# Update on Nuclear Data Research at RPI

*Report to CSEWG*

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# Measurements Completed/in Progress

*Italics*= in progress

- **Transmission**
  - $H_2O$ - 0.5-20 MeV, 250m flight path
  - W - 0.5-20 MeV, 250m flight path
  - Pb - 0.5-20 MeV, 250m flight path
- **Capture**
  - $^{56}Fe$ - 500 eV - 500 keV, 45m flight path
- **Scattering**
  - Pb – 0.5 – 20 MeV
  - Hf – Resonance Scattering
  - *Zr <0.5 MeV in development*
- **Thermal Scattering**
  - Quartz at temperatures of 20, 300, 550, 600 °C.
  - Polyethylene at temperatures of 295 K and 5 K.

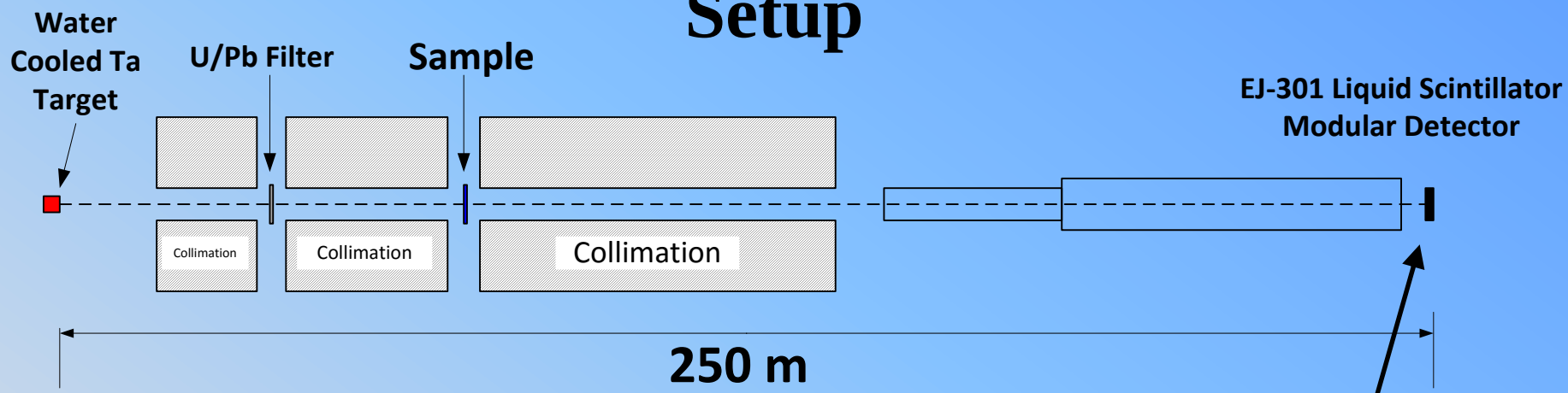
# Planned Measurements

- **Scattering**
  - Zr - for E<0.5 MeV, continue development
- **Transmission**
  - $^{95,96}$Mo,$^{54}$Fe - to complement capture above 180 keV
- **Photoneutron**
  - Be, Ta – measurements with 20-60 MeV bremsstrahlung
- **Capture**
  - $^{56}$Fe – continue measurement
  - $^{95,96}$Mo,$^{54}$Fe, 45m station 1 keV to 500 keV.
    - If unavailable, one of the following $^{92/94}$Mo, $^{nat}$Hf

# Data Analysis

| Measure | Sample | Status |
|---|---|---|
| **High Energy** | Fe, Ti, Ta, Cu, Zr, $^{92/94,95,96,98,100,nat}$Mo | High energy (0.5-20MeV) transmission, publication in preparation |
| **RRR and URR** | Cs, Rh , Re, Fe, Ta<br>$^{161,162,163,164}$Dy<br>$^{236}$U<br>$^{155,156,157,158,160}$Gd<br>$^{153,nat}$Eu<br>$^{92/94,95,96,98,100,nat}$Mo | Resonance analysis in progress<br>Resonance analysis in progress, $^{164}$Dy - publication in internal review<br>$^{236}$U - publication submitted to progress in nuclear energy<br>Gd isotopes – published, NSE Vol. 180, Number 1, May 2015.<br>Eu – published , Annals of Nuclear Energy, Vol. 69, pp. 74-89, 2014.<br>$^{95}$Mo URR – Published in Phys. Rev. C |
| **Scattering** | $^{238}$U<br>Fe<br>Pb | $^{238}$U – published, Annals of Nuclear Energy, Vol. 73, pp. 455-464, 2014.<br>Fe – analysis near completion<br>Pb – analysis in progress |
| **Thermal Scattering** | $H_2O$, polyethylene, quartz | Analysis in progress |

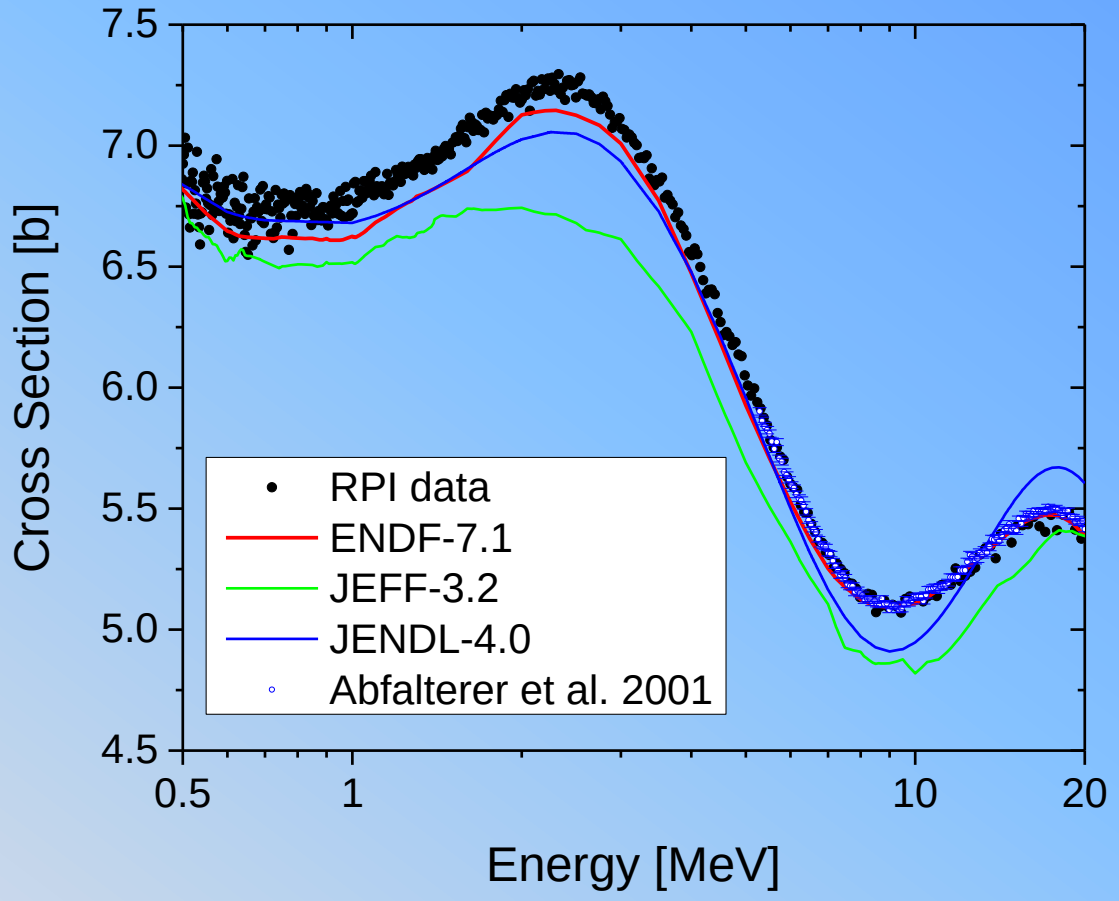
# High Energy Transmission Experimental Setup




Graphite Samples

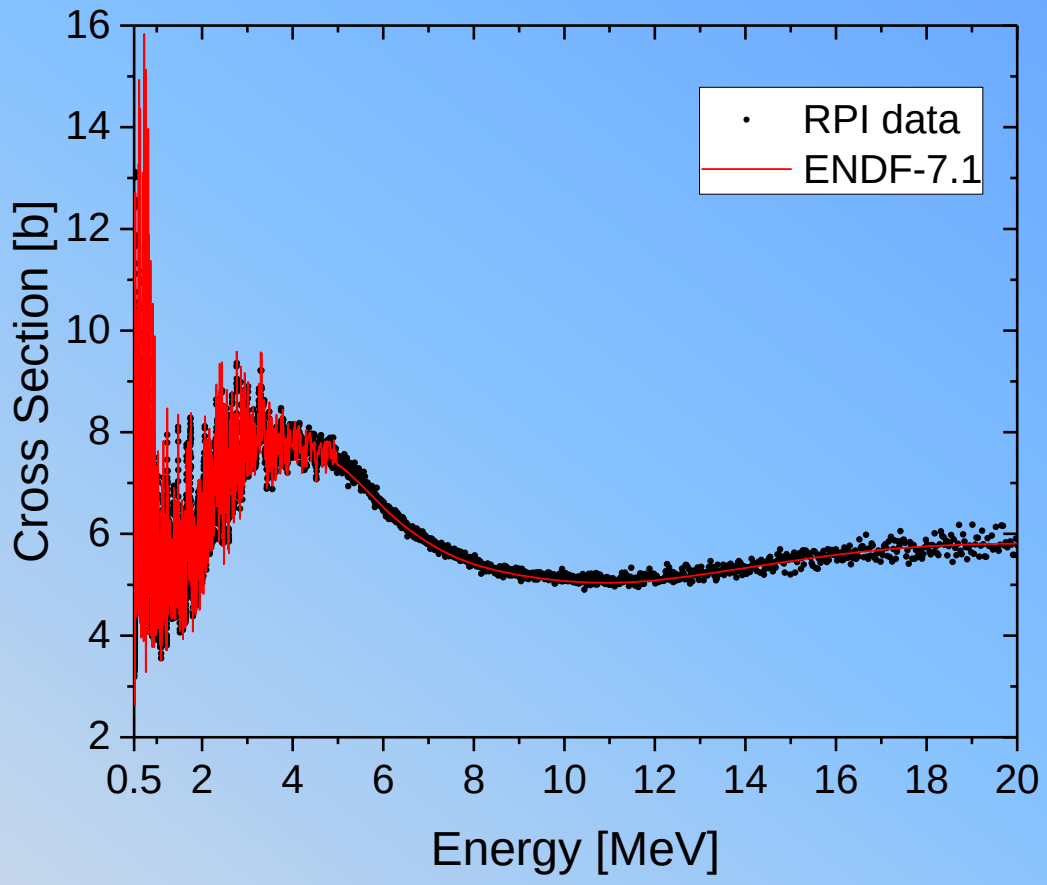
# Total cross section of $^{nat}W$

- Used 250m flight station with 2 modules of EJ-301 detector
- Measured two sample thicknesses: 4.5 and 5.5 cm
- ENDF/B-7.1 is in good agreement above 8 MeV
- The RPI data agree well with the Abfalterer et al. 2001 experimental data
- Below 8 MeV the evaluations need improvement.



# Total Cross Section of $^{nat}$Pb

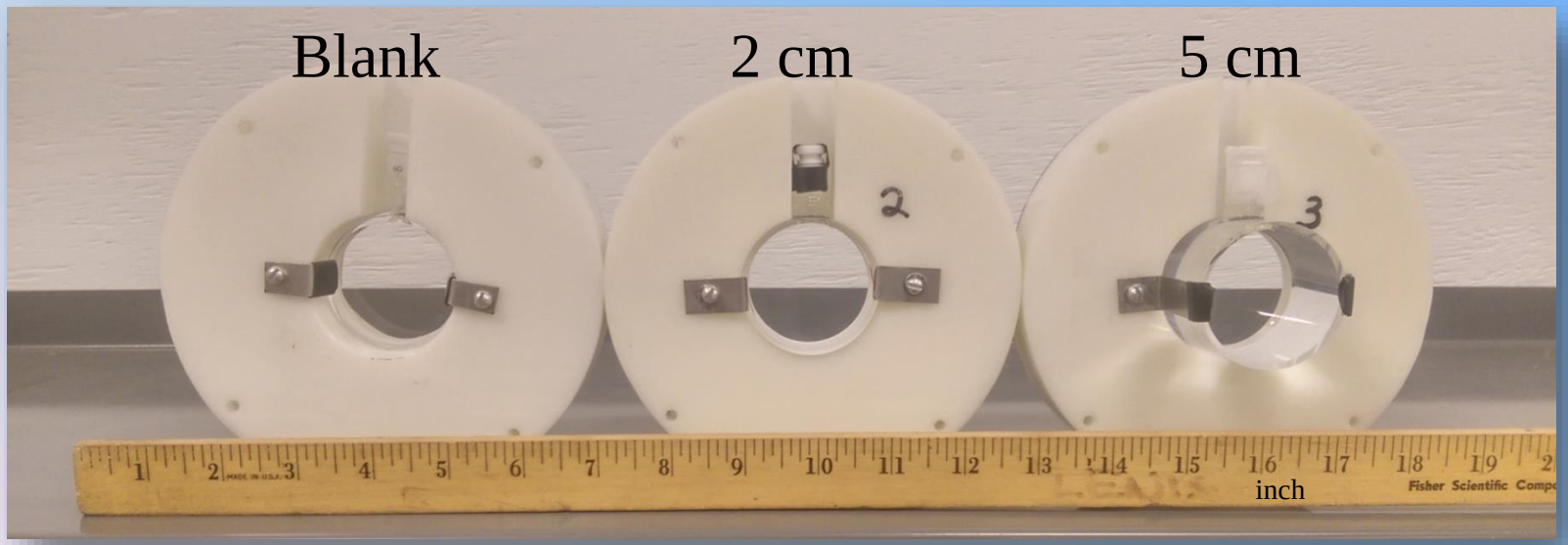
- Was measured to supplement a Pb Scattering measurement
  - No anomalies were observed in the sample material
- Measured two sample thicknesses: 9 and 12 cm
- The data are in good agreement with ENDF/B-7.1
- Resonance structure is evident below 5 MeV



# Update on Oxygen total cross section

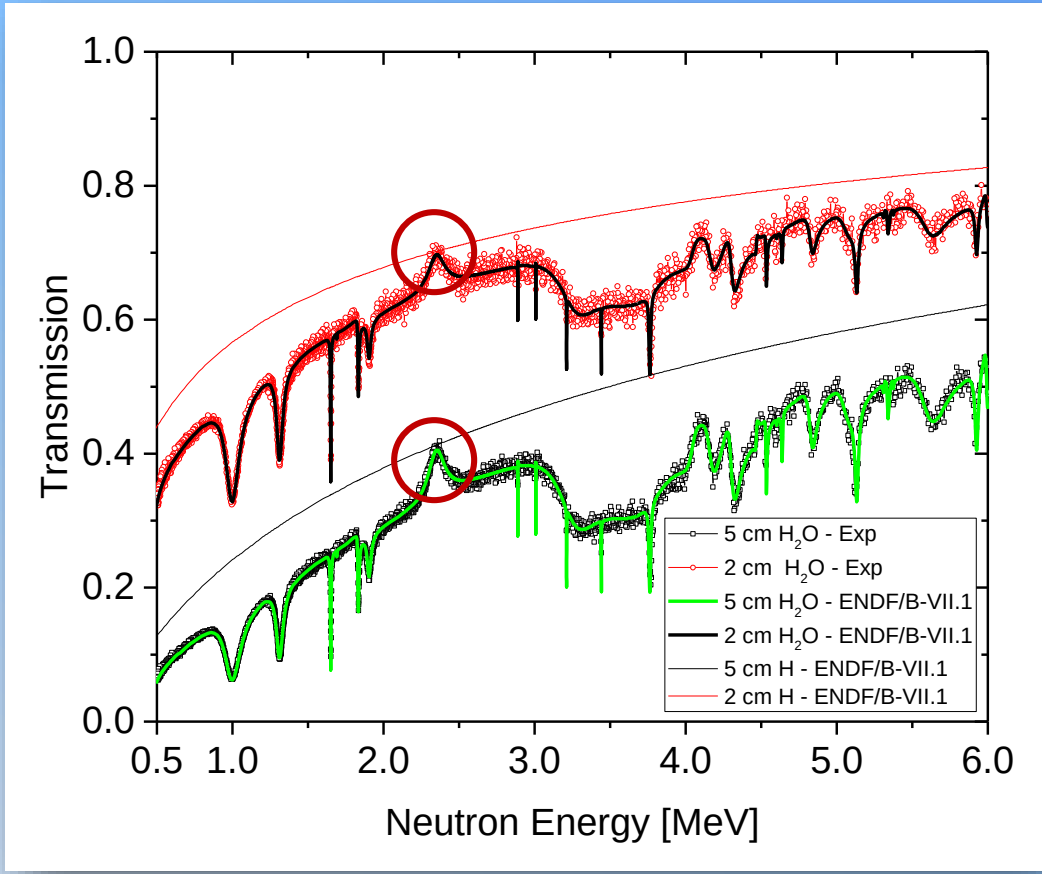
# $H_2O$ Samples

- Used a spectroscopic quartz cell to contain research grade water
  - Outgas the water by drawing vacuum for ~1 minute.
  - Mounted the cells in a polyethylene holder
  - Made sure there was no air bubble in the cell
  - Monitored the sample using a camera to make sure air bubbles were not formed
  - Monitored the room temperature to characterized the variations (±1.5° C)
- Used two cell thicknesses: 2 cm and 5 cm, about 5 cm diameter.
- Measured an empty cell as an open beam
- 13 cm thick graphite sample was used for verification and energy calibration

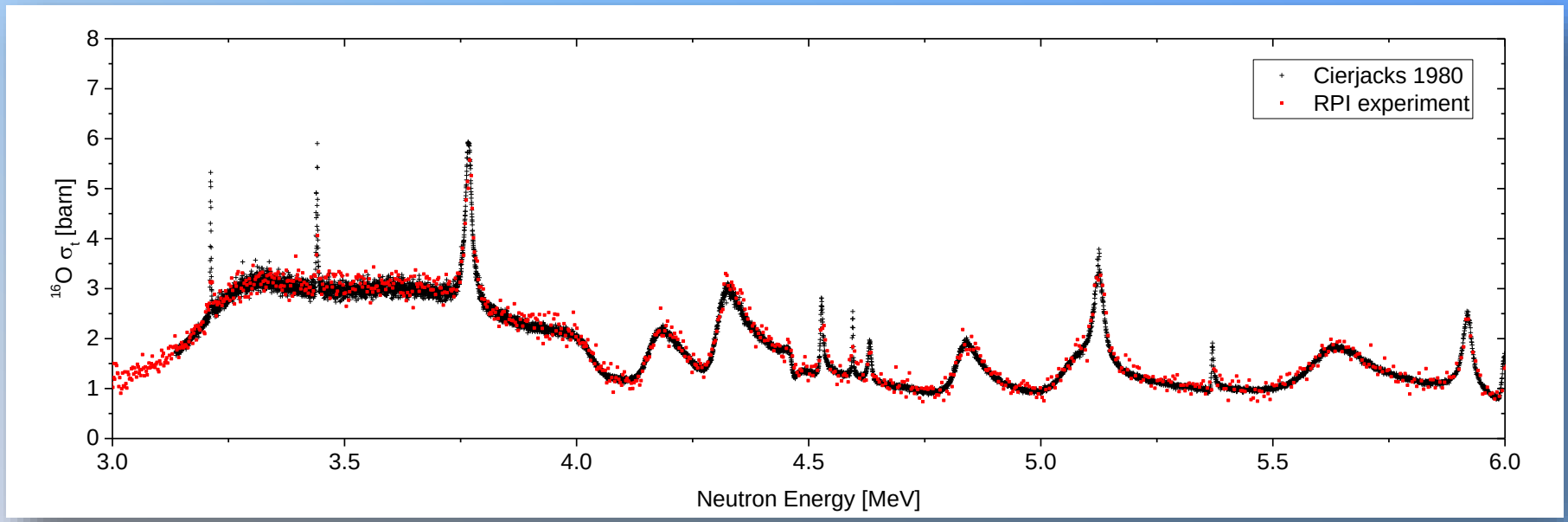


# $H_2O$ transmission measurement

- Measurements of 2 cm and 5 cm thick $H_2O$ in thin walled quartz optical cells.
- Used 250 m TOF and 10 ns pulse width.
- Used 3 fission chambers as beam monitors.
  - The experiment requires "good" monitor normalization
- In the $^{16}O$ cross section minima at 2.34 MeV mostly $H_2$ was measured
  - **Provides verification of the normalization**
- Used carbon for energy calibration



# Comparing Normalization with Other Data Sets




| Energy range 3.2 MeV < E < 6 MeV | $C/E_{RPI}$ | $C/E_{RPI}$ Statistics |
|---|---|---|
| **ENDF/B-VII.1** | 0.988 | ±0.002 |
| **Leal 1** | 1.030 | ±0.002 |
| **Leal 2** | **1.006** | ±0.002 |
| **Hale** | 1.012 | ±0.002 |
| **Cierjacks 80** | 0.968 | ±0.002 |
| **Cierjacks 68** | 1.009 | ±0.002 |
| **Johnson 74** | **0.996** | ±0.002 |

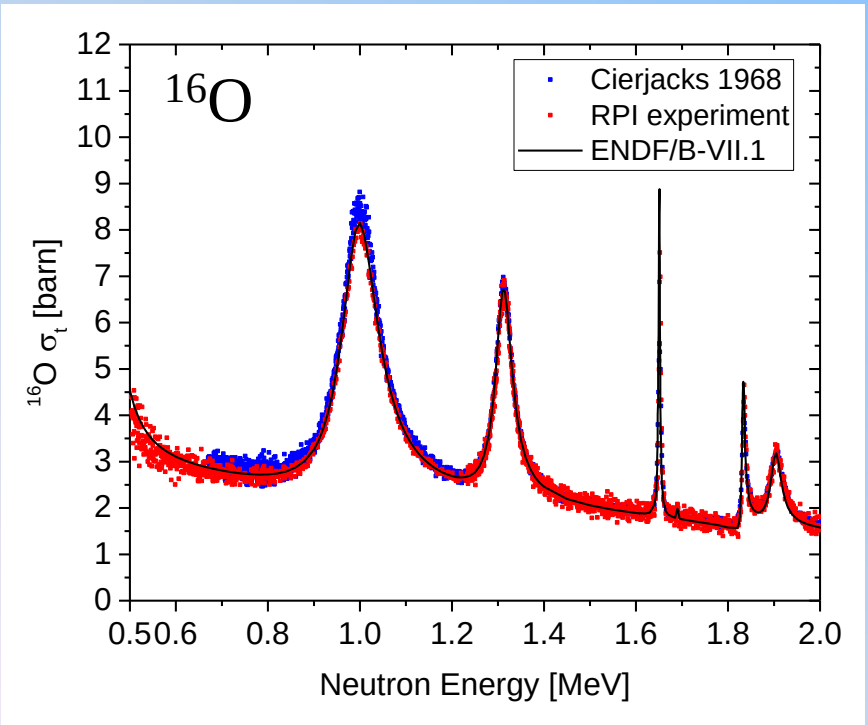
Normalization uncertainty:

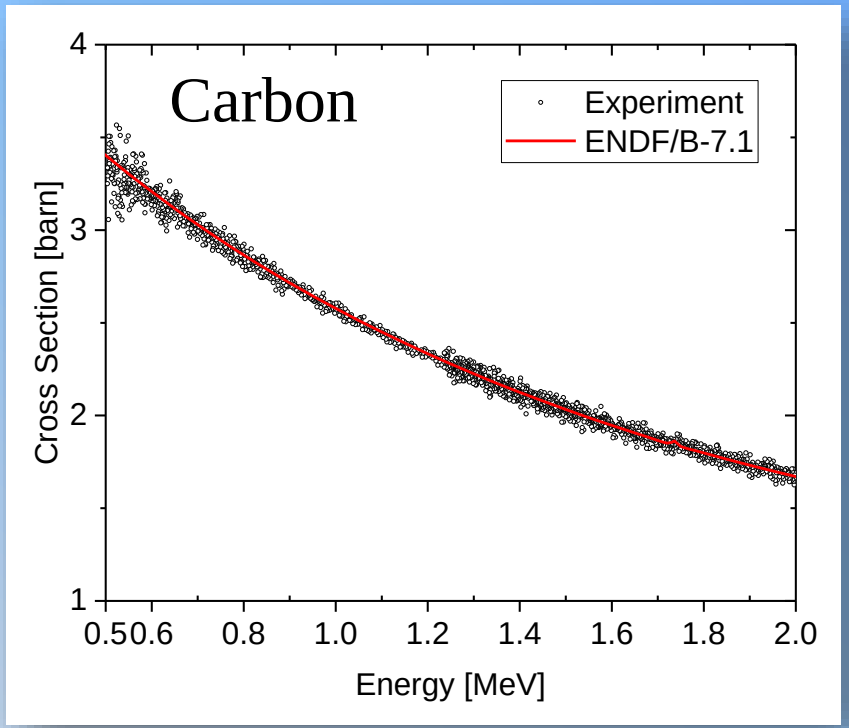
$$\frac{\sigma^{H}_{\exp}}{\sigma^{H}_{ENDF}} = 0.996 \pm 0.003^{*}$$

*Statistical

# Other $^{16}O$ observations

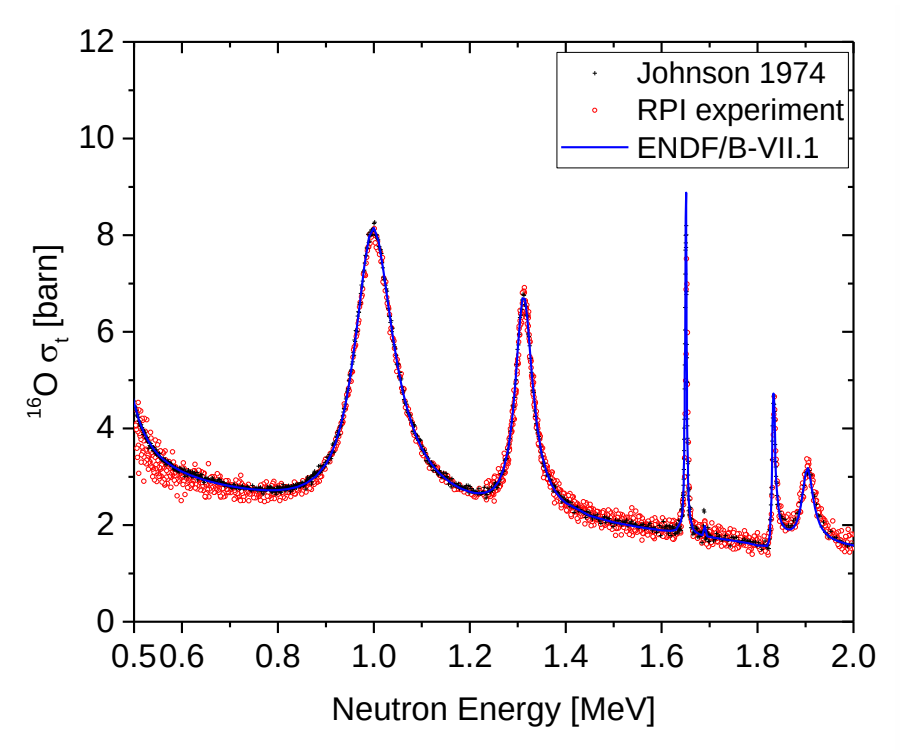
- RPI energy resolution is better than Cierjacks 68
- There is some disagreement at the peak of the 1 MeV resonance
- Carbon transmission measured at the same experiment shows good agreement with the evaluation

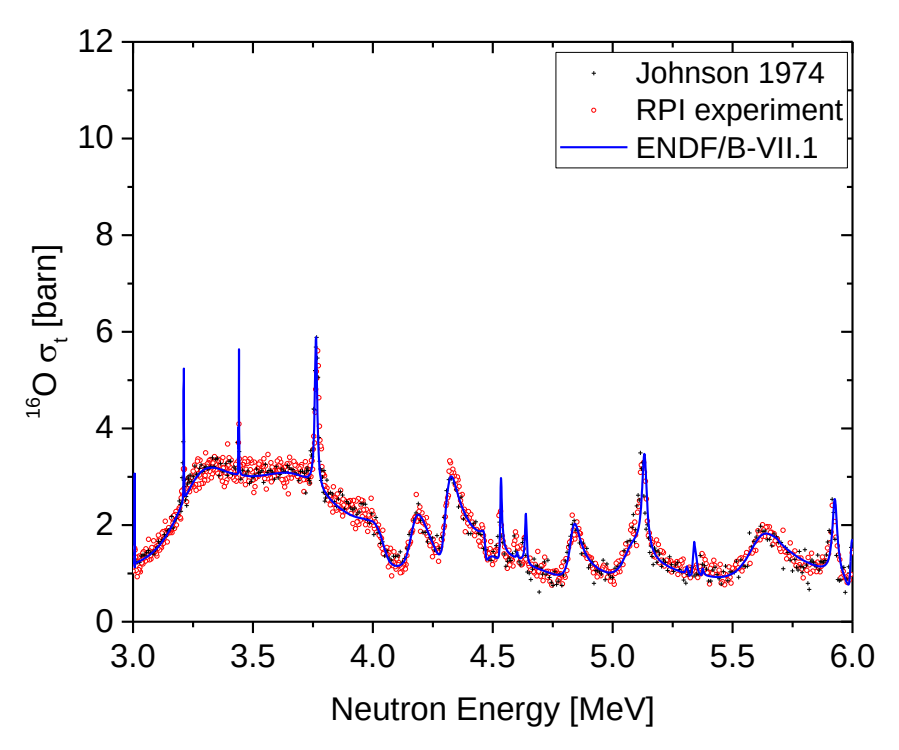


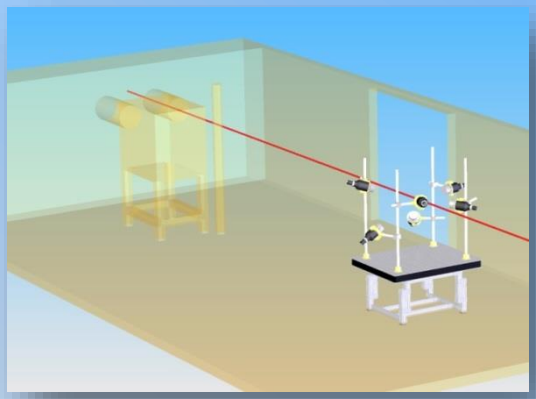



# RPI and Johnson 74

- Overall good agreement
  - Good agreement in the 1 MeV resonance.
  - ENDF is based on the Johnson data
- The Johnson 74 data has slightly better energy resolution.
- There is a slight energy shift between the two experiments

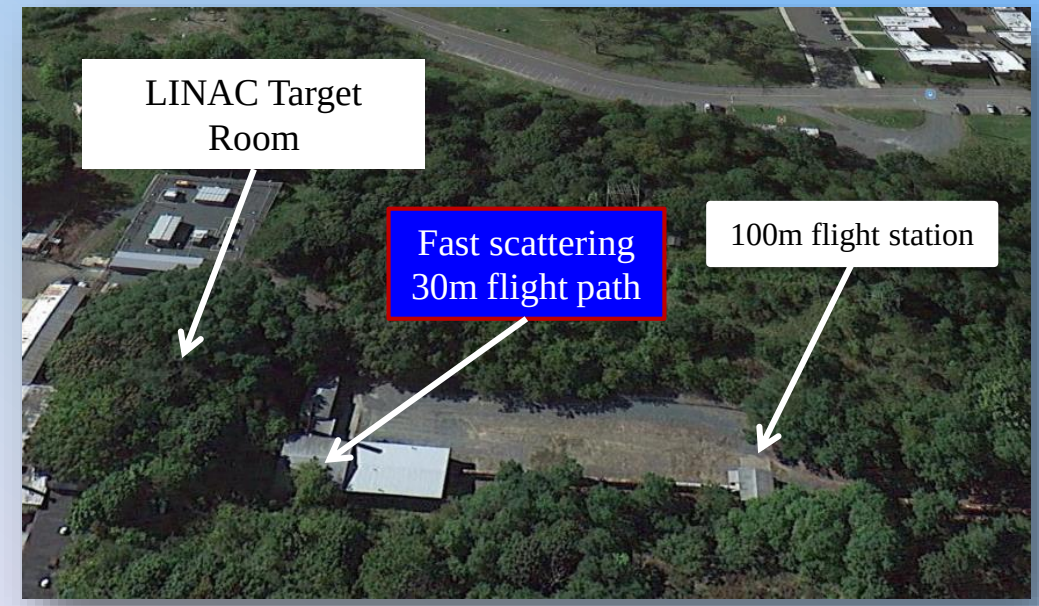




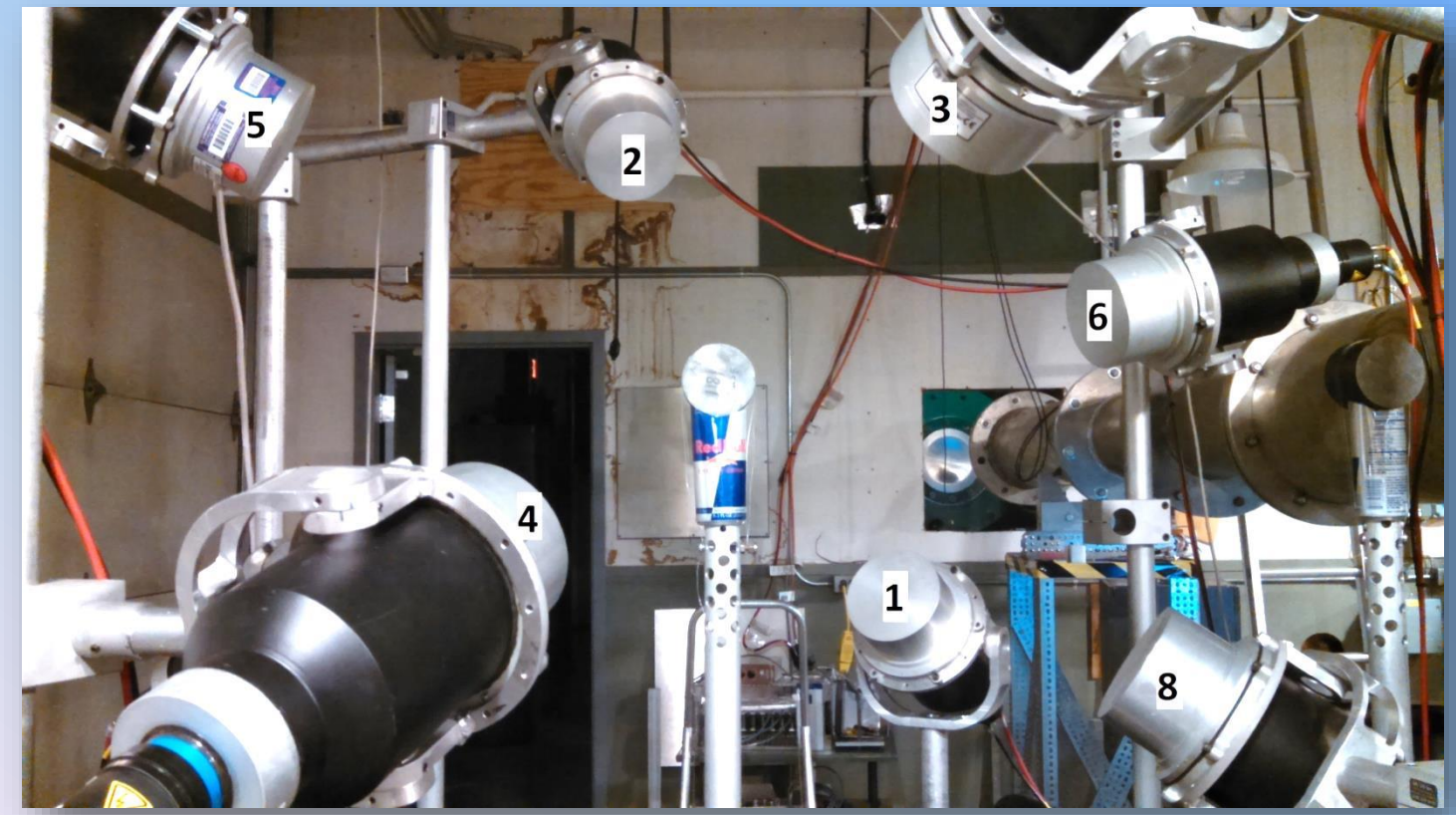
# Fast Neutron Scattering

Quasi-differential neutron scattering and angular distributions.



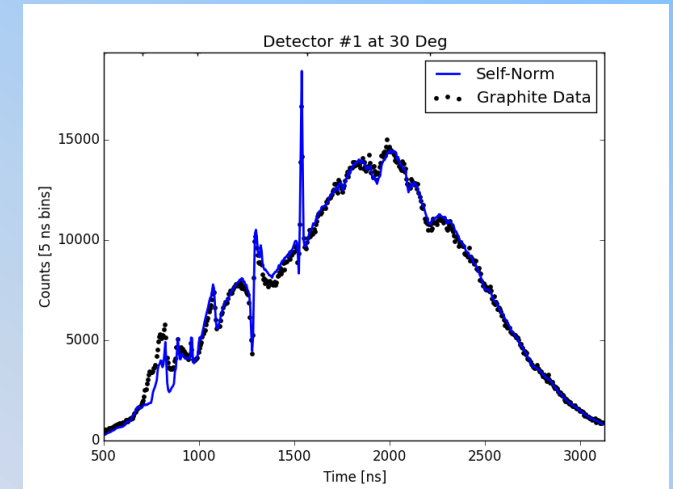
# Angle Set 1 (45, 70, 100, 150 degrees)

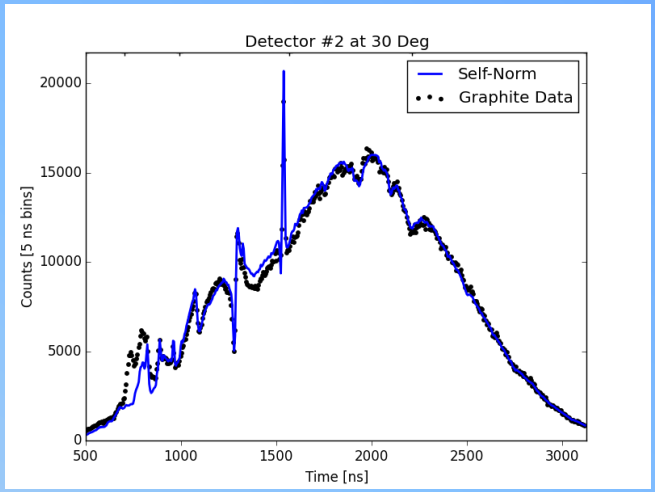
- Use 8 liquid scintillators, 2 are always at the same angle
- Total of 7 different angles (one pair of detectors is stationary)

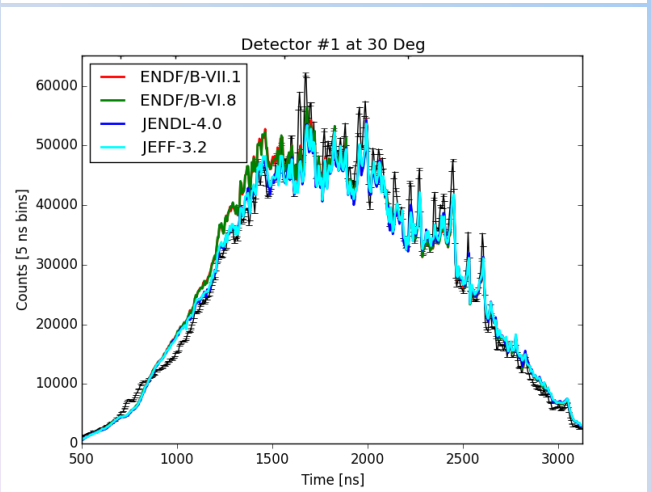


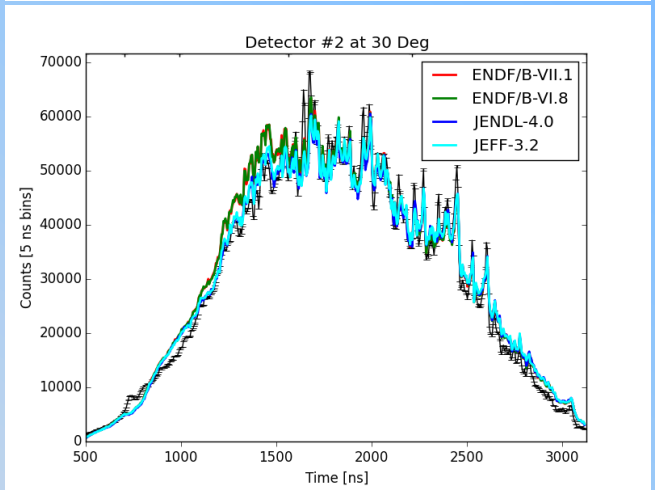
# Pb Scattering at 30 deg

- Experiment and evaluation are in good agreement for both C and Pb

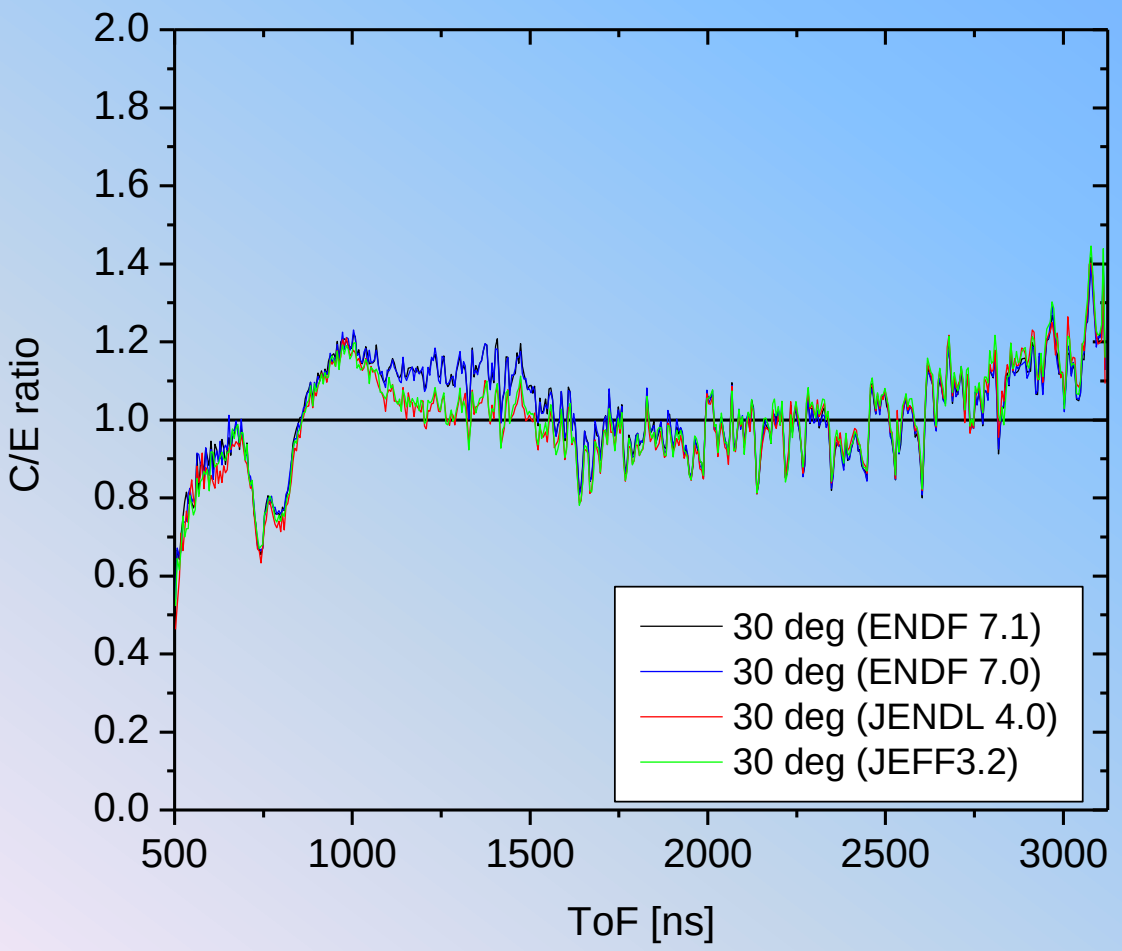


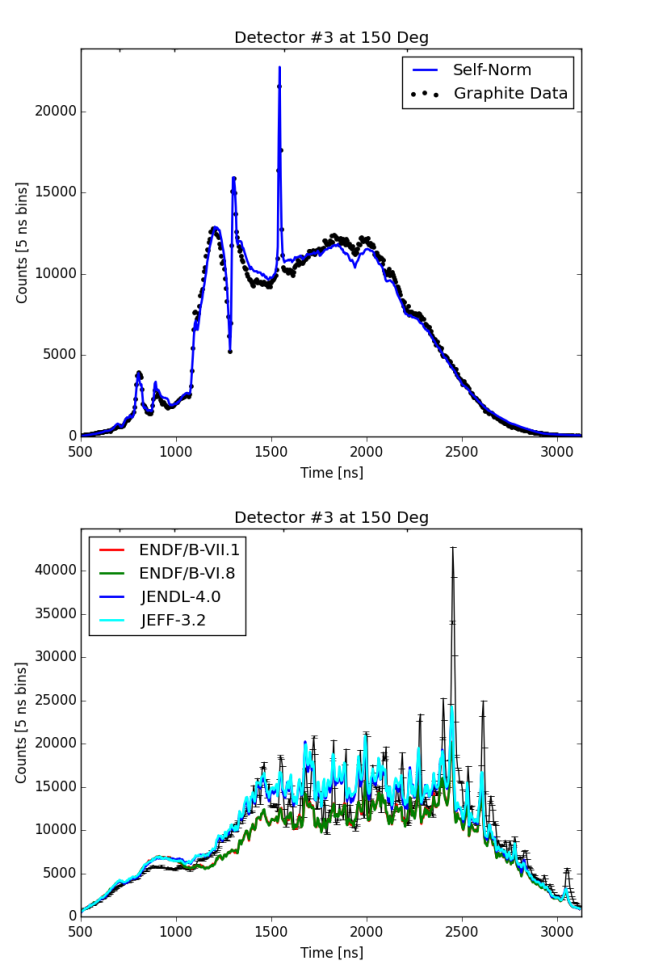
# C/E values as a function of ToF

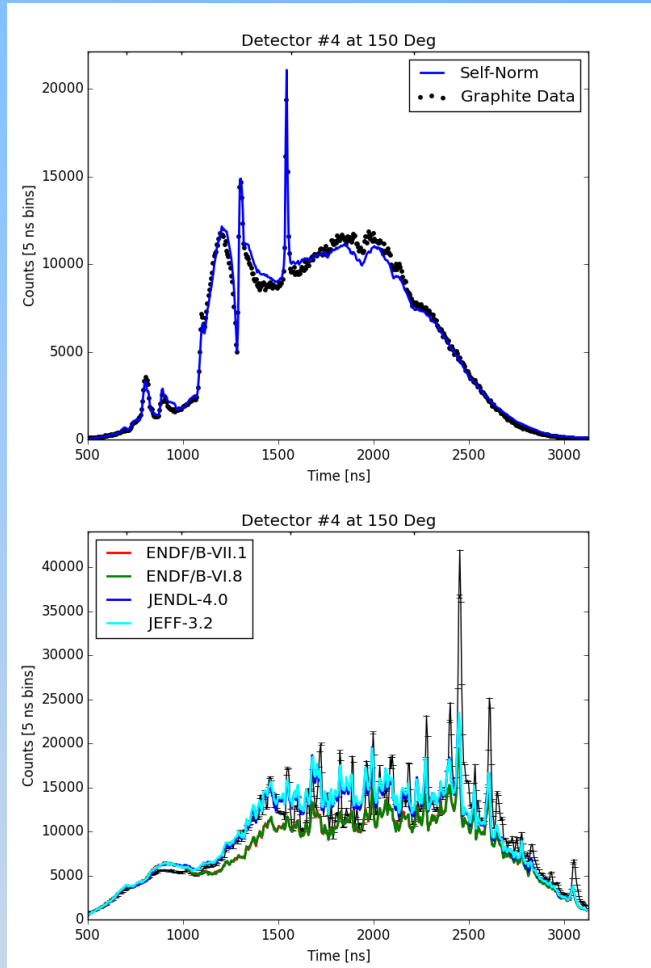



- Relatively good agreement between experiment and evaluations
  - Discrepancies at low and high energy

# Pb results at 150 deg

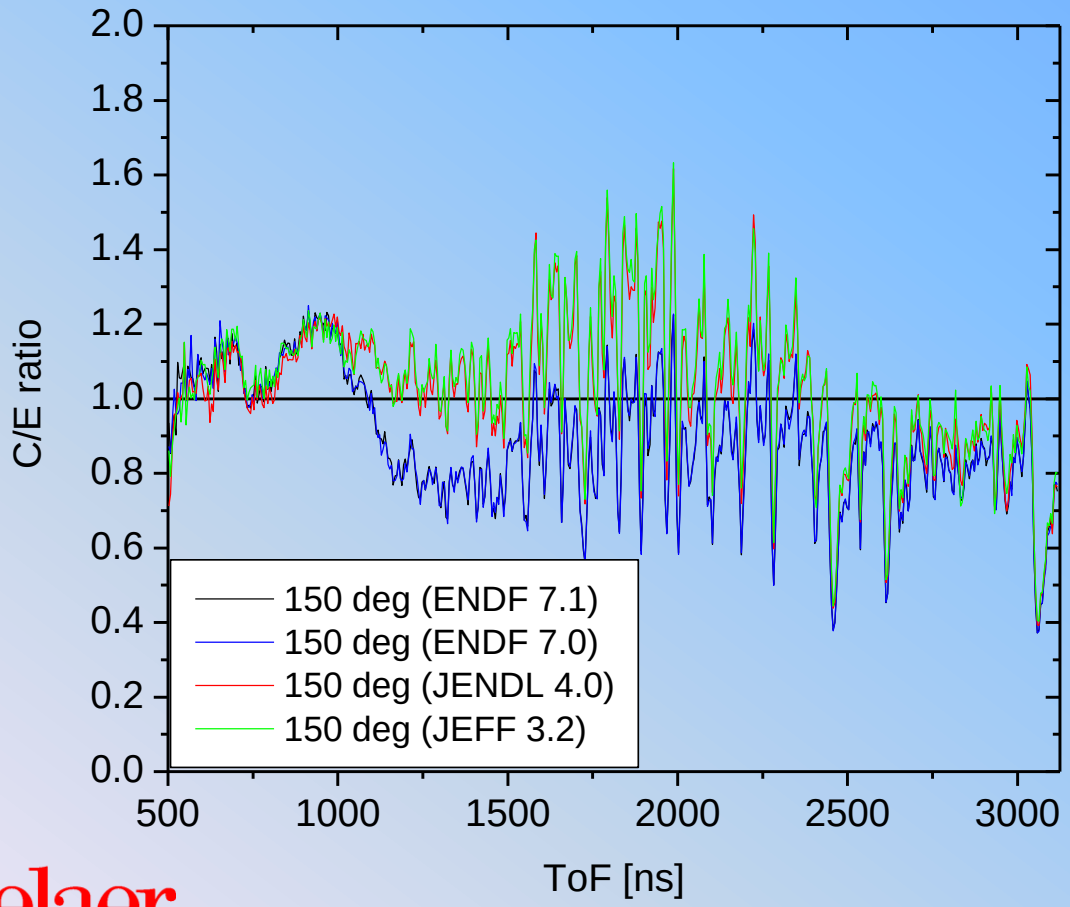
- Carbon measurements agree with simulation
- For Pb, ENDF underpredicts the experiment



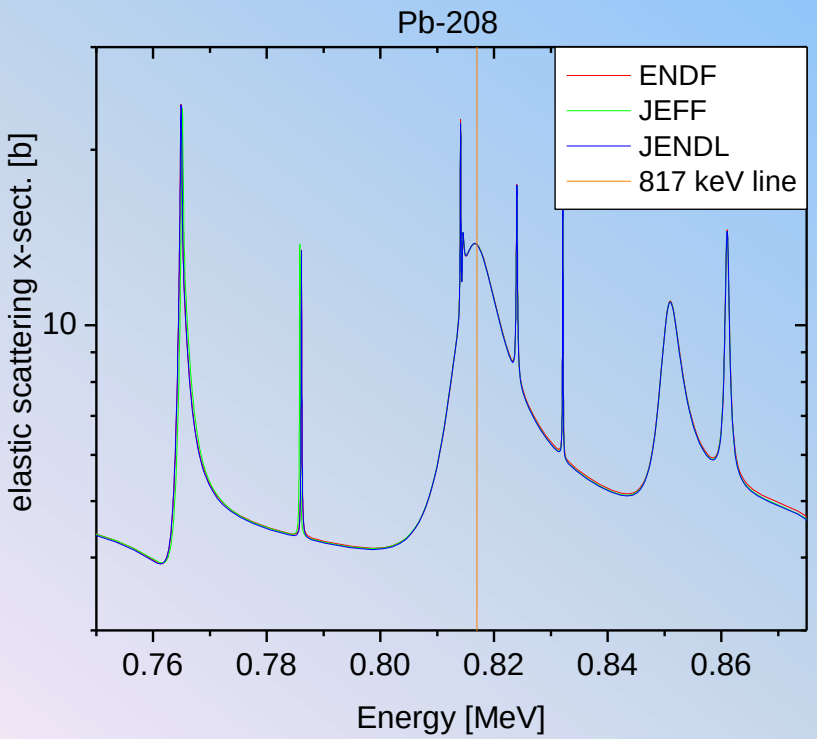
# C/E values as a function of ToF

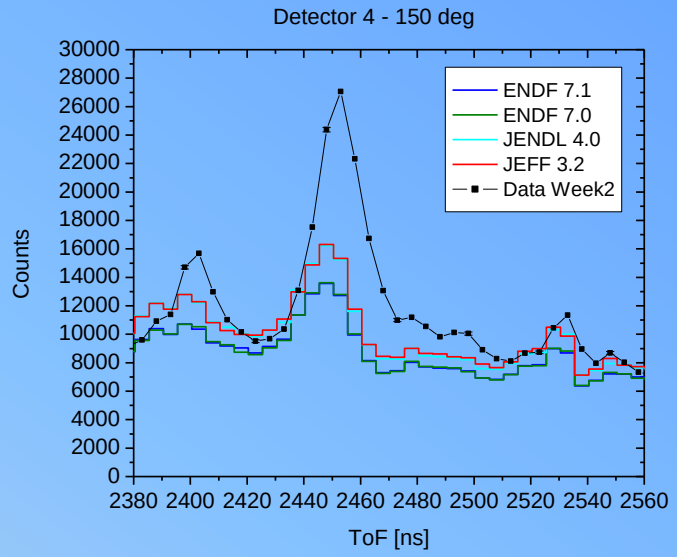
- Poor agreement between experiments and evaluations
  - Can see resonances not fitting well
  - ENDF 7.1 is underestimating the data
  - JENDL 4.0 and JEFF 3.2 are overestimating the data

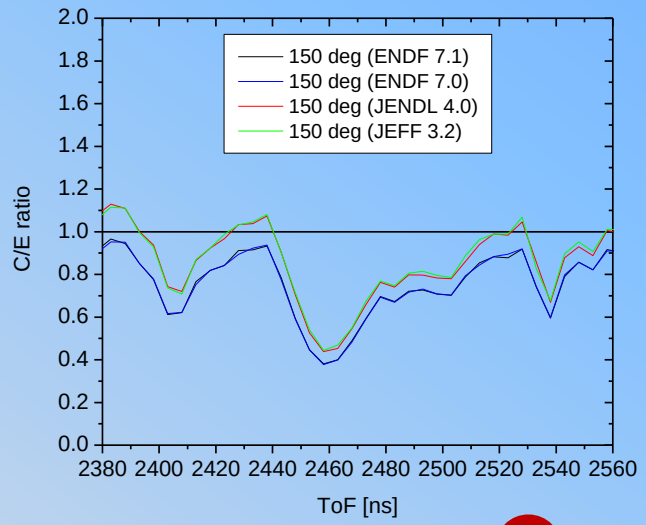


# Resonance in Pb-208 at 817 keV

- Some resonances show disagreement at different angles
  - Could be related to spin or angular momentum assignment.

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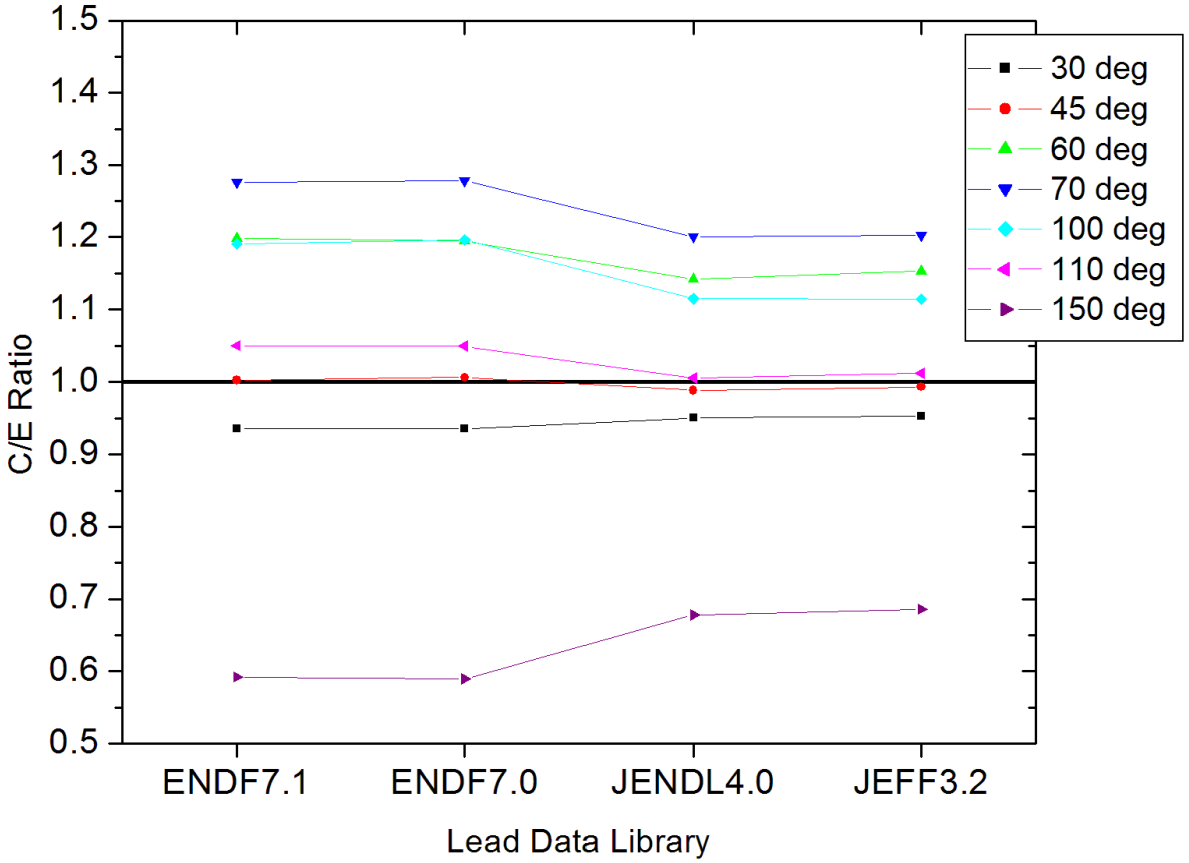
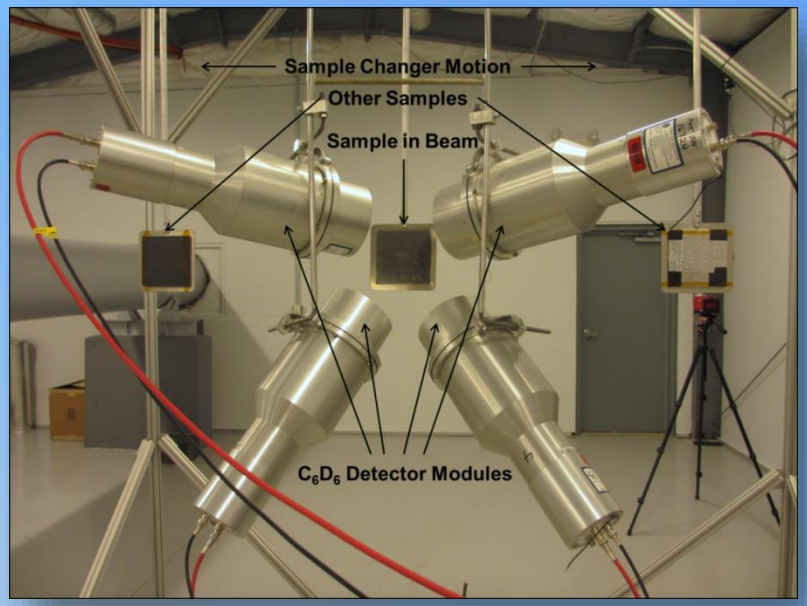
# Resonance at 817 keV C/E values




- JENDL 4.0 shows the best agreement with our experiment
- Forward angle measurements have the best agreement in this energy region

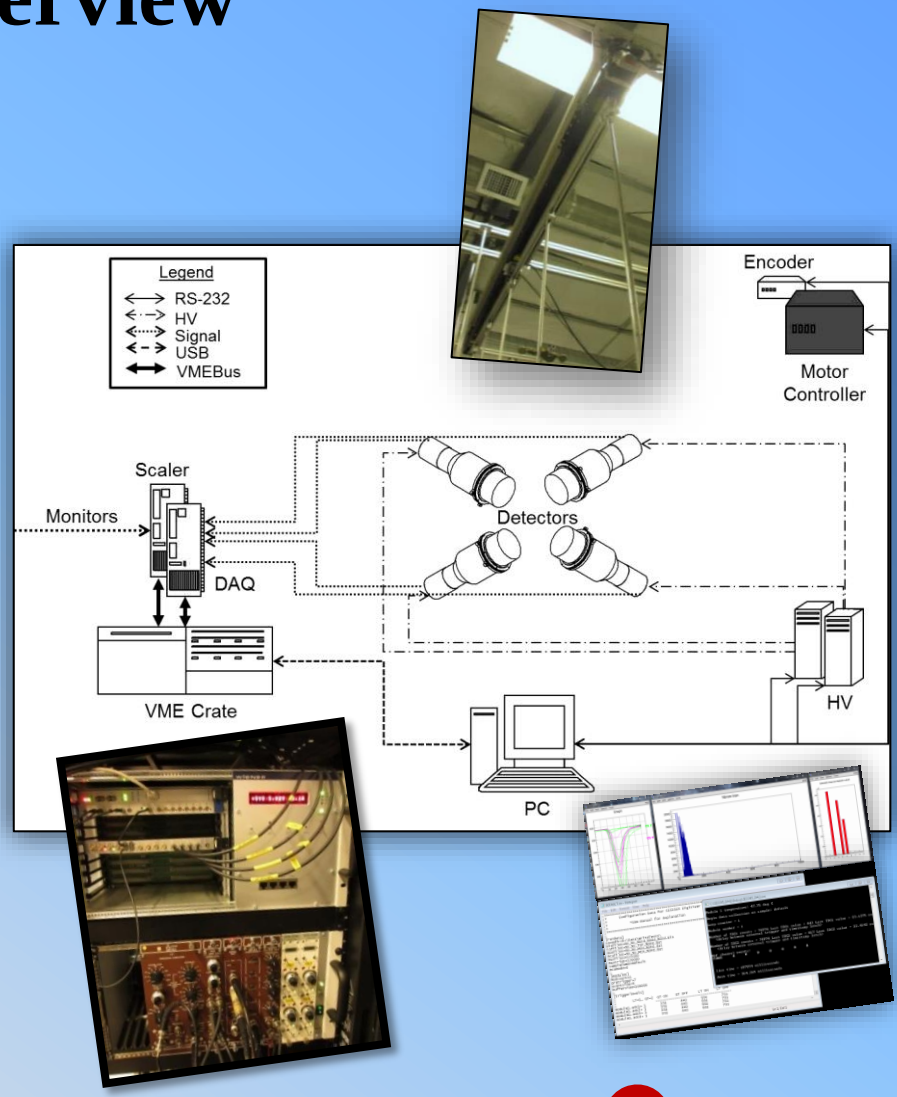
# Mid-Energy Capture Detector System Overview

- 4 $C_6D_6$ detector modules manufactured by Eljen Technology
- **Low mass, low neutron sensitivity design**
- Located at 45m flight path in newly constructed flight station
- Measurements made from 1 eV to 1 MeV




# Mid-Energy Capture Detector System Overview

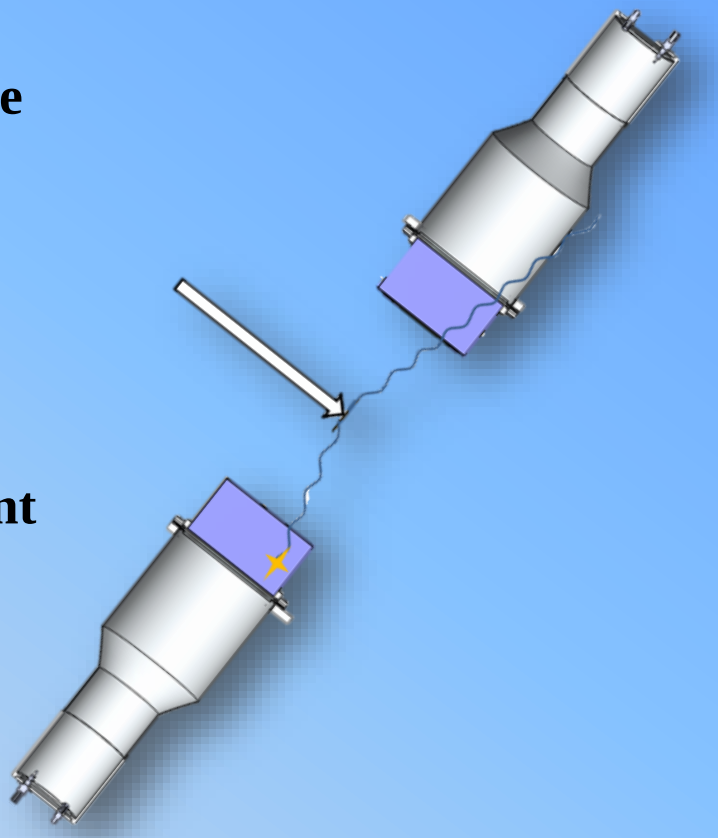
- **Sample Changer**
  - Velmex BiSlide linear translation table w/ stepper motor and magnetic position encoder
- **Data Acquisition**
  - 8-channel SIS3305 digitizer w/ 10-bit, 1.25GHz functionality
- **Beam Flux Monitoring**
  - 8-Channel MDGG-8 Flexible Delay/Gate Generator & Scaler
  - Use fission chambers as monitors
- **Detector Bias**
  - 2 Dual-channel 3kV NHQ-203M high voltage supplies
- **Software**
  - Custom C/C++ libraries for system control, data acquisition, visualization and data analysis



# Mid-Energy Capture Detector Principle of Operation

Uses the "**Total Energy**" detection principle:

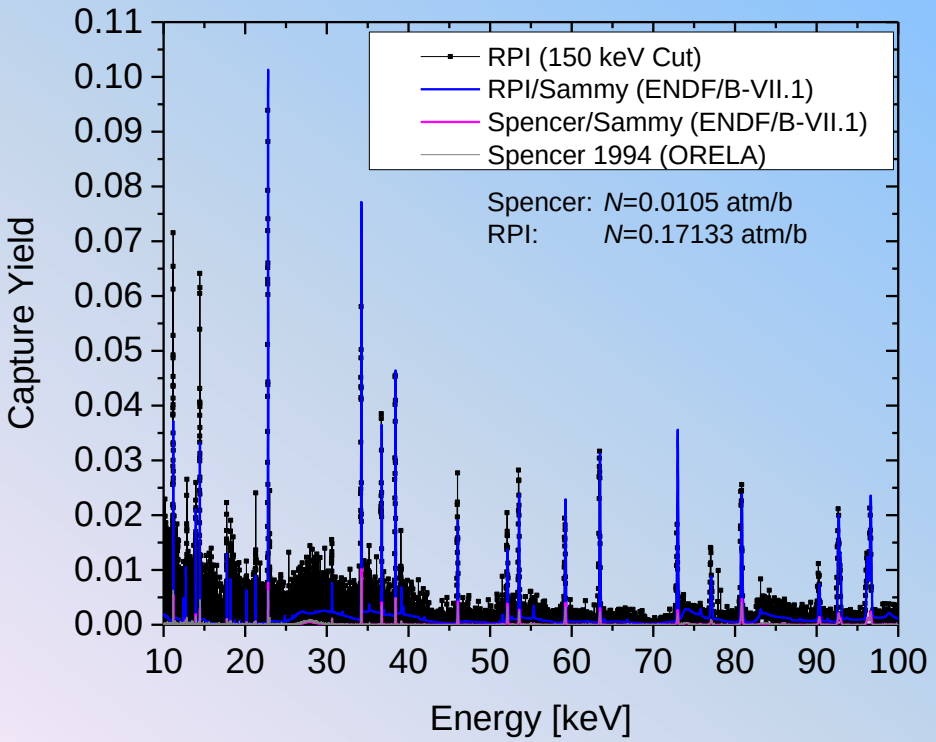
1. Detect only a **single photon per capture** cascade
2. Assert that the detection **efficiency is proportional** to the incident photon energy
3. Given 1 and 2, it can be shown that the total **efficiency to detect a capture event is proportional to the total excitation energy** of the compound nucleus, and insensitive to the cascade.

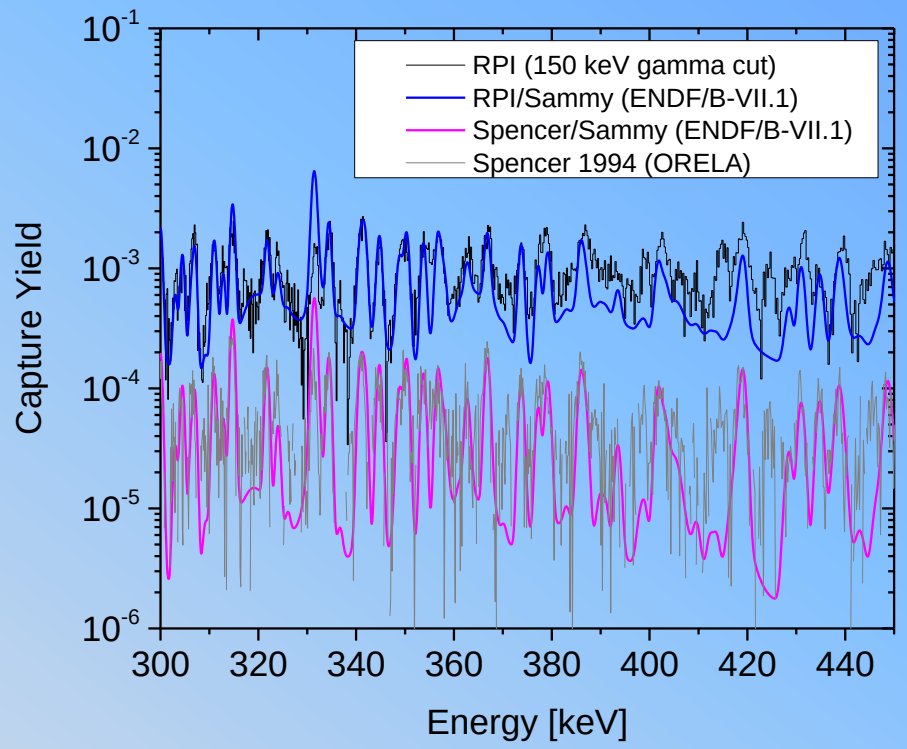


**Requires a weighting function**

# $^{nat}$Fe Capture measurment

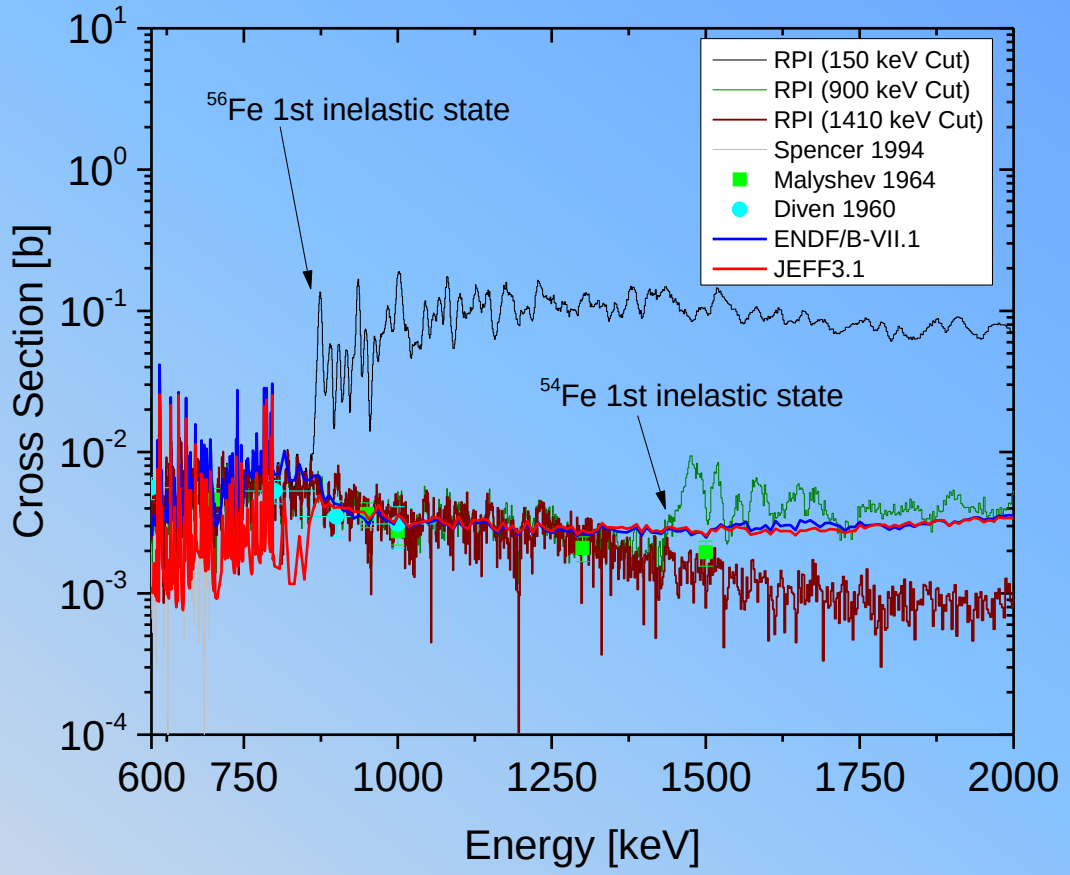
- $^{nat}$Fe was used as a test to compare with evaluations and other measurements
  - The RPI data (45m flight path) has good energy resolution compared to the Spencer ORELA data (40m flight path)
  - The RPI data provide information above 700 keV (next slide)



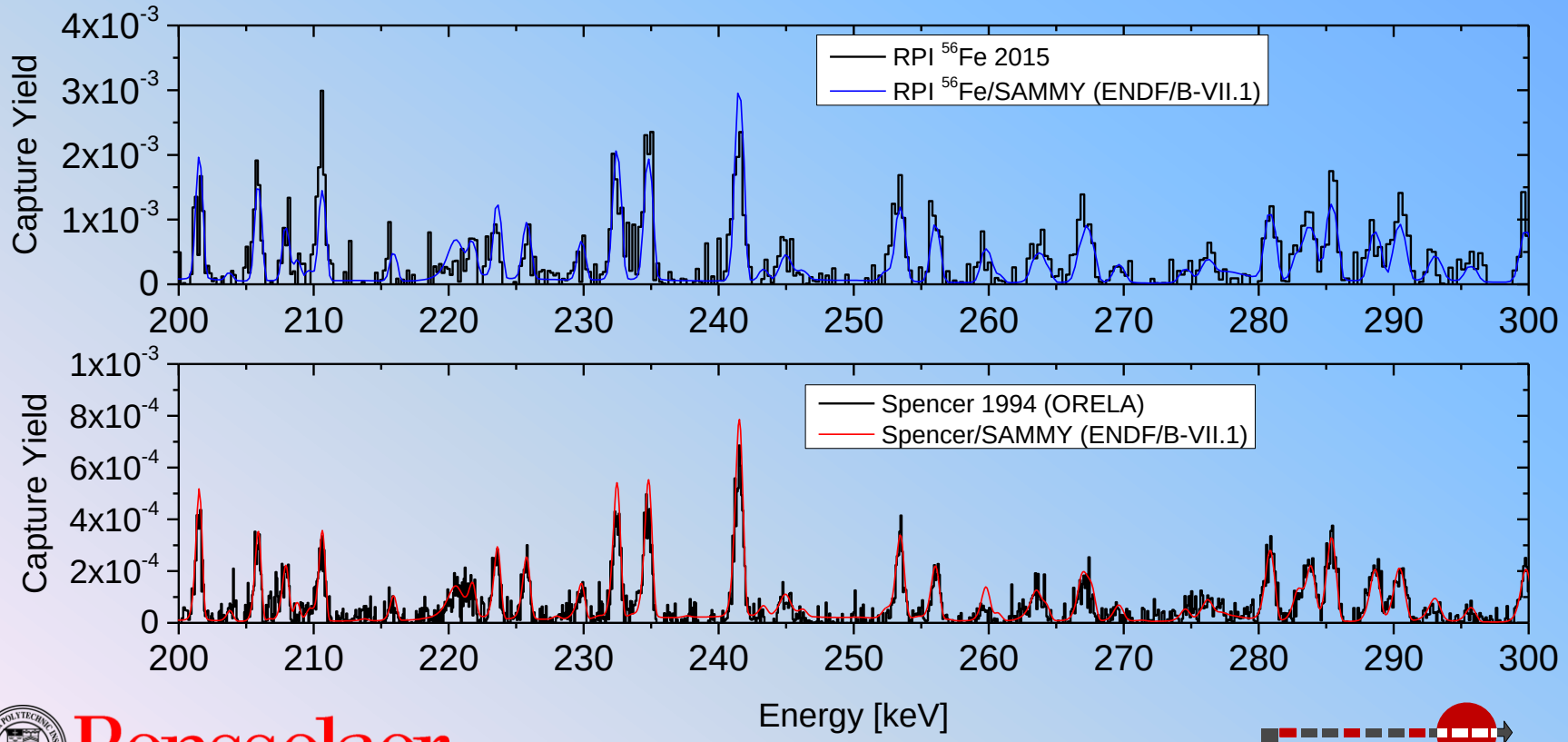
# $^{nat}$Fe Capture Cross Section above 847 keV

- New capture data obtained above 847 keV and 1409 keV inelastic states in $^{56}$Fe and $^{54}$Fe
- Capture signal separated from inelastic scattering signal by post-processing digitized waveforms with different energy deposition cutoffs
- Good agreement with other experiments
- Above 1400 MeV, the data are lower than the evaluations



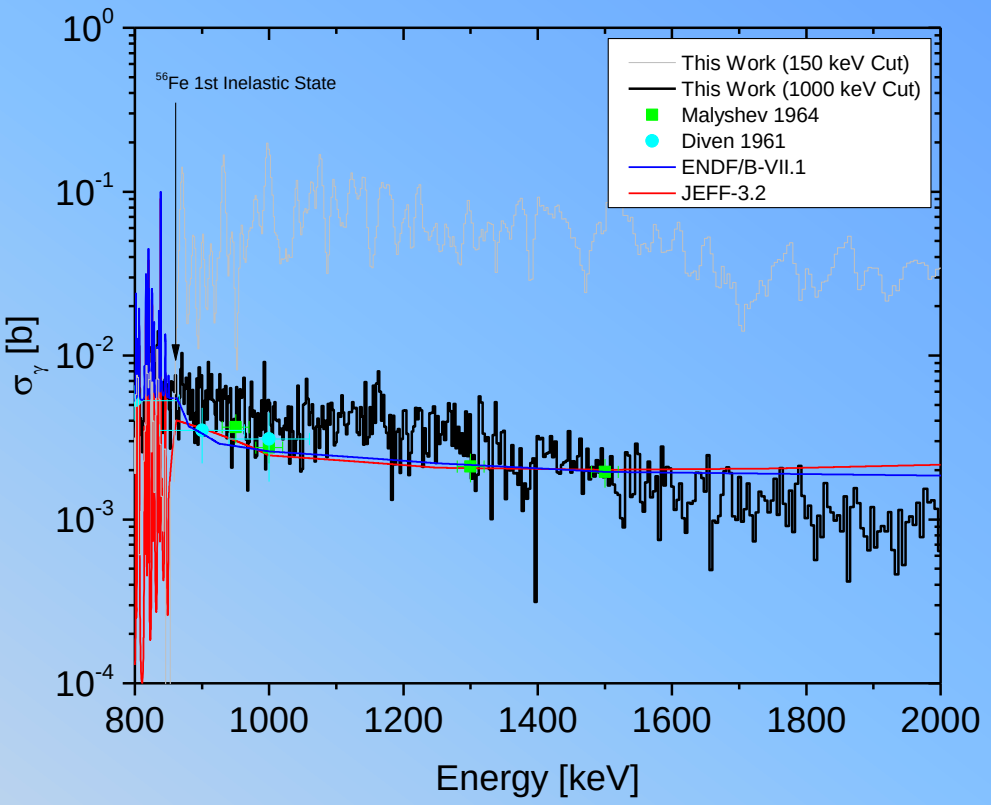
# $^{56}$Fe Capture measurement

- $^{56}$Fe sample was 7mm thick.
  - Data was collected up to 2 MeV
- The data is in good agreement with the Spencer Data (was used to generate ENDF/B-VII.1)
  - Although there are some differences
- The statistical accuracy is not sufficient yet.



# $^{56}$Fe Capture Cross Section above 847 keV

- New capture data obtained above 847 keV and 1409 keV inelastic states in $^{56}$Fe and $^{54}$Fe
- Capture signal separated from inelastic scattering signal by post-processing digitized waveforms with different energy deposition cutoffs
- Good agreement with other experiments
  - The data seems slightly higher that our $^{nat}$Fe results
- Above 1400 MeV, the data are lower than the evaluations

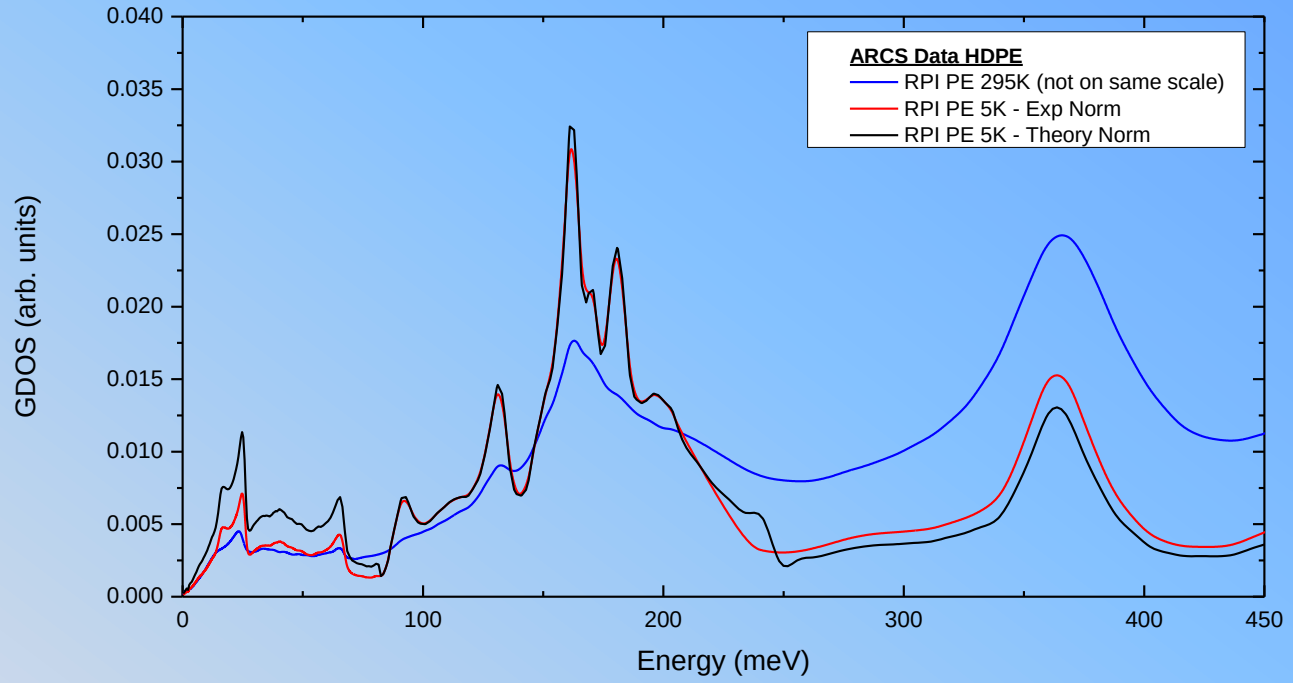


# Thermal Scattering

# Thermal Scattering Overview

- Preformed measurements at SNS
  - SEQUOIA
    - Water
    - Medium Density Polyethylene (MDPE)
  - ARCS
    - High Density Polyethylene (HDPE) 295 °K and 5 °K
    - Quartz ($SiO_2$) at 20, 300 550, 600 °C
  - VISION (measures $S(\omega)$)
    - Lucite, Lexan, Polyethylene at 5 °K and 295 °K
- The double differential scattering data (DDSD) can be used to benchmark thermal scattering evaluations
- Method to generate $S(\alpha,\beta)$ from the experimental data are under development:
  1. Convert the data ($S(Q,\omega)$) to phonon spectrum (use low values of Q to limit multiple phonon scattering)
  2. Remove the elastic peak from the DDSD and convert the inelastic part directly to $S(\alpha,\beta)$
- Developed capabilities to use LAMMPS code to calculate the phonon spectrum and scattering kernel.

# Phonon spectrum from measured $S(Q,E)$




- Low temperature measurements are essential in order to resolve the structure.
- Convert the measured $S(Q,E)$ data for phonon spectrum using the SNS DAVE code:

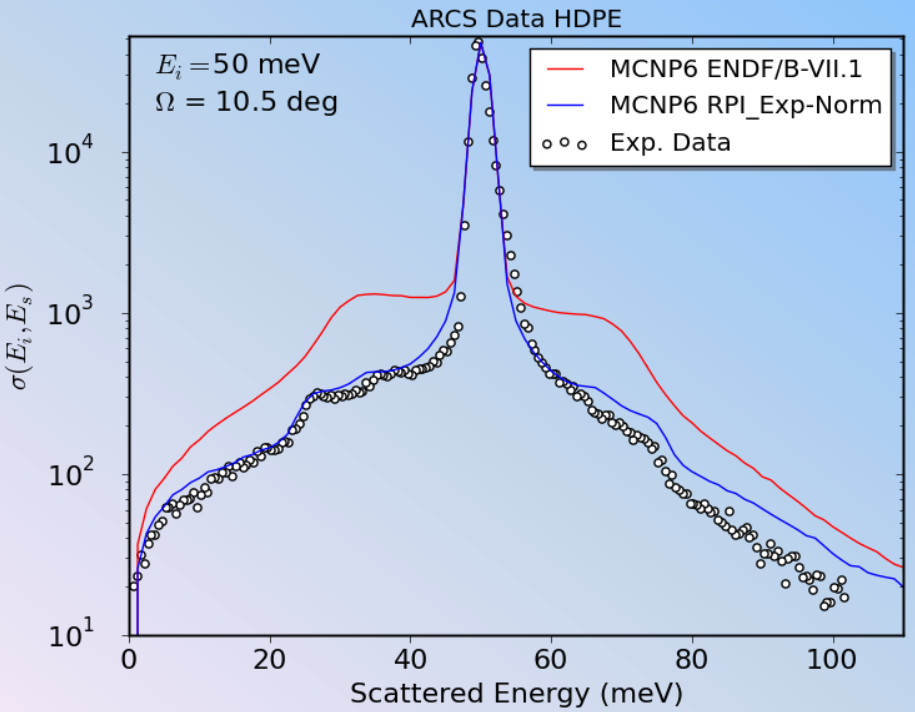
$$S(Q,E) = \frac{\hbar^2 Q^2}{6ME}\exp(-\langle u^2\rangle Q^2)G(E)[n(E,T)+1] \qquad n(E,T) = \frac{1}{\exp\left(\frac{E}{k_B T}\right)-1}$$

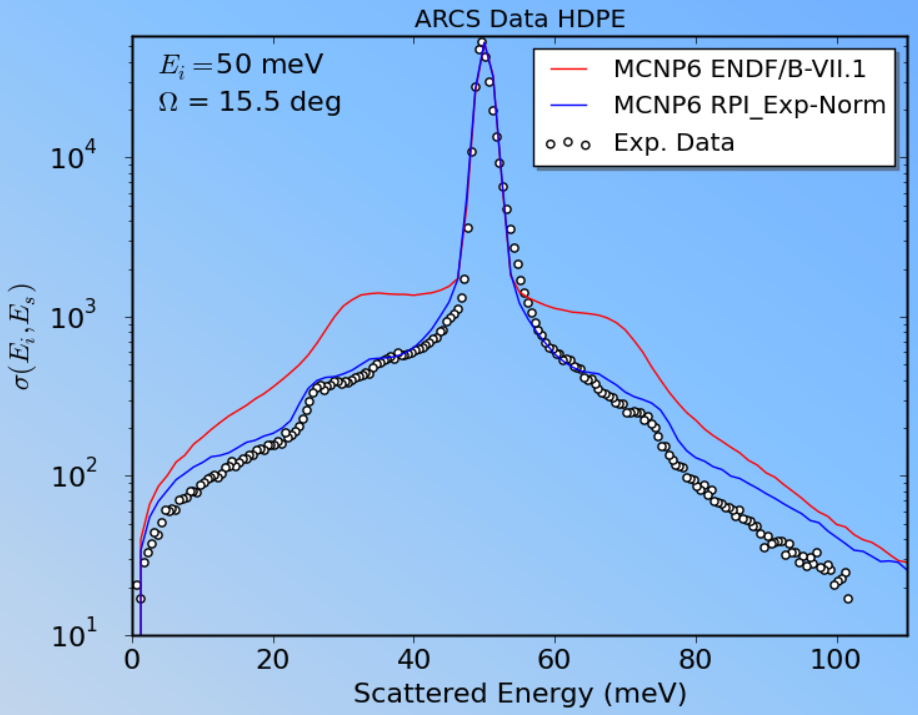
$G(E)$ - generalized phonon density-of-states(GDOS),
$Q$ - wave vector transfer,
$S(Q,E)$ - structure dynamics factor,
M - mass of the atom,
$\langle u^2 \rangle$ - mean square displacement.

# Example for HDPE

## Experiment Normalized GDOS

- The phonon spectrum was processed with NJOY 2012
- The experimental response simulated with MCNP 6
- The agreement with the experiment is improved

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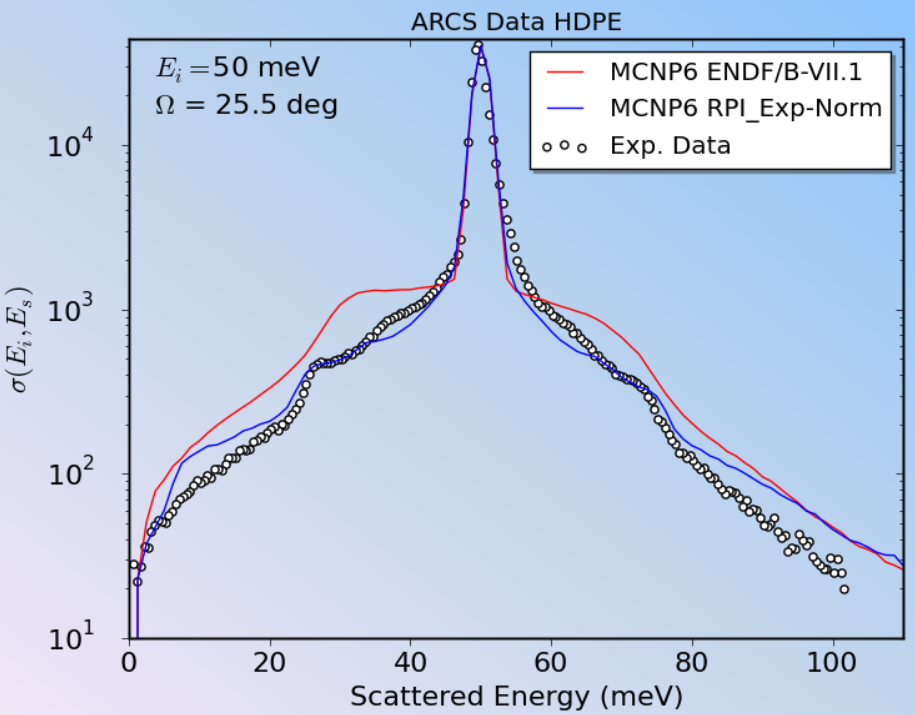
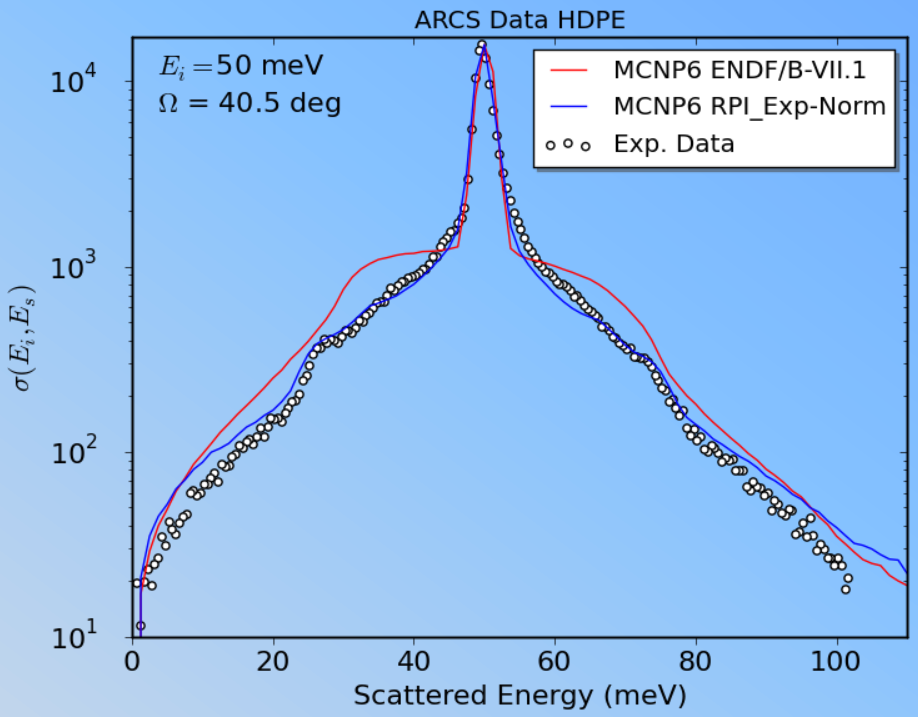
# Example for HDPE other angles Experiment Normalized GDOS

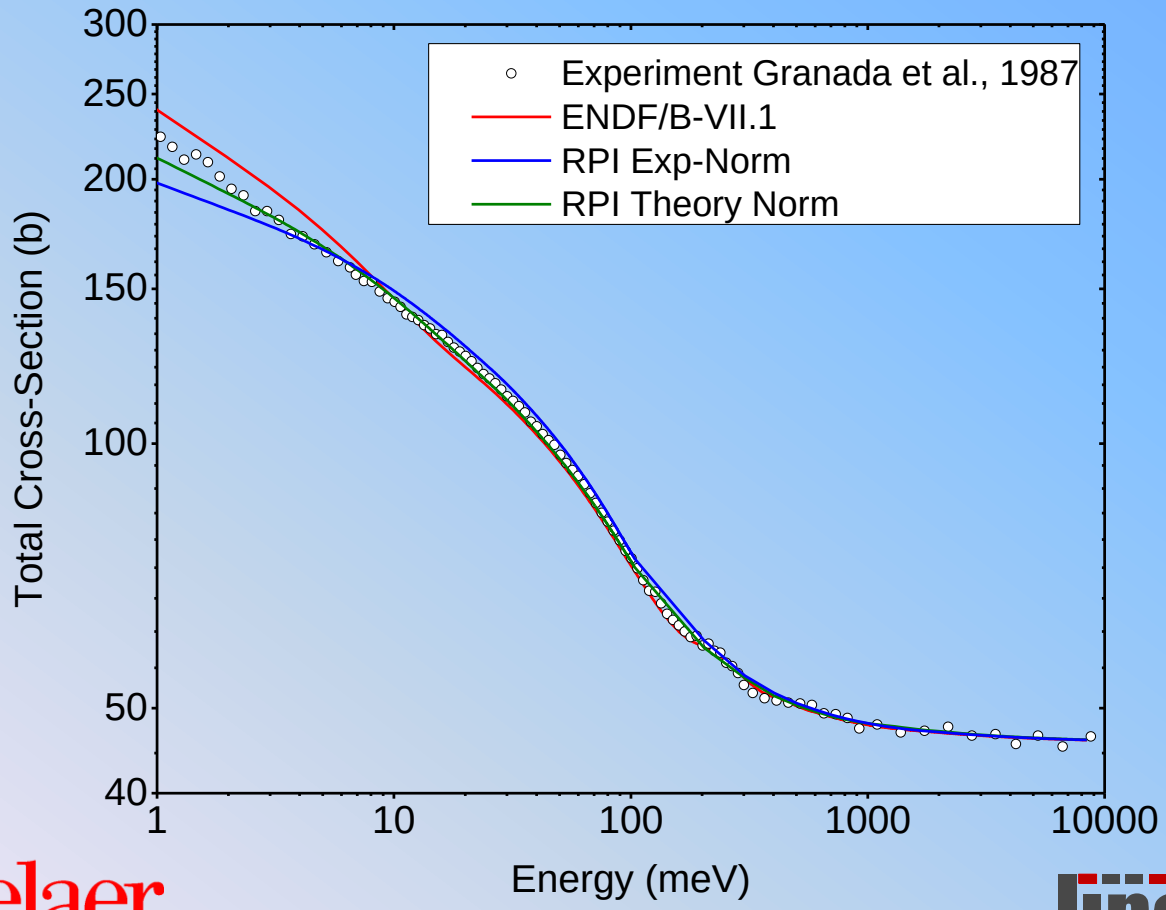
- Similar improvements
- Other incident energies and angels available



# Polyethylene Total Cross Section

- The experimentally derived phonon spectrum is in good agreement with the total cross section measurement.
- The Experimental vs theory driven measurement give slightly different results



# Summary

- **Recent publications**
  - Gd isotopes – published, NSE Vol. 180, Number 1, May 2015.
  - Eu – published , Annals of Nuclear Energy, Vol. 69, pp. 74-89, July 2014.
  - $^{238}$U – published, Annals of Nuclear Energy, Vol. 73, pp. 455-464, November 2014.
  - $^{95}$Mo URR – published, Phys. Rev. C 92, 024601, 2015.
- **Analysis in progress**
  - High energy (0.5-20 MeV) transmission: Fe, Ti, Ta, Cu, Zr and $^{92/94,95,96,98,100,nat}$Mo
  - RRR (capture/transmission) : $^{161,162,163,164}$Dy, Cs, Rh , Re, Fe,
  - URR capture: Ta
  - $^{nat}$Fe neutron scattering
  - Thermal scattering $H_2O$, polyethylene, quartz
- **Measurements since the last CSEWG meeting**
  - Transmission: $H_2O$, Pb, W
  - Scattering: Pb
  - Capture: $^{56}$Fe
- **Planned/in progress measurements**
  - Scattering: Zr
  - Capture: $^{95}$Mo