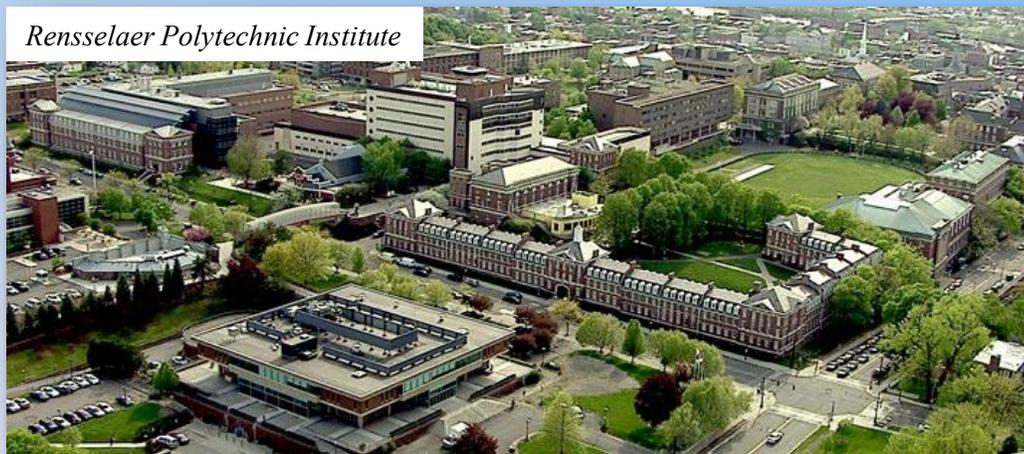


Overview of Nuclear Data Measurement and Analysis at RPI

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CSEWG meeting, January 6-9, 2026, BNL

This work was partially supported by the Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the U.S. Department of Energy and Naval Reactors and partially performed under appointment to the Rickover Fellowship Program in Nuclear Engineering sponsored by Naval Reactors (NR) Division of the National Nuclear Security Administration (NNSA).

Outline

- Neutron Induced Capture and Fission γ -ray Spectra and Yield Measurements (I. Parker, K. Keparutis)
- Thermal neutron die-away measurements (B. Wang)
- Elemental zirconium thermal capture experiment (G. Siemers, I. Parker)
- Photonuclear Production Yield Measurements at the RPI LINAC (D. Fritz)
- Other talks about RPI evaluation work in evaluation session:
 - New $^{90,91}\text{Zr}$ Evaluations (G. Siemers)
 - $^{90,91}\text{Zr}$ evaluation in the unresolved Resonance Region (A. Golas)

Neutron-Induced Capture and Fission γ -ray Spectra Measurements at the RPI LINAC

I. Parker and K. Keparutis

*This material is partially based upon work supported by the U.S. Department of Energy,
Office of Science, Office of Nuclear Physics, under Award Number DE-SC0024679.
“Development of Benchmark Measurements for Capture Gamma Cascades”*

*This work was partially performed under appointment to the Rickover Fellowship Program
in Nuclear Engineering sponsored by Naval Reactors (NR) Division of the National Nuclear
Security Administration (NNSA).*

RPI γ -ray Spectra Measurements:

Measurements coupled with updated simulation methods provide a tool that can be used to **assess the accuracy of γ -ray production data** stored in nuclear data libraries.

- Updated simulation method: **mod-MCNP6.2/DICEBOX**

Primary motivation – To test evaluated γ -ray production data.

- Applications: γ -ray heating, reactor and shielding calculations, isotope identification via active neutron interrogation, nuclear structure studies, etc.
- Develop methods to separate measured capture and prompt fission γ -ray spectra.
- Develop test suite/benchmark to assess quality of evaluated data.

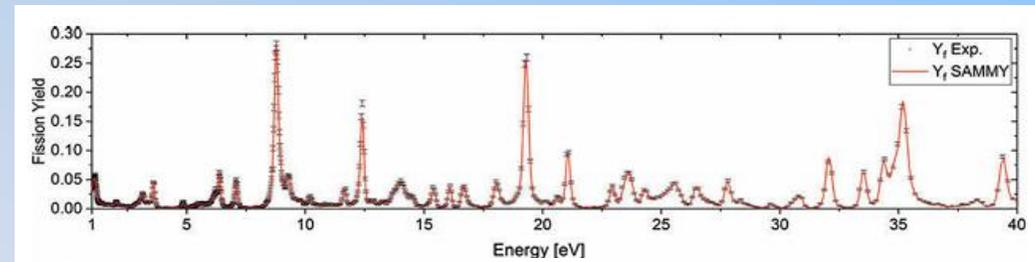
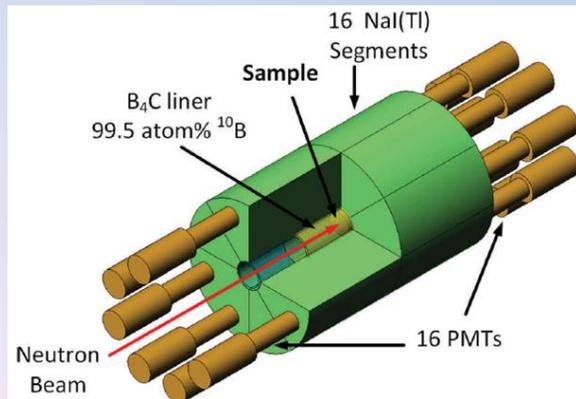


Measured Samples: $0.01 \text{ eV} \leq E_n \leq 100.0 \text{ eV}$		
<u>^{56}Fe</u>	$^{55}\text{Mn}/\text{natCu}$	^{59}Co
natTa	<u>natU</u>	^{235}U
<u>natCd</u>	<u>natAu</u>	natIn
<u>natCu</u>	<u>^{55}Mn</u>	<u>natZr</u>

Measurement & Simulation Capabilities:

RPI γ -Ray Multiplicity Detector:

- $\sim 4\pi$ 16 segment NaI(Tl) detector array.
- 1 cm thick B_4C liner enriched to 99.5 atom % ^{10}B to absorb scattered neutrons.
- Up to 96% efficient to detect γ -ray cascades.
- Located 25.6m from neutron production target.
- Digitizer collects energy deposition for each detector segment and event time, used for TOF method.
- Historically used for neutron capture yield measurements in energy range from 0.01 eV – 3 keV.



¹Werner, C. J., (2018). *MCNP version 6.2 release notes* (LA-UR-18-20808). Los Alamos National Laboratory.

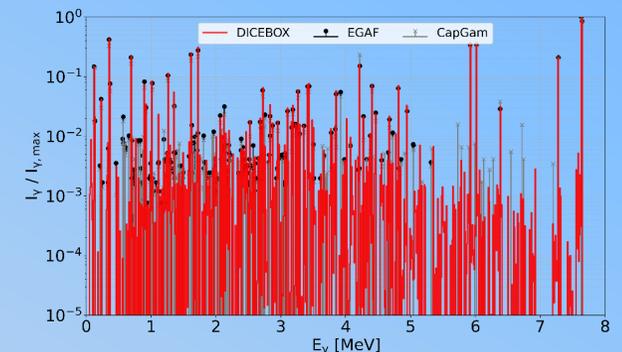
²Y. Danon et al., EPJ Web of Conferences 294 01001 (2024)

³Bečvář, 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](https://doi.org/10.1016/S0168-9002(98)00787-6).

⁴Lawrence Livermore National Laboratory. (n.d.). *GIDI+* (General Interaction Data Interface Plus) [Computer software]. GitHub. <https://github.com/LLNL/gidiplus>

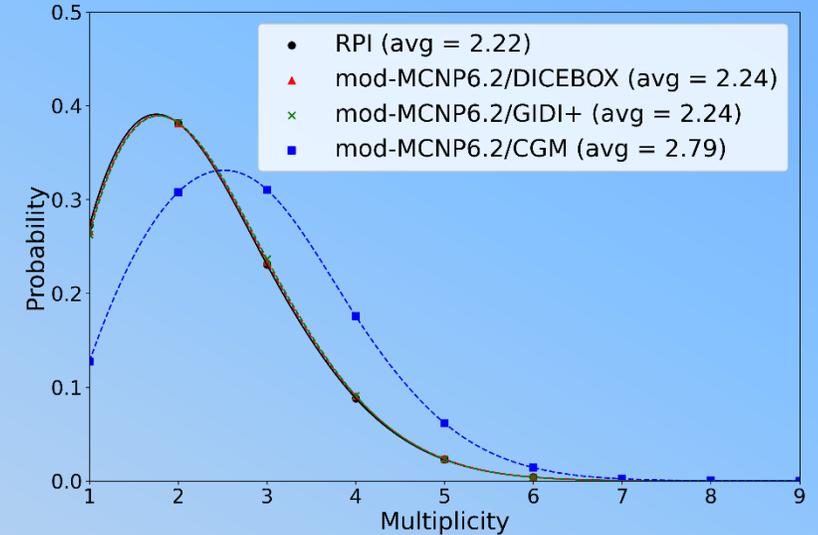
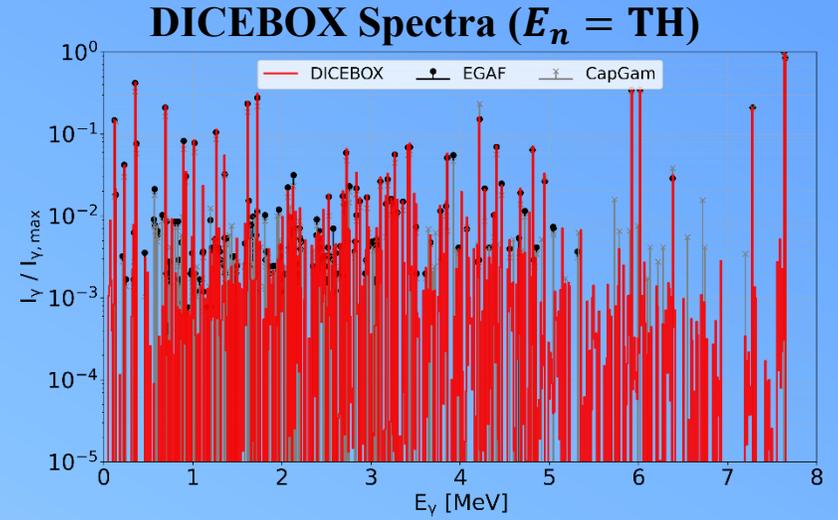
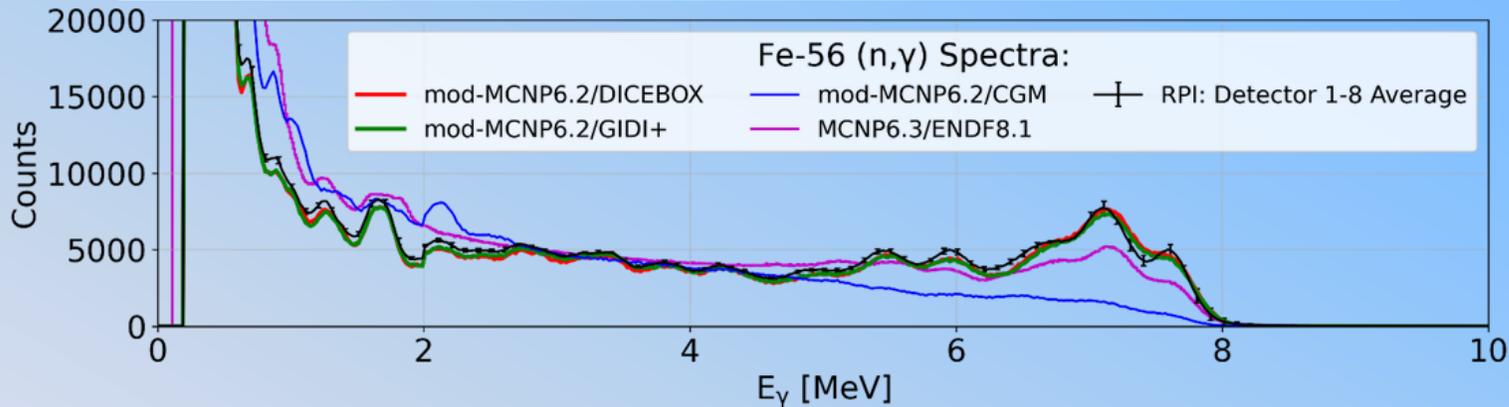
Mod-MCNP6.2^{[1][2]}:

- 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 gamma cascades.
- Outputs energy deposited for each detector segment per neutron history.
 - Enables simulation and measurements to be processed identically.
- Cascades files are generated with DICEBOX^[3], GIDI⁺^[4], or other cascade generation codes.

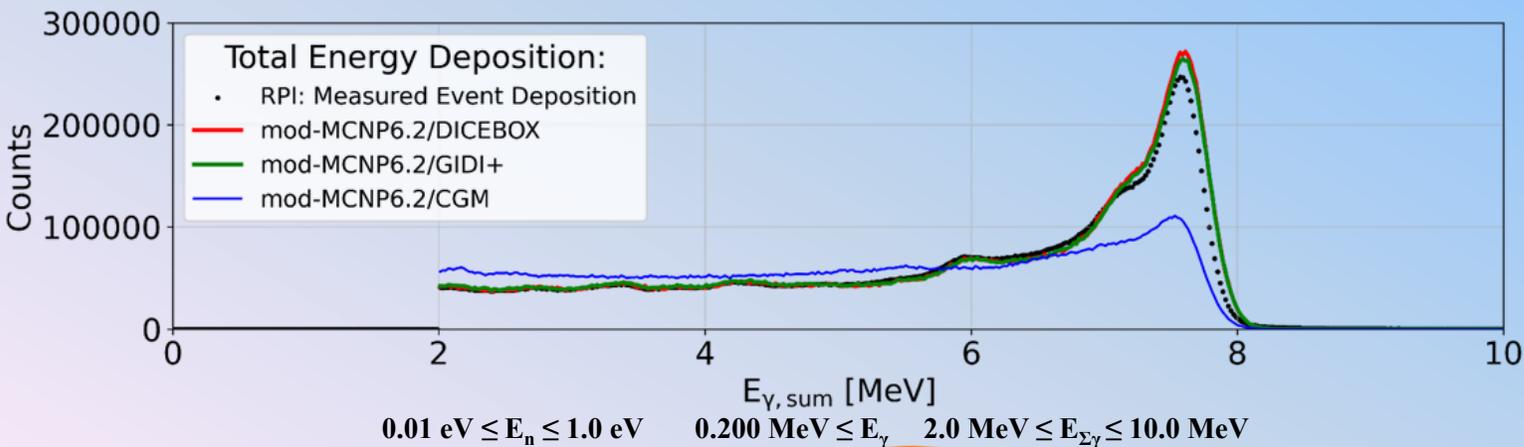


Method Validation with ^{56}Fe :

Using R.B. Firestone^[1] gamma-ray data as the input to cascade generators, simulations match experimental data collected at the RPI LINAC.



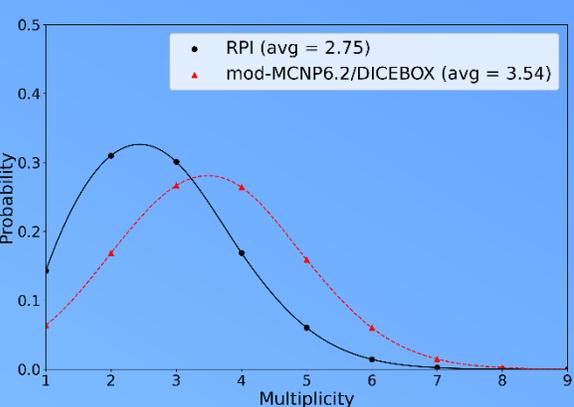
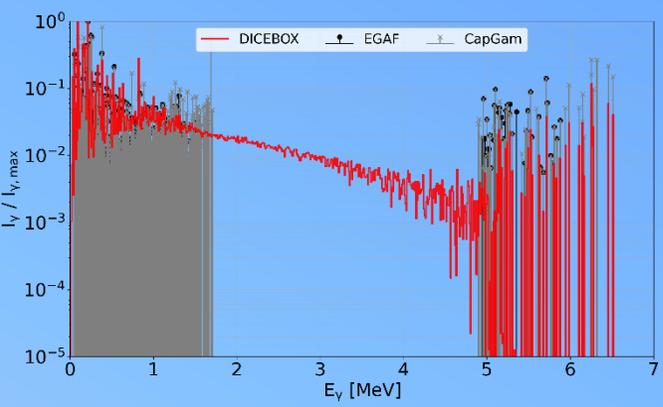
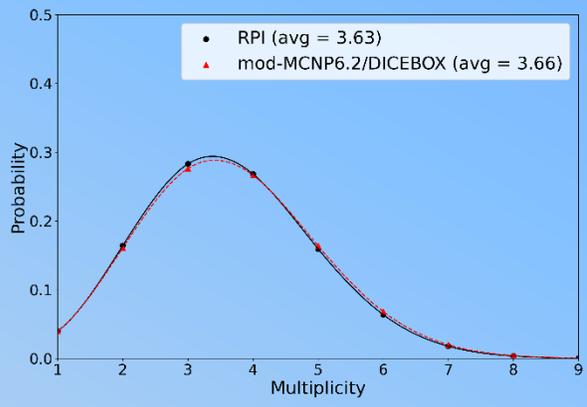
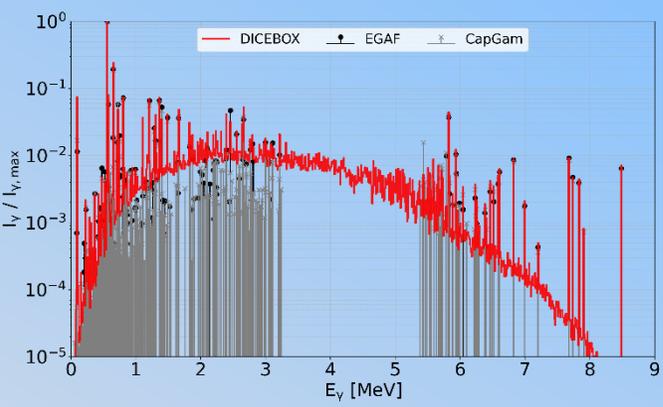
^[1]R. B. Firestone et. al., Phys. Rev. C **95**, 014328 (2017).



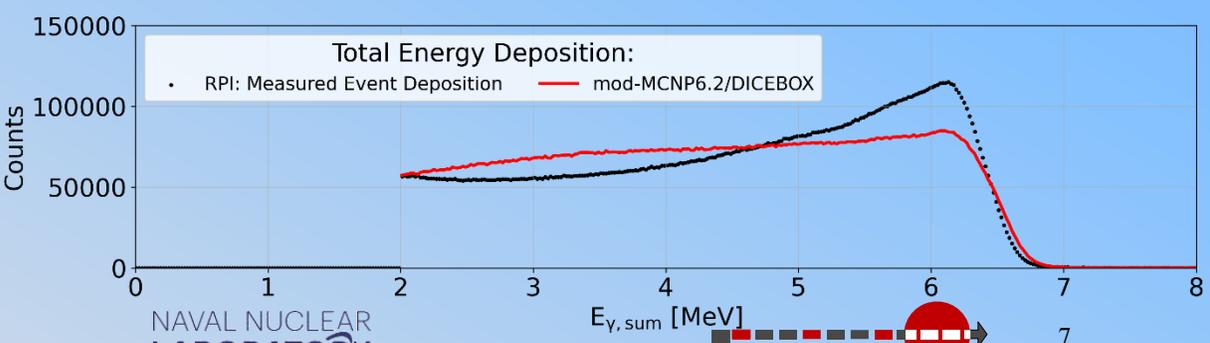
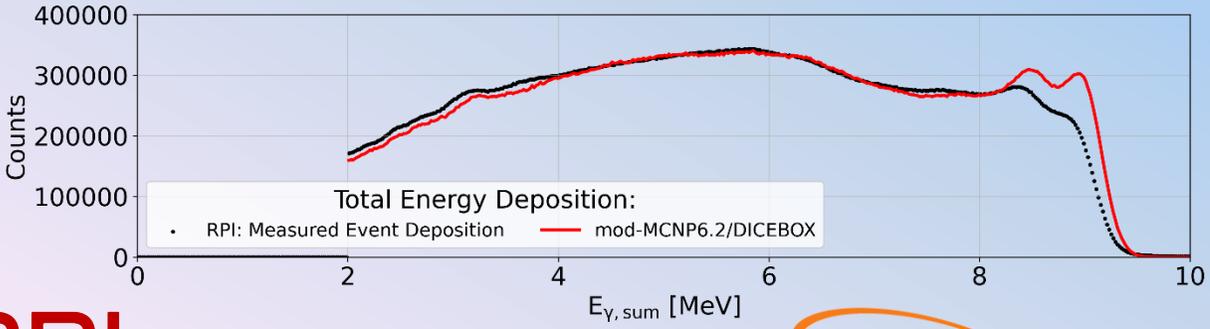
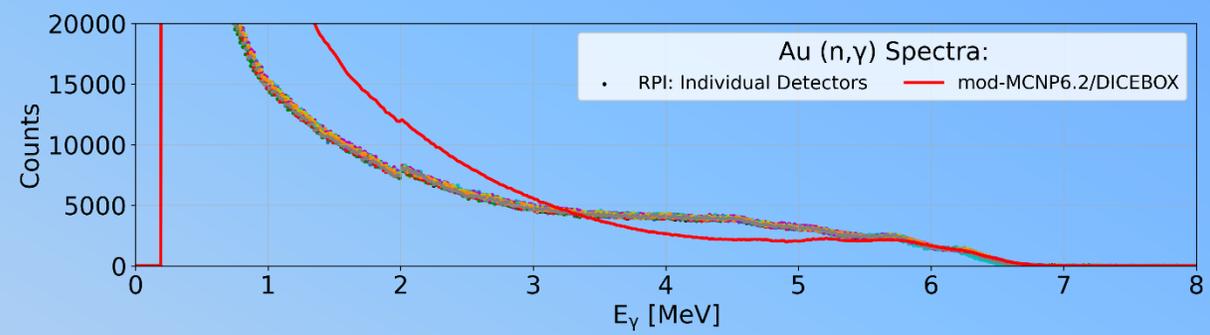
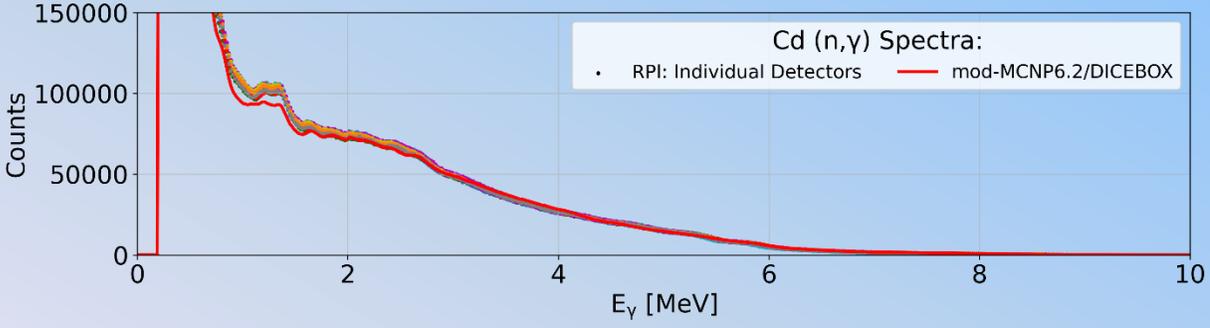
Isotope	Abundance	$\sigma_t(0.0253 \text{ eV})$	$\sigma_v(0.0253 \text{ eV})$
Cd-113	0.1222	19994.01	19969.33
Rest	0.8778	55.9	22.36

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

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



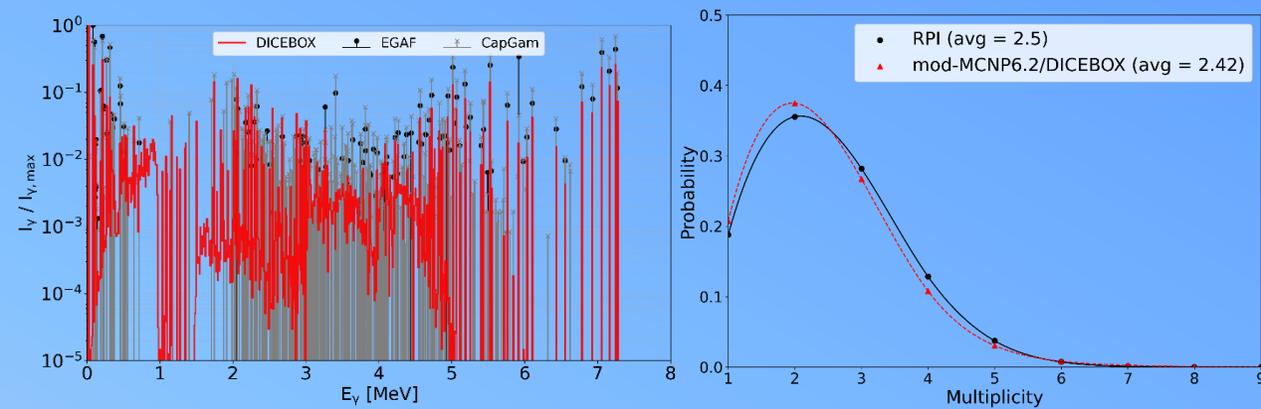
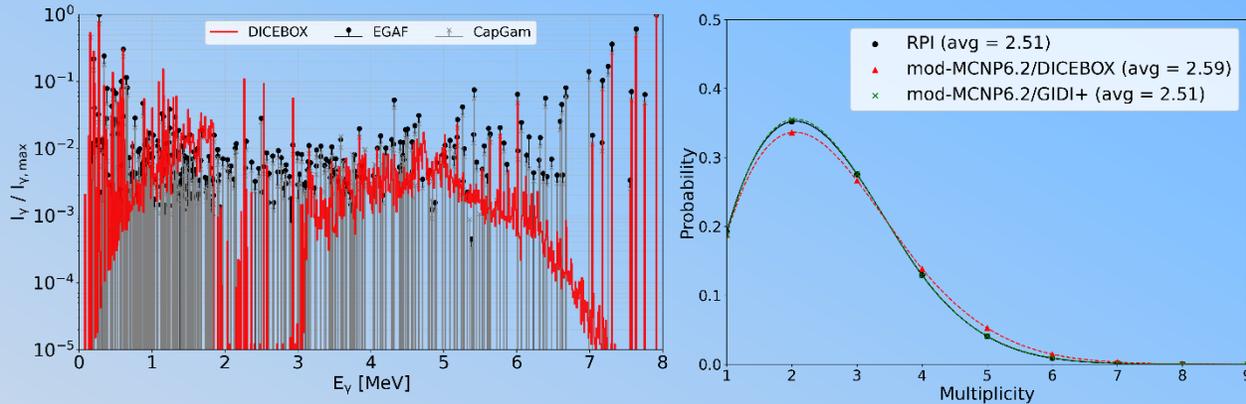
¹¹³Cd only in DICEBOX, all other Cd isotopes in CGM



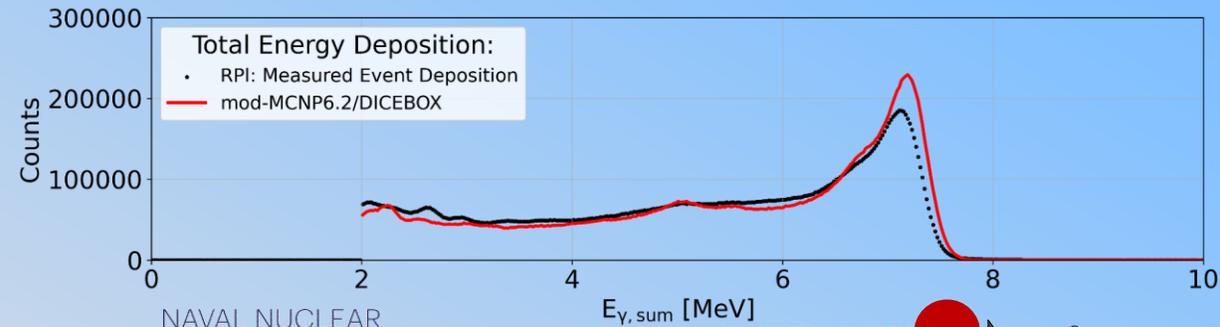
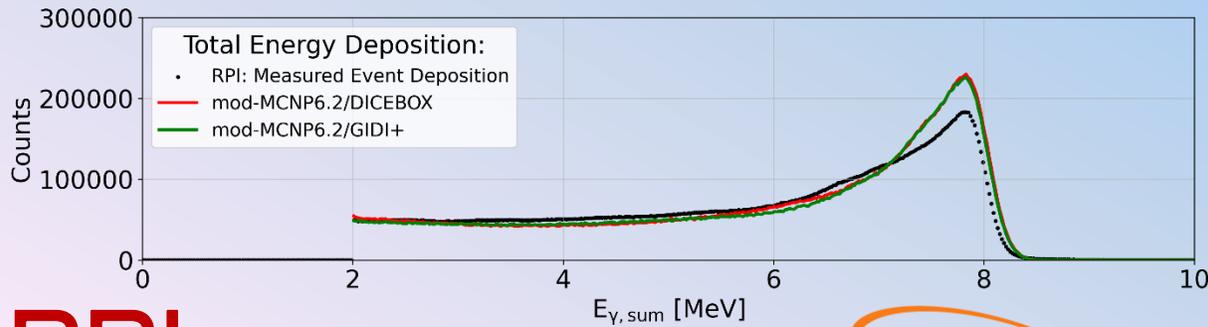
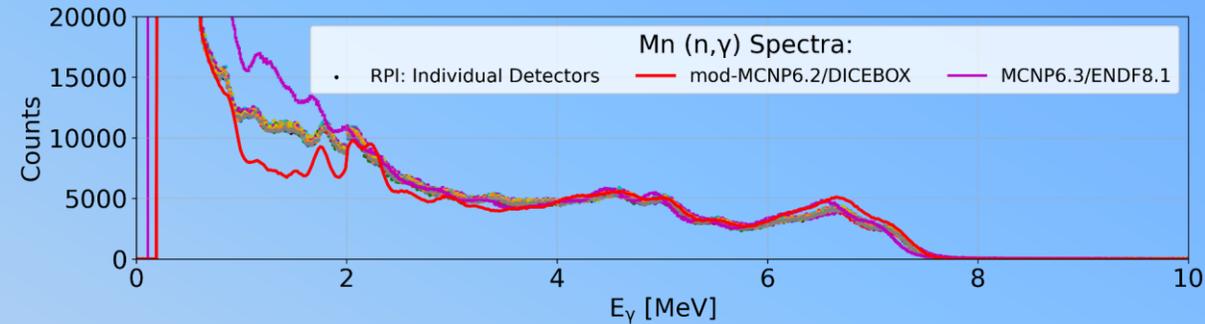
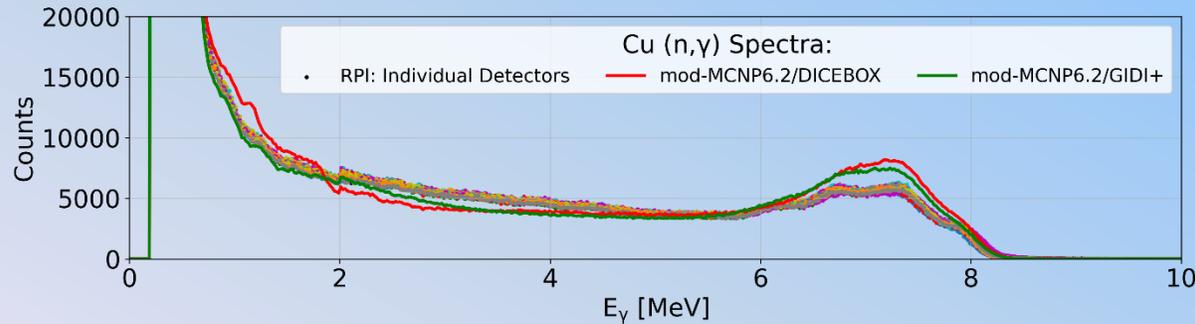
Isotope	Abundance	$\sigma_t(0.0253 \text{ eV})$	$\sigma_v(0.0253 \text{ eV})$
Cu-63	0.6915	6.61	4.47
Cu-65	0.3085	16.04	2.15

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

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



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

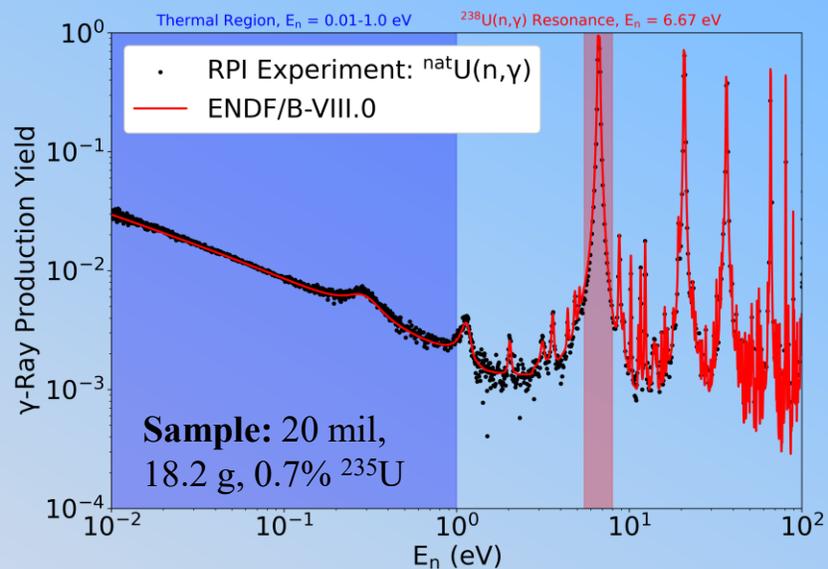


Test Suite/Benchmark Development:

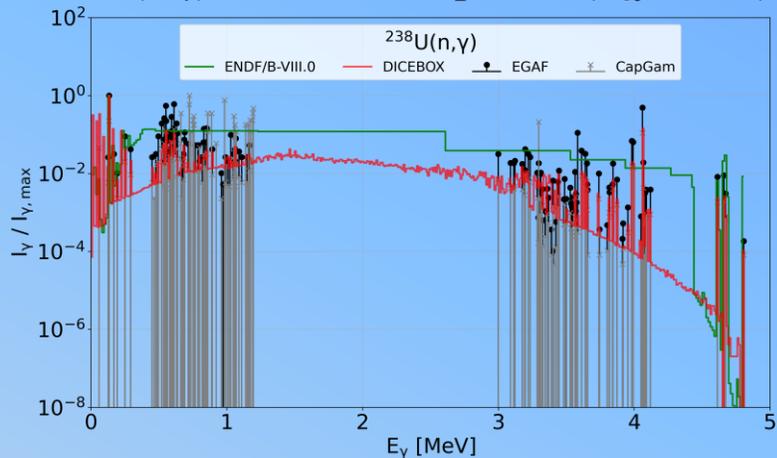
- DOE Grant deliverables include a template, necessary tools, example inputs, and test data.
- With ^{56}Fe /DICEBOX validation method, next step is uncertainty quantification.
- Preliminary list had been generated, with ongoing work into each source.

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 Emissions	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 negligible, predicted to be for thermal neutrons due to B_4C liner.
Energy Calibration & Detector Alignment	Calculations performed to convert pulse integrals to 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.

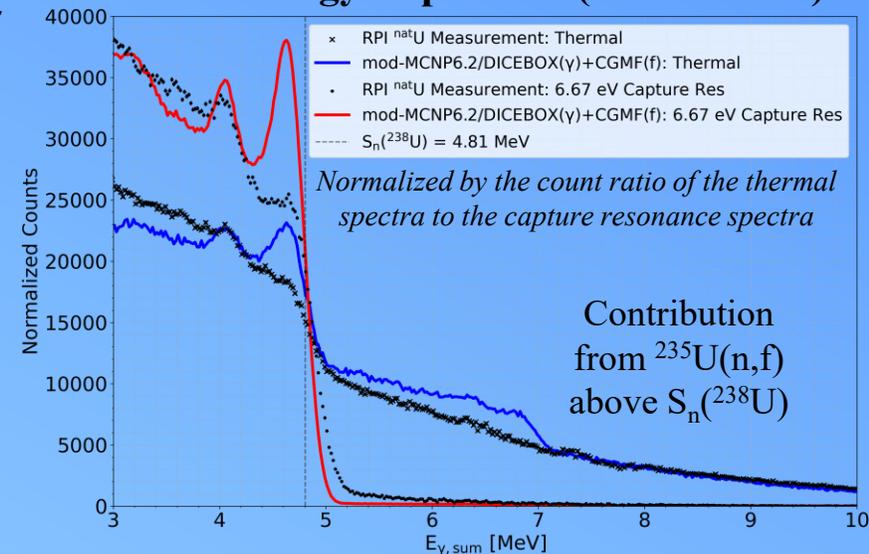
natU Measurement



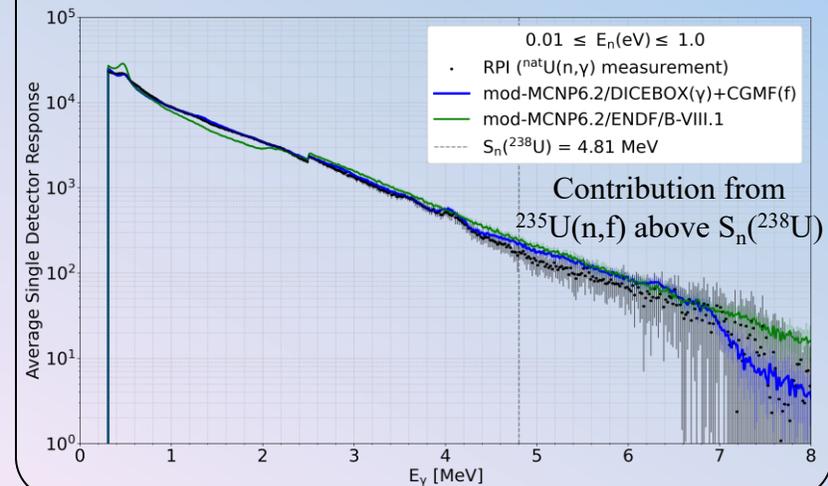
$^{238}\text{U}(n,\gamma)$ DICEBOX Spectra ($E_n = \text{TH}$)



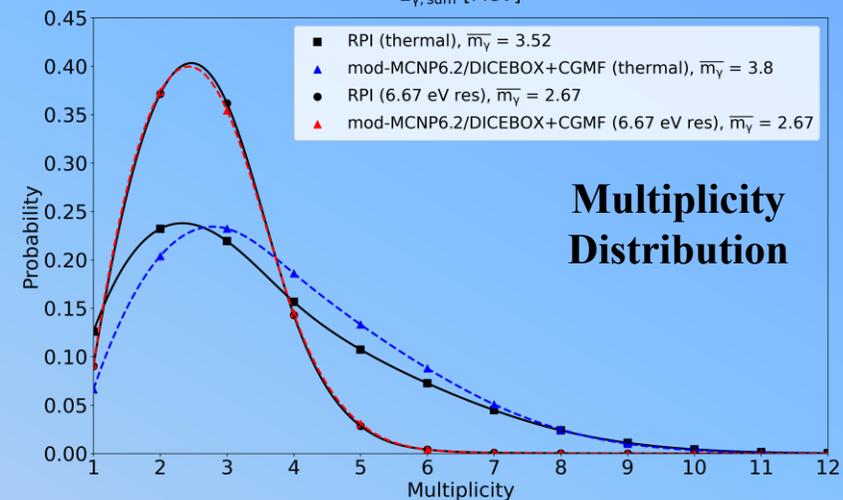
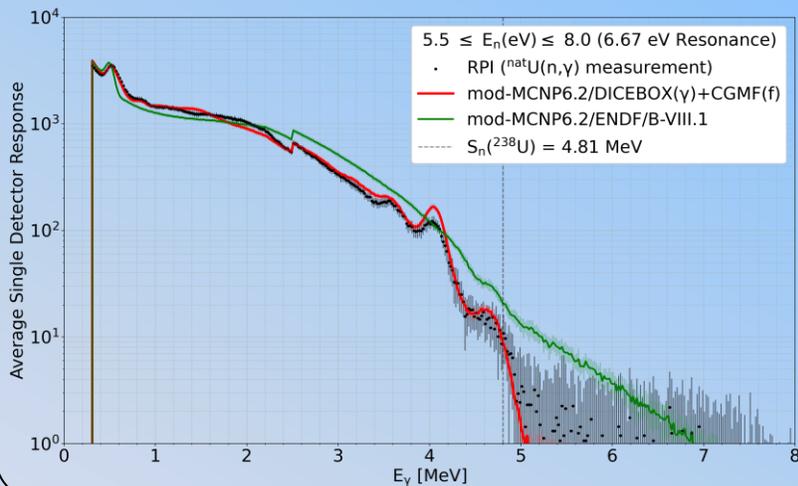
Total Energy Deposition (Coincidence)



Thermal ($0.01 \leq E_n[\text{eV}] \leq 1.0$) yield for ^{nat}U sample is dominated by fission $^{235}\text{U}(n,f)$



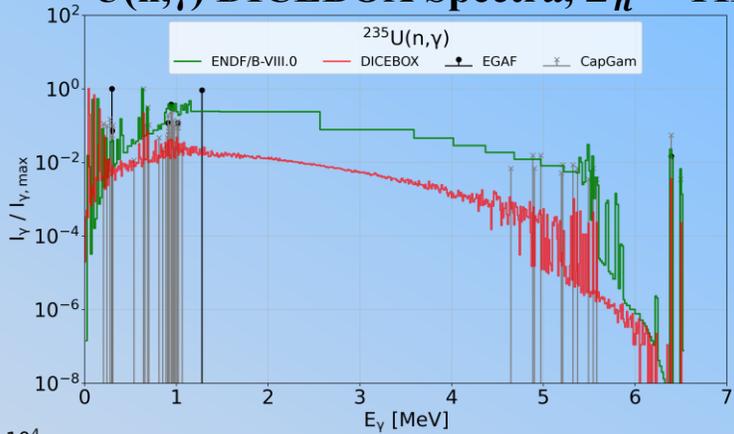
Large capture $^{238}\text{U}(n,\gamma)$ resonance at 6.67 eV ($5.5 \leq E_n[\text{eV}] \leq 8.0$)



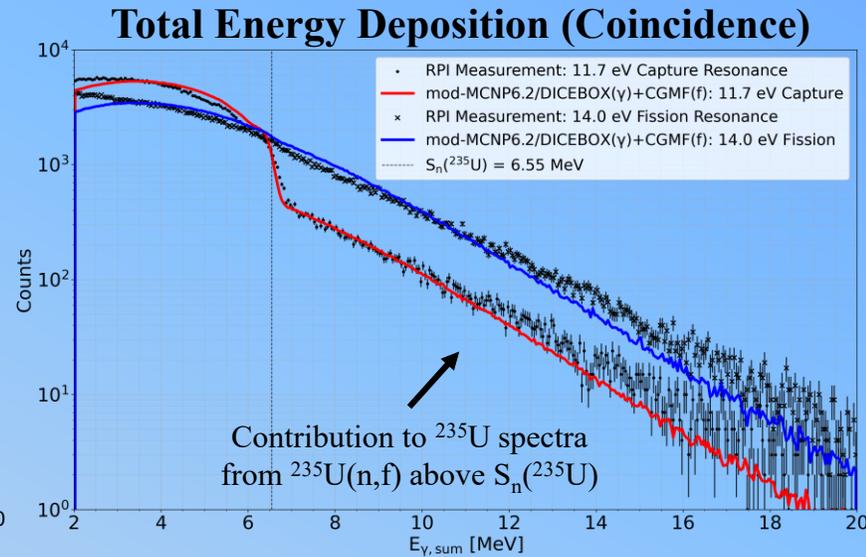
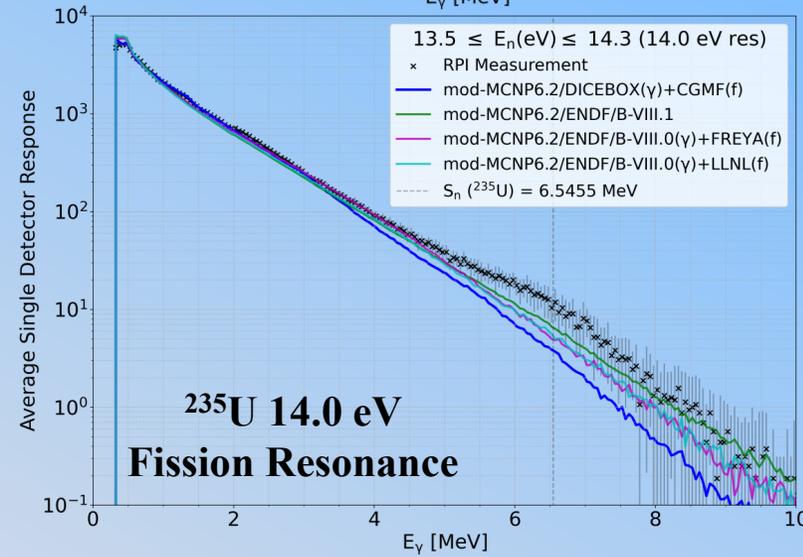
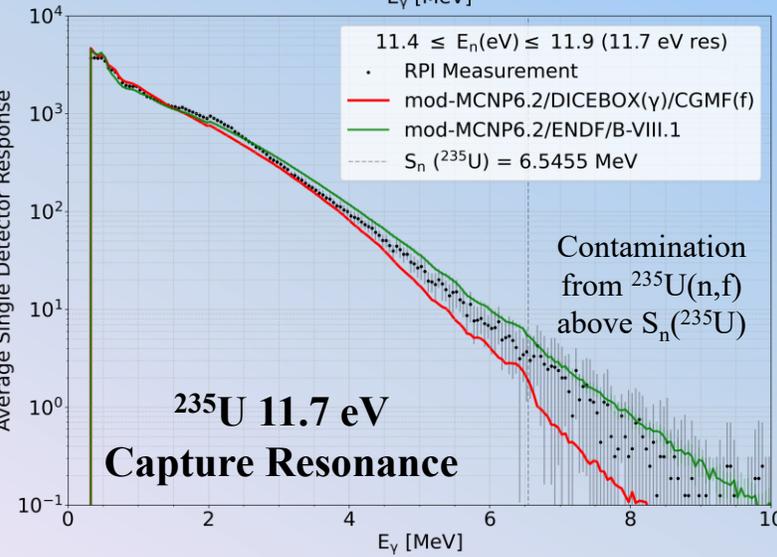
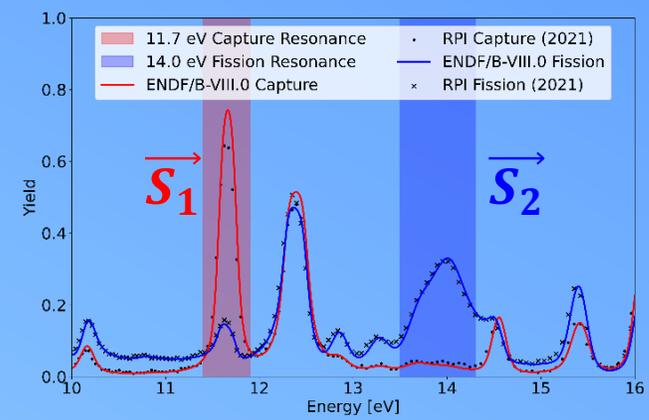
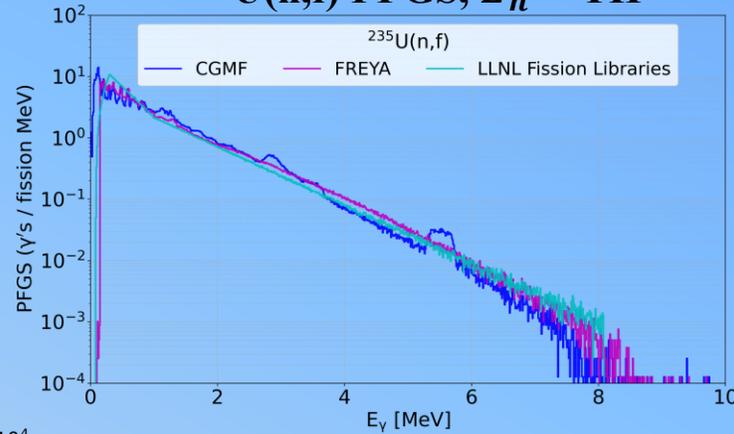
Demonstrates fission γ rays can be removed from spectra in a capture-dominated resonance

^{235}U Capture and Fission Resonance γ -Ray Spectra (Uncorrected)

$^{235}\text{U}(n,\gamma)$ DICEBOX Spectra, $E_n = \text{TH}$



$^{235}\text{U}(n,f)$ PFGS, $E_n = \text{TH}$



Suggests ENDF/B-VIII.1 ACE PFGS is more accurate than the CGMF calculation in MCNP6.2 (discrepancy from ~5-8 MeV)
 A **correction** needs to be made to remove the fission γ rays from the ^{235}U 11.7 eV capture resonance γ -ray spectra

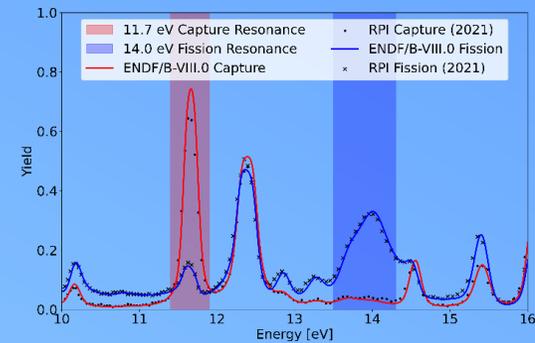
^{235}U Capture and Fission Resonance γ -Ray Spectra (Corrected)

$$\vec{S}_\gamma = \frac{\alpha_{2,f}\vec{S}_1 - \alpha_{1,f}\vec{S}_2}{\alpha_{1,\gamma}\alpha_{2,f} - \alpha_{1,f}\alpha_{2,\gamma}}$$

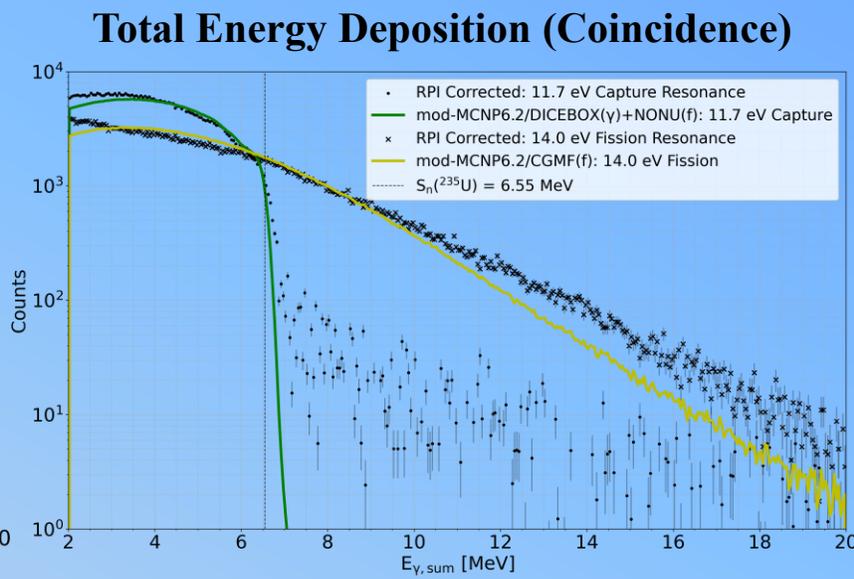
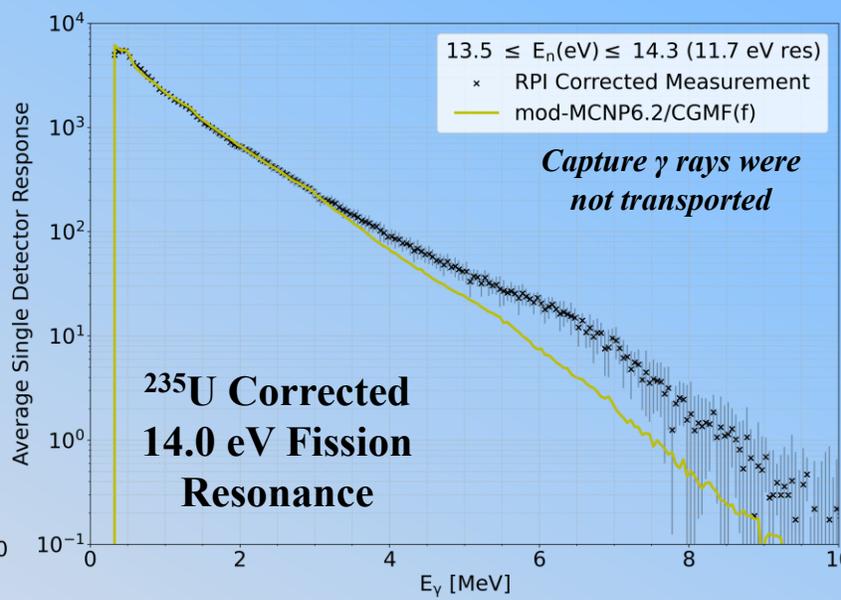
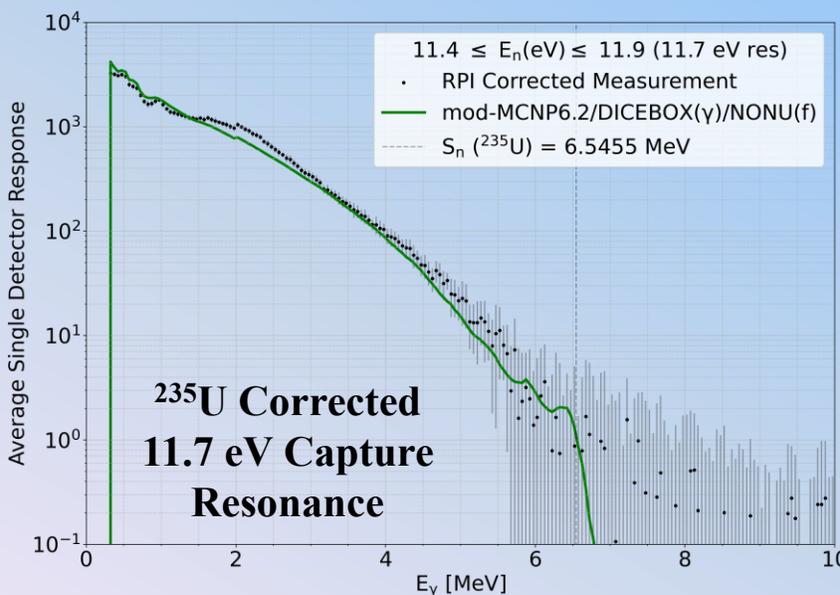
$$\vec{S}_f = \frac{\alpha_{1,\gamma}\vec{S}_2 - \alpha_{2,\gamma}\vec{S}_1}{\alpha_{1,\gamma}\alpha_{2,f} - \alpha_{1,f}\alpha_{2,\gamma}}$$

$\alpha_{i,\gamma}$ = fraction of capture in resonance i
 $\alpha_{i,f}$ = fraction of fission in resonance i
 \vec{S}_γ = Capture ONLY
 \vec{S}_f = Fission ONLY

\vec{S}_1
Capture Res
 $E_n = 11.7 \text{ eV}$
 $\alpha_{1,\gamma} = 0.7495$
 $\alpha_{1,f} = 0.2505$

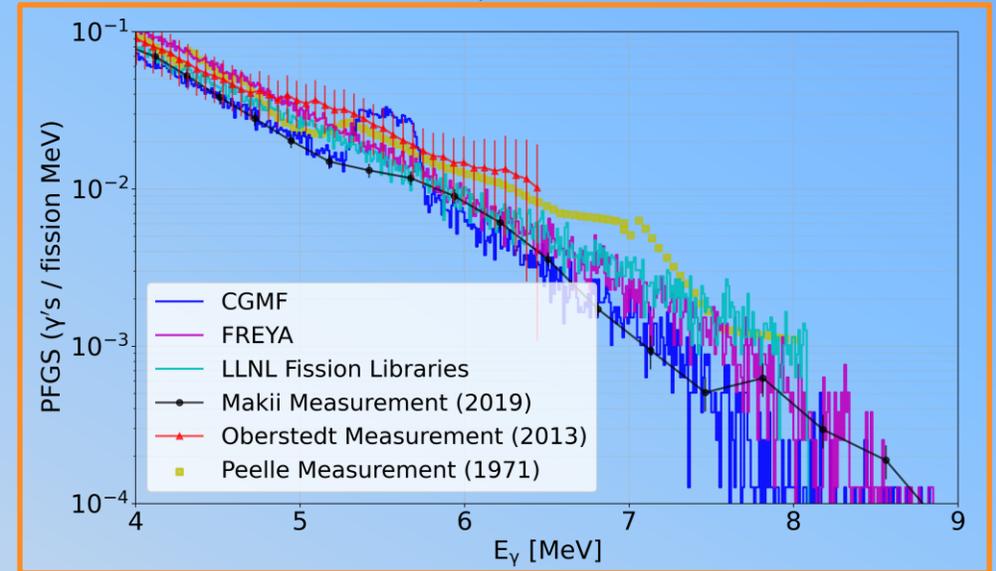
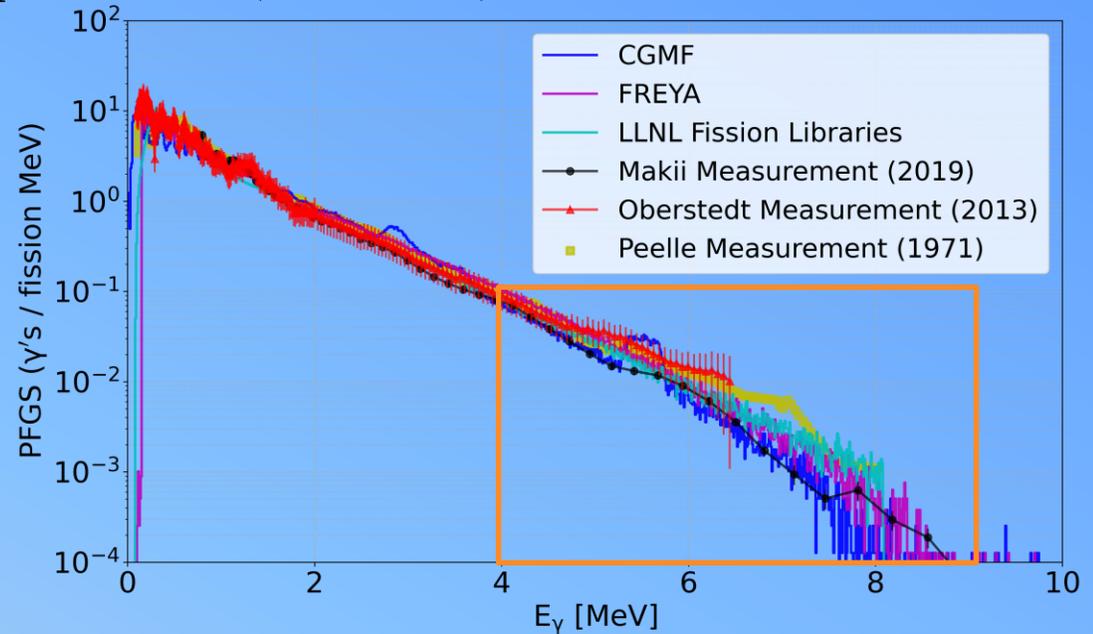
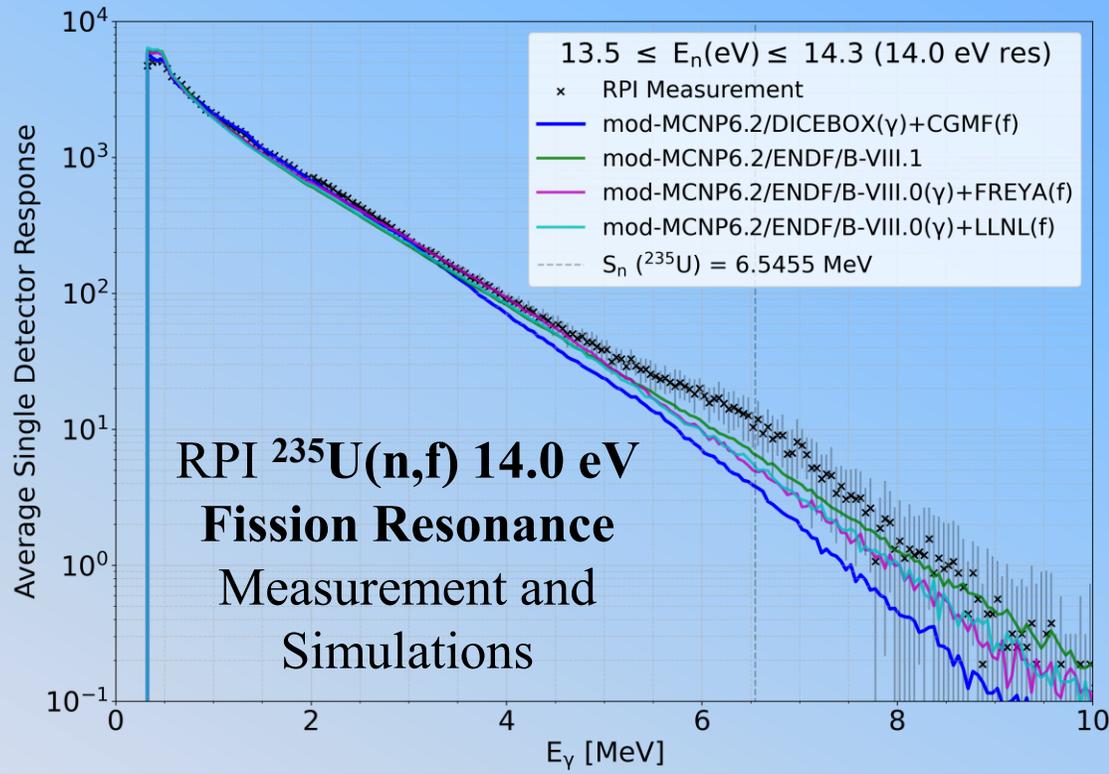


\vec{S}_2
Fission Res
 $E_n = 14.0 \text{ eV}$
 $\alpha_{2,\gamma} = 0.1536$
 $\alpha_{2,f} = 0.8464$



Correction removes γ rays contributing to the 11.7 eV capture resonance spectra above $S_n(^{235}\text{U}) = 6.55 \text{ MeV}$ due to fission
 CGMF does not agree with the measured RPI γ -ray spectra in the 14.0 eV fission resonance above 3 MeV

Prompt Fission γ -Ray Spectra (PFGS)



There is an increase in counts from 4-8 MeV in the RPI measured 14.0 eV fission resonance γ -ray spectra compared to simulations.

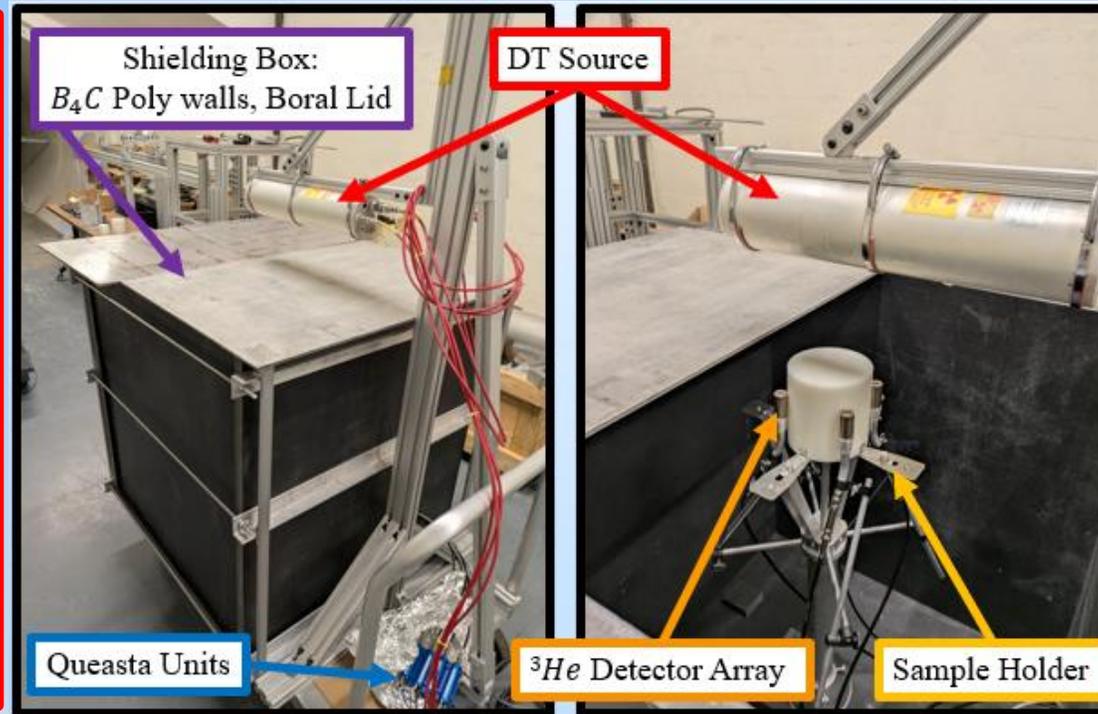
Other measurements (Oberstedt and Pelle) seem to agree with the increase in counts in the PFGS compared to calculations with MCNP6.2 (CGMF, FREYA, and the LLNL fission libraries)

Pulsed Neutron Die Away Experiments for TSL Validation at RPI

Benjamin H. Wang

Nuclear Engineering PhD Student

Department of Mechanical, Aerospace and Nuclear Engineering
Rensselaer Polytechnic Institute, Troy, NY, 12180

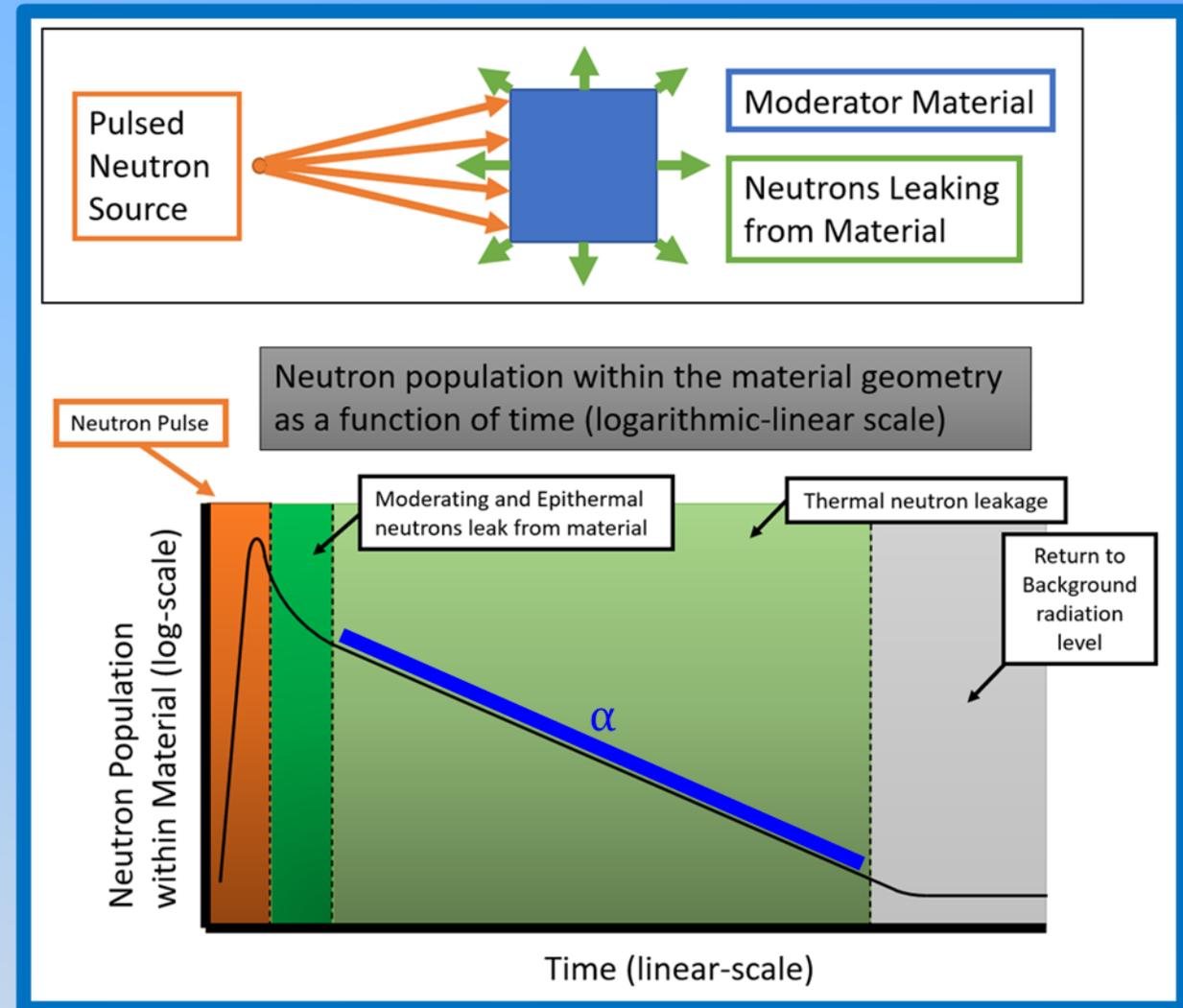


Gaertner LINAC Center– Rensselaer Polytechnic Institute

11/03/2025

Motivation

- Provide Experimental Data to verify and improve $S(\alpha, \beta)$ libraries for various moderators
- Non-Criticality Integral measurement method
 - $\alpha = \frac{d(\#neutrons)}{dt}$
 - Final comparison result: α (Experimental) vs α (Simulation)



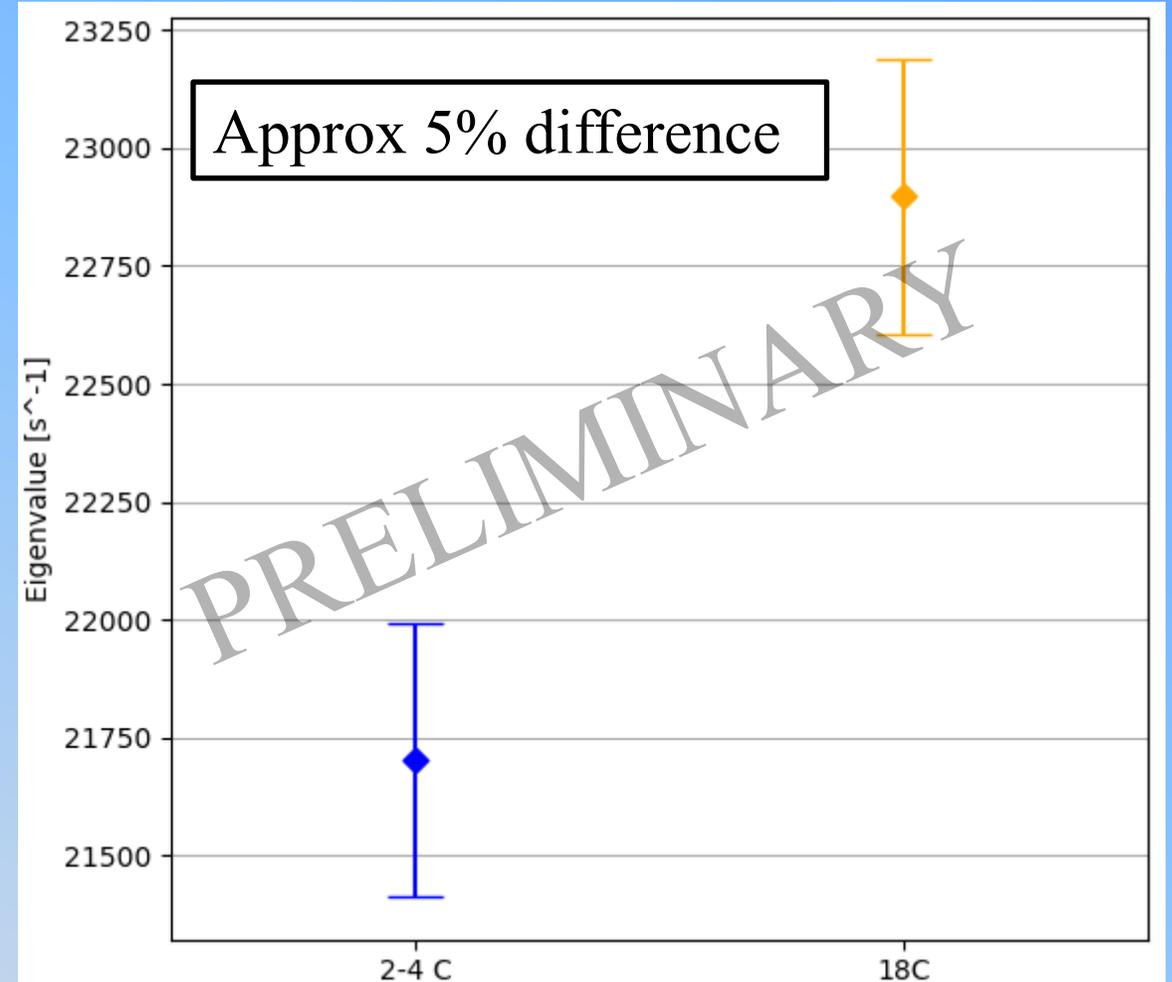
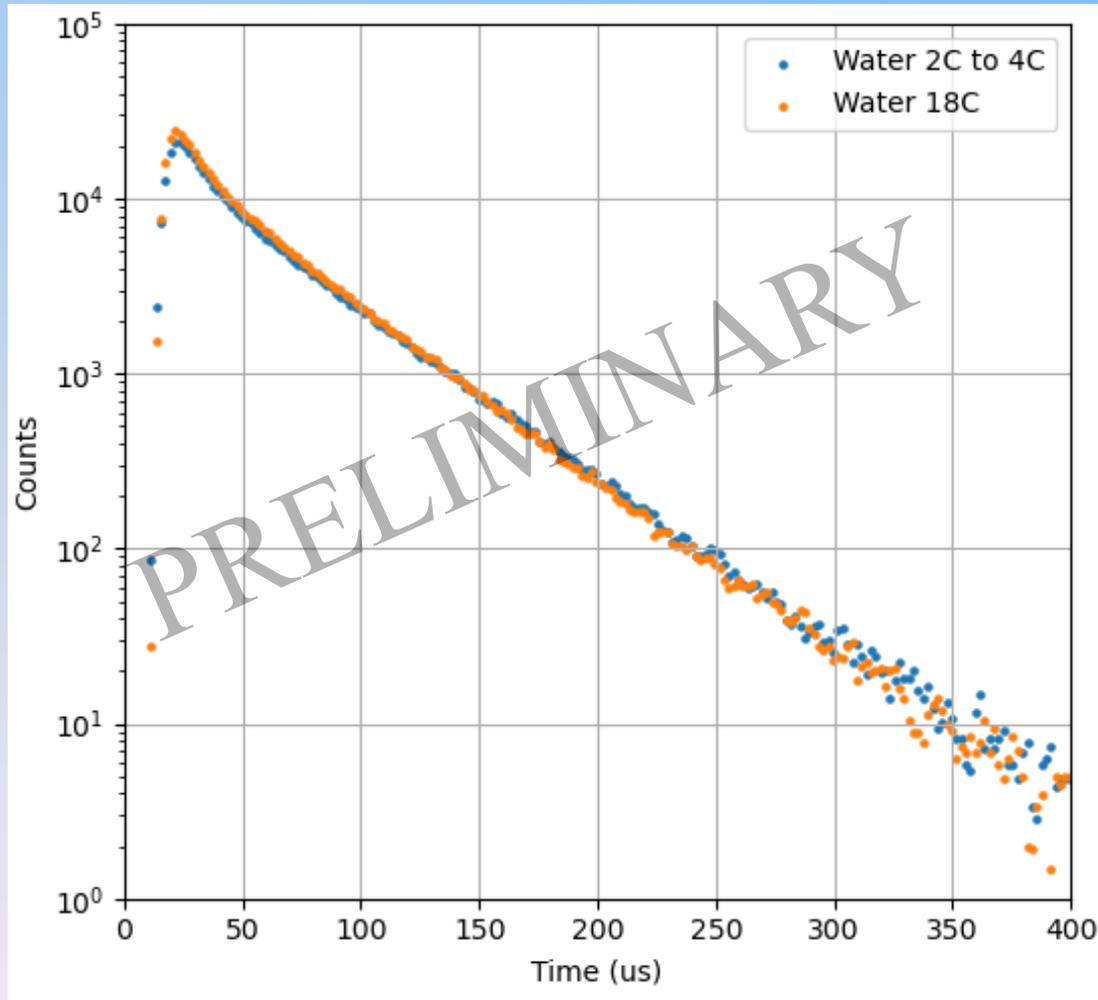
Low Temperature Water PNDA Measurements

- Preliminary PNDA of light water between 0C and 10C.
 - 4C is max density for light water
 - Below 4C density ↓ with temperature ↓ , as proto ice crystals form



DataQ DI245, Data Logger wt. T-type thermocouples

Preliminary Low Temperature Water (360g)

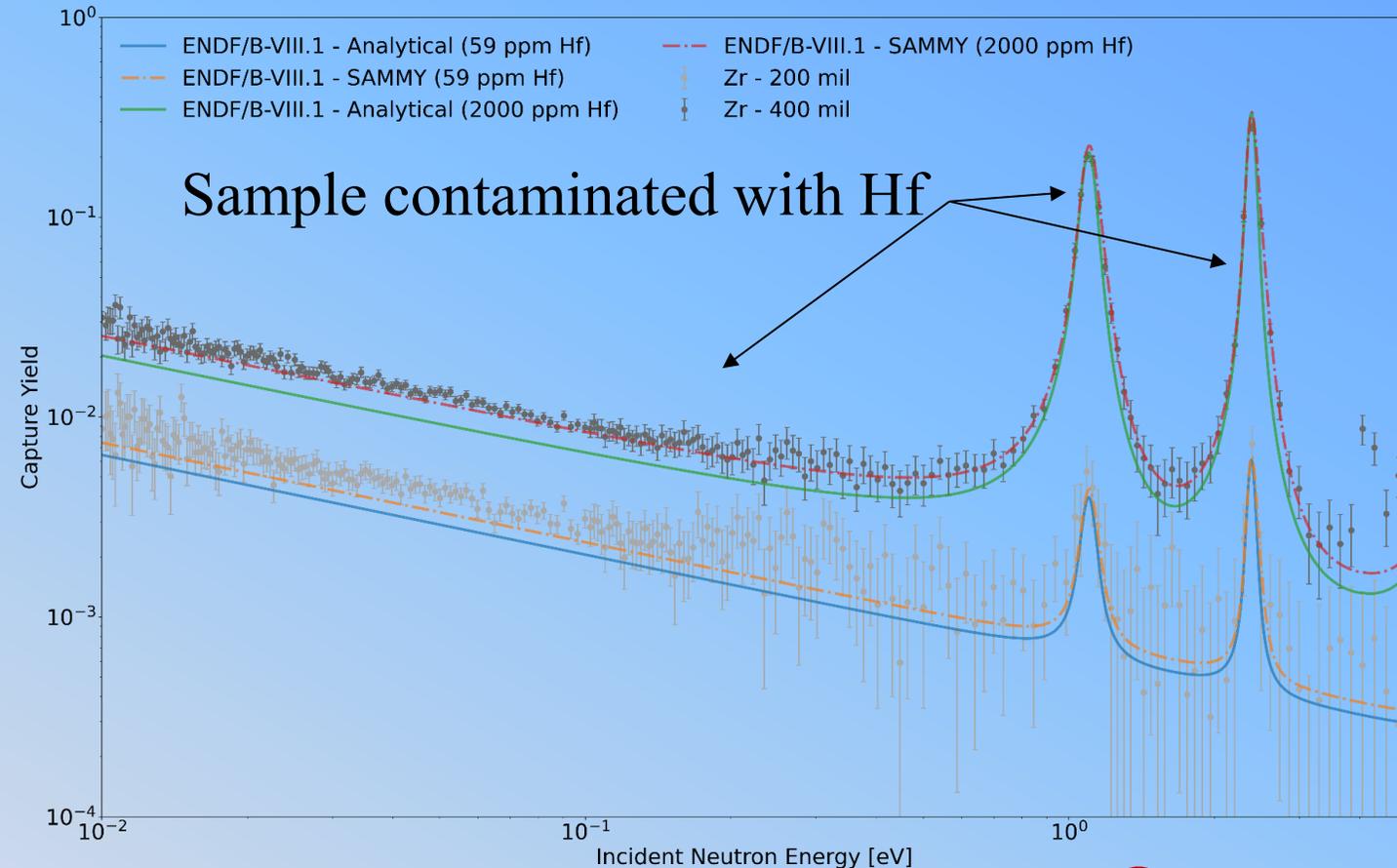


Natural Zirconium Thermal Neutron Capture Yield Measurement

Greg Siemers, Ian Parker

Elemental Zirconium (n,γ) Measurement

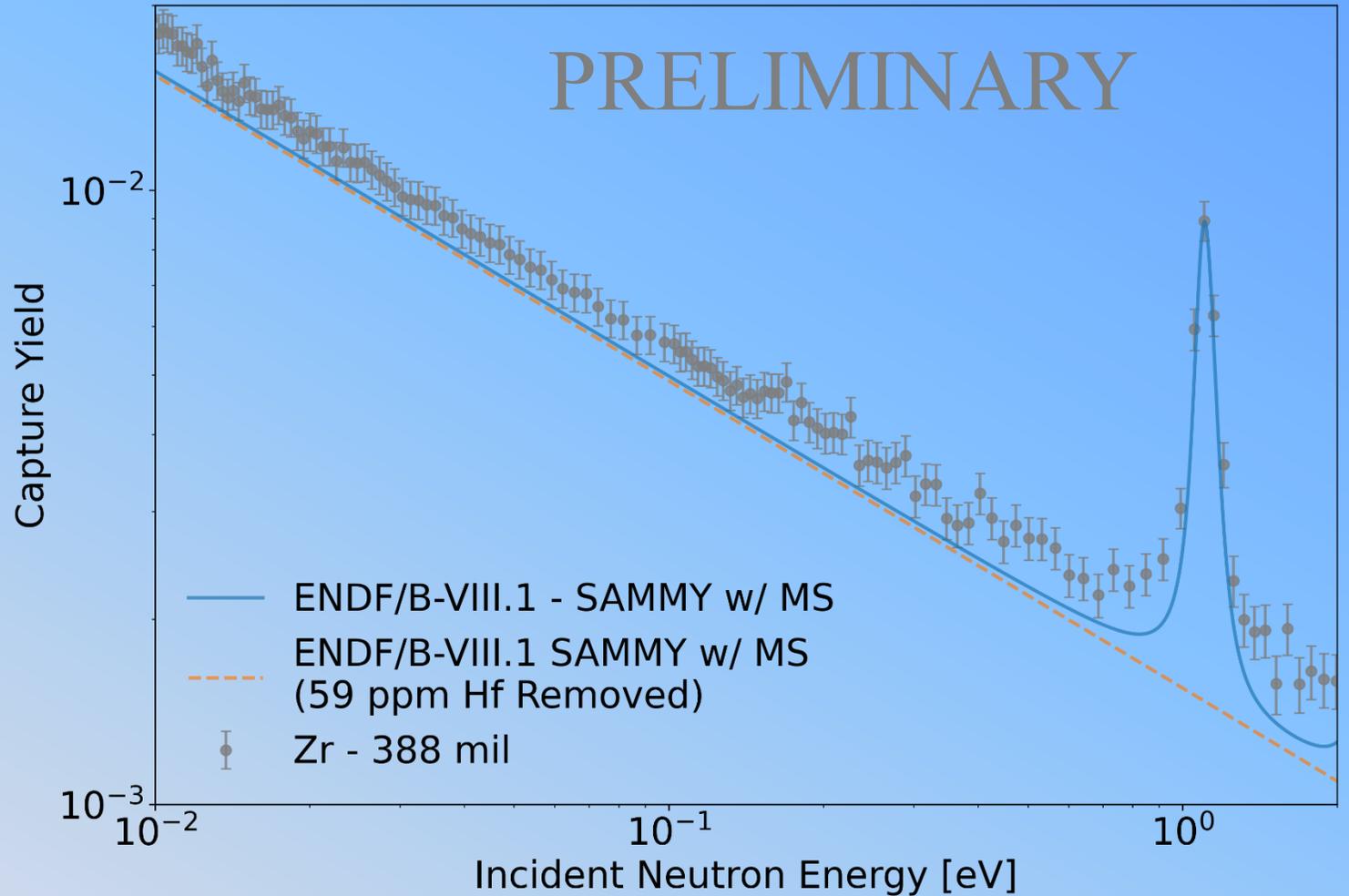
- Measurement performed in late August 2025 using the RPI multiplicity detector
- Several available Zr samples of varying thickness (and two procurement batches) stacked to obtain measurable yield
- Hf content in measured yield did not match the anticipated result from vendor provided mass spec
- 200 mil (batch #1) and 400 mil (batch #2) samples were split and measured independently
 - 400 mil sample had high Hf content (~2000 ppm) and was discarded



Preliminary Zirconium Capture Yield

$$Y_{Zr} = \frac{\dot{C}_{Zr} - \dot{C}_{Open} \cdot \left(\frac{M_{Zr}}{M_{Open}}\right)}{\phi} \cdot f_n \cdot \left(\frac{\eta_{Cd}^y}{\eta_{Zr}^y}\right)$$

- Final measured sample was six stacked batch #1 elemental Zr samples totaling 388 mil
 - Difficulties limited total Zr data acquisition time to a few hours
 - Preliminary results find the ENDF/B-VIII.1 evaluation low
 - Longer measurement needed to verify initial findings
- Both In and Cd measured to assess the merit of each material as neutron flux normalizer
 - 99.9% $^{10}\text{B}_4\text{C}$ used to measure incident neutron flux profile
 - Cross-normalization performed with 0.625 eV ^{113}Cd resonance in this analysis
- Pb measured to determine false capture signal due to neutron scattering into detector Al
 - Effects of which were shown to be small ($\sim 1\text{e-}4$ yield)



Photonuclear Production Yield Measurements at the RPI LINAC

D. Fritz

This work was supported by Eckert & Ziegler Analytics. This material is based upon work supported by the U.S. Nuclear Regulatory Commission. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the NRC.

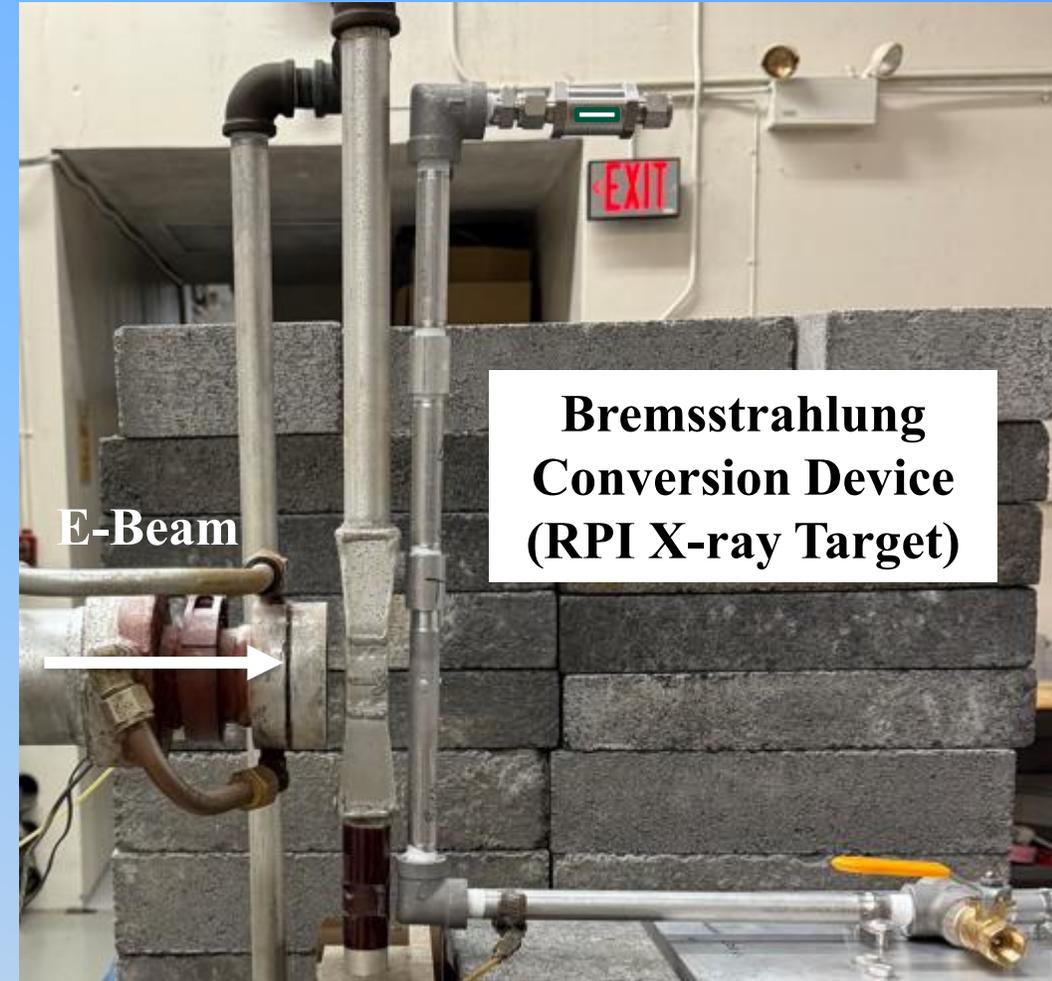
Nuclear Data Validation for Isotope Production

Objectives

- Integral validation of Np-237 photonuclear and fast neutron ($E < 50$ MeV) data as related to Pu-236 production.
 - Gamma spectroscopy performed on precursors, with alpha spectroscopy performed on chemically separated final products.
- Integral validation of non-actinide photonuclear data relevant to production of various isotopes.
 - Gamma spectroscopy performed post-irradiation.

General Conclusions

- Large discrepancies observed between photonuclear data evaluations (IAEA/PD-2019, TENDL-2023). IAEA/PD-2019 only outperforms TENDL-2023 for some reaction channels.
- Discrepancies observed between evaluations and experiment for Np-237 neutron capture. Evaluations are within 8% of one another.



Nuclear Data Validation for Isotope Production

Np-237

- Discrepancies between photonuclear evaluations and experiments for Pu-236 production, with IAEA/PD-2019 outperforming TENDL-2023.
- Discrepancies seen between experiments and neutron evaluations for Pu-238 production.



Pu-236 Photonuclear Production Yields [kBq/μAh-g]			
	Experiment	IAEA/PD-2019	TENDL-2023
Yield	0.629	0.529	0.337
C/E	N/A	0.841	0.536



Pu-238 Neutron Production Yields [Bq/μAh-g]				
	Experiment	ENDF/B-VIII.1	JEFF-4.0	JENDL-5.0
Yield	0.651	0.941	0.927	0.875
C/E	N/A	1.445	1.423	1.344

Natural Nickel

- Significant differences between photonuclear evaluations and experiments for some produced isotopes (Ni-57, Co-58).
- For only some channels, IAEA/PD-2019 outperforms TENDL-2023.
- ENDF/B-VIII.1 has adopted IAEA/PD-2019 data for all Nickel isotopes.

Select Major Nickel Activation Products at End of Bombardment			
Isotope	IAEA/PD-2019 [kBq/μAh]	TENDL-2023 [kBq/μAh]	Experiment [kBq/μAh]
Ni-57	1061.4	852.9	1397.3
Ni-56	5.1	6.1	6.3
Co-58	0.8	1.3	2.5

**Uncertainties for experimental results are on the order of 5 – 10%. Uncertainties in modeling accuracy (non-nuclear data) are estimated to be on the order of 20% - 30%. Additional measurements recommended & planned.

Summary

- Neutron capture γ -ray cascade spectra and yields were measured in the resolved resonance region and compared to evaluations using mod-MCNP-6.2/DICEBOX simulations
 - Completed measurements of thermal neutron capture cascade spectrum for multiple isotopes: ^{56}Fe , $^{\text{nat}}\text{Mn}/^{\text{nat}}\text{Cu}$, $^{\text{nat}}\text{Co}$, $^{\text{nat}}\text{Ta}$, $^{\text{nat}}\text{U}$, ^{235}U , $^{\text{nat}}\text{Cd}$, $^{\text{nat}}\text{Au}$, $^{\text{nat}}\text{In}$, $^{\text{nat}}\text{Cu}$, $^{\text{nat}}\text{Mn}$, $^{\text{nat}}\text{Zr}$
 - Separated fission from capture cascade spectra for U-235
 - Identified source of uncertainties towards a development of a validation suit
- Pulsed neutron die-away method was developed as a tool to provide data for validation of TSLs
 - Completed measurements for low temperature water.
- Measurement of Zr neutron capture at a function of energy in the thermal region shows feasibility, a longer measurements is needed.
- Large discrepancies observed between photonuclear evaluations and experimental yield data. IAEA/PD-2019 outperforms TENDL-2023 for only some channels.