Validating Thermal Neutron Capture γ-Ray Data using the RPI Gaerttner LINAC Center

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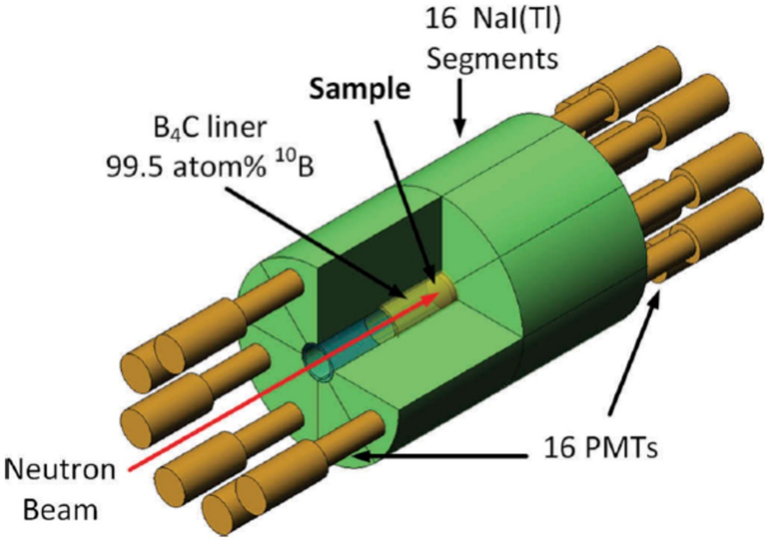
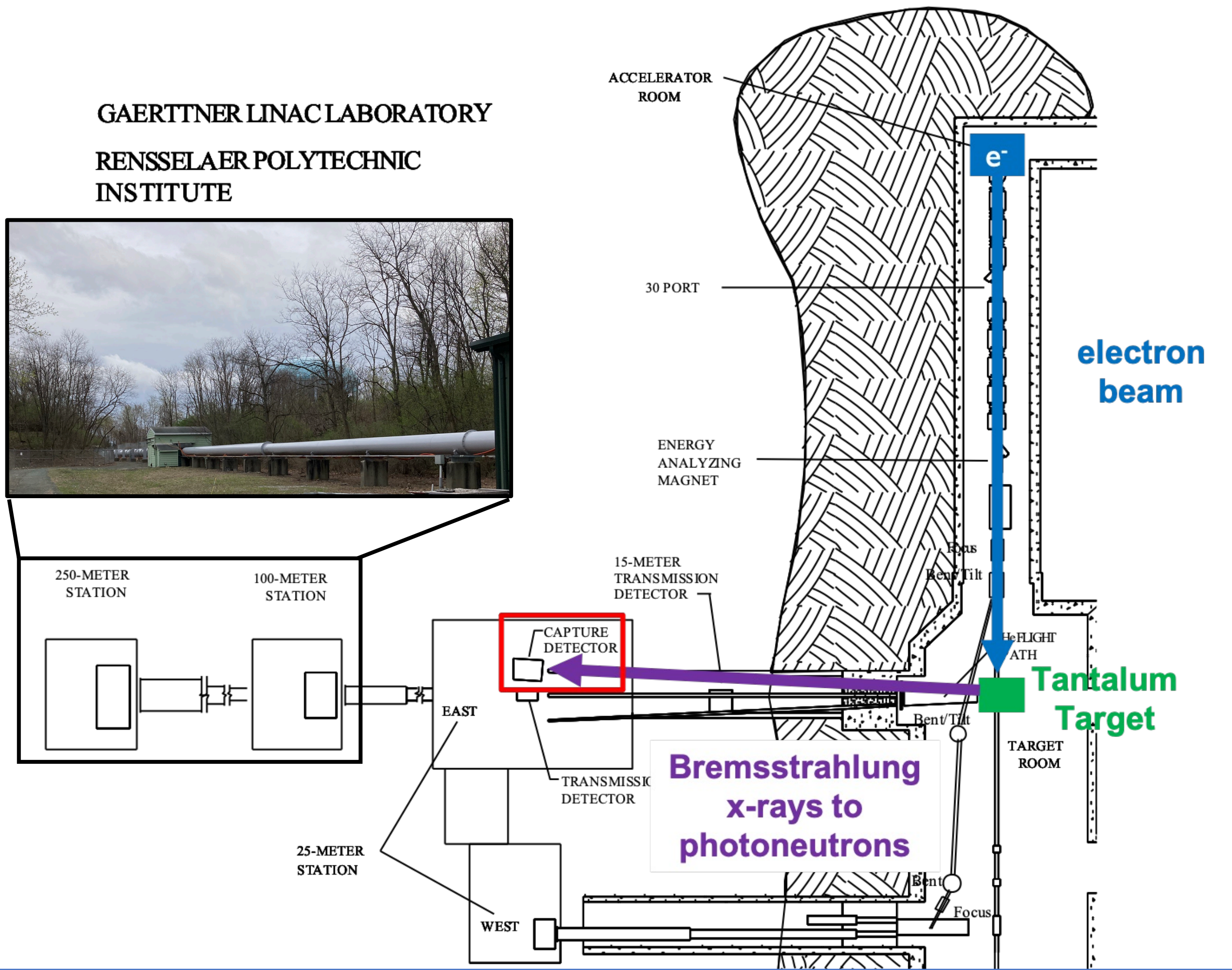
Outline

- **Introduction**: RPI Gaertner LINAC Center, Neutron Capture Reactions, Project Goals & Motivation
- **Experimental Methods**: RPI Capture γ-Ray Multiplicity Detector
- **Simulation Methods**: Current Status & Modifications
- **Validation**: ^{56}Fe γ-ray Spectra Measurements
- **Conclusions & Future Work**

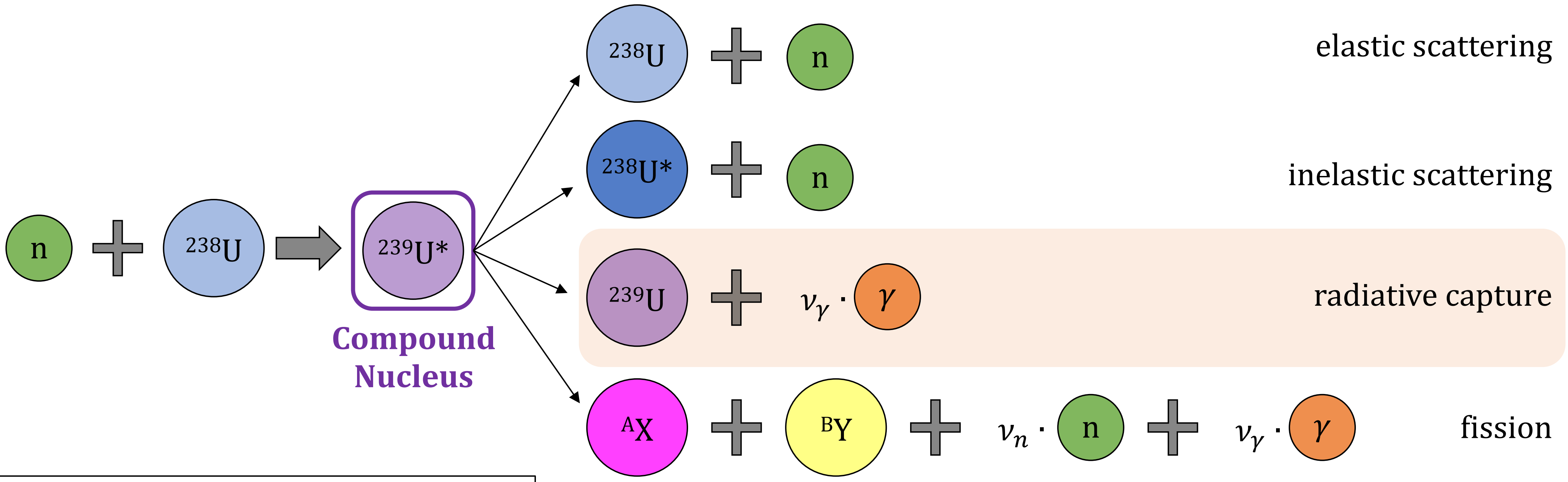


RPI Gaerttner Linear Accelerator (LINAC) Center



What do we measure?

Results of various neutron interactions



* indicates excited nucleus

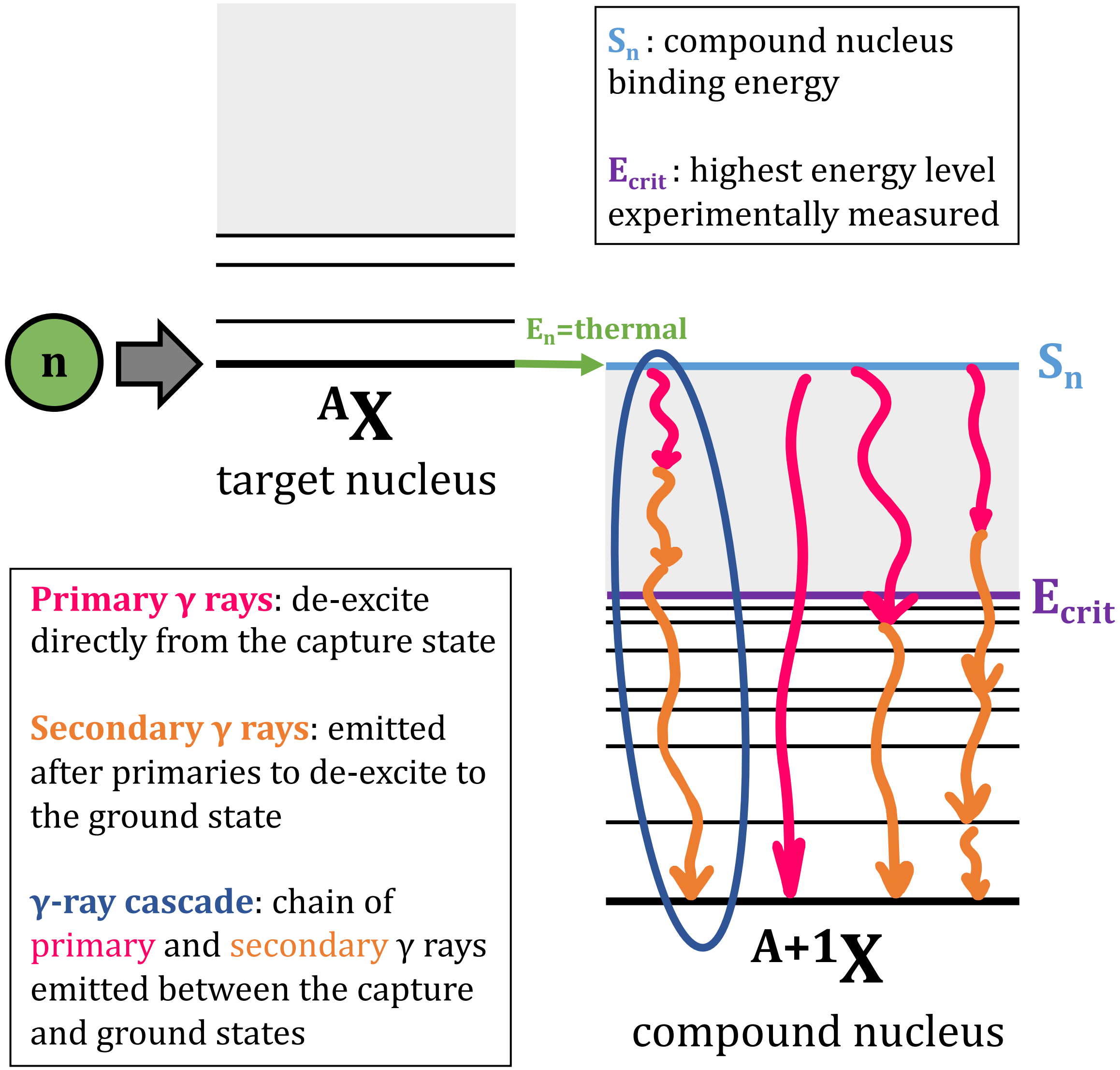
ν_γ = # γ-rays released per capture reaction

^{A}X and ^{B}Y are fission products

ν_n = # neutrons released per fission reaction

Charged-particle and neutron-producing reactions can also occur but are not included in this research

Thermal Neutron Capture Reactions



S_n : compound nucleus binding energy

E_{crit} : highest energy level experimentally measured

Primary γ rays: de-excite directly from the capture state

Secondary γ rays: emitted after primaries to de-excite to the ground state

γ-ray cascade: chain of primary and secondary γ rays emitted between the capture and ground states

Project Goals

1 Develop **experimental methods** to measure **γ-ray cascades** produced by thermal neutron capture reactions

2 Update **simulation methods** to:

1. Accurately model **γ-ray cascades** emitted during compound nucleus de-excitation
2. Simulate **γ-ray cascades** travelling through detection systems

3 Use both methods to **assess the accuracy of thermal neutron capture induced γ-ray data** stored in nuclear data libraries

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Why do we want to measure and simulate neutron capture γ-ray cascades?

Research Areas

- Nuclear structure studies
  - Energy levels, spins and parities
- Improving γ-ray de-excitation models

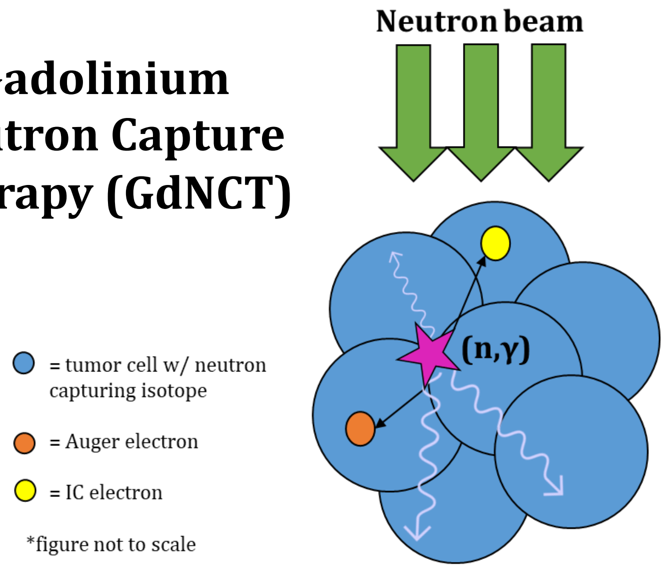
Applications

- γ-ray heating
- Radiation shielding
- Nuclear medicine
- Neutrino & particle physics
- Active neutron interrogation
  - Industry (coal, oil-well logging)
  - Controlled substance detection
  - Non-proliferation
  - Space exploration

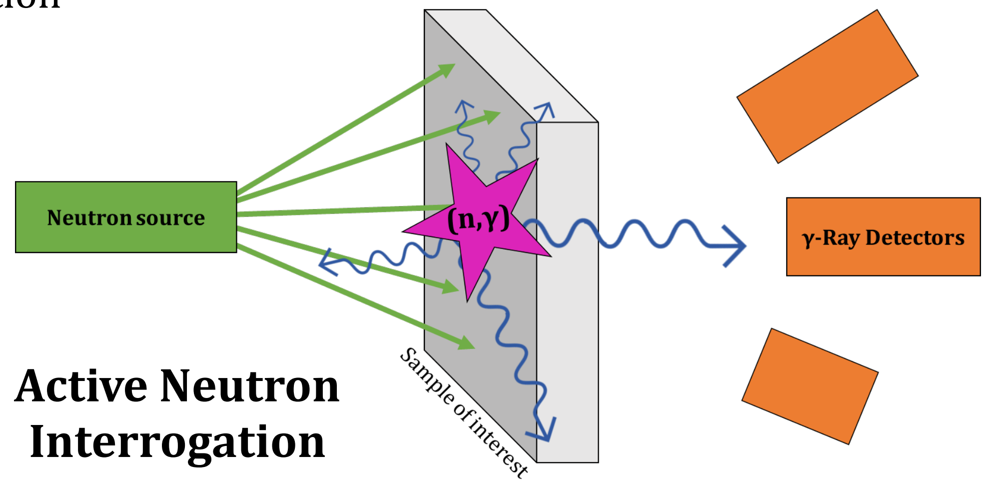
Measurement Types

- Single Detector
- Coincidence Measurements
  - Multiple detectors to measure many γ rays emitted in a cascade
- **RPI capture γ-ray data can be used to test *both***

Gadolinium Neutron Capture Therapy (GdNCT)



Active Neutron Interrogation

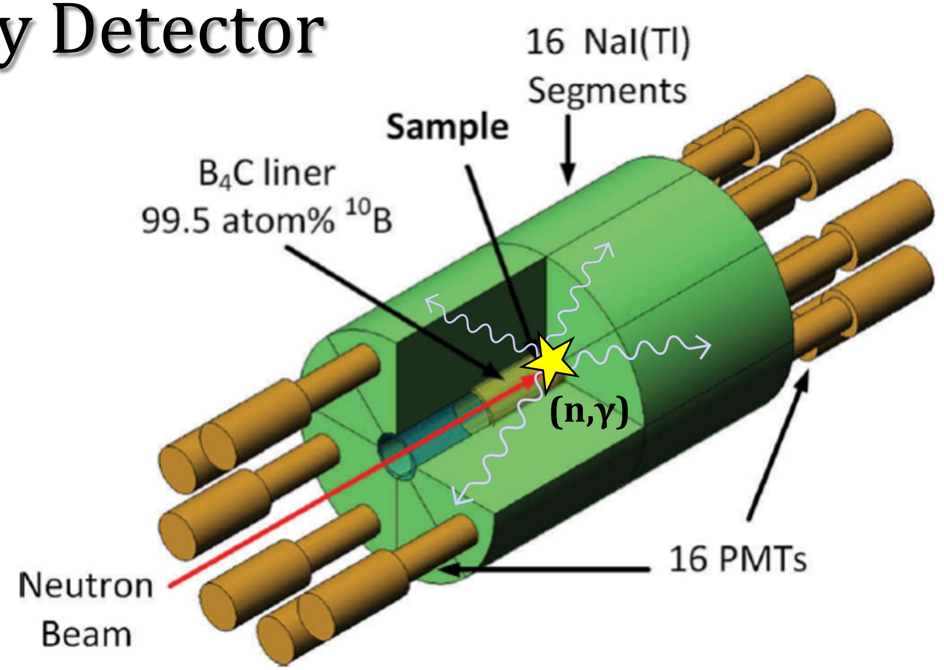


Experimental Methods

RPI Capture γ-Ray Multiplicity Detector

- **16 segment NaI(Tl) capture γ-ray multiplicity detector**
  - 20 L of NaI(Tl) surrounding the sample
  - A 1 cm thick B_4C ceramic sleeve (enriched to 99.5 atom% in ^{10}B) is used inside the detector to absorb neutrons scattering from the sample
  - Up to 96% efficiency for detecting γ-ray cascades
  - Located 25 m from the neutron-producing target
  - Time-of-flight (TOF) method used to determine incident neutron energy

- **Used for neutron capture yield and γ-ray spectra measurements**
  - Incident neutron energies: 0.001 eV – 3 keV



Simulation Methods

Step 1: Model Neutron Capture γ-Ray Cascades using DICEBOX

DICEBOX/ENSDF (+Firestone)

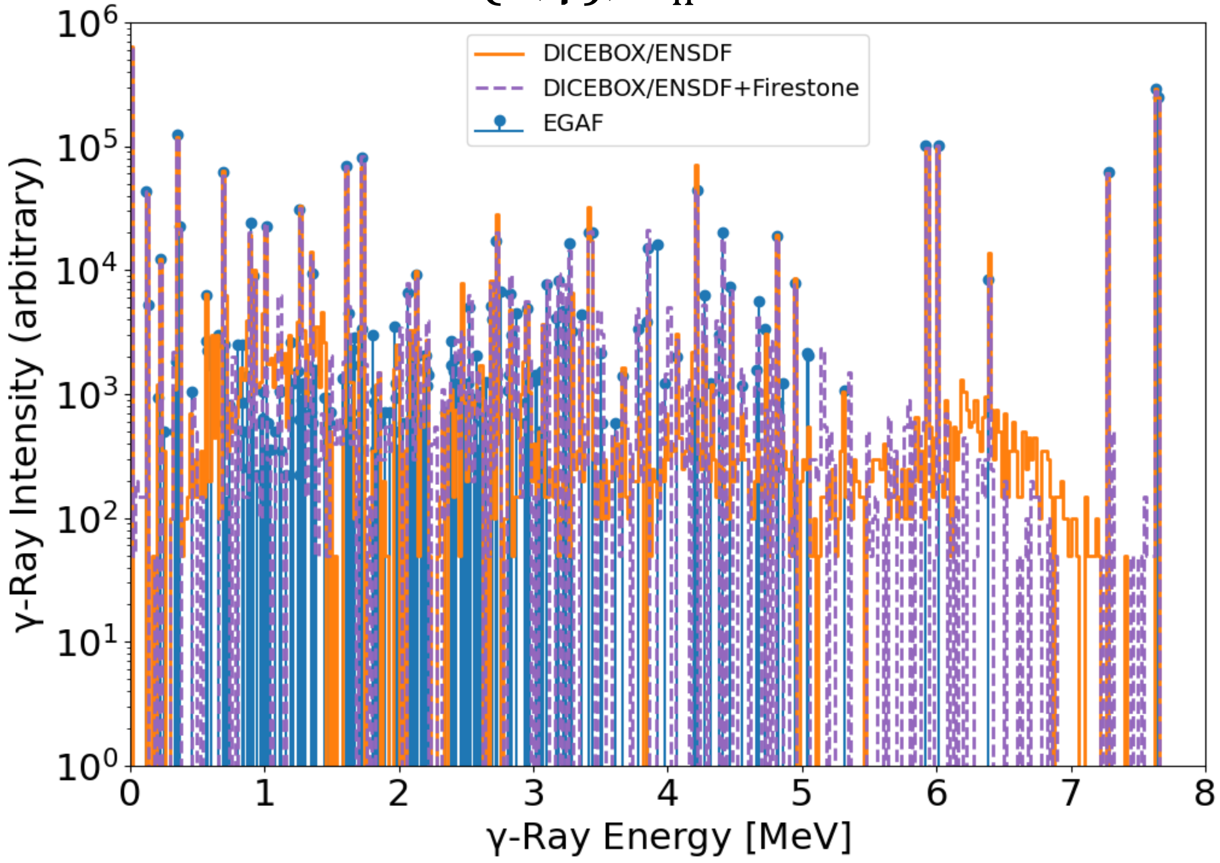
Models full γ-ray cascades using evaluated nuclear data (ENSDF + RIPL-3)

Input tuned to R. B. Firestone et. al., Phys. Rev. C **95**, 014328 (2017)

EGAF

Shows experimentally measured primary γ-ray lines (does not necessarily represent the full cascade)

$^{56}Fe(n,\gamma)$, E_n = thermal



Simulation Methods

Step 2: Transport γ-ray cascades through the RPI Capture Detector System

MCNP-6.2/ACE

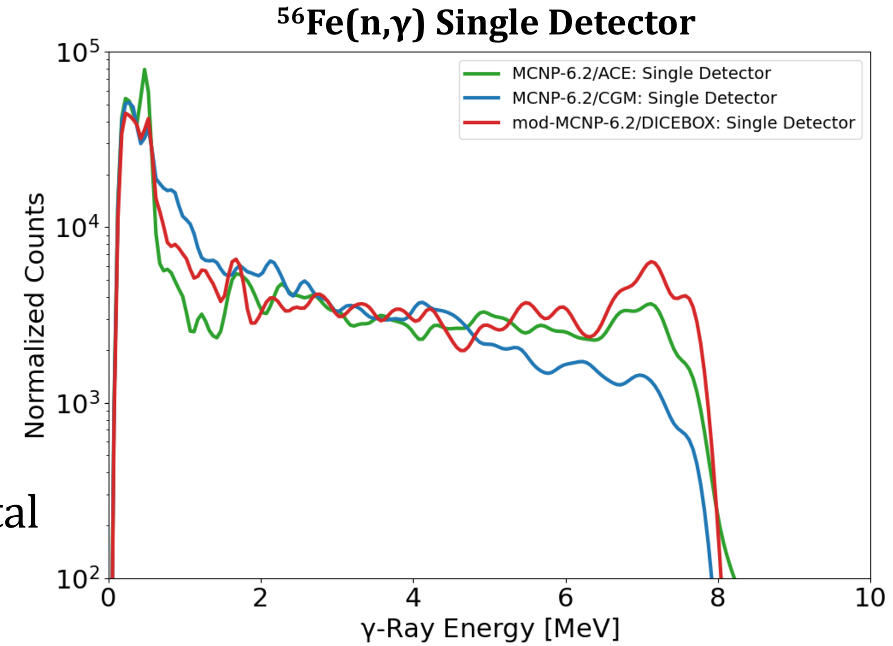
- Extracts γ-ray data from ACE files (ENDF/B-VIII.0)
- Total energy deposition spectra is expected to disagree with experimental data because the simulation does not include coincidence events

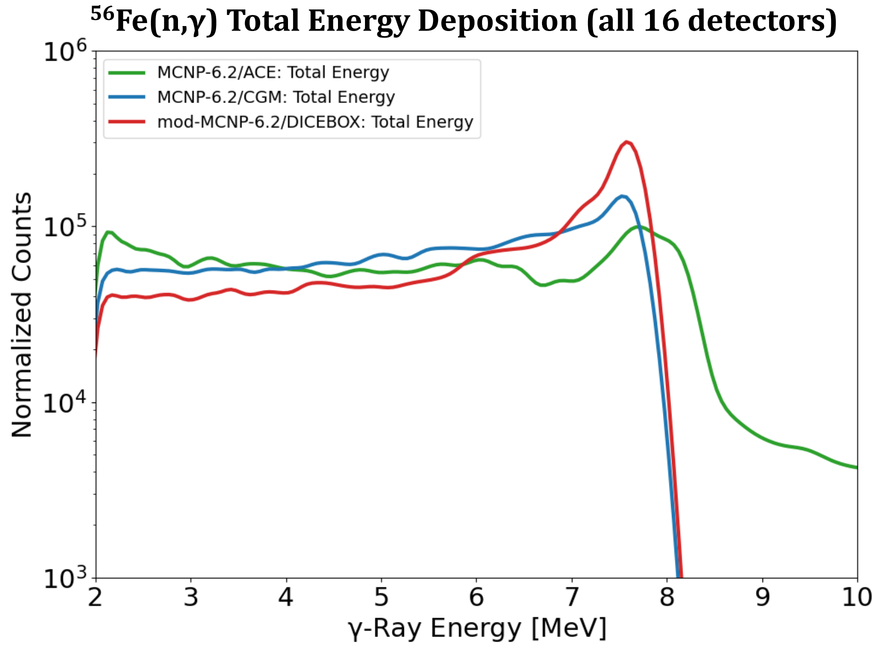
MCNP-6.2/CGM

- **C**ascading **γ**-Ray **M**ultiplicity
- Produces correlated secondary γ-ray emissions (cascades)
- γ rays transported through the detector geometry using MCNP-6.2

mod-MCNP-6.2/DICEBOX

- γ-ray cascades generated using DICEBOX
- γ-ray cascades transported through the detector geometry using a modified version of MCNP-6.2
- Generates an output file to tally γ-ray energy deposition in detector segments (enables event-by-event analysis including coincidence)





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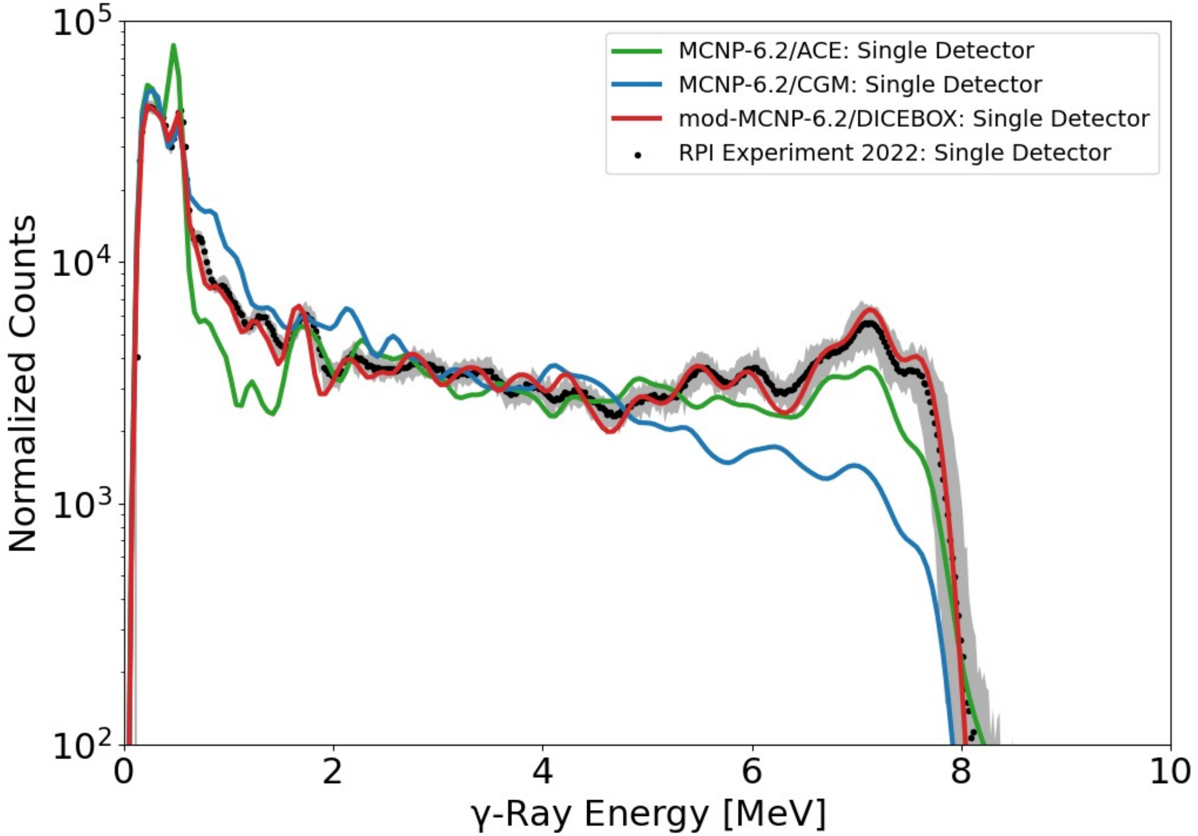
Validation of Experimental + Simulation Methods

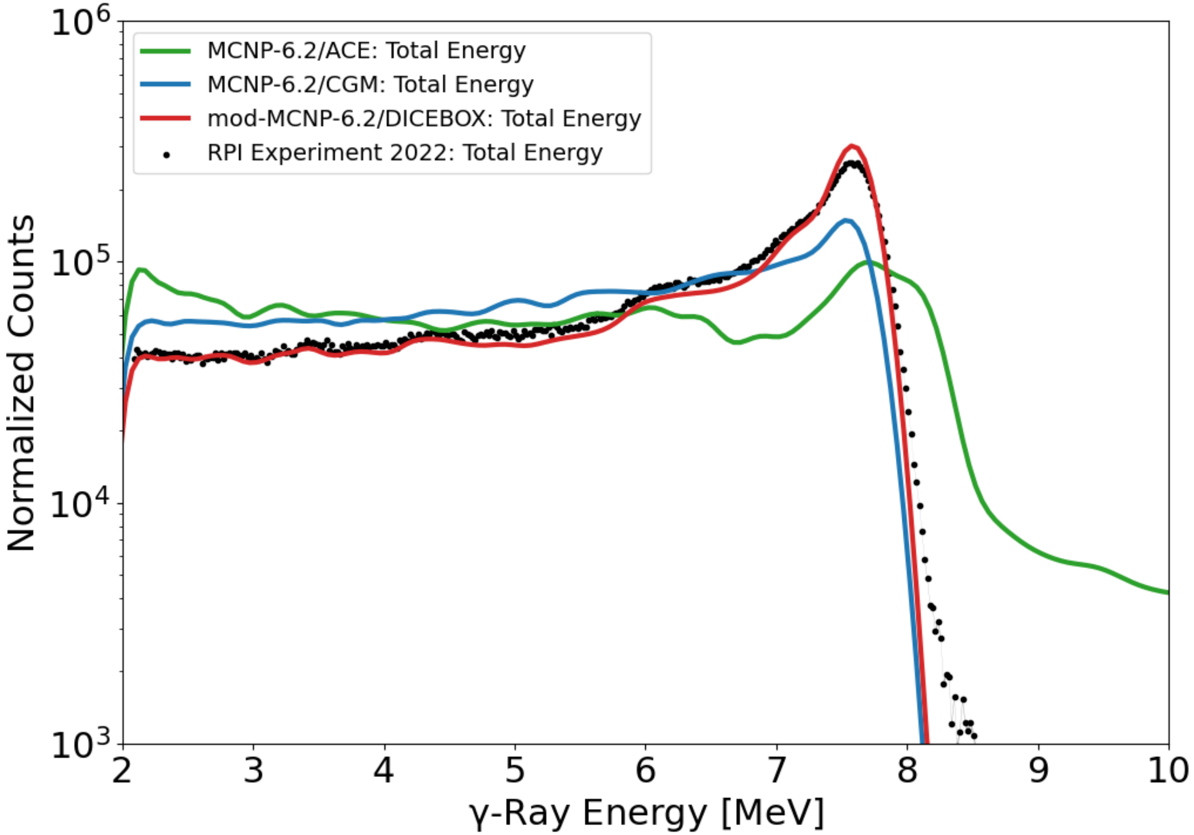
Compare Experimental γ-ray Spectra to Simulated Results

^{56}Fe(n,γ) Single Detector Spectra



Black data points = average single detector response
Gray band indicates the range of the 16 detectors

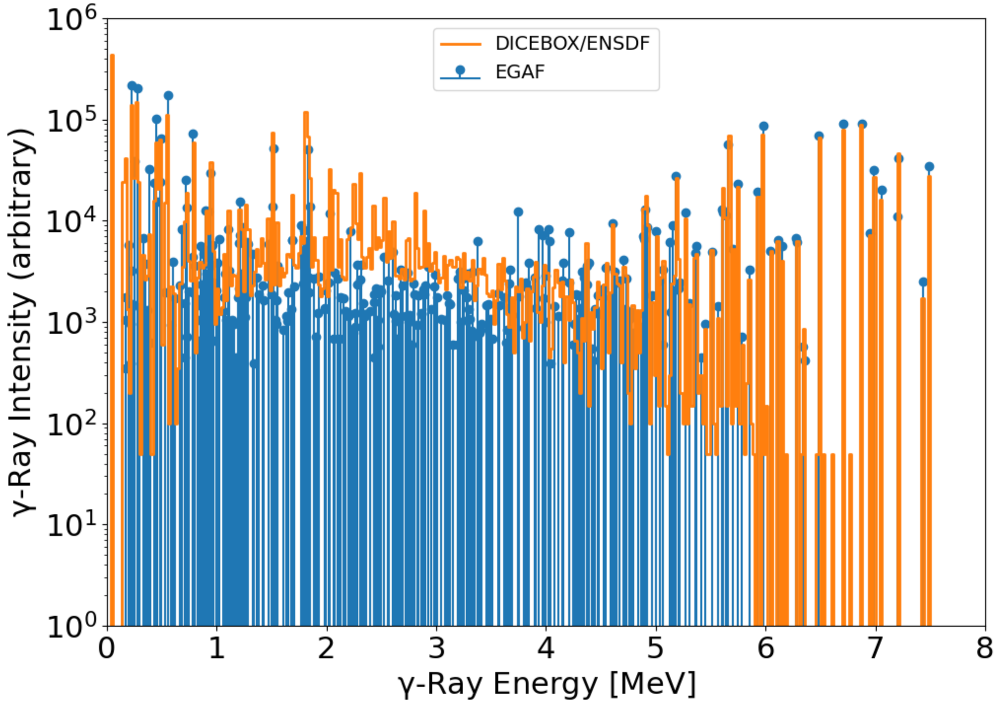
^{56}Fe(n,γ) Total Energy Deposition (all 16 detectors) Spectra



Gray band indicates the uncertainty in total energy deposition (size is on the order of the data points)

Further Validation

^{59}Co Thermal Neutron Capture



DICEBOX/ENSDF

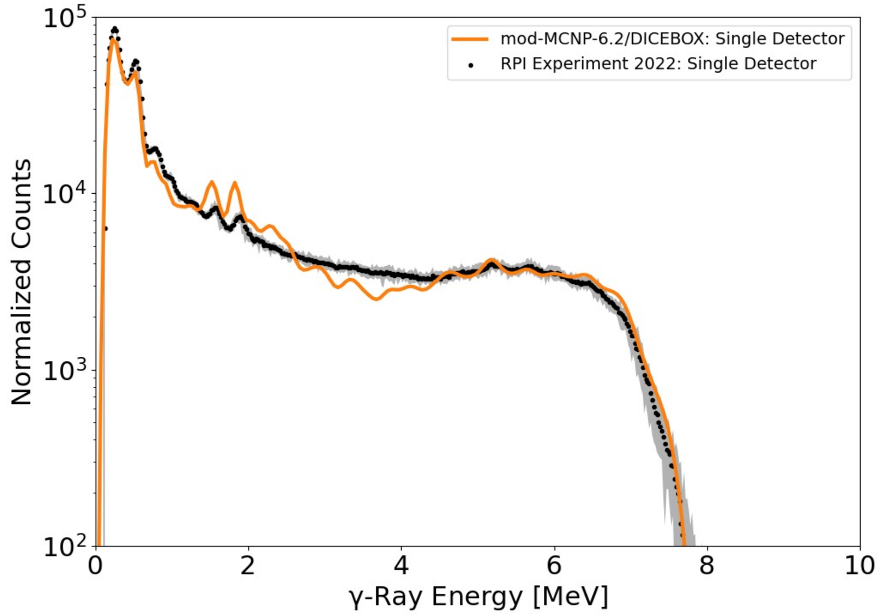
Models full γ-ray cascades using evaluated nuclear data (ENSDF)

EGAF

Experimentally measured γ-ray intensities

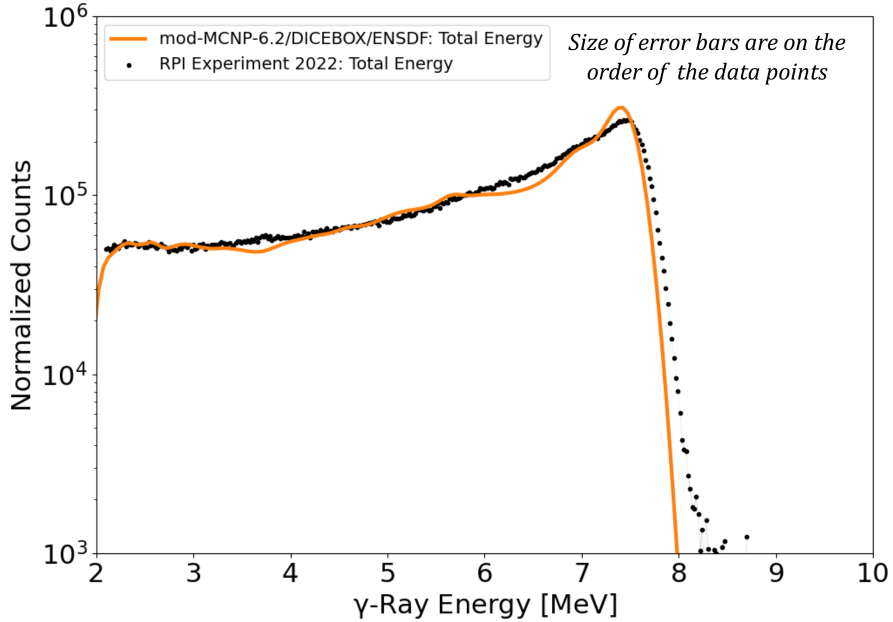
^{59}Co(n,γ) Single Detector

Black data points = average single detector response
Gray band indicates the range of the 16 detectors



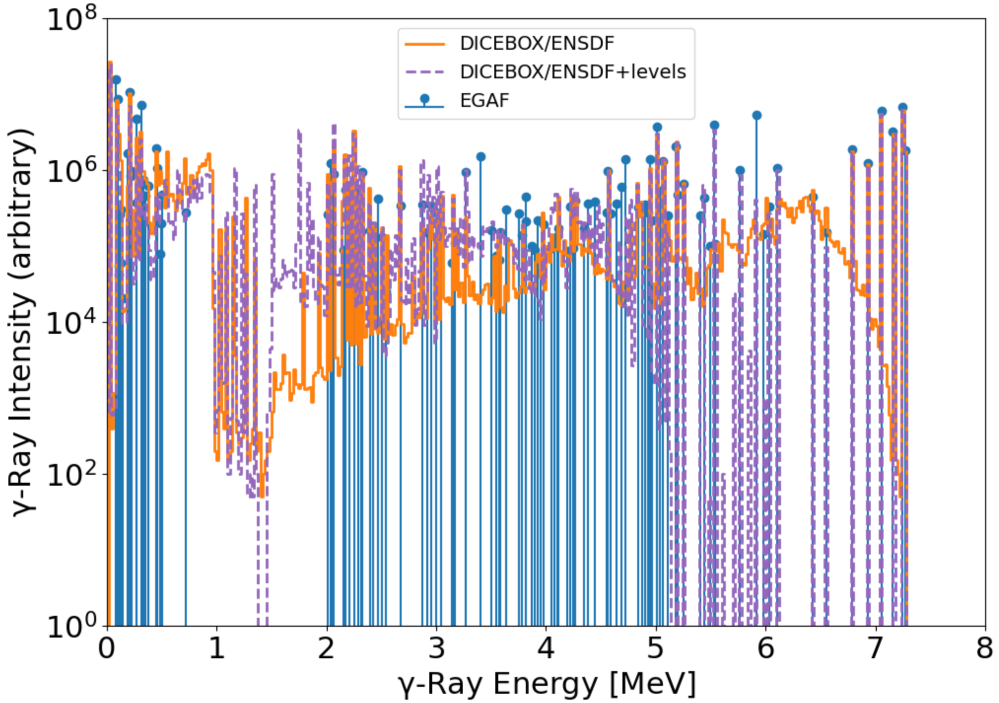
^{59}Co(n,γ) Total Energy Deposition (all 16 detectors)

Size of error bars are on the order of the data points



Further Validation

^{55}Mn Thermal Neutron Capture



DICEBOX/ENSDF

Models full γ-ray cascades using evaluated nuclear data (ENSDF)

DICEBOX/ENSDF+levels

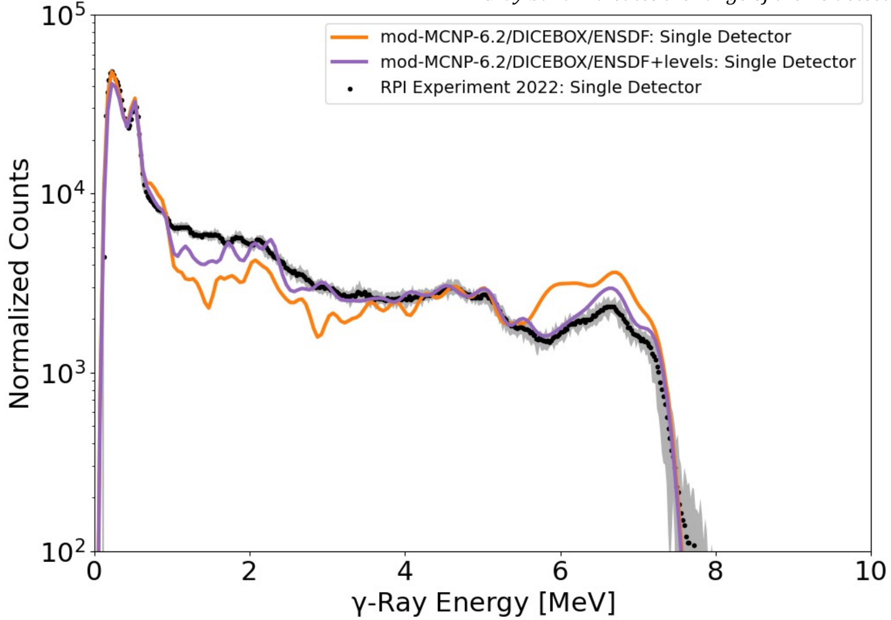
Models full γ-ray cascades using evaluated nuclear data (ENSDF)
+ additional levels that DICEBOX previously excluded

EGAF

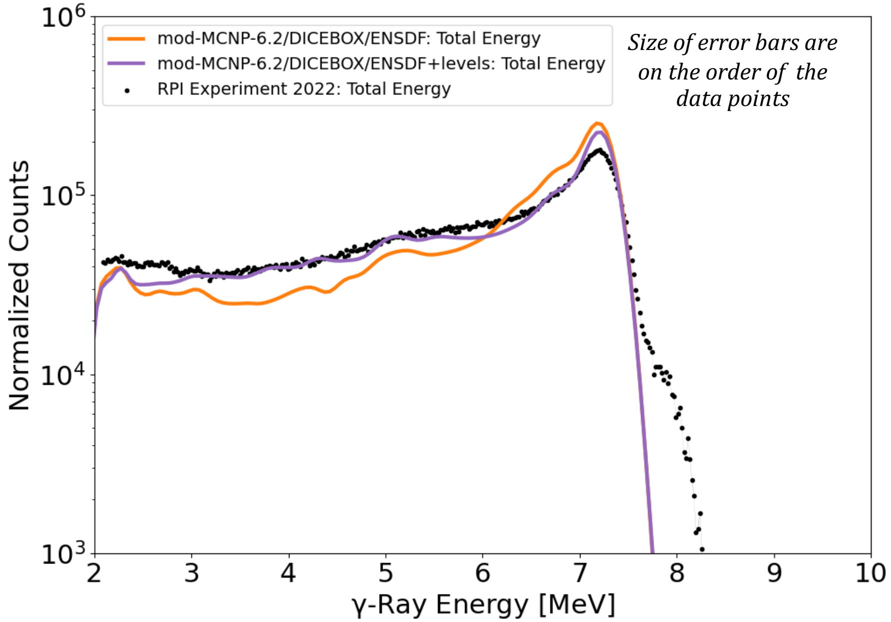
Experimentally measured γ-ray intensities

^{55}Mn(n,γ) Single Detector

Black data points = average single detector response
Gray band indicates the range of the 16 detectors



^{55}Mn(n,γ) Total Energy Deposition (all 16 detectors)



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Conclusions

- The experimental and simulation methods have been developed to test the accuracy of thermal neutron capture γ-ray data in nuclear data libraries.
- Measuring capture γ-ray spectra with the RPI Capture γ-Ray Multiplicity Detector system has been validated using the $^{56}Fe(n,\gamma)$ measurement.
  - **When the neutron capture γ-ray cascade data is well-known, the experimental γ-ray energy spectra can be accurately simulated using mod-MCNP-6.2/DICEBOX.**
- Validation of the system has been extended with ^{55}Mn and ^{59}Co thermal neutron capture measurements

Future Work

Complete the analysis of experimental capture γ-ray spectra for $^{\mathbf{nat,235}}\mathbf{U}$ and compare to **mod-MCNP-6.2/DICEBOX** simulations

- Challenge: separate fission-induced γ rays from capture

Dr. Robert Block at RPI Gaerttner LINAC Center (1971)

Thank you!
Questions?

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