LA-UR-23-21969

Approved for public release; distribution is unlimited.

Title: Measurements of Independent Fission Product Yields

Author(s): Duke, Dana Lynn; Snyder, L.; Montoya, Kristina Brown; Connolly, Devin Sean; Greife, Uwe; Latta, J.; Lyons, S.; Wood, L.; Fulsom, B.; Moore, M.

Intended for: Workshop on Applied Nuclear Data Activities, 2023-02-27/2023-03-02 (Crystal City, Virginia, United States)

Issued: 2023-02-27

LA-UR-xxxxxxxxxxx

Measurements of Independent Fission Product Yields

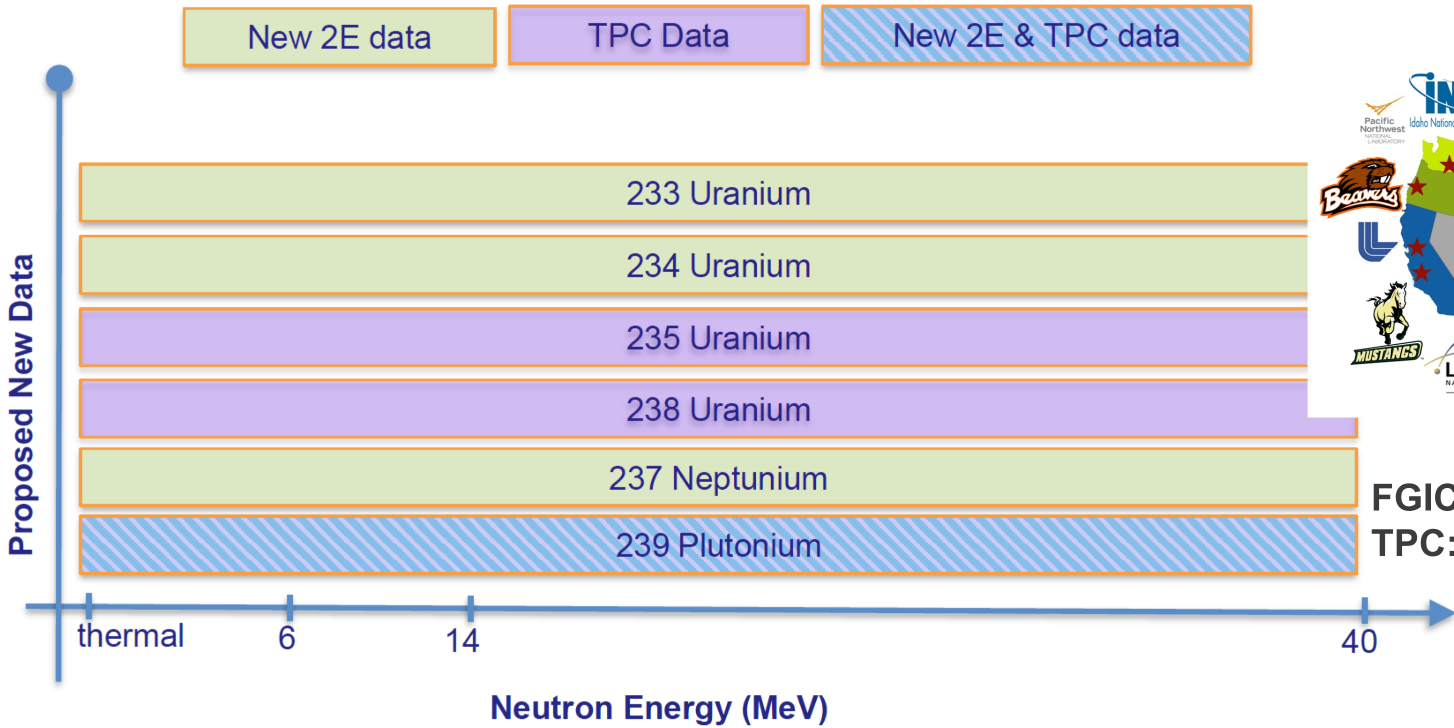
Workshop on Applied Nuclear Data Activities (WANDA)
Mar. 2, 2023

K.B. Montoya*, D.L. Duke, D. Connolly (LANL)
L. Snyder (LLNL)
L. Wood, B. Fulsom, M. Moore, S. Lyons (PNNL)
U. Greife & J. Latta* (CSM)

*Ph.D. students

The goal of this experiment is to fill gaps in IFPY nuclear data and improve quantification of uncertainty in new measurements.

We will accomplish this by leveraging existing and newly applied technologies: 2E Frisch Gridded Ionization Chamber (FGIC) and the fission Time Projection Chamber (fissionTPC)

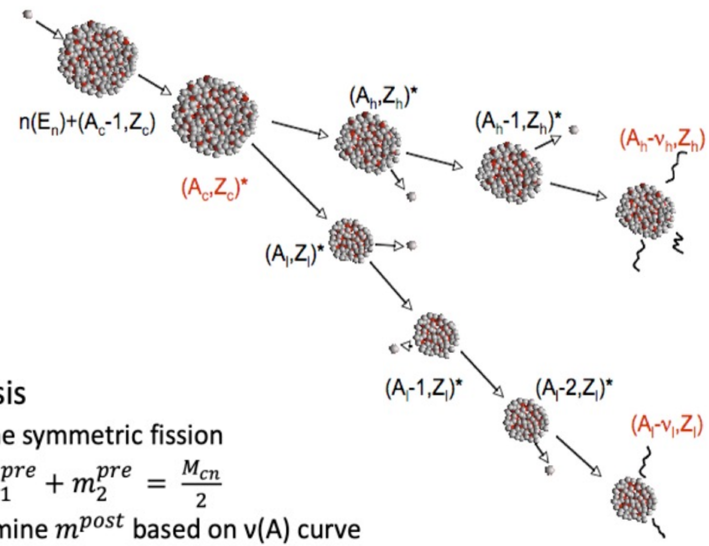


FGIC: ^{237}Np, ^{233}U, ^{239}Pu
TPC: ^{235}U, ^{238}U, ^{239}Pu

FOA Information: D. Duke, L. Snyder, L. Wood. Measurements of IFPY's. LAB 18-1903

The 2E Method

Independent yields refers to fragments' configuration prior to any beta decay.



Iterative analysis relying on conservation of momentum

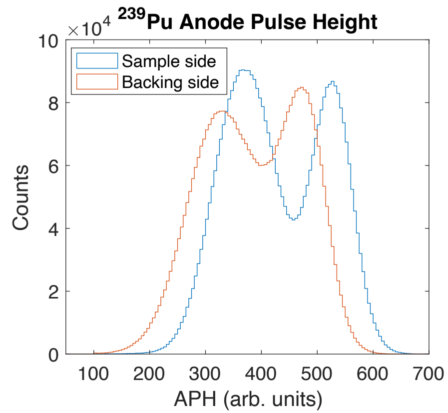
- Advantages: Independent FPY, Pre-& Post-Neutron Emission
  - Measured at earliest possible time, before beta-decay
- Disadvantages: Mass only, Limited resolution
  - 3-5 AMU, Typical

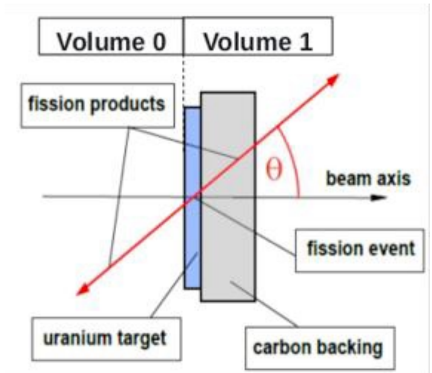
- 2E Analysis
  - Assume symmetric fission
    - $m_1^{pre} + m_2^{pre} = \frac{M_{cn}}{2}$
  - Determine m^{post} based on ν(A) curve
  - Recalculate m^{pre}
    - $m_1^{preNew} = M_{cn} \times \frac{E_2}{E_1/_b + E_2}$
    - $b = \frac{m_2^{pre} \times m_1^{post}}{m_2^{post} \times m_1^{pre}}$
  - Iterate to convergence criteria
    - $m^{pre} - m^{preNew} < 0.125$

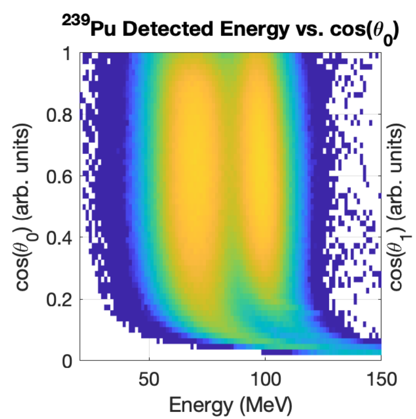
D.L. Duke, et al.
PRC 94, 054604 (2016)

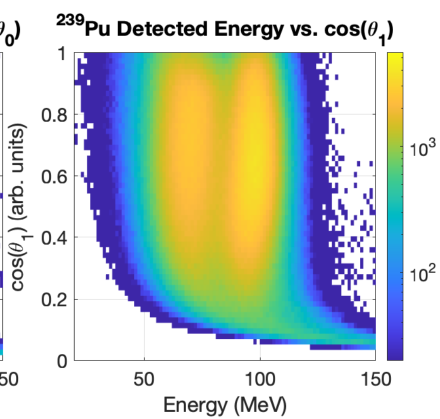
FGICs are a proven technology used to measure fission observables such as IFPY, TKE, and Cross Sections.

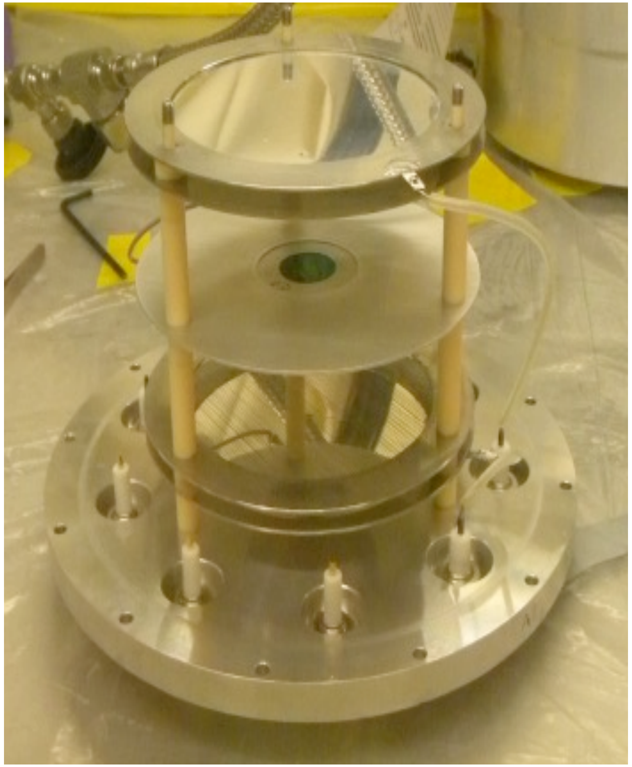
This detector type was used in most of the existing IFPY measurements, which provide about 3-5 amu mass resolution







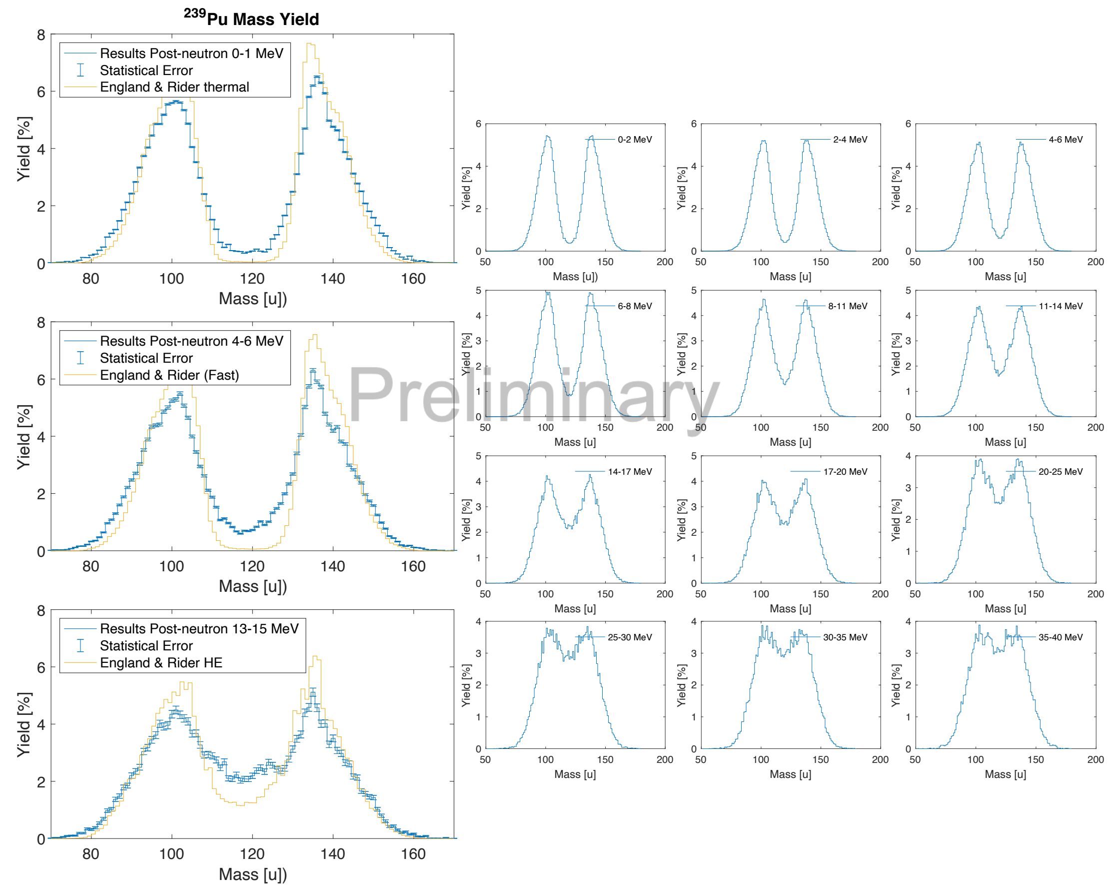




[1,2,3]

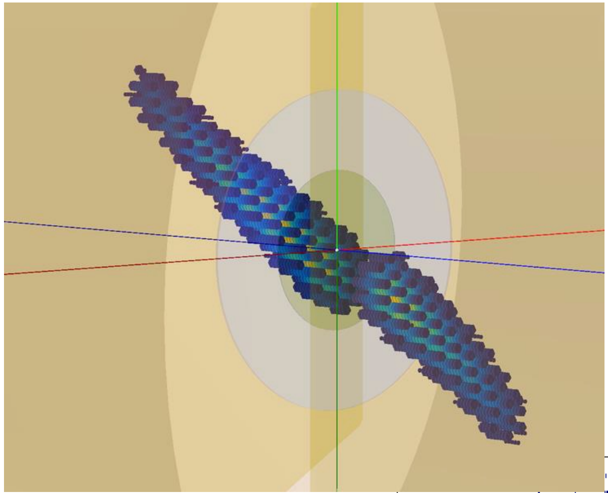
FGIC Analysis Status

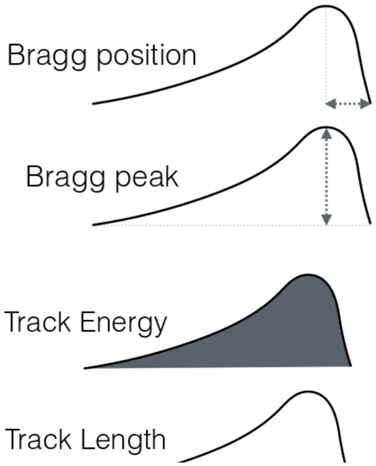
- ^{237}Np data submitted for publication in Journal of Physics G
- ^{233}U and ^{239}Pu data analysis under final review. Successful alpha correction resulted in mass yields shown
- ^{234}U data was not collected
- Expected completion of ^{233}U, ^{239}Pu by Q1 CY23

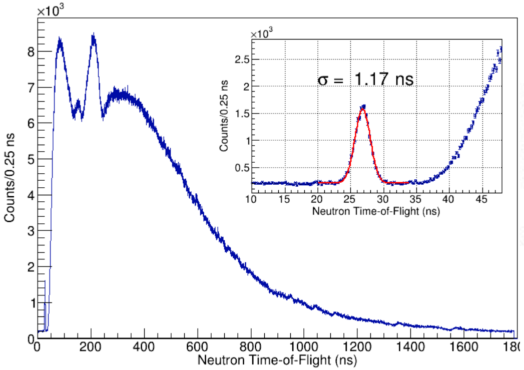


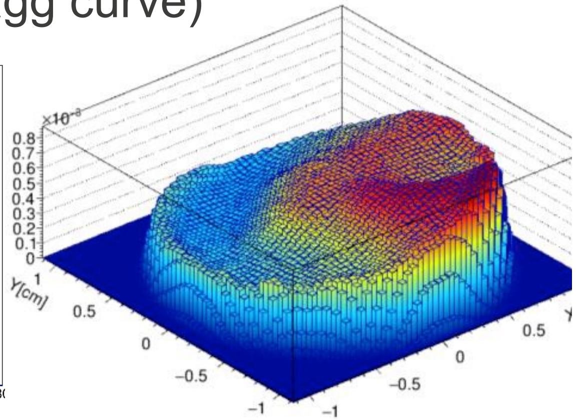
Quantities measured by the fissionTPC

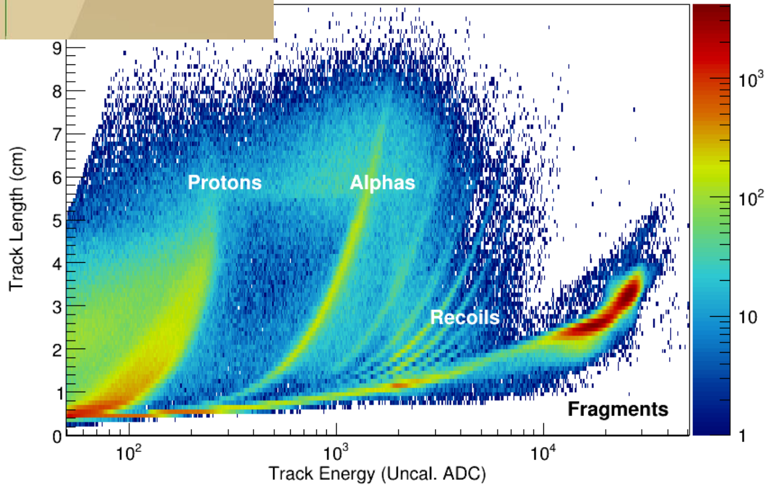
3D ionization profile for individual tracks provides:
- Track length
- Total energy
- Location & value of max ionization
- Interaction vertex
- Track direction
- Ionization profile (Bragg curve)











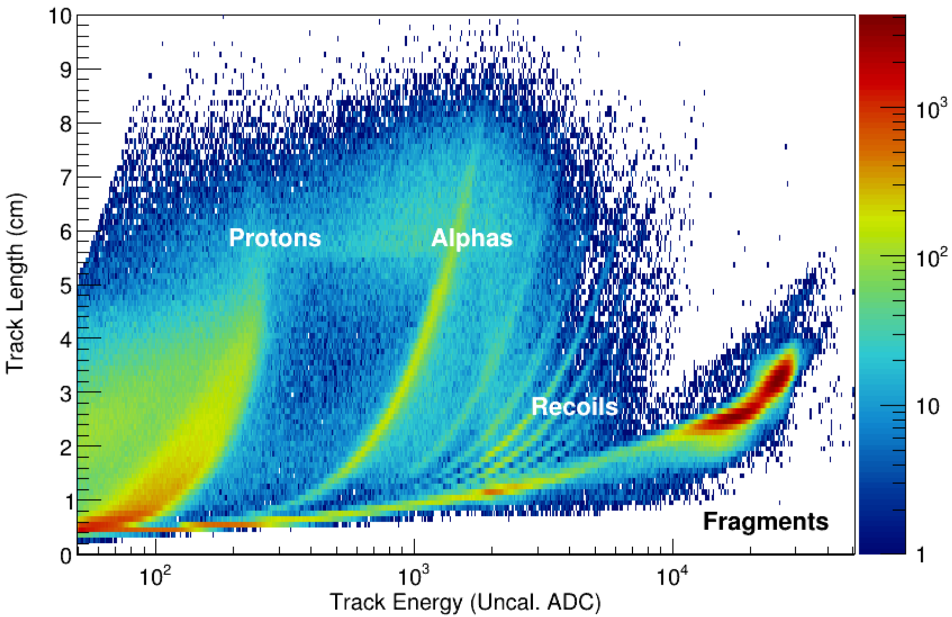
The 2E Method with the fissionTPC

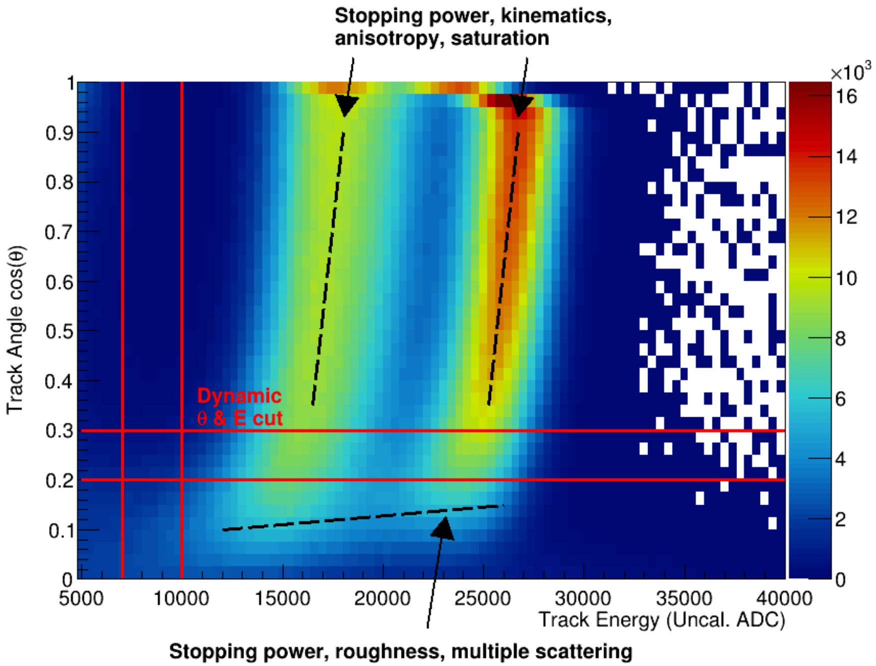
Advantage: Wealth of information

- Direct measurement of angle : energy loss correction
- High dynamic range: Energy resolution determination independent of fission fragments

Disadvantage: Reduced energy resolution

- 3k channel/anode
- Not optimized for energy

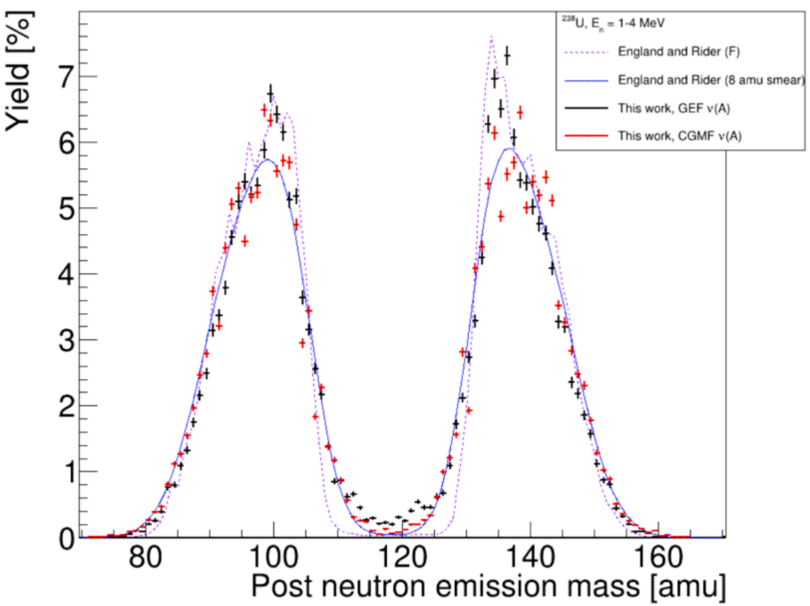


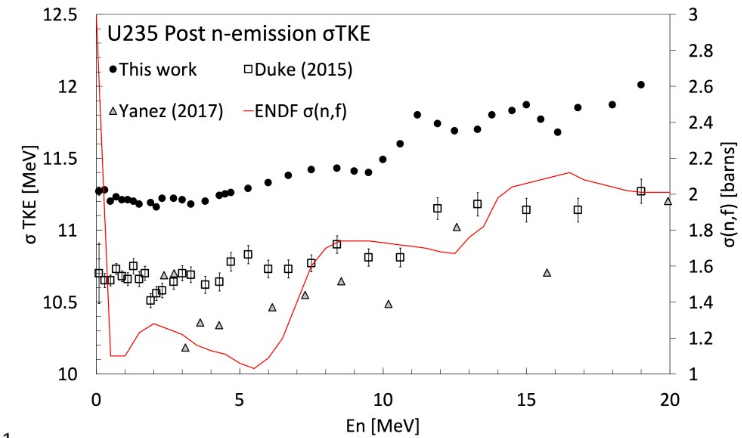


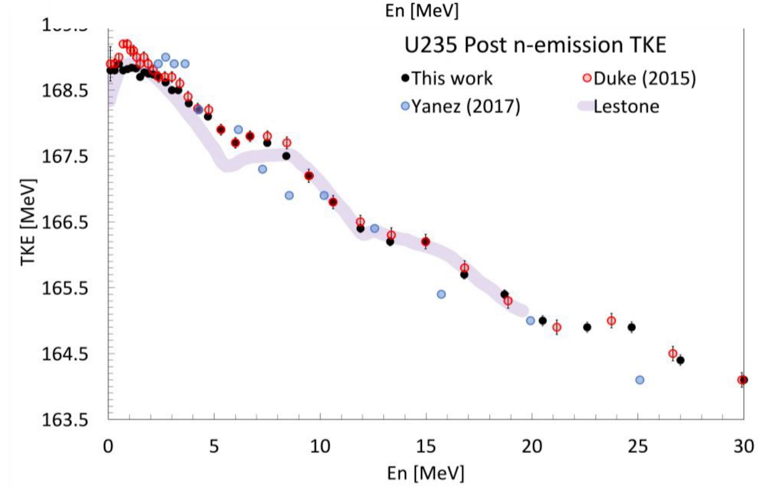
FissionTPC 2E Results

Latta, Joseph. Fission Fragment Mass and Energy Distributions for Neutron Induced Fission of 235 U, 238 U and 239 PU Measured with the NIFFTE Time Projection Chamber. Diss. Colorado School of Mines, 2021.

- Comparison ^{235}U to England & Rider indicates 7-8 AMU resolution
- This is in agreement with the estimate based on fissionTPC energy resolution



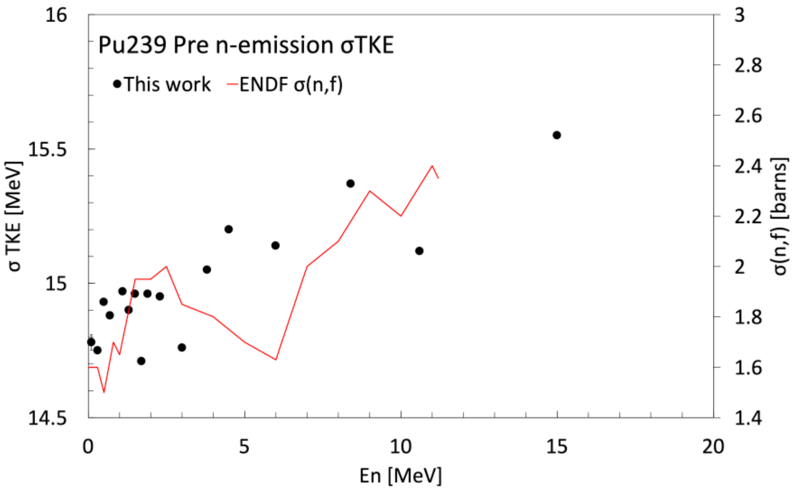


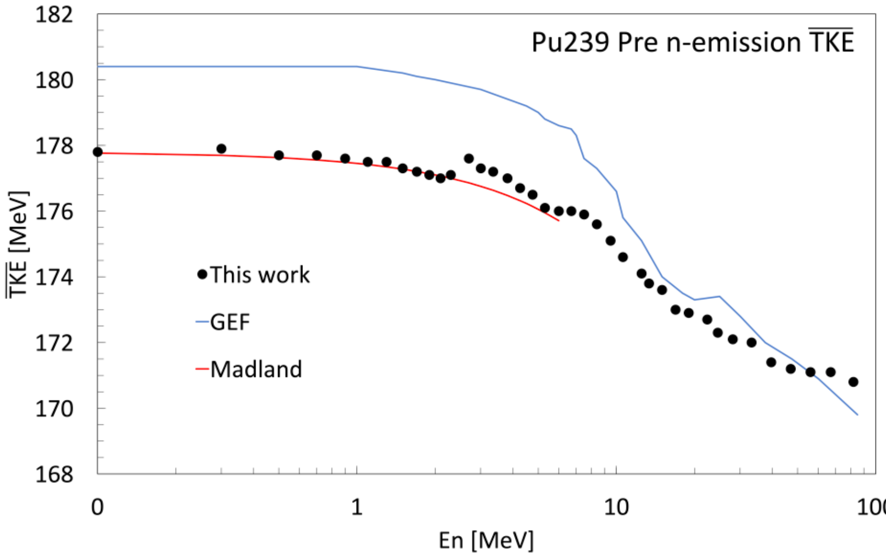


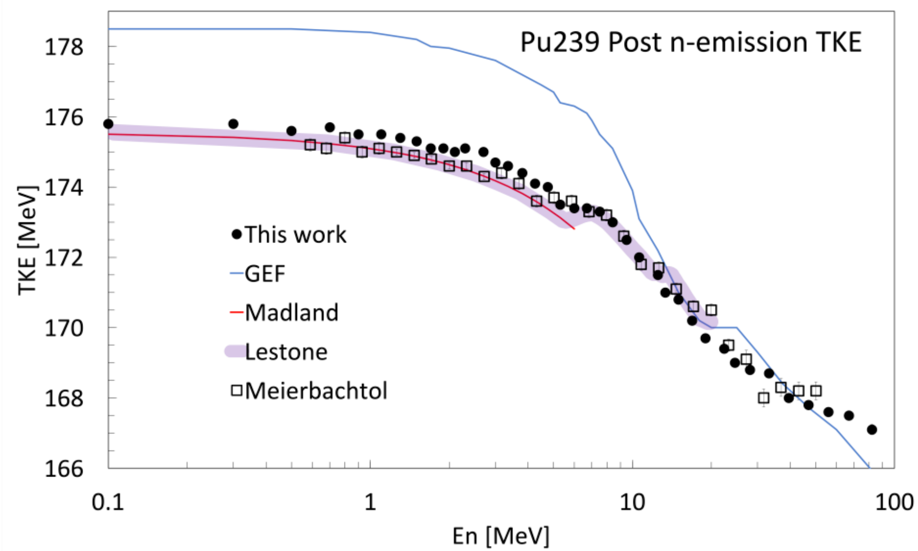
FissionTPC 2E Results

Latta, Joseph. Fission Fragment Mass and Energy Distributions for Neutron Induced Fission of 235 U, 238 U and 239 PU Measured with the NIFFTE Time Projection Chamber. Diss. Colorado School of Mines, 2021.

- First measurement of ^{239}Pu(n,f) Pre-neutron TKE above 5 MeV
- IFPY for ^{239}Pu not completed







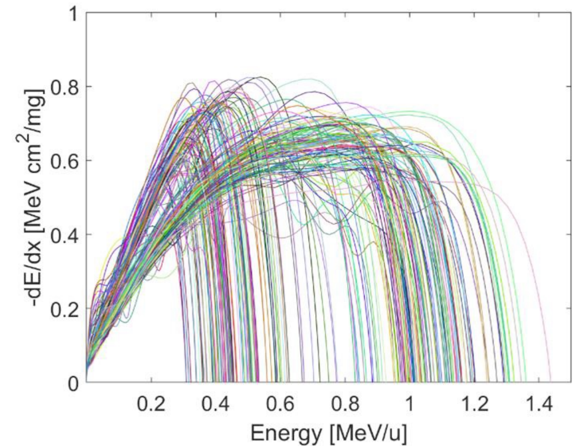
Bragg Curve Analysis with the fissionTPC for ^{235}U Elemental (Z) IFPY

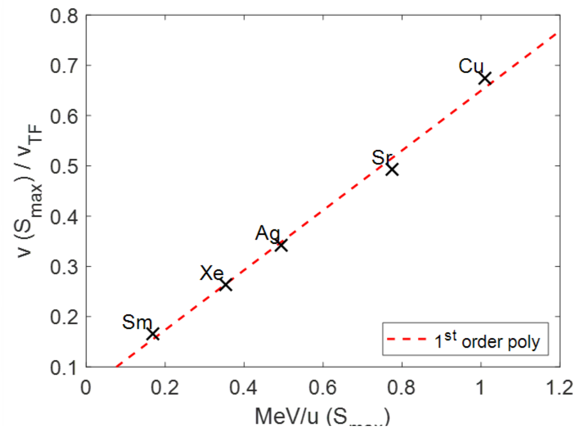
Moore, M. E., et al. "Stopping Force Analysis of 235U Elemental Fission Product Yields for En= 0.11–92.4 MeV." Nuclear Data Sheets 184 (2022): 1-28.

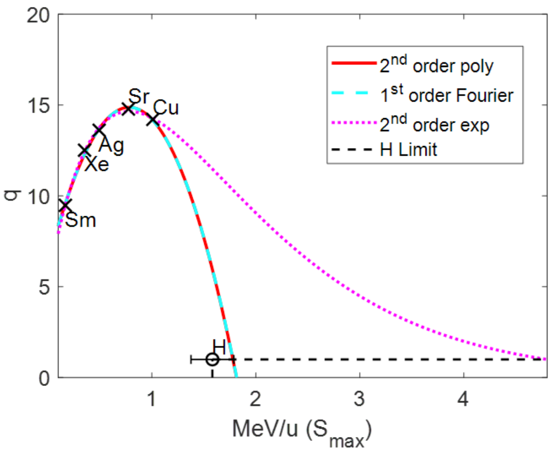
- Using input mass value and velocity produced by 2E analysis and Bragg curves
- Using Standard Thomas-Fermi charge for *effective* charge
- Empirically fit parameters of atomic number at the instant of maximum stopping power
- 3 Z resolution

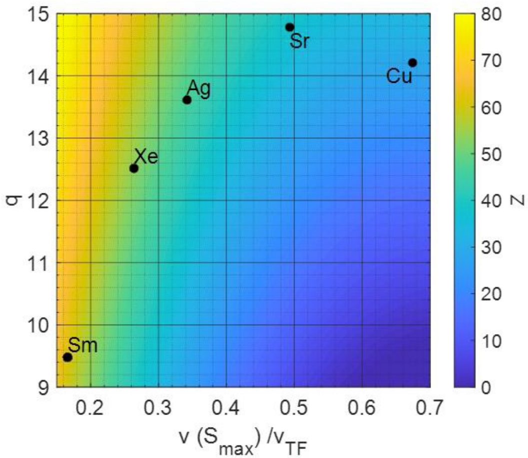
$$S = \frac{4\pi Z_1^2 Z_2 e^4}{mv^2} L; \quad L = \begin{cases} \ln\left(\frac{Cmv^3}{Z_1 e^2 \omega}\right) & \text{Bohr} \\ \ln\left(\frac{2mv^2}{h\omega}\right) & \text{Bethe} \end{cases}$$

$$q = Z_1 \left[1 - e^{-\frac{v}{v_{TF}}}\right]; \quad v_{TF} = Z_1^{2/3} v_0$$





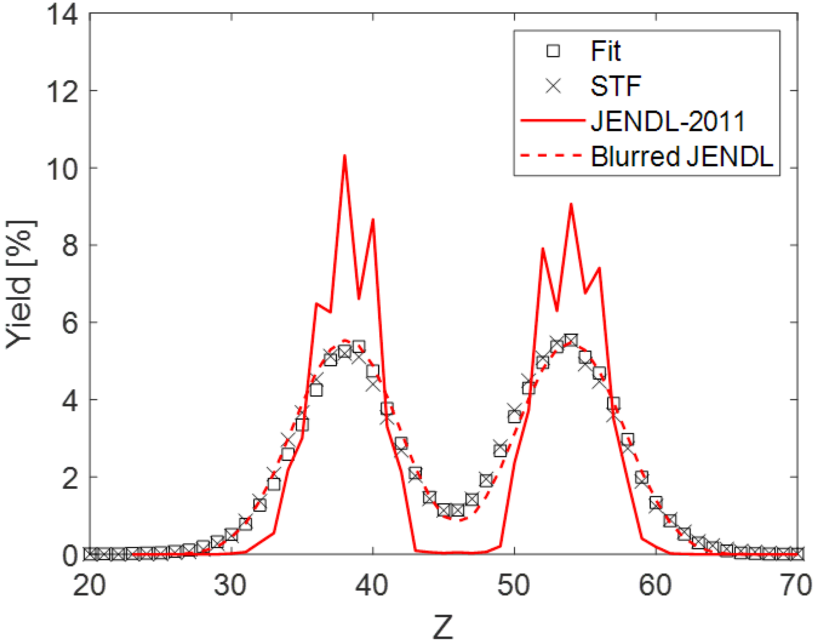


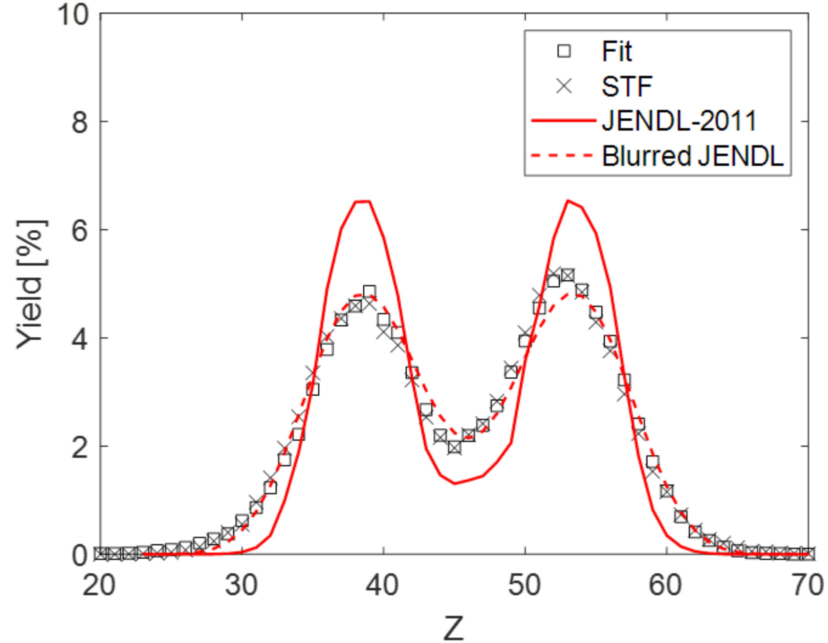


Bragg Curve Analysis with the fissionTPC for ^{235}U Elemental (Z) IFPY

Moore, M. E., et al. "Stopping Force Analysis of 235U Elemental Fission Product Yields for En= 0.11–92.4 MeV." Nuclear Data Sheets 184 (2022): 1-28.

- First of its kind measurement, explores the method; Limitations and possible improvements
- A good review of references for fission fragment (heavy ion) stopping
- Paper does include data tables





Conclusion: We are leveraging the strengths of both detectors to provide multiple IFPY data sets with reduced uncertainty.

- New data collected, objectives largely met
- FissionTPC analysis explored partial uncertainties. 2E uncertainty dominated by energy resolution followed by systematic effects of prompt neutron estimates
- Stopping force analysis for Z yield was completed. Improvements in energy resolution and calibration could make such an analysis very useful

LANL

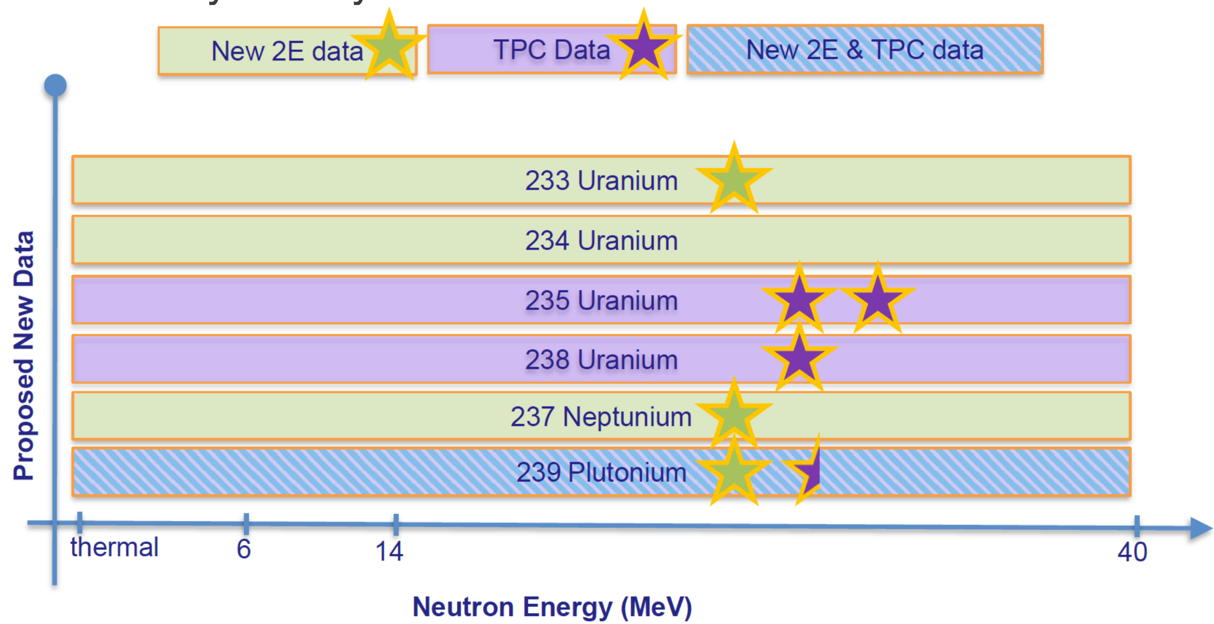
Publication of ^{233}U, ^{237}Np, and ^{239}Pu results (plus dissertation), Data submission to NNDC

LLNL/CSM

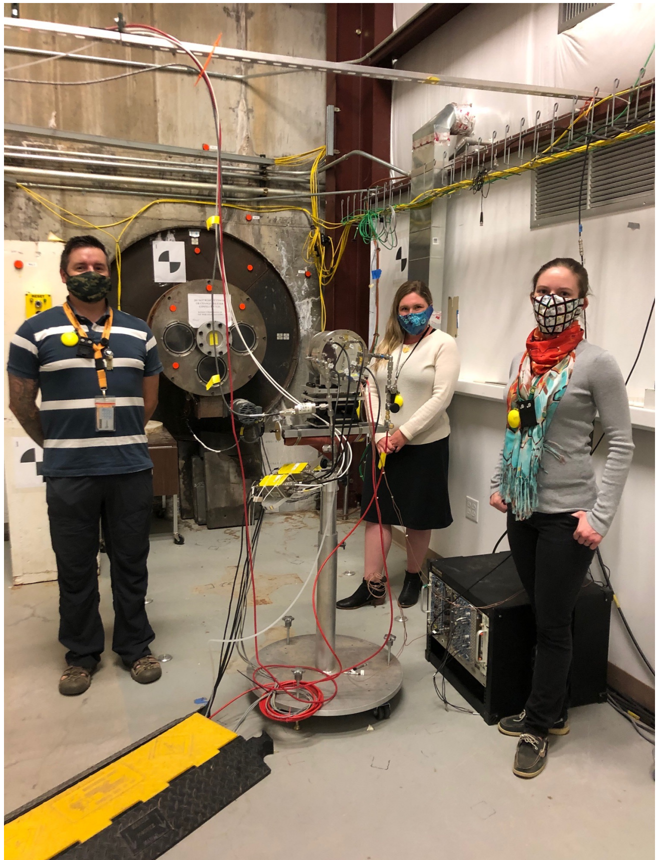
Publication of ^{235}U, ^{238}U results (plus dissertation)

PNNL

Publication of stopping power study method, Completion of machine-learning study with larger data set, Publication of machine-learning methodology and results

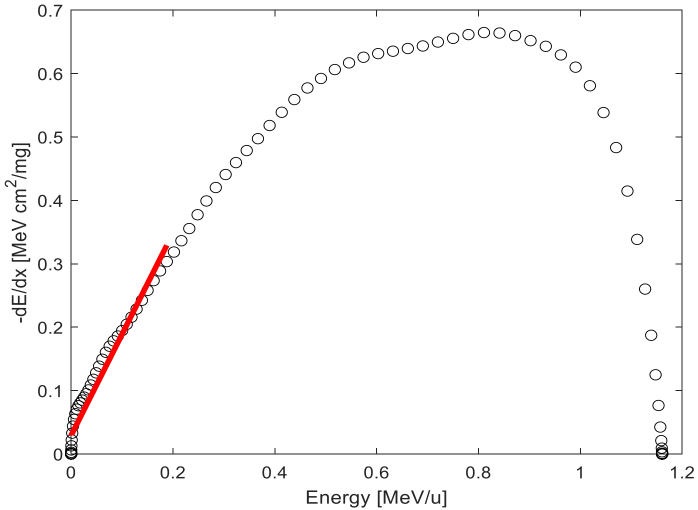


Thank you for your attention!



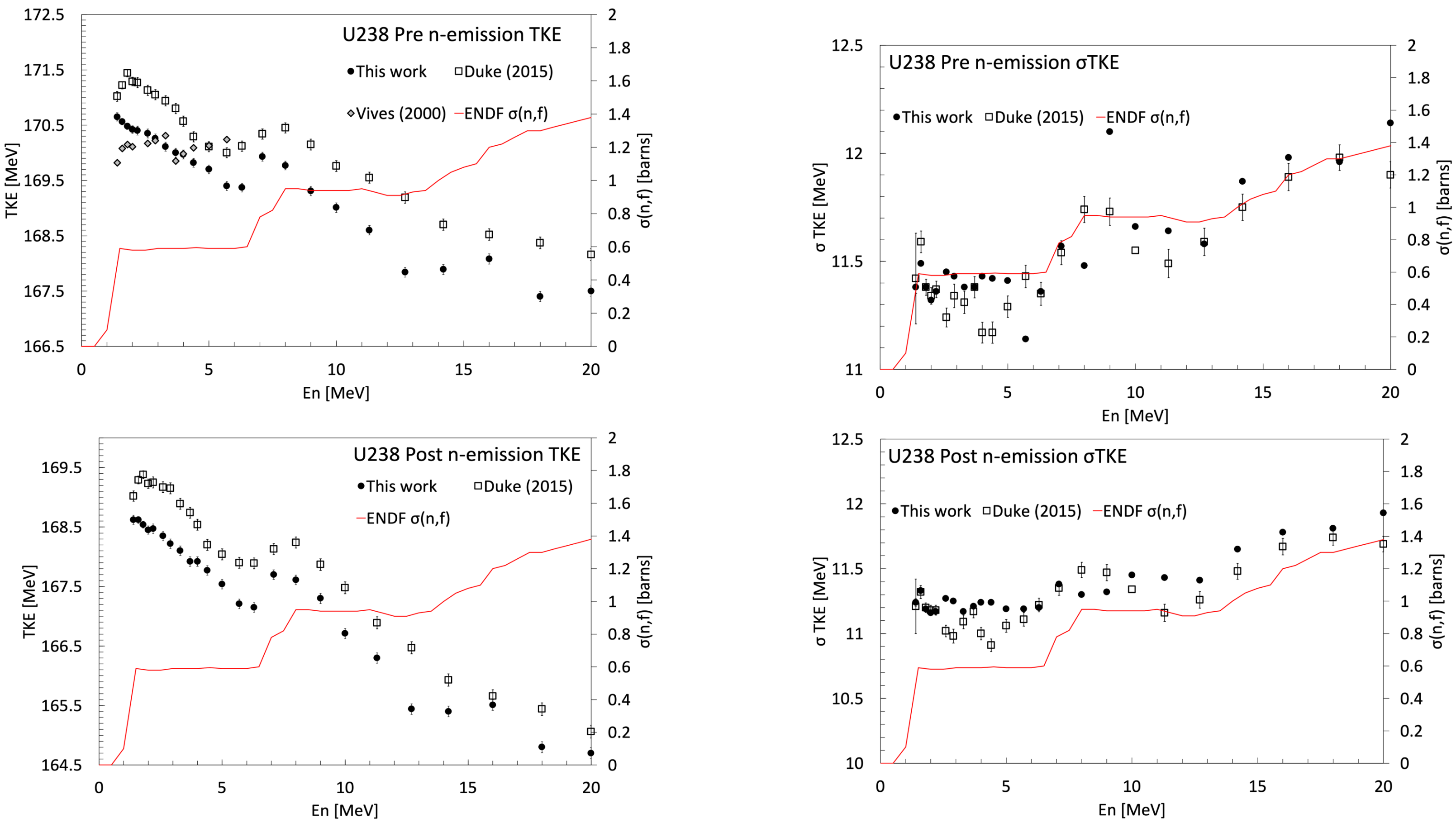
1) D.L. Duke et al. *Phys. Rev. C.* 94:54-60 Nov. 2016.
2) S. Mosby et al. *Nuc. Inst. & Meth. A.* 757:75-81. Aug. 2014.
3) Budtz-Jørgenson et al. *Nuc. Inst. & Meth. A.* 258.2:209-220 Aug. 1987.
4) M. Heffner et al. *Nuc. Inst. & Meth. A.* 759:50-64. Sept. 2014
5) D. L. Duke. PhD Dissertation. Colorado School of Mines. 2015.
6) Yanez et al. *Nuclear Physics A* 970:65-77, February 2018.
7) ENDF/B.VIII Nucl. Data Sheets 148(2018)1.
8) Moore, M. E., et al. "Stopping Force Analysis of 235U Elemental Fission Product Yields for En= 0.11–92.4 MeV." *Nuclear Data Sheets* 184 (2022): 1-28.
9) Latta, Joseph. *Fission Fragment Mass and Energy Distributions for Neutron Induced Fission of 235 U, 238 U and 239 PU Measured with the NIFFTE Time Projection Chamber*. Diss. Colorado School of Mines, 2021.

- **Looking at energy loss in MeV-cm^2/mg as alternative for improved discrimination**
  - Fitting low-order polynomial to energy-normalized tail of the areal density stopping power
  - Correlation of stopping to Z is well-known for ^{235}U for incident neutron energies of 100-500 keV



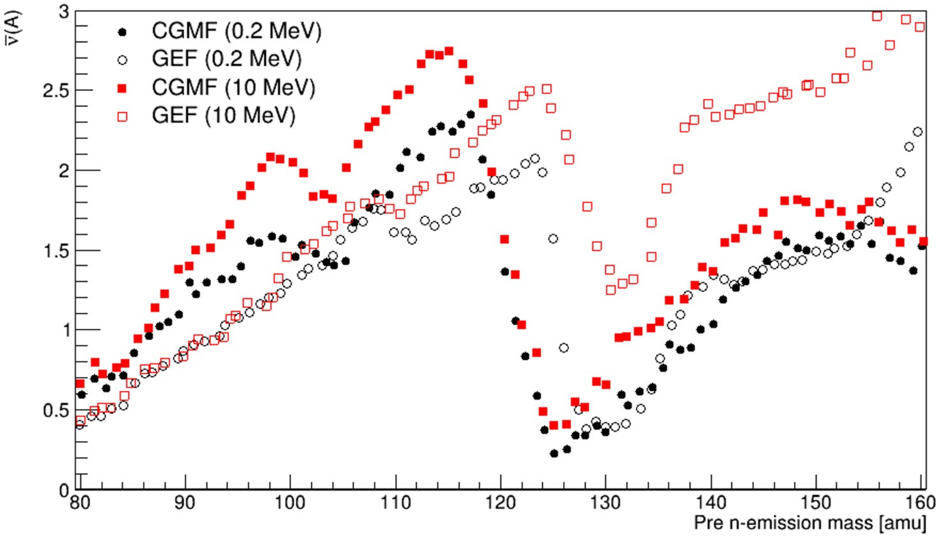
Stopping power fit for Z=40

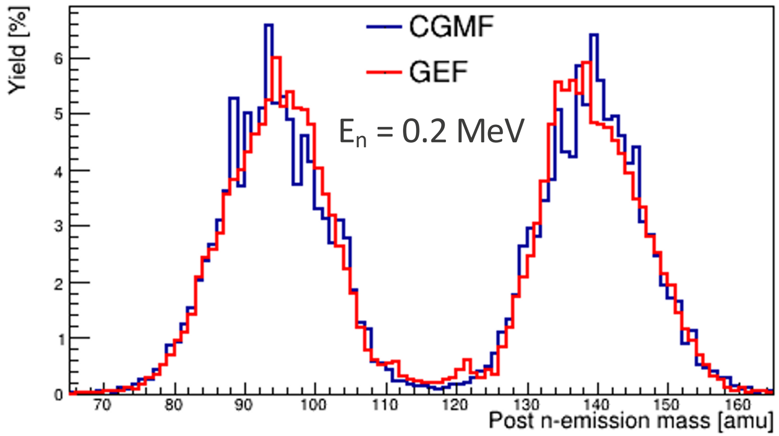
Reanalysis of FissionTPC data with 2E method shows good agreement with previous measurements.

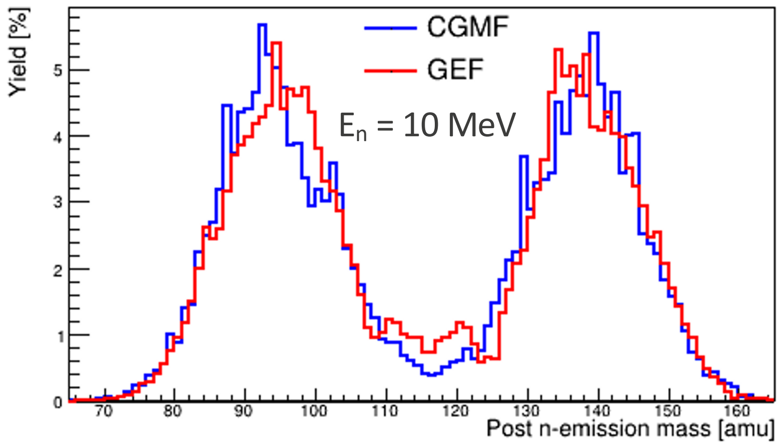


Effect of model inputs on 2E analysis

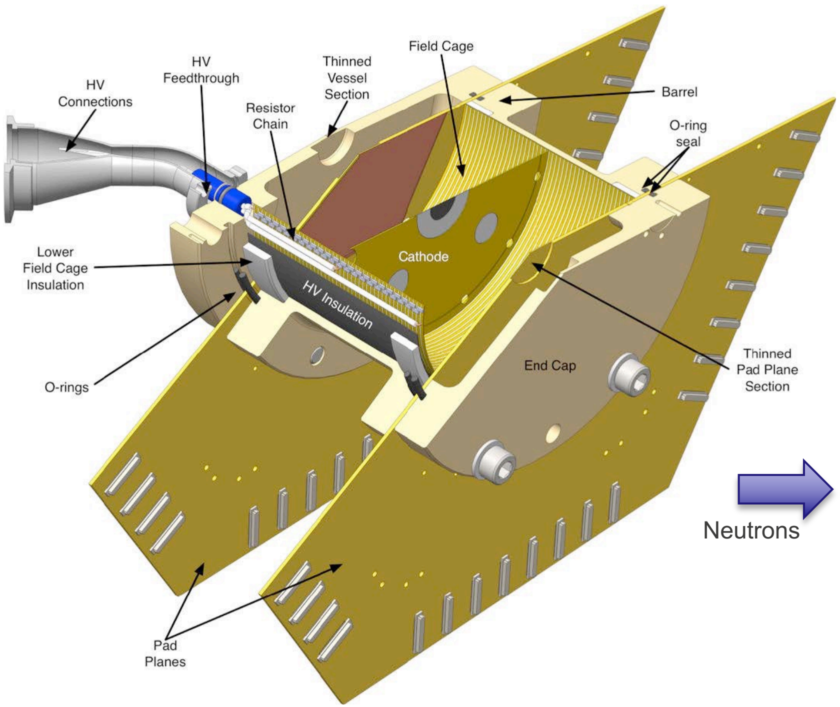
U235 Neutron multiplicity models

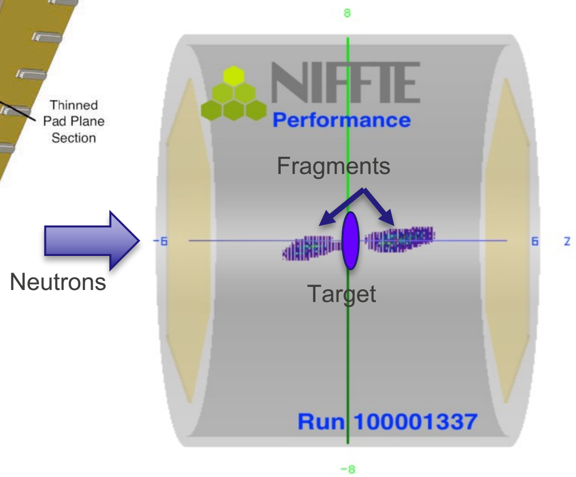




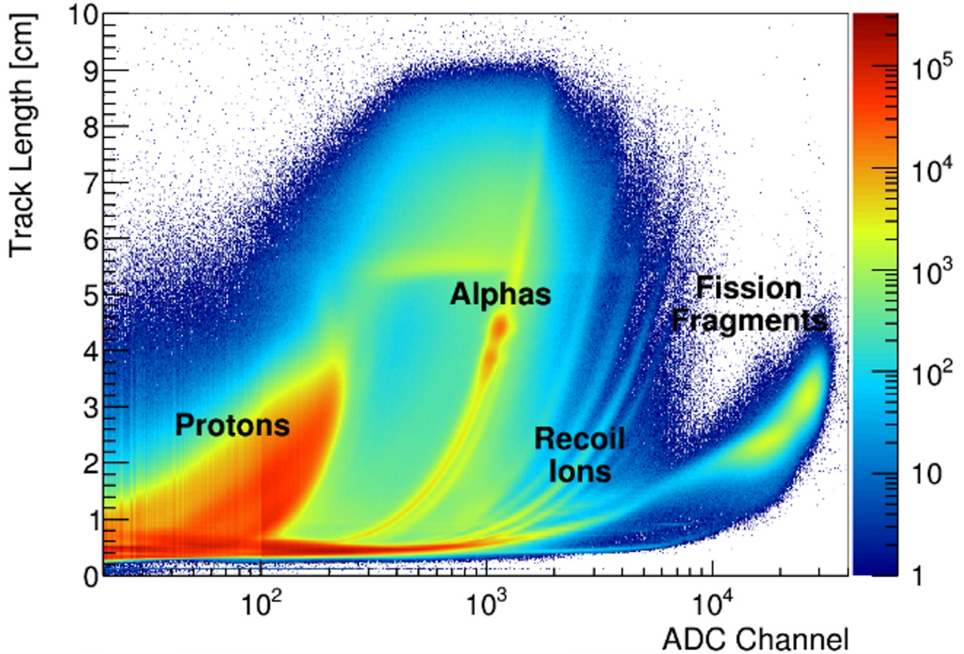


How does the fissionTPC work?





fissionTPC Data



- Utilize advantages of fissionTPC such as measured track angle, 3D track reconstruction, track length and particle identification capability (address alpha pile-up in 239Pu data).
- Probe uncertainties related to energy loss in target/backing, v(A), and pulse height defect .
- Inform Bragg Curve Analysis