Nuclear Data for Criticality Safety and Reactor Applications at the Gaerttner LINAC Center

Y. Danon, **R. Bahran, E. Blain, A. Daskalakis**, E. Liu, **B. McDermott, S. Piela, D. Williams**

Rensselaer Polytechnic Institute, Troy, NY, 12180

and

D. Barry, R. Block, T. Donovan, B. Epping, G. Leinweber, M. Rapp

KAPL, Bechtel Marine Propulsion Corporation, Schenectady, NY ,12301

American Nuclear Society Meeting, Town & Country Hotel &Resort, San Diego, CA, November 11-15, 2012

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Why Should We Care About Nuclear Data?

Example: Reactor Physics Calculations

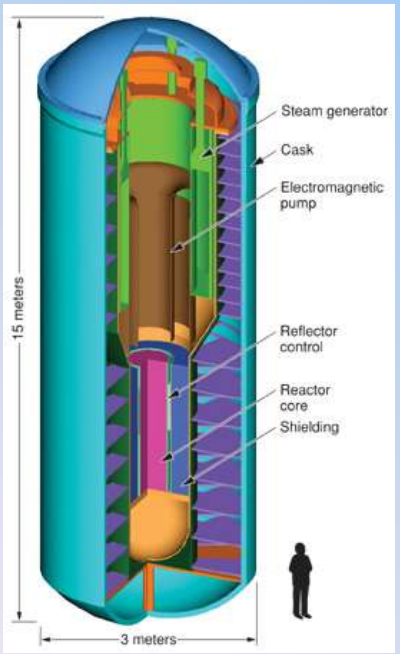
Nuclear Data

Geometry Data

Computational Methods (Physics)

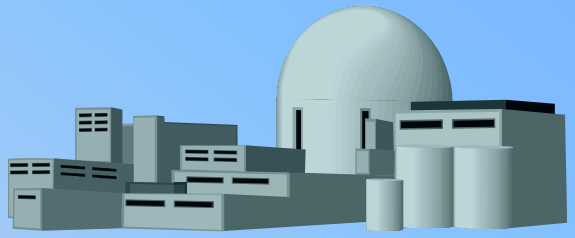
Results

- Effective neutron Multiplication factor
- Neutron flux
- Burnup
- Kinetics



www.llnl.gov

The Shippingport Reactor (Critical in 1957)
http://www.pabook.libraries.psu.edu/palitmap/Shippingport.html



Physics Design Limitations

- Modern computational methods are greatly improved
- Monte Carlo Methods
  - Advantages
    - Can describe the geometry at a level of a CAD drawing.
    - Includes different physics models in great detail.
    - Can solve time dependent problems.
  - Limitations
    - **Accuracy is only limited by Nuclear Data and Physics models**
    - Slow for some types of calculations (but computers are getting faster)

GODIVA

www.lanl.gov

The Nuclear Data Program at the RPI Gaerttner LINAC Laboratory

- Driven by a 60 MeV pulsed electron LINAC ~**10^{13} n/s**
- **Neutron transmission**
  - Resonance region: 0.001 eV- 600 keV,
  - High energy region: 0.4- 20 MeV
- **Neutron Capture**
  - Resonance region: 0.01-1000 eV
  - Resolved and unresolved resonance region (under development)
- **Neutron Scattering**
  - High energy region: 0.4 MeV- 20 MeV
  - Resonance scattering
- **Prompt fission neutron spectra and multiplicity**
- **Lead Slowing Down Spectrometer (LSDS)**
  - Fission cross section and fission fragment spectroscopy.
  - (n,α) and (n,p) cross sections on small (radioactive) samples.
  - Assay of used nuclear fuel

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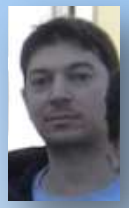
Other Related Talks in This Meeting

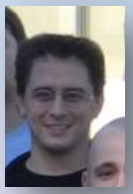


- **Monday 2:20 P.M., ACCELERATOR APPLICATIONS: GENERAL,**

Quasi-Differential Neutron Scattering Measurements of ^{238}U, **A. M. Daskalakis**, R. M. Bahran, E. J. Blain, B. J. McDermott, S. Piela, Y. Danon (Gaerttner LINAC Center, RPI), D. P. Barry, G. Leinweber, R. C. Block, M. J. Rapp (Bechtel Corp., KAPL)

- **Monday 3:55 P.M., REACTOR PHYSICS: GENERAL - I**

Thermal Total Cross Sections of Europium from Neutron Capture and Transmission Measurements, **G. Leinweber**, D. P. Barry, R. C. Block, M. J. Rapp, J. G. Hoole (Bechtel Marine Propulsion Corp., KAPL), Y. Danon, R. M. Bahran, D. G. Williams (RPI), J. A. Geuther (Kansas State Univ), F. J. Saglime III (RPI)



- **Monday, 4:00 p.m. - 6:00 p.m., STUDENT POSTER SESSION**

Brian McDermott , A Detector Array for Measuring Neutron Capture Cross Sections in the keV Region

- **Thursday 1:25 P.M., DATA ANALYSIS IN NUCLEAR CRITICALITY SAFETY - II**

Total Cross Section Measurements of Highly Enriched Isotopic Mo in the Resolved and Unresolved Energy Regions, **R. M. Bahran**, A. M. Dasklakis, B. J. McDermott, E. J. Blain, Y. Danon (RPI), D. P. Barry, G. Leinweber, M. J. Rapp, R. C. Block (KAPL), D. G. Williams (US Military Academy)

FY 2011-2013 (Technical) Milestones Overview

FY 2011

1. **Analysis**: Complete SAMMY analysis on Gd (Q1).
2. **Capability development**: Complete calculations to estimate efficiencies for several detector concepts (C_6D_6, BaF_2, NE-226) (Q2).
3. **Capability development**: Purchase prototype detectors of the selected concepts and perform scoping measurements with prototype detectors (Q4).
4. **Measurements**: Measure ^{56}Fe total cross section in the high energy range (0.5 MeV-20 MeV) (Q3).

FY 2012

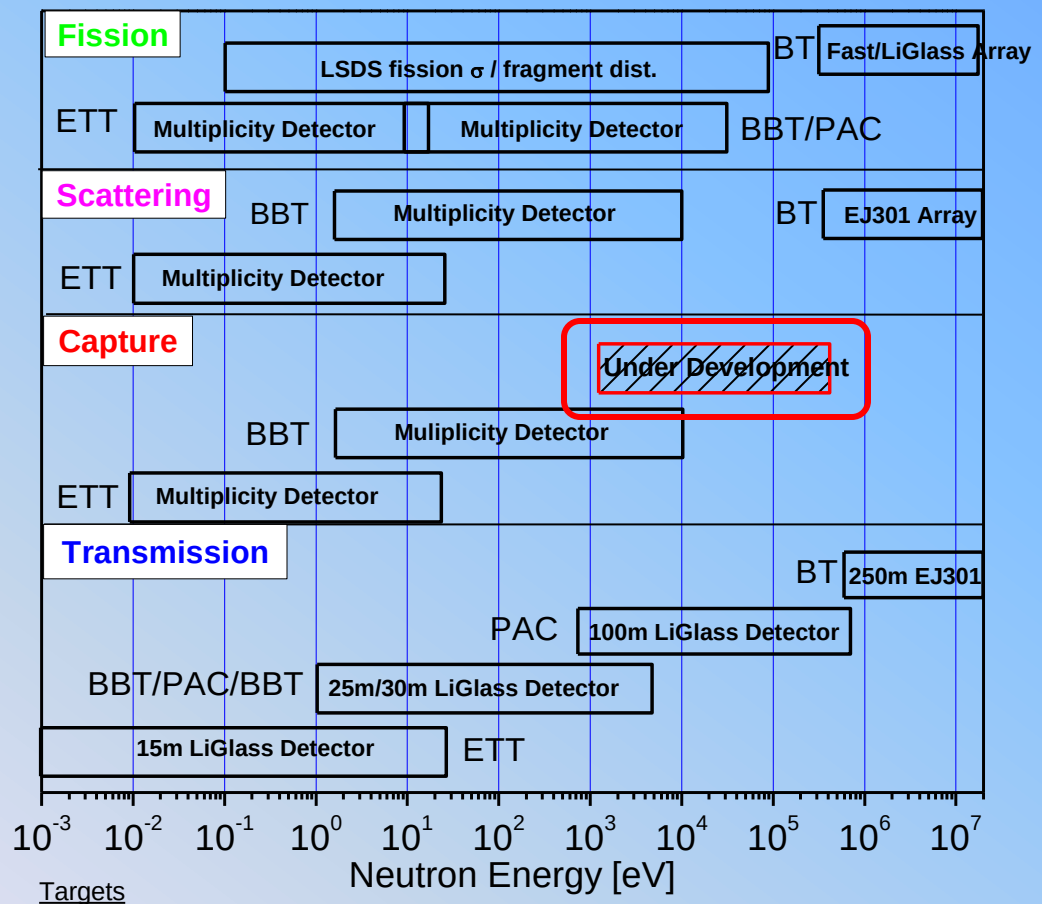
1. **Documentation**: Complete ^{56}Fe documentation (carry over from FY11) (Q1)
2. **Capability development**: Perform scoping measurements with prototype detectors (Q2)
3. **Measurements**: Complete measurement of ^{238}U scattered and fission neutrons (0.5-20 MeV) (Q4).
   Measurements: Complete transmission measurements to supplement ORNL measurements planned at Institute for Reference Materials and Measurements (Q4).

FY 2013

1. **Capability development**: Complete construction of RPI capture detection system and qualify system.
2. **Measurements:** Perform thermal neutron scattering measurements of water at elevated temperatures from room temperature up to 550K and SiO_2 (glass) at room temperature (as an example of other moderators) (Q4) (currently SNS is down, exploring LANSCE)

Capability Development

- Develop Mid energy (1 - 300 keV) capture detector



Targets
ETT- Enhanced Thermal Traget
BBT - Bare Bounce Target
BT- Bare Target on Axis
PAC - PacMan Target

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New 40-50 m Flight Station

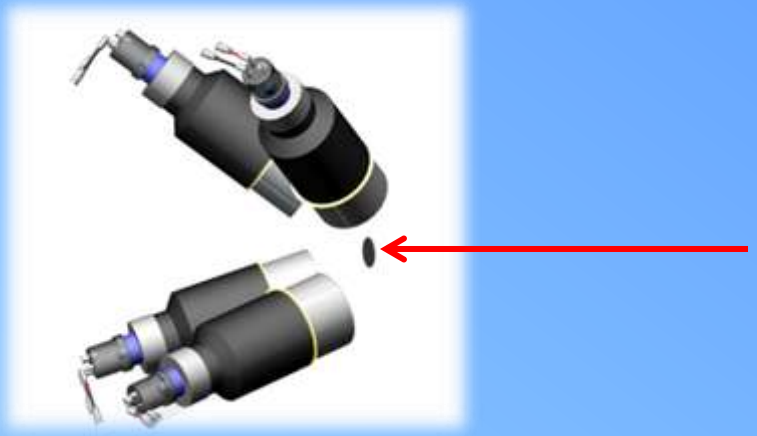
- Enable capture measurements in the keV region within a reasonable experiment time.

New Flight Station

- Flight Station construction completed in FY 12
- FY 13 plan
  - Install evacuated flight tubes
  - Install capture detector array
  - Design a sample changer

Mid-Energy Capture Detector

- 4 deuterated benzene (C_6D_6) liquid scintillators with low neutron sensitivity
- Located at newly constructed 40m flight station
- 10-bit, 8 channel Struck Systems SIS3305 digital data acquisition system allows for low dead time operation
- Low mass design to minimize background contributions from neutrons captured in detector and surrounding structural materials

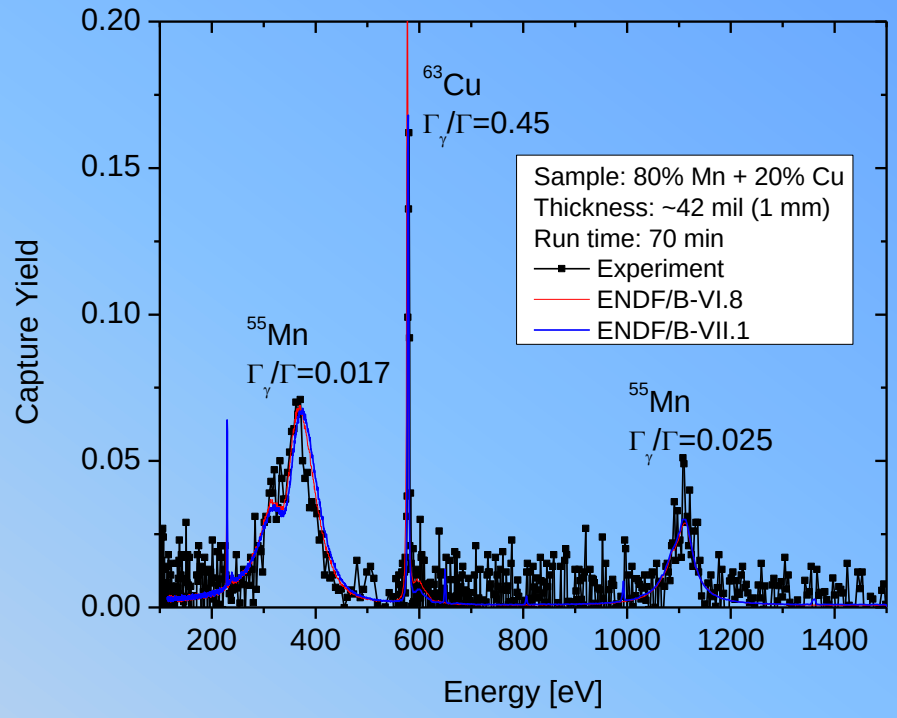


CAD model of the detector array and sample

A picture of the prototype detector

Mid-Energy Capture Detector First Test

- Capture measurements performed on Mn/Cu sample using existing analog TOF setup
- Experimental results are in good agreement with ENDF/B-VI.8 and VII.1 data libraries
- No contribution from scattered neutrons is apparent
- Future experiments will incorporate a digital DAQ system

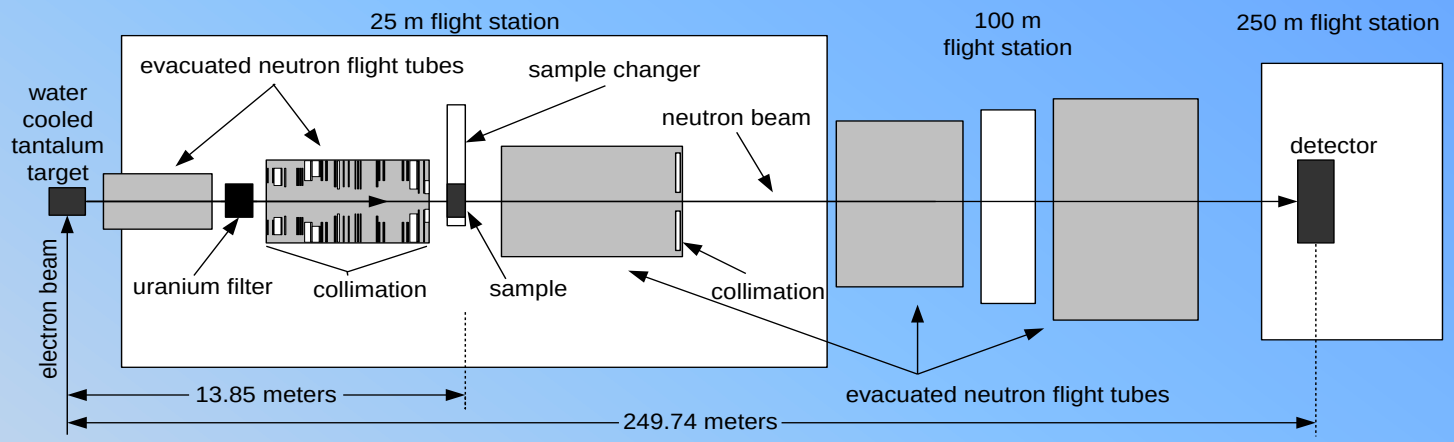


Measurements Completed This Year

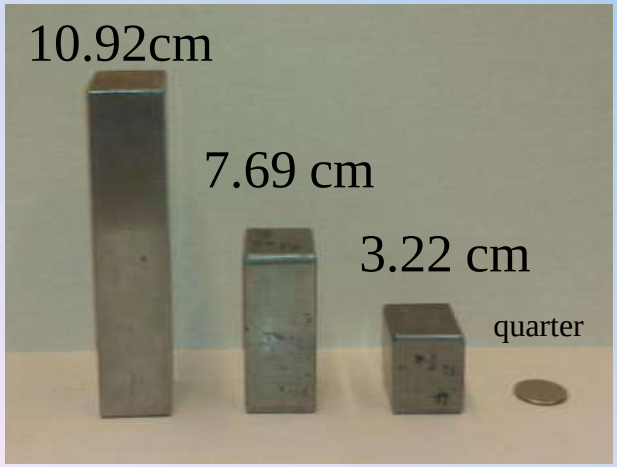
- **Transmission**
  - ^{56}Fe, 0.5-20 MeV, 250m flight path

- **Scattering**
  - ^{238}U, Neutron Scattering (7 angles), 0.5-20 MeV, 30m flight path.
  - ^{56}Fe, Neutron Scattering (7 angles), 0.5-20 MeV, 30m flight path

250m Transmission Experimental Setup

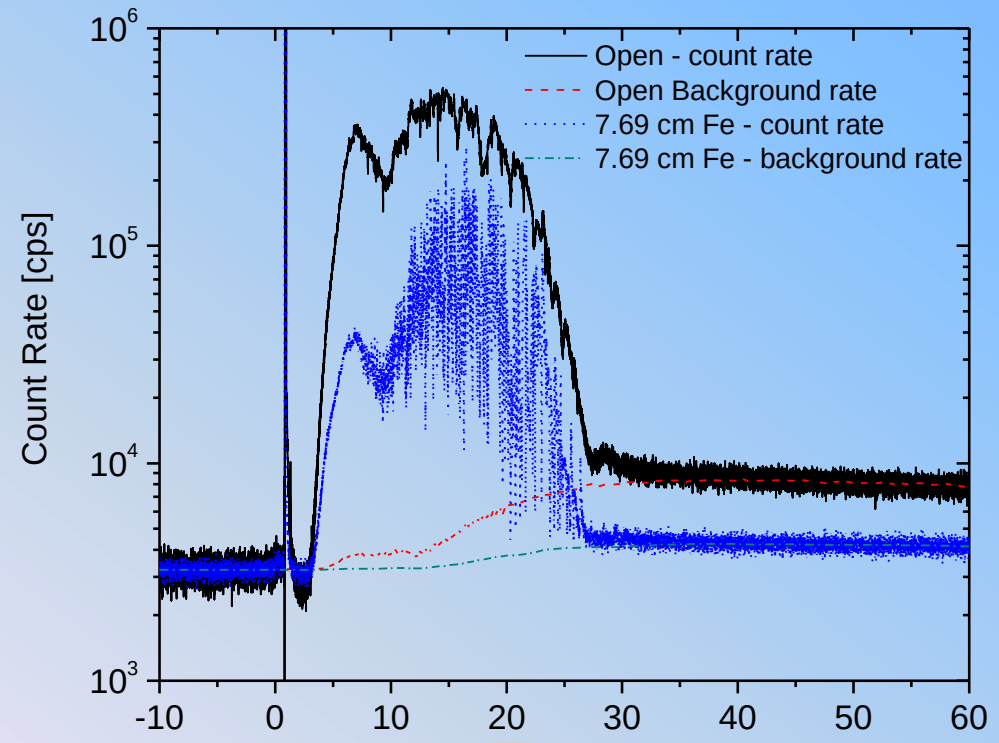


Fe-56 Samples



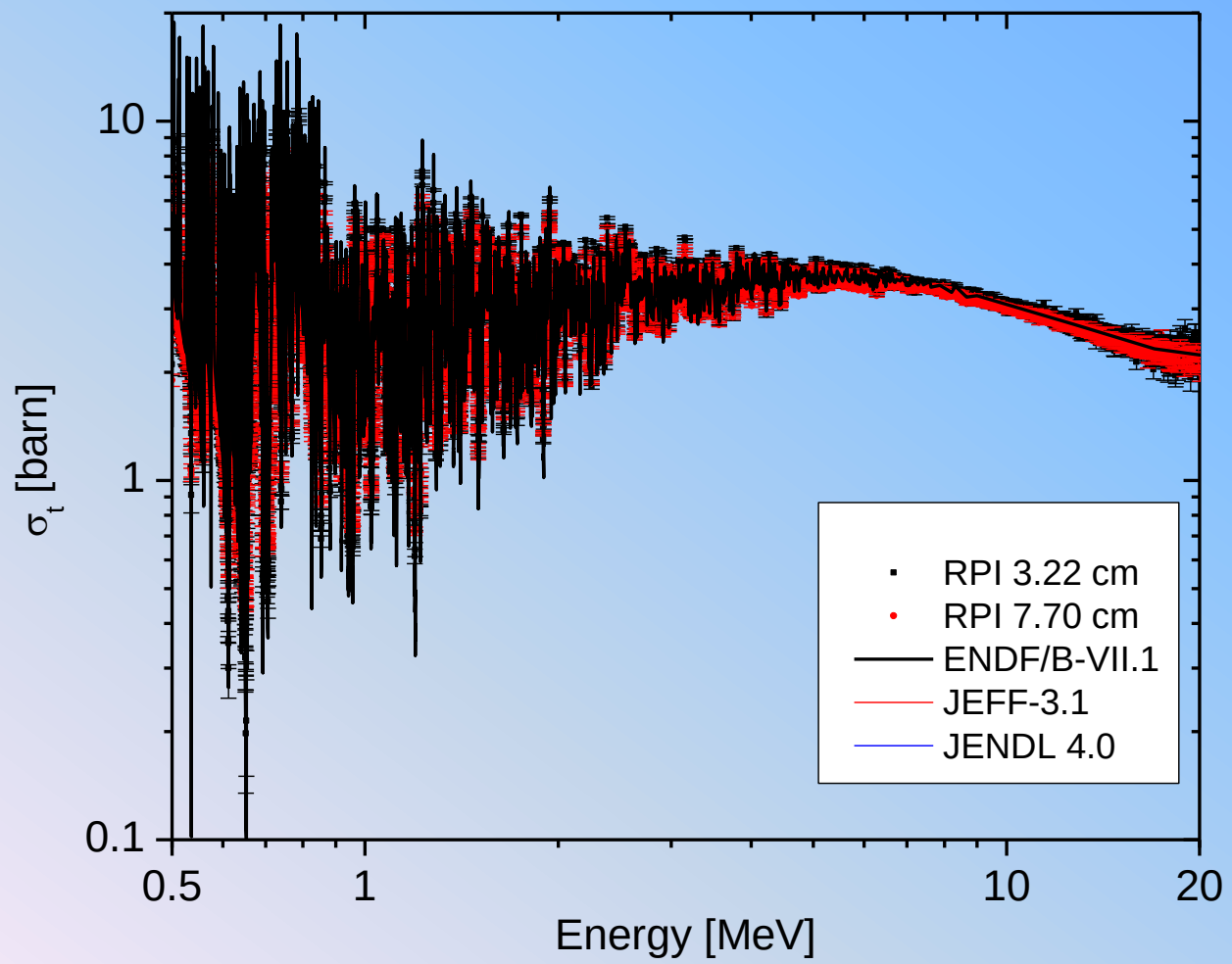
250m Time of Flight and Background Spectra

- Background is mostly from gamma interaction with the detectors
  - Used 1” diam. beam
  - Shape calculated using MCNP and fitted to measured data
  - Verified using thick carbon samples.



^{56}Fe Total Cross Section Measurements (NCSP)

250 m Flight Path



- Measured at 250 m flight station with 8 ns pulse width.
- Three sample thicknesses were used 3.22 cm, 7.698 cm, and 10.918 cm
- Sample is 99.87% metallic ^{56}Fe
- Can help extend the resolved resonance region above 892 keV
- Above 900 keV only two other data sets are available on EXFOR (Harvey et al. and Cornelis et al.)

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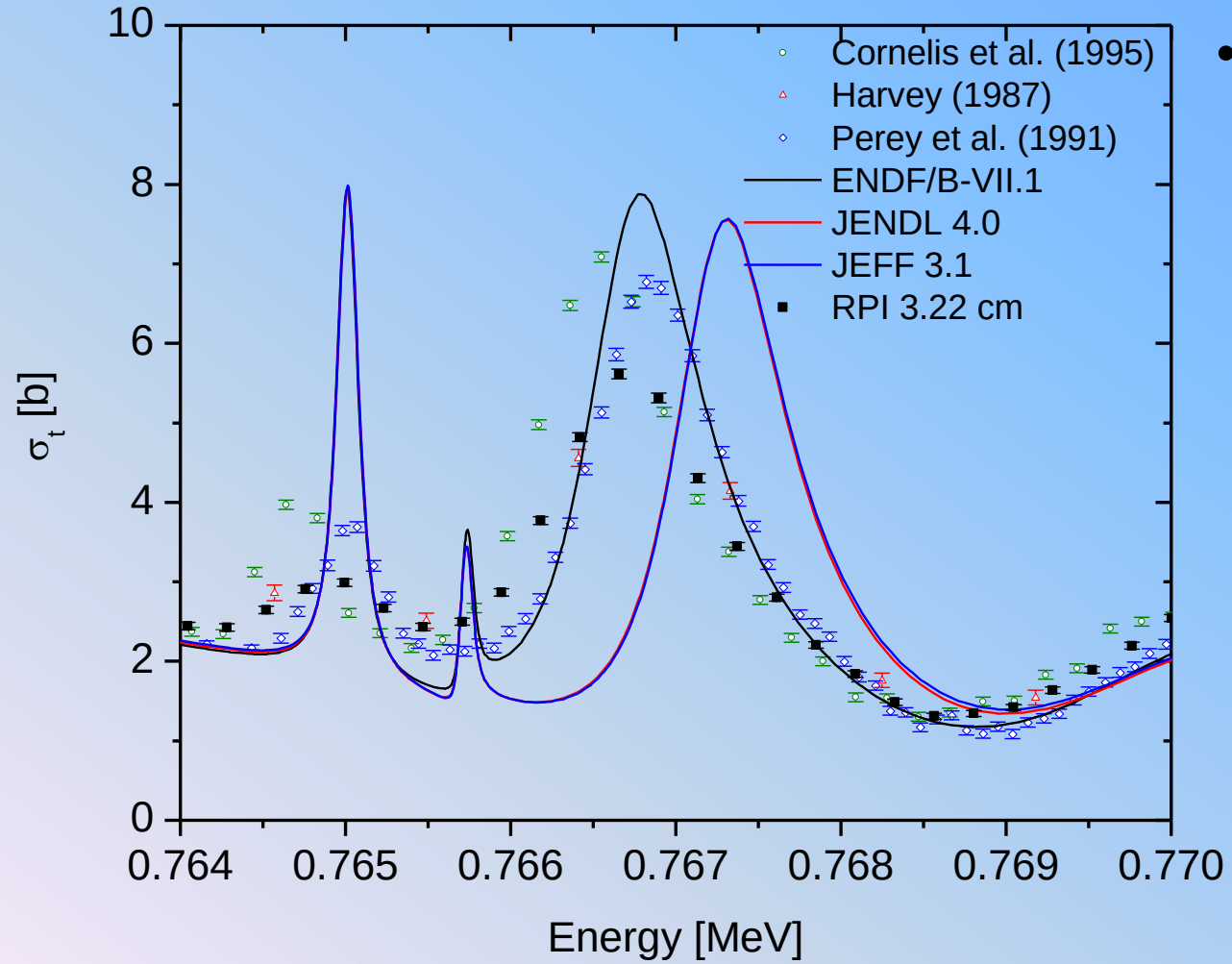
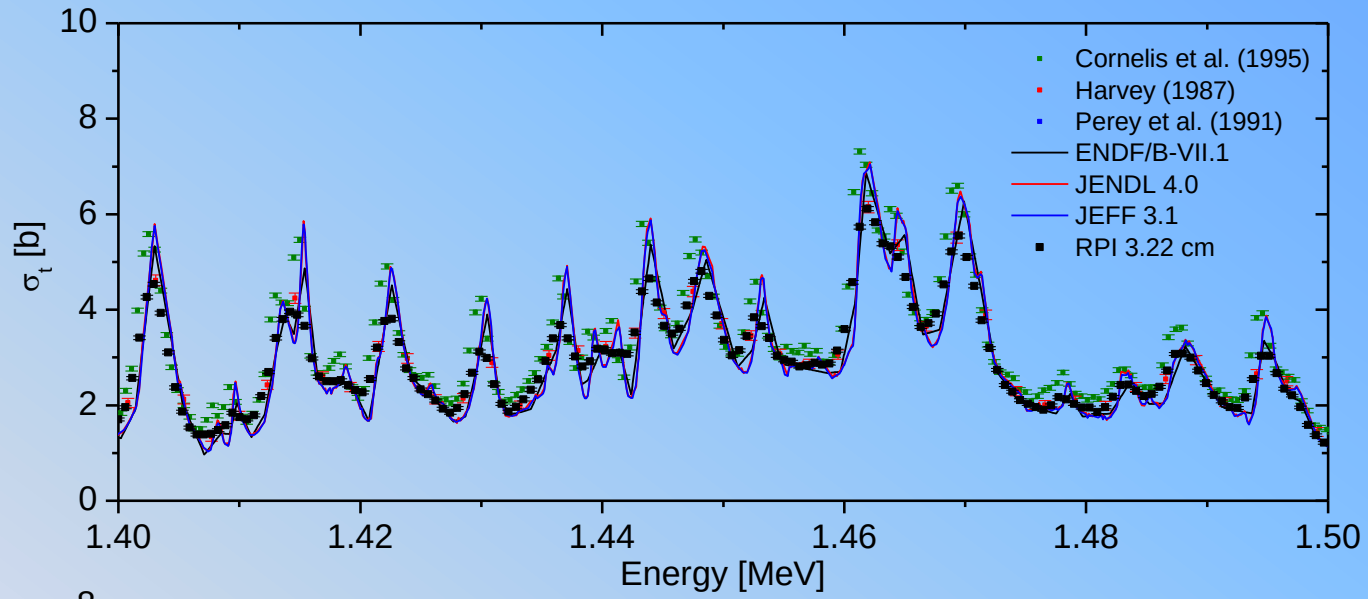
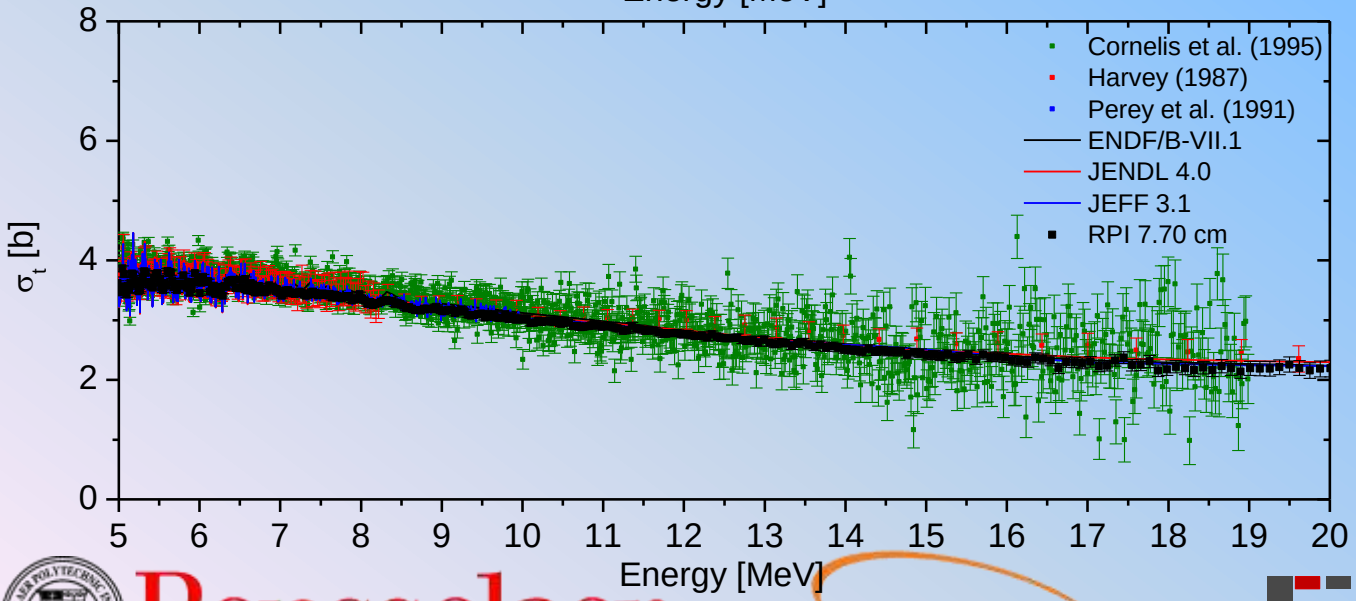
Fe-56 Total Cross Section – E< 1 MeV



- There is an energy shift between the experiment and evaluations

^{56}Fe Total Cross Section Measurements

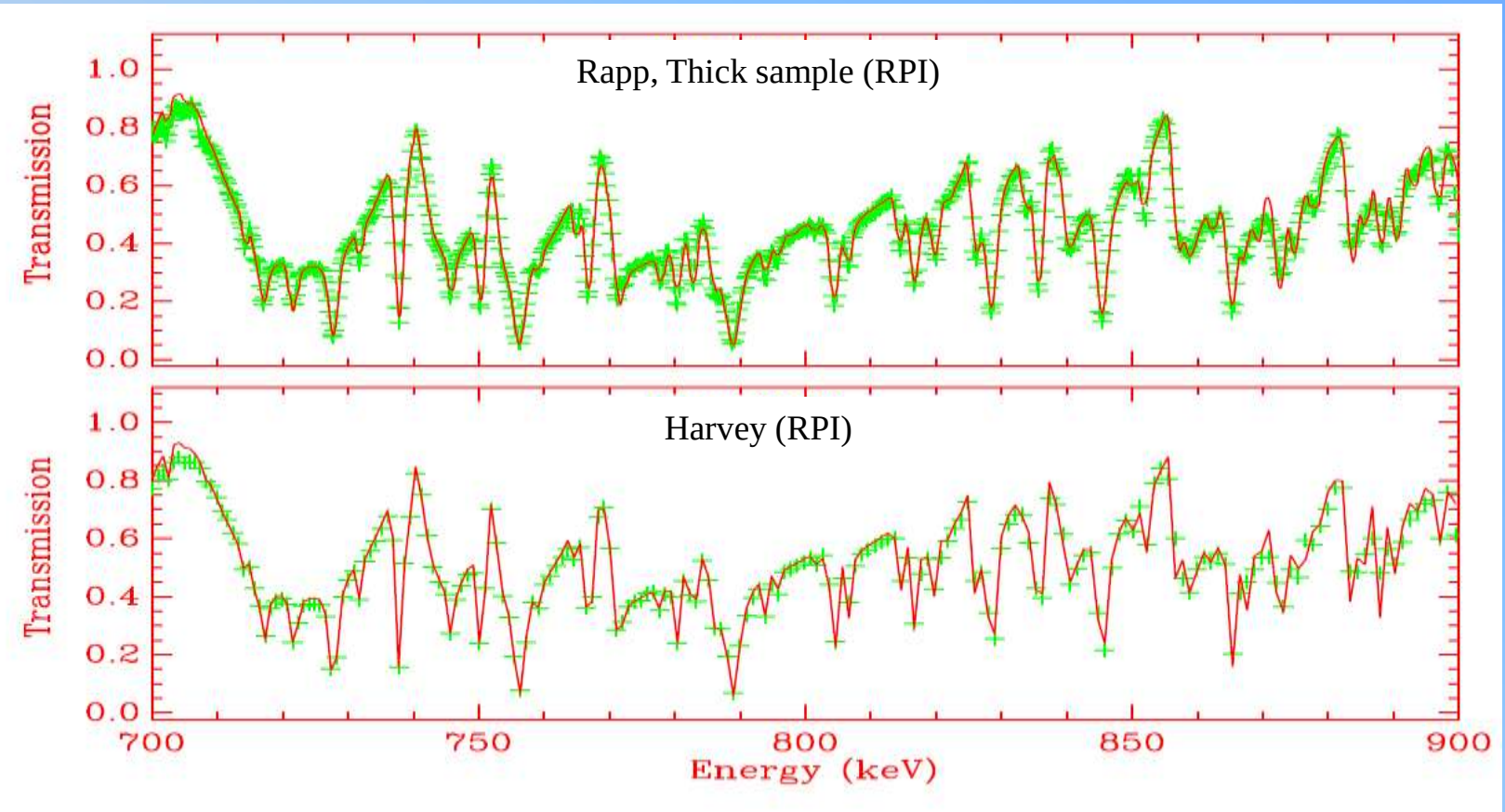




- New data have good energy resolution but lower then Cornelis et al.
- The Cornelis et al. data are based on an oxide sample Fe_2O_3 (corrected for O_3)
- Above 10 MeV the data have low errors and are in good agreement with both ENDF/B-VII.1 and JEFF 3.1

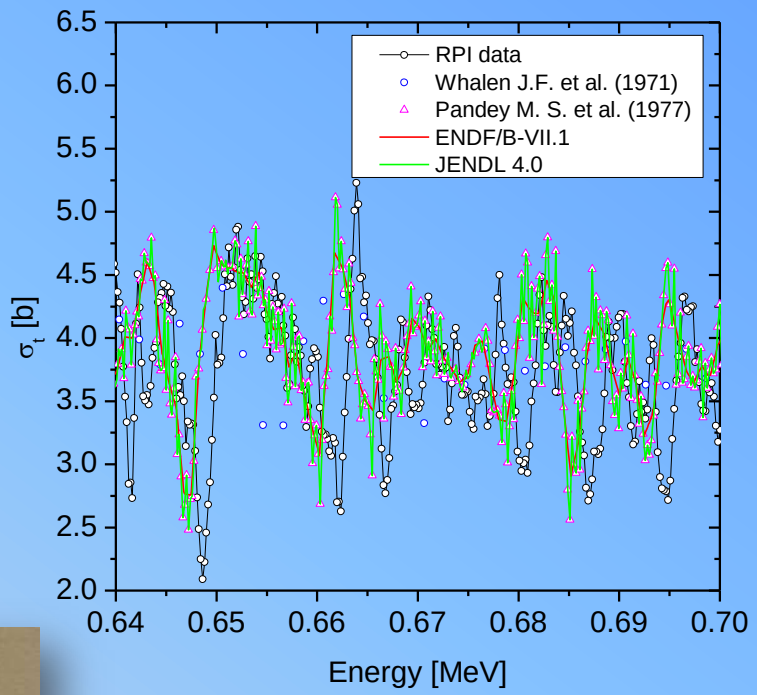
Fe-56 SAMMY Fit From ORNL

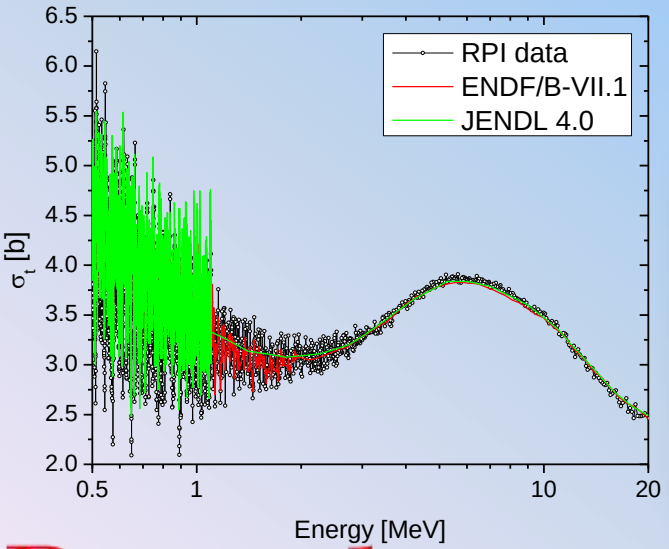
- The RPI transmission data are in good agreement with the Harvey data with slightly better energy resolution

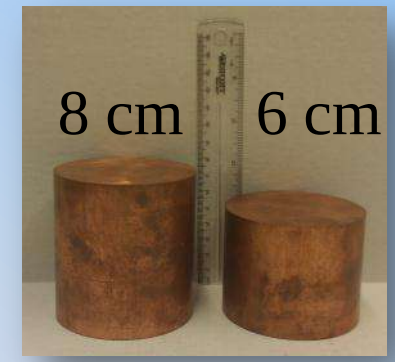


Cu Total Cross Section Measurements 0.5 – 20 MeV (250m flight path)

- All Evaluations similar with the exception of JENDL 4.0
  - Follows the isotopic measurements by Pandey et al.
  - JENDL shows more structure below 1.1 MeV, but smoothes to average value prior to other libraries (1.1 MeV vs. 2.0 MeV)
- Shift in energy seen in evaluations







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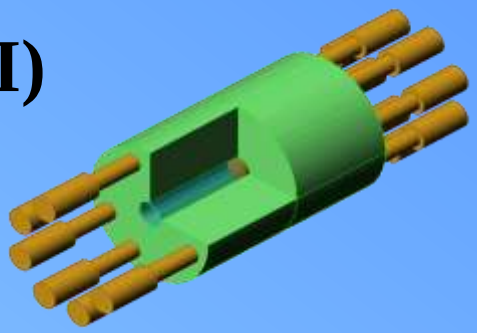
Capture Measurements of Gd and Dy Isotopes (NCSP/RPI)



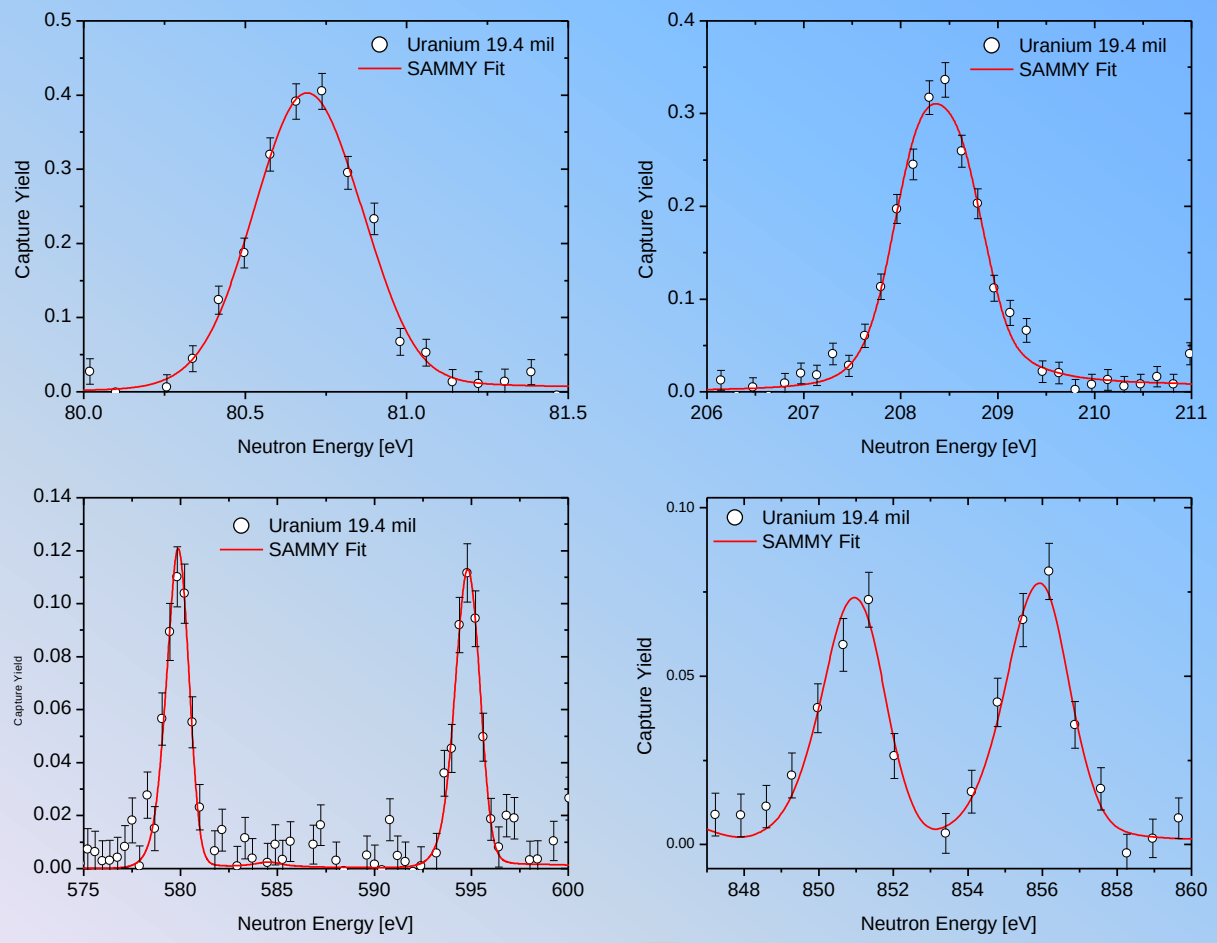
- Resonance parameter analysis of $^{155, 156,157,158,160}$Gd nearly complete.
  - ^{155,157}Gd resonance region was extended to 1000 eV
  - Used transmission data from previous RPI measurements to test resonances parameters below 300 eV
- Resonance parameter analysis of ^{161,162,163,164}Dy data started

Gd enriched samples

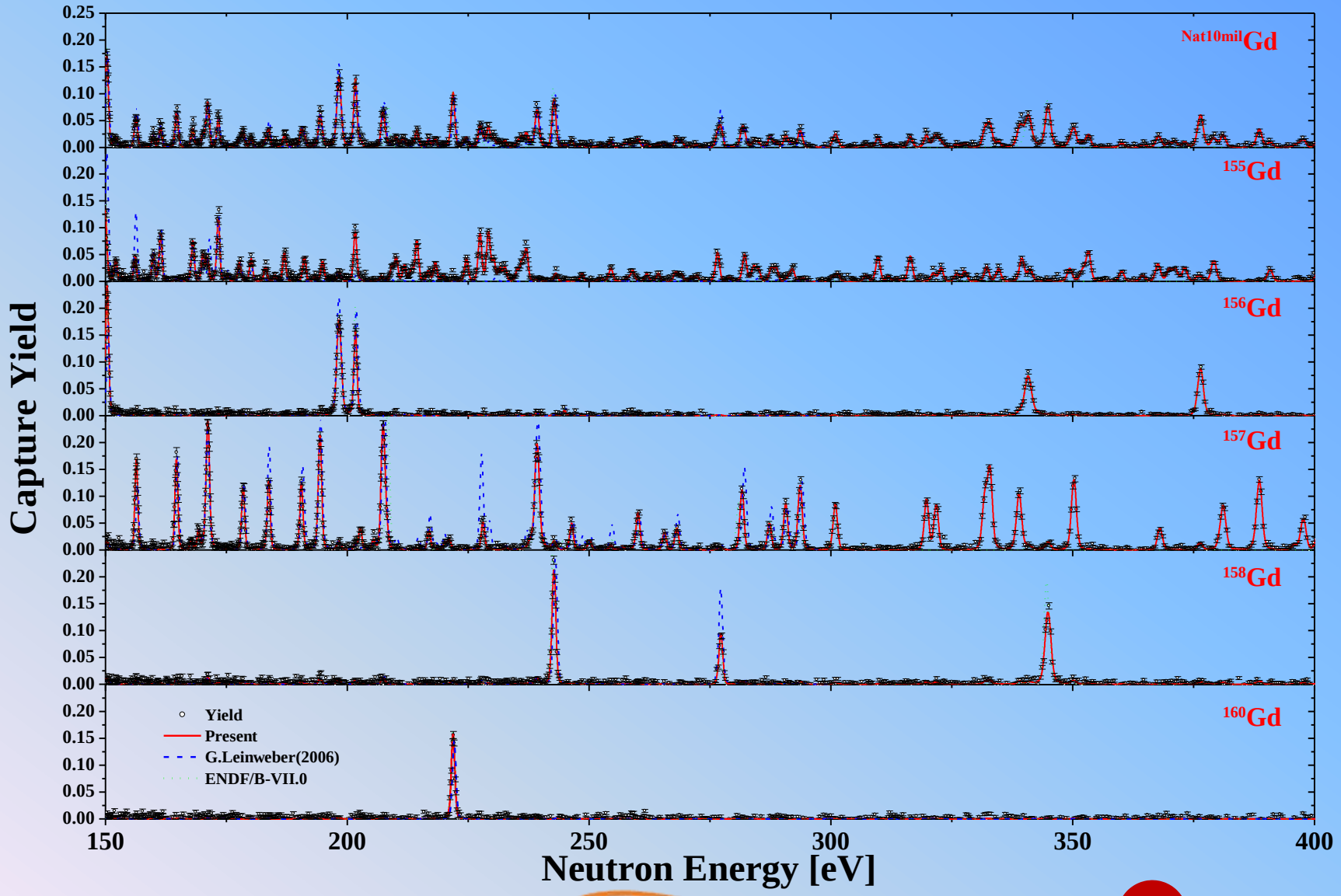
Dy enriched samples

Resolution function fitted to ^{238}U

- Obtained an energy resolution function up to 1 keV



SAMMY fits to ^{155,156,157,158,160}Gd Capture Yield



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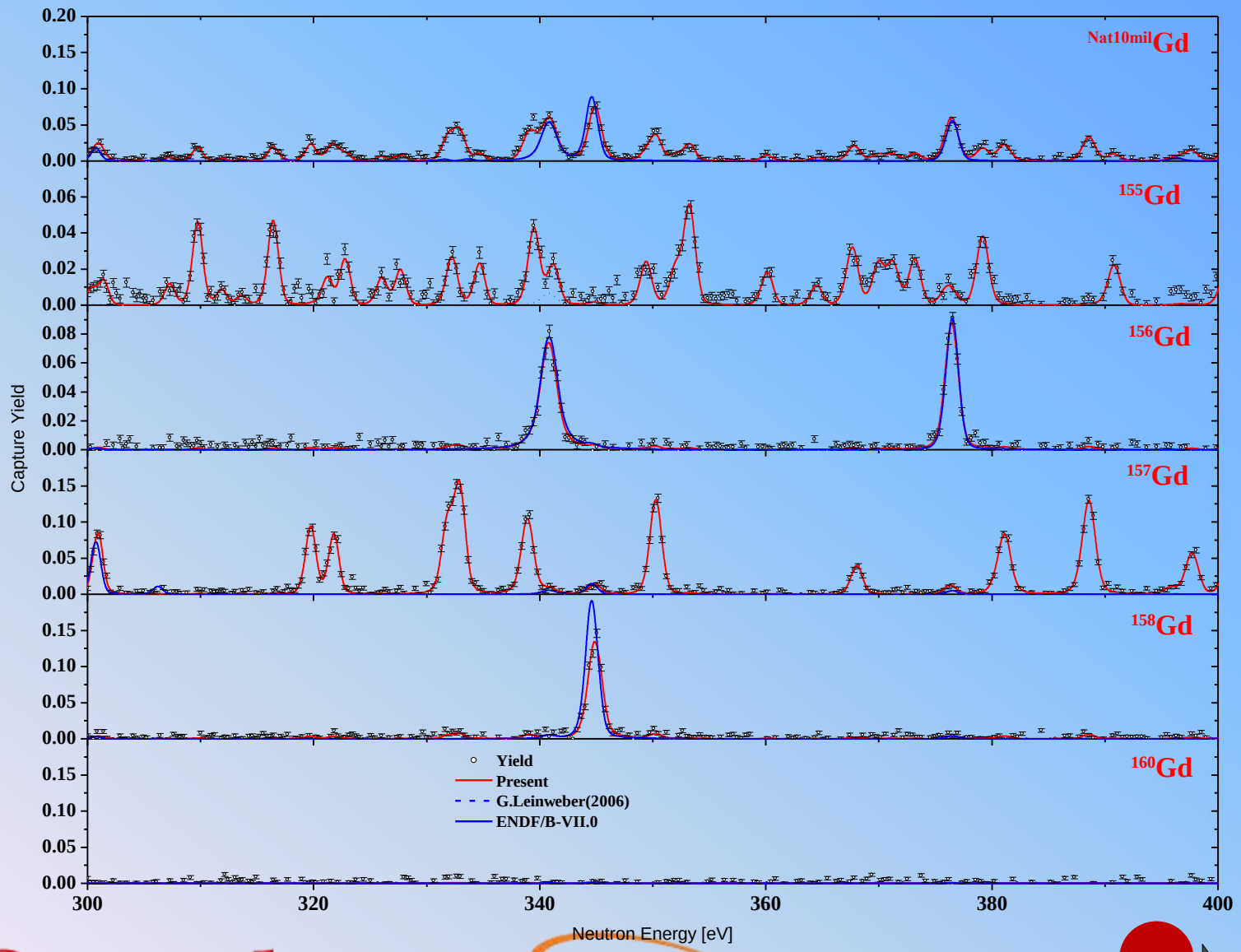
^{155,156,157,158,160}Gd Capture Yield 300-400 eV



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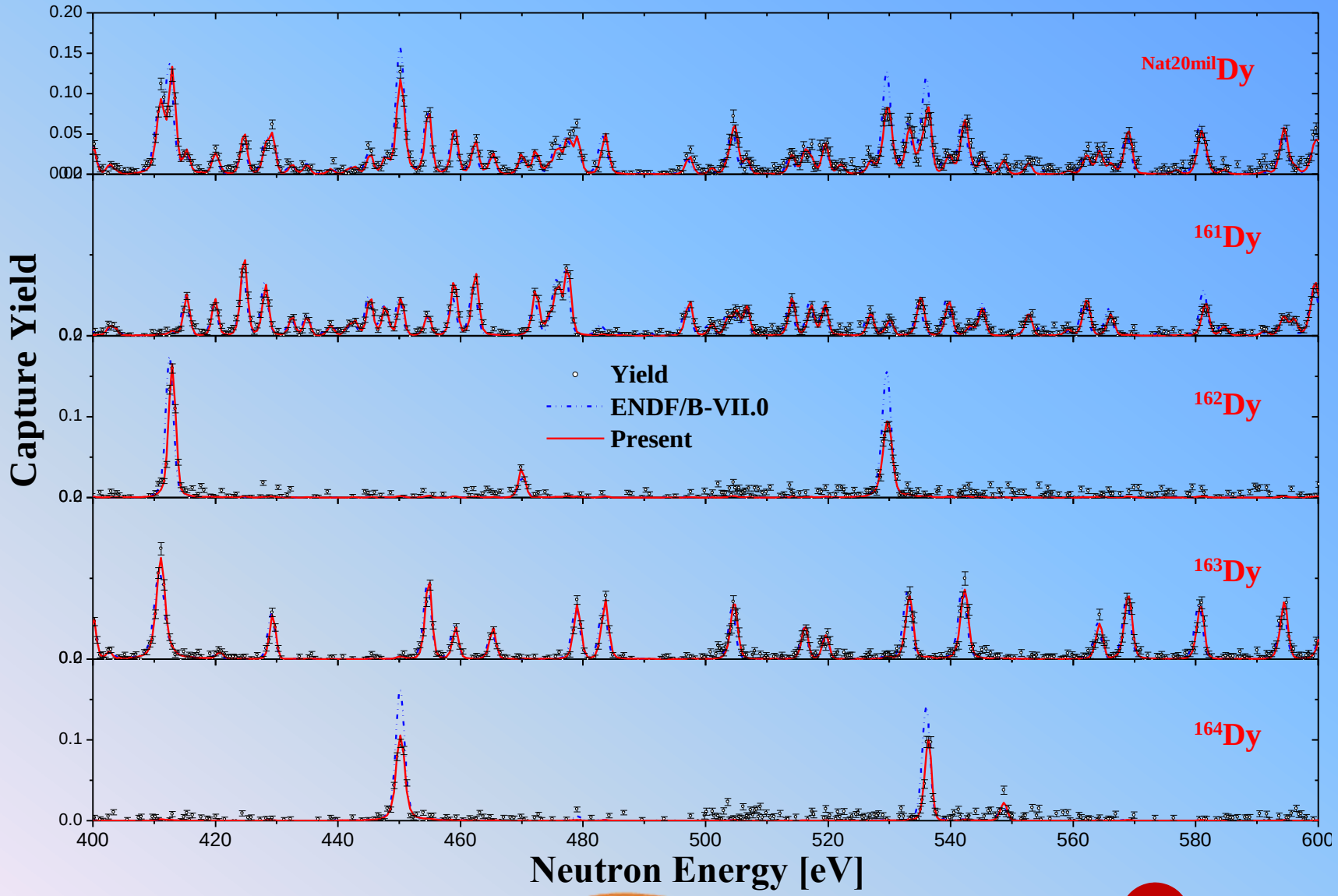
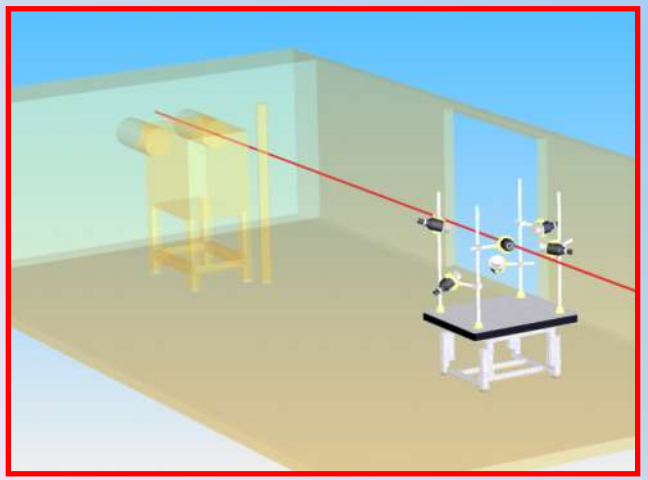
SAMMY fits to ^{161,162,163,164}Dy Capture Yield



^{238}U Scattering/Fission Measurement

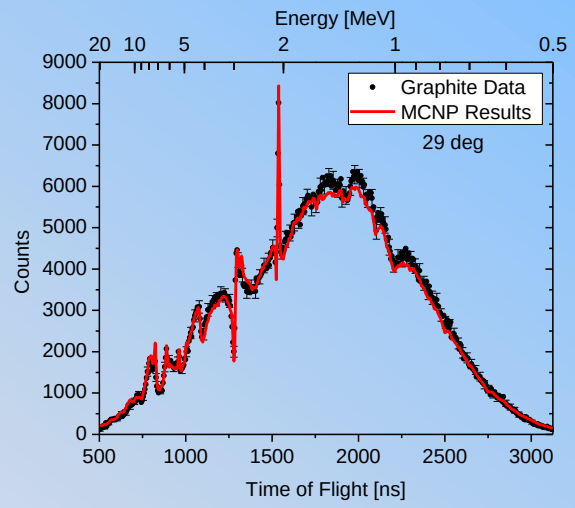
- Measured in September 2011.
- Measured scattered (elastic+ inelastic) and fission neutrons
- Use ^{238}U sample thickness of 0.375” (0.95 cm)
- Measured at angles of 27, 77, 112, 156 (two detectors at each angle)
- Compared measured data to MCNP simulations
  - Obtain neutron flux shape from a U-235 fission chamber in beam
  - Obtain detector efficiency curves from an in beam measurement with EJ-301 detectors
- Use 7 cm graphite sample for verification of system and methodology

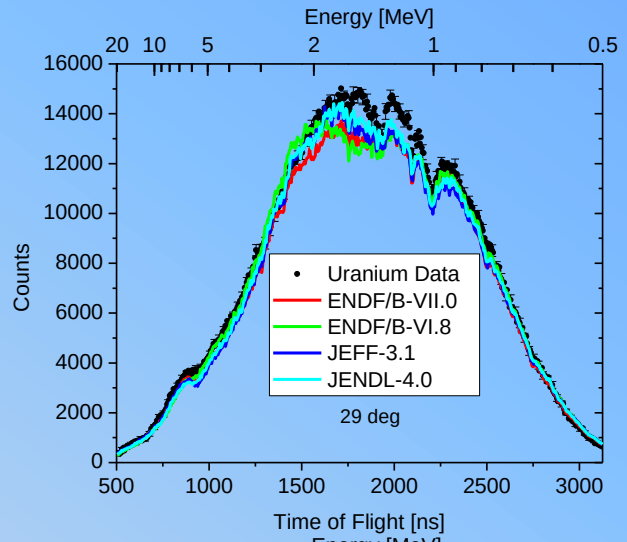


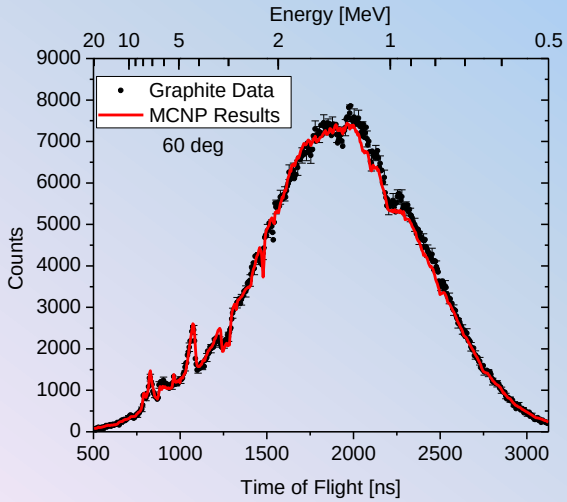
^{238}U Disc Samples

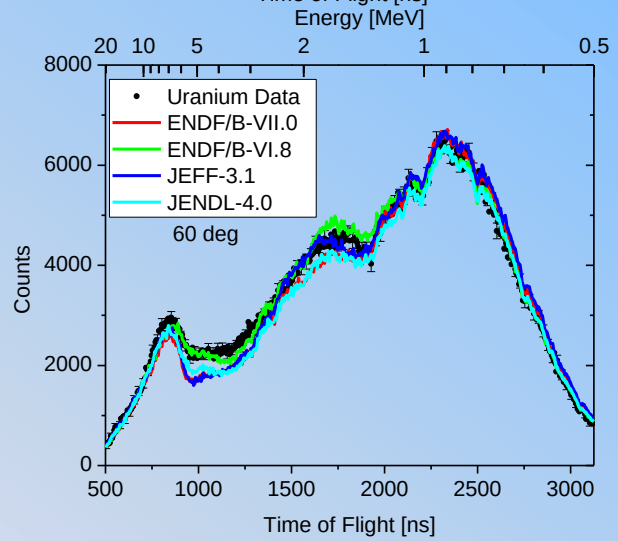
- Obtained from Y-12 with the support of NCSP and facilitation by ORNL

^{238}U Scattering - Forward Angles







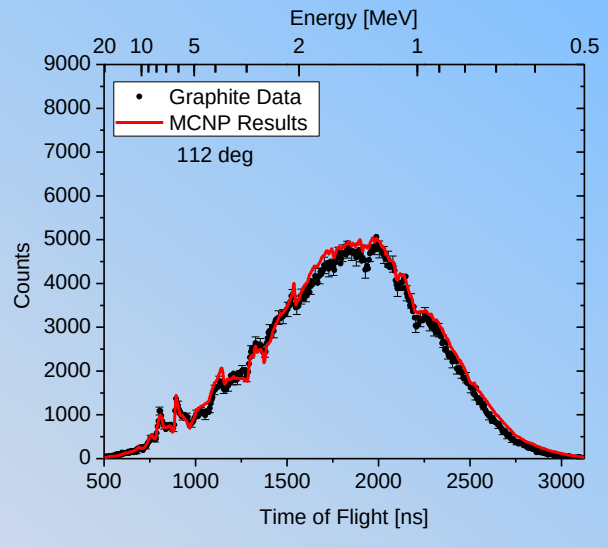


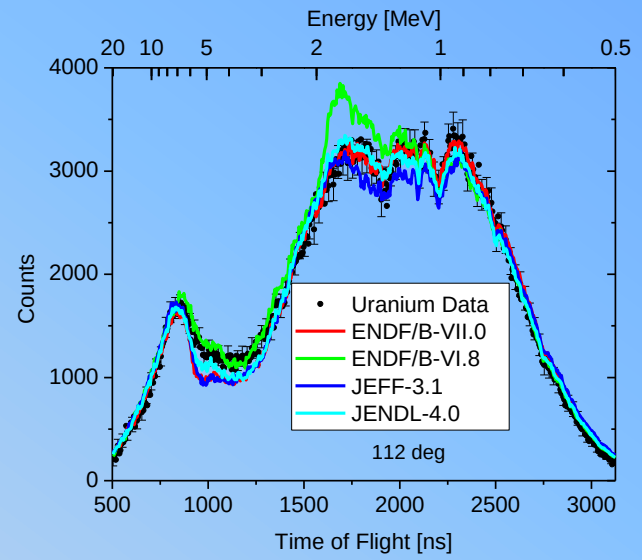
ROI=0.5 to 20 MeV

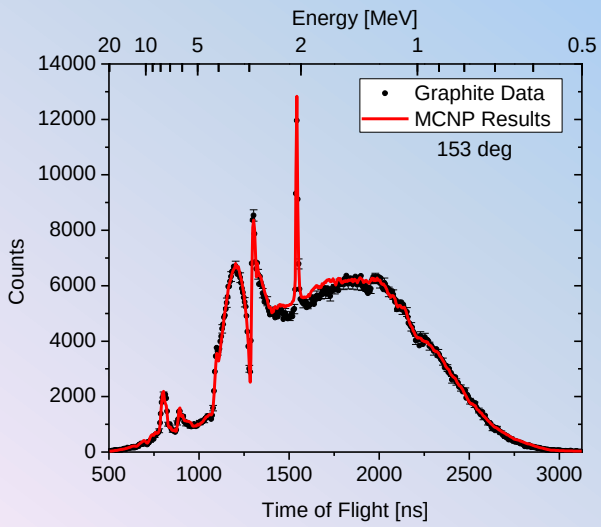
Library	$(C/E)_{ROI}$
ENDF/B-VII.0	0.935 (0.001) [0.012] {0.022}
ENDF/B-VI.8	0.963 (0.001) [0.012] {0.022}
JEFF-3.1	0.947 (0.001) [0.012] {0.022}
JENDL-4.0	0.961 (0.001) [0.012] {0.022}

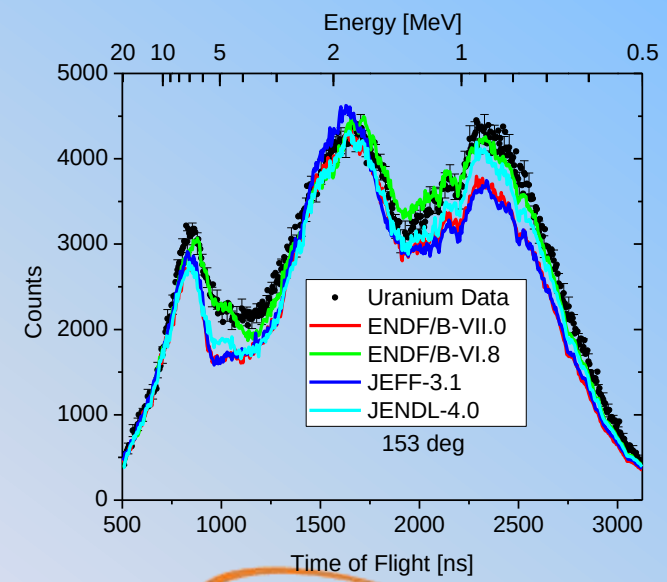
Library	$(C/E)_{ROI}$
ENDF/B-VII.0	0.970 (0.001) [0.007] {0.015}
ENDF/B-VI.8	1.005 (0.001) [0.007] {0.015}
JEFF-3.1	0.997 (0.001) [0.007] {0.015}
JENDL-4.0	0.947 (0.001) [0.007] {0.015}

^{238}U Scattering – Back Angles









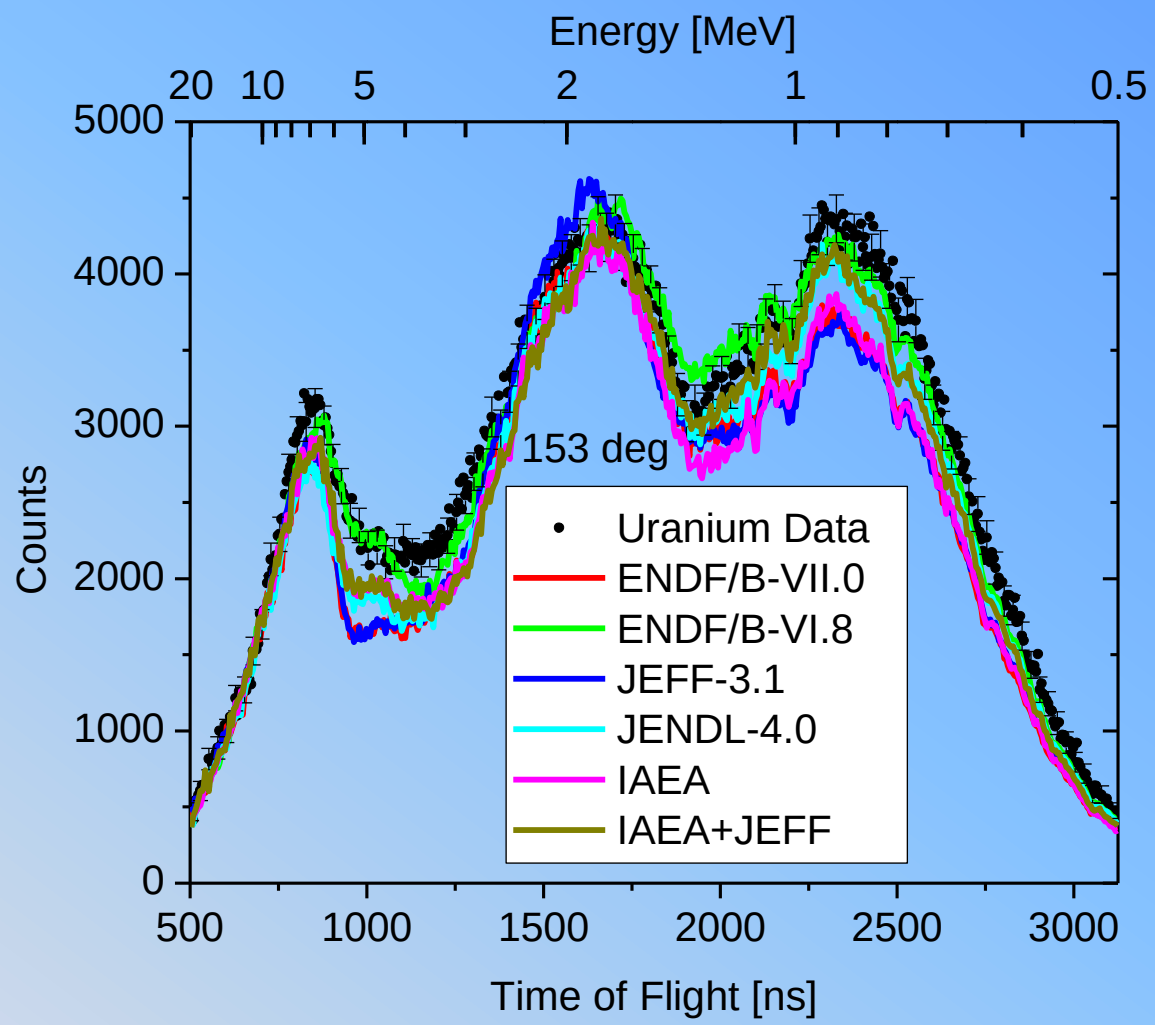
ROI=0.5 to 20 MeV

Library	$(C/E)_{ROI}$
ENDF/B-VII.0	0.998 (0.002) [0.012] {0.051}
ENDF/B-VI.8	1.049 (0.002) [0.012] {0.051}
JEFF-3.1	0.976 (0.002) [0.012] {0.051}
JENDL-4.0	0.994 (0.002) [0.012] {0.051}

Library	$(C/E)_{ROI}$
ENDF/B-VII.0	0.880 (0.001) [0.007] {0.021}
ENDF/B-VI.8	0.979 (0.002) [0.007] {0.021}
JEFF-3.1	0.893 (0.001) [0.007] {0.021}
JENDL-4.0	0.914 (0.001) [0.007] {0.021}

^{238}U Scattering Revisited

- Following the WINS meeting we interacted with Andrej Trkov and Roberto Capote from IAEA to help improve new ^{238}U evaluation
- The new evaluation performed well at forward angles
- At back angles the IAEA evaluations with JEFF angular distributions performed better than JEFF3.1 and ENDF/B-VII.1 but for E> 2 MeV still lower than the experimental data (ENDF/B-VI.8 performs better).



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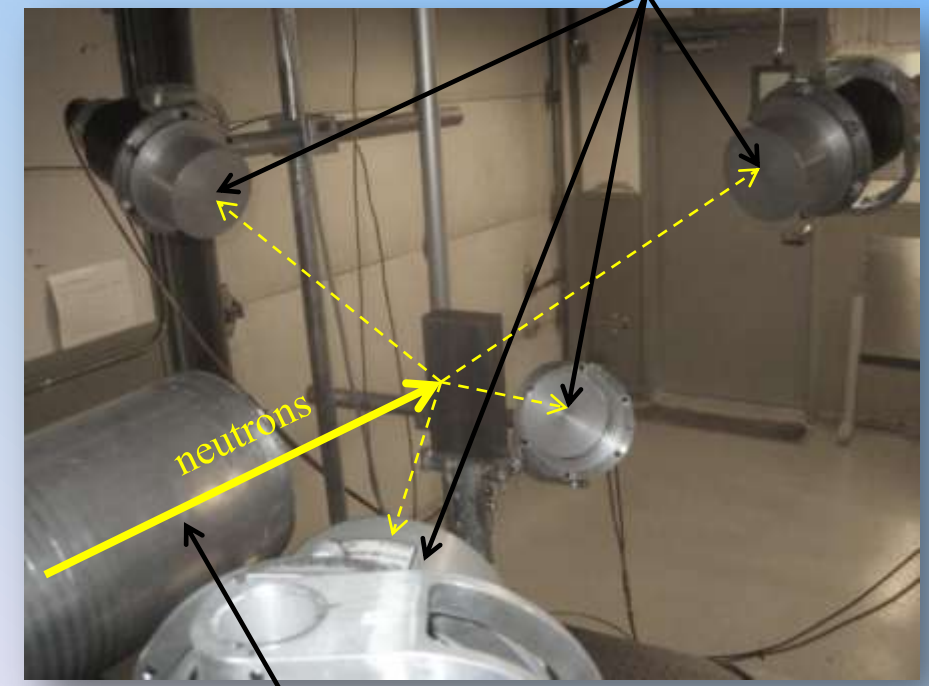
^{56}Fe Scattering Measurement - Setup

EJ-301 Liquid Scintillator Neutron Detectors



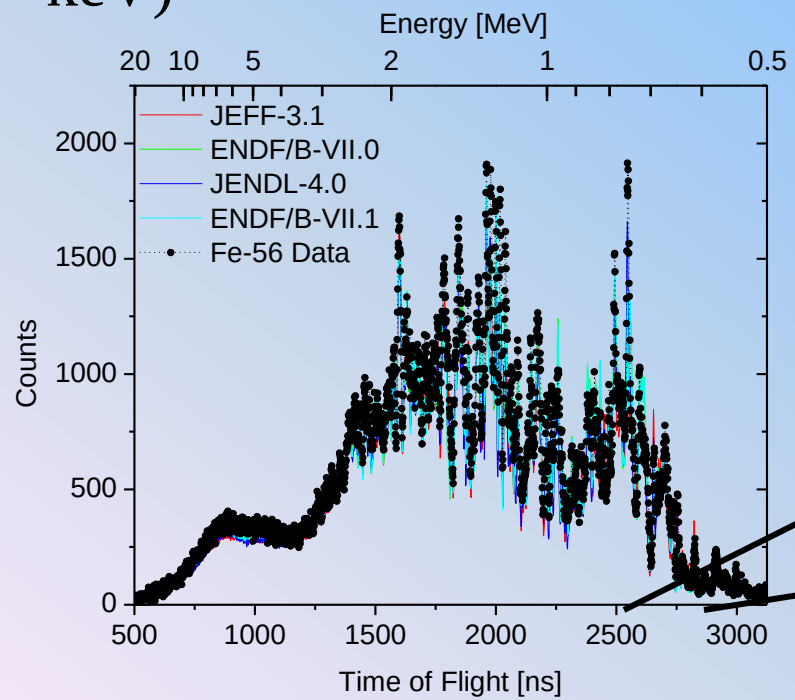
Evacuated Flight Tube

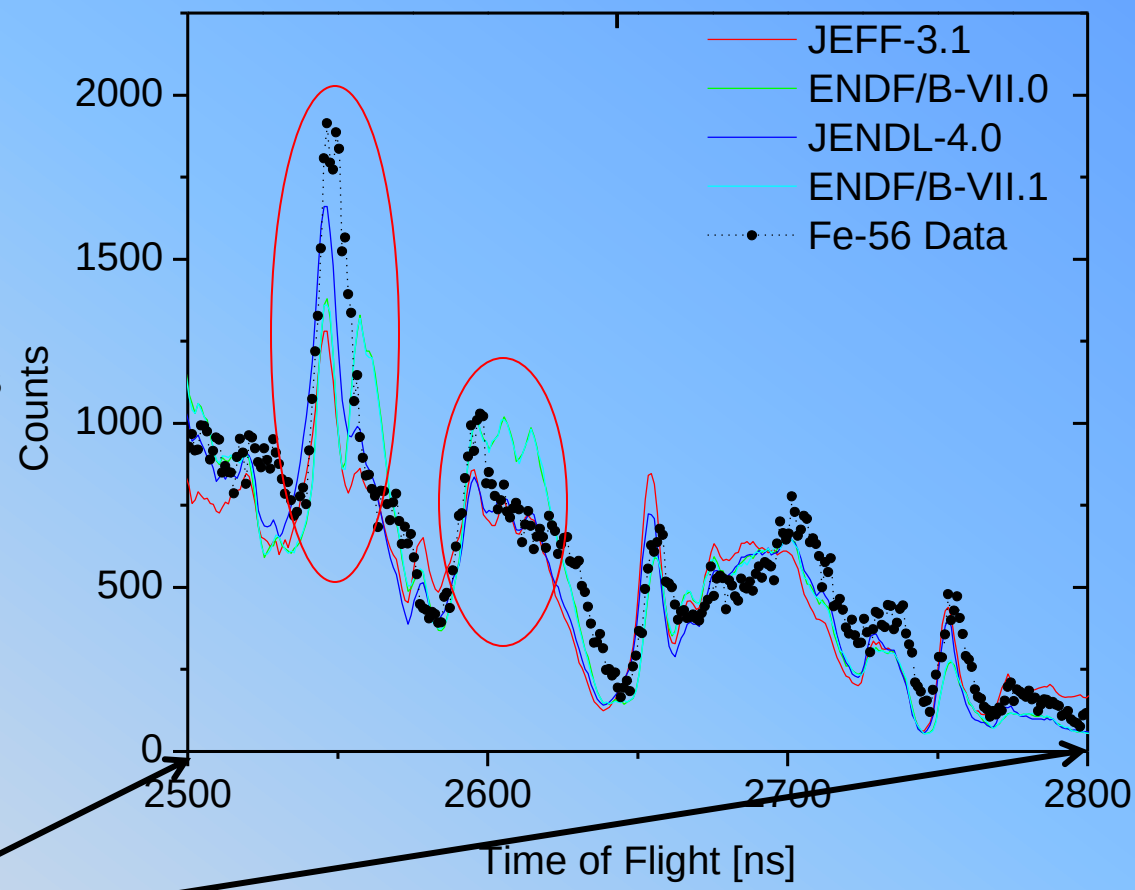
- ^{56}Fe Sample
- 99.87% metallic ^{56}Fe
- Dimensions 77.0 x 152.6 x 32.2 mm

The neutron beam size is smaller than the sample.

^{56}Fe Scattering Measurement – Results 155°

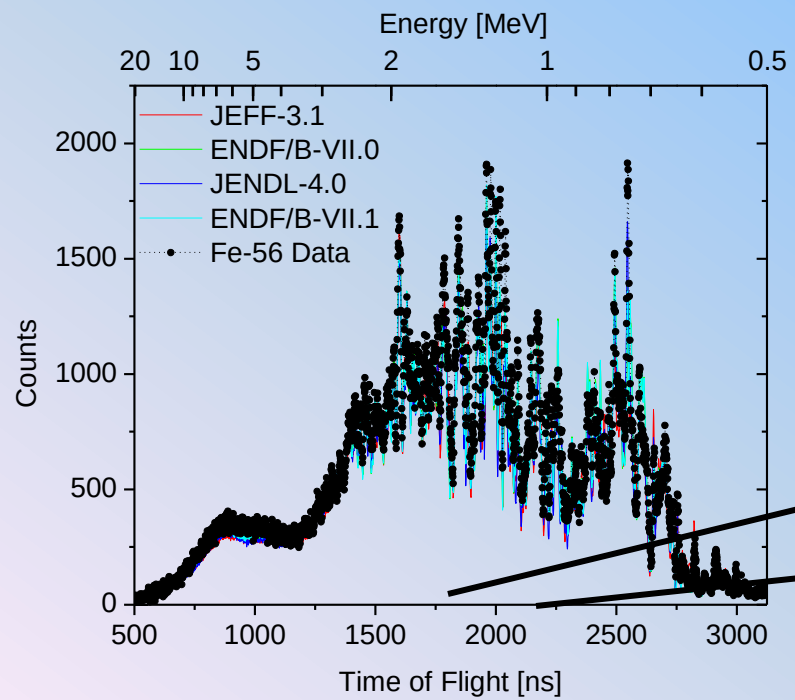
The energy resolution is sufficient to show some discrepancies in the resonance region (E<850 keV)

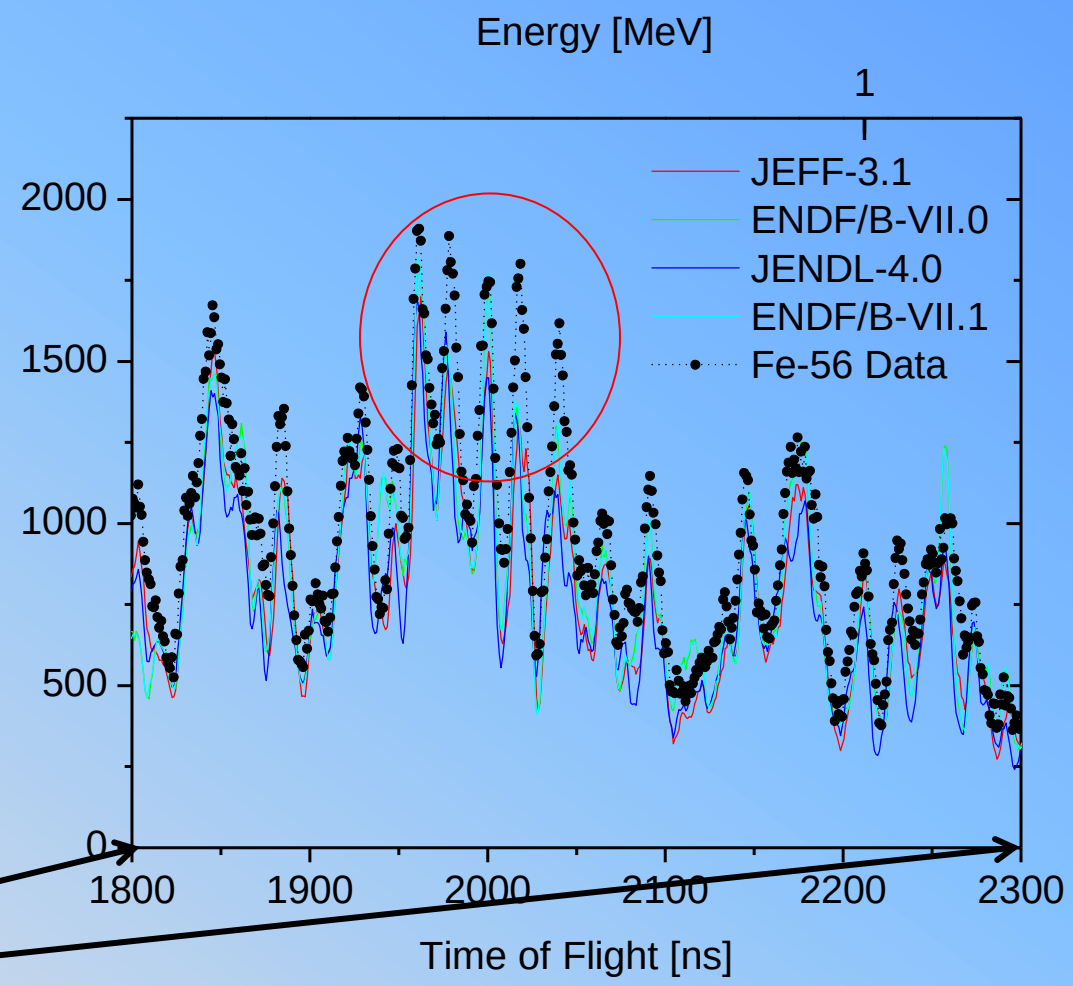




Fe-56 Scattering Measurement – Results 155°

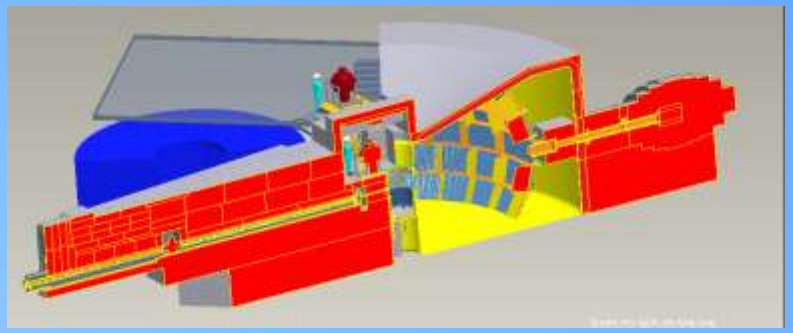
- Above the first inelastic state (E>847 keV) there are some differences with the evaluations
- We are exploring the possibility to extract double differential cross section data from these experiments.





Thermal Scattering Experiment at SEQUOIA (SNS)

- SEQUOIA:
  - Fine-Resolution Fermi Chopper Spectrometer at SNS
  - E_i = 10 to 2000 meV
  - 900 ^{3}He detector tubes
  - Scattering angles: -30° to -3° horizontal and 3° to 60° vertical
  - Flux: > 1×10^5 neutrons/cm^2/s
  - Resolution: $\Delta E/E_i \sim 1\%$



- Double differential cross section for inelastic scattering:

$$\frac{d^2\sigma}{d\Omega dE'}\left(E \to E', \Omega \to \Omega'\right) = \frac{\sigma_b}{4\pi kT}\sqrt{\frac{E'}{E}}e^{-\frac{\beta}{2}}S(\alpha,\beta)$$

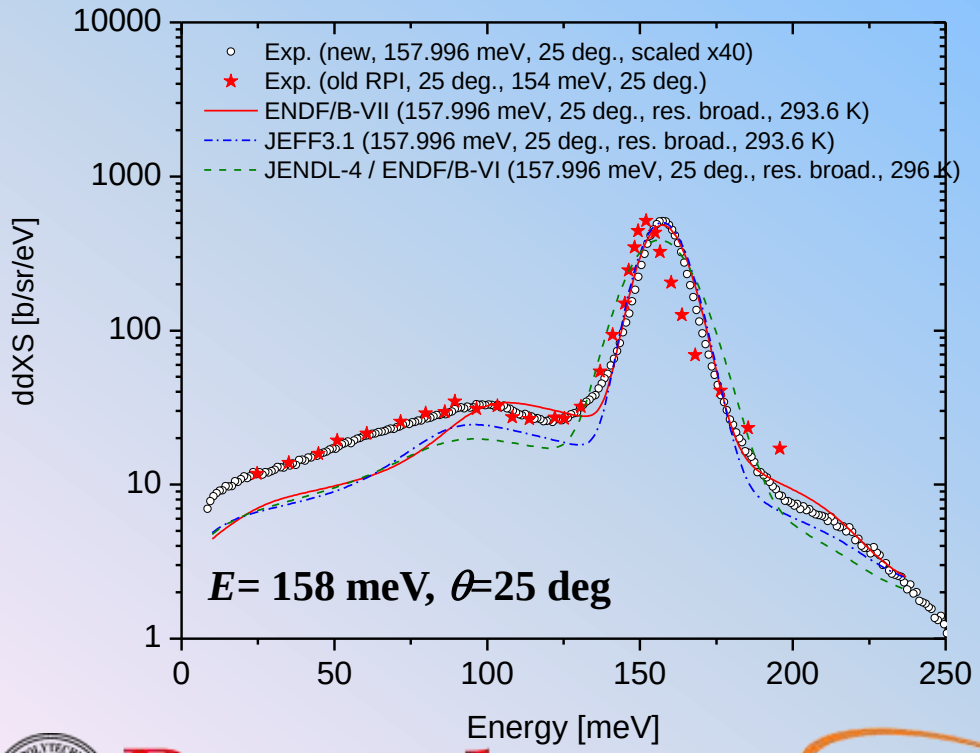
$$\alpha = \frac{E'+E-2\sqrt{E'E\cos\theta}}{AkT} = \frac{\hbar^2\kappa^2}{2MkT} \qquad \beta = \frac{E'-E}{kT} = \frac{\varepsilon}{kT}$$

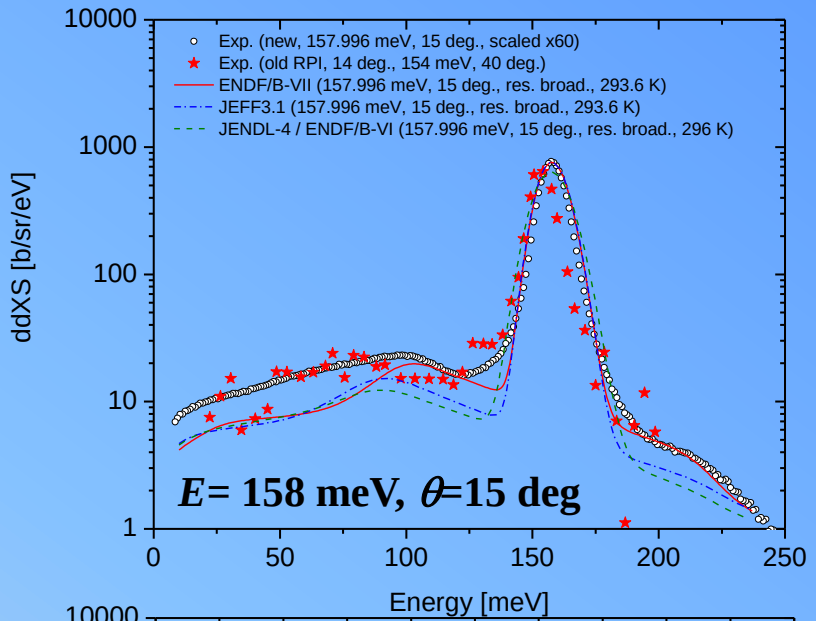
Thermal Scattering Measurements

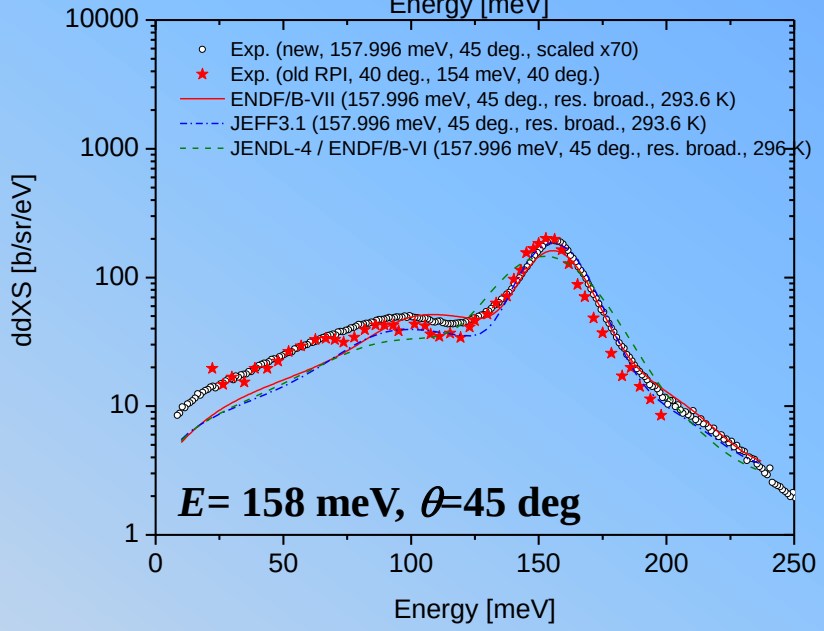
Started FY 13

Emily Liu(RPI), Alexander Kolesnikov(ORNL/SNS)

- **Two PhD students joined this project.**
- **SNS has target problems → run cycle delayed**
- RPI previously measured at SNS:
  - Samples: **H_2O**, Poly, Empty Can, Vanadium
  - E_i (eV): 0.055, 0.16, 0.25, 0.6, 1, 3, 5







Summary

- NCSP program at RPI is focused on Nuclear Data measurements:
  - The program is a collaboration with KAPL/RPI and NCSP
  - Leverages all the equipment and experience available to the KAPL/RPI group
  - Contributes to the establishment of new experimental capabilities
  - Educates undergraduate, graduate, and postdoctoral students in experimental neutron physics and experimental techniques
- Results to date
  - Finished capture measurements, data reduction, and SAMMY analysis of Gd isotopes
    - Data for Gd and Dy were delivered to ORNL
    - Publication of Gd data is in preparation
  - Measured total cross section of ^{56}Fe from 0.5 to 20 MeV
    - Data were delivered to ORNL
  - Completed a set of scattering/fission measurements for ^{238}U
  - Completed elastic + inelastic scattering measurements for ^{56}Fe
  - Developing a new capability to measure capture cross sections in the mid energy (keV) range
    - Experiments with prototype detector completed
    - Detector array was ordered
    - Detector array holder in fabrication