FissionTPC Cross Section Ratio Results and Their Impact

$^{239}\text{Pu}(n,f)/^{235}\text{U}(n,f)$

CSWEG
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Publications

Measurements of the normalized $^{238}$U(n,f)/$^{235}$U(n,f) cross section ratio form threshold to 30 MeV …

- **R. Casperson, et al.**
  - *PRC* 97, 034618 (2018)

Fission Fragment Angular Anisotropy in Neutron-Induced Fission of $^{235}$U …

- **V. Geppert-Kleinrath, et al.**

Measurement of $^{235}$U Anisotropy and Linear Momentum Transfer.

- **D. Hensle, et al.**
  - *PRC* 102, 014605 (2020)

The fissionTPC…

- **M. Heffner, et al.**
  - *NIM A* 759 (2014) 50-64
Outline

- Part I: FissionTPC data analysis
  - Cross section *shape* analysis & validations presented
  - Efficiency and Nonuniformity in target & beam corrections
  - Status of absolute normalization discussed

- Part II: GMA Data Fit
  - We are assessing the impact of the new ratio measurement.
Quantities measured by the fissionTPC

- Neutron time-of-flight measured
- 3D ionization profile for individual tracks provides:
  - Track length
  - Total energy
  - Track direction
  - Bragg Peak
  - Interaction vertex
Parameterized model incorporating energy loss effects for fission fragments exiting target material

- Energy-Angle data is fit
- Recent inclusion of FREYA code and Geant4 in model
- Validation of earlier data-driven only model
Neutron Flux Profile & Target Overlap

Correction required if beam and actinide target have spatial non-uniformity

\[ \frac{\sum_{XY} \phi_{s,i} \cdot n_{s,i}}{\sum_{XY} \phi_{x,i} \cdot n_{x,i}} = 1 \neq \frac{\sum_{XY} (\phi_{s,i} \cdot n_{s,i})}{\sum_{XY} (\phi_{x,i} \cdot n_{x,i})} \]

Fragments (data)  Alphas (data)  FF/alpha (data)

Pu-239

Pu-239

\[ \text{OT} = \text{Overlap Term} \]
\[ = B \sum_i \frac{n_i}{\sum_j n_j \sum_k T_k} \]
\[ = B \frac{1}{\sum_j n_j \sum_k T_k} \sum_i n_i T_i \]
\[ \text{OT}^{Pu} = \frac{1}{\sum_k \alpha_{Pu}^{f'}} \sum_j \frac{f_j^{Pu}}{\alpha_j} \sum_i l_i \]
\[ \text{OT}^{U} = \frac{1}{\sum_i \alpha_i^{f'}} \sum_j f_j \]

Data driven correction
“U-corrected Pu-overlap term”

Dot product

Before Rotation  After Rotation

Overlap Correction Factor

0.3 0.4 1 2 3 4 5 6 7 8 9 10 20

1.08 1.07 1.06 1.05 1.04 1.03 1.02
Validations and Sensitivity Studies

- **Rotation of fissionTPC**
  - Flips beam and target non-uniformity

- **XY-binned cross section**
  - Make measurement in small bins where beam is relatively uniform
  - Requires rescaling of each bin target normalization ratio

- **Radial cuts**
  - Has large effect on overlap correction

- **Tracking sensitivity studies**
  - Tracking bias, resolution
  - Target alignment
  - Space charge distortion

- **Normalization Validation**
  - Remeasure target-atom normalization
  - Remeasure cross section ratio (future work)
Rotation Validation

Flip beam:
- Direction alters alignment of beam and target hotspot
- Kinematic boost alters efficiency
Rotation Validation

- Significant, 3-4 % change in efficiency and overlap terms
- Effects both shape and overall normalization
- Strong validation
“Before” and “After” rotation cross section ratios agree
Binned Cross Section Analysis

- Average many cross section ratios binned such that the beam and/or target are uniform
- Each one renormalized
- Methods agree
Target Atom Normalization

- A combination of a Si detector and mass spectrometry were used to determine the target atom normalization
- Si det. design based on NIST prescription
Target Atom Normalization Validation

- Results are reported as a ratio of target atom number, to eliminate the need to have a precision understanding of the Si detector setup geometry
- Method depends on Mass Spec. to get a final answer
- **Mass spec.** measurements made *multiple times from multiple samples* over multiple years
- **Target counting measured** in detector *multiple times*
- **Target counting analysis** was performed independently at **LANL/LLNL**
- Absolute alpha counting in fissionTPC not accurate enough currently
Normalization Compared to ENDF8

- Significant systematic deviation from ENDF
- This is *not* the collaboration’s stated position
Comparison to Data

- Deviation with other data is consistent with ENDF
- Larger deviations between all data at higher energies
PART I: Summary

- We are confident of the Cross Section Shape Measurement
- Two obvious concerns:
  - Is the overlap handled correctly?
  - Is the measurement of the target normalization correct?
- Validations Performed:
  - Rotation & radial cuts have significant effects on overlap and efficiency. *They are strong validations*
  - Two methods for nonuniformity correction agree
  - Target was remeasured and reanalyzed by multiple teams
  - Target was counted in Silicon detector *only after* beam data was collected. It is possible that it was damaged. This would have had no effect on the cross section measurement
- We will remeasure for normalization
- Next Steps:
  - Now capable of vapor deposition of $^{239}$Pu
  - Characterize target before and after a new beam measurement
  - At this point we intend to publish recommended as shape data but will include our normalization work
Impact of the new data

Step 1

Establish our best experimental knowledge of $^{239}$Pu(n,f) with a GMA evaluation.

Step 2

Fit parameters of a physical model for the simultaneous evaluation of $^{239}$Pu(n,f) and other related observables.
$^{239}$Pu(n,f) needs revisiting

**Step 1**

Establish our *best experimental* knowledge of $^{239}$Pu(n,f) with a **GMA evaluation**.
The GMA database: types of data

Table 2. Data Types Used in the Simultaneous Evaluation

<table>
<thead>
<tr>
<th>MT</th>
<th>Data Type</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Absolute cross section</td>
<td>$\sigma_{n,t}^{(235\text{U})}$</td>
</tr>
<tr>
<td>2</td>
<td>Cross section shape</td>
<td>$c \cdot \sigma_{n,t}^{(6\text{Li})}$, $c$ unknown</td>
</tr>
<tr>
<td>3</td>
<td>Absolute cross section ratio</td>
<td>$\sigma_{n,t}^{(238\text{U})}/\sigma_{n,t}^{(235\text{U})}$</td>
</tr>
<tr>
<td>4</td>
<td>Ratio shape</td>
<td>$c \cdot \sigma_{n,t}^{(239\text{Pu})}/\sigma_{n,t}^{(6\text{Li})}$, $c$ unknown</td>
</tr>
<tr>
<td>5</td>
<td>Sum of cross sections</td>
<td>$\sigma_{\text{tot}}^{(6\text{Li})} = \sigma_{n,n}^{(6\text{Li})} + \sigma_{n,x}^{(6\text{Li})}$</td>
</tr>
<tr>
<td>6</td>
<td>Spectrum averaged cross section</td>
<td>$\sigma_{n,t}^{(239\text{Pu})}$, Av. $^{252}\text{Cf}$ SF</td>
</tr>
<tr>
<td>7</td>
<td>Absolute ratio of cross section vs. sum of cross sections</td>
<td>$\sigma_{n,t}^{(238\text{U})}/\sigma_{n,\alpha}^{(10\text{B})}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma_{n,\alpha} = \sigma_{n,\alpha 0} + \sigma_{n,\alpha 1}$</td>
</tr>
<tr>
<td>8</td>
<td>Shape of type 5 data</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Shape of type 7 data</td>
<td></td>
</tr>
</tbody>
</table>

The GMA (Gauss-Markov-Aitken) equations

- Generalized least-squares.
- Assumes normal distribution of random variables.
- Linearization close to most probable value.
- Linear algebra problem, good numerical implementation.

\[ p = \left( A^T V_y^{-1} A \right)^{-1} A^T V_y^{-1} y \]
\[ V_p = \left( A^T V_y^{-1} A \right)^{-1} \]

best parameters
best covariances
measured covariances
measured parameters
design matrix
evaluation
GMA at work: implementation of GMA equations for $^{239}\text{Pu}(n,f)$

$^{239}\text{Pu}(n,f)$ data in the GMA October 2004 database
GMA at work: implementation of GMA equations for $^{239}$Pu(n,f) after the application of the GMA equations, best experimental values, errors, and covariances for $^{239}$Pu(n,f) are obtained.
Combining the TPC data with the GMA database

$^{239}\text{Pu} \ (n,f)$
Combining the TPC data with the GMA database: converting to shape data

\[
\sigma (b) = \begin{cases} 
\text{with TPC data (shape)} \\
\text{without TPC data} 
\end{cases}
\]

\(^{239}\text{Pu}(n,f)\)
Combining the TPC data with the GMA database

Ratio of values with TPC data /without TPC data

$^{239}$Pu(n,f) ratio of values with/without TPC

- Absolute
- Shape

Ratio of errors with TPC data /without TPC data

$^{239}$Pu(n,f) ratio of errors with/without TPC

- Absolute
- Shape

$E$ (MeV)
Part II: Summary

- We are assessing the impact of the new ratio measurement.
- As a first step, we presented here the GMA evaluation, which establishes the status of our experimental knowledge of $^{239}$Pu$(n,f)$ cross sections, uncertainties, and covariances.
- Next step: fit of the physical parameters of a Hauser-Feshbach+Coupled Channels model of reaction and decay work in progress.
Backup
Motivation: Spread in $^{239}$Pu(n,f)/$^{235}$U(n,f) data does not justify a 1% evaluation
Background terms

- Recoil and alpha backgrounds ($C_r, C_\alpha$) found to be negligible, i.e. TPC has good PID capabilities
- Any uncertainty from this assumption accounted for in efficiency model
- Wraparound corrected for with standard methods
Contamination correction

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atom %</th>
<th>Alpha Activity (%)</th>
<th>Overlapping with peak of interest (POI)?</th>
<th>Fission Cross-Section at 10 MeV</th>
<th>Fission Yield at 10 MeV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{233}\text{U}$</td>
<td>0.01862</td>
<td>29.1</td>
<td>No</td>
<td>2.25</td>
<td>0.024</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>0.03448</td>
<td>34.4</td>
<td>No</td>
<td>2.16</td>
<td>0.042</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>99.6767</td>
<td>34.7</td>
<td>POI</td>
<td>1.76</td>
<td>99.7</td>
</tr>
<tr>
<td>$^{236}\text{U}$</td>
<td>0.17009</td>
<td>1.78</td>
<td>Yes</td>
<td>1.53</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>0.09984</td>
<td>0.00548</td>
<td>Yes</td>
<td>1.00</td>
<td>0.057</td>
</tr>
<tr>
<td>$^{235}\text{Pu}$</td>
<td>0.0002</td>
<td>0.84</td>
<td>Yes</td>
<td>2.82</td>
<td>0.00025</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>99.1323</td>
<td>95.97</td>
<td>POI</td>
<td>2.24</td>
<td>99.1</td>
</tr>
<tr>
<td>$^{240}\text{Pu}$</td>
<td>0.8675</td>
<td>3.19</td>
<td>Yes</td>
<td>2.24</td>
<td>0.87</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>&lt;0.0015</td>
<td>&lt;0.00001</td>
<td>Yes</td>
<td>1.99</td>
<td>&lt;0.0013</td>
</tr>
<tr>
<td>$^{242}\text{Pu}$</td>
<td>0.00242</td>
<td>0.00016</td>
<td>No</td>
<td>1.92</td>
<td>0.00021</td>
</tr>
</tbody>
</table>

Table 2: Isotopes and effects on cross-section measurement.
Detailed MCNP model gives neutron flux spatial profile for both actinide targets, as a function of neutron energy

- Proton beam energy loss in the spallation target results in a non-uniform neutron beam profile
- Importantly, the spatial profile varies with neutron energy (at the TPC)

We use the MCNP model to account for:
- flux attenuation in the target backing
- scattering (change in energy) between TOF measurement and fission initiation
Radius Cut Validation

- Aggregate shape changes
- Target Edge alignment constitutes large nonuniformity
- Large impact on the overlap term and target renormalization (1mm rad. cut \(\rightarrow \sim 7\%\) change normalization)
FissionTPC Padplane Alignment Sensitivity

- Misalignment of padplanes could cause an apparent misalignment of the targets (reconstructed vs. real)

- Beam induced events with enough energy to “punch-through” the central cathode are used to determine the alignment

- Potential misalignment of up to 200 µm expected as a result of construction technique
- Tracking algorithm is “focused” to eliminate hexagonal biasing of track vertices
- There is a polar angle dependence such that the average is un-biased but some angle ranges make it more apparent
Pointing Resolution and Bin Size

- Tracking resolution is \(~300 \mu m\)
- Overlap term has normalization some sensitivity to bin size
- Edge of target represent large nonuniformity
Tracking Studies Summary

- Normalization Sensitivities up to 1%
- Tracking effects on overlap all corrected for. Uncertainties < 1%
- No effect on shape
FissionTPC Future

- Advanced, well characterized instrument
- X(n,cp)Y measurement
- XS, Angle, A/Z, multi-particle
- Workshop March 2018
- Identified 6Li(n,t)a