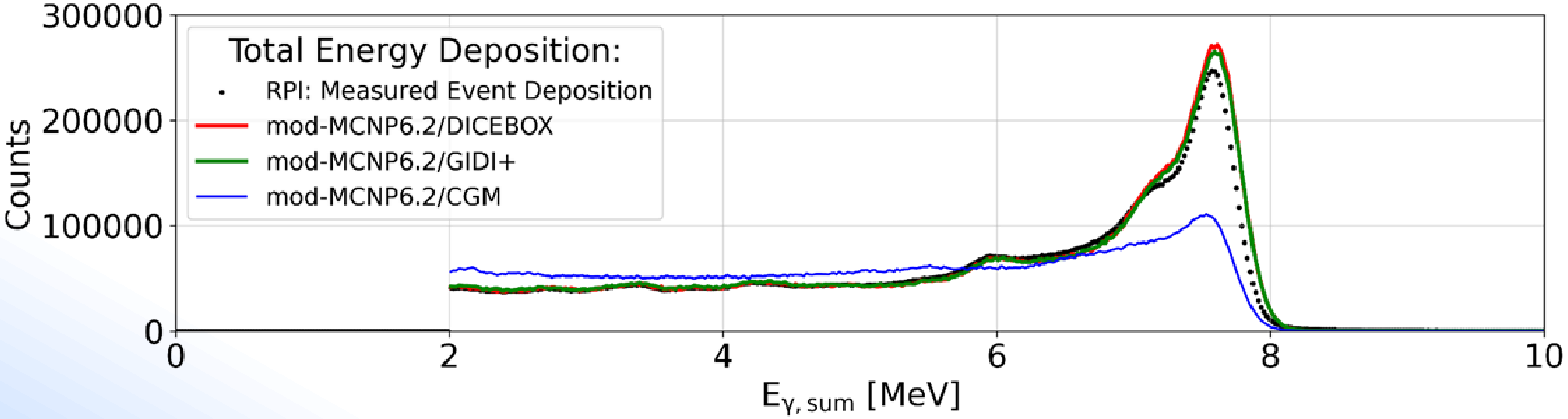
[1]Werner, C. J., (2018). *MCNP version 6.2 release notes* (LA-UR-18-20808). Los Alamos National Laboratory.
[2]Y. Danon et al., EPJ Web of Conferences 294 01001 (2024)
[3]Bečvář, F. (1998). Simulation of γ cascades in complex nuclei with emphasis on assessment of uncertainties of cascade-related quantities. *Nuclear Instruments and Methods in Physics Research Section A, 417*(2-3), 434-449. https://doi.org/10.1016/S0168-9002(98)00787-6.
[4]Lawrence Livermore National Laboratory. (n.d.). *GIDI+ (General Interaction Data Interface Plus)* [Computer software]. GitHub. https://github.com/LLNL/gidiplus

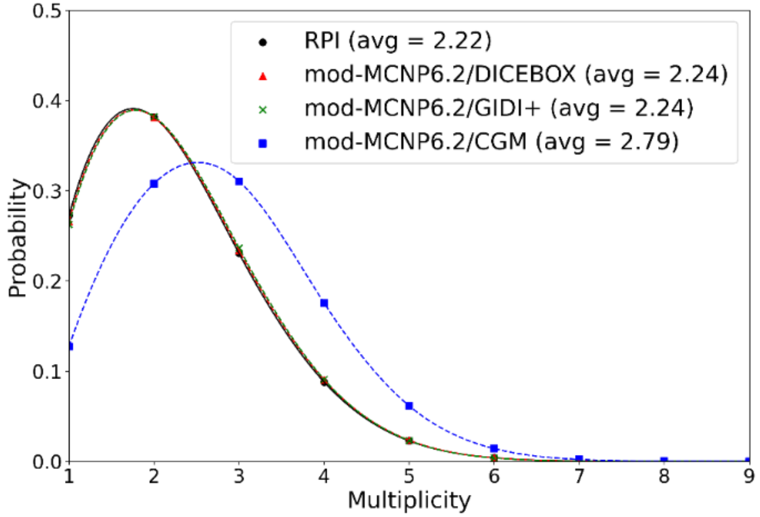
Method Validation with Fe-56:

Fe-56 primary gamma-ray energies and intensities are well known through the binding energy for thermal neutron capture[1] and will be the first benchmark completed as the best case for this method.









0.01 eV ≤ E_n ≤ 1.0 eV   0.200 MeV ≤ E_γ 2.0 MeV ≤ $E_{\Sigma\gamma}$ ≤ 10.0 MeV

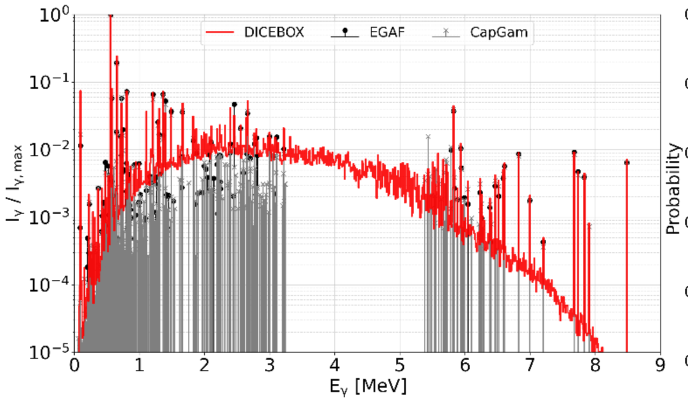
[1]R. B. Firestone et. al., Phys. Rev. C **95**, 014328 (2017).

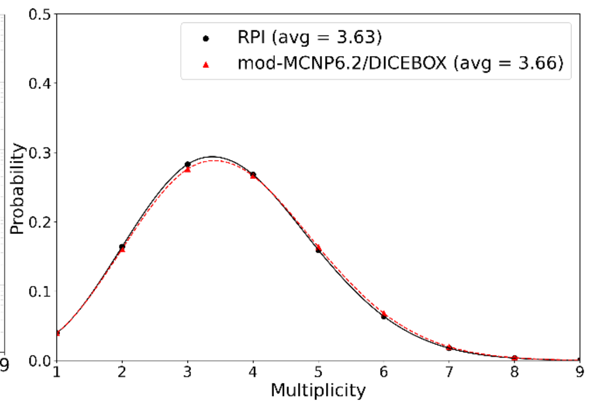
GIDI+ provided by E. Chimanski.

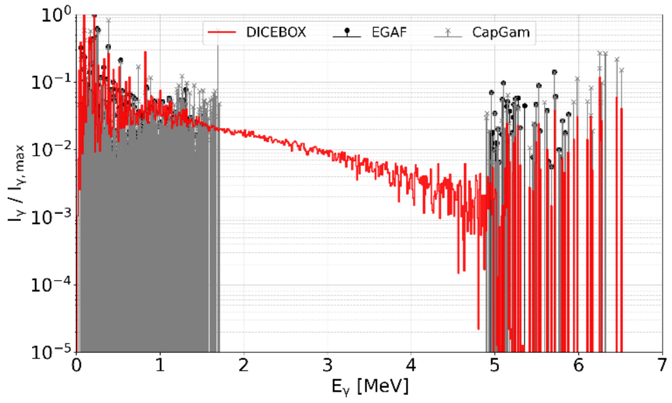
Isotope	Abundance	σ_t(0.0253 eV)	σ_γ(0.0253 eV)
Cd-113	0.1222	19994.01	19969.33
Rest	0.8778	55.9	22.36

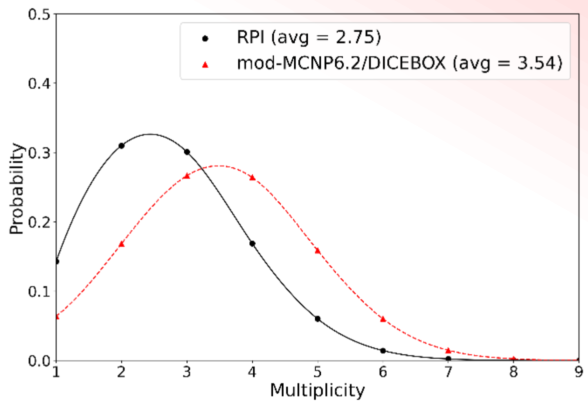
Results: ^{nat}Cd, ^{197}Au

$0.01\ \text{eV} \le E_n \le 1.0\ \text{eV}$
$0.200\ \text{MeV} \le E_\gamma$
$2.0\ \text{MeV} \le E_{\Sigma\gamma} \le 10.0\ \text{MeV}$

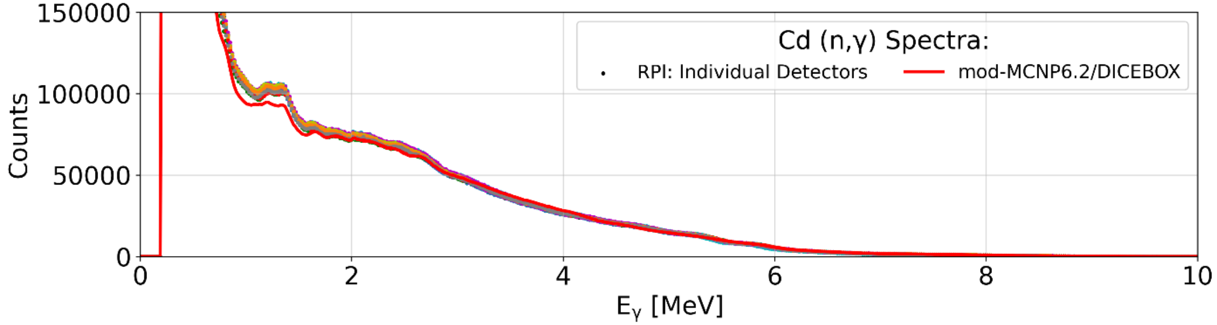


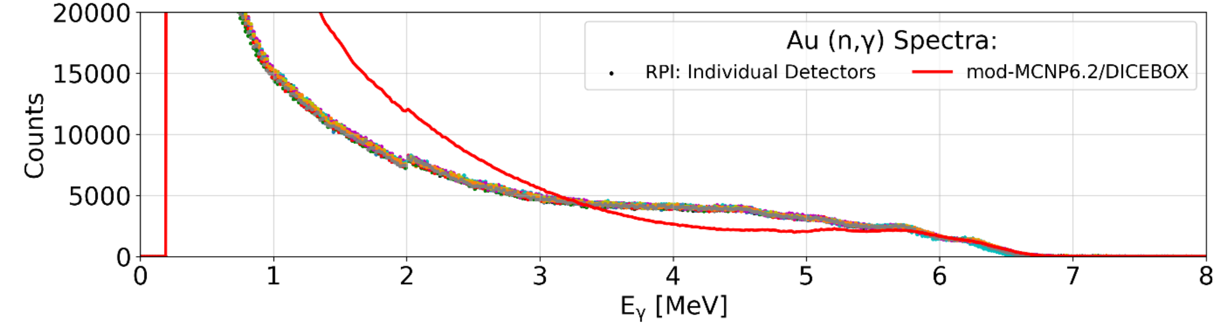


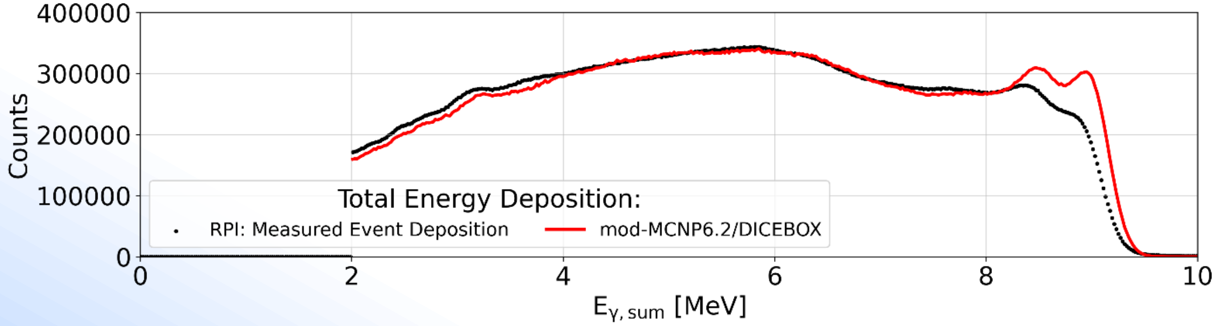


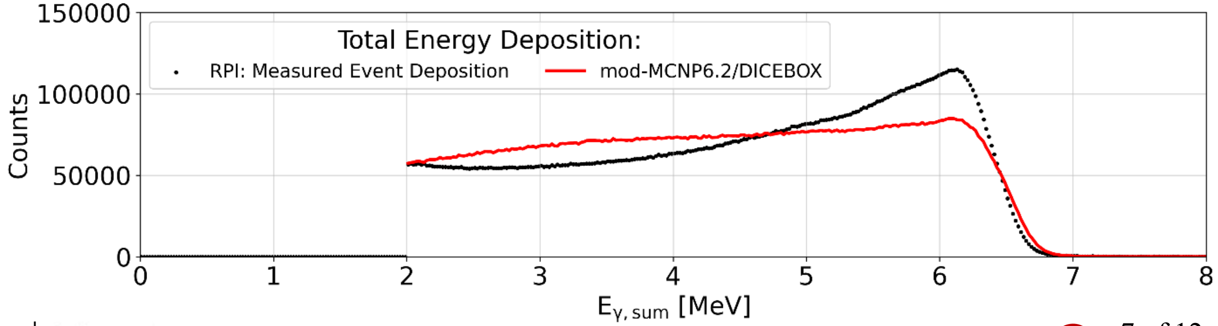


^{113}Cd *only* in DICEBOX, all other Cd isotopes in CGM





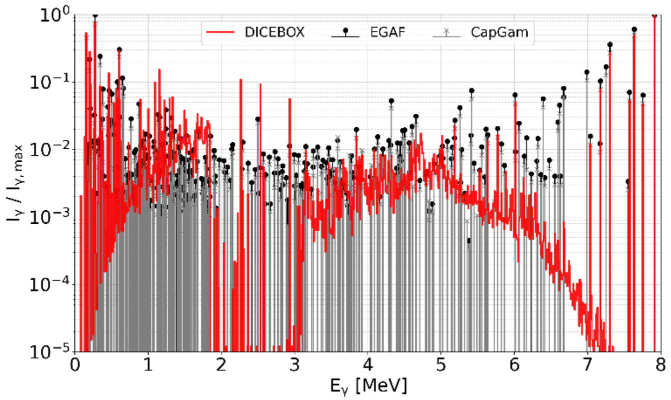


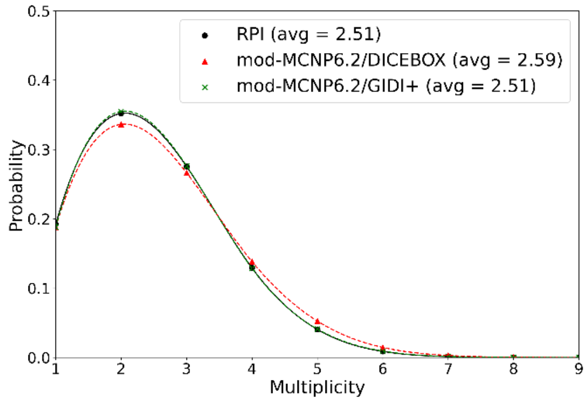


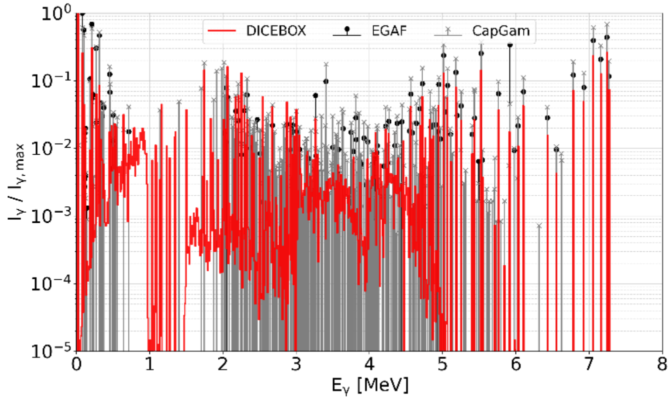
Isotope	Abundance	$\sigma_t(0.0253\ eV)$	$\sigma_\gamma(0.0253\ eV)$
Cu-63	0.6915	6.61	4.47
Cu-65	0.3085	16.04	2.15

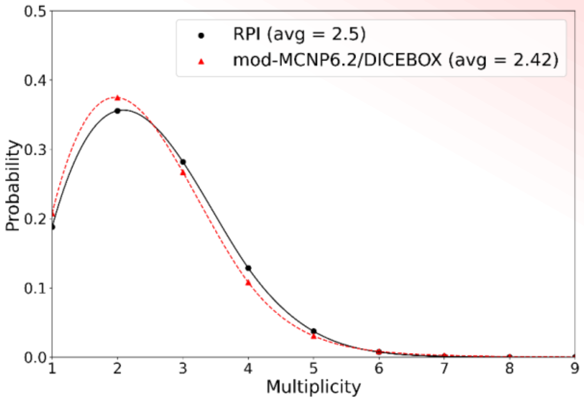
Results: ^{nat}Cu, ^{55}Mn

$0.01\ eV \le E_n \le 1.0\ eV$
$0.200\ MeV \le E_\gamma$
$2.0\ MeV \le E_{\Sigma\gamma} \le 10.0\ MeV$

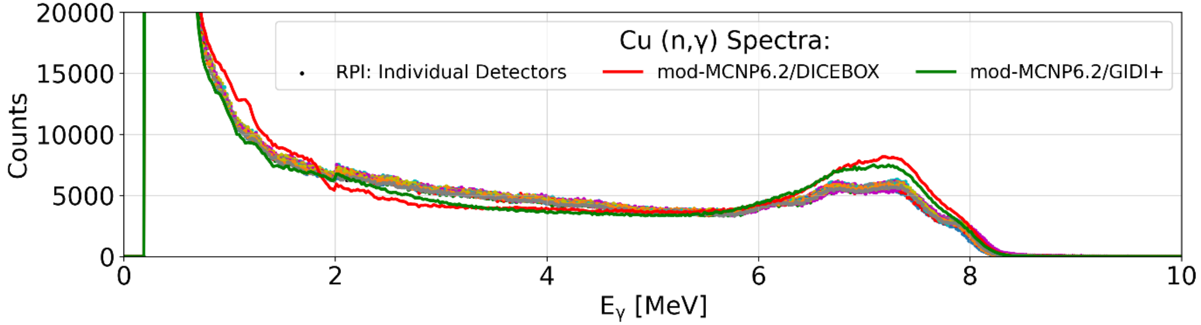


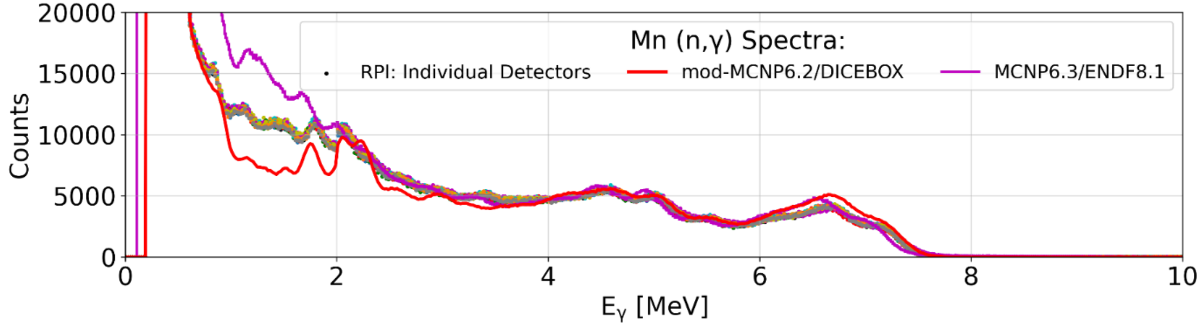


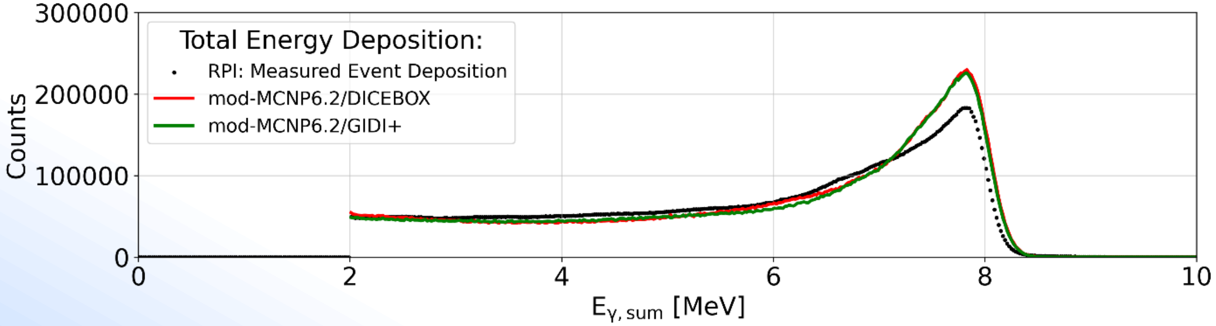


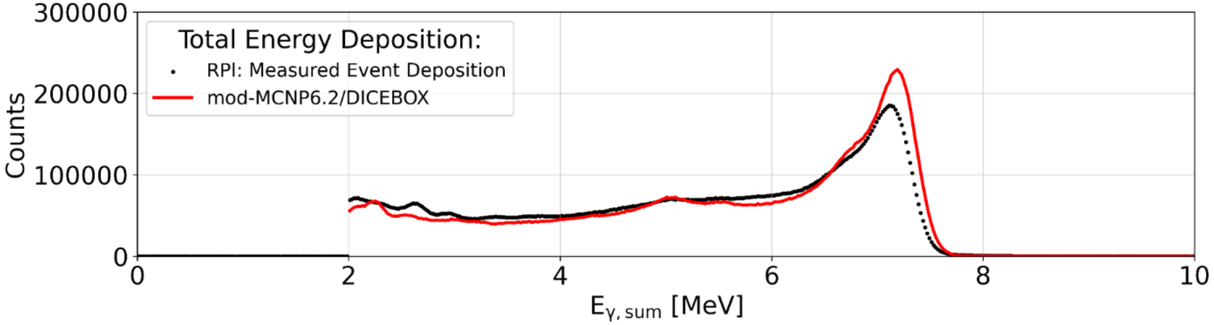


^{63}Cu *only* in DICEBOX/GIDI+, ^{65}Cu in standard CGM





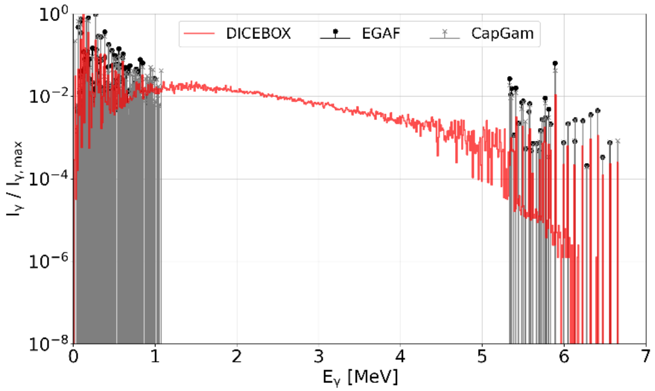


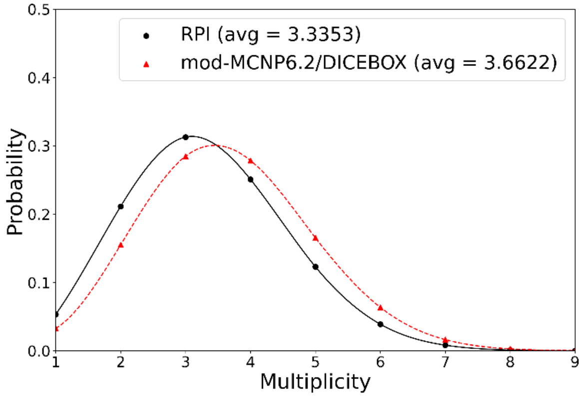


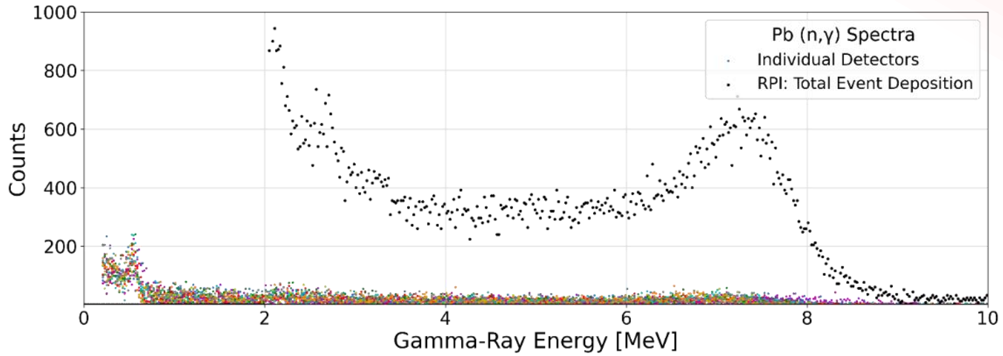
Isotope	Abundance	$\sigma_t(0.0253\ eV)$	$\sigma_\gamma(0.0253\ eV)$
In-113	0.0429	15.82	12.13
In-115	0.9571	204.79	202.28

Results: ^{nat}In, ^{nat}Zr

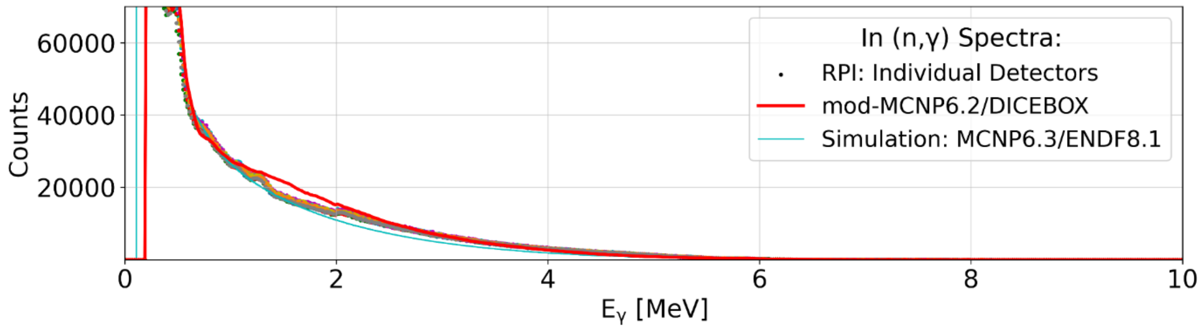
Isotope	Abundance	$\sigma_t(0.0253\ eV)$	$\sigma_\gamma(0.0253\ eV)$	S_n [MeV]
Zr-90	0.5145	5.306	0.010	7.194
Zr-91	0.1122	10.954	1.205	8.634
Zr-92	0.1715	7.291	0.226	6.734
Zr-94	0.1738	8.708	0.050	6.461
Zr-96	0.028	4.873	0.020	5.569

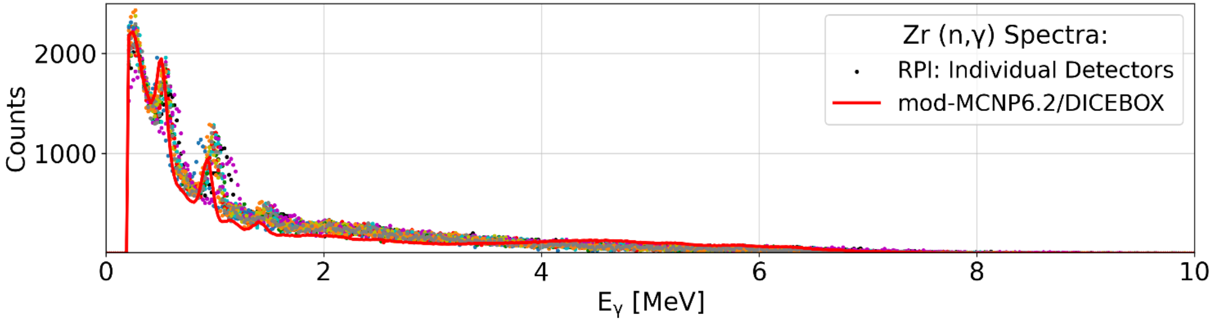


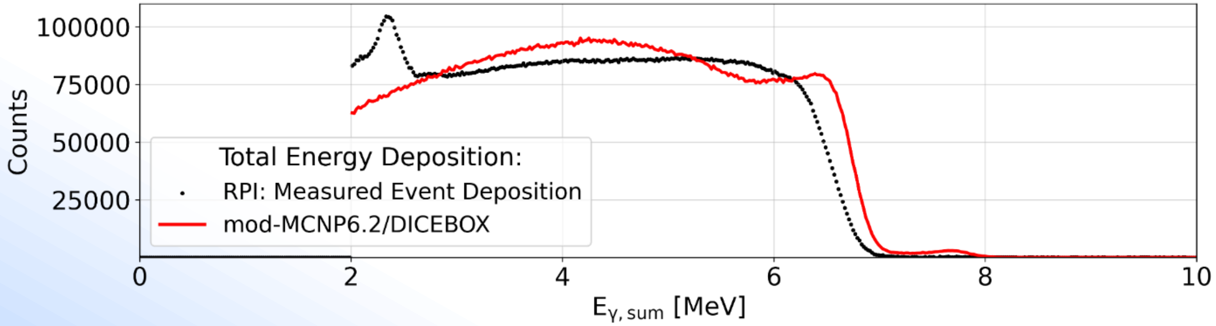


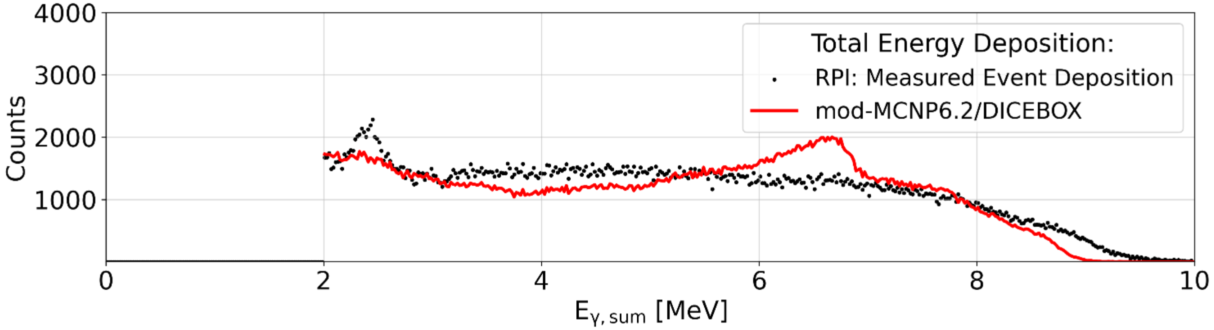


^{115}In *only* in DICEBOX, ^{113}In in standard CGM









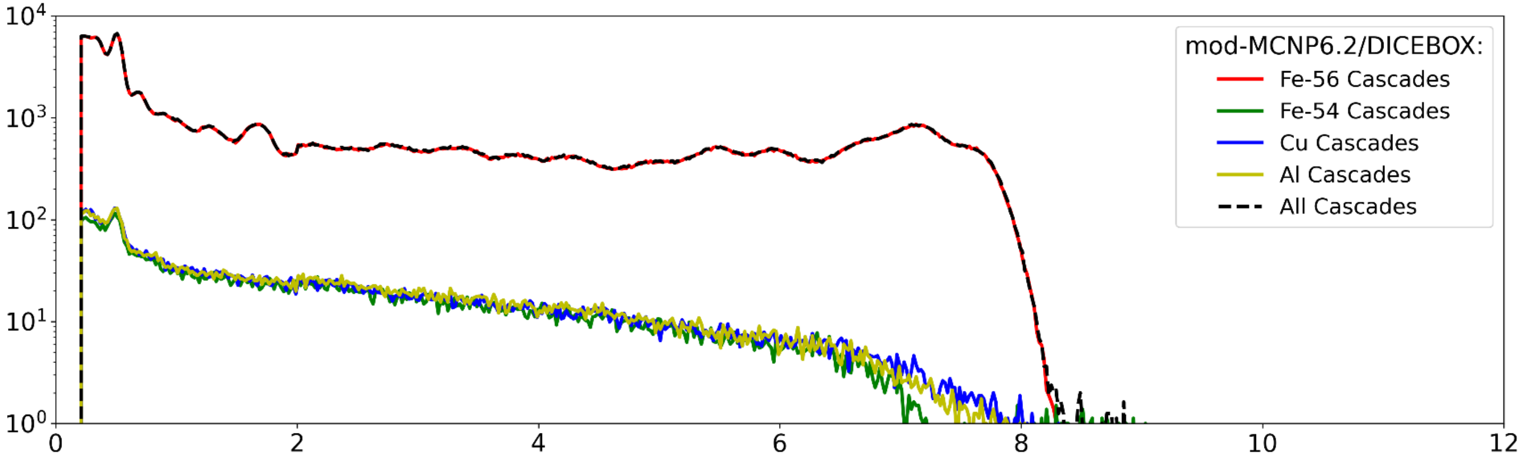
Benchmarking:

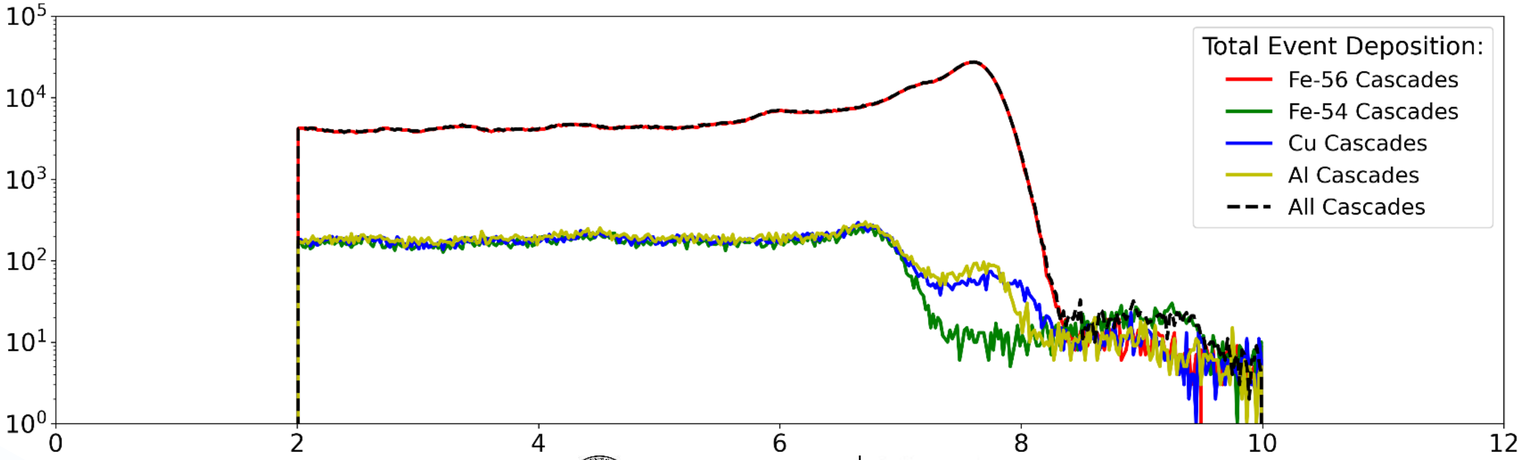
With a finalized result of the validation isotope, Fe-56, the largest sources of uncertainty need to be quantified & compared with other measurements.

Source:	**Description:**	**Assessment Strategy:**
Gamma-Ray Attenuation	Gamma rays emitted that lose energy and/or do not reach the detector.	Quantify the effect of gamma-ray transport on the accuracy of energy deposition.
Non-Sample Gamma-Ray Spectra Contributions	Capture in air, aluminum, or boron can emit gamma rays.	Remove in simulation & assess results. Further analysis will focus on changing size, density, etc.
NaI False Capture	Neutrons in system scattering & capturing in iodine.	Determine if contribution is negligible, expected to be for thermal neutrons due to B_4C liner in the detector system.
Energy Calibration & Detector Alignment	Calculations performed to convert pulse integrals to gamma-ray energy.	Calculate the effect of uncertainty in energy calibration for the comparison between measured and calculated gamma-ray spectra.
Processing Settings	Individual & coincident discriminators. Coincidence time.	Identify the effects of analysis parameter choices on the resulting spectra.

Non-Sample Gamma-Ray Spectra Contributions:

- Using DICEBOX to create cascades for impurities in the Fe-56 sample and prominent system materials, the resulting spectra better predicts the measured spectra, however their contributions must be quantified when comparing to Fe-56 evaluations.
- Further work will assess the spectra inclusions for samples with higher scattering yields (i.e. Pb).
- Preliminary results show that the measured spectra is primarily from Fe-56 gamma-ray emissions.





$0.01\ eV \leq E_n \leq 1.0\ eV$
$0.200\ MeV \leq E_\gamma$
$2.0\ MeV \leq E_{\Sigma\gamma} \leq 10.0\ MeV$

Conclusions:

- **With complete evaluated gamma-ray production data, as observed with Fe-56, calculations predict measured spectra & multiplicity.**
- DICEBOX & GIDI+ are both capable of reproducing gamma-ray cascades for complete evaluated gamma-ray data.
- Uncertainty analysis is crucial to identify discrepancies in evaluated data vs methodology.

Future Work:

- **Continue uncertainty analysis toward benchmark template, using Fe-56 as a baseline.**
- Investigate capabilities to separate spectra for multi-isotopic samples.
- Upcoming measurement to continue to test benchmark possibilities and limitations – Samples TBD.