Recent Results from Neutron-Induced Fission

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On behalf of the LLNL/LANL/TUNL Collaboration

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Outline

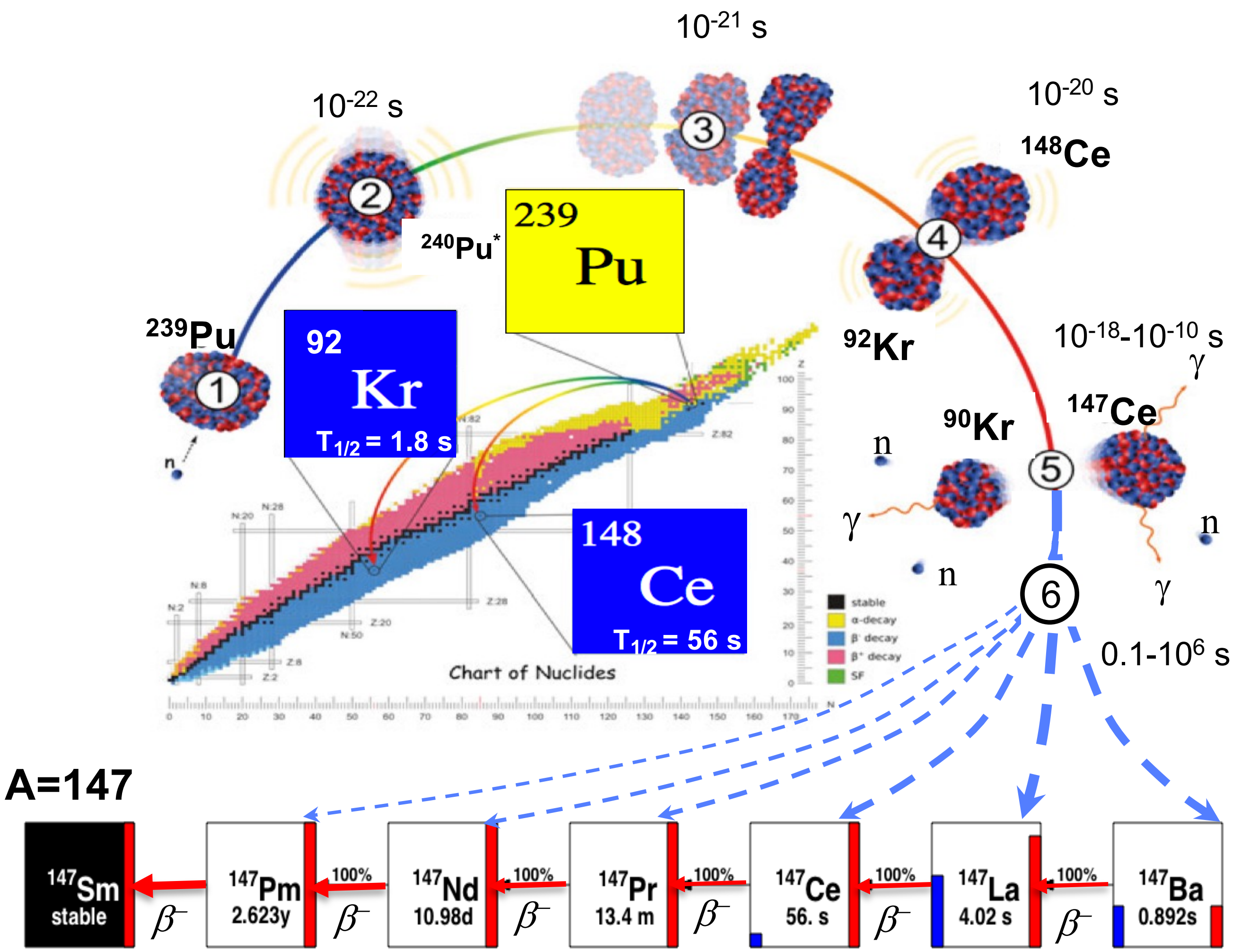
Motivation

Recent Experimental Studies and Results

- Long- and short-lived fission-product yields from neutron induced fission on ^{239}Pu, ^{235}U, and ^{238}U

Summary

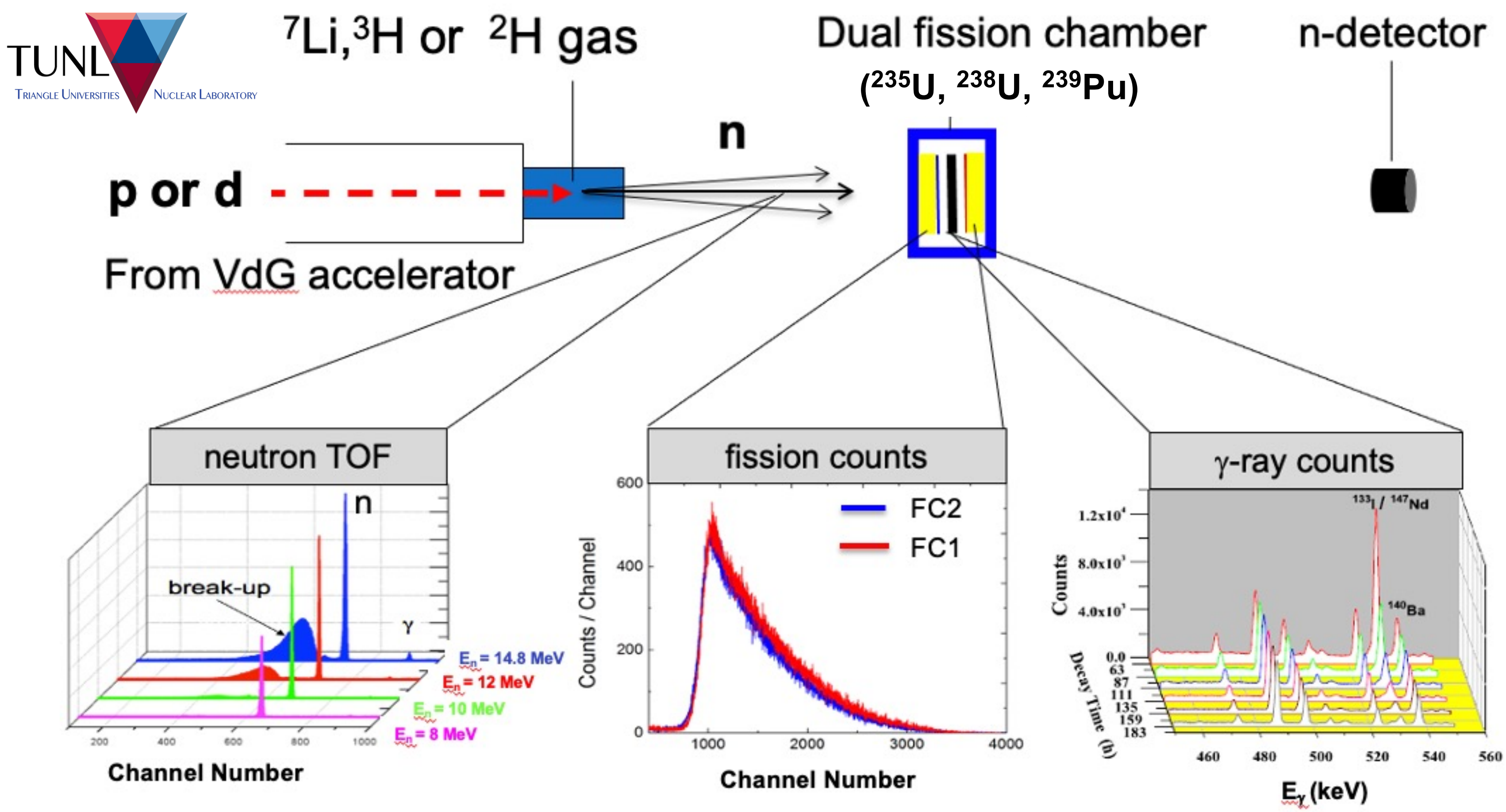
Fission Process and Observables



1. A neutron captures on ^{239}Pu
2. Compound nucleus of ^{240}Pu
3. ^{240}Pu deforms and elongates
4. ^{240}Pu scissions into two FFs
5. Independent yields: FPs de-excite by prompt n and γs
6. Cumulative yields

We develop high-precision fission product yield energy dependence from 0.1 to 15 MeV

Measurement of Long-Lived Fission Products Using Monoenergetic Neutron Beams

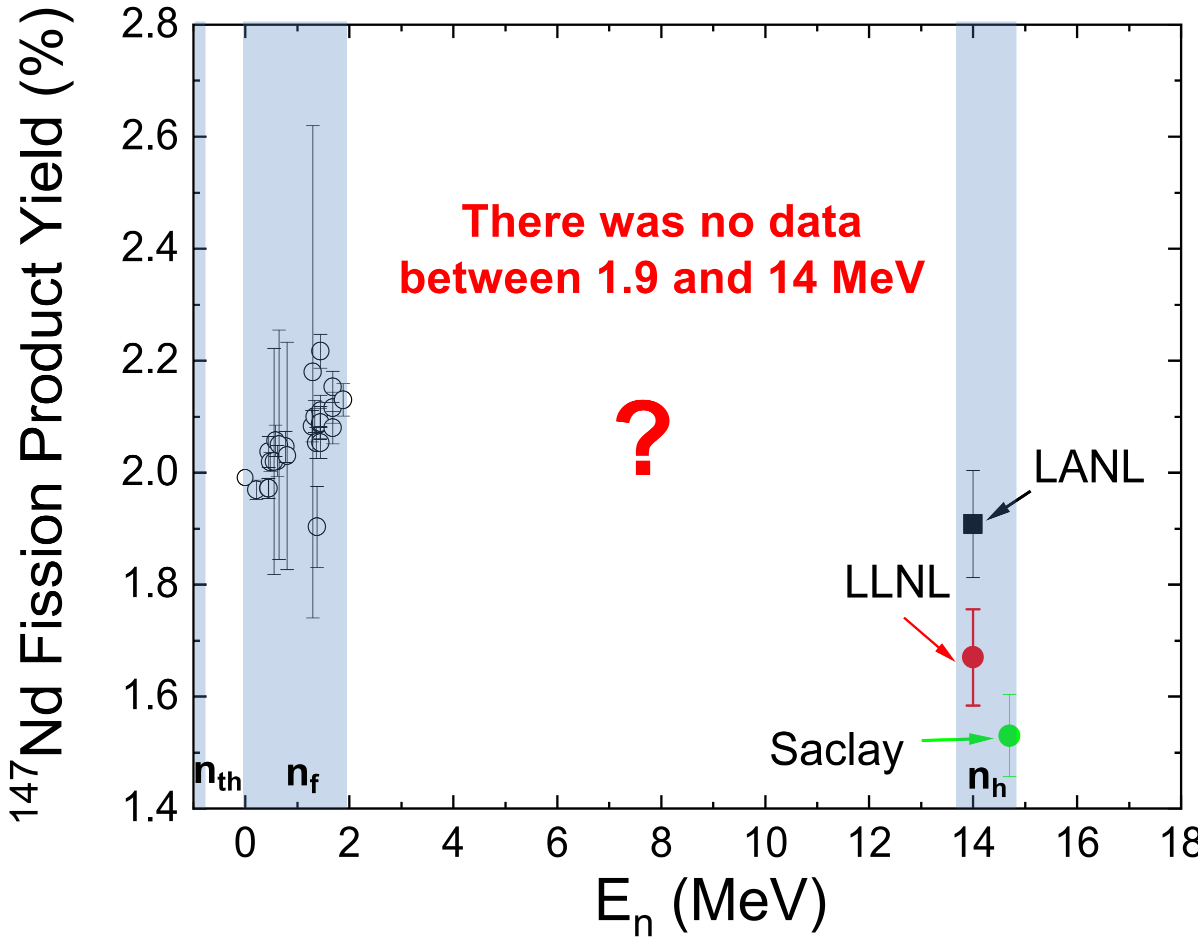


Fission Product Yield = N_X / N_{fis}

N_X = number of atoms of a specific fission product

N_{fis} = total number of fissions

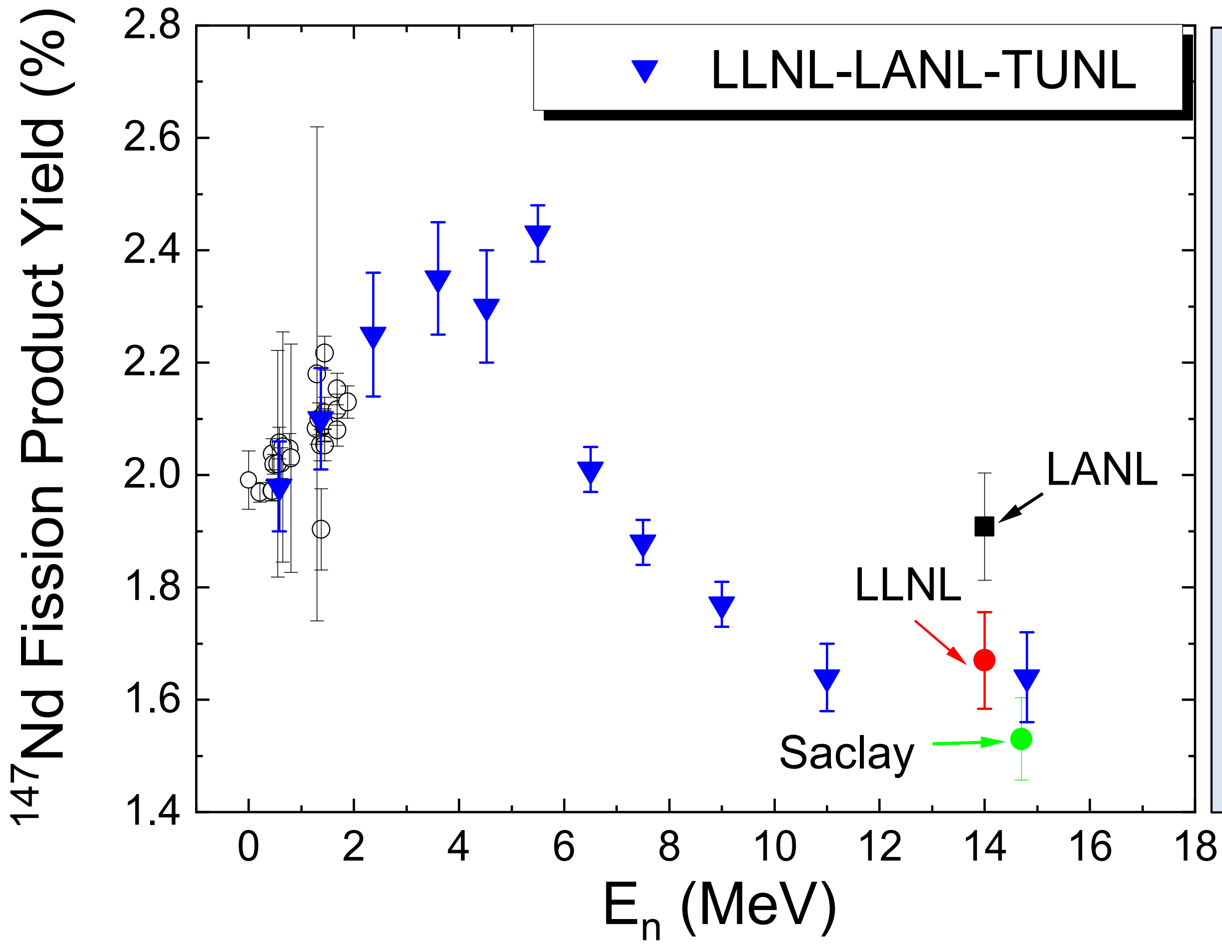
Motivation: Lack of FPY Data in Broad Energy Range for the Major Actinides



- **The last major fission yield evaluation was produced in 1994 as part of ENDF/B-VI nuclear data library**
- **Only three neutron energies – n_{th}, n_f, n_h**
- **Mostly low energy data from critical assembly or fast reactors**
- **Very scarce experimental data at the MeV-range**
- **Large discrepancy (~25%) at 14 MeV**

M.B. Chadwick *et al.* Nuclear Data Sheets 111 (2010) 2923
I. Thompson *et al.* Nucl. Sci. Eng. **171**, 85 (2012)

First Results: ^{147}Nd FPY from Neutron-Induced Fission of ^{239}Pu



- Our measurements at TUNL support the critical assembly data
- There is a positive slope of the ^{147}Nd FPY from 0.5 to ~4.0 MeV:

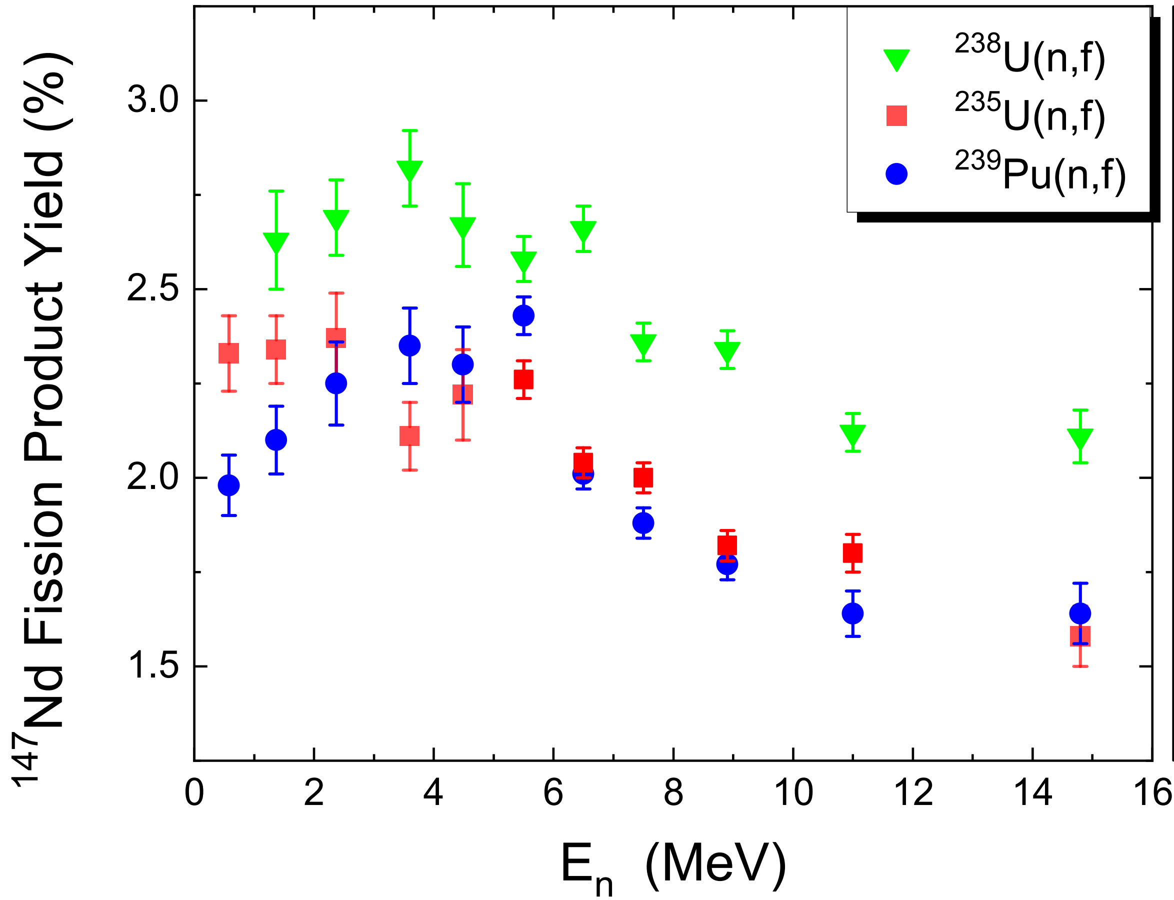
  $\Delta Y(^{147}Nd)/\Delta E_n = (5.8 \pm 1.5)\%/MeV$

- At higher energies the FPY for ^{147}Nd turns over and decreases
- Compared to the FPY at 4.6 MeV, the FPY has decreased by 30% at 14.8 MeV

M.E. Gooden et al., NDS 131, 319 (2016)
M.E. Gooden et al., PRC 109, 044604 (2024)
J. Silano et al., NIMA 1063, 169234 (2024)

K. Kolos et al., PRC 110, 024307 (2024)
M.A. Kellett et al., Appl. Rad. and Iso. 166, 109349 (2020)

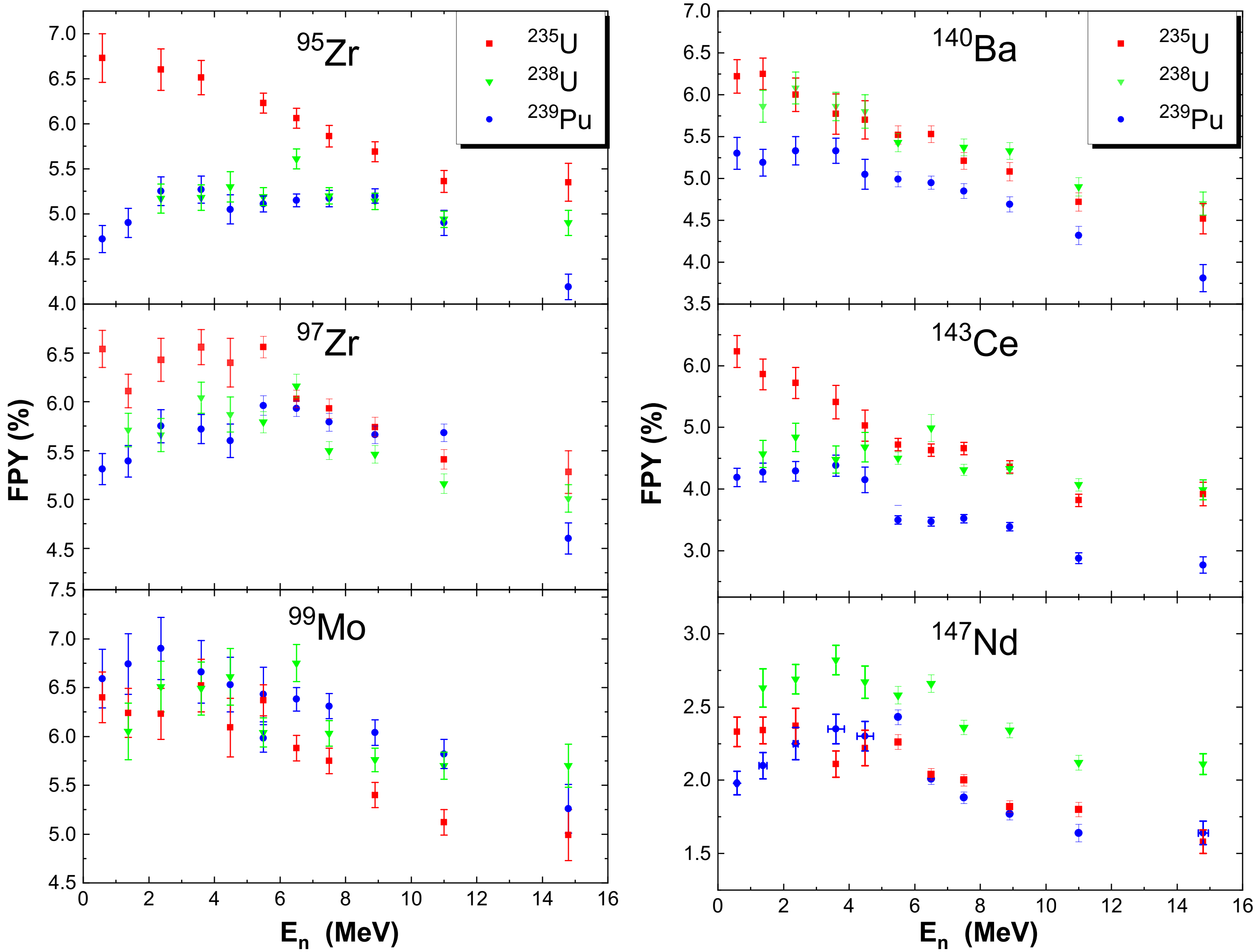
^{147}Nd FPY from Neutron-Induced Fission of ^{235}U, ^{238}U, and ^{239}Pu



- The slope of ^{147}Nd FPY from ~5.0 to 14.8 MeV is negative in all three fissile actinides
- Combined with our previous ^{147}Nd FPY data this trend is consistent with FPYs toward 14.8 MeV energy
- Significant reduction in the total uncertainties of the present mid-energy data compared to our previously published results

A. Tonchev *et al*. Submitted to Nucl. Data Sheets (2024)

Fission Product Yields from $^{235,238}U(n,f)$ and $^{239}Pu(n,f)$



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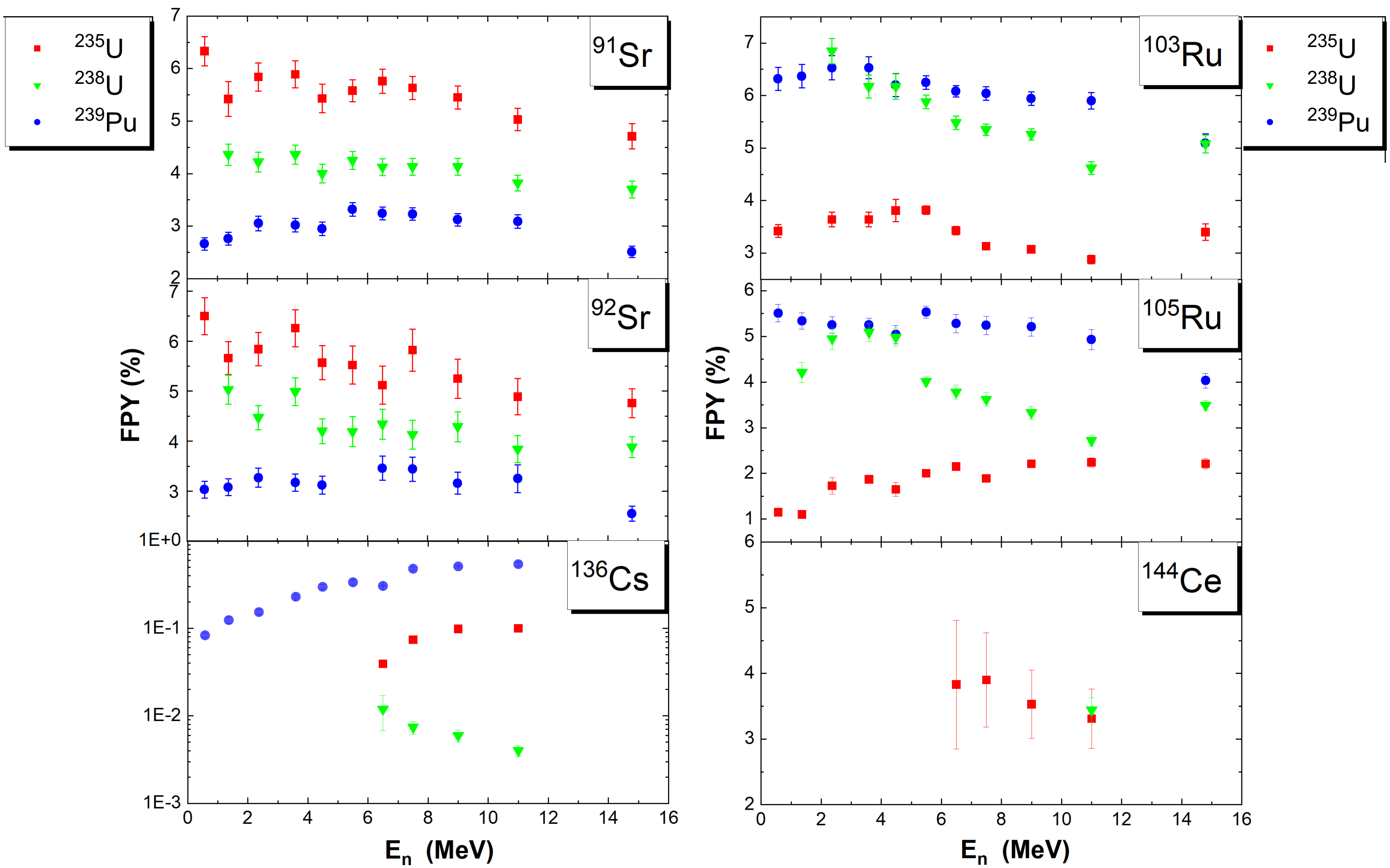

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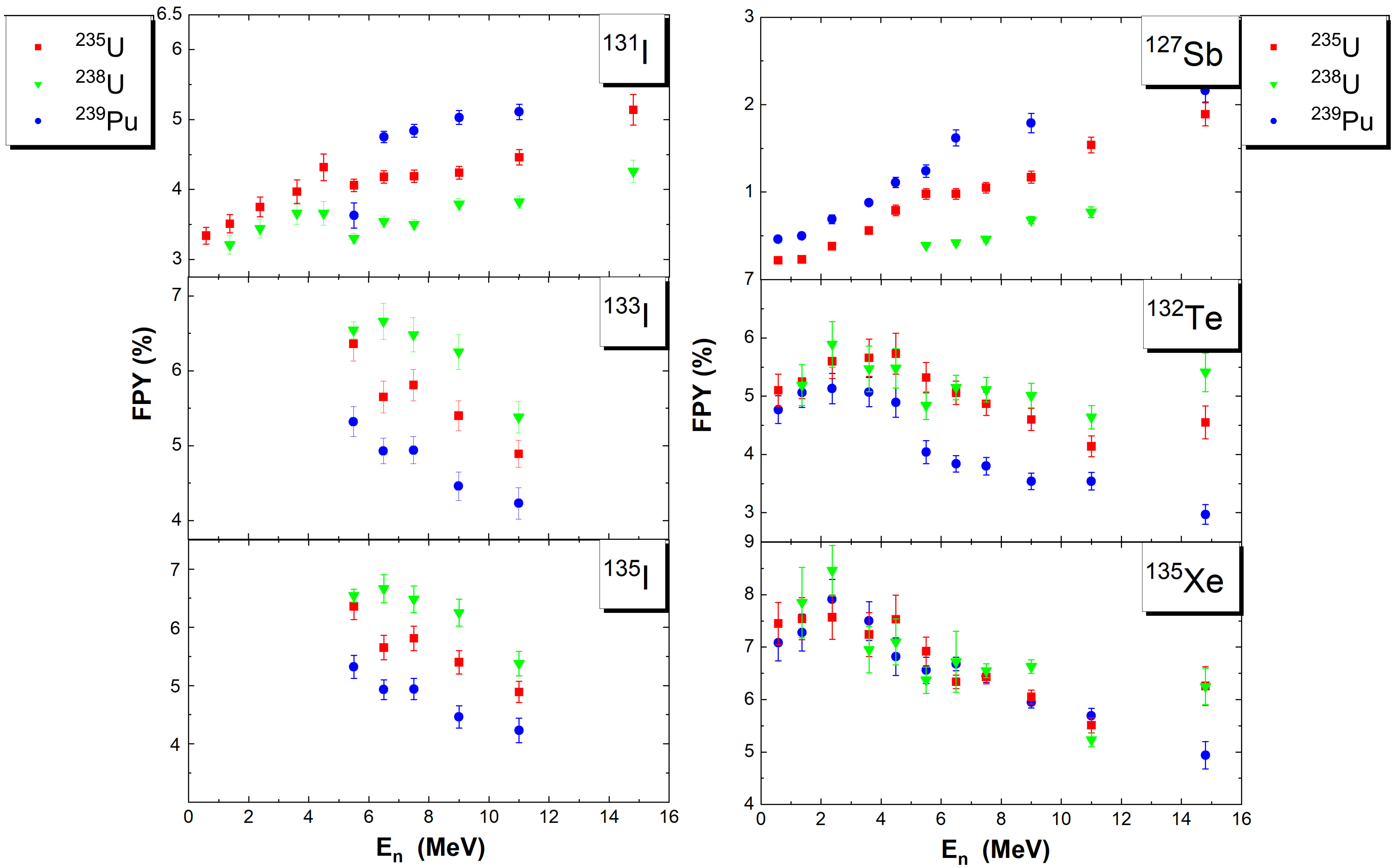
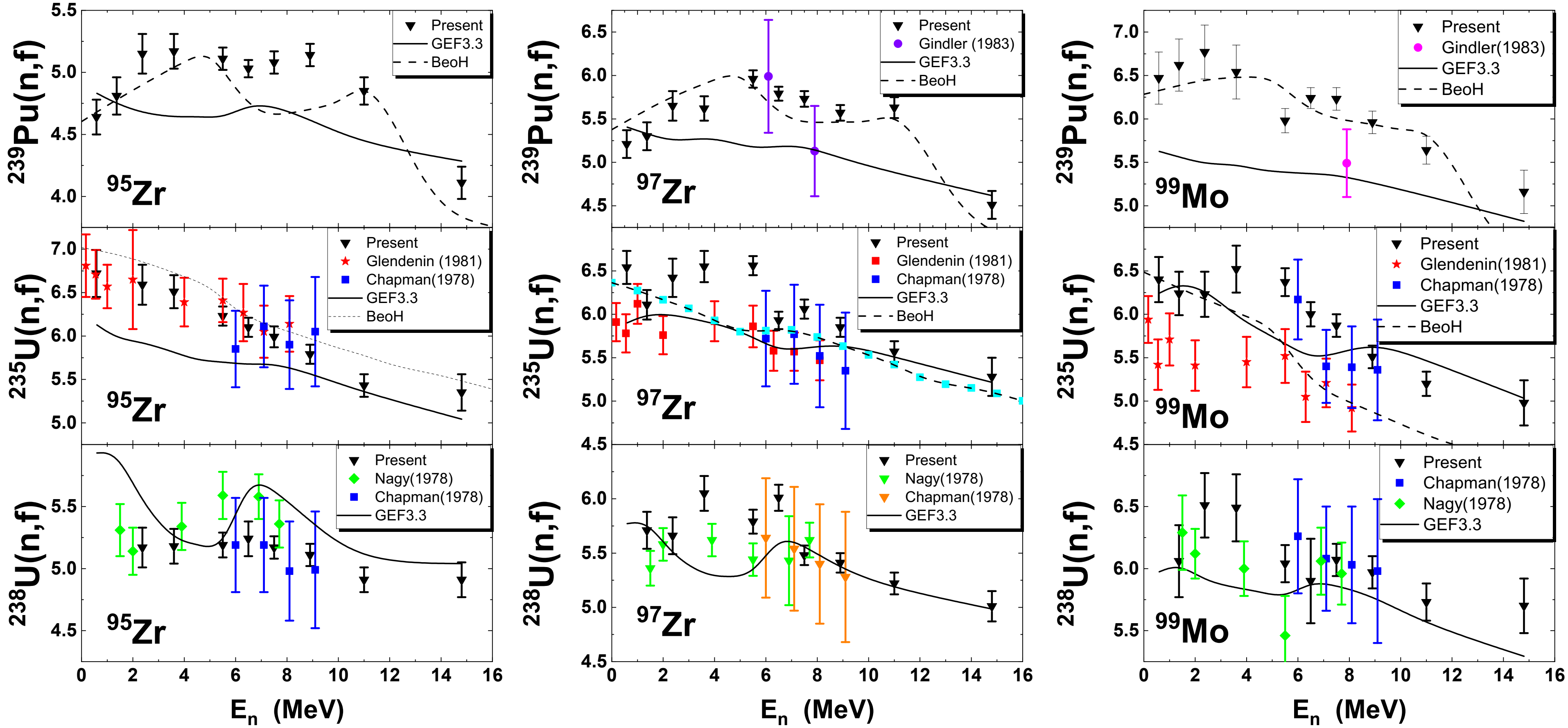


Comparison with GEF and BeoH



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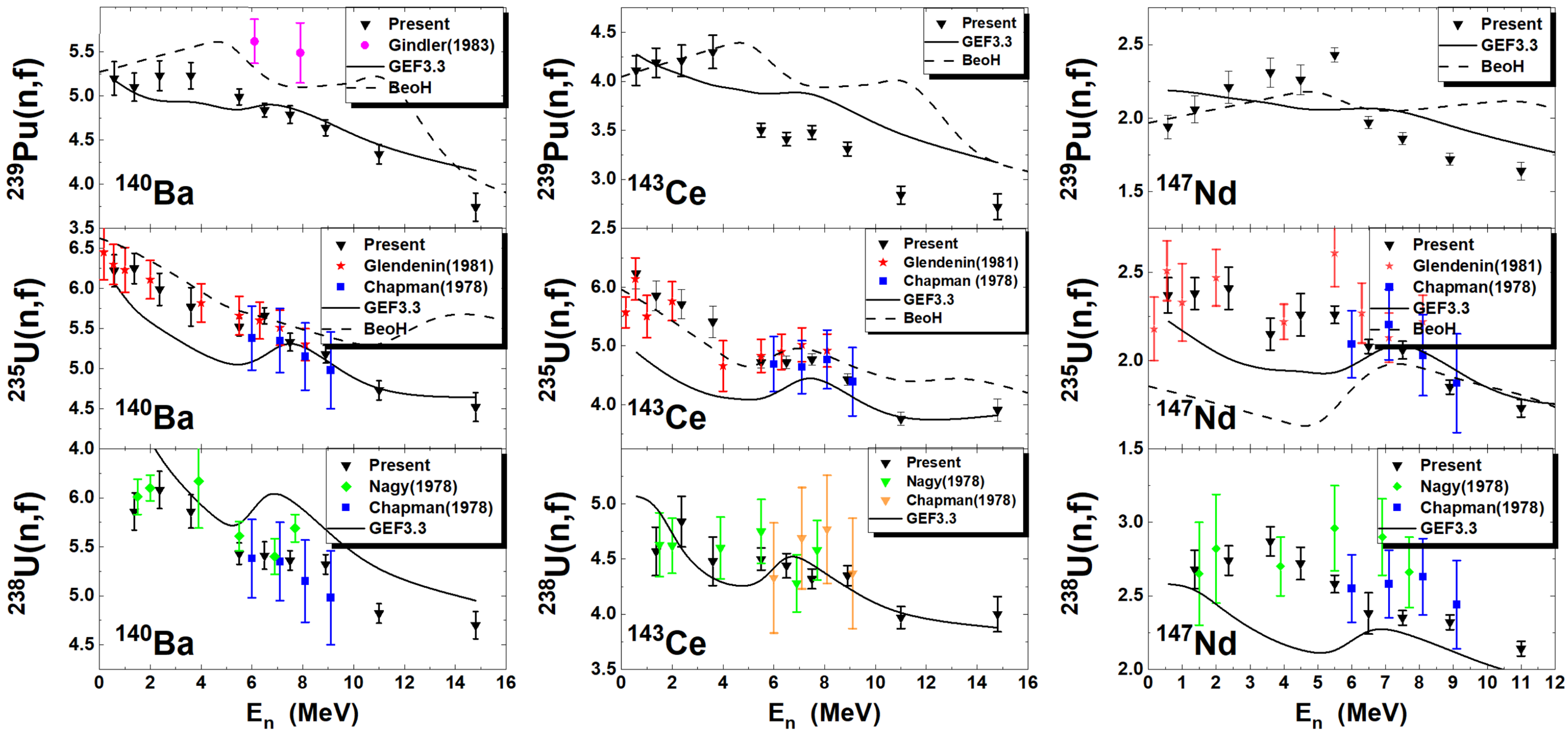
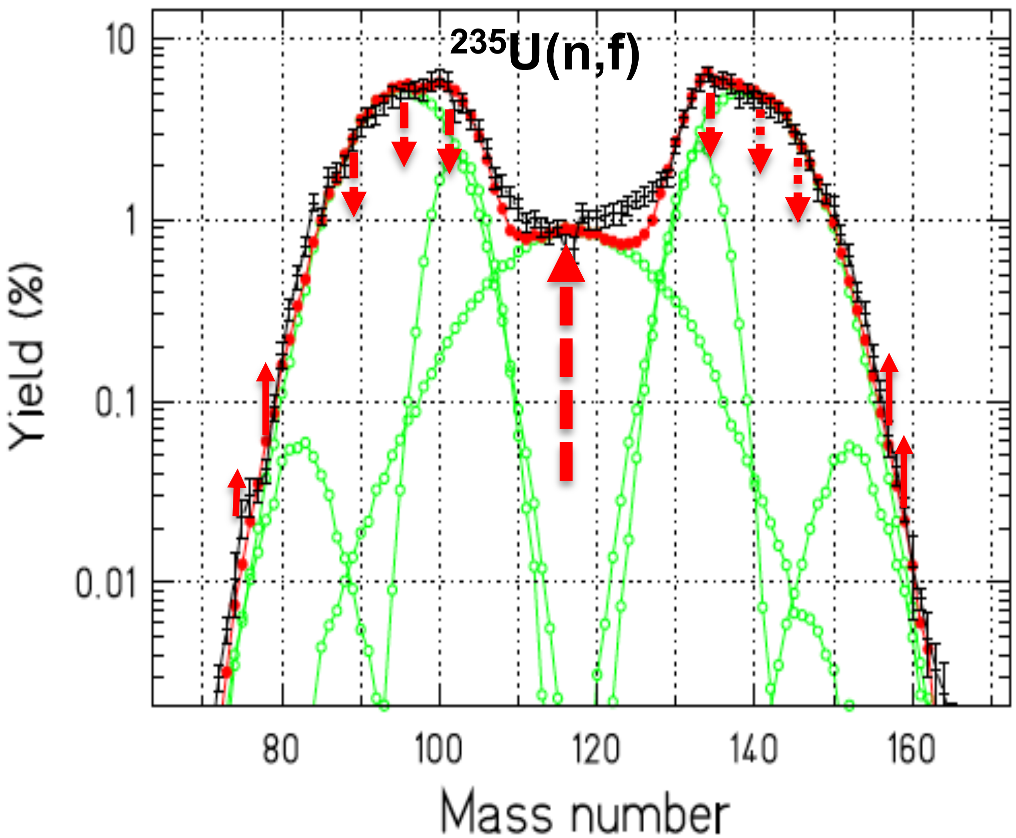


Fission Product Mass Distribution: What Have We Learned So Far?



At higher energies, 4 – 15 MeV:

All is consistent with what we know

- The symmetric FPYs steeply increase
- The two asymmetric FPY's slightly decrease
- The very asymmetric FPY's (the wings) slightly increase

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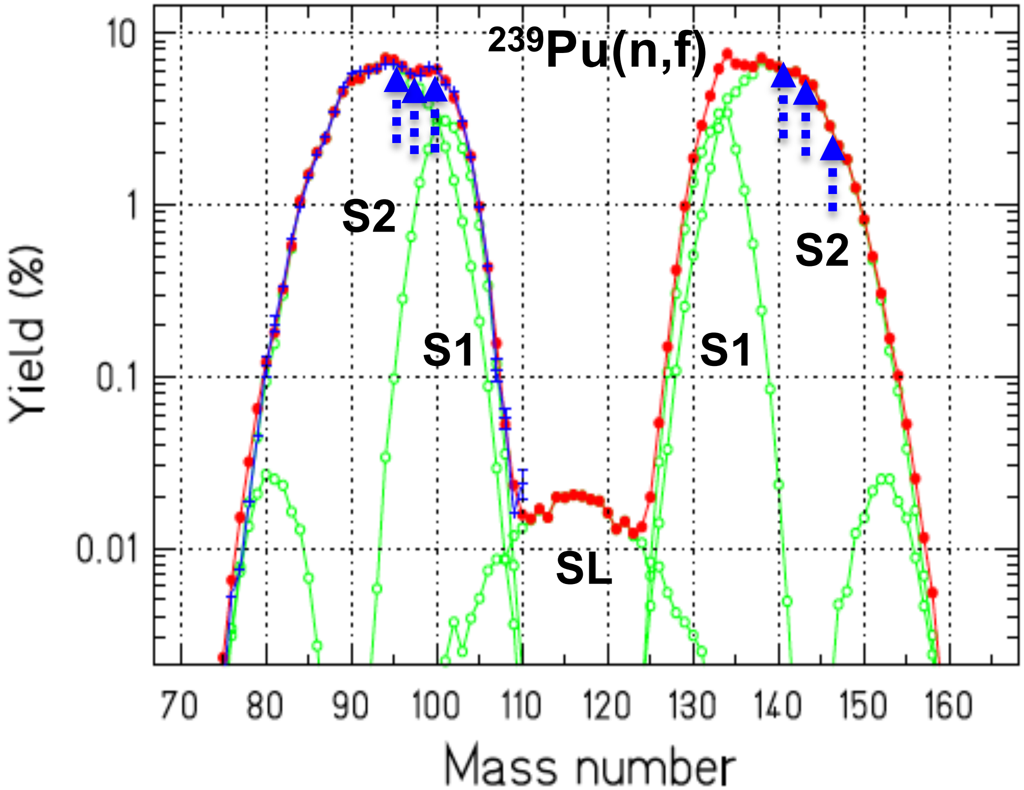


GEF 3.1 Calculations

At higher energies, 4 – 15 MeV:

All is consistent with what we know

- The symmetric FPYs steeply increase
- The two asymmetric FPY's slightly decrease
- The very asymmetric FPY's (the wings) slightly increase

At lower energies, 0.5 – 4 MeV:

- Some high yields from the two asymmetric mass distributions increase

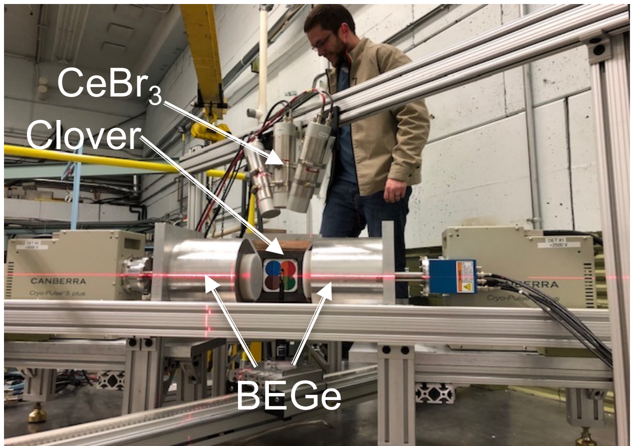
Expand the theoretical capabilities to understand the evolution of the FPY at low neutron energies

Short-Lived Fission Product Yield Data from Neutron-induced Fission on ^{235}U, ^{238}U, and ^{239}Pu

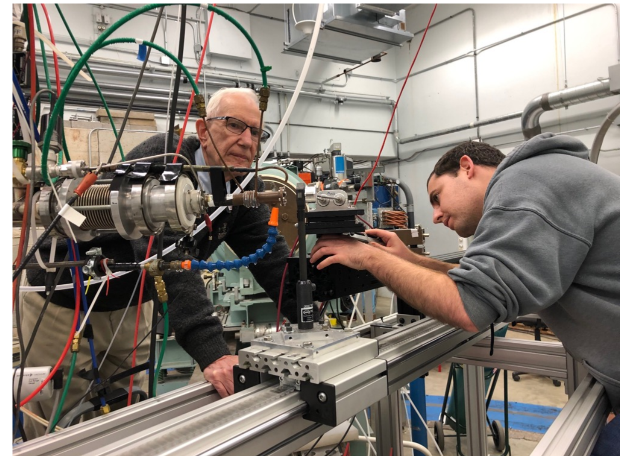
Measurement of Short-Lived Fission Products Using RABITTS

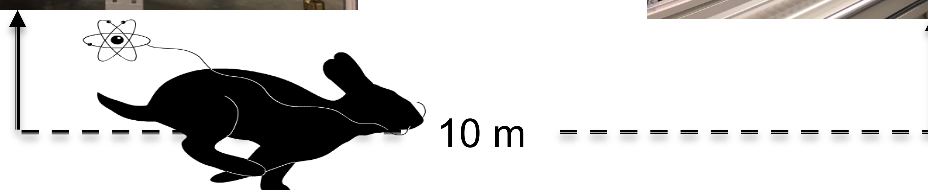
RApid
Belt-driven
Irradiated
Target
Transfer
System

Counting Area

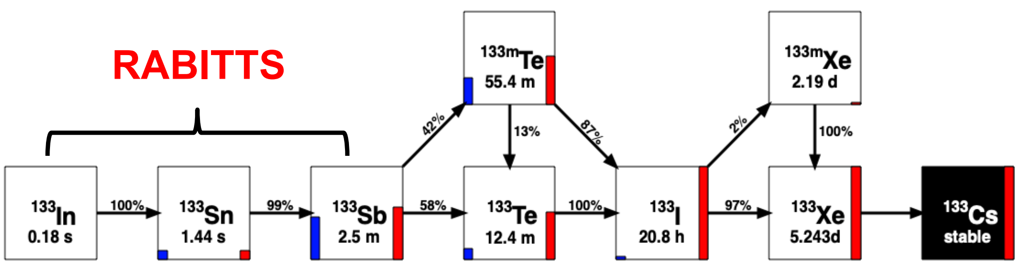


Irradiation Area





RABITTS

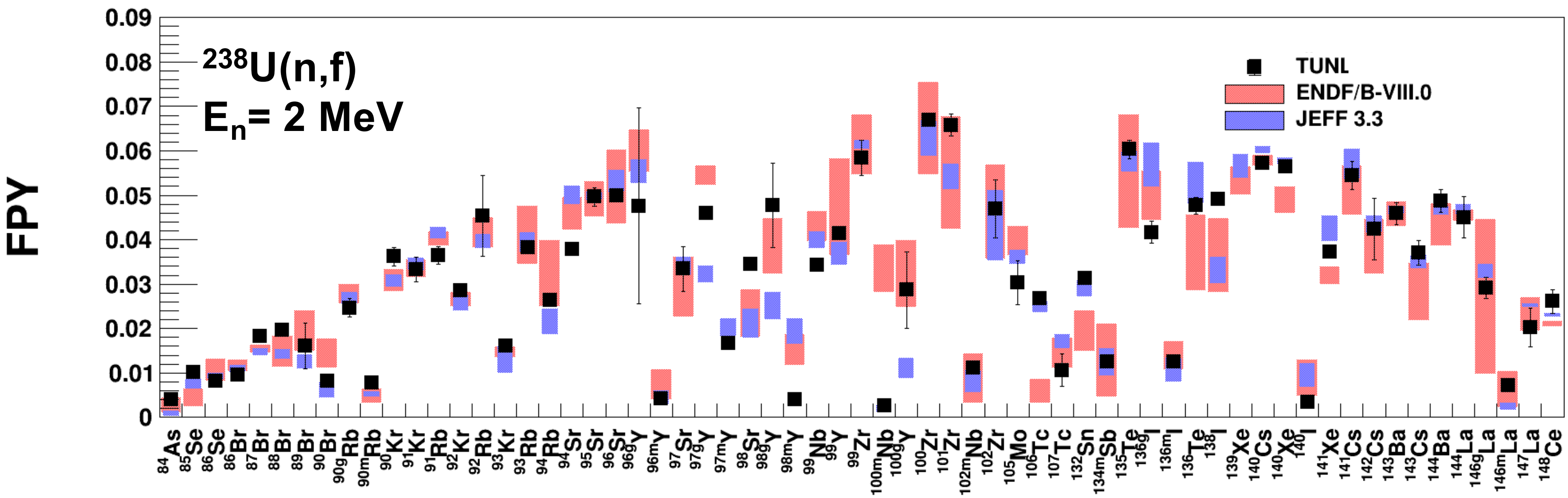


S. Finch *et al.* Nuc. Instrum. Meth A **1025**, 166127 (2022)

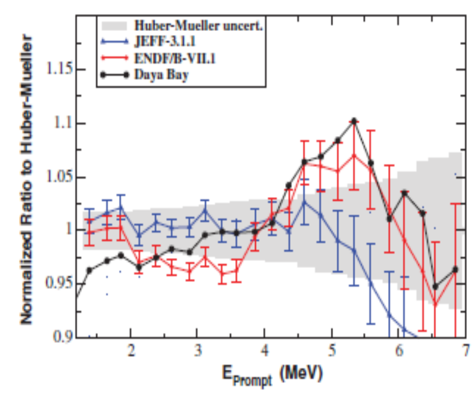
- Fully automated system moves targets between irradiation and counting positions
- Maximum speed 10 m/s
- FPY data for FPs with half-lives of sub-second to a few minutes
- Developed analytical methods to process complex gamma-ray spectra

Reaching the very short-lived fission product yields

FPYs from ^{238}U(n,f) to Support Reactor Anti-Neutrino Anomaly

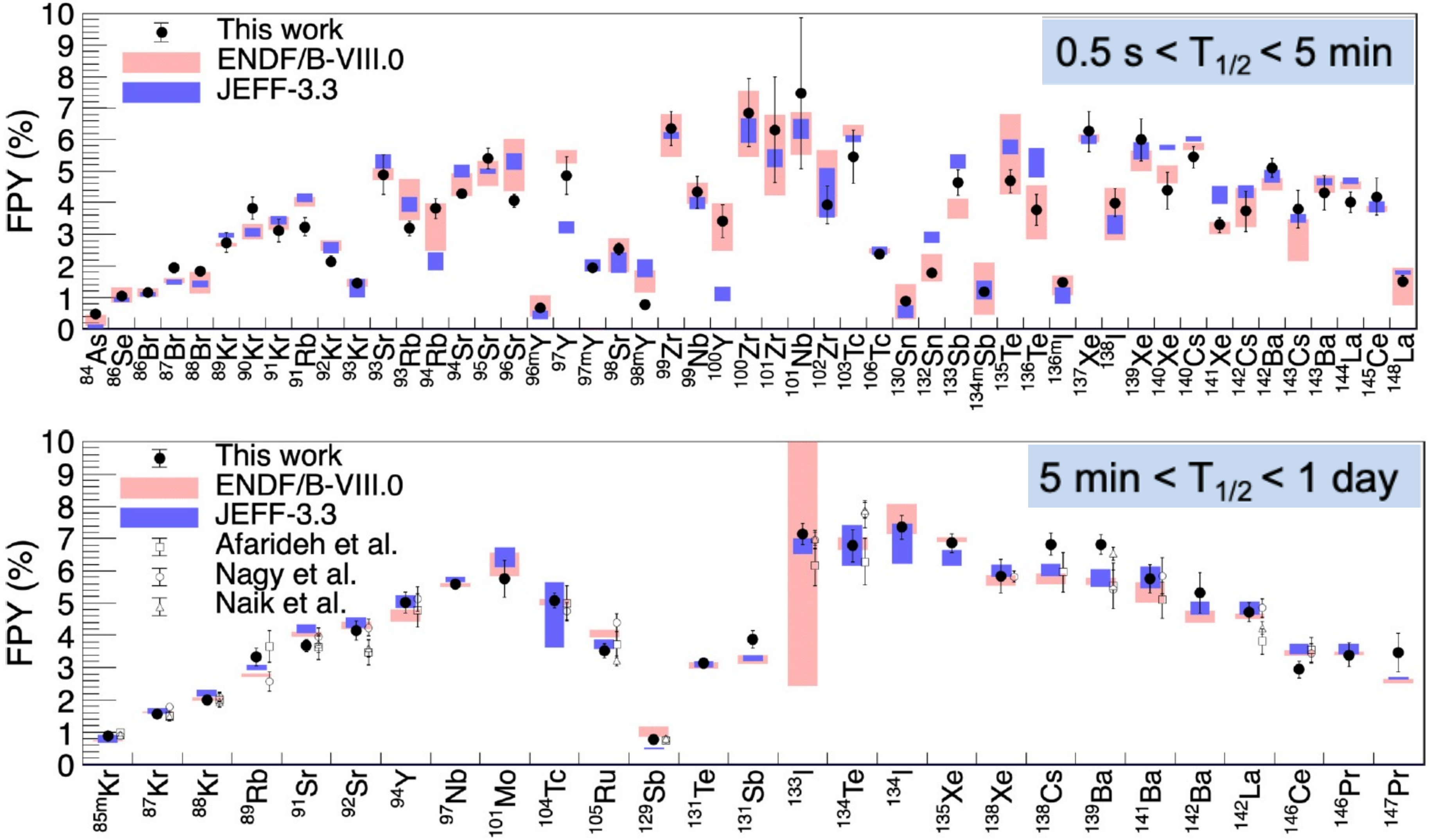


- 60 short-lived fission products with half-lives from seconds to minutes on ^{235}U, ^{238}U, and ^{239}Pu at E_n = 0.06, 0.5, 2.0, 4.6, 9.0, and 14.8 MeV
- Isomeric fission-yield ratios for a handful of fission products to support theory assessment on average fission fragments angular momentum
- Support nuclear data evaluation groups to identify the most important FPs contributing to the reactor anti-neutrino anomaly and the so called “bump”



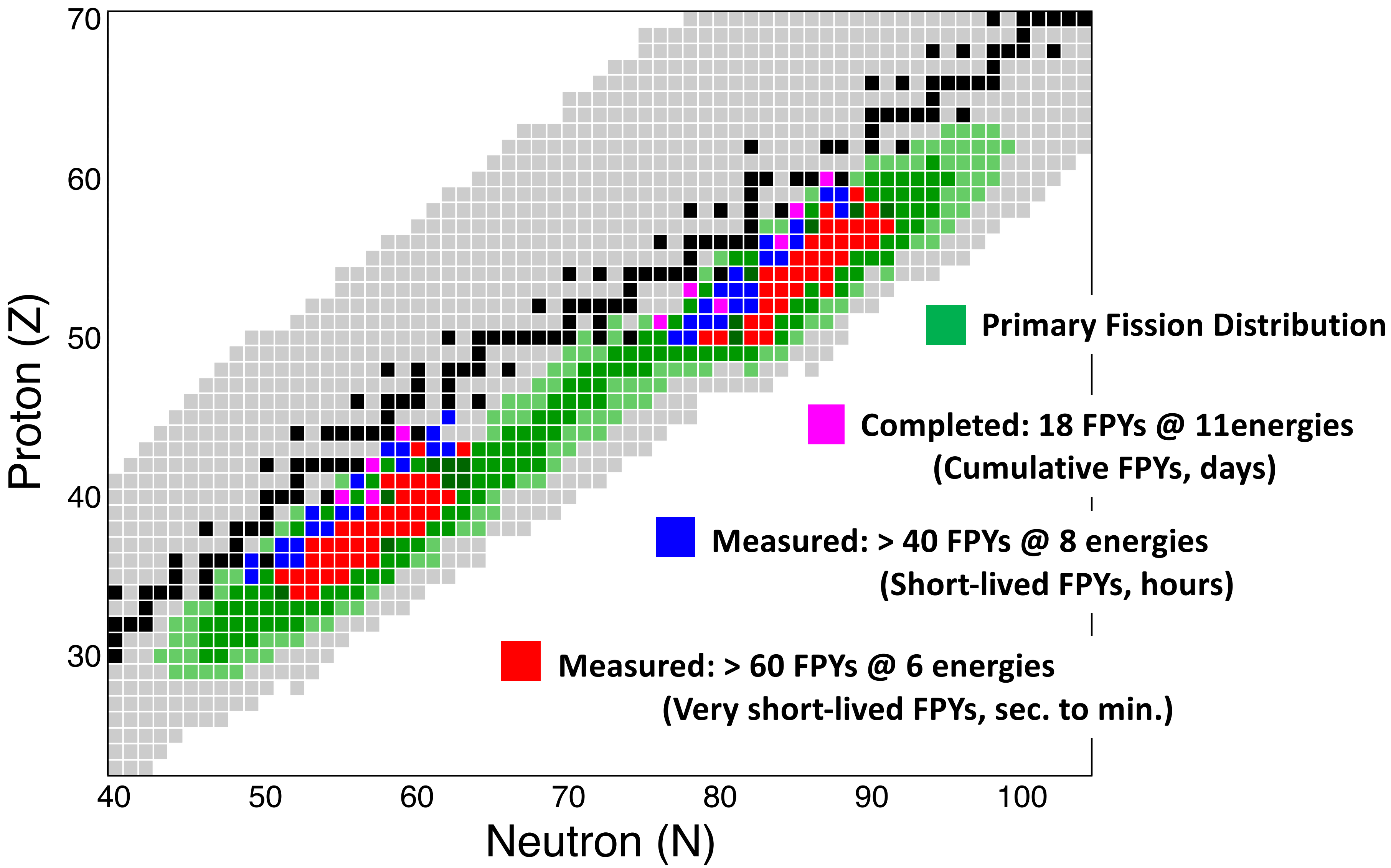
W. Tornow et al. prepared for publication

Short-Lived FPYs from ^{238}U(n,f) at E_n=4.6 MeV



A. Ramirez et al. **107**, 05408 (2023)

Summary: Fission Product Yield Real Estate Map



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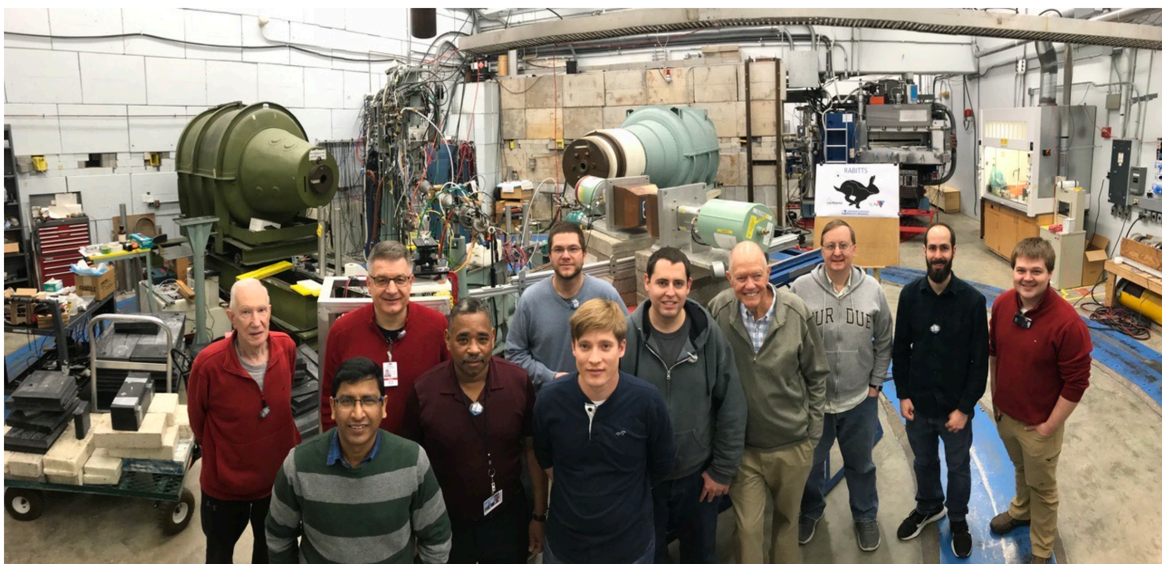

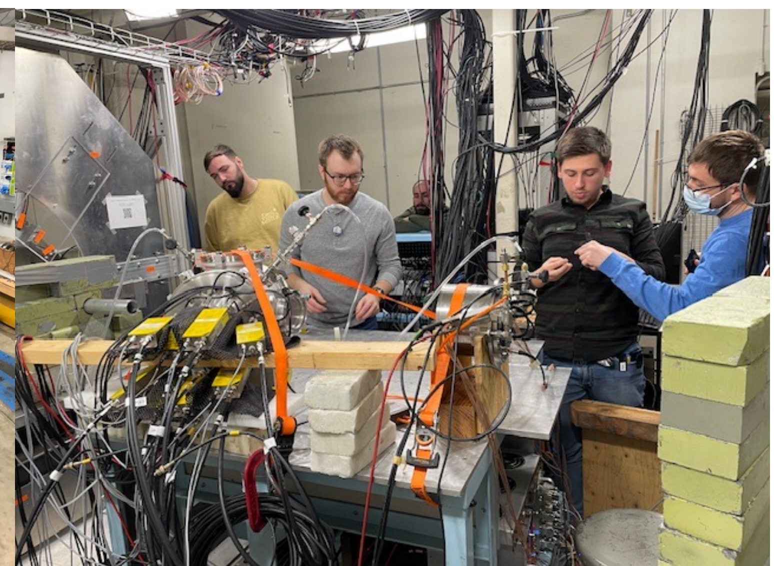

Strong Partnerships With Various Research Groups to Study Fission

Error estimation on the FPY Measurements:

Relative FPY Ratio

1. Statistical uncertainties of γ-ray peak counts (1-2%)
2. Relative HPGe detector efficiency (1-2% including the fit)

Absolute FPY energy dependency:

1. Statistical error of γ-ray peak counts (1-3%)
2. Absolute detector efficiency (2-3% including the fit)
3. Branching ratios (0.2 – 8% (^{147}Nd))
4. Absolute FC efficiency (3% experimentally, 0.5% simulation)
5. Kinematic focusing (up to 1.4%)
6. Isotopic corrections (0.2% for ^{239}Pu, larger for ^{235}U)
7. Low energy neutrons (<1%)
8. Neutron flux fluctuation correction (<0.3%)
9. Efficiency conversion ratio between close and standard geometry (<1%)
10. True coincidence summing (<1.5%)
11. Random coincidence summing (<0.2%)
12. Sample weight (<0.4%)
13. Self-absorption of γ-ray (0.3 – 3%)

Summary

- Our cumulative FPYs provide a comprehensive set of data from the three major actinides in the energy region from 0.5 to 15.0 MeV with small neutron energy steps
- The data analysis was significantly improved, reducing the overall uncertainties and providing more quantitative basis for evaluating of these cumulative FPY data
- We developed new capabilities to perform correlation measurements in fission in direct reactions that can be benchmarked with inverse kinematic measurements

We are in the midst of a fission renaissance!