The Neutron Induced Fission Fragment Tracking Experiment: High-precision Fission Cross Section Measurements with a Time Projection Chamber

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Motivation:
Study and Improve Cross-Section Ratio Systematics

- Nuclear data uncertainties strongly influence design and operation margins in nuclear defense and energy applications.
- Spread of existing data suggest uncontrolled and/or unrecognized systematic uncertainties.

\[ \frac{239\text{Pu}(n,f)}{235\text{U}(n,f)} \]

\[ \pm 1\% \text{ rectangular uncertainty on ENDF/B-VII.1} \]

Tovesson+ (J,NSE,165,224,2010)
Shcherbakov+ (S,ISINN-9,257,2001)
Staples+ (J,NSE,129,149,1998)
Lisowski+ (S,NEANDC-305,177,1991)
Weston+ (J,NSE,84,248,8307)
Meadows (R,ANL-NDM-83,198310)
Canci+ (J,NSE,68,(2),197,197811)
Carlson+ (J,NSE,66,205,197805)
Poenitz (J,NSE,47,228,197202)
Savin+ (R,YFI-8,12,196912)
White+ (J,JNE,21,671,196708)
Smirenkin+ (J,AE,13,(4),366,1962)
Quantities in the Cross Section Ratio Equation

\[ \frac{\sigma_x}{\sigma_s} = \frac{\epsilon_{ff}^s \Phi_s}{\epsilon_{ff}^x \Phi_x} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY} (\phi_s,i \cdot n_s,i)}{\sum_{XY} (\phi_x,i \cdot n_x,i)} \cdot \frac{w_x^{-1}}{w_s^{-1}} \cdot \frac{C_{ff}^x}{C_{ff}^s} \cdot \frac{C_r^x}{C_r^s} \cdot \frac{C_{\alpha}^x}{C_{\alpha}^s} \cdot \frac{C_{bb}^x}{C_{bb}^s} \]

- Efficiency for fission fragment detection
- Relative neutron flux
- Spatial overlap of beam fluence and target thickness PDFs
- Total number of target atoms
- Detector live time
- Measured fission fragments
- Beam-induced non-fission events
- Spontaneous alpha decays
- Fission fragments with incorrect neutron energy
Time Projection Chambers

- Take 3D ‘snapshots’ of charged particle tracks
- Developed since the 1970’s for high energy physics, nuclear physics, and particle astrophysics

Unique features of the FissionTPC:
- First TPC to operate in a high energy neutron beam
- Wide dynamic range requirement – cover specific ionization range between protons and fission fragments
- High interaction rates (MBq $\alpha$-particle activity from Pu targets)
The NIFFTE fissionTPC will allow detailed study of potential systematics

- Particle identification
  - Full track reconstruction, incl. \( dE/dx \) for PID
  - Rejection of alpha & recoil backgrounds

- Target/beam non-uniformities
  - In-situ beam profiling, target radiography
  - Multi-actinide targets

- Reference standards
  - Will use H bearing gas/target to measure \((n,f)\) relative to \(^1\text{H}(n,\text{el})\)
fission TPC Design

- Dual volume MICROMEGAS TPC
- 2976 x 2 hex pads (2mm), 54mm drift length
- 95% Ar / 5% isobutane drift gas

TPC description:

M. Heffner, et. al., NIMA, 10.1016/j.nima.2014.05.057

DAQ design:

M. Heffner, et. al., IEEE TNS 60 (2013) 2196

- Custom DAQ
  - Every pad recorded at 50MHz
  - Cathode recorded at 1GHz for neutron TOF measurement
  - $55 per channel
fissionTPC Operation

- Cross-section measurements performed at LANSCE 90L beamline
- Data volume ~ 100s of TB/yr

- Wide variety of targets used & planned:
  - $^{239}$Pu, $^{235}$U, $^{238}$U, $^{252}$Cf, $^{244}$Cm
  - multi-actinide
  - thin & hydrogenous backings
  - activities as high as ~MBq
Quantities measured by the TPC

- Neutron time-of-flight measured to infer neutron energy.
- 3D ionization profile for individual tracks provides:
  - Track length
  - Total energy
  - Location & value of max ionization
  - Interaction vertex
  - Track direction
Target Atom Number Ratio

Measured using TPC, and a precision $\alpha$-particle Counting System for validation

**TPC Determination**

- Select parameter regions, identical for each target, where reliable tracking has been demonstrated
  - Avoid regions with high straggling, higher energy daughter lines, …
  - Correct for double counting and other tracking artifacts, esp. for Pu-239

**$\alpha$CS Determination**

- Counting setup defines identical & repeatable solid angle for actinide targets
- Mass Spec. results constrain isotope ratios in spectral fit

**TPC Result:** $N_{U5}/N_{P9} = 1.759 \pm 0.011$

**$\alpha$CS Result:** $N_{U5}/N_{P9} = 1.760 \pm 0.010$
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

- Wrap-around correction ($C_{bb}$) represents low-energy tail in nToF spectrum, extending into following micropulses.
- Wrap-around shape is product of cross section & neutron flux transformed into nToF domain
  - ideally requires full simulation with free geometry/spallation physics
  - At present, a logarithmic spline is used
- Fit model for single-micropulse wraparound tail to whole-macropulse structure
  - Most significant constraint on wraparound is from tail of last micropulse
Neutron Flux Profile & Attenuation
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
Neutron Flux Profile & Target Overlap

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

‘Fission/Alpha’ distribution provides representation of neutron beam flux profile at each energy; MCNP profile translated & scaled to match via fit to account for model/data discrepancies.

Fission/Alpha (data)  Alphas (data)  FF/alpha (data)  Raw MCNP Beam Profile

FY17 Pu-239/U-235 data set

Before TPC Rotation

After TPC Rotation

Alphas (data)

Raw MCNP Beam Profile

Scaled MCNP Beam Profile

(These profiles do not cover same neutron energy range, but pictorially represent the procedure)
Fission Fragment Efficiency

Developed phenomenological model to describe fragment detection efficiency

- Incorporates myriad of effects:
  - fragment straggling in target
  - fission product yields
  - fragment stopping power
  - quantum and kinematic anisotropy
  - target thickness, composition, and surface roughness.
- Implemented via multi-parameter fit of observable distributions to Monte Carlo data realizations

\[
\frac{\sigma_{\text{eff}}}{\sigma_s} = \frac{\epsilon_{\text{eff}}}{\epsilon_s} \cdot \frac{N_s}{N_x} \cdot \frac{\sum_{XY} (\phi_{s,i} n_{s,i})}{\sum_{XY} (\phi_{x,i} n_{x,i})} \cdot \frac{w_{s}^{-1}}{w_{x}^{-1}} \cdot \frac{(C_{s}^{x} - C_{s}^{x}) - C_{s}^{x}}{(C_{s}^{x} - C_{s}^{x}) - C_{s}^{x}}
\]

\[
\text{U-238: } 1.3 < E_n < 2.5 \text{MeV} \quad \text{U-235: } 0.16 < E_n < 0.42 \text{MeV}
\]

Figures from forthcoming U-238/U-235 ratio publication submitted to PRC

Fractal model of target surface roughness

Data

Simulation

Measured fragment energy

Lawrence Livermore National Laboratory

LLNL-PRES-705783
Uncertainty & Validation

- Residual (unaccounted for) systematic uncertainties estimated by **cut variation**
- Uncertainty propagation & covariance performed by sampling fit parameter dists.
- Validations performed by **TPC rotation** and **data set decimation**, e.g.:
  - Odd vs. Even run numbers
  - Morning vs. Night (time of day)
  - First vs. Last half of run
U-238/U-235 Fission Cross Section Ratio

- Used ‘half moon’ actinide deposits on thin backing
- Unable to normalize neutron flux using recoil protons due to gain non-uniformity, energy dependent spatial variation (acceptance) and possible TPC tilt
- Therefore, normalized to ENDF/B-VIII.\(\beta 3\) at 14.5 MeV

Fission Vertices

Figures from forthcoming U-238/U-235 ratio publication submitted to PRC
Pu-239/U-235 Fission Cross Section Ratio

- Used back-back deposits on thick backing – x-y overlap allows neutron flux normalization as described earlier
- Performing final validations of efficiency model, including TPC rotation
- Preliminary ratio presented here
  - Approaching 1% relative uncertainty goal, with primary contributions coming from normalization, efficiency model, and event statistics

Aim to submit Pu-239/U-235 ratio publication before end of 2017
Conclusion

- The NIFFTE fissionTPC can probe systematic uncertainties in fission cross-section measurements

- The fully instrumented TPC has been operating since 2013

- Instrument performance has been being characterized through a broad range of measurements & detailed simulation studies

- $^{239}\text{Pu}(n,f)/^{235}\text{U}(n,f) \ & \ ^{238}\text{U}(n,f)/^{235}\text{U}(n,f)$ cross section ratio, $^{235}\text{U}$ Fission Anisotropy measurements nearing publication

- $^{239}\text{Pu}(n,f)/^{1}\text{H}(n,\text{el})$ measurements will be the focus of future data taking periods
Backup Slides
**Fission TPC Time-of-Flight**

**U238 & U-235 ToF Distribution**

- Timing resolution = 2.03 ns FWHM
- Better or comparable to fission chamber

![ToF Distribution Graph](image1)

**Flight Path Length Measurement**

- Carbon-filter technique
- Flight Path = 8059 ± 3 (stat) ± 1 (syst) mm
- Validated with auxiliary fission chamber data and physical measurements

![Flight Path Graph](image2)