Recent Results from Neutron- and Photo-Induced Fission

Anton Tonchev

FIESTA

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Los Alamos

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Outline

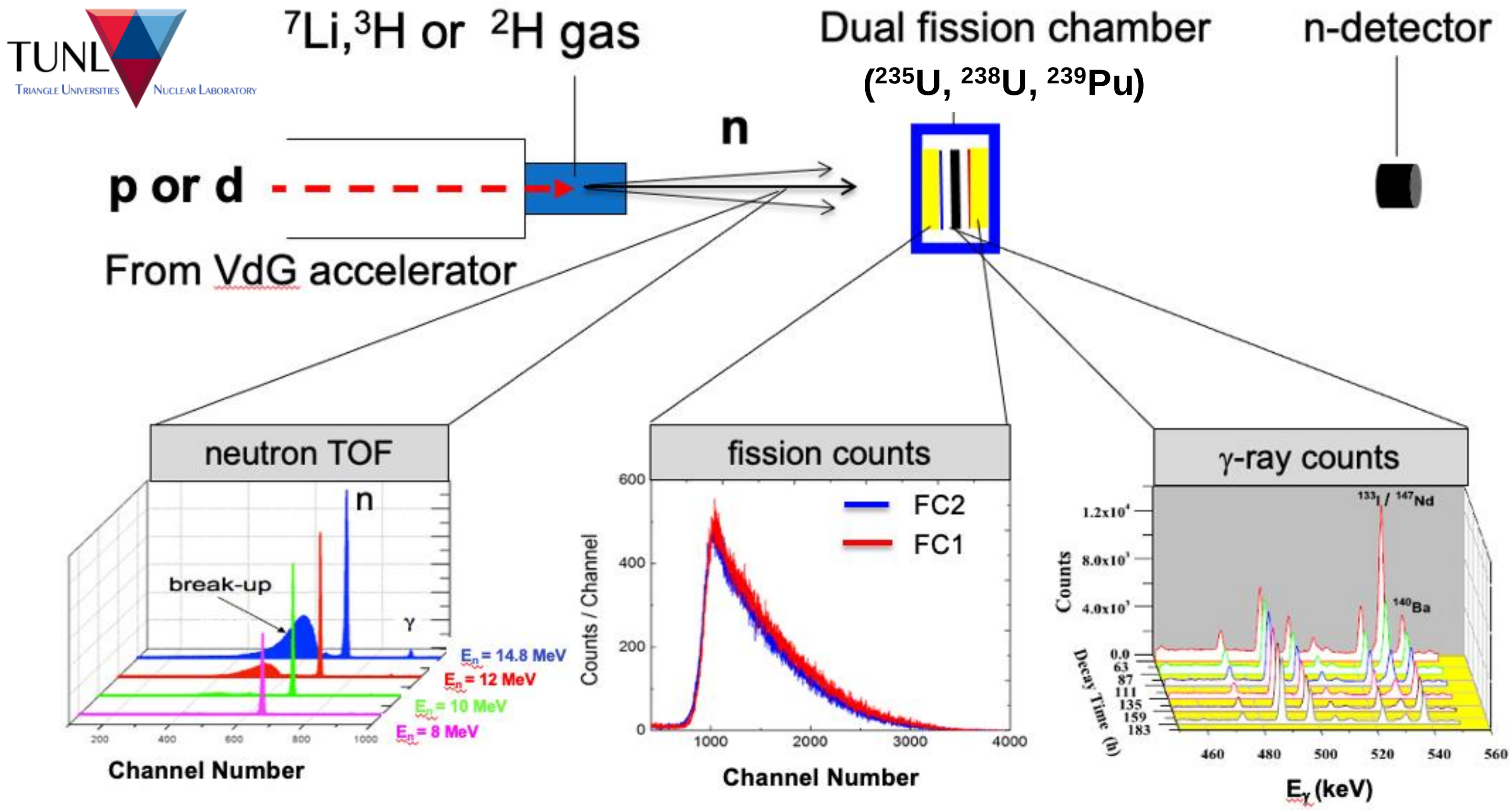
Motivation

Recent Experimental Studies and Results

- Cumulative fission-product yields from neutron induced fission on ^{239}Pu, ^{235}U, and ^{238}U
- Correlation measurements in direct and inverse reactions

Summary

Measurement of Long-Lived Fission Products Using Monoenergetic Neutron Beams

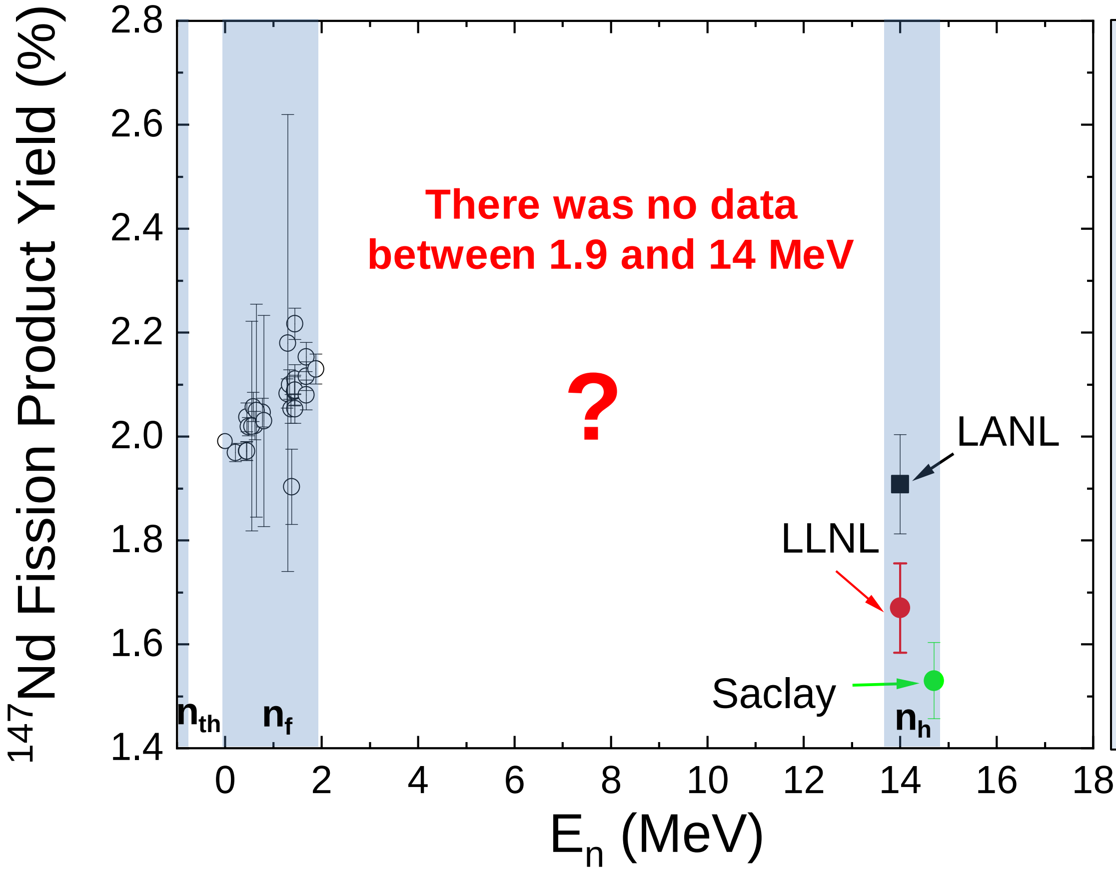


Fission Product Yield = N_X / N_{fis}

N_X = number of atoms of a specific fission product

N_{fis} = total number of fissions

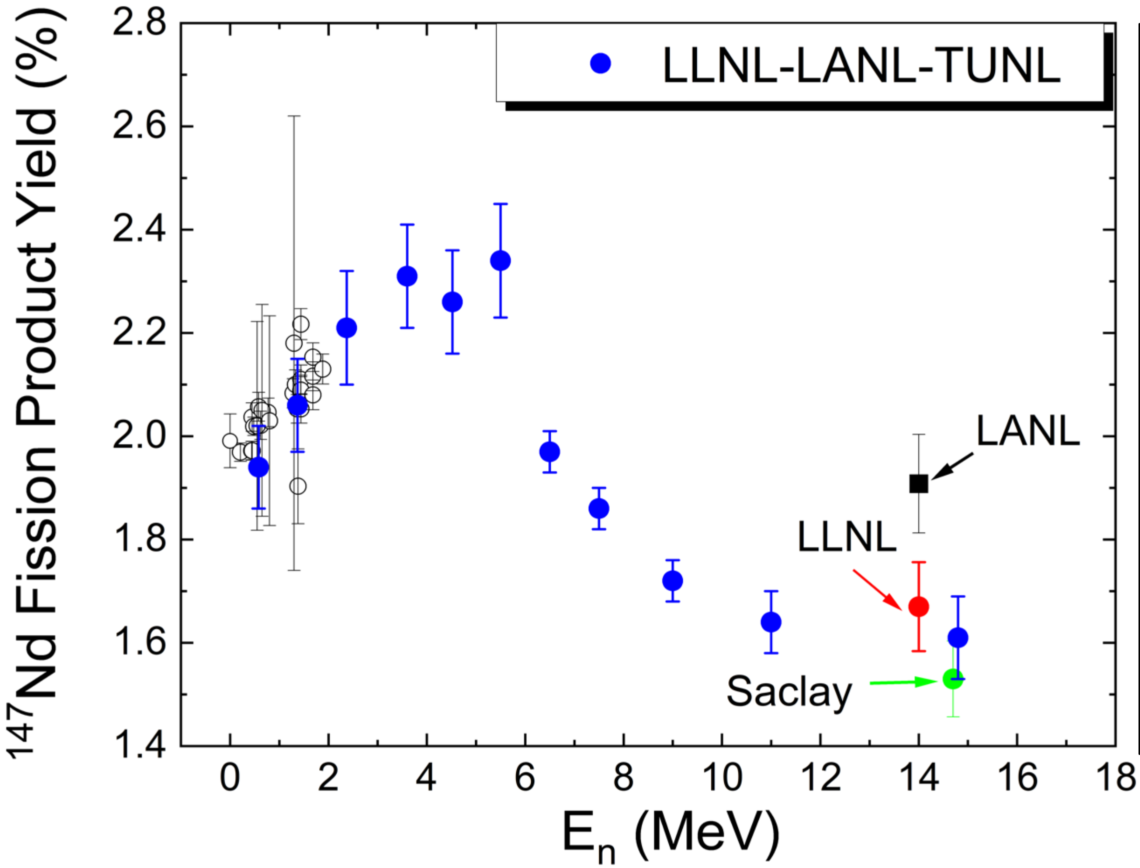
Motivational Factors: Luck of FPY Data in Broad Energy Intervals for the Major Actinide Isotopes



- 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 Result: ^{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:

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

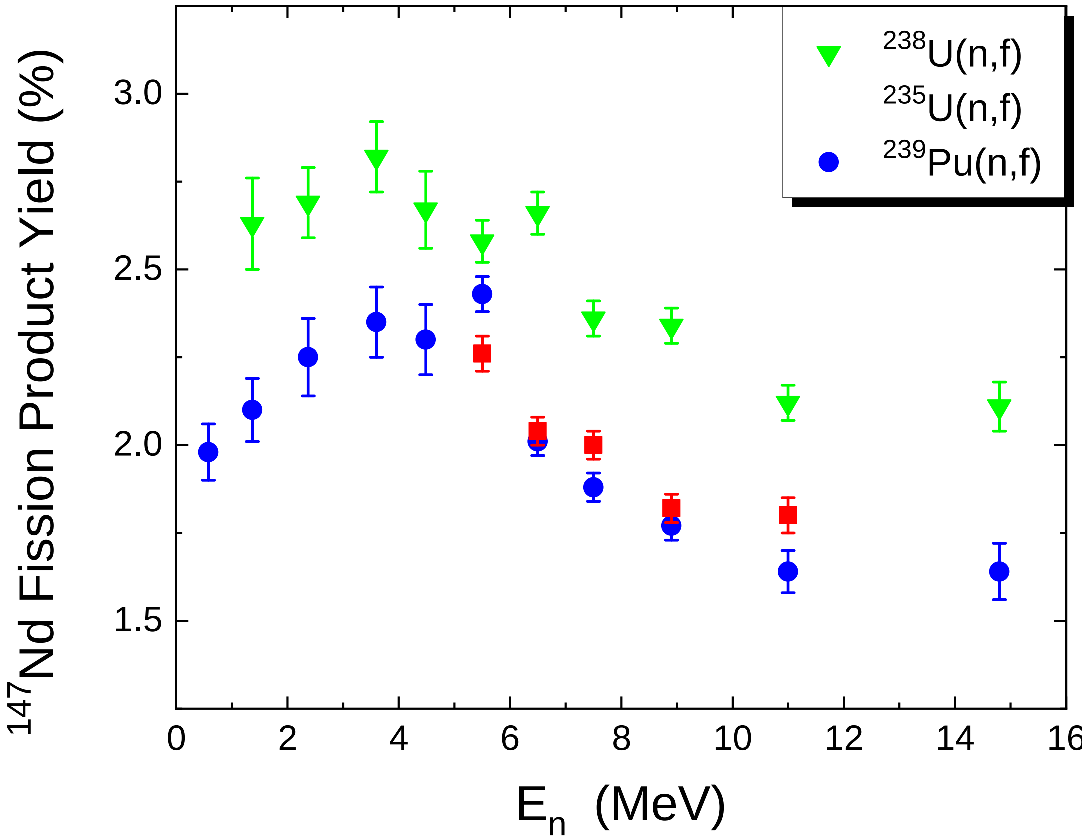
- At higher energies the FPY for ^{147}Nd turns over and decreases
- Compared to the FPY at 4.6 MeV, the FPY has decreased by 30% at 14.8 MeV

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)

New branching-ratio data for ^{147}Nd:

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

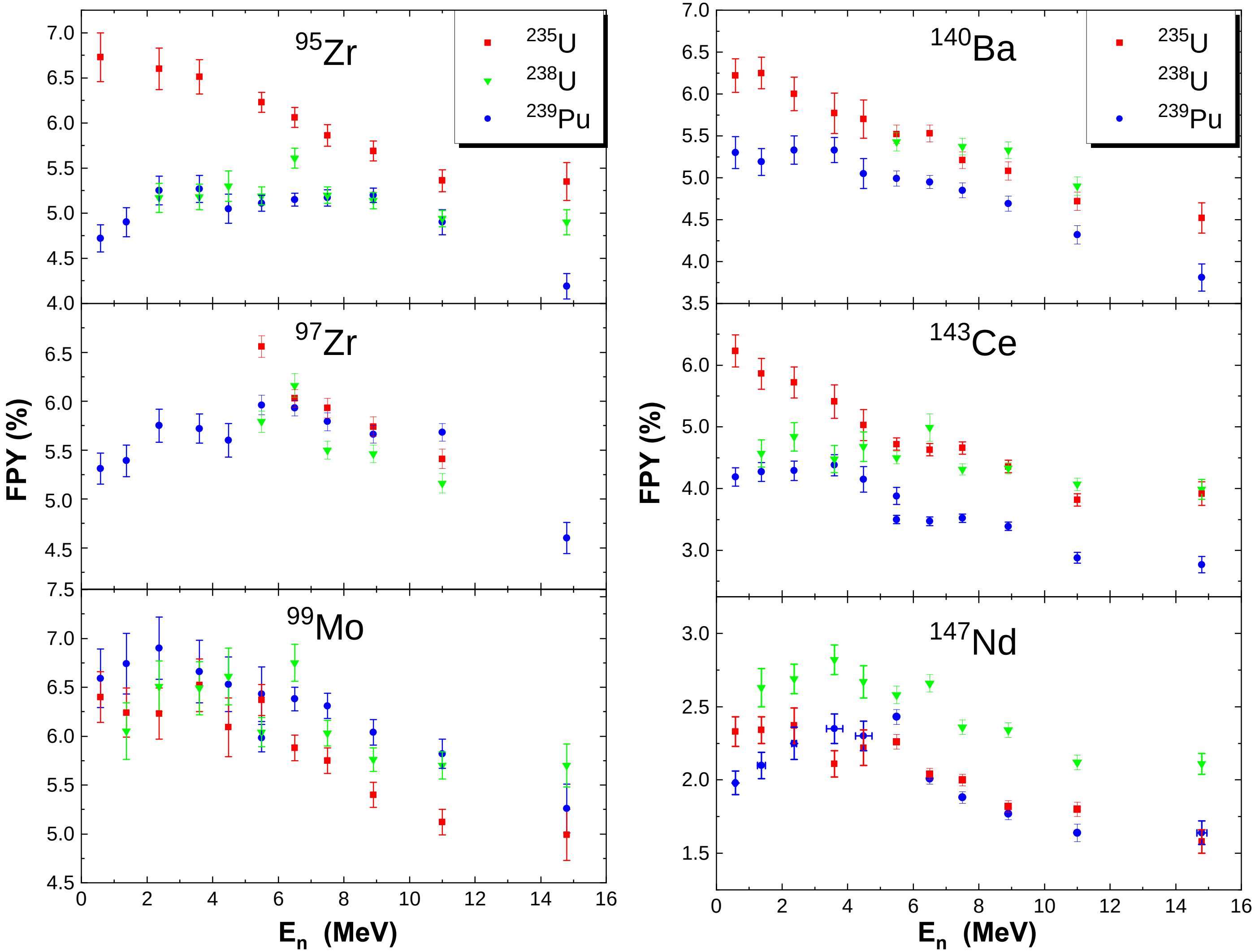
^{147}Nd FPY from Neutron-Induced Fission of ^{235}U, ^{238}U, and ^{239}Pu



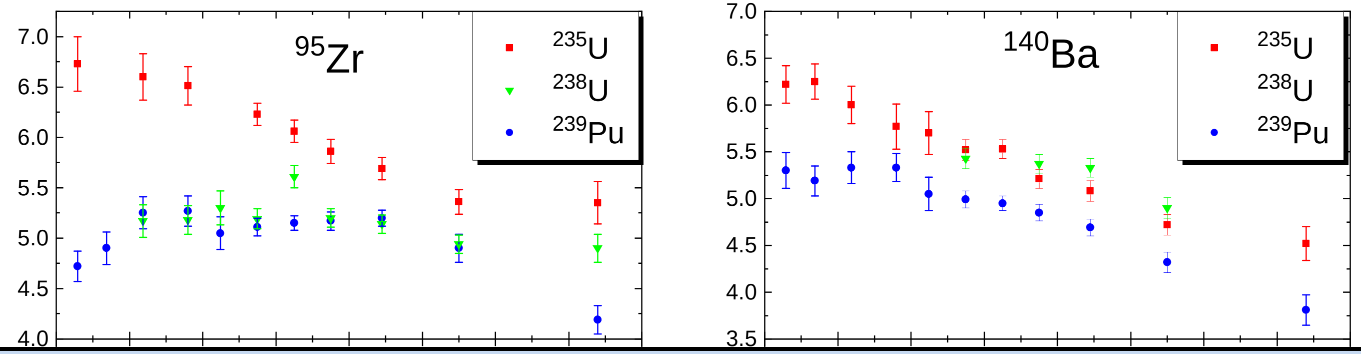
- The slope of ^{147}Nd FPY from ~5.0 to 14.8 MeV is negative in all three fissile actinides
- Combined with our previous ^{147}Nd FPY data this trend is consistent with FPYs toward 14.8 MeV energy
- Significant reduction in the total uncertainties of the present mid-energy data compared to our previously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

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

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



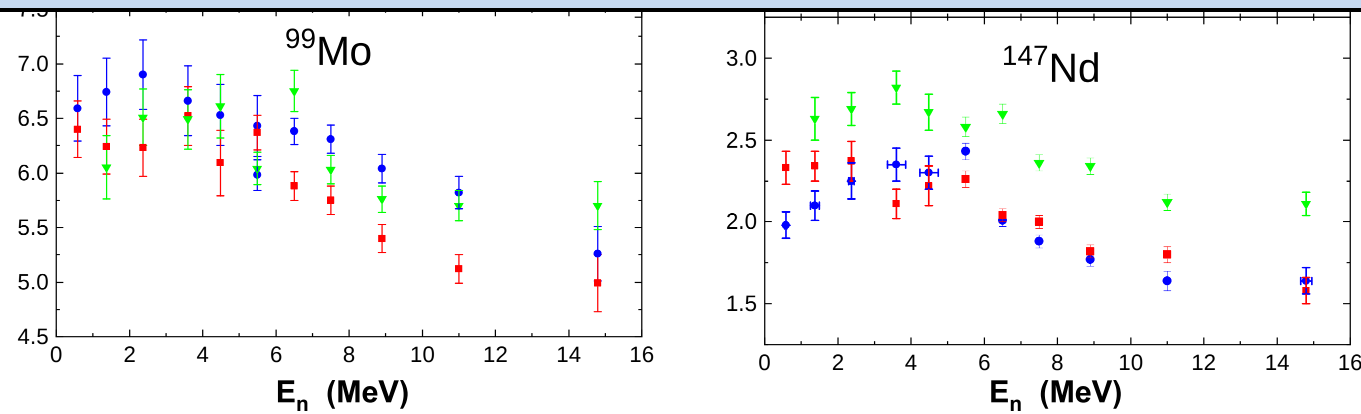
Fission Product Yields from $^{235,238}U(n,f)$ and $^{239}Pu(n,f)$



Total of 18 cumulative FPYs:

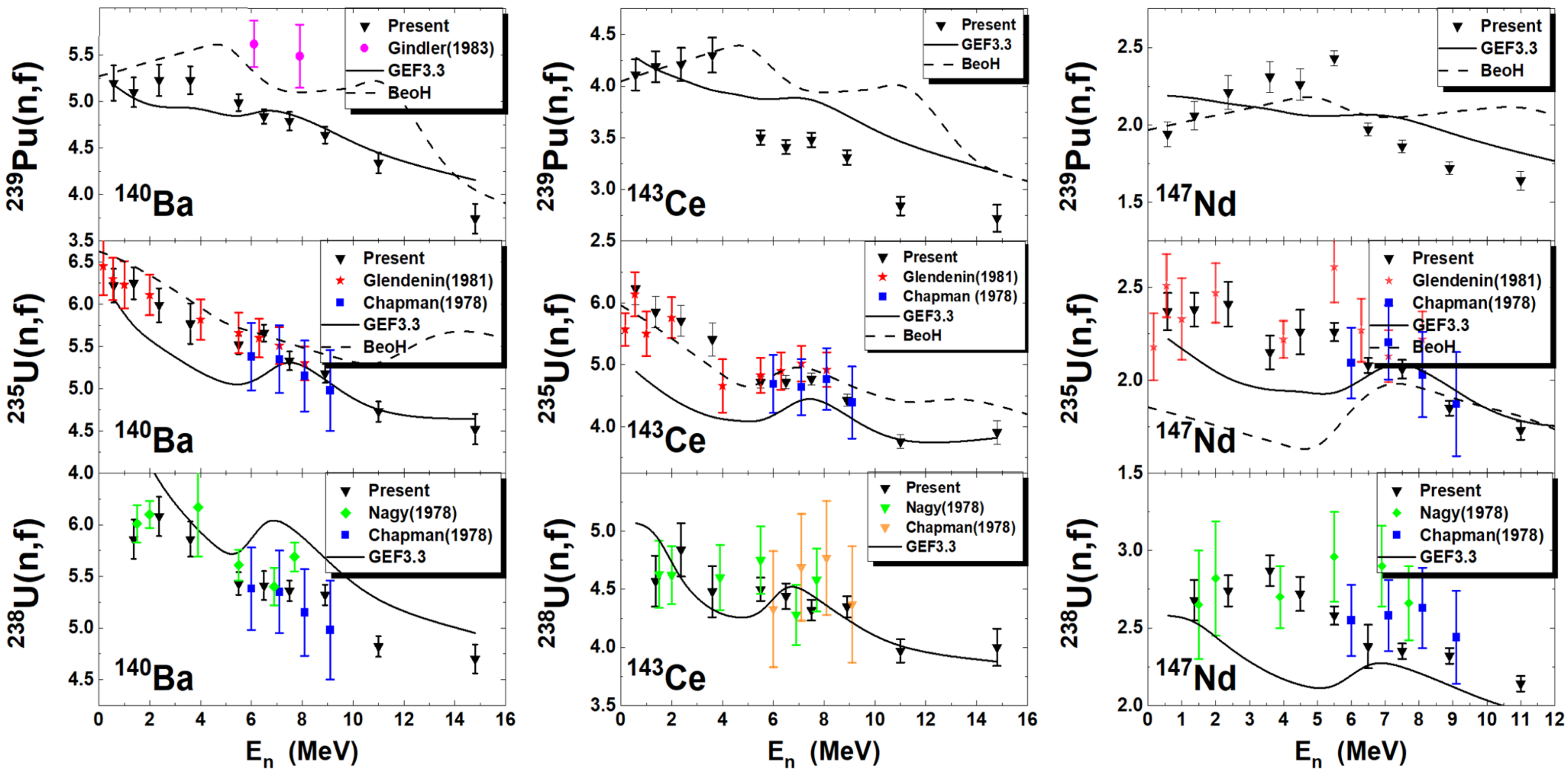
^{91}Sr, ^{92}Sr, ^{95}Zr, ^{97}Zr, ^{99}Mo, ^{103}Ru, ^{105}Ru, ^{127}Sb, ^{131}I, ^{132}Te, ^{133}I, ^{135}I, ^{135}Xe, ^{136}Cs, ^{140}Ba, ^{143}Ce, ^{144}Ce, and ^{147}Nd

have been measured



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

Comparison with GEF and BeoH

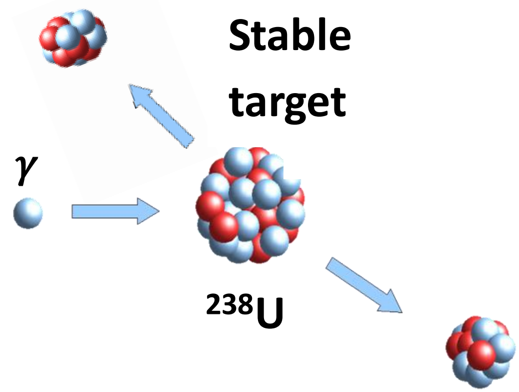


A.E. Lovell, T. Kawano, *et al*. Phys. Rev. C **103**, 014615 (2021)
A.E. Lovell, T. Kawano, *et al.* EPJ Web of Conferences **284**, 04015 (2023)
K.H. Schmidt, *et al*., Nuclear Data Sheets **131**, 107 (2016)

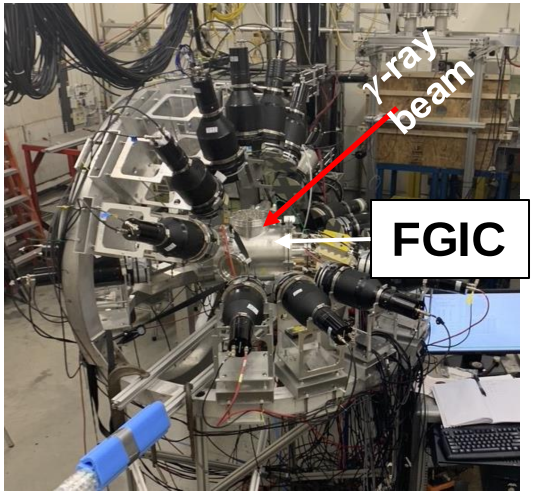
Benchmark Inverse Kinematics Fission Observables in $^{238,239}U$ with Direct Reactions Measurements

Direct reactions at HIGS:

- Stable target
- Slow-moving fragments
- $^{234,238}U(\gamma,f)^{234,238}U$
- Monoenergetic photon beams: $6.2 \leq E_{\gamma} \leq 13$ MeV
- Frisch-grid IC surrounded with an array of neutron and γ-ray detectors

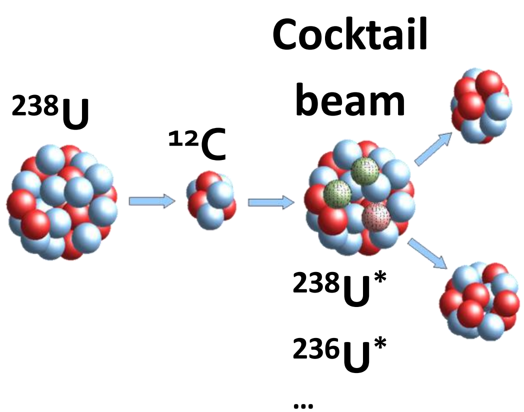


HIGS

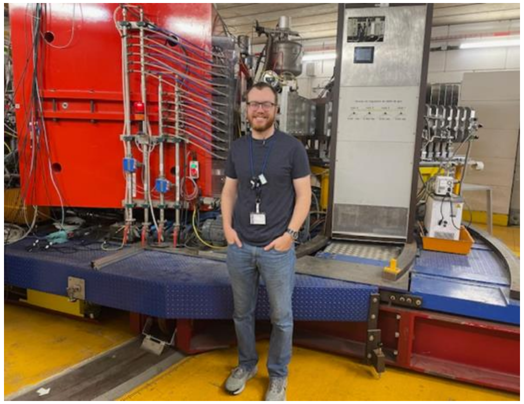


Inverse reactions at GANIL:

- Radioactive cocktail beam of “targets”
- Fast-moving fragments
- ^{236}U and ^{240}Pu
- VAMOS spectrometer with new PISTA dE/E telescope array
- PISTA array allows determination of the excitation energy to ~ 1 MeV

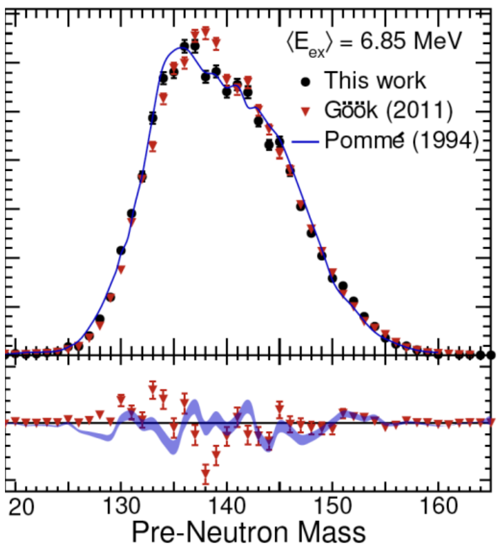


GANIL



HIGS Experiment Results From $^{238}U(\gamma,f)$: Fission Product Yield Mass Distribution

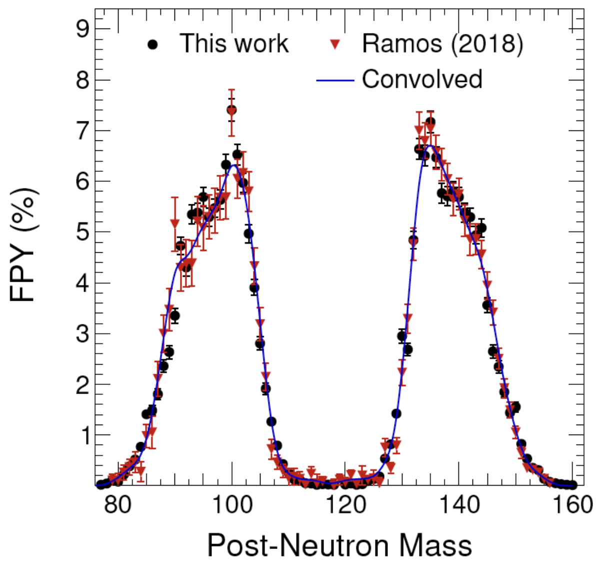
Compared to bremsstrahlung



Pre-neutron FPY mass distribution at $\langle E_{ex}\rangle$ = 6.85 MeV

Gook *et al.* NPA, 851 (2011)

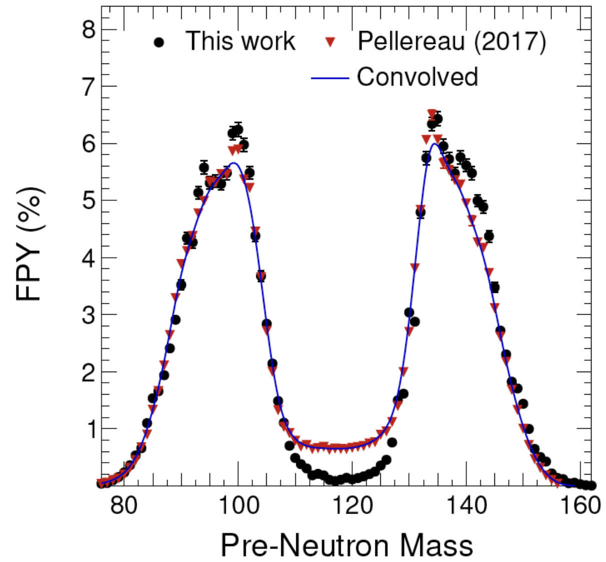
Compared to VAMOS



Pre-neutron FPY mass distribution at $\langle E_{ex}\rangle$=7.5 MeV

Ramos *et al.* PRC 97, 054612 (2018)

Compared to SOFIA

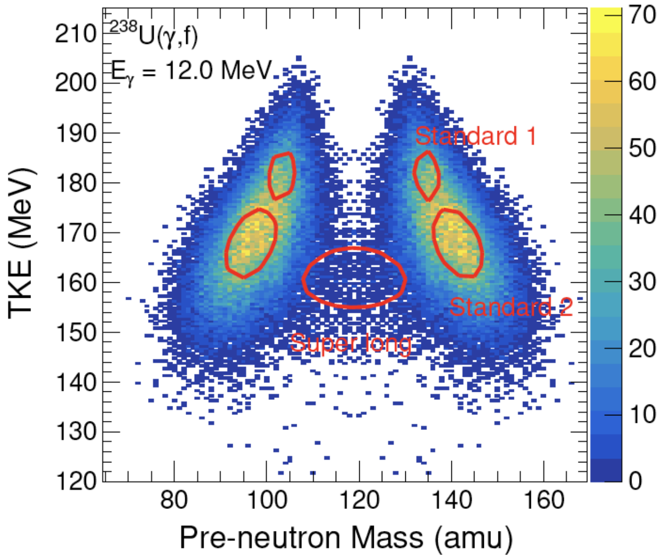


Pre-neutron FPY mass distribution at $\langle E_{ex}\rangle$= 12.2 MeV

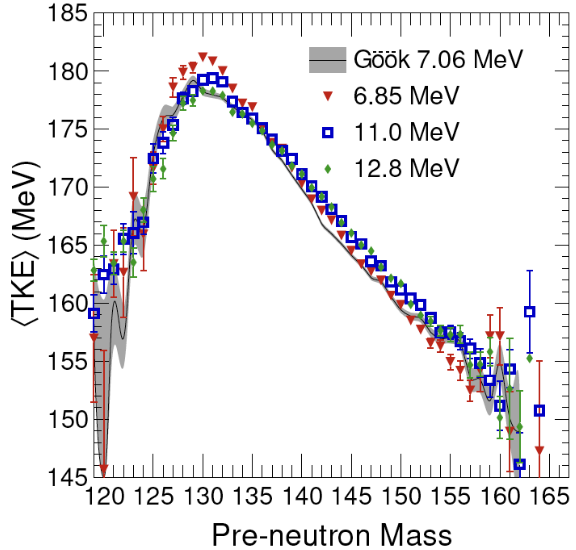
Pellereau *et al.* PRC 95, 054603 (2017)

R. Malone et al. Paper in preparation

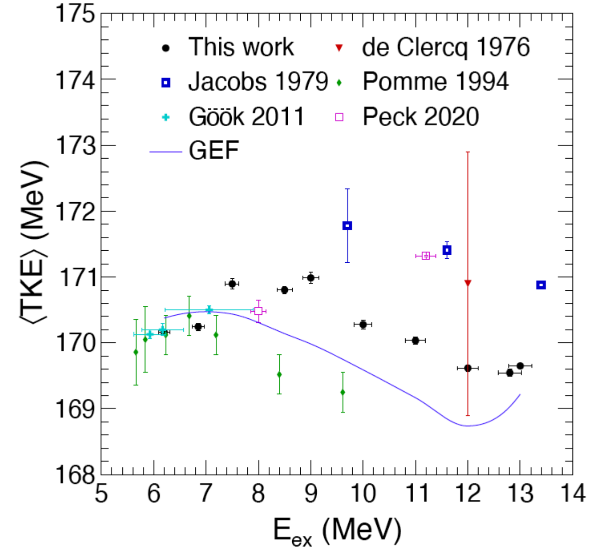
HIGS Experiment Results From $^{238}U(\gamma,f)$: Average Total Kinetic Energy Distribution <TKE>



Full fragment TKE vs. mass distribution at E_γ = 12 MeV



Average TKE vs. mass distributions at E_γ=6.85, 11.0 and 12.8 MeV

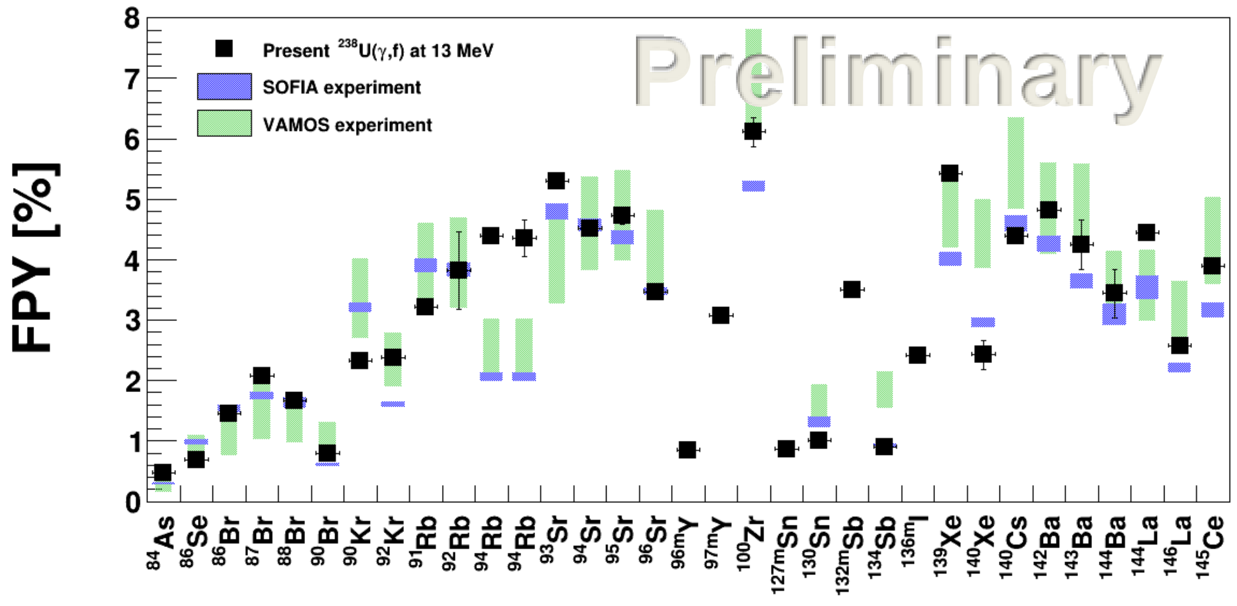


Pre-neutron <TKE> distribution as a function of excitation energy

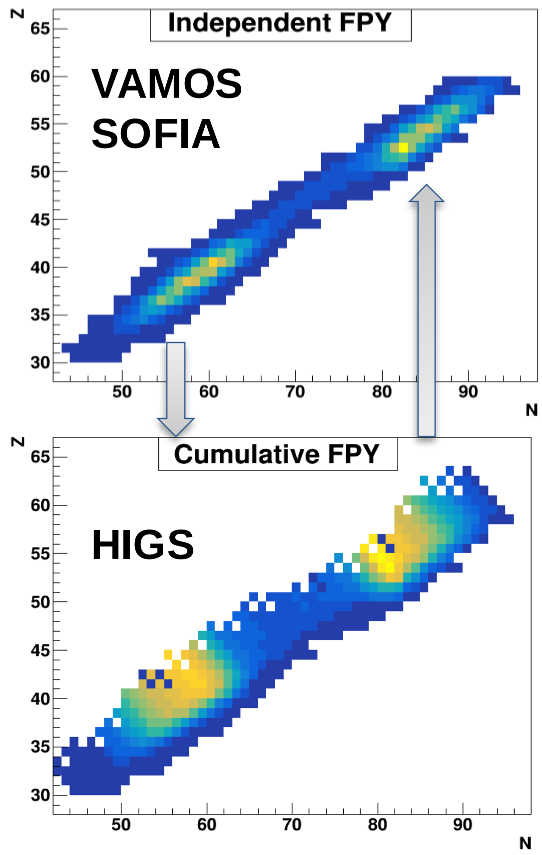
R. Malone et al. Paper in preparation

Comparison between HIGS cumulative and SOFIA independent FPY measurements

Completed data collection at HIGS on ^{235}U, ^{238}U, and ^{239}Pu at $E_\gamma = 13$ MeV



I. Tsorxe *et al*. Paper in preparation



VAMOS 2018: Ramos *et al*. PRC **97**, 054612 92018)
SOFIA 2017: Pellereau *et al*. PRC **95**, 054603 (2017)

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!

Acknowledgements

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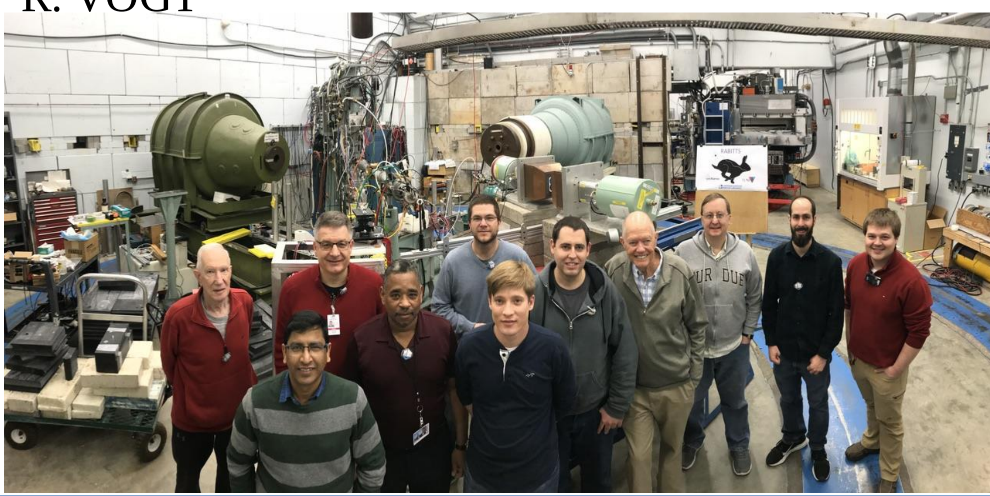
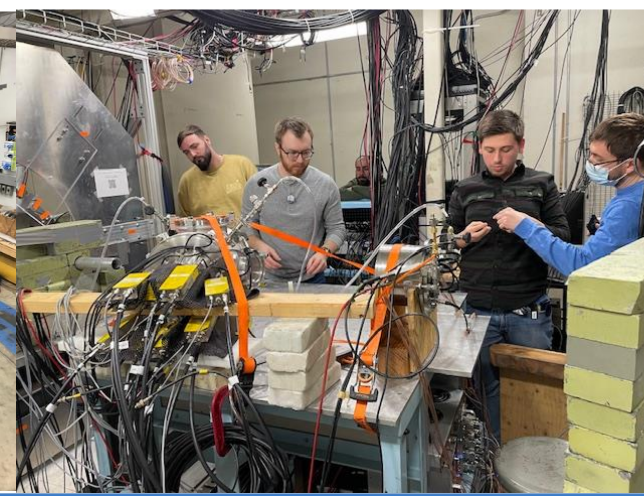
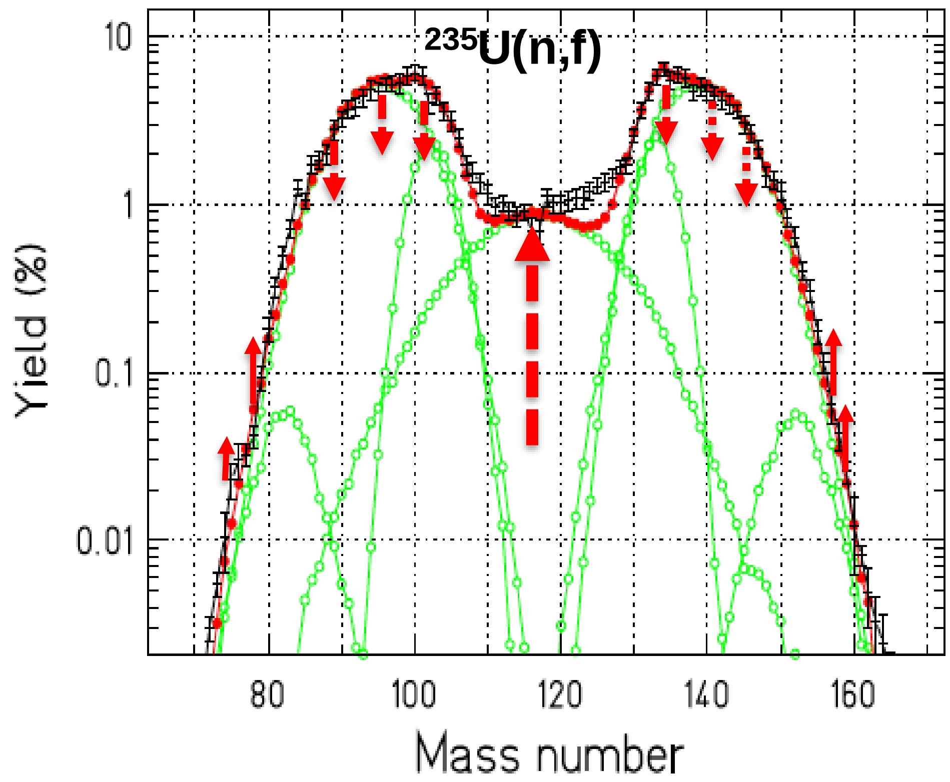
A. CHATILLON
B. MAUSS
C. LENAIN
A. LEMASSON (GANIL)

Strong Partnerships With Various Research Groups to Study Fission

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

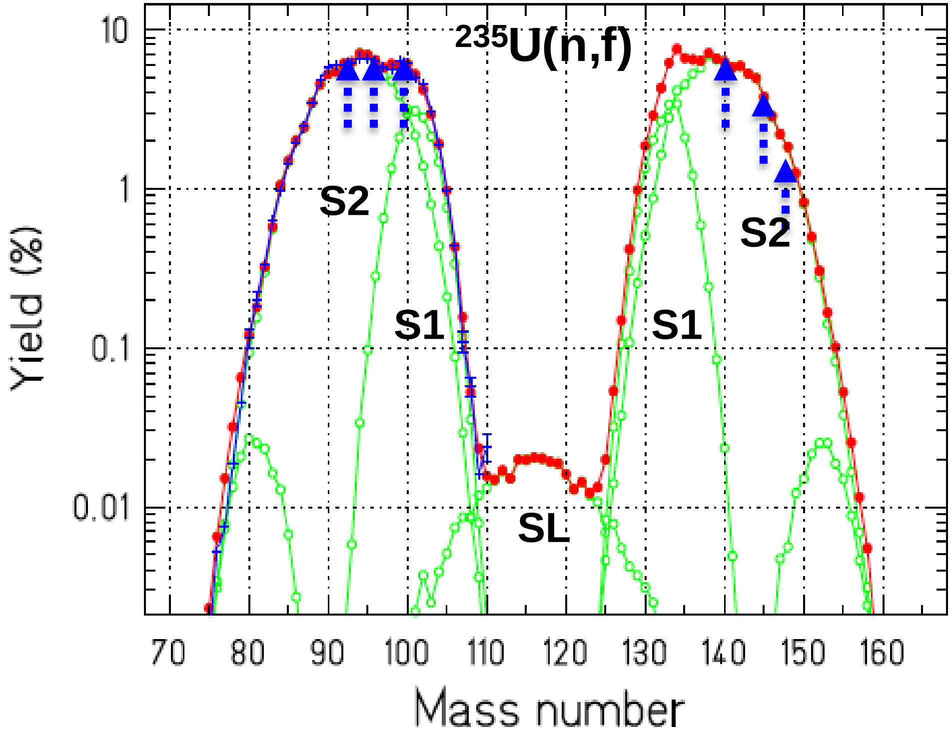


At higher energies, 4 – 15 MeV:

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

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



GEF 3.3 Calculations

At higher energies, 4 – 15 MeV:

All is consistent with what we know

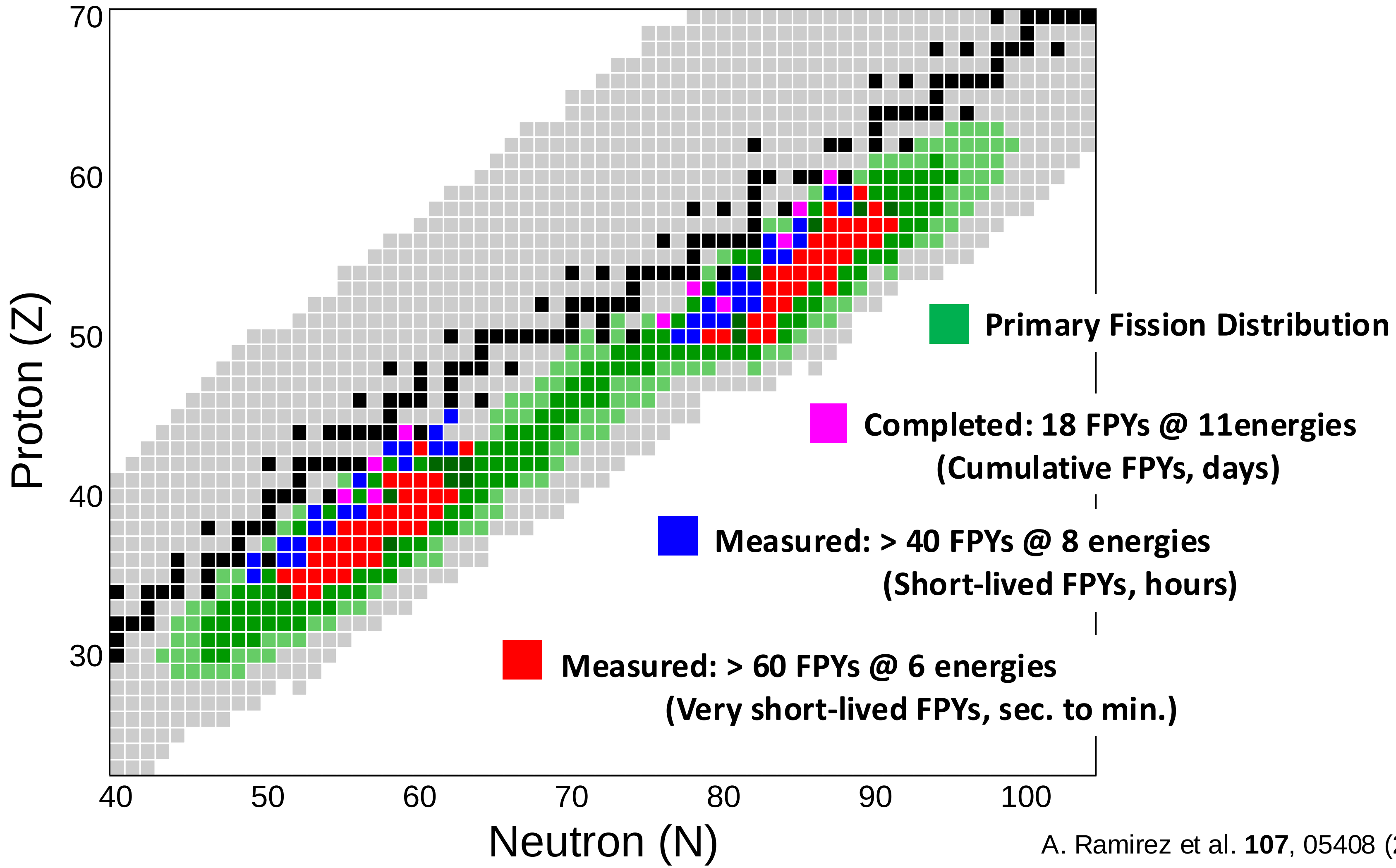
- The symmetric FPYs steeply increase
- The two asymmetric FPY's slightly decrease
- The very asymmetric FPY's (the wings) slightly increase

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

Summary: Fission Product Yield Real Estate Map



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

We are in the midst of a fission renaissance!

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%)