Nuclear Data Measurement and Analysis at RPI

2019 Report at CSEWG

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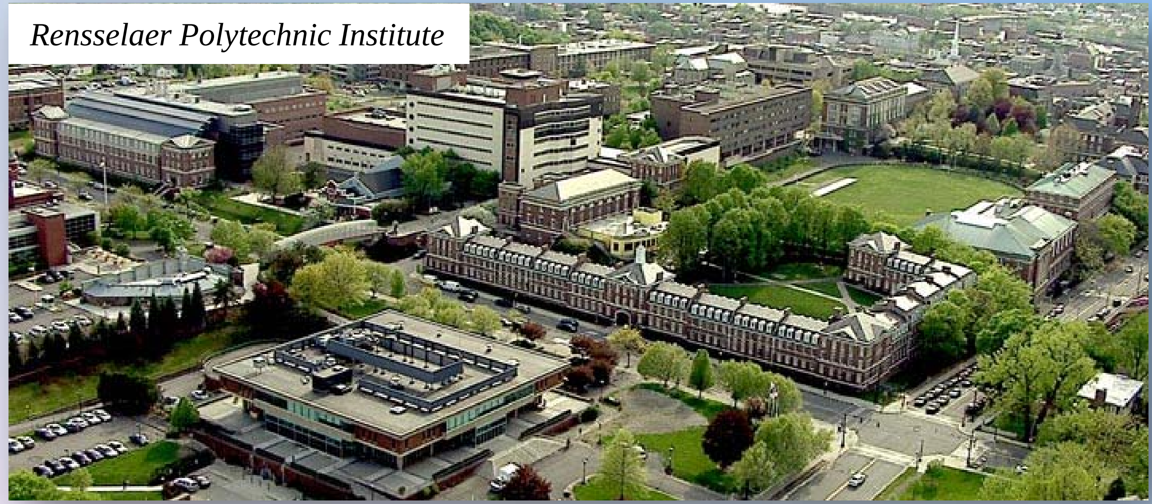

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CSEWG meeting, November 4, 2019 @ BNL

Research was partially supported by NCSP, and SSAA (DE-NA0002906)

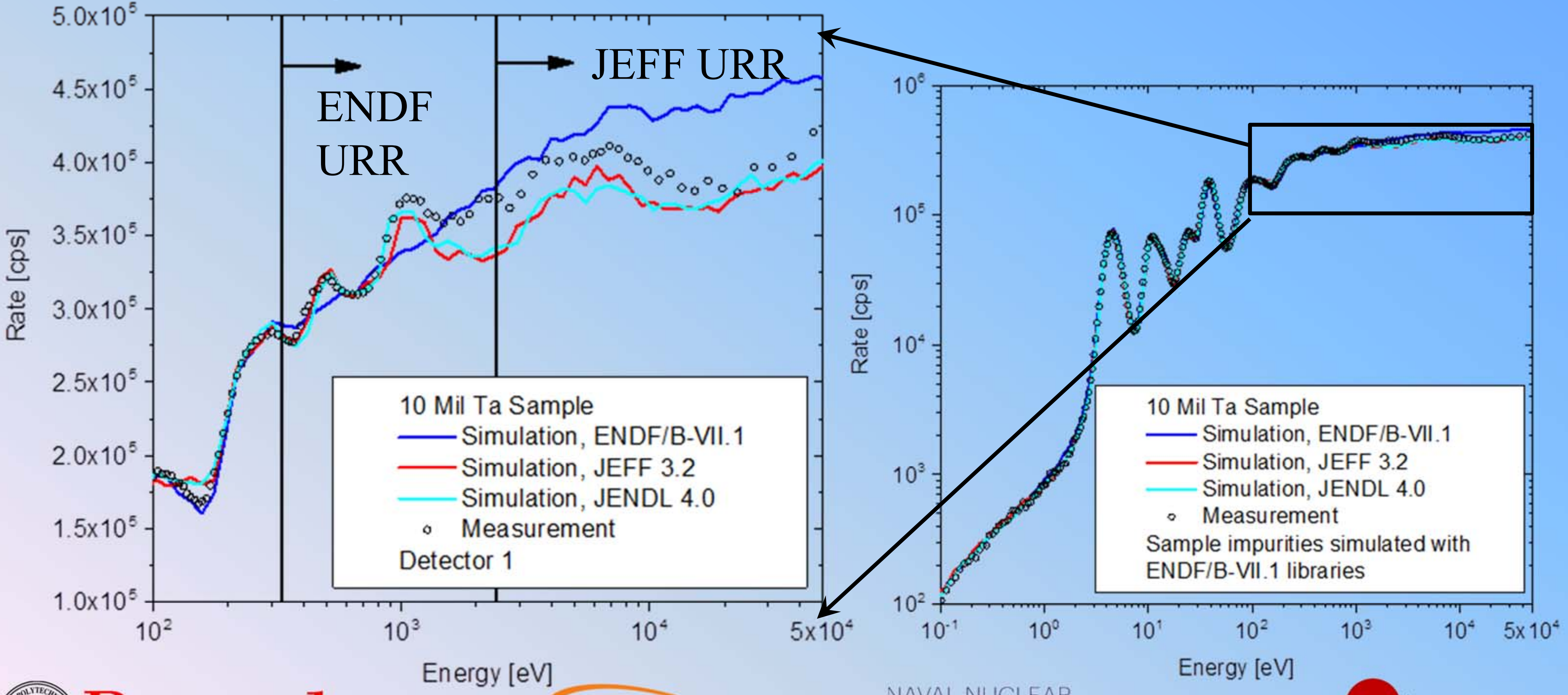
Outline

- **Neutron Transmission and Capture Measurements**
  - Ta resonance parameter in RRR and URR
- **KeV Neutron Scattering**
  - Progress for Zr and Cu
- **Fast Neutron Scattering**
  - Progress for U-235 and Pu-239

Ta Neutron Transmission and Capture analysis in the RRR and URR

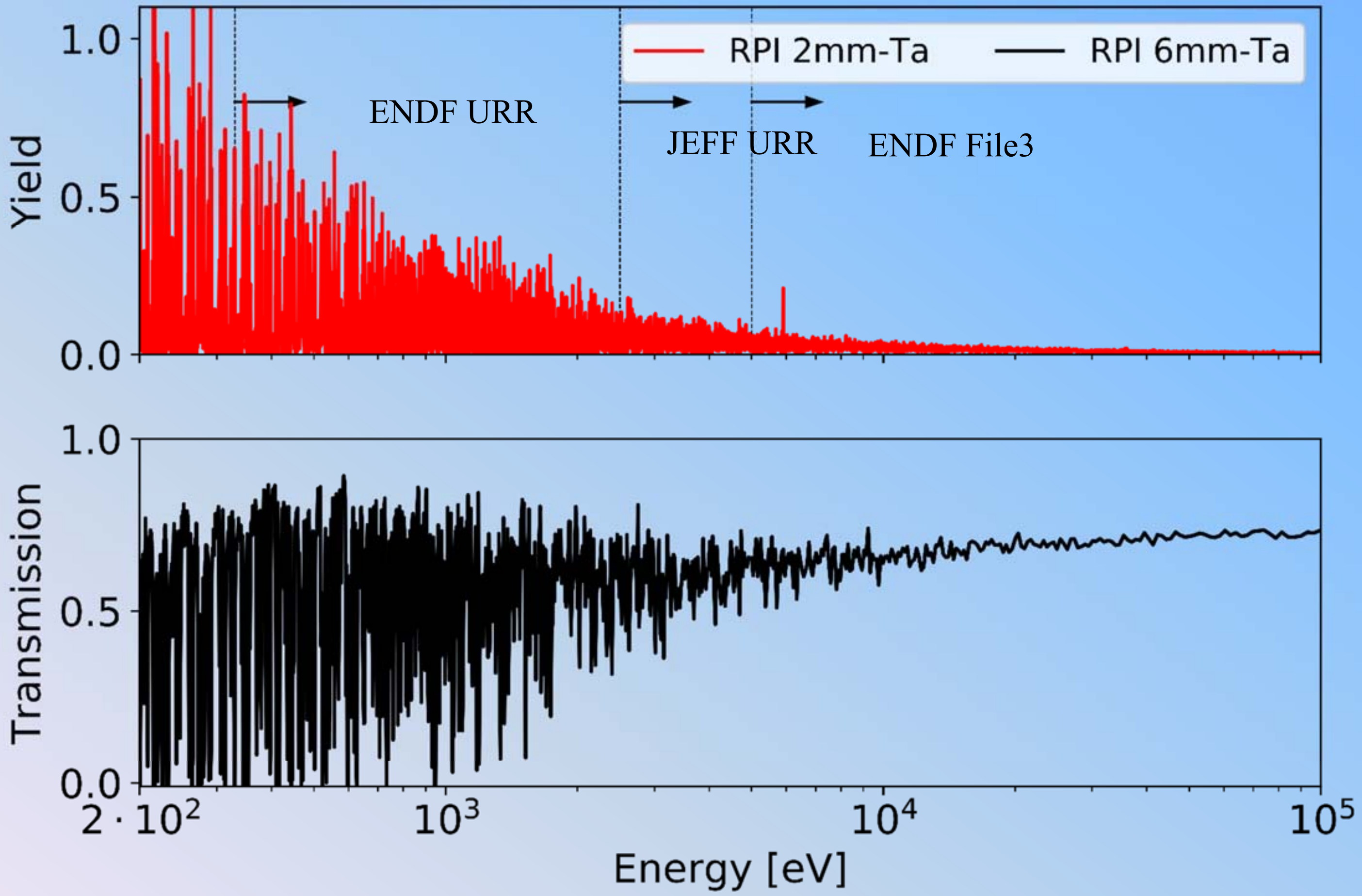
Ta URR measurements - Motivation

- Discrepant evaluated libraries
- Simple isotope for testing URR methodology
- Lead Slowing Down Spectrometer (LSDS) study: Discrepancies between libraries in simulated capture rate



Ta Transmission and Capture Measurements

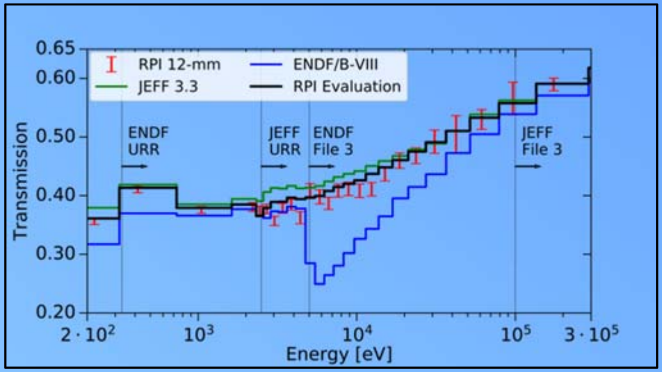
- Used 100m flight station for transmission and 45m for capture
  - Sample thicknesses included: 1, 3, 6 mm Ta.
- High resolution data resolving resonance structure up to 10 keV
- URR self-shielding test using transmission through a thick 12mm Ta sample



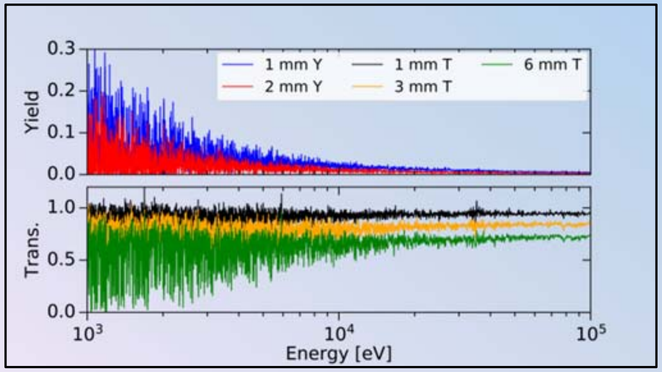
The big picture

Measurement

Validation



Evaluation



SAMMY/FITACS

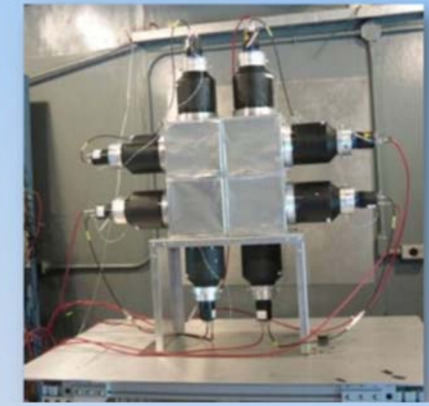
NJOY21

MCNP 6.1

Novel Use of Thick-Sample Transmission Measurement: Validating the URR

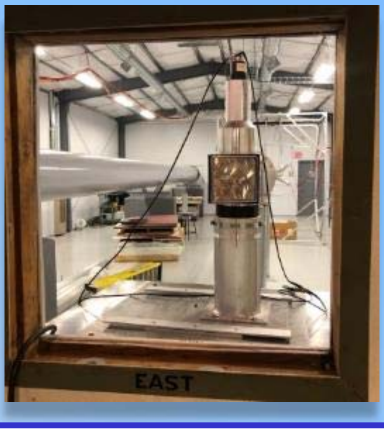
Detectors and Measurements

MELINDA (100m)



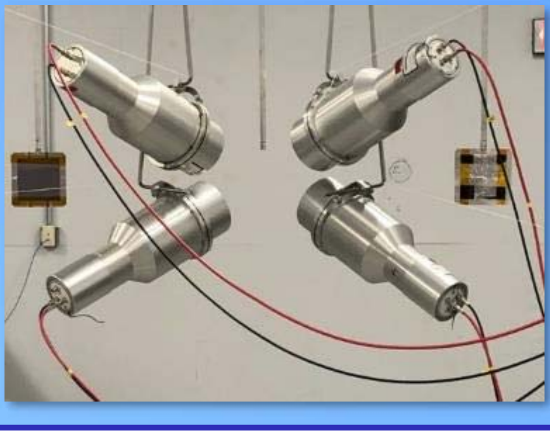
- High energy resolution
- Fast timing
- Large active detector area
- Data-processing well understood

^{6}Li glass (35m)



- Relatively good energy resolution
- Fast timing
- Shorter flight-path enables greater count rate
- higher count rate allows freedom of neutron targets

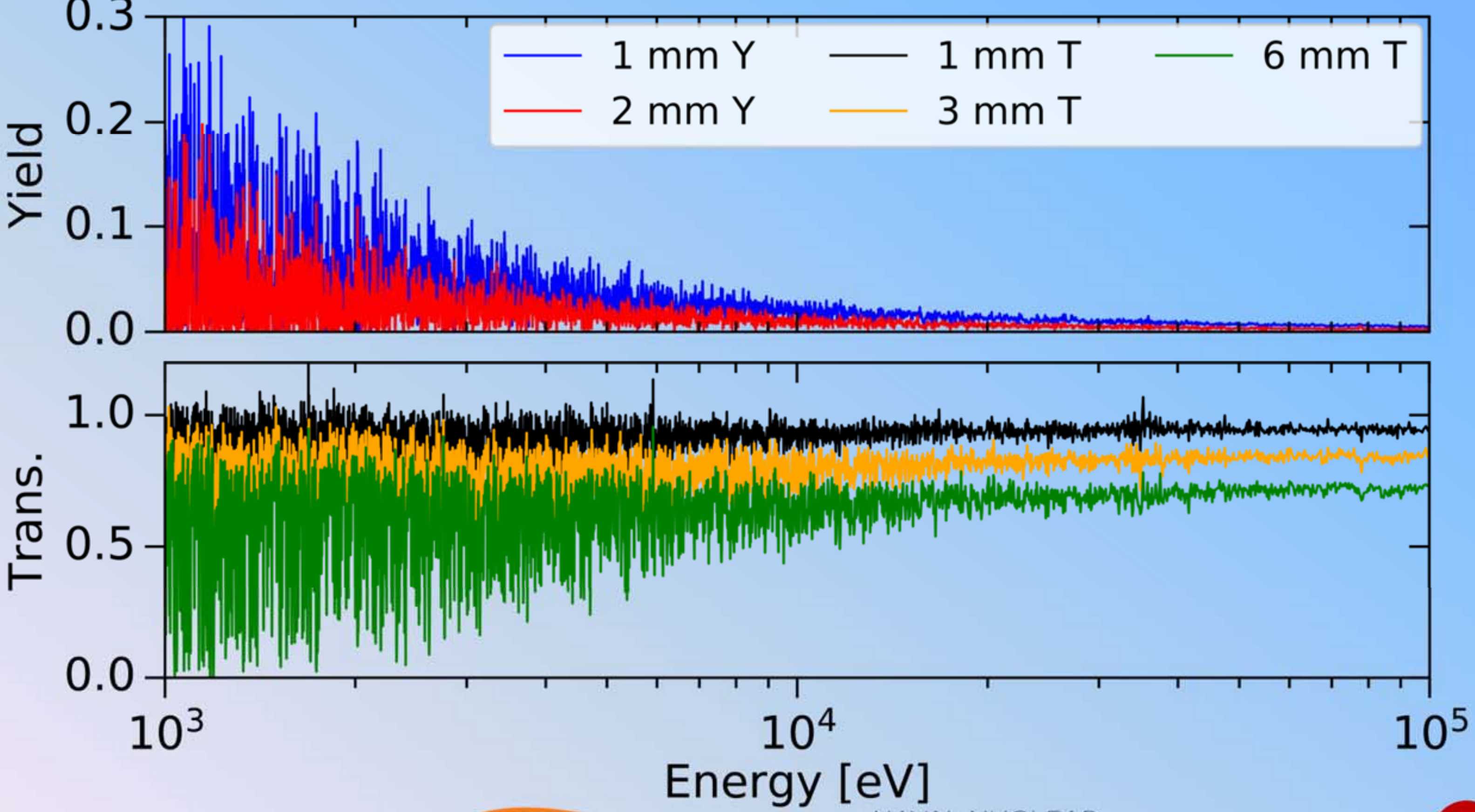
C_6D_6 Detector (45m)



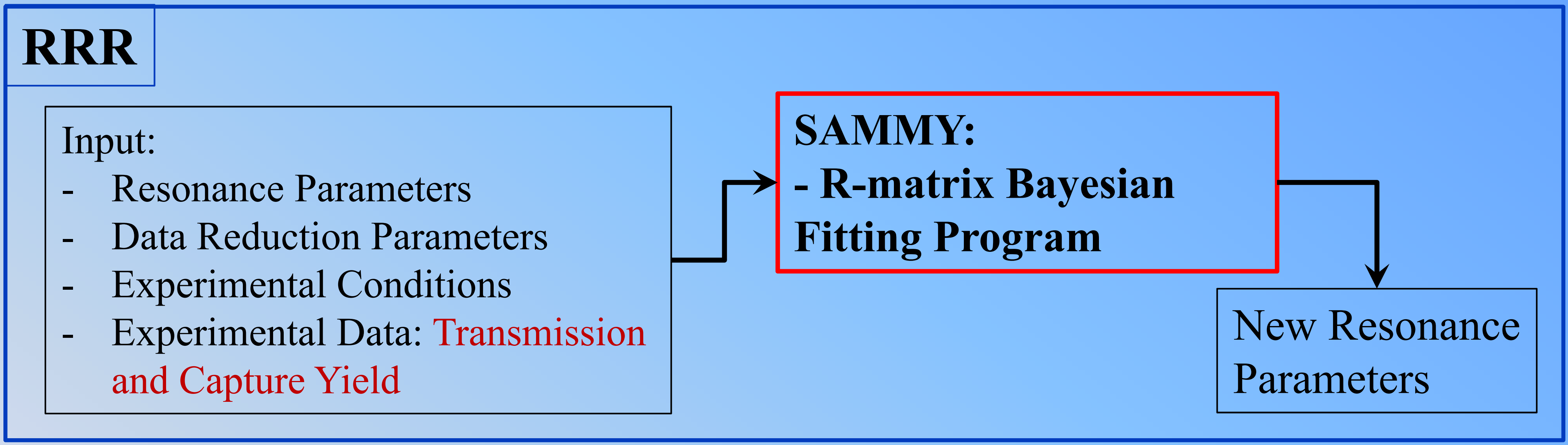
- Highest energy resolution for capture at RPI
- Low Neutron sensitivity
- Designed with digital acquisition system

Data to Evaluate

- ^{181}Ta Evaluation Datasets:
- Capture Yield: 1 and 2 mm
- Transmission: 1, 3, and 6 mm



SAMMY Evaluation

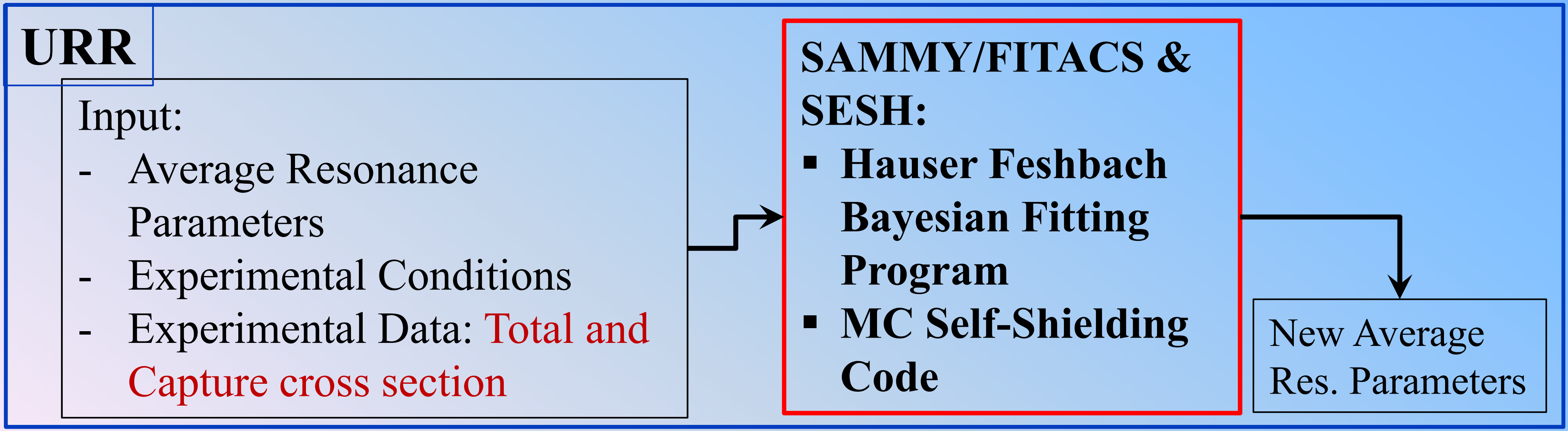


RRR

Input:
- Resonance Parameters
- Data Reduction Parameters
- Experimental Conditions
- Experimental Data: Transmission and Capture Yield

SAMMY:
- R-matrix Bayesian Fitting Program

New Resonance Parameters



URR

Input:
- Average Resonance Parameters
- Experimental Conditions
- Experimental Data: Total and Capture cross section

SAMMY/FITACS & SESH:
- **Hauser Feshbach Bayesian Fitting Program**
- **MC Self-Shielding Code**

New Average Res. Parameters

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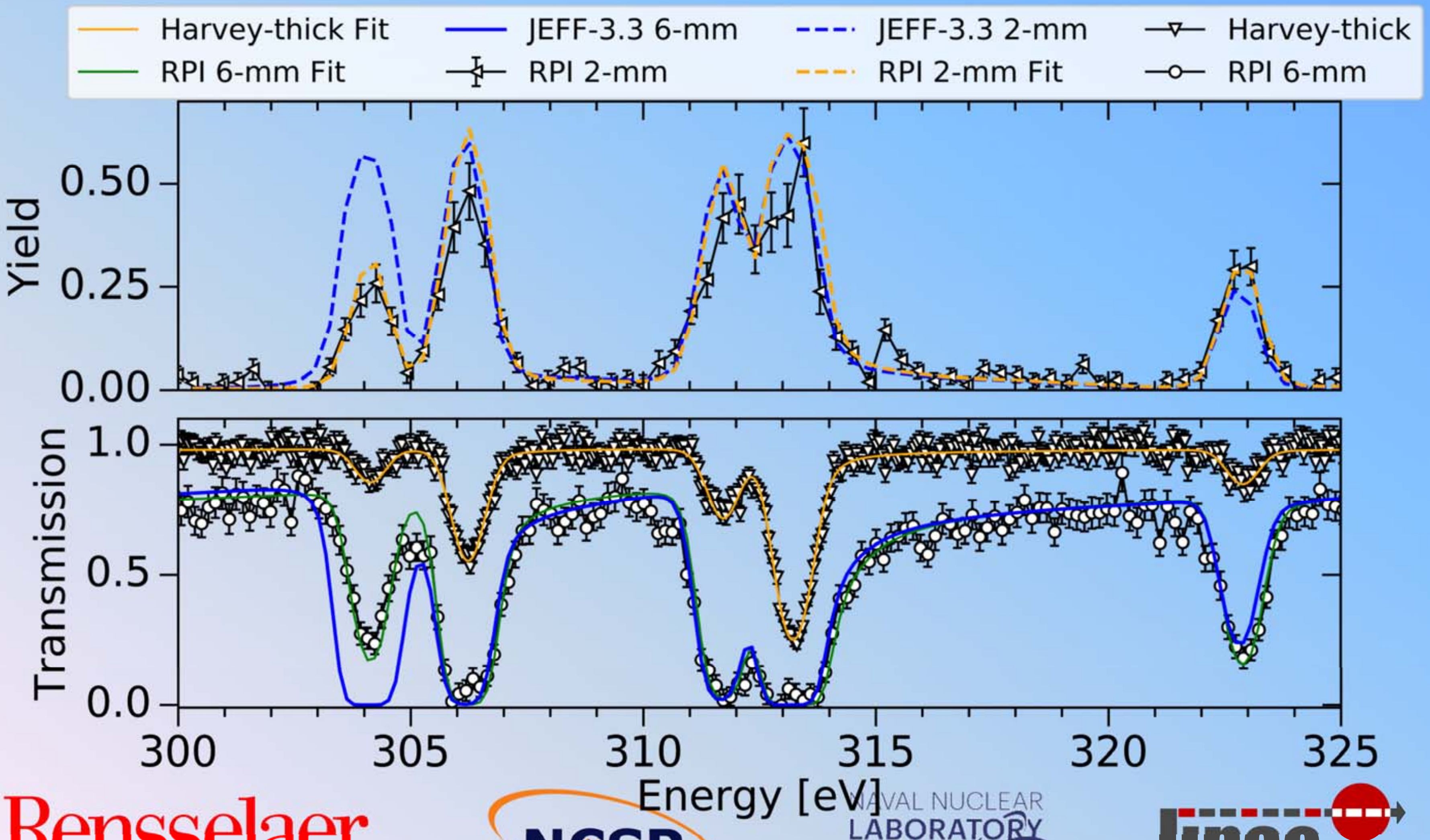
Data to Evaluate: RRR (one example)

End of ENDF/B-VIII.0 RRR:

- 304 eV resonance updated
- Transmission and capture yield are well resolved



URR Transmission Enhancement Math

Neutron transmission at energy E: $T(E) = e^{-n\sigma_t(E)}$

The "true" average transmission from energy E_1 to E_2

$$\langle T\rangle = \frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-n\sigma_t(E)}dE = \frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-n[\sigma_t(E)+\langle\sigma_t\rangle-\langle\sigma_t\rangle]}\,dE$$

$$\langle T\rangle = e^{-n\langle\sigma_t\rangle}\overbrace{\frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-n[\sigma_t(E)-\langle\sigma_t\rangle]}dE}^{\text{Enhancement due to }\sigma_t(E)\text{ fluctuations}}$$

Note: positive and negative contributions

$$\boxed{\text{sft(E)}= \frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-n[\sigma_t(E)-\langle\sigma_t\rangle]}dE} \qquad \boxed{\bar{T} = e^{-n\langle\sigma_t\rangle}}$$

Self-shielded

$\langle T\rangle = \bar{T} * sft(E)$ where sft$(E) > 1$, → $\boxed{\langle T\rangle > \bar{T}}$ → $\boxed{\langle\sigma_t\rangle < \bar{\sigma}_t}$

Evaluation procedure must preserve the fluctuations of $\sigma_t(E)$

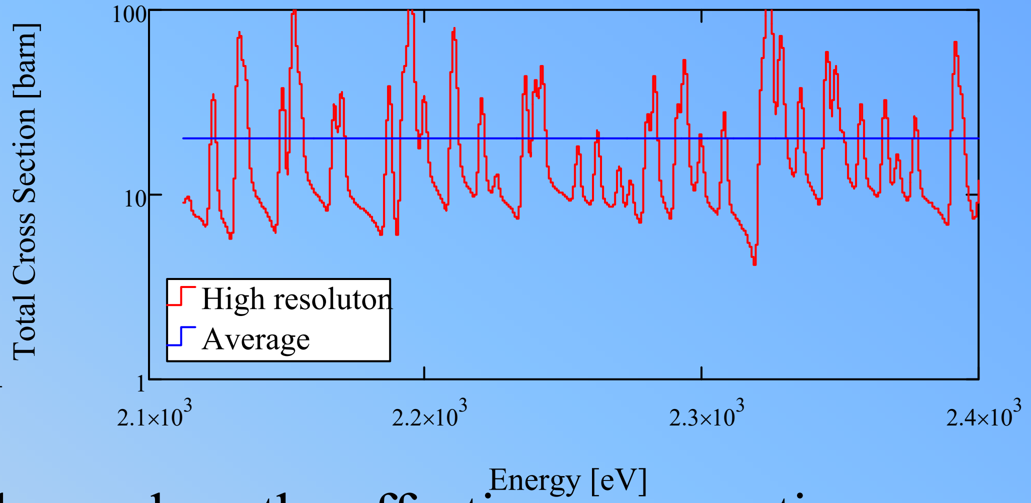
URR Transmission Enhancement Example

- Example calculating neutron transmission through a 6 mm Ta sample
- If the cross section was known in high energy resolution, the “true” transmission:

$$\boxed{\langle T\rangle = \frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-N\cdot\sigma_t(E)}dE = 0.59}$$

- If we use the average cross section :

$$\bar{T} = \frac{1}{E_2-E_1}\int_{E_1}^{E_2} e^{-N\cdot\langle\sigma_t\rangle}dE = e^{-N\cdot\langle\sigma_t\rangle} = \xcancel{0.51}$$



- Fluctuations enhance transmission and thus reduce the effective cross section (relative to the average) hence the term self shielding
- When measuring the total cross section with a thick sample a correction for the self shielding is needed.
  - Can use two sample thicknesses →
  - Can use a model based approach → SESH

Froehner, et al, “Cross-section fluctuations and self-shielding effects in the unresolved resonance region “, International Evaluation Co-operation volume 15 (NEA-WPEC--15), Nuclear Energy Agency of the OECD, NEA, (1995).

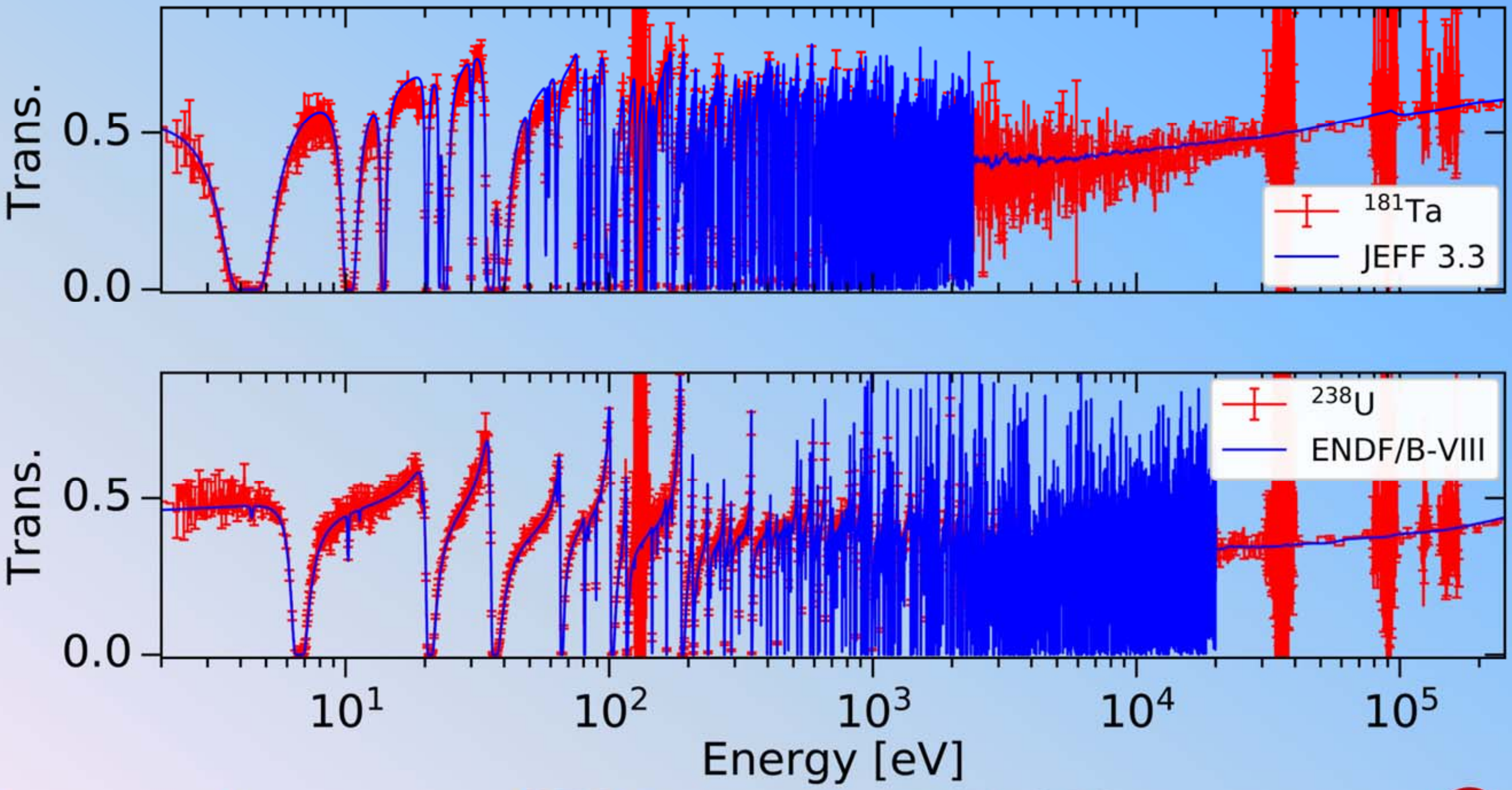
Thick sample Transmission for URR validation

- ^{6}Li doped scintillating glass detector at flight path of 35 m
- 2 PMT’s viewing a light tight aluminum case

“A window to better nuclear data…”

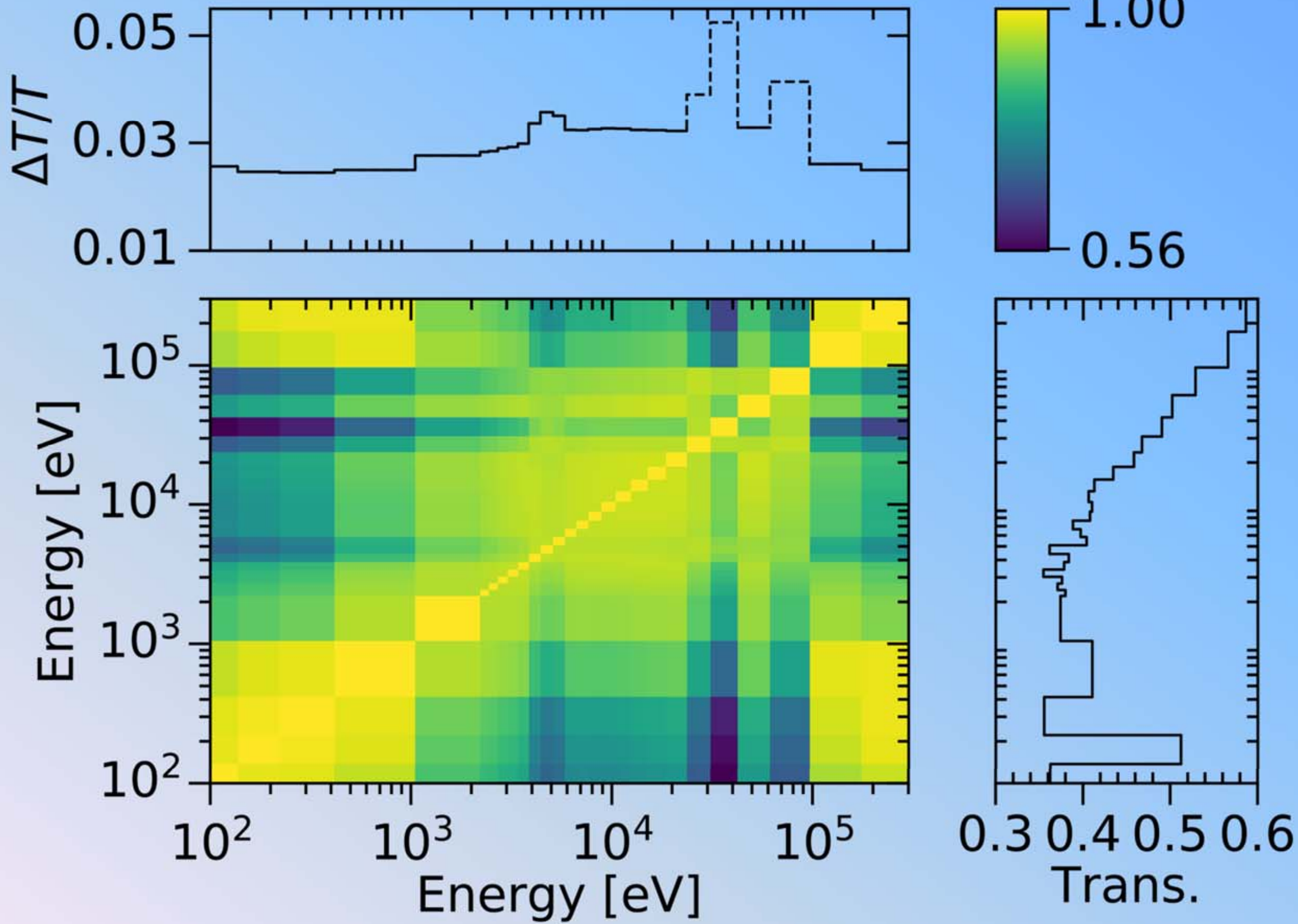
Validation transmission data

- ^{181}Ta Validation Dataset:
  - Transmission: 12 mm
  - ^{238}U verification dataset



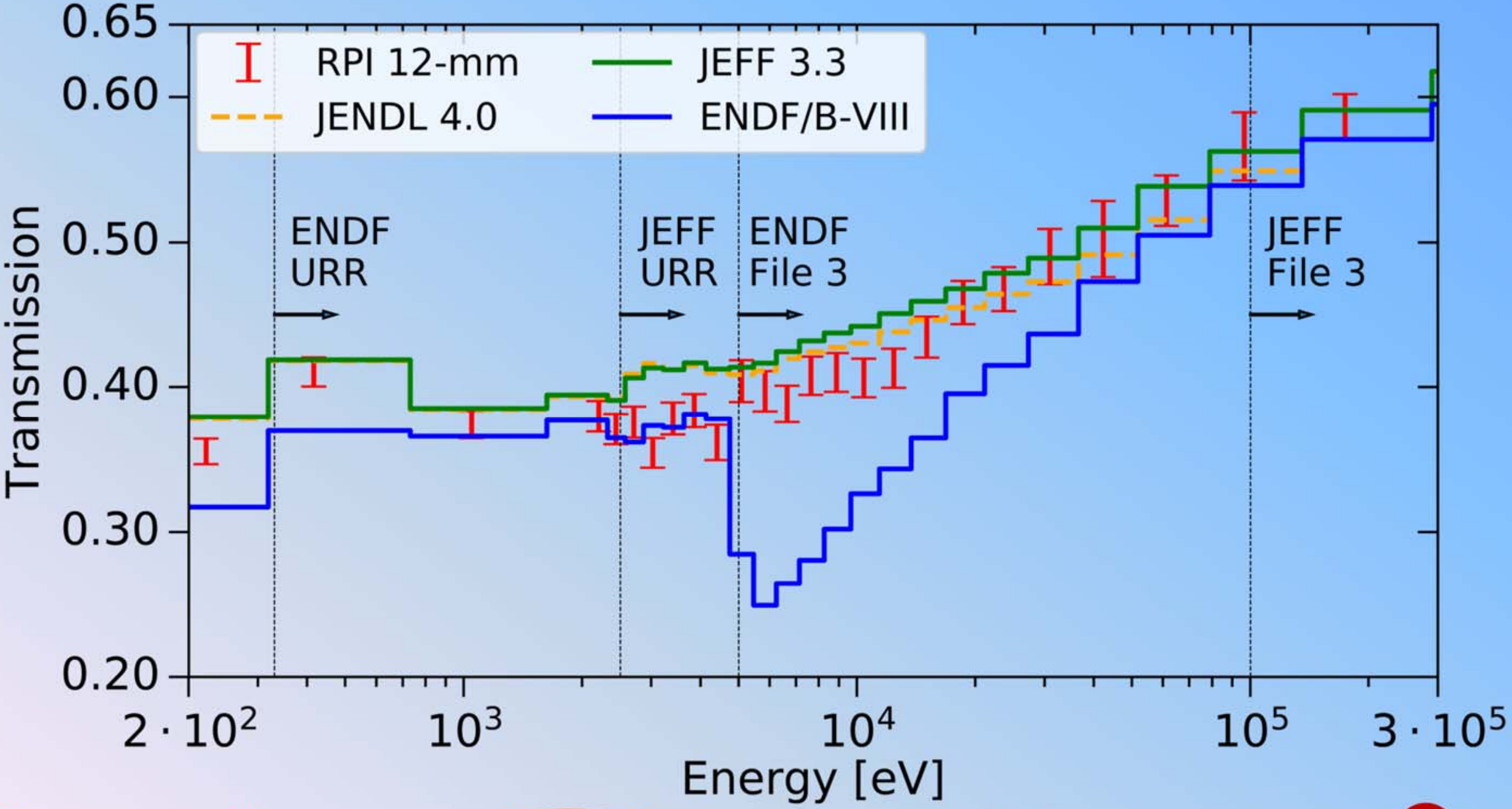
Validation Transmission

$$C_y = F_x C_x F_x^T = F_{x,stat} C_{x,stat} F_{x,stat}^T + F_{x,sys} C_{x,sys} F_{x,sys}^T$$



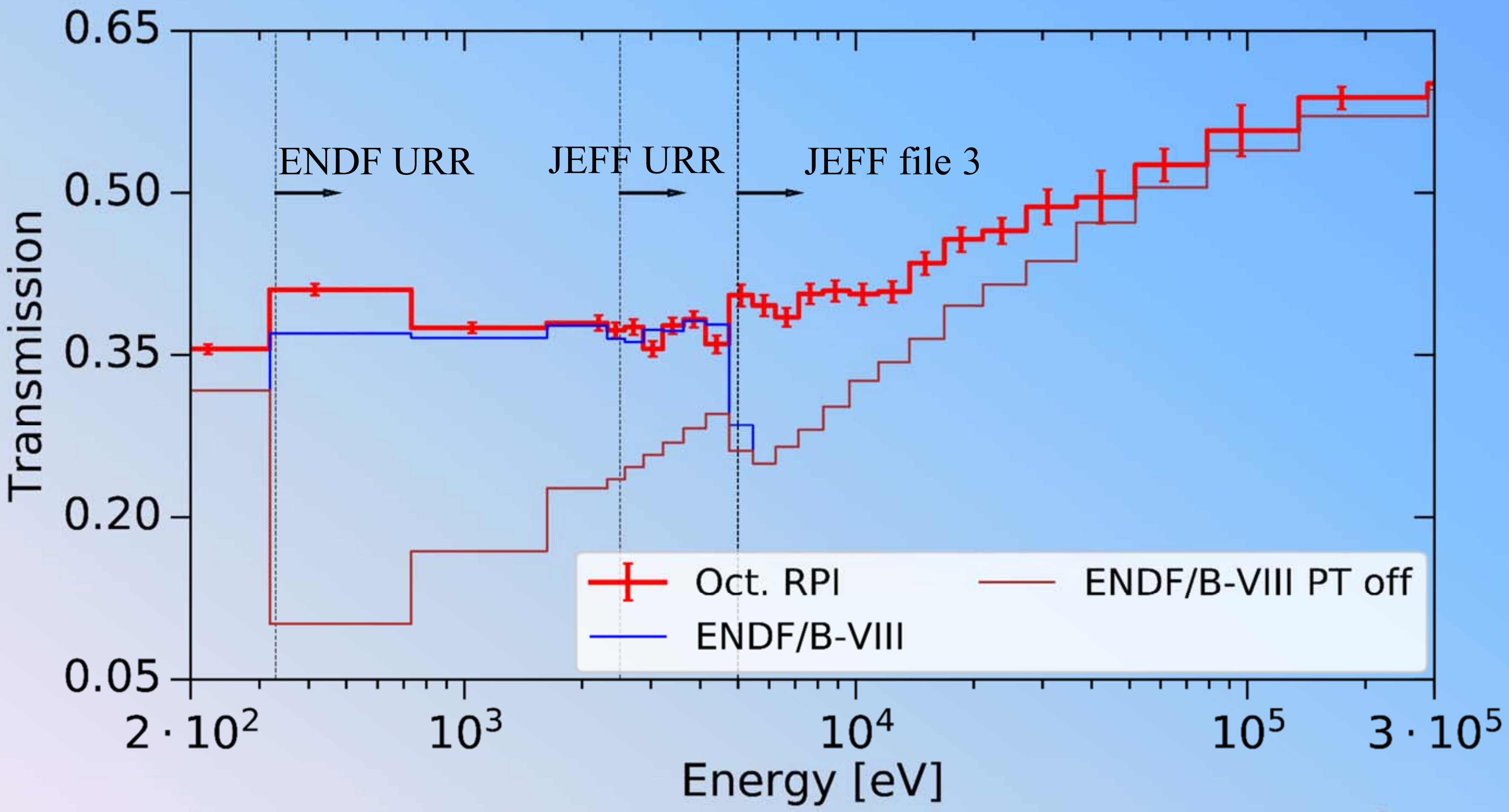
Validation Transmission and evaluations

- Transmission for 12 mm Ta sample
  - Grouped to have about 50 resonances per bin
- Observe the limitations of the URR treatment using JEFF-3.3, JENDL-4.0, and ENDF/B-VIII.0

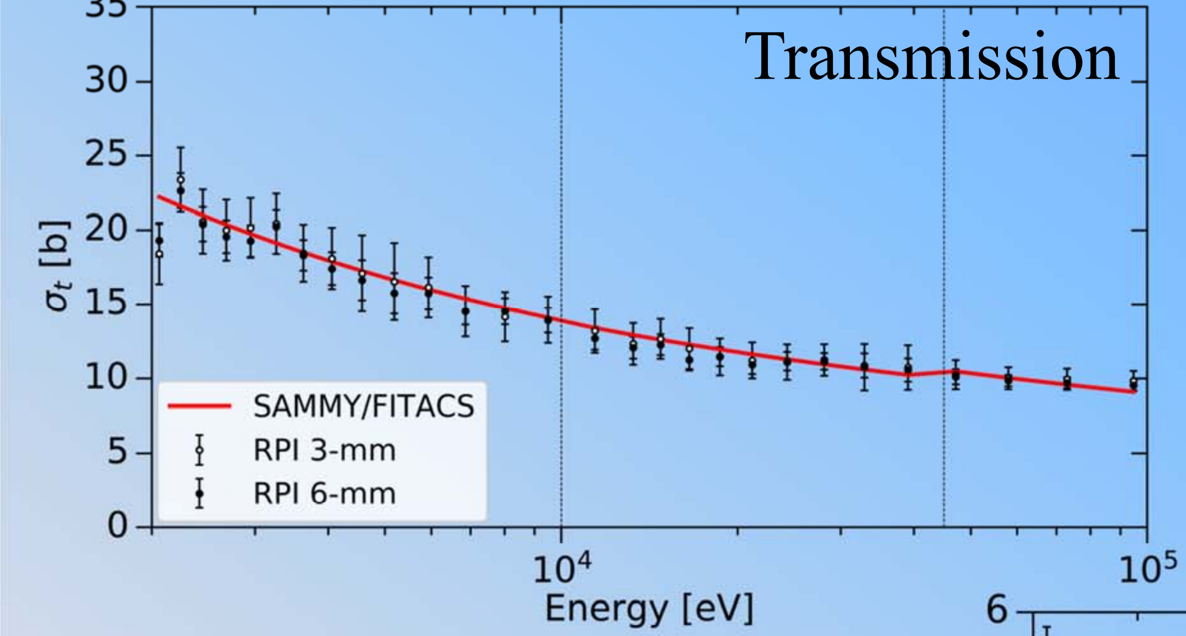


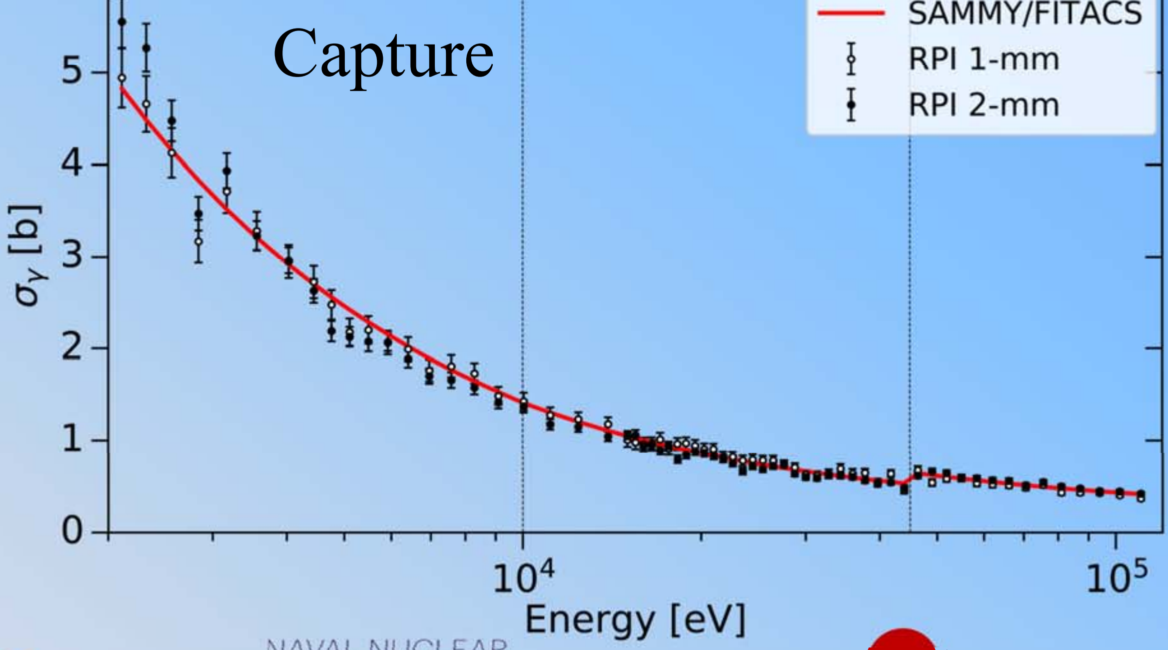
Resonance Self-Shielding effect in Ta

- The effect of self shielding is shown by turning off the URR treatment in MCNP
- Near 400 eV self-shielding reduces the transmission by a factor of about 4



Multi-Region URR evaluation



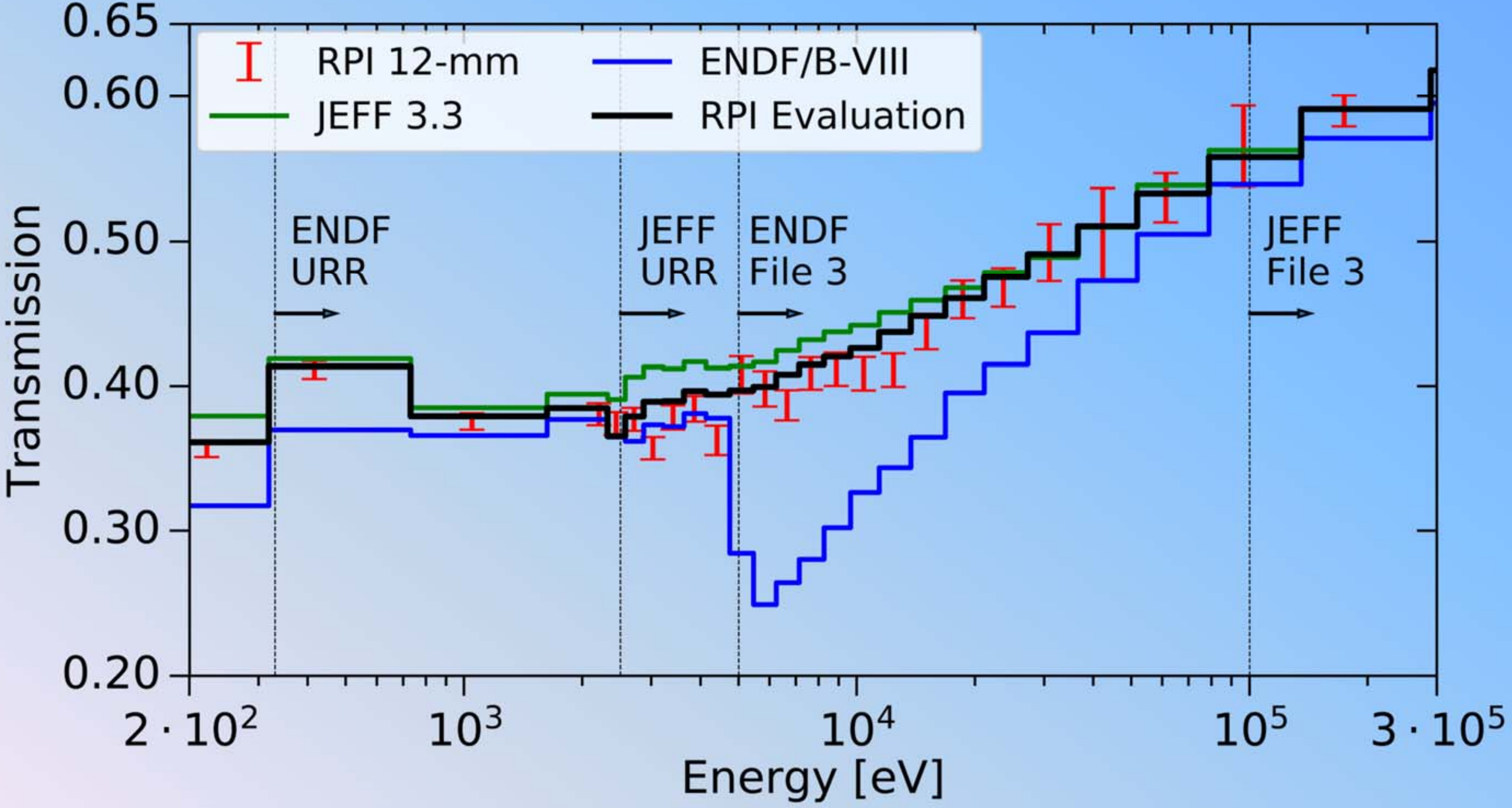


E-regions fit:

- 2-10 keV
- 10-45 keV
- 45-120 keV

RPI Evaluation: Updated JEFF-3.3

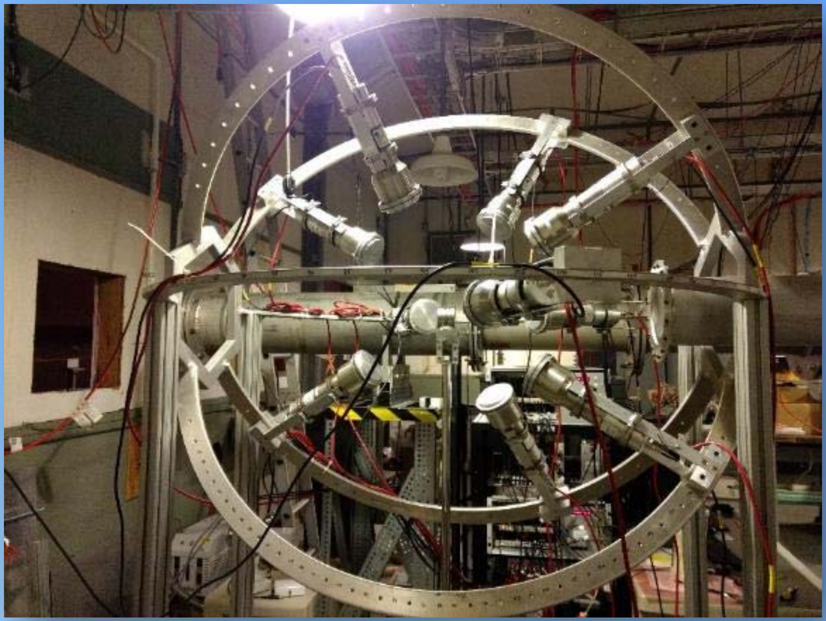
- Updated RRR and URR parameters
- Very sensitive to a_c, D and other $\langle Pars \rangle$
- Using the RPI evaluation we can improve agreement with measured data



KeV Neutron Scattering

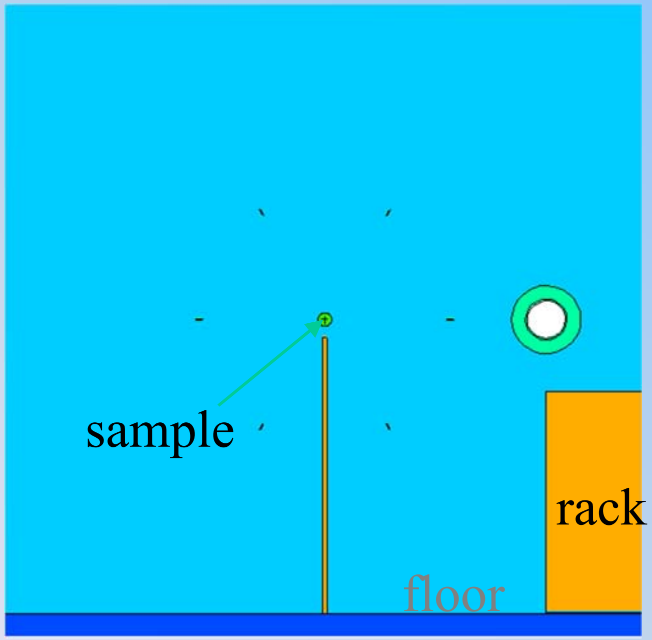
A Multi Angle Neutron Detection Array

- **Questions to answer:**
  - How well do current evaluations represent the elastic scattering cross section and angular distribution for a sample of interest?
  - Where are the problems in the sample of interest cross section or angular distribution?

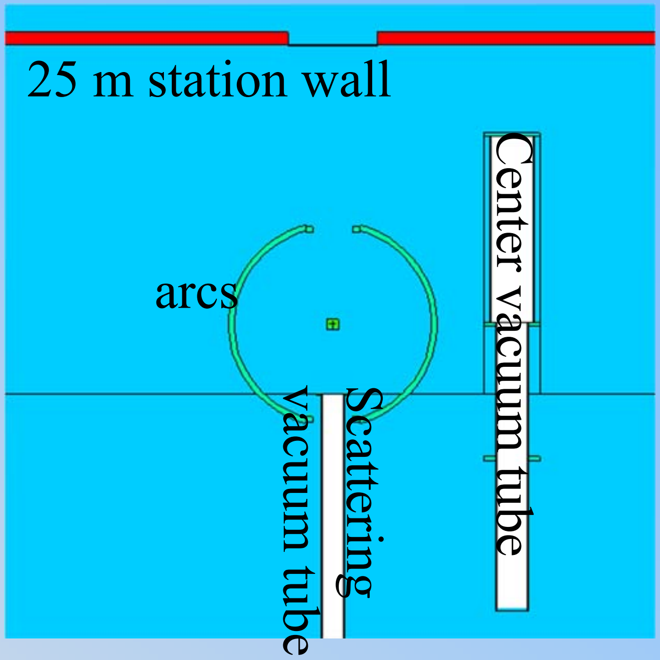


- **Detector Array**
  - 10 detectors: eight ^{6}Li neutron(+γ) detectors and 2 ^{7}Li γ detectors
    - 1.27 cm thick x 7.62 cm diam. Li-Glass
  - Detectors mounted at preset angles between 30 and 150 degrees
  - Sample changer with 3 posts moves samples in-beam
  - MCNP model of the array to test out how different evaluations reproduce scattering data

MCNP Simulation: Geometry



keV array front view cross section



keV array top view cross section

Elements included in Model:

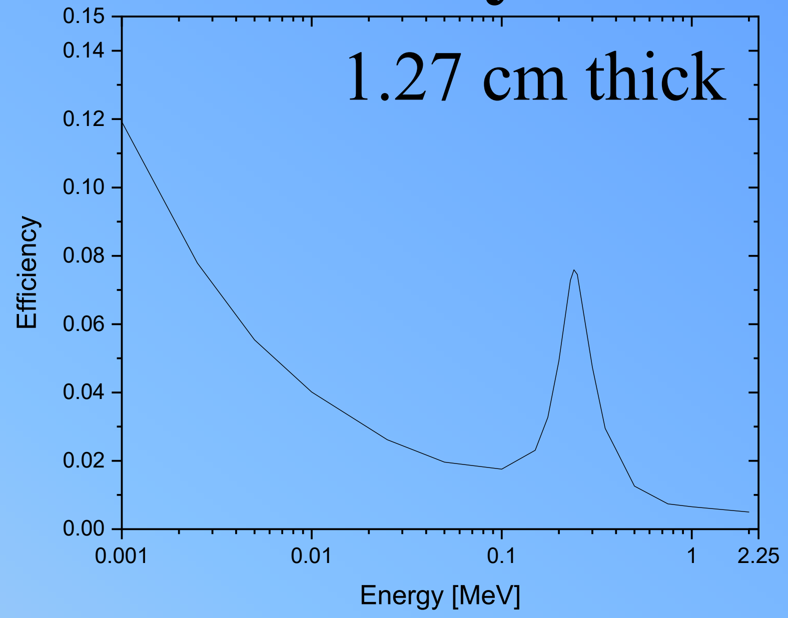
- Floor
- Filters in West beamline
- Center beamline vacuum tube
- West 25 m vacuum tube
- Wall behind the array
- Equipment rack near array

Approximations in Model:

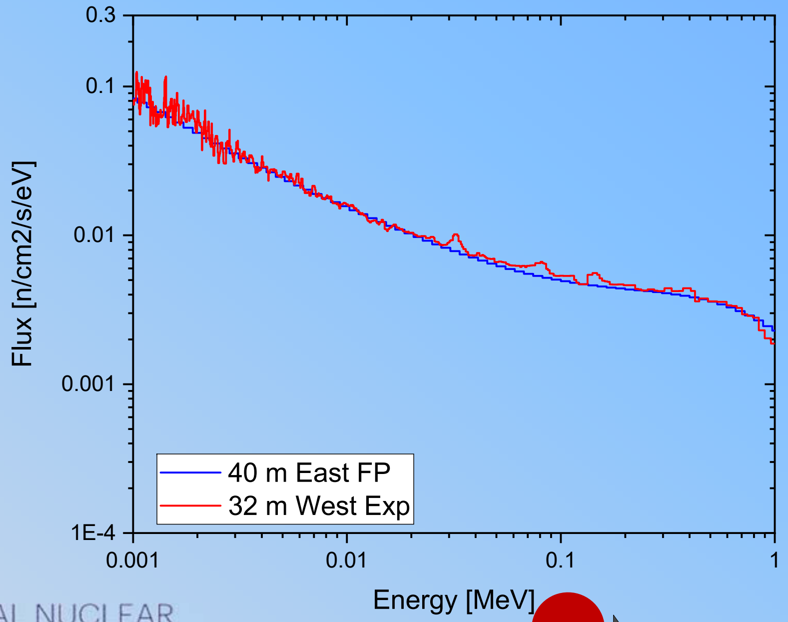
- Ideal collimation
- No materials more than 5 m from sample
- Detectors are an F5 tally convoluted with front face detection efficiency

Flux and Li-Glass Detector Efficiency

- **Li-Glass detector efficiency**
  - Efficiency modeled in MCNP
  - Efficiency shape measured with detectors in-beam and known neutron flux shape
  - Relative efficiency measurements using a slightly moderated Cf-252 source

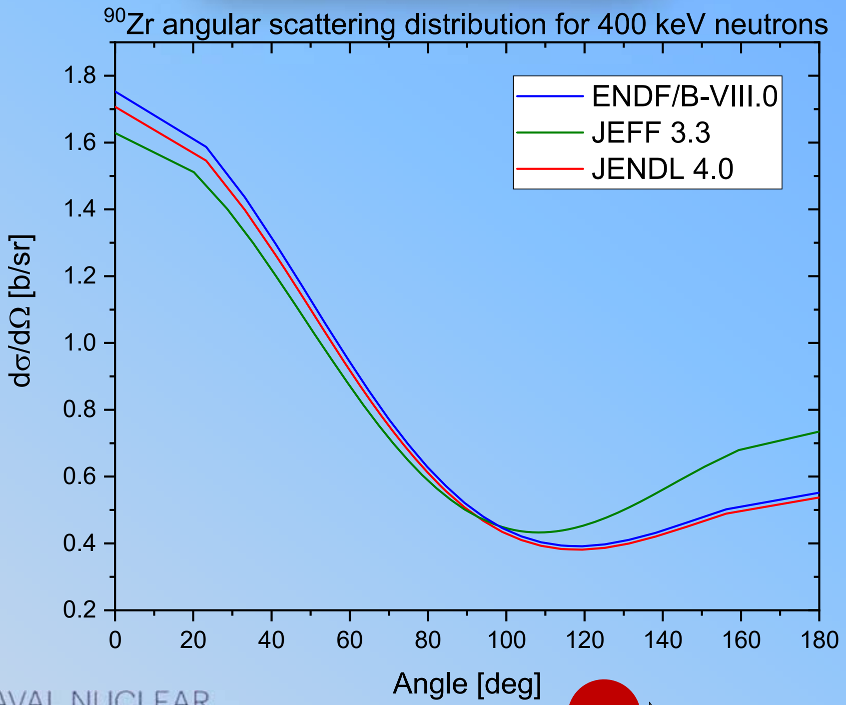


- **Neutron flux shape measurement**
  - Measured flux shape with an in-beam fission chamber
    - Some structure in the measured flux because of Al, O and N resonances
  - Consistent with previous flux measurements at 40 m East detector system



Zirconium Scattering Measurement

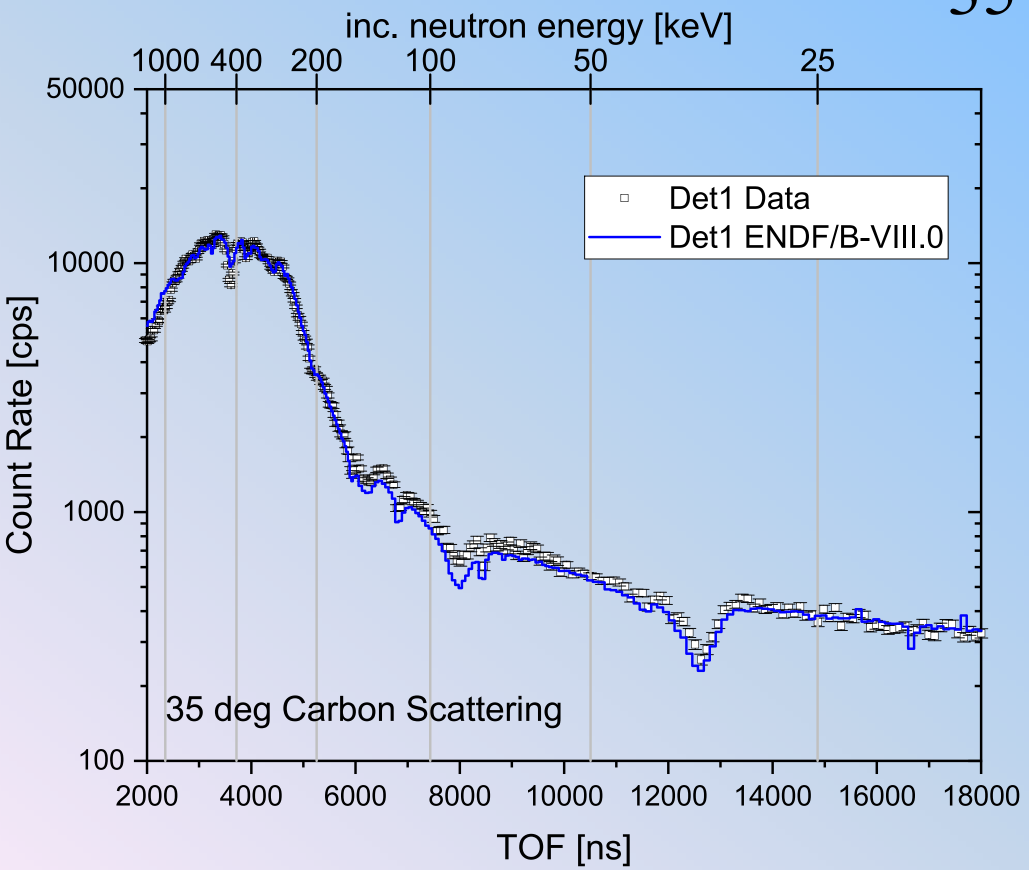
- 4 cm thick cylindrical natural zirconium sample
- 7 cm carbon sample as reference
- 1 keV to 1 MeV energy range
- Measured keV neutron scattering at 4 angles (2 detectors at each angle)
  - 35, 70, 115,150 deg

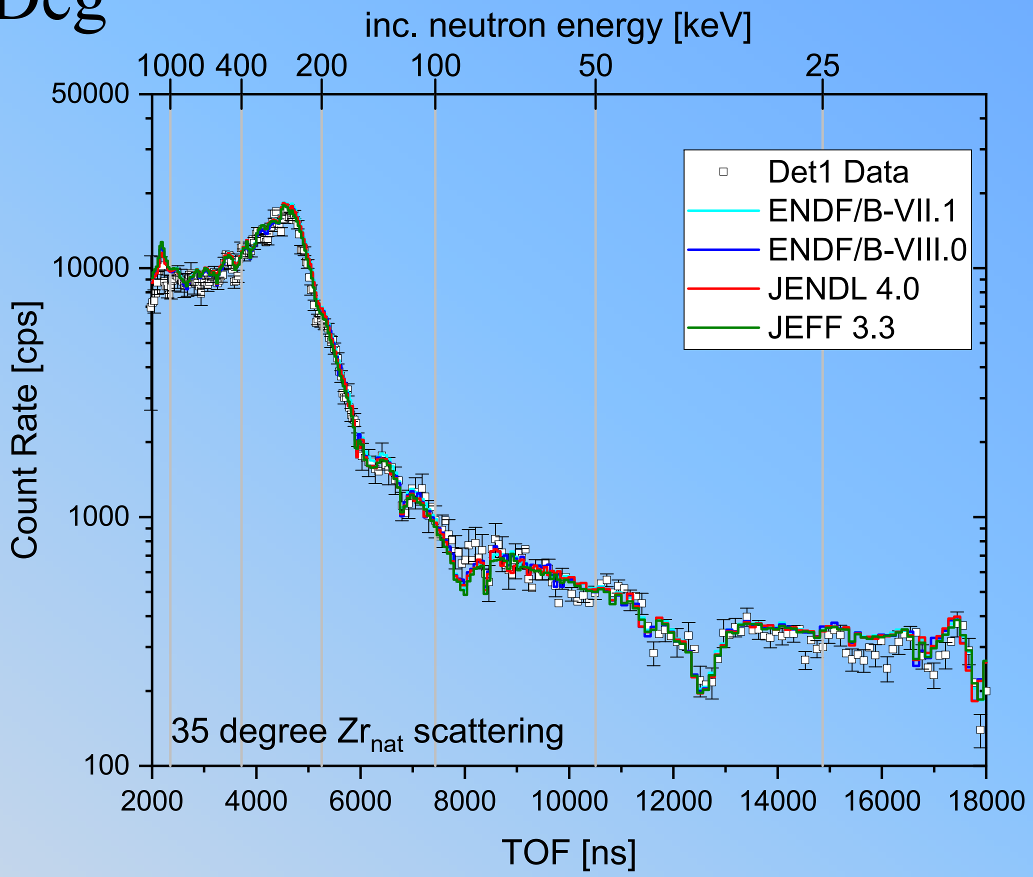


Zirconium Scattering TOF Results

- Overall good agreement between the Zr experiment and evaluations
- Carbon evaluation lower than experiment
  - Investigating possible issues with efficiency, flux, or carbon simulation

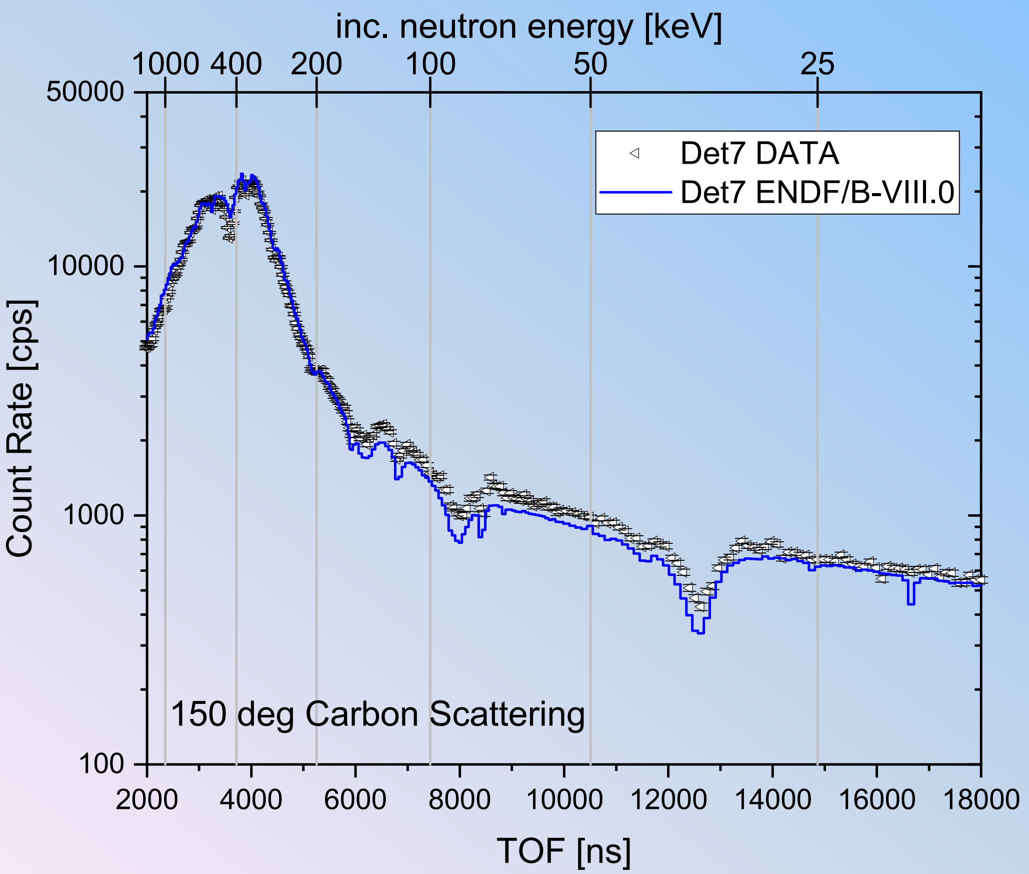
35 Deg

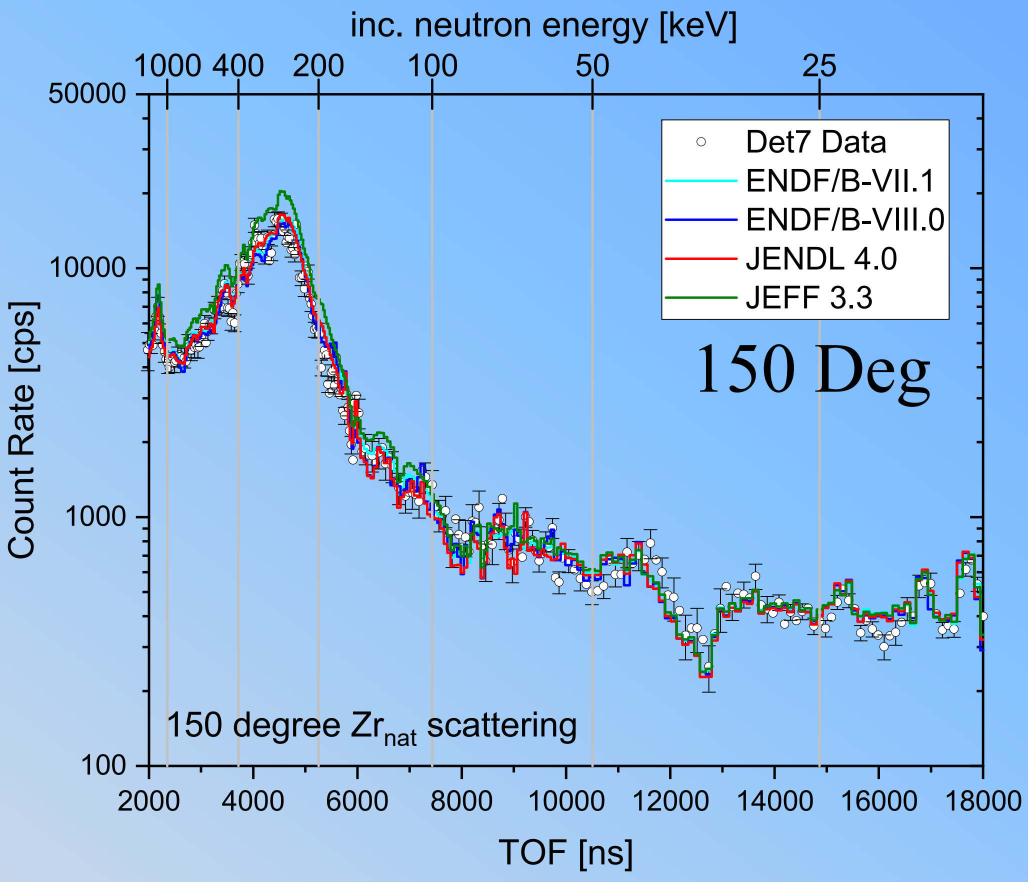




Zirconium Scattering TOF Results

- Overall good agreement between the Zr experiment and evaluations
  - JEFF 3.3 is high above 100 keV

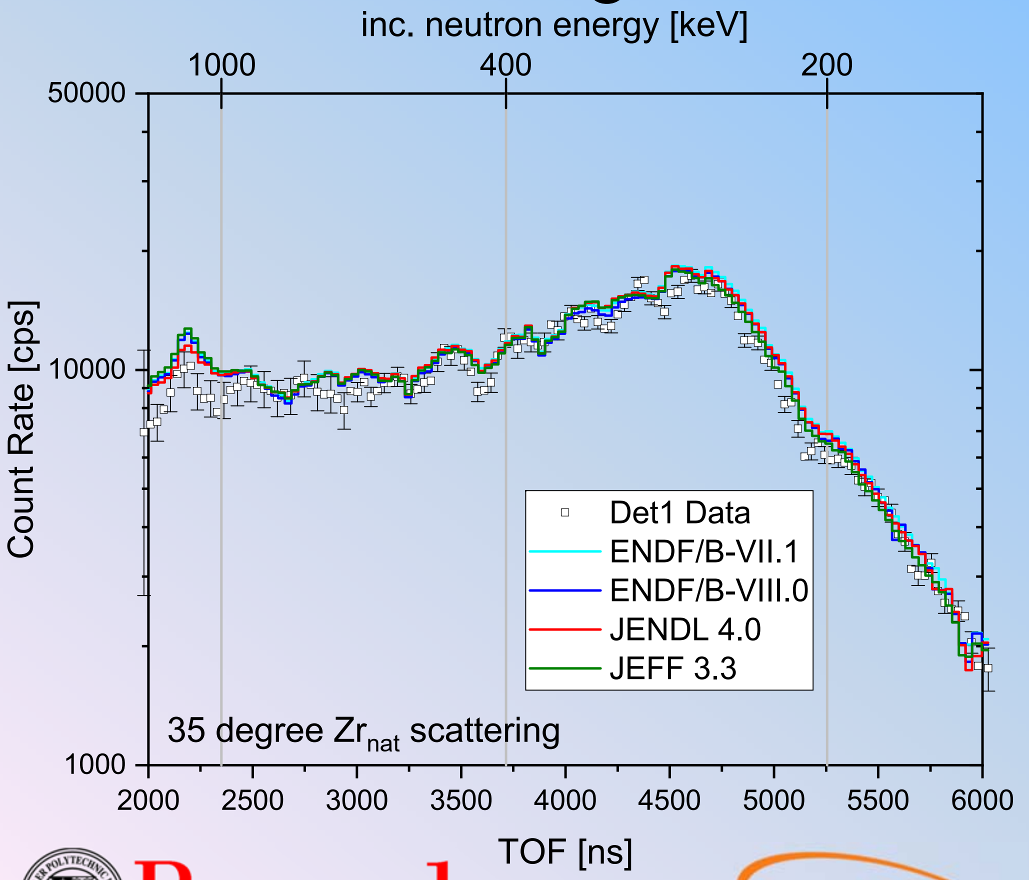




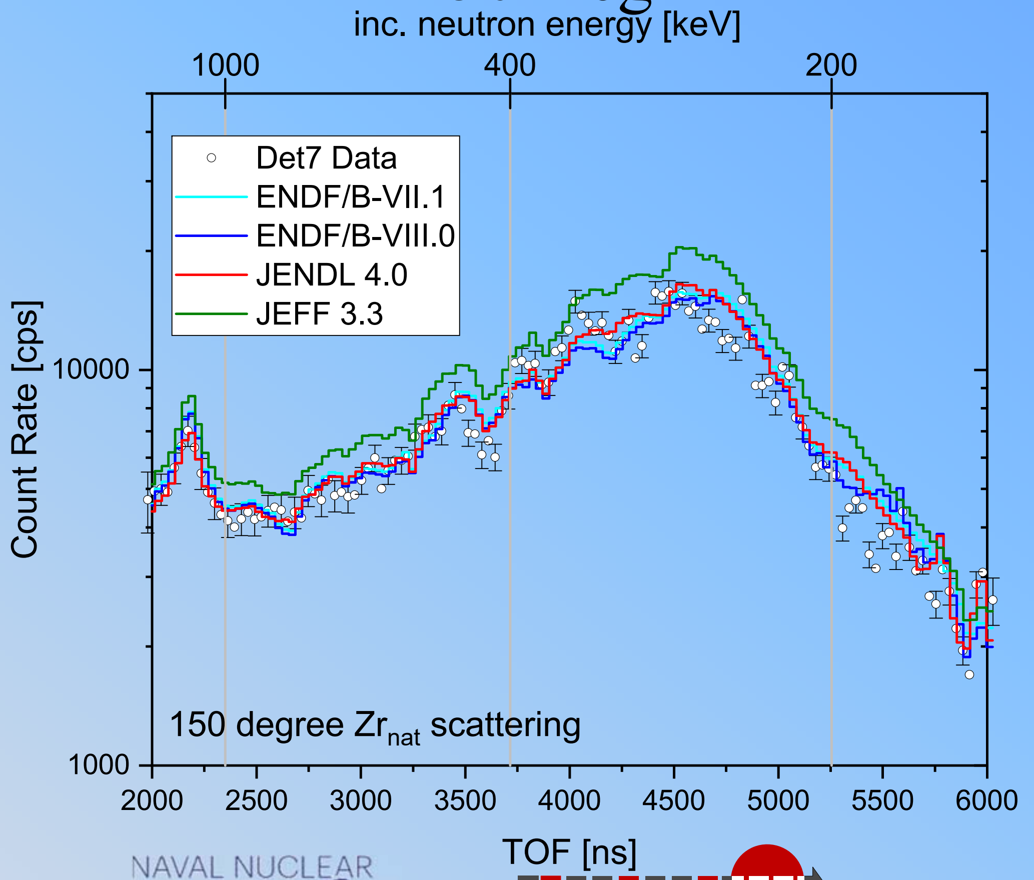
Zirconium Scattering Conclusions

- Differences between evaluations between 0.1 – 1 MeV
- The extended RRR in ENDF/B-VIII and JENDL 4.0 better reproduces the experimental data

35 Deg



150 Deg



Copper Scattering Measurement

- On the NCSP list
- Zeus benchmark
  - Intermediate energy benchmark with HEU and graphite plates and a copper reflector
  - Discrepancies in the critical benchmark
  - Possible issues in the angular distribution
- Experiment
  - 3 cm natural copper sample
  - 7 cm carbon sample as reference
  - 1 keV to 1 MeV energy range
  - Measured keV neutron scattering at 4 angles (2 detectors at each angle)
  - 35, 70, 115, 150 deg
  - Upgraded digitizer (SIS3316, 12 ch, 4 ns)

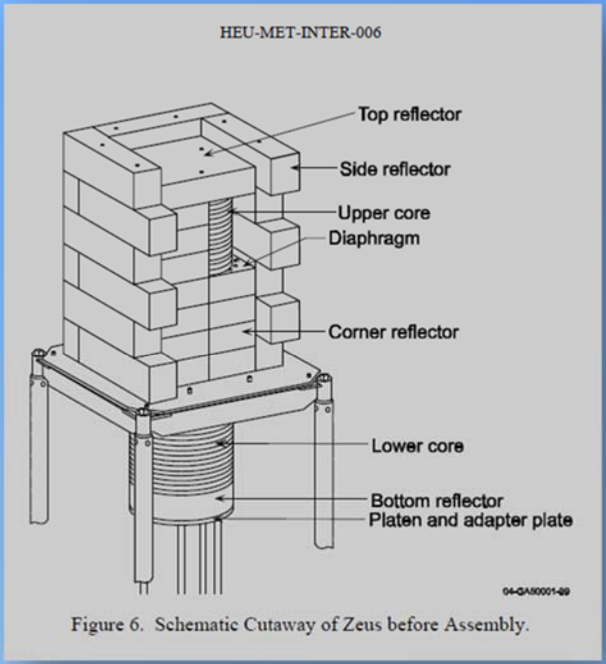
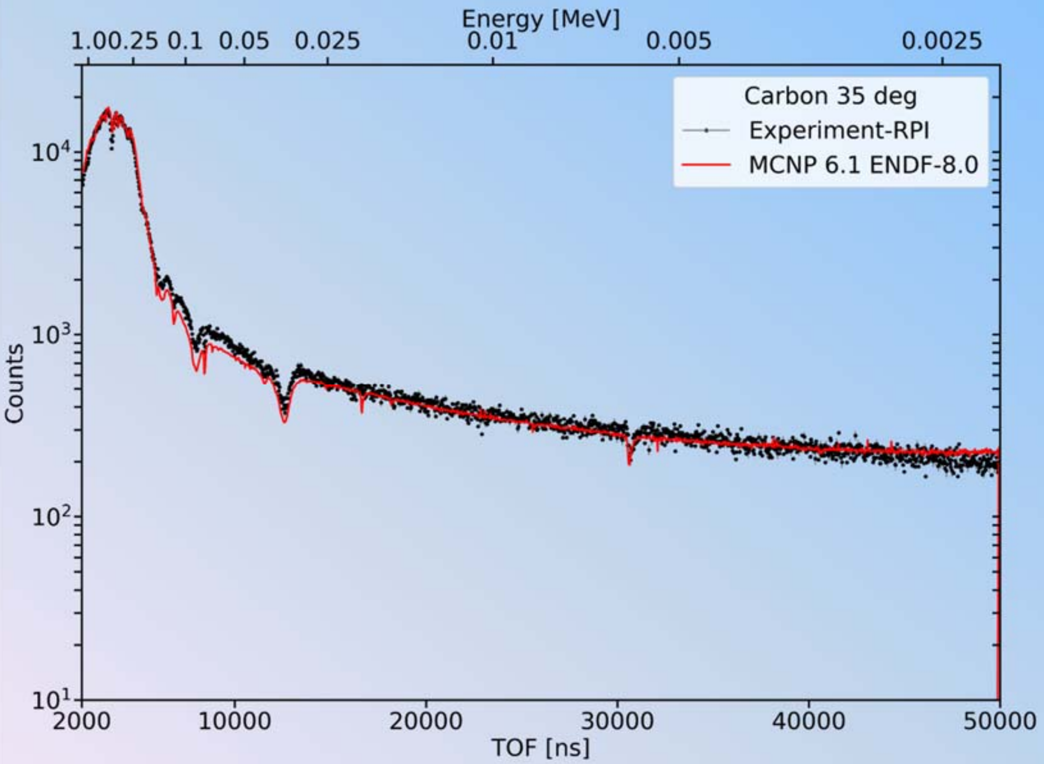
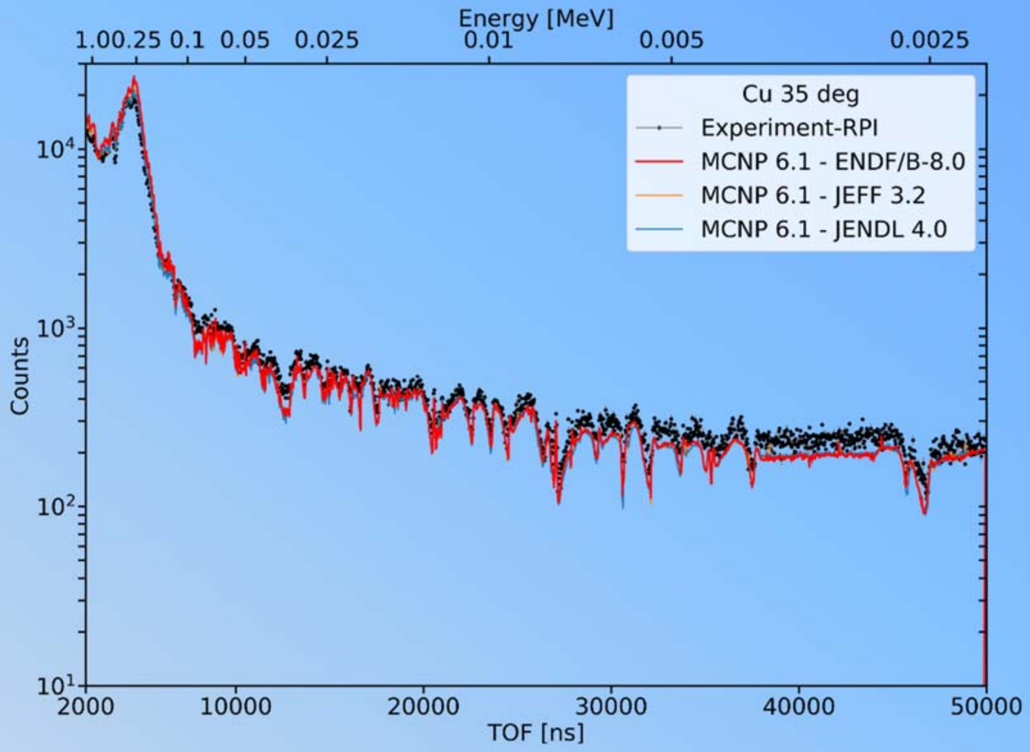

HEU-MET-INTER-006

Figure 6. Schematic Cutaway of Zeus before Assembly.

Copper Scattering – 35 deg

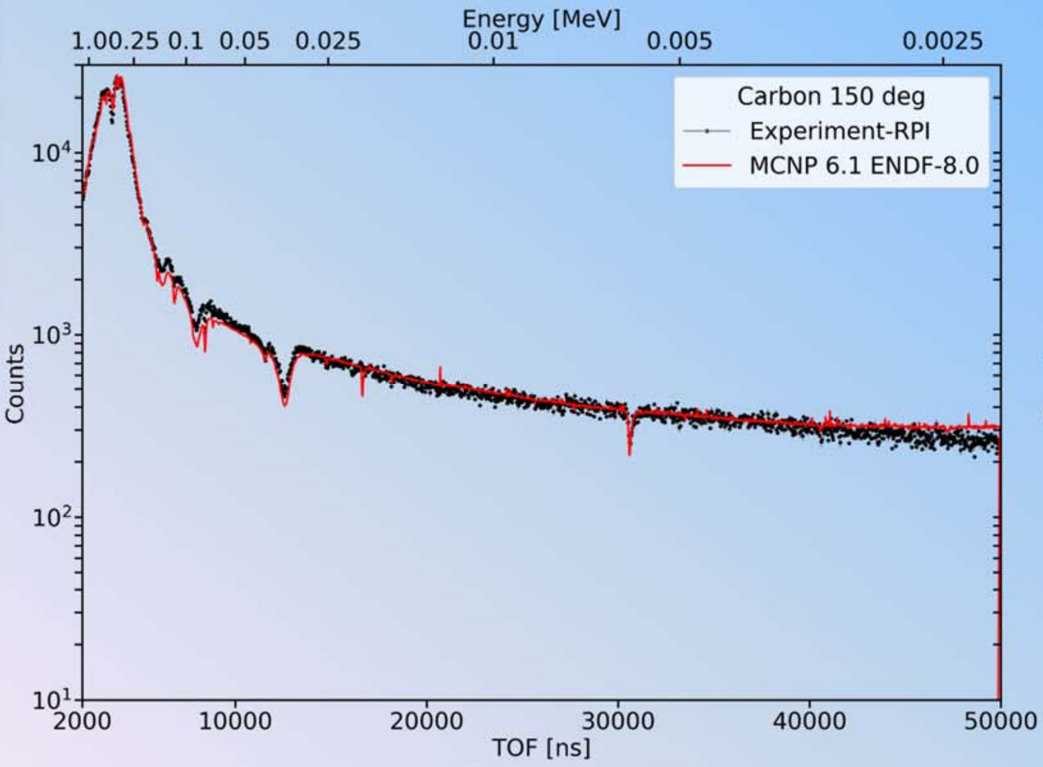
Overall good agreement between the Cu experiment and evaluation

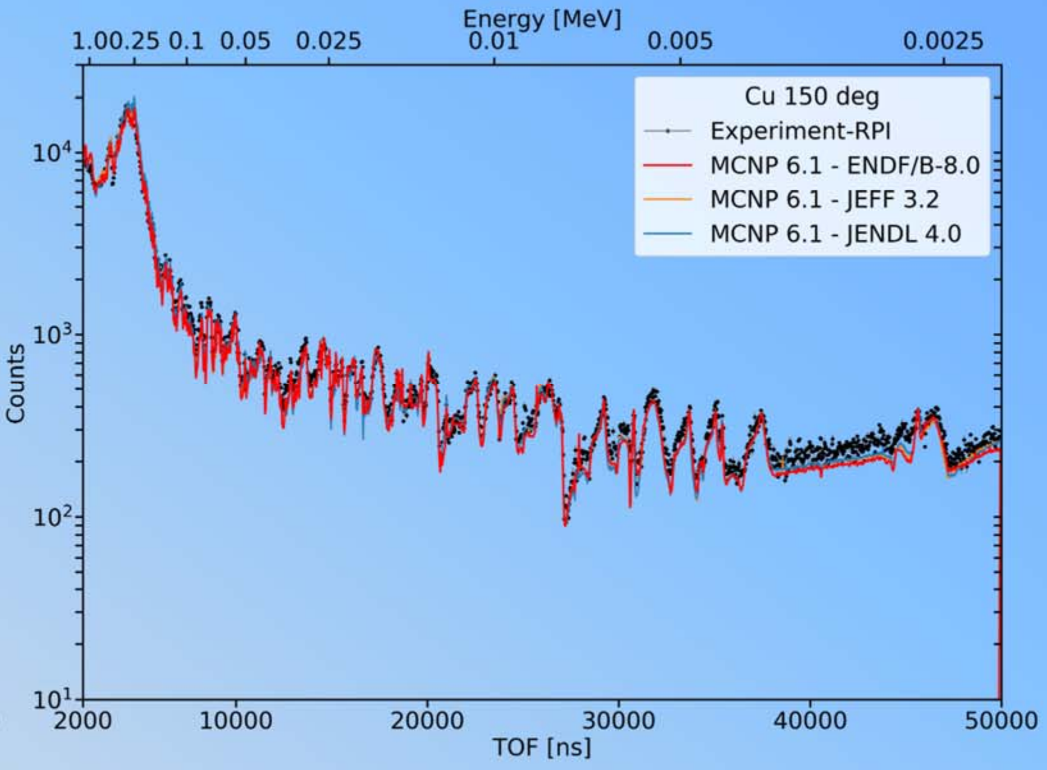




Copper Scattering – 150 Deg

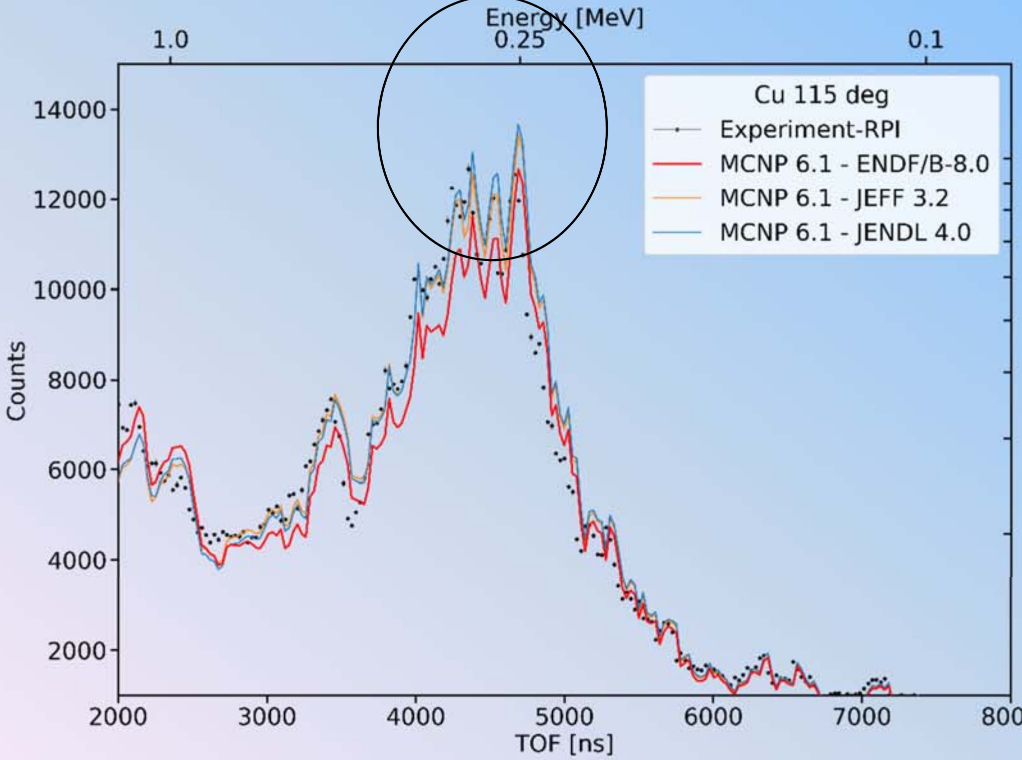
- Overall good agreement between the Cu experiment and evaluation
- Evaluations seem close to each other

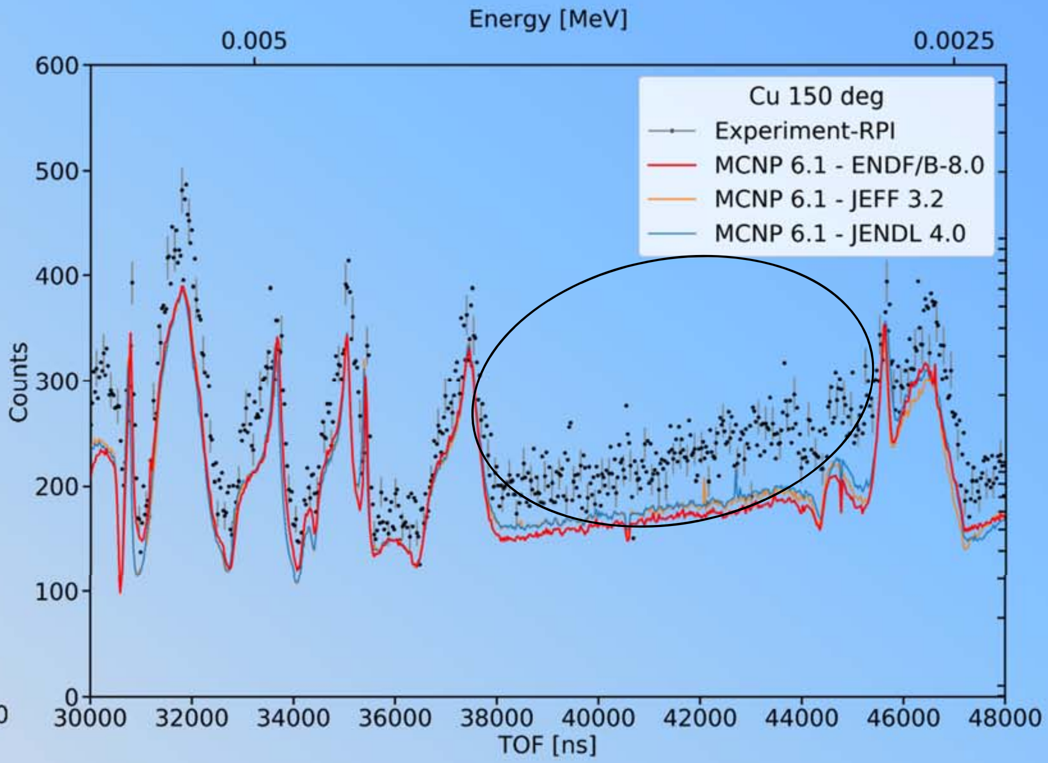


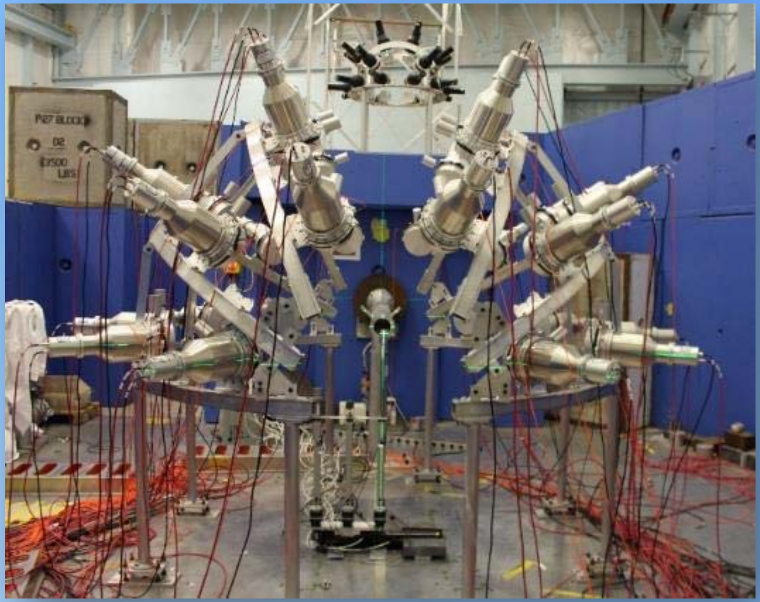


Copper Scattering Closer Look

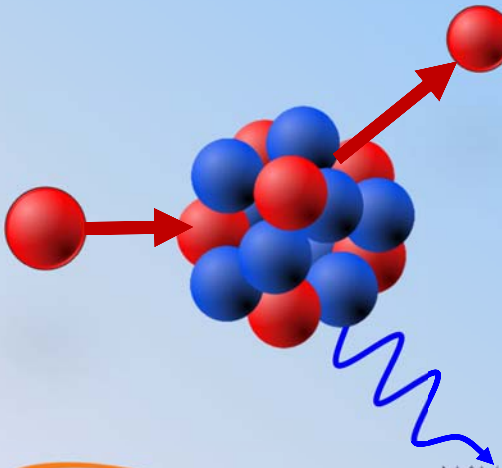
- Closer look shows some discrepancies between experiment and evaluations at the low and high keV energy range
  - Near 250 keV differences between evaluations at some angles
  - Near 3 keV the evaluations seem low at all angles





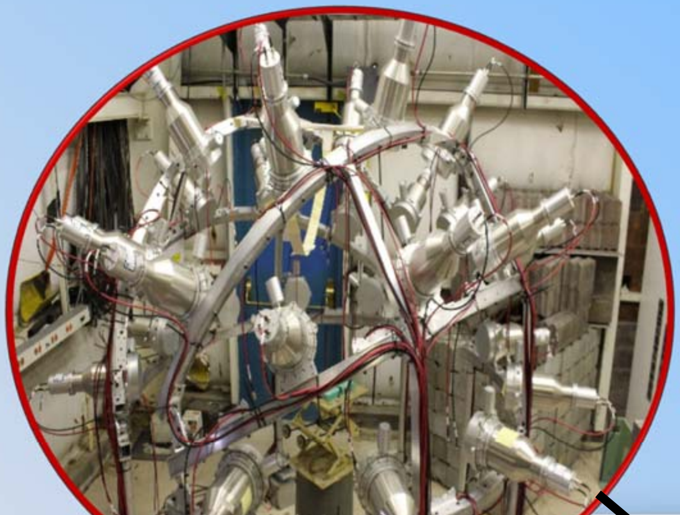


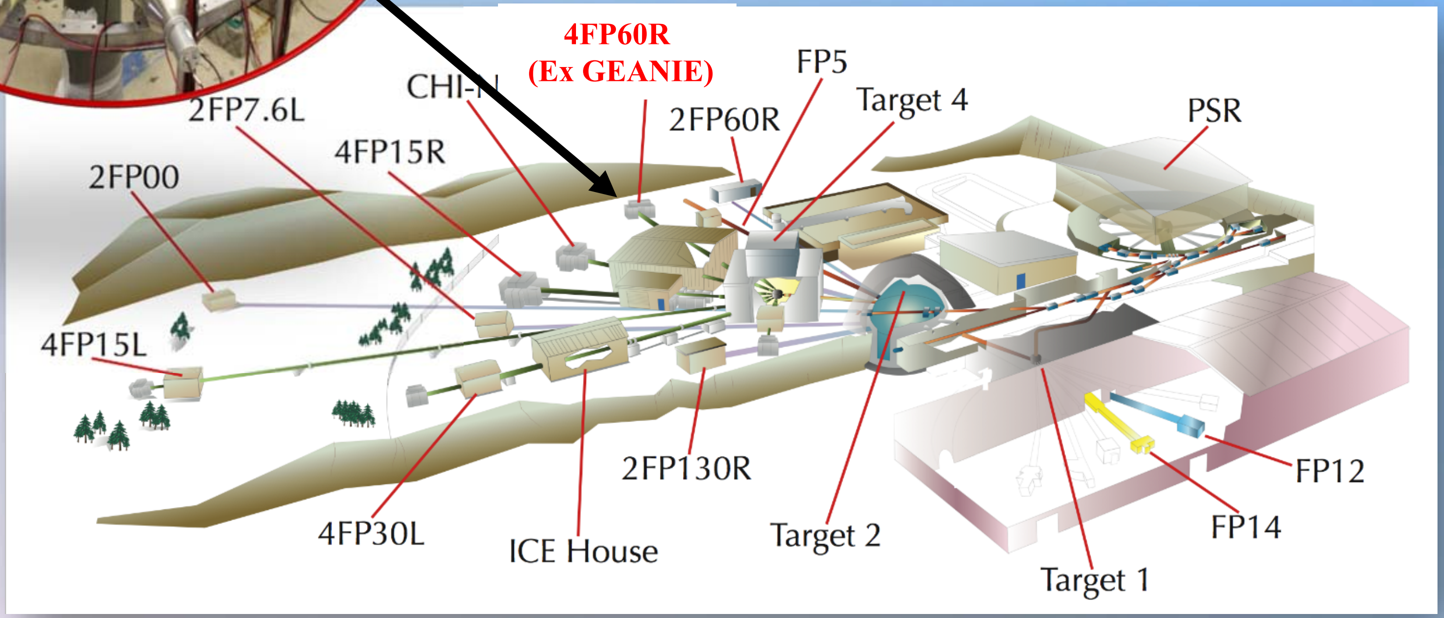
Fast Neutron Induced Neutron Emission from U-235 and Pu-239



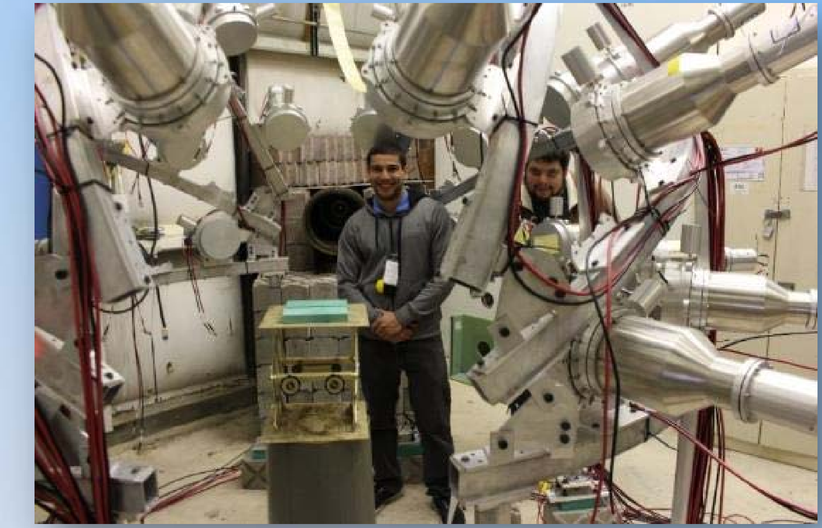
Fast neutron Scattering Experiments at LANL

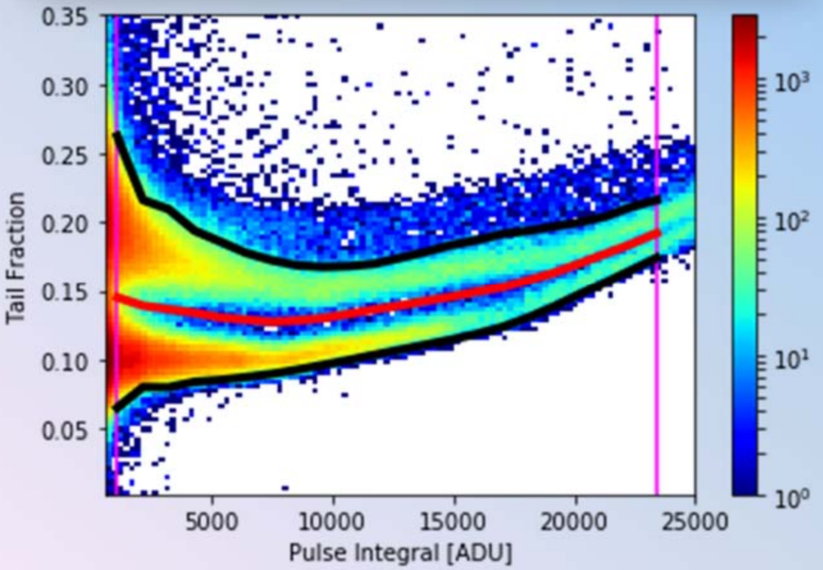
- Used the Chi Nu EJ-309 detector array
  - 56 (used 28) detectors, arranged in 2 “quarter-spheres”
- Detectors were connected to digitizers
  - Pulse shape analysis using long and short gate
  - Full event pulse was also saved
- Use 4FP60R with 21.5 m flight path + 1 m sample to detector





Experimental Setup





- 28 EJ-309 17.8 cm in diam x 5 cm thick
- LANSCE operated at 100 Hz
  - 625 us macro-pulse
  - Micro-pulses spaced 1.8 us apart
  - Proton pulse width < 0.5 ns
- U-235 fission chambers for flux monitoring
- Used CAEN VX1730B Digitizers
  - 500 MHz sampling rate
- Pulse shape discrimination to separate neutrons from gammas.
- Installed a 3 position sample changer

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NAVAL NUCLEAR LABORATORY

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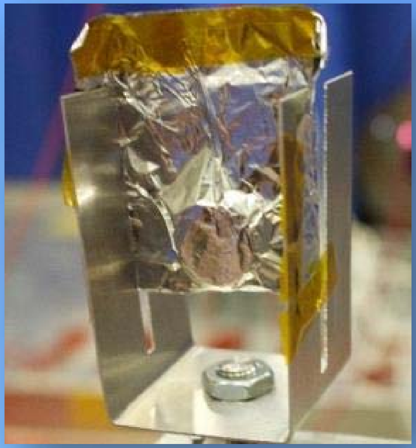
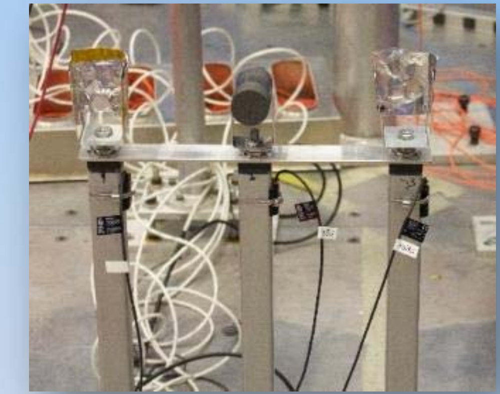
Samples

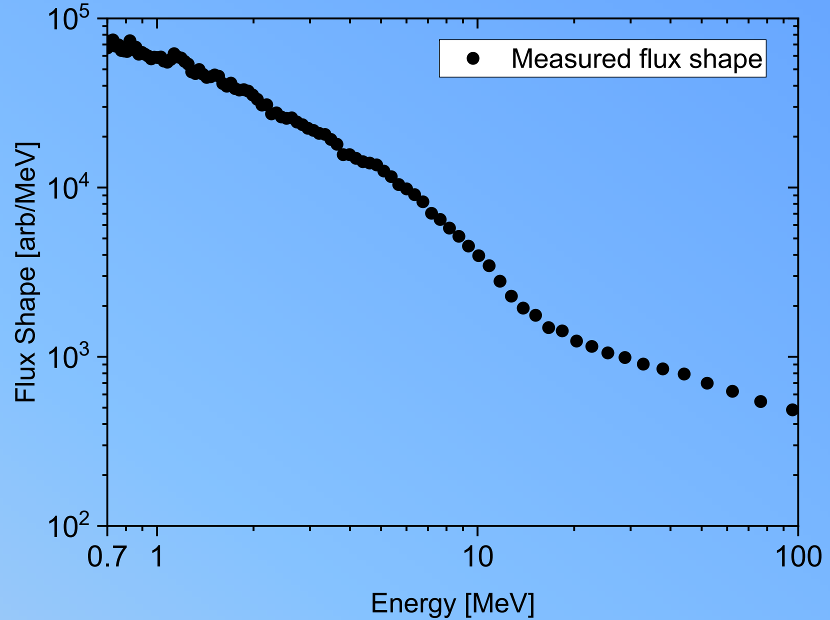
- **U-235**
  - 49.5g Sample (93 wt.% U-235)
  - Truncated cone shape
  - Encapsulated in 2 mil total thickness aluminum foil
- **Pu-239**
  - 24g Pu (93% Pu-239, 6% Pu-240 and 3.6% Ga)
  - stainless steel encapsulation blank
- **Graphite**
  - 38.6g graphite reference sample
  - 1.5” (3.81 cm) diameter x 0.8” (2.04 cm) thick
- **Three position sample changer**
  1. ^{235}U, C, blank
  2. ^{239}Pu, C, blank
  3. Thin C, Polyethylene, blank

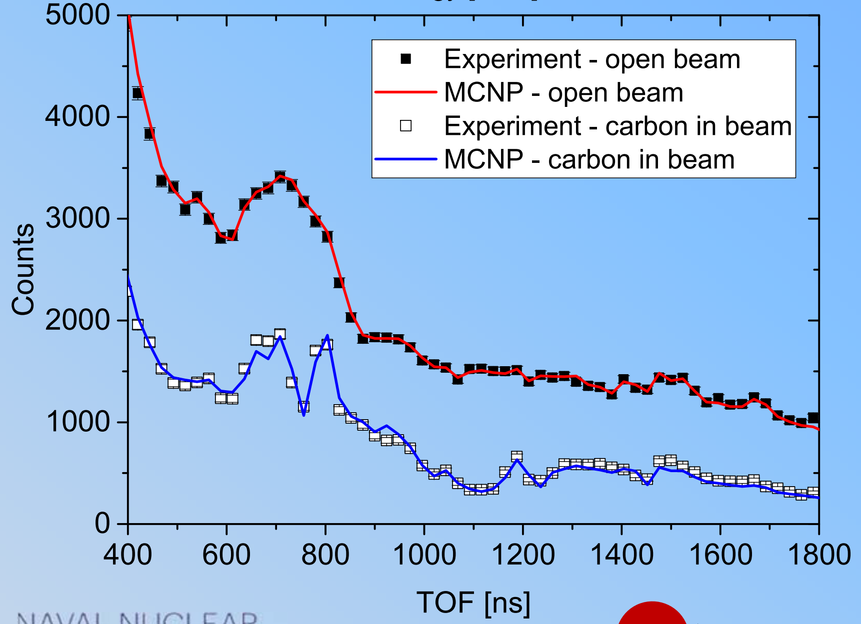




Neutron flux shape measurements

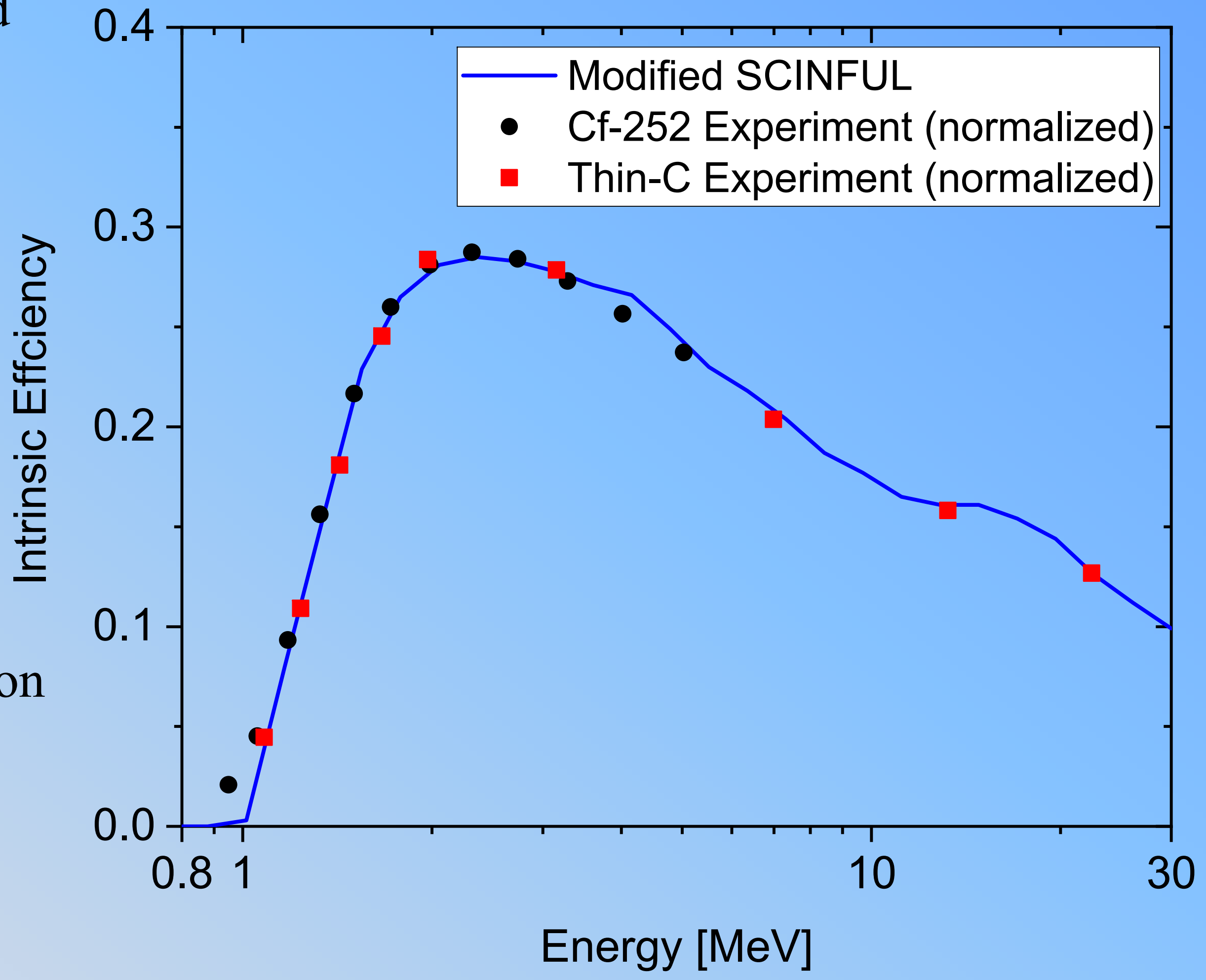
- Use a ^{235}U fission chamber (FC) located at 28.75 m flightpath
- Flux shape is obtained from a ratio of the FC counts to fission cross section. (use ENDF-7.1 IAEA-STD to 200 MeV)
- Beam filters were removed from the flux
- The flux is smoothed and used as the MCNP source for the scattering experiments



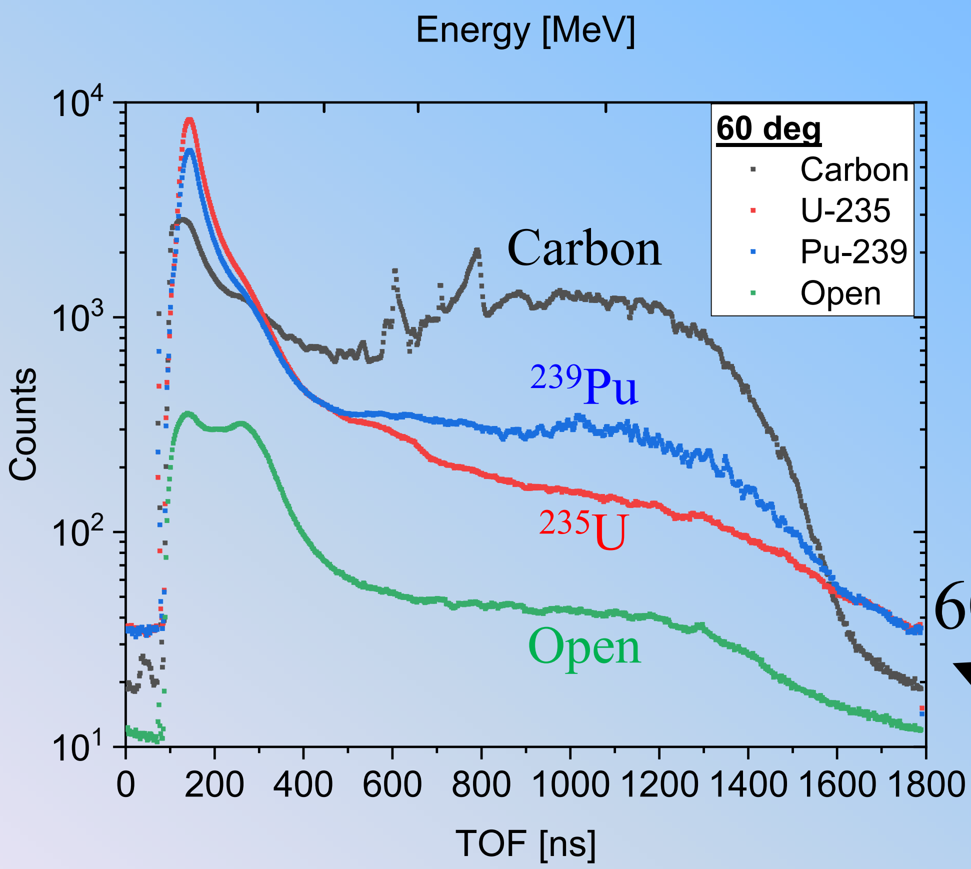


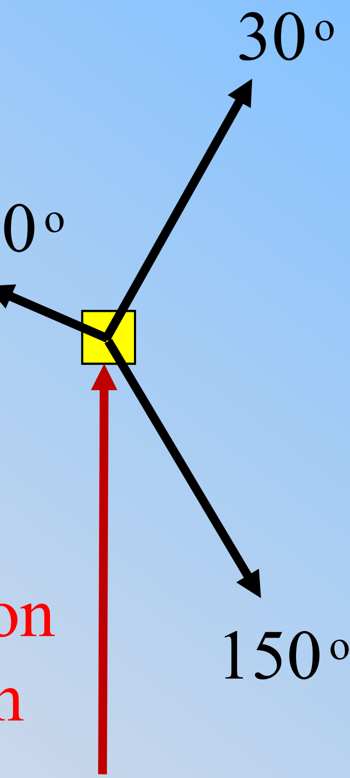
Detector Efficiency

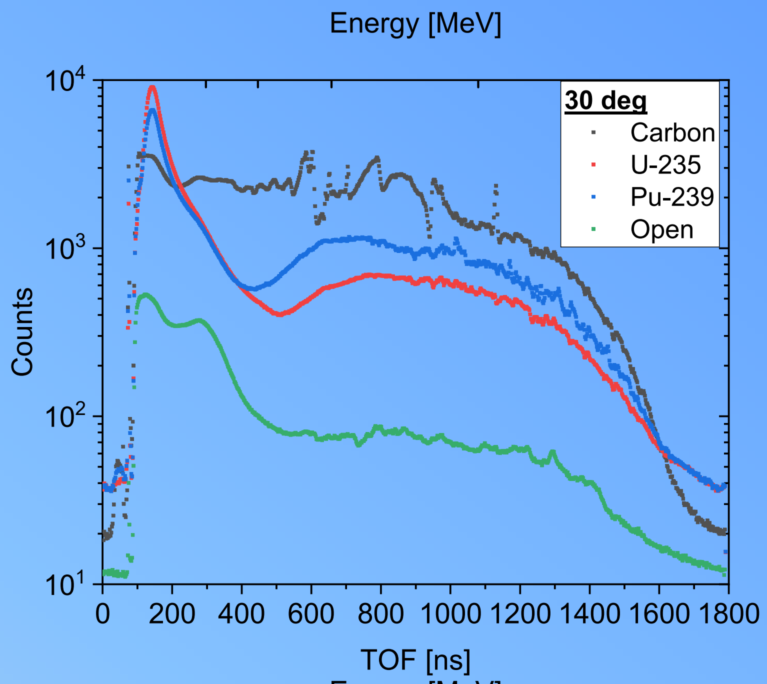
- The efficiency must be measured using identical experimental settings and analysis tools as the primary experiment
- Use a modified version of SCINFUL to simulate EJ-309 detectors
- Validate with
  - ^{252}Cf
  - Thin (1 mm) graphite sample
- Short 1 m flight path and detection timing limited the upper energy possible with ^{252}Cf
  - Scattering from a thin carbon sample is an alternative.

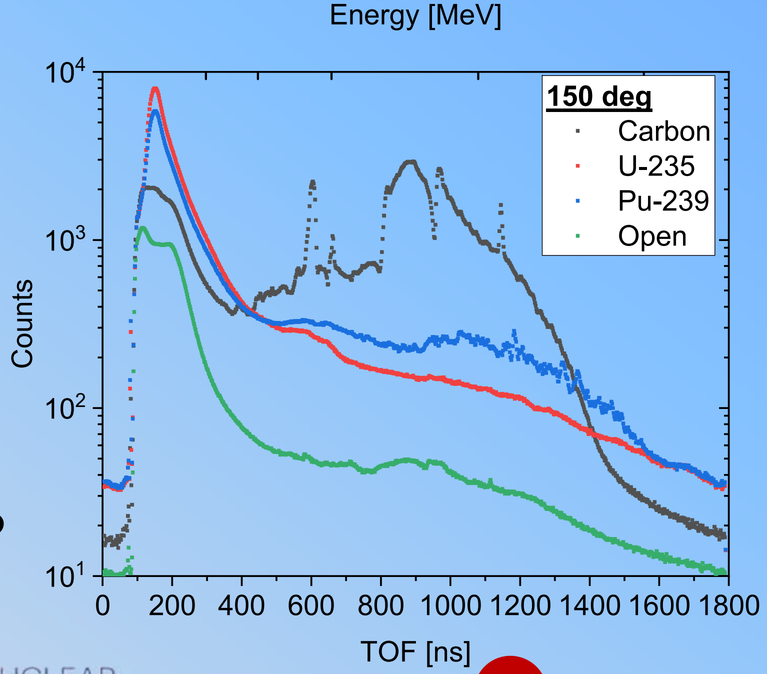


Raw Data









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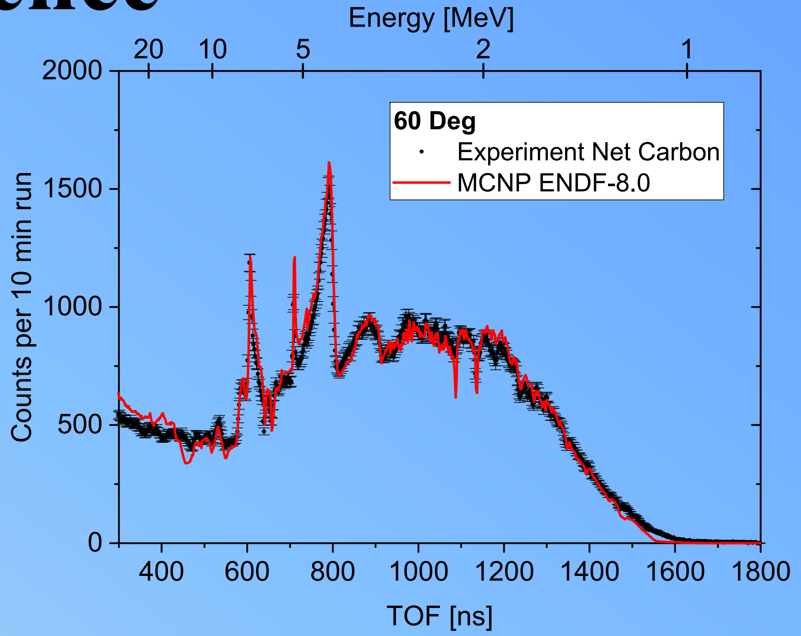
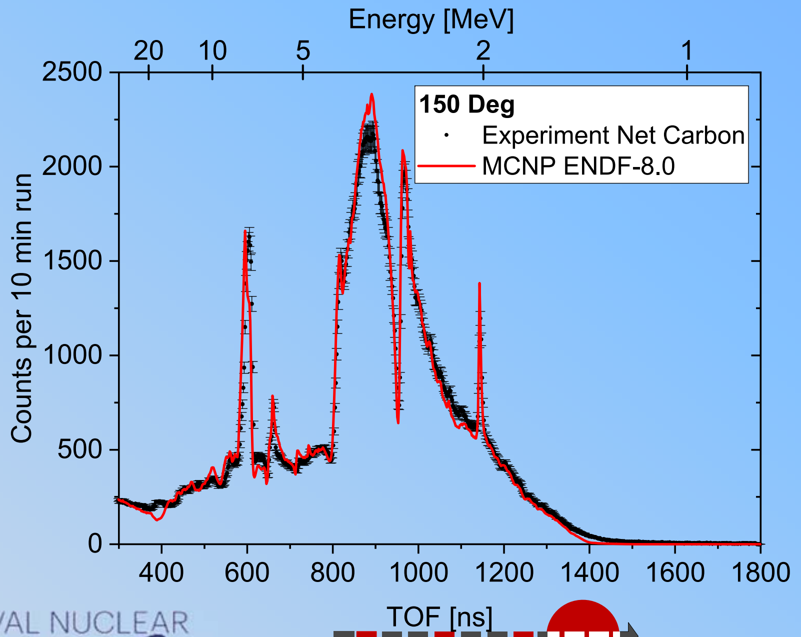
Carbon Reference

- Carbon (graphite) is used as a reference
  - Scattering cross section is well known.
  - All major carbon evaluations are nearly the same.
  - The resonance structure is used to validate the source to sample and sample to detector distances, and time zero used in the experiment.
  - Carbon resonances' angular distributions were modeled with MCNP and ENDF-8 and are in good agreement with the experiment.

- Carbon was used for normalization



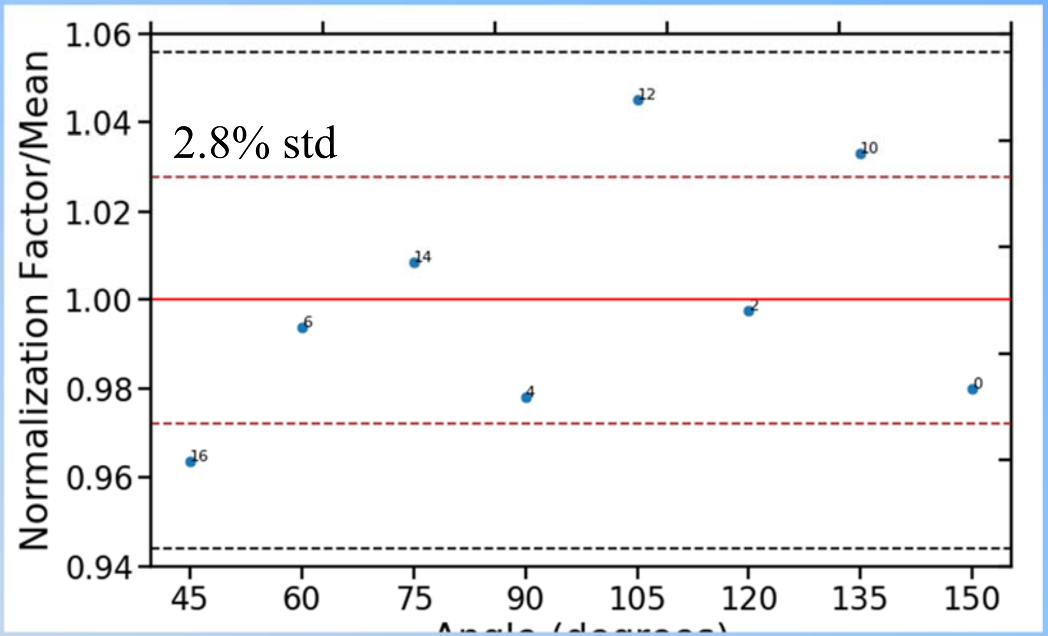


Normalization of the simulation to the experiment

- The ratio of carbon experiment to MCNP simulation should be the same at every measured angle
  - Assuming the carbon evaluation is very good
  - Good experiment
- When plotted we observe a standard deviation of about 2.8%.
  - Used as an estimate of the systematic uncertainty.
  - There is disagreement of about 6.5% at forward angle
- The mean was used to normalize the carbon and ^{235}U and ^{239}Pu.
- Alternative approach
  - For each angle (detector): normalize the ^{235}U and ^{239}Pu measurements to carbon
  - Use the standard deviation as an estimate of the systematic uncertainty.

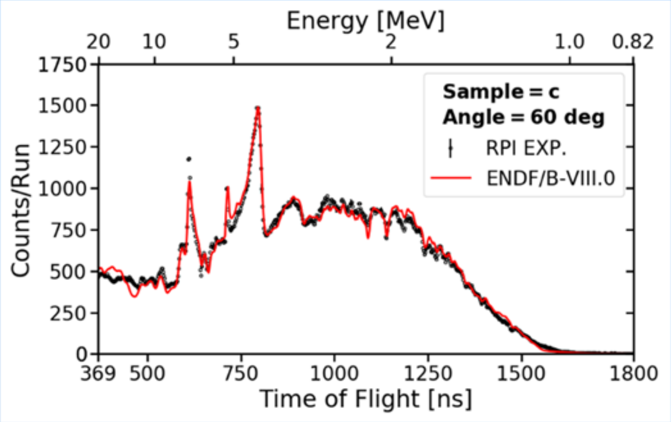
It is important that the normalization procedure will preserve the angular distribution information derived from ^{235}U and ^{239}Pu samples

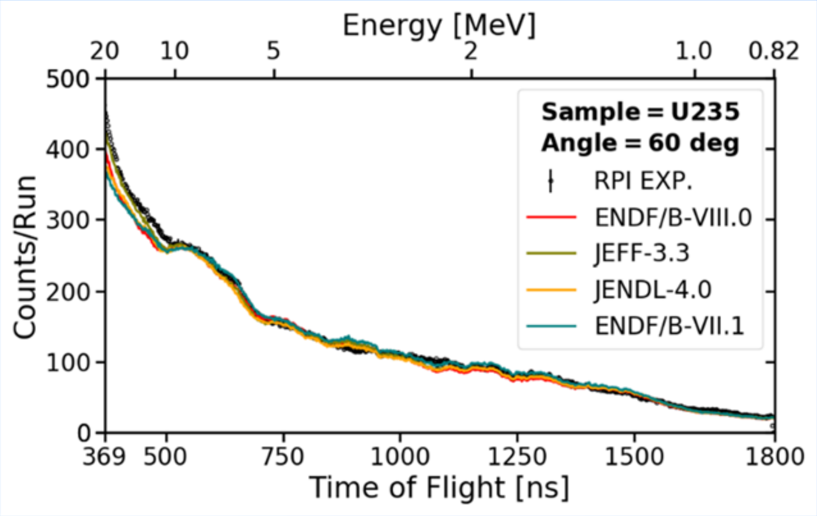
Carbon normalization for U-235 experiment

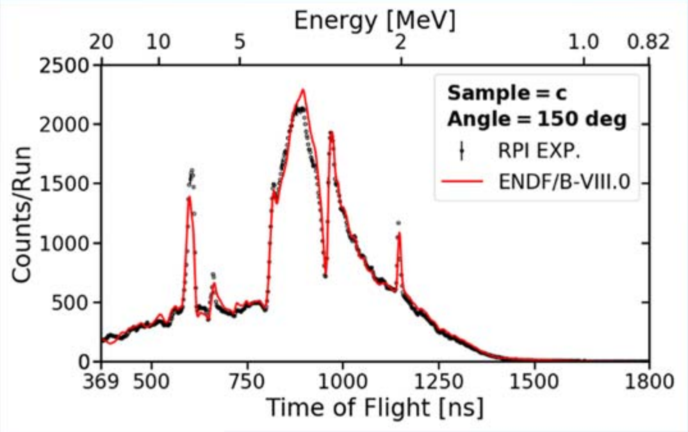


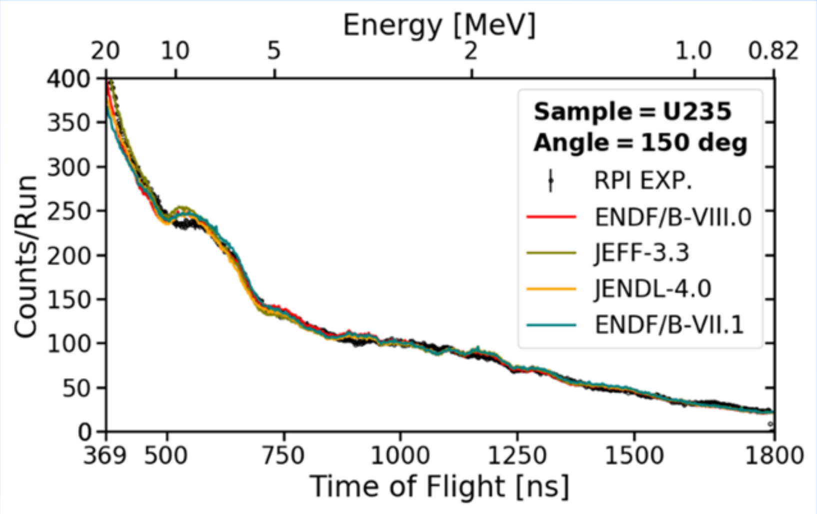
^{235}U results (full room simulation)

- Used one factor to normalize the simulation to experiment of both carbon and ^{235}U
- Carbon is in good agreement (some deviations at resonance peaks)
- For E<10 MeV ^{235}U show good agreement between experiment and simulation
- Both angles show differences between 4-8 MeV
- Below 10 MeV all evaluations are very similar.
- More angles are available



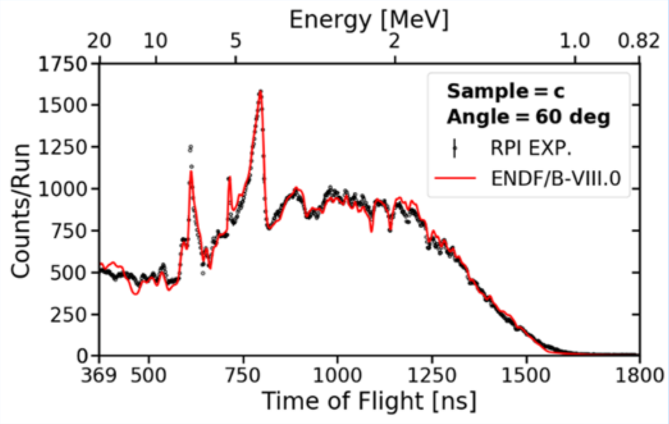


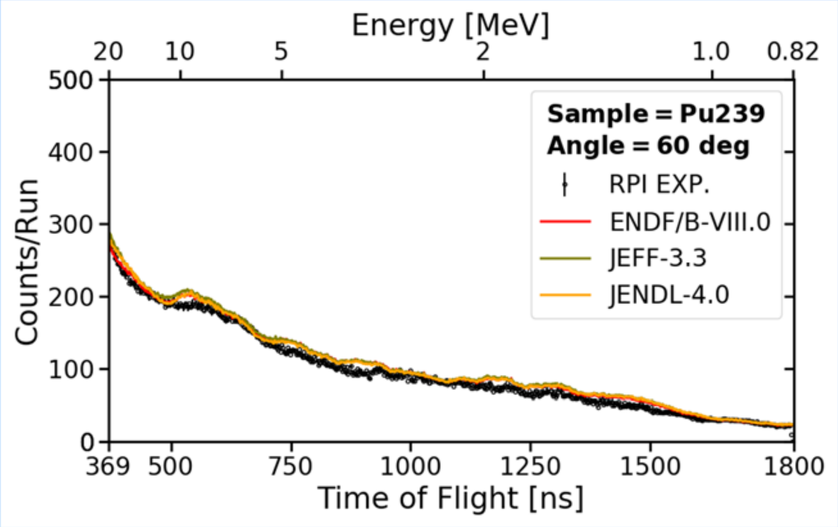


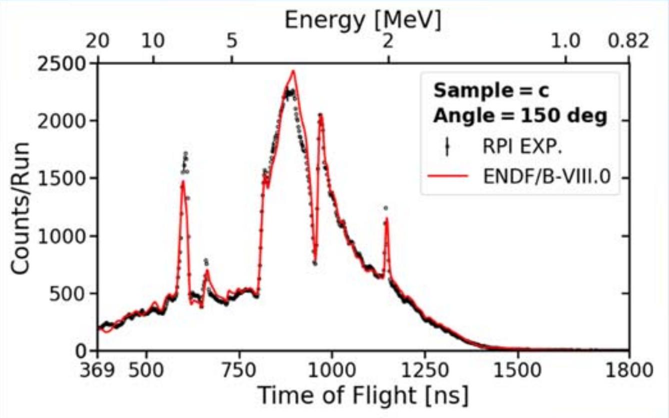


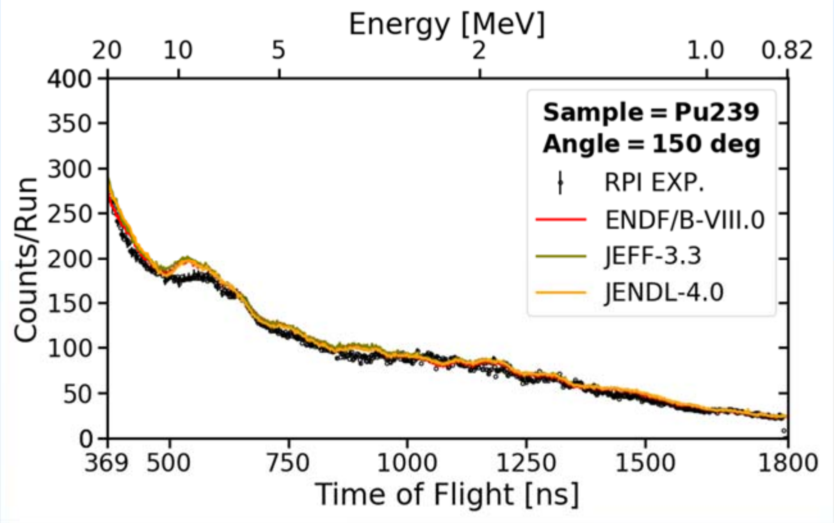
^{239}Pu results (full room simulation)

- The ^{239}Pu neutron emission yield is similar in shape to the ^{235}U yield
- The simulation is higher than the experimental data.
- Carfeul attention to the encapsulation of this sample









Summary

- **Analysis of Ta transmission and capture was completed**
  - SAMMY was modified to handle a weighting function (required for analysis of capture data performed using C_6D_6 gamma detectors)
  - New RRR and URR resonance parameters were derived
  - A thick sample transmission experiment was found very useful for validation of self-shielding performance of URR parameters.

- **KeV scattering was measured for Zr and Cu**
  - Analysis is in progress to resolve small disagreement with carbon

- **Analysis of ^{235}U and ^{239}Pu neutron-induced neutron emission is in progress**
  - Focusing on estimating the effects of room return.