Experiments with Neutron Induced Neutron Emission

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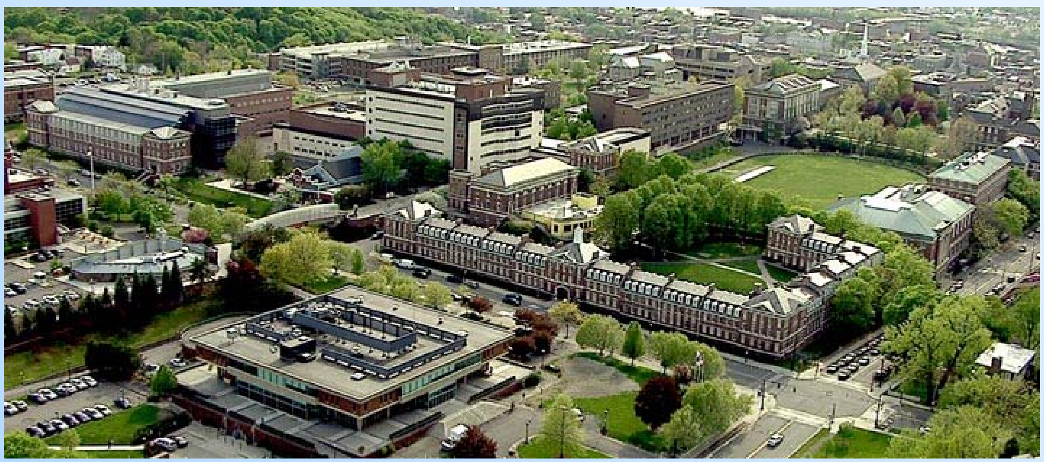

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Scattering Collaboration

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Outline

- **Introduction**
  - Need for new scattering experiments
- **Overview of fast neutron induced neutron emission methodology developed at RPI**
  - Experiment setup and methodology
  - Examples - results for ^{238}U, ^{nat}Fe
- **Experiment with fast neutron induced neutron emission from ^{235}U, ^{239}Pu and Carbon at LANL**
- KeV neutron scattering

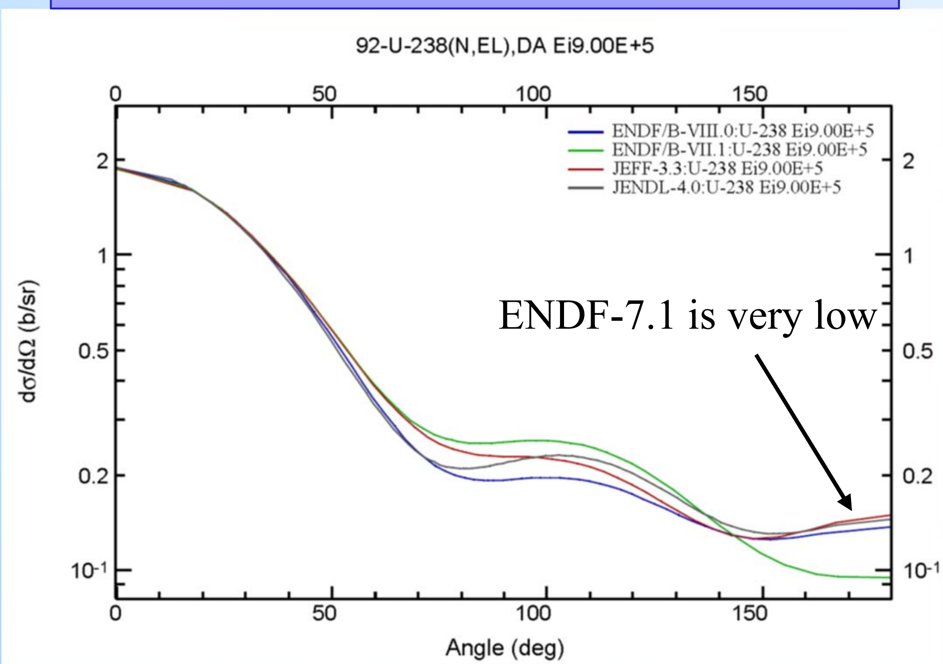
Elastic / inelastic neutron scattering

- **Important for neutron (and gamma) transport calculations**
  - Applications: criticality, nuclear power reactors, shielding, oil well logging, SNM detection, others…
- **Quantities of interest**
  - Neutron cross section and angular distribution
  - Gamma production from inelastic scattering and its angular distribution
  - Neutron energy transfer (requires inelastic levels)
- **Energy range of interest - from URR to fast**
  - In the RRR, resonance parameters can be used to calculate both cross sections and angular distribution.
  - URR difficult to model angular distributions experimental data is needed.
  - Experimental data needed in the fast energy range.

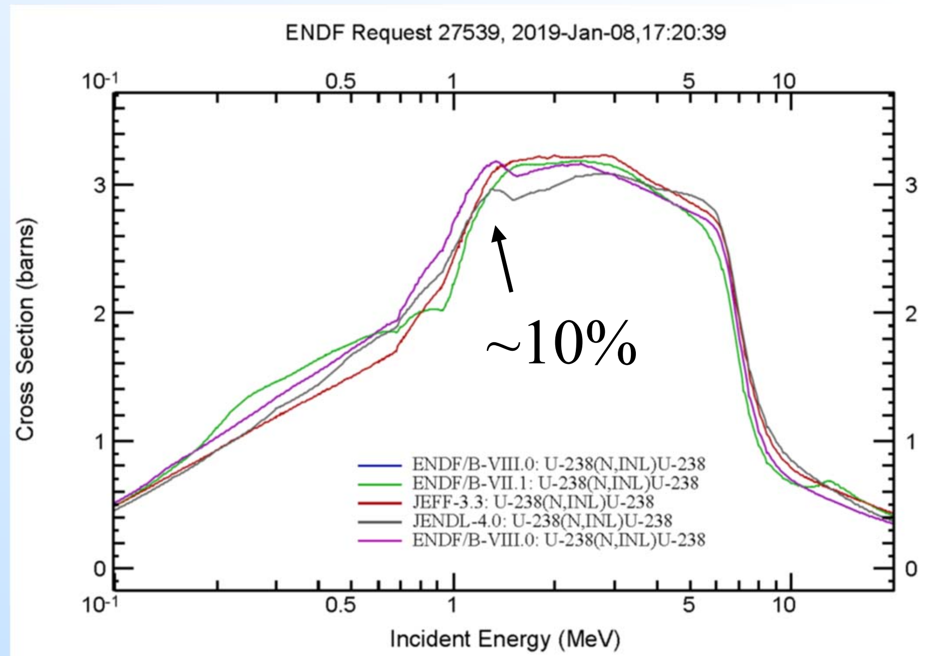
Current evaluated scattering data

- **Hard to measure and thus evaluate**
  - Large uncertainties.
- **Example: “well known” U-238 (improved in ENDF/B-8.0)**

Elastic angular distribution E_n=0.9 MeV
Notice: ENDF-7.1 at back angles



(n, inelastic) cross section



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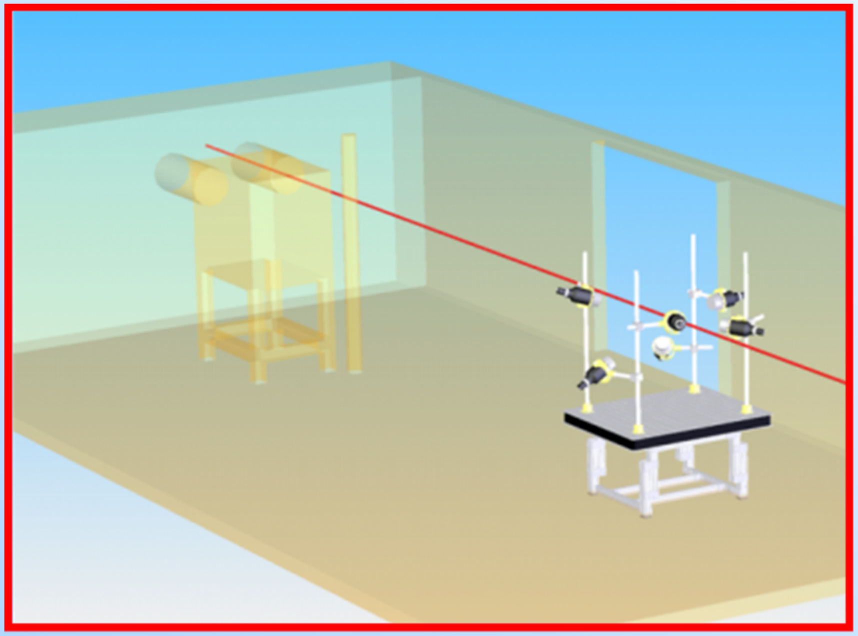
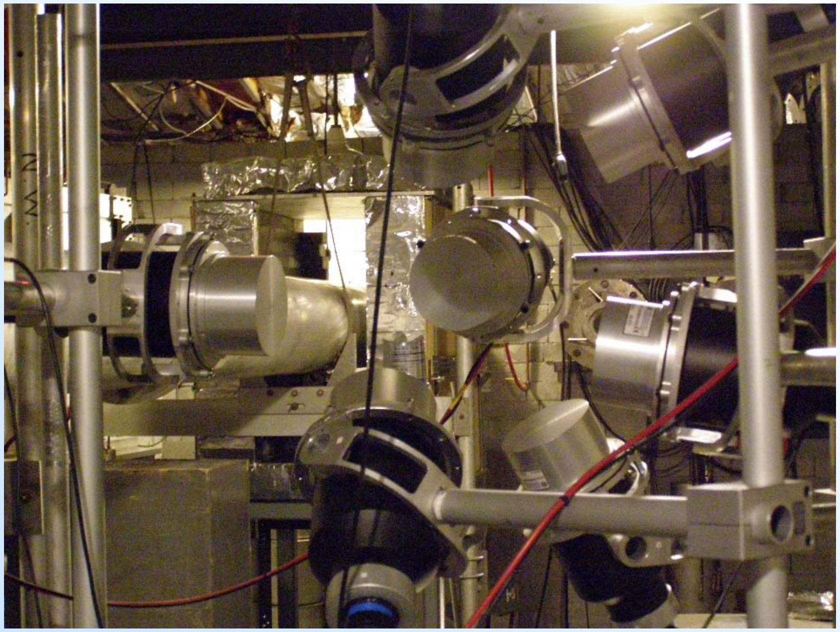
The RPI fast neutron scattering system

- Use a 60 MeV pulsed electron LINAC to produce neutrons (white neutron source)
- Use samples with different thicknesses (enhance multiple scattering)
- Use 8 angles, two detectors measured each angle.
- Measure all scattered neutrons





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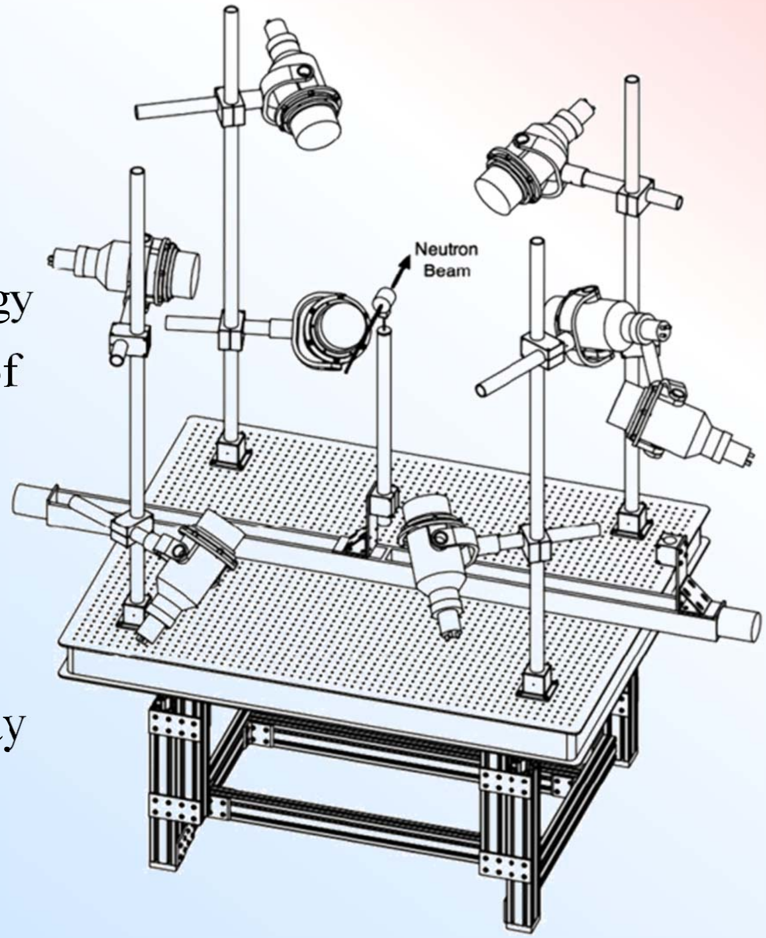
Objectives

- Provide accurate validation data for scattering cross sections and angular distributions in the energy range from 0.5 to 20 MeV
- Can be developed to provide differential elastic and inelastic scattering cross section measurements

Methodology

- Characterize the neutron flux and detector efficiencies
- Measure the neutron scattering distribution at several angles around the sample
  - TOF used to measure the neutron's incident energy
  - Liquid scintillators used to enable classification of neutrons and gammas
- Measurements are compared with detailed simulations of the system
  - Different cross section libraries assessed
- Identify energy/angle regions where libraries may be improved by comparing:
  - Total Angular TOF Data
  - Inelastic-to-Elastic Ratios
  - Elastic Angular TOF Data



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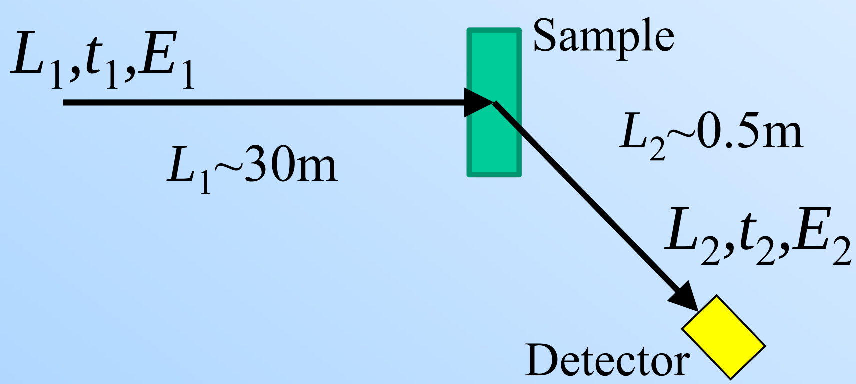
TOF Scattering Yield Measurement

- Measure the total TOF $t=t_1+t_2$
- For all scattering events $E_2<E_1$
- In most cases the energy loss is small $E_1 \sim E_2$
- Since $t_1>>t_2$ and $E_1 \sim E_2$ then for presentation the incident neutron energy E_1 is calculated using t and $L=L_1+L_2$



$$E(t) \approx m_n c^2 \cdot \left(\frac{1}{\sqrt{1-\left(\frac{L}{c \cdot t}\right)^2}} - 1 \right)$$

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First Order Approximation of the Scattering Yield

Detector Efficiency

Probability to Interact

$$Y(E,\phi) \propto \eta(E')\Phi(E)\left(1 - e^{\Sigma_t(E)L}\right)\frac{\sigma_s}{\sigma_t}\frac{f(E,\phi)}{2\pi}$$

Incident Flux

Probability to Scatter in direction ϕ

In this approximation multiple scattering is ignored

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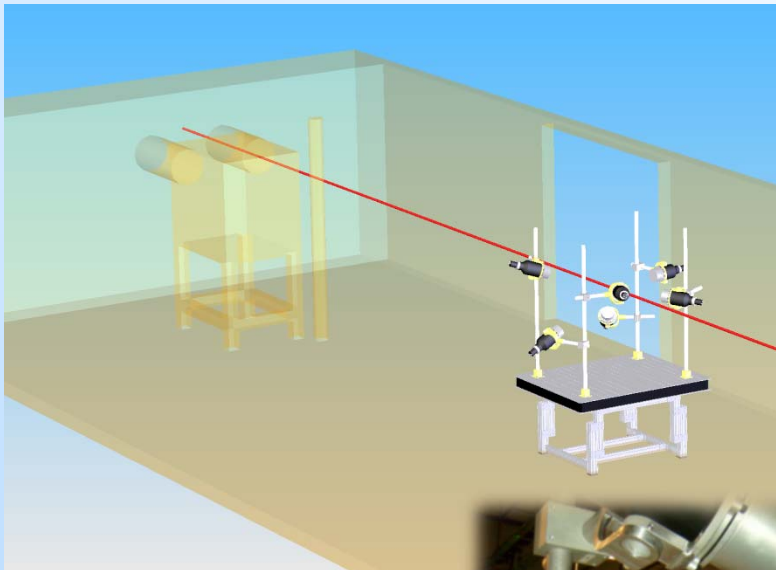
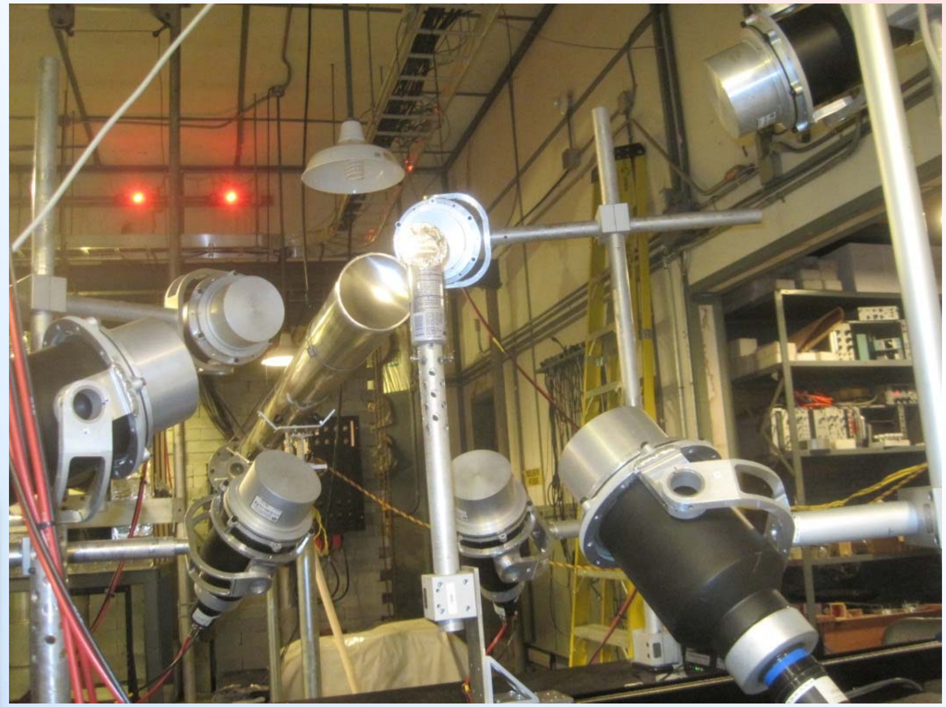
Scattering Detection System: Experimental Setup

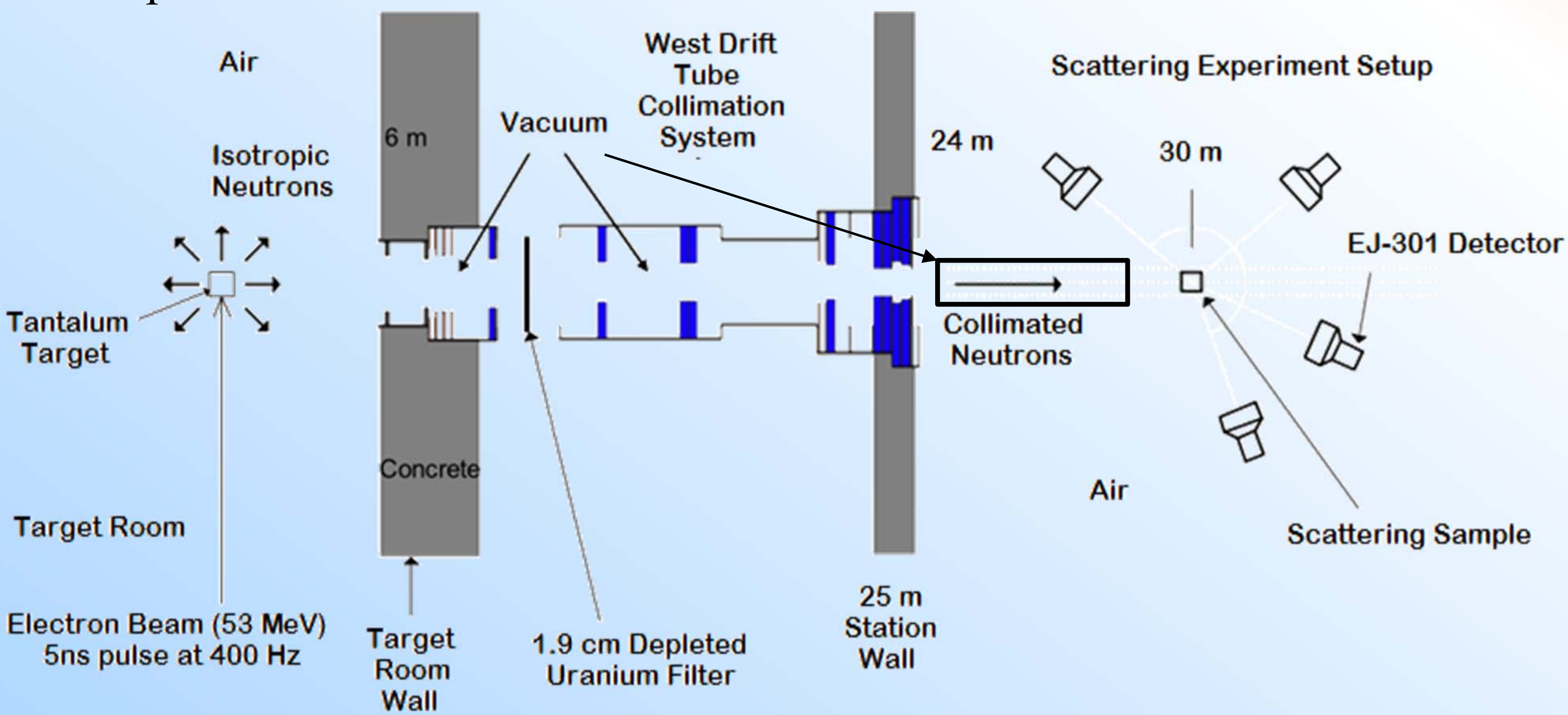




Low mass sample holder

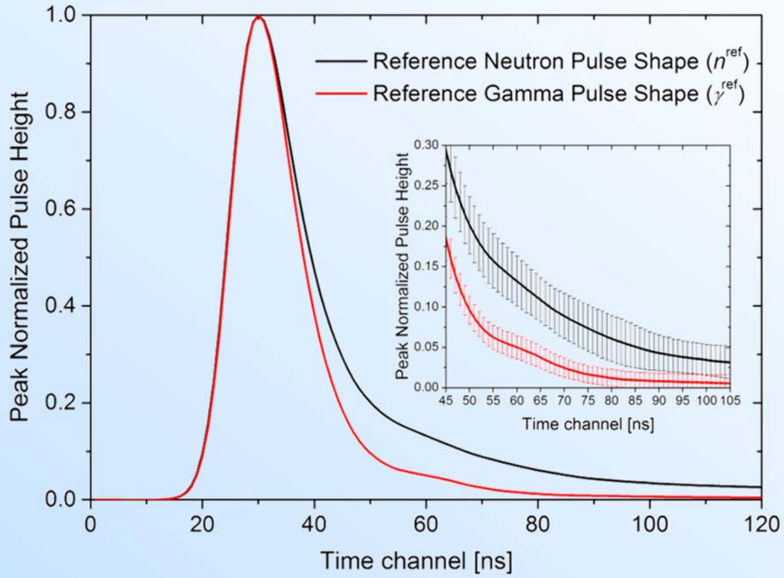
Experimental Setup Overview

- A well-collimated continuous-energy pulsed neutron beam scatters from a sample and is measured by detectors positioned around the scattering sample



Data Reduction

- Sum all files (Graphite, Open, ^{238}U or ^{Nat}Fe)
- Process data using **pulse shape analysis (PSA)** (classify neutron/gamma)
- **Remove falsely classified gammas** from neutron counts



$$C_{i,j} = D^S_{i,j} - D^O_{i,j} \cdot \frac{M^S}{M^O}$$

$C_{i,j}$ - Total neutron counts from sample-in

$D^S_{i,j}$ - Measured neutron counts during sample-in measurement

$D^O_{i,j}$- Measured neutron counts during open beam

M^S - Monitors counts during sample-in measurement

M^O - Monitors counts during open beam measurement

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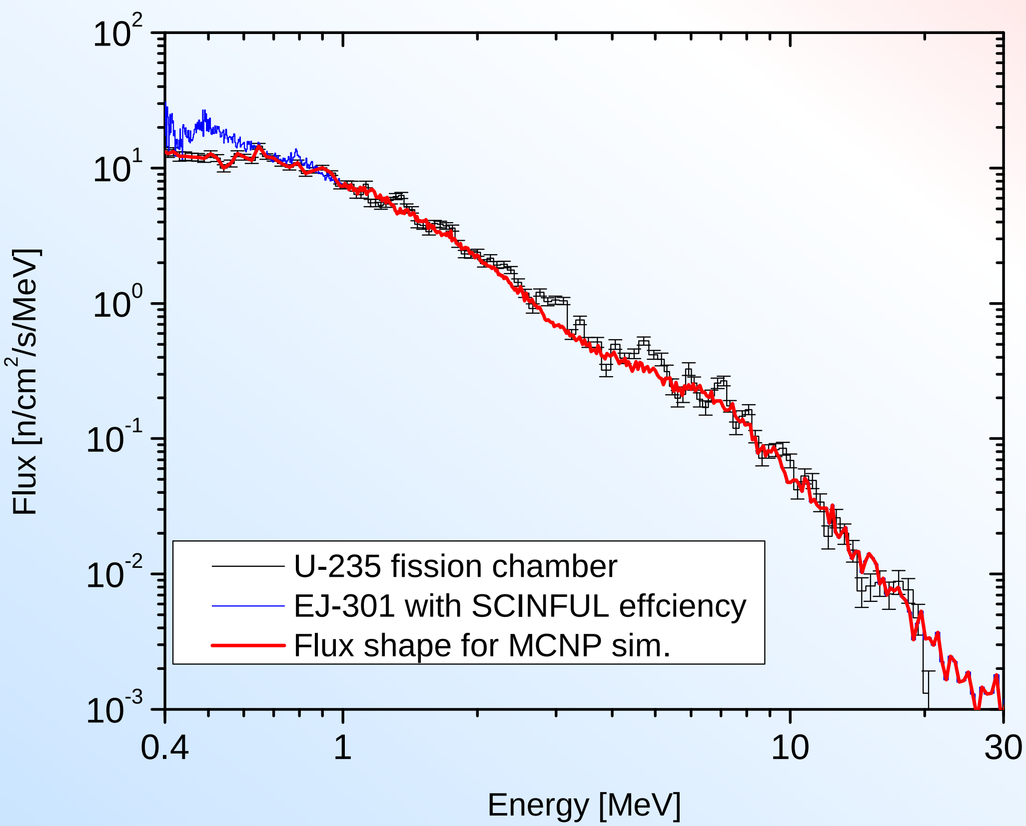
Flux Shape Measurement (at RPI)

- Used a cylindrical fission chamber with ~391 mg ^{235}U in the sample position
- Use ENDF/B-VI.0 fission cross section
- Correct for transmission of all materials between the source and sample
- Compare to a similar measurement using EJ301 and SCINFUL calculated efficiency
- Combine the two data sets using fission for E< 1 MeV



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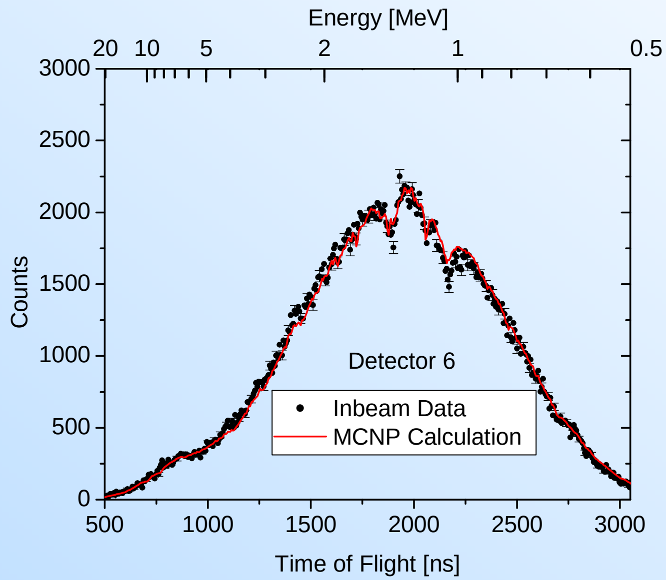
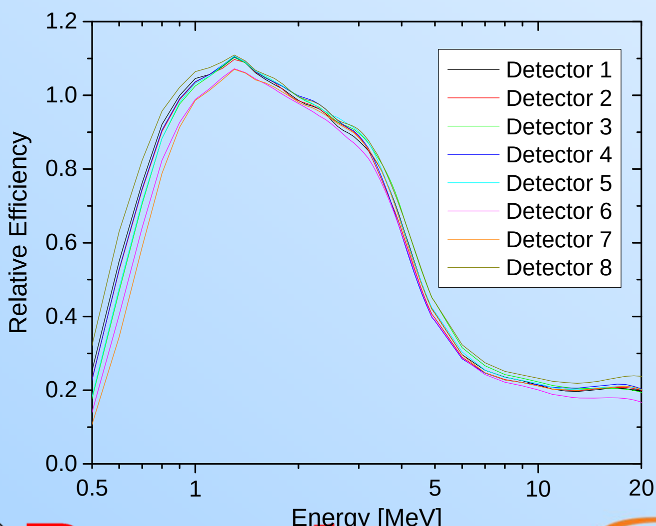
Detector Efficiency as a Function of Energy (at RPI)





- Objective:
  - MCNP simulation of EJ301 response in the sample position must precisely agree with the measurement
- Methodology:
  - Use in-beam (low-power) measurement for each detector.
  - Use the measured flux as a source in MCNP simulation of the in-beam detector response
  - In MCNP set the detector efficiency η=1 (tally only the neutron flux shape)
  - Divide the measured response by the simulation results to get the efficiency η(E) for each detector
  - During the experiment periodic gain calibrations are done to minimize gain shift.

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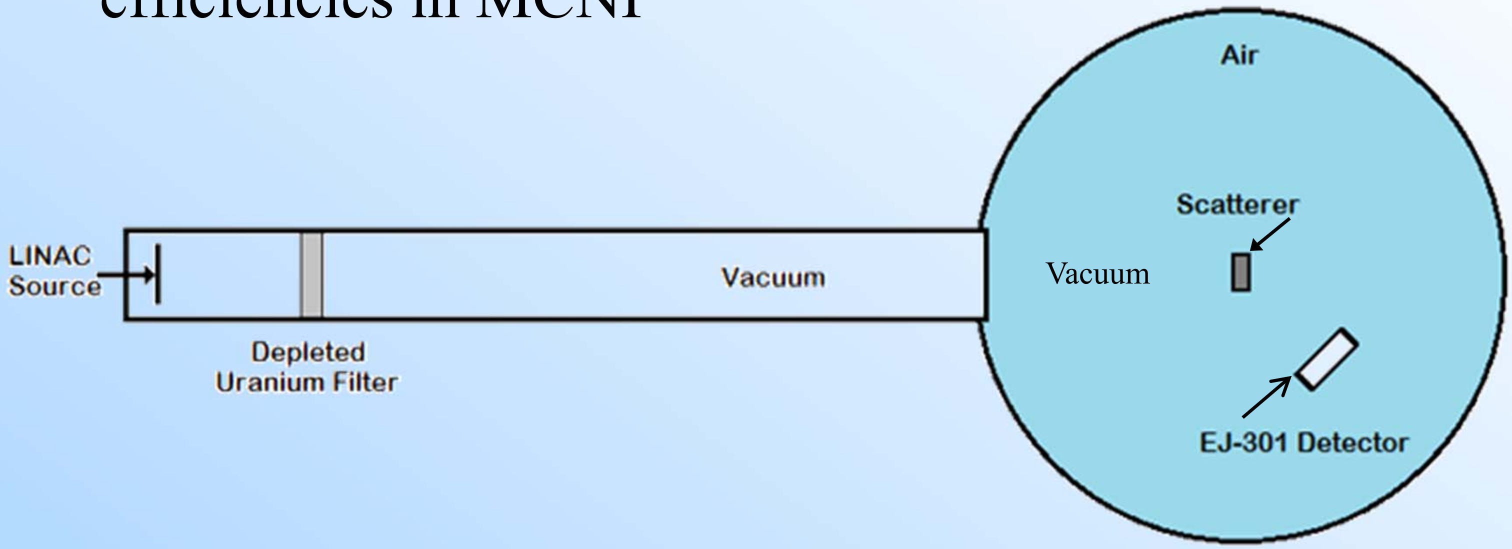
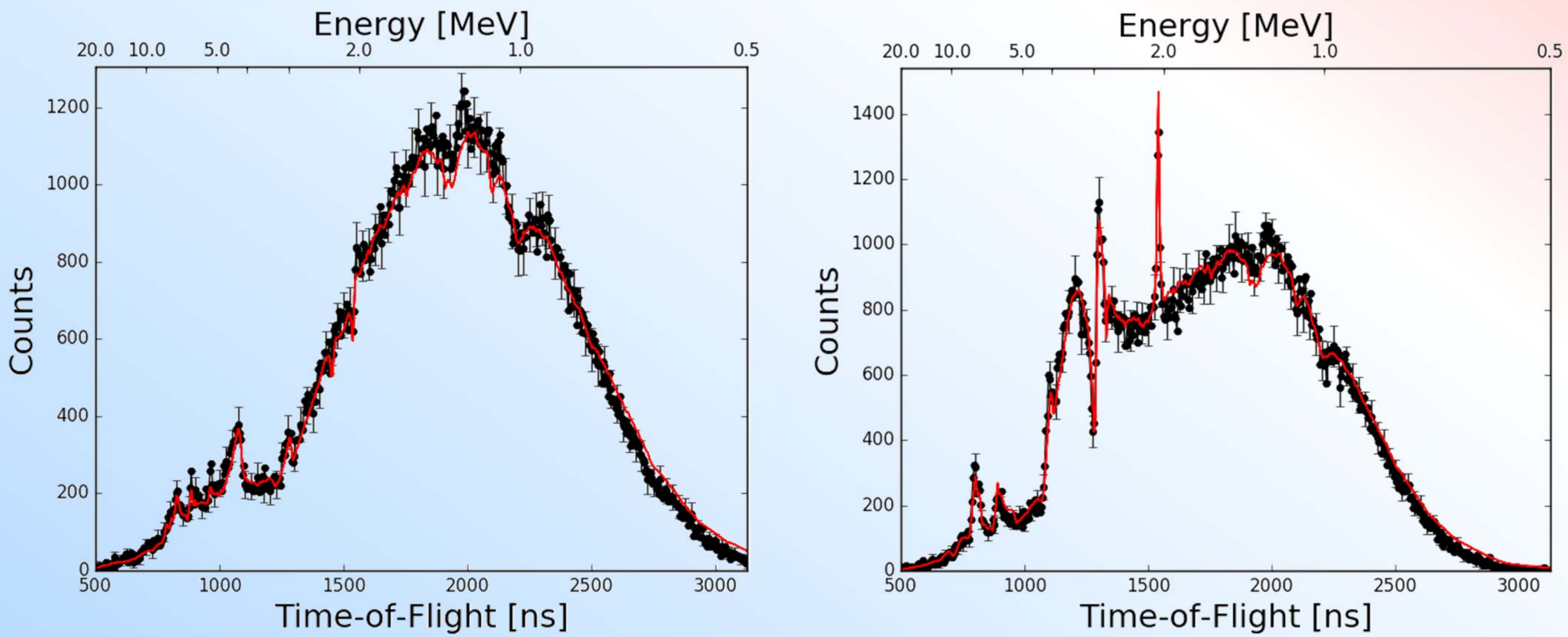
MCNP Simulation Geometry

- Geometry
  - Includes air, U-238 filter, Al and Mylar vacuum windows.
- An array of F5 point tallies were used to model each EJ-301 detector
  - Convolute tallies with energy-dependent detector efficiencies in MCNP



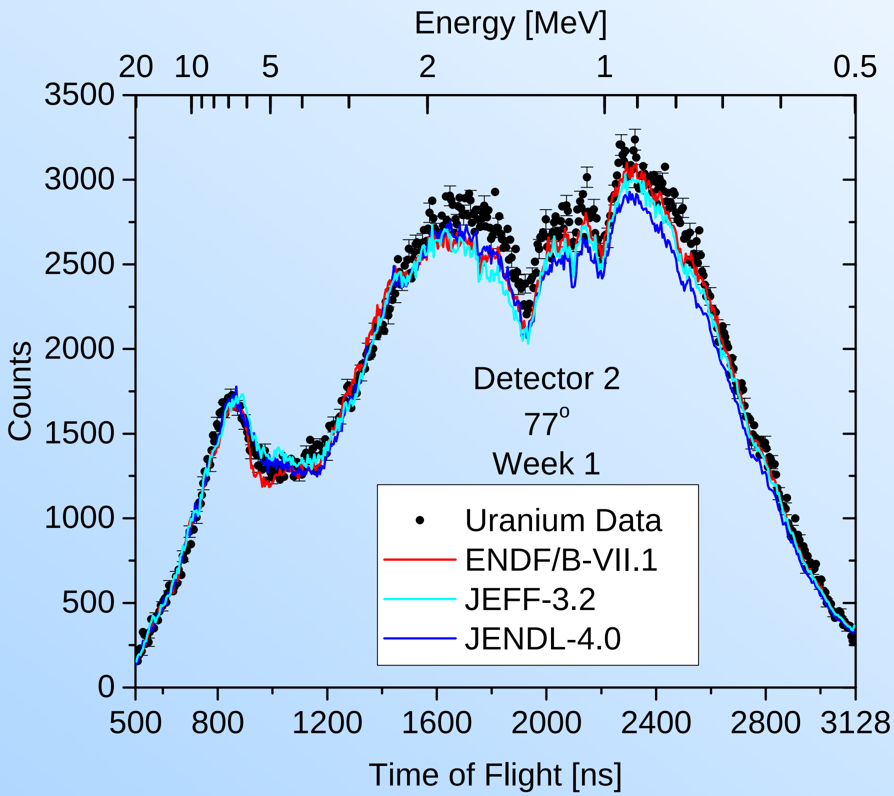
Graphite Normalization

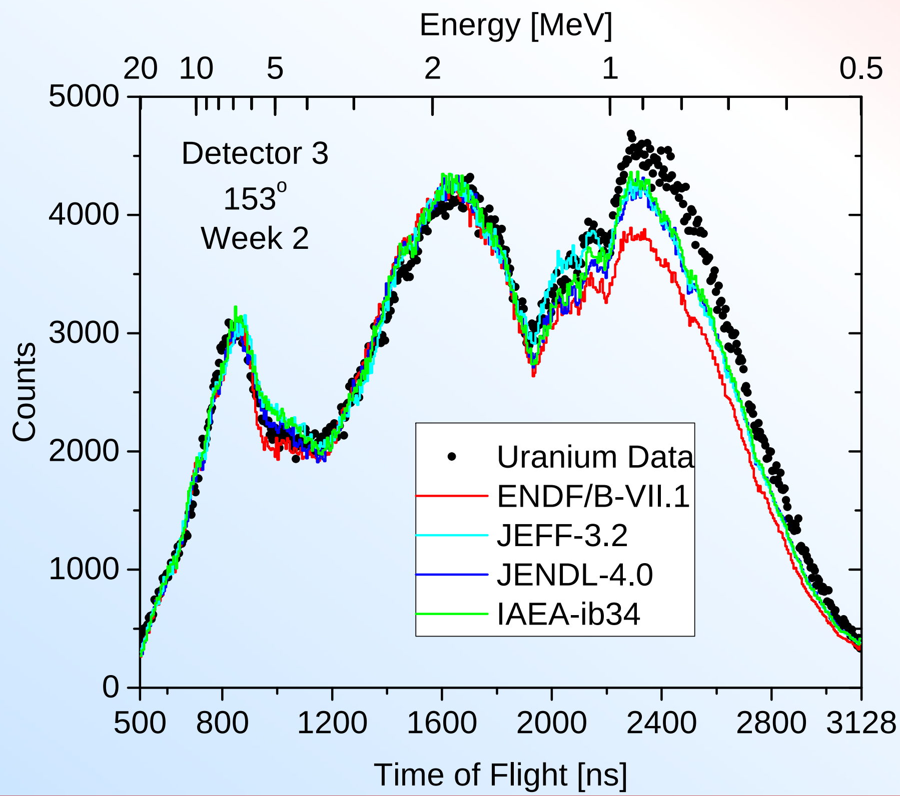


- MCNP was normalized for each detector and an average and standard deviation calculated
- Differences between experimental data and MCNP calculations (ENDF/B-VII.1) used to estimate systematic uncertainties
  - Average systematic uncertainty ~3-5%

^{238}U TOF Results

- Measurement consistency was confirmed by examining the response from detectors that were not repositioned between experiments
- Observed differences that occur between ^{238}U experimental data and the MCNP simulations can provide evaluators with additional information needed to construct a more accurate ^{238}U library





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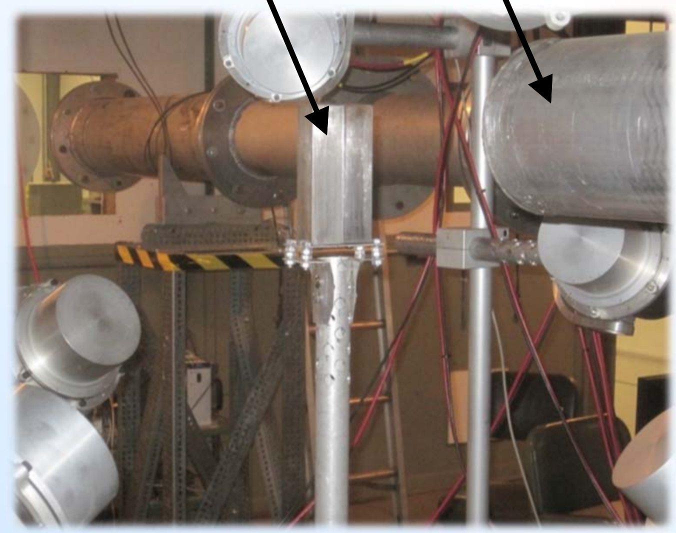
^{Nat}Fe Scattering Experiment Setup

- ^{56}Fe Identified as an isotope of interest for Gen IV reactors WPEC-SG26 and CIELO
- Iron consists of 4 naturally occurring isotopes:
  - ^{54}Fe (5.845%), ^{56}Fe **(91.754%)**, ^{57}Fe (2.119%), and ^{58}Fe (0.282%)
- TOF experiments for ^{Nat}Fe were performed similar to ^{238}U experiments:
  - 7 angles were measured
  - Detectors at ≈156° were not repositioned
  - Three data sets were collected:
    - ^{Nat}Fe, C, Open Beam
  - Beam monitors recorded fluctuations in neutron intensity



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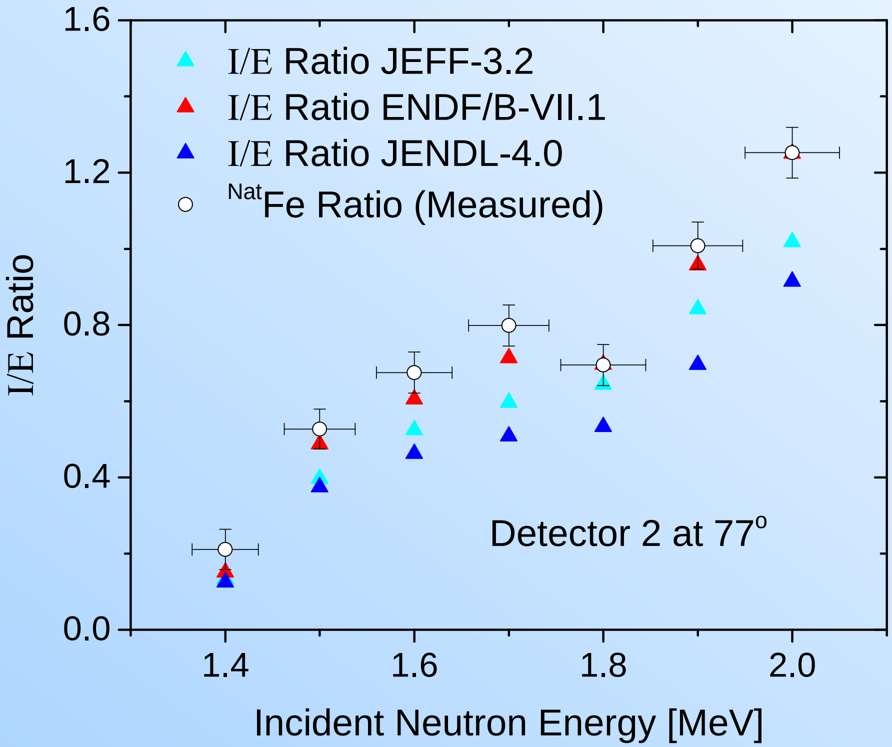
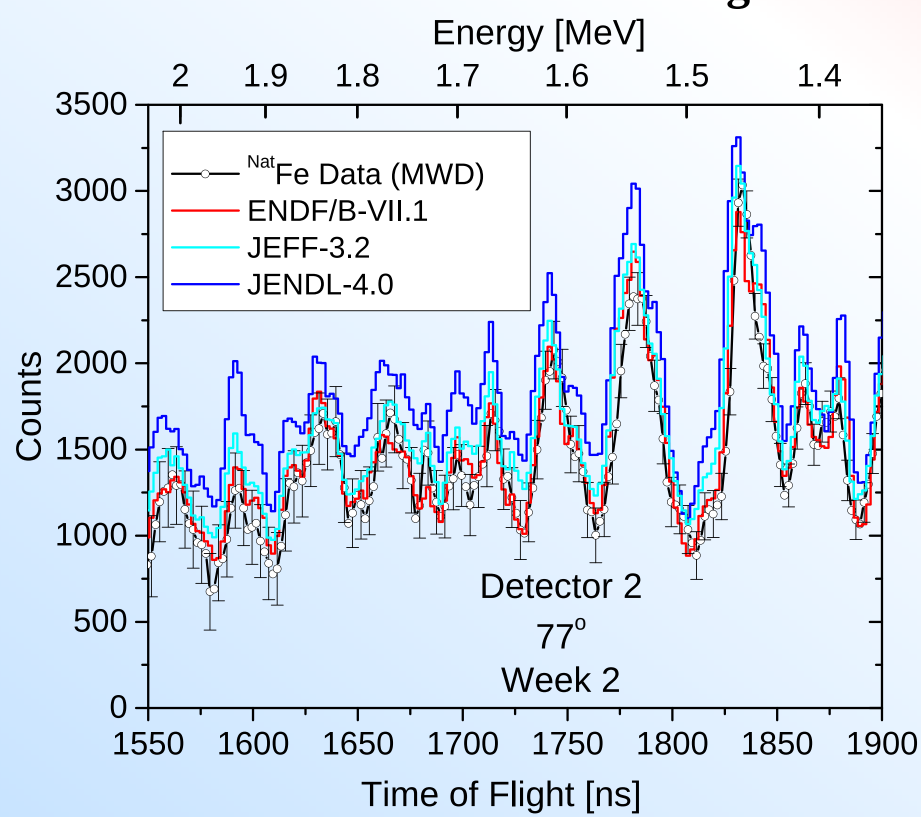
^{Nat}Fe Elastic Scattering

- The JENDL-4.0 evaluation overestimated the elastic signal at 77°
- It seems that the I/E ratio for JENDL is low because the elastic scattering is too high.

Inelastic/Elastic ratio

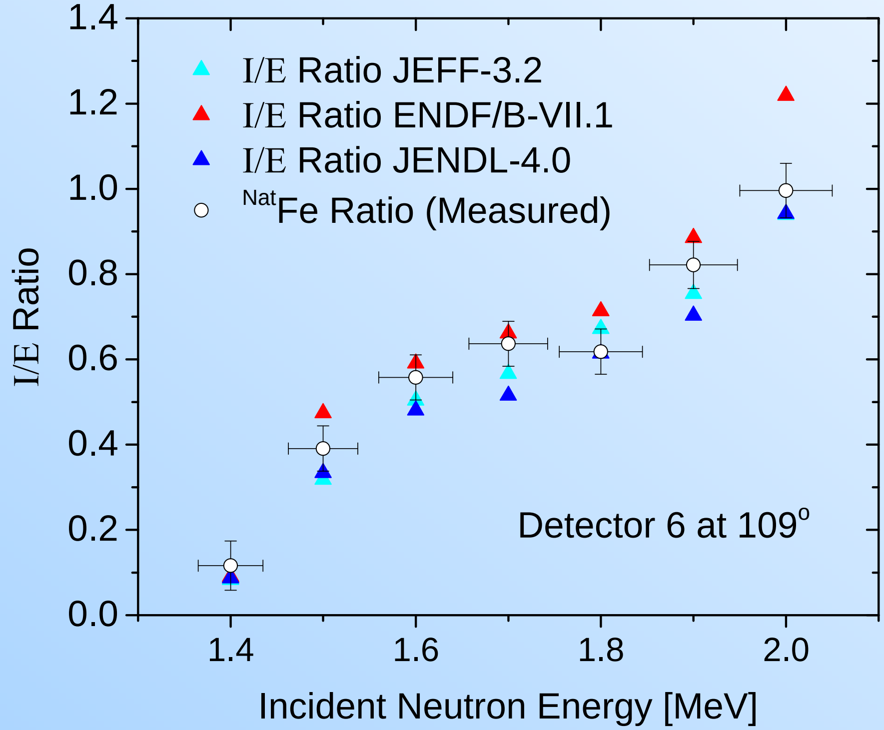


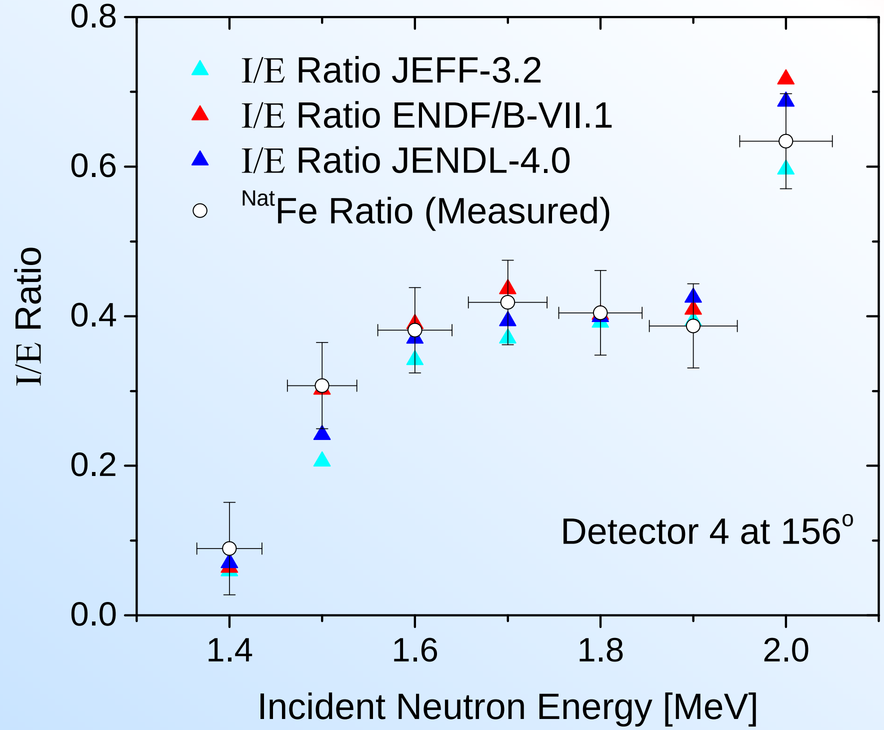
Elastic Scattering



^{Nat}Fe I/E Results

- **Results – Back Angles:**
  - All evaluations had good agreement up to 2.0 MeV where ENDF/B-VII.1 overestimates the inelastic to elastic (I/E) ratio





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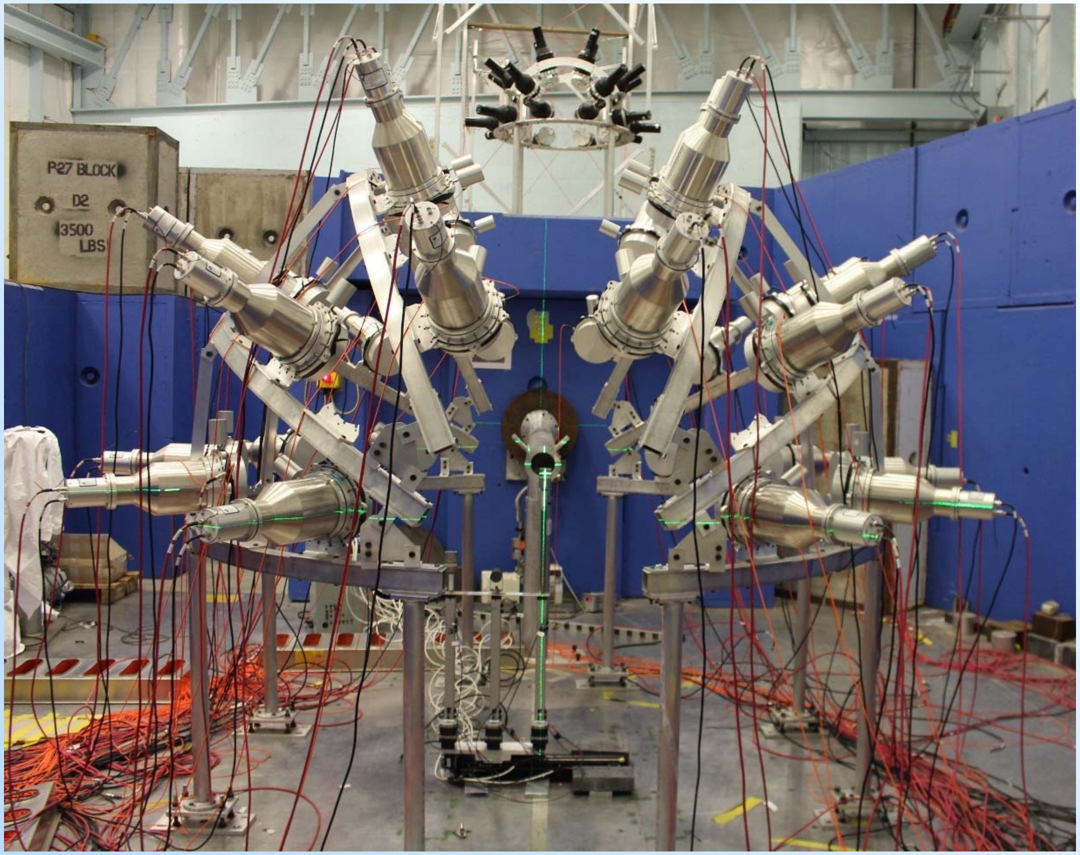
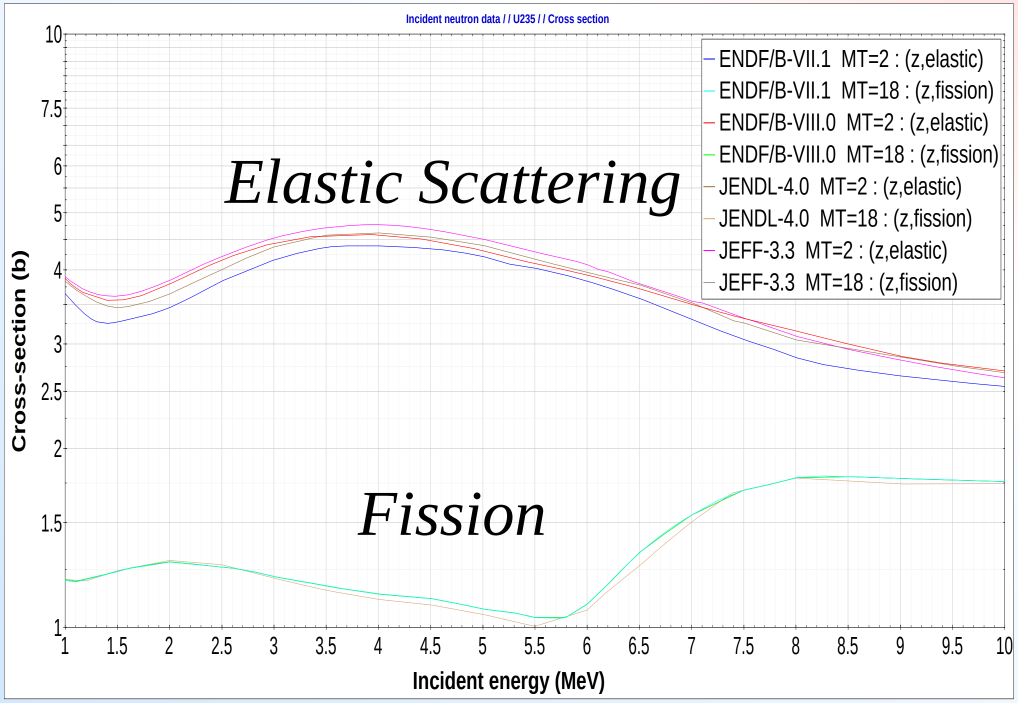
Fast ^{235}U and ^{239}Pu neutron Scattering Experiments at LANL



Motivation

- **Use the RPI methodology for ^{235}U and ^{239}Pu**
  - Carbon as a reference
- **In this case fission has a much larger contribution.**
  - Fission neutron angular distribution relative to then incident neutron beam is important
  - More neutron per event
- **Experimental setup is different**
  - Micro/Macro pulse structure 1.8us / 600us, overlap at ~0.7 MeV for a 20 m flight path distance.
  - Detector efficiency from SINCFUL with validation using ^{252}Cf, and Carbon measurements



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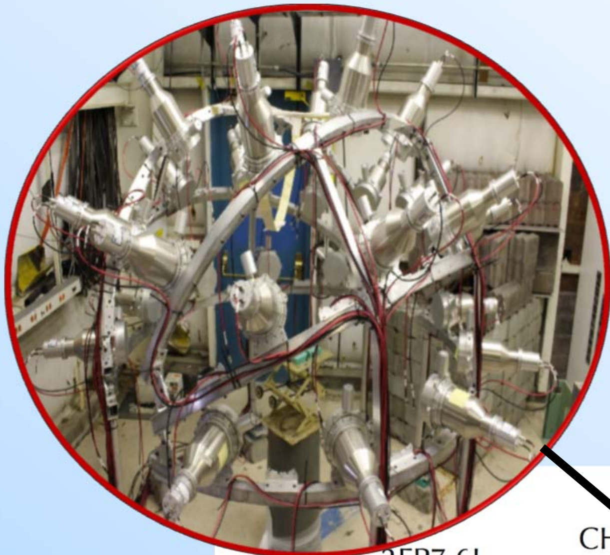
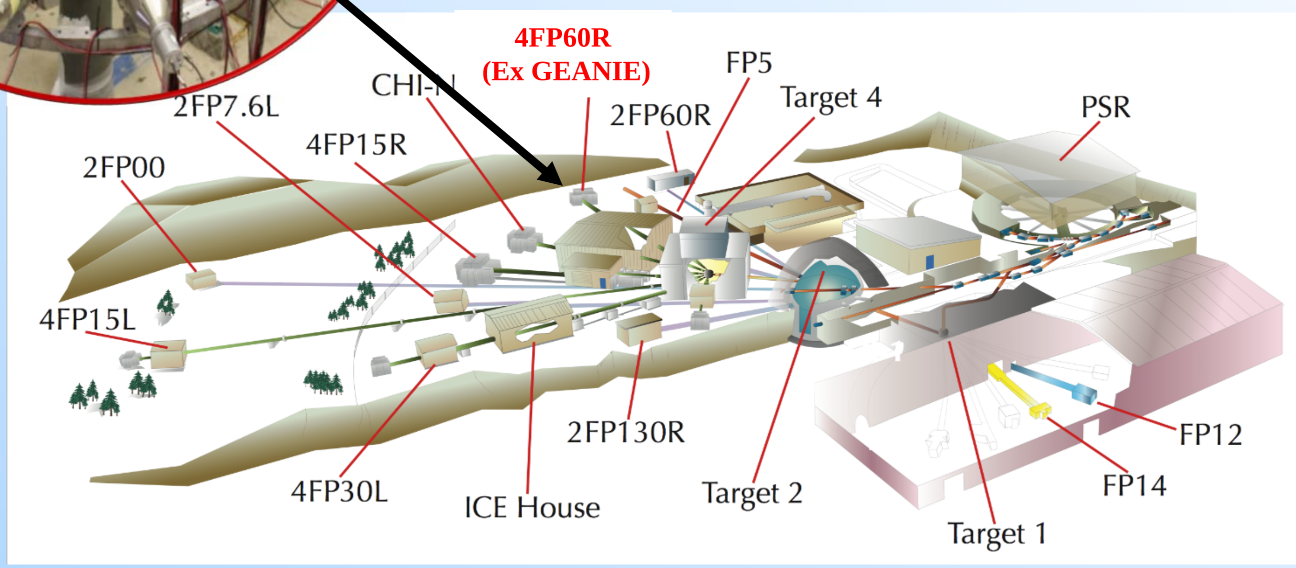
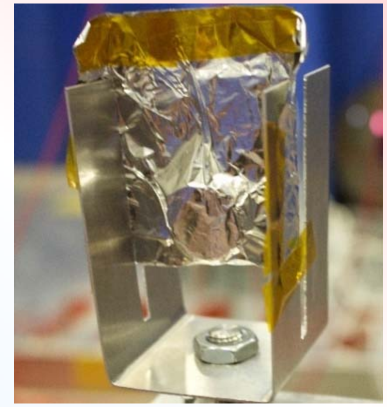
Fast neutron Scattering Experiments at LANL

- **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**

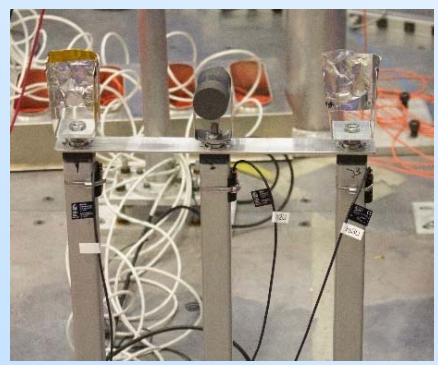




Samples

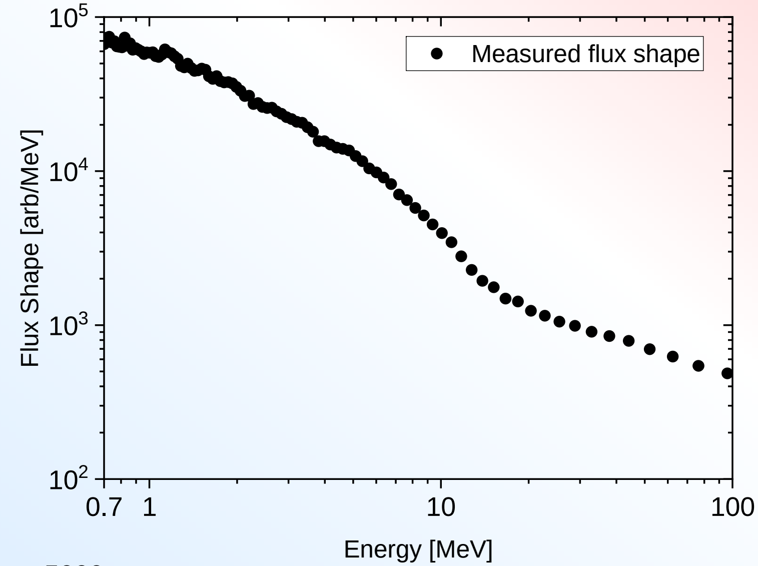


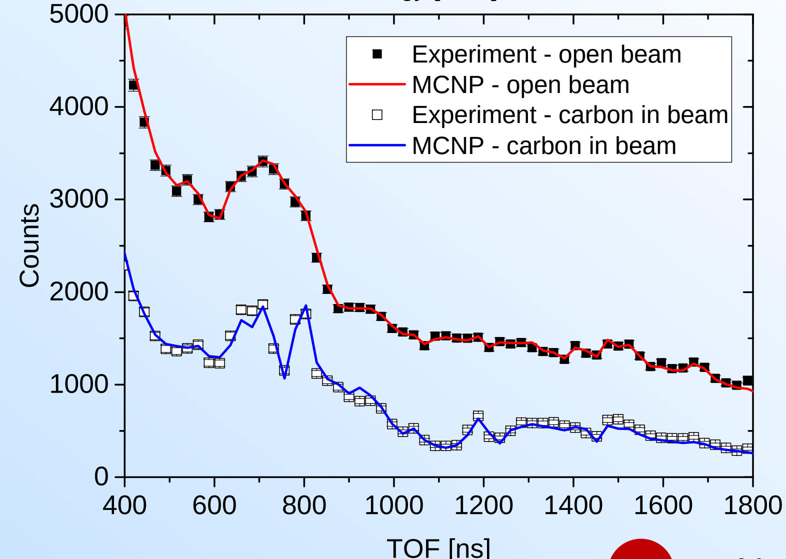
- **U-235**
  - 49.5g Sample (93 wt.% U-235)
  - Truncated cone shape
  - Encapsulated in 2 mil total thickness aluminum foil
- **Pu-239**
  - 24g Pu (93% Pu-239, 6% Pu-240 and 3.6% Ga)
  - stainless steel encapsulation blank
- **Graphite**
  - 38.6g graphite reference sample
  - 1.5” (3.81 cm) diameter 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**





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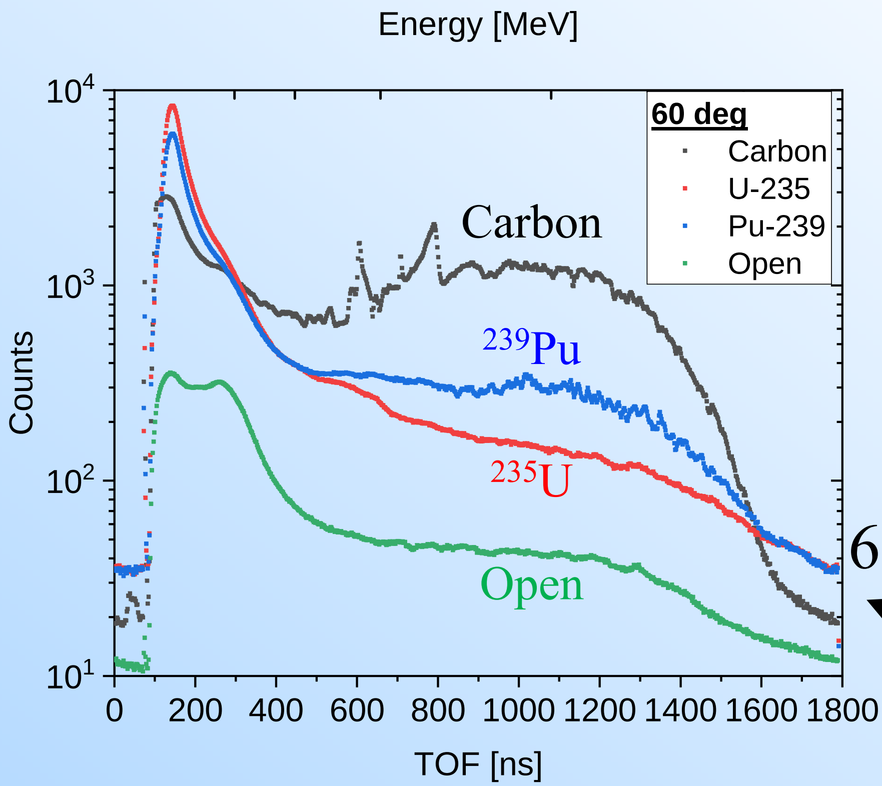
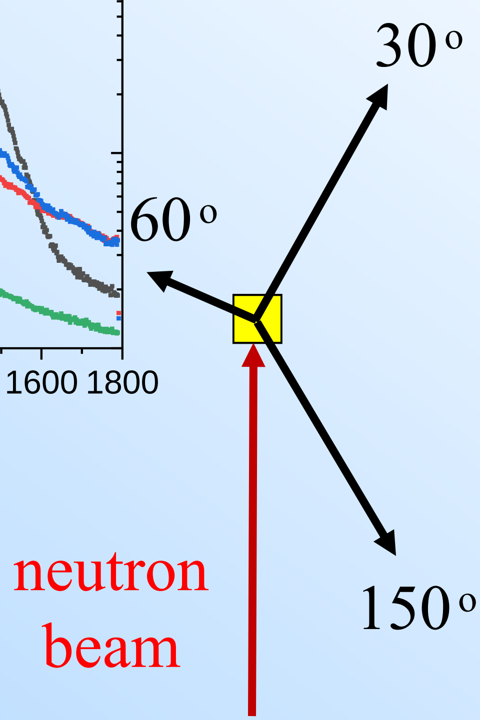
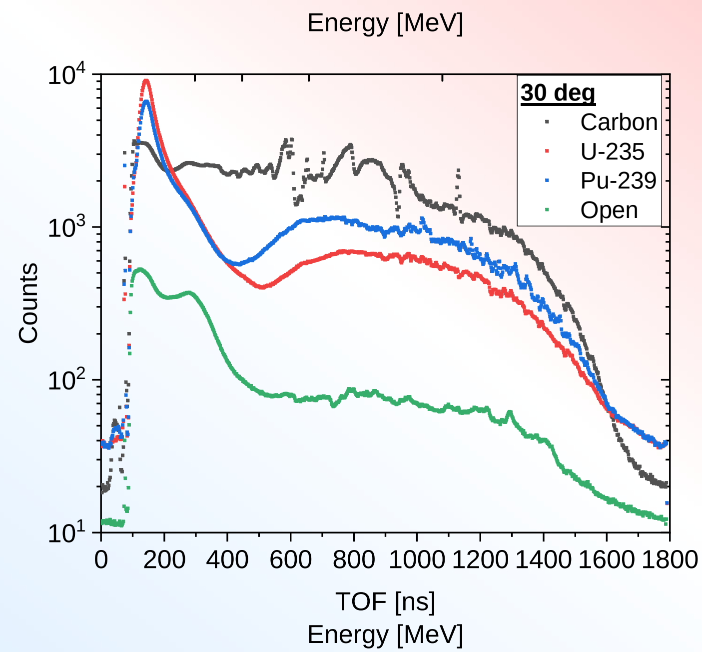
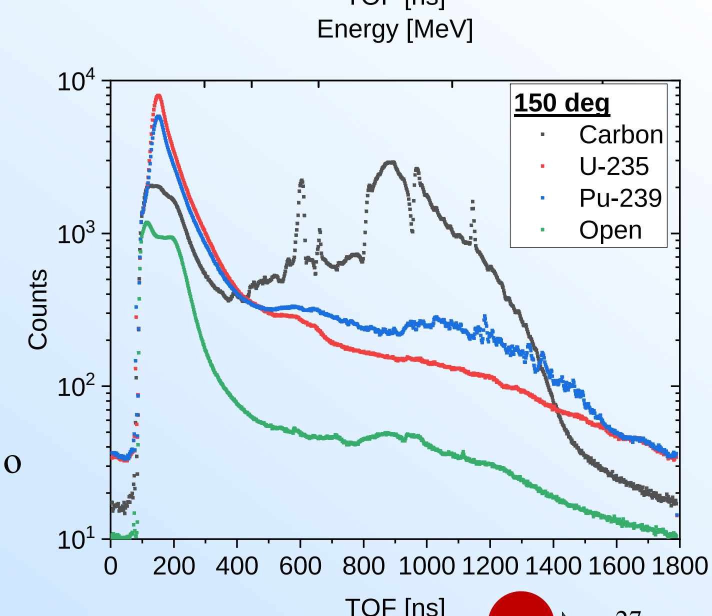
Raw Data









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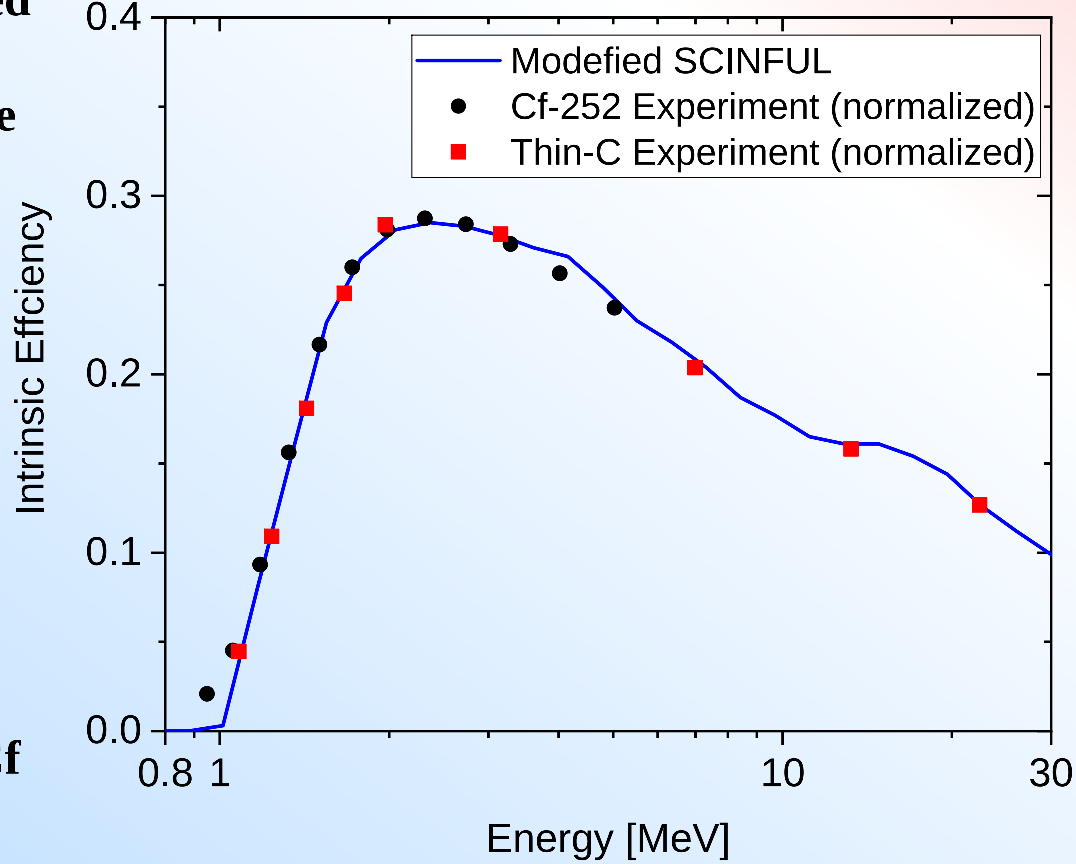
Detector Efficiency

- **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.



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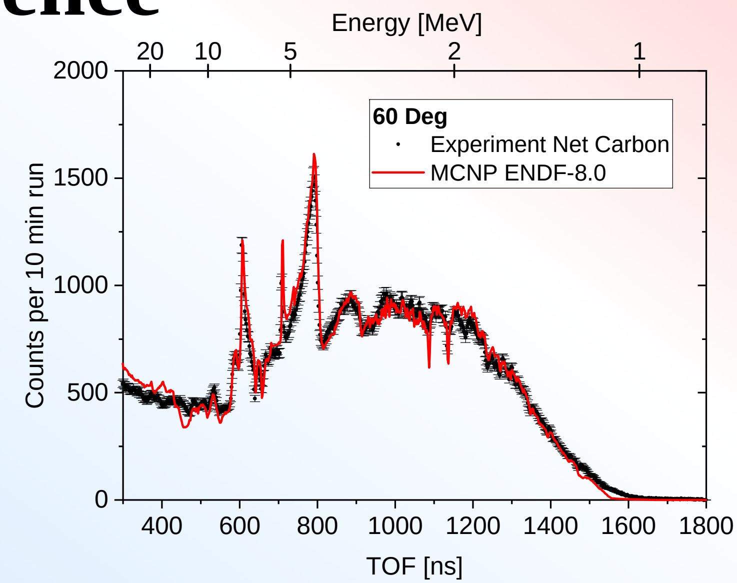
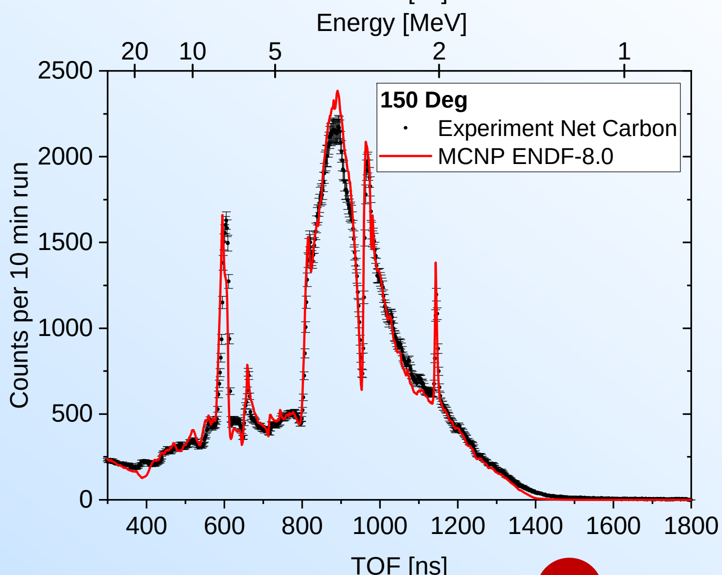
Carbon Reference

- **Carbon (graphite) is used as a reference**
  - Scattering cross section is well know.
  - 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 were with MCNP and ENDF-8 and are in good agreement with the experiment.

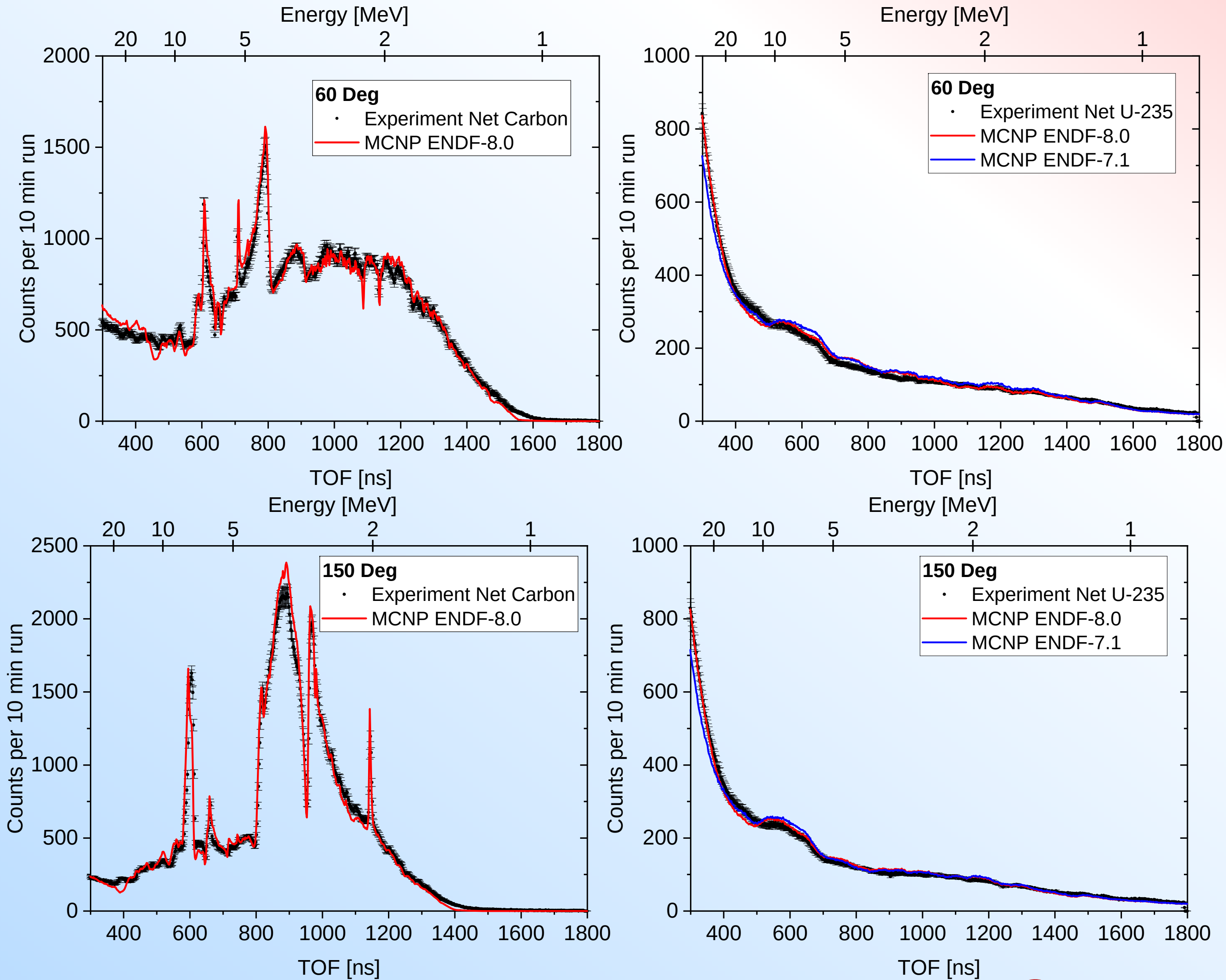
- **Carbon was used for normalization**





^{235}U results

- Used one factor to normalize the simulation to experiment of both carbon and ^{235}U
- Carbon is in good agreement and ^{235}U shows good agreement between experiment and simulation.
- Both angles show differences between 4-8 MeV
- The more recent ENDF-8.0 agrees with the experiment better above 4 MeV.



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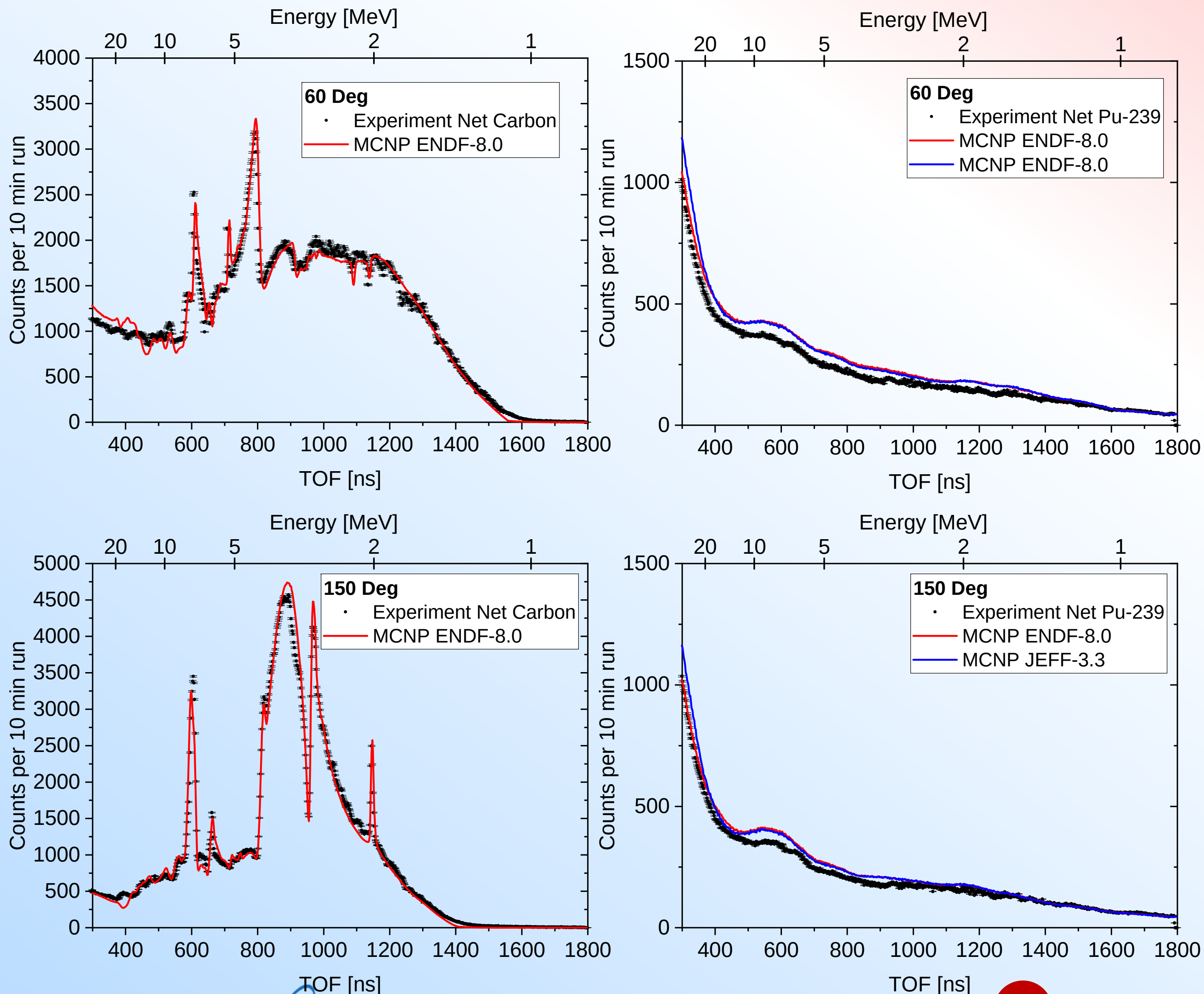
^{239}Pu results

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



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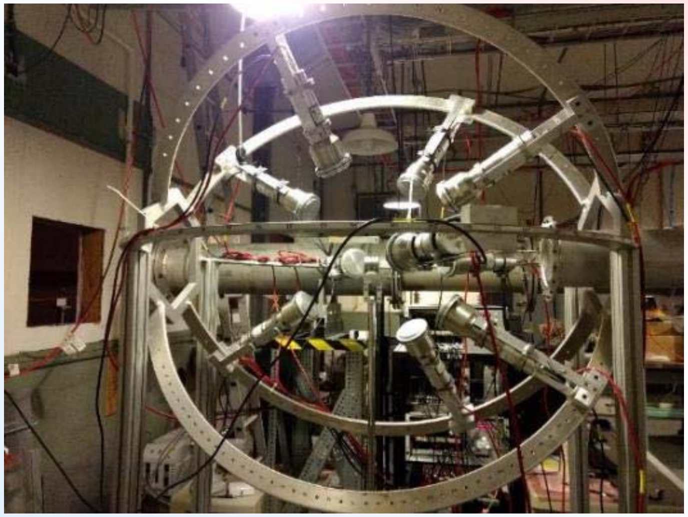
A Multi Angle Neutron Detection Array (AMANDA)



- **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

Copper KeV scattering measurement

- Motivation – 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 thick natural copper disk sample
  - 7 cm thick carbon disk 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

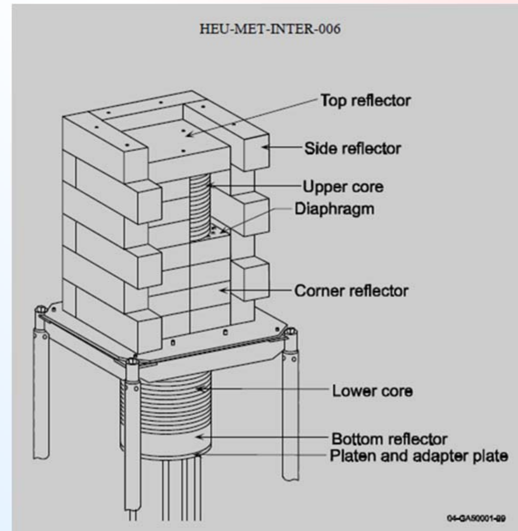


Figure 6. Schematic Cutaway of Zeus before Assembly.

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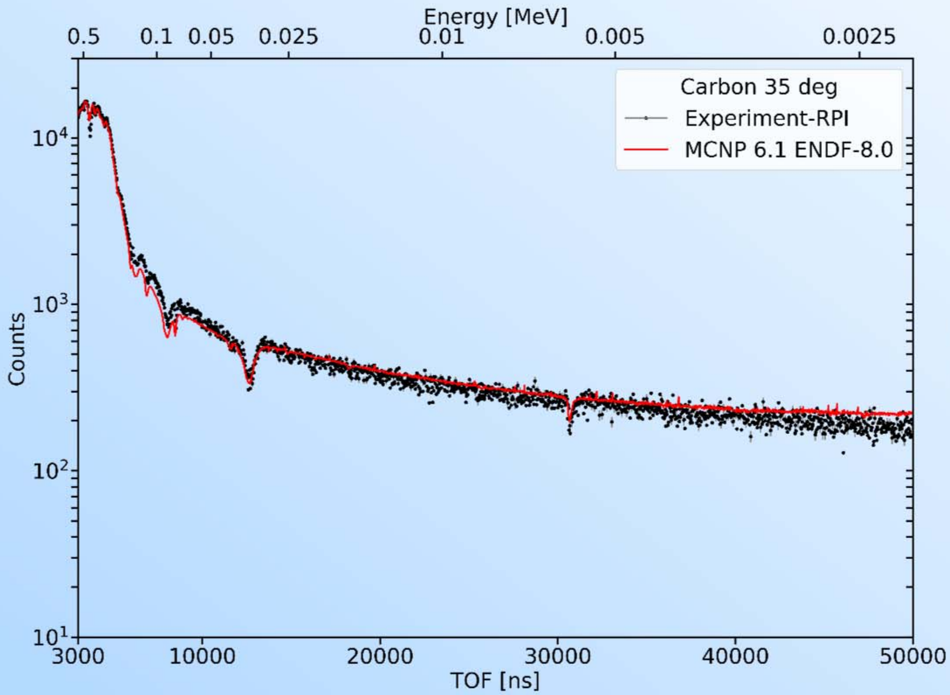
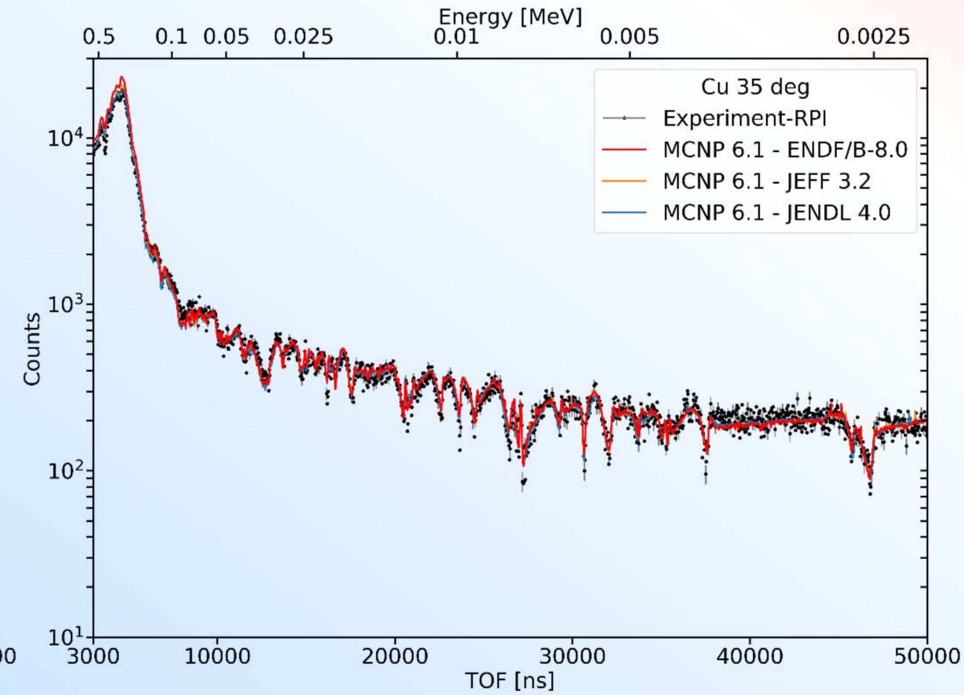
Copper scattering – 35 deg

- Overall good agreement between the Cu experiment and evaluation
- Found a problem in ENDF-8 with the first resonance in B-11, used JENDL-4





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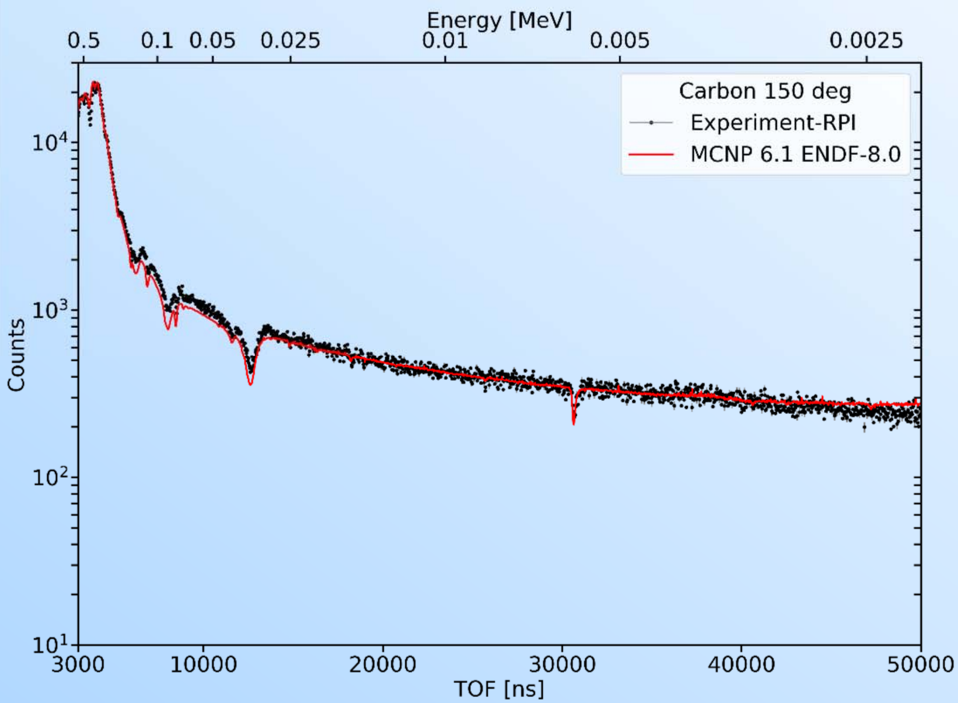
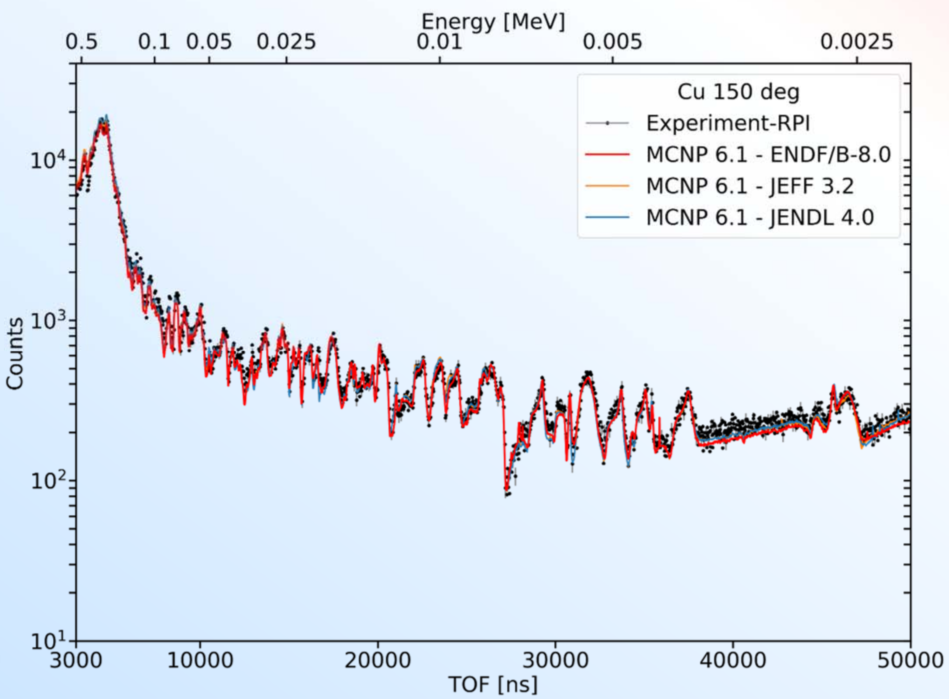
Copper scattering – example 150 deg

Overall good agreement between the Cu experiment and evaluation





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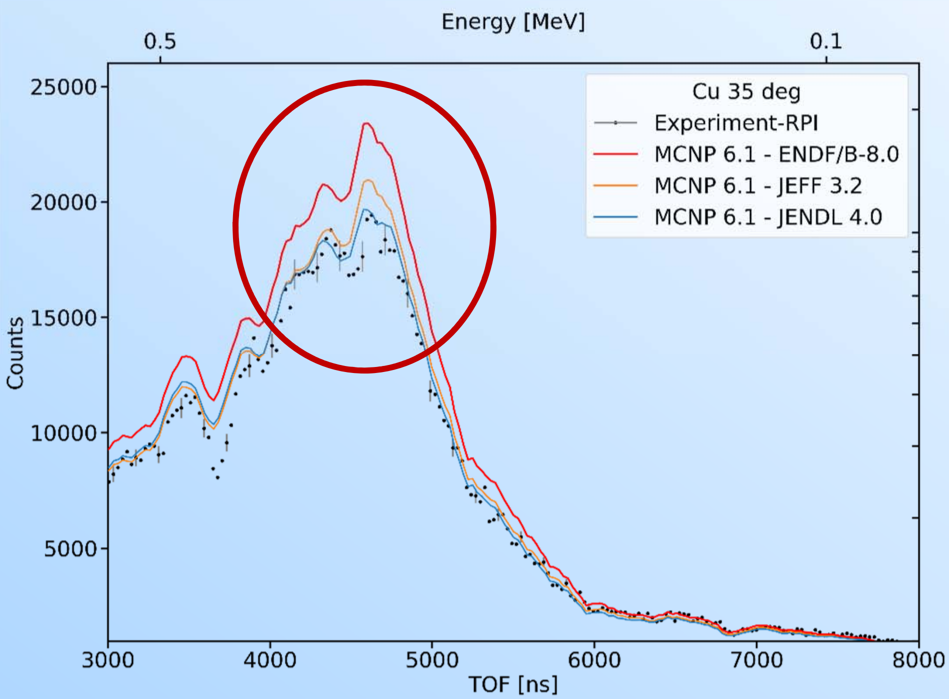
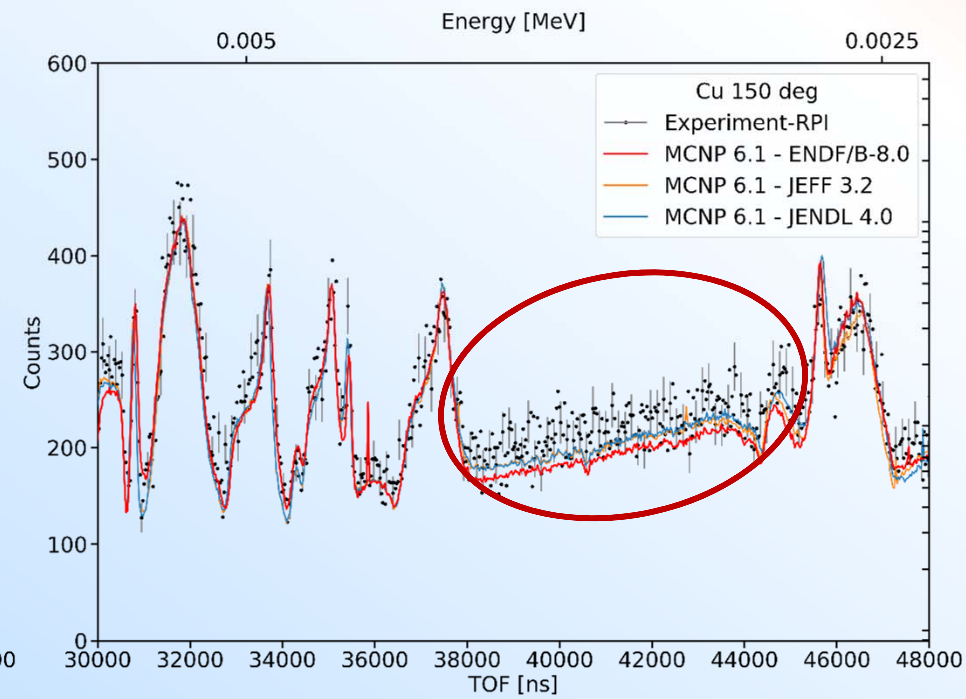
Copper scattering closer look

- 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





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Scattering Related Group Publications

- **Journal**
  - A. M. Daskalakis, E. J. Blain, B. J. McDermott, R. M. Bahran, Y. Danon, D. P. Barry, R. C. Block, M. J. Rapp, B. E. Epping and G. Leinweber, **"Quasi-differential elastic and inelastic neutron scattering from iron in the MeV energy range**", Annals of Nuclear Energy, vol. 110, pp. 603 - 612, 2017.
  - E. Blain, A. Daskalakis, R.C. Block, D. Barry, Y. Danon, "***A method to measure prompt fission neutron spectrum using gamma multiplicity tagging***", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 805, Pages 95-100, 1 January 2016, (invited: Special Issue in memory of Glenn F. Knoll).
  - A.M. Daskalakis, R.M. Bahran, E.J. Blain, B.J. McDermott, S. Piela, Y. Danon, D.P. Barry, G. Leinweber, R.C. Block, M.J. Rapp, R. Capote, A. Trkov, "***Quasi-differential neutron scattering from 238U from 0.5 to 20 MeV***", Annals of Nuclear Energy, Volume 73, Pages 455-464, November 2014.
  - R. Capote, A. Trkov, M. Sin M. Herman, A. Daskalakis, and Y. Danon, "***Physics of Neutron Interactions with ^{238}U: New Developments and Challenges***", Nuclear Data Sheets 118, 26–31, (2014).
  - D. P. Barry, G. Leinweber, R. C. Block, and T. J. Donovan, Y. Danon, F. J. Saglime, A. M. Daskalakis, M. J. Rapp, and R. M. Bahran, "***Quasi-differential Neutron Scattering in Zirconium from 0.5 MeV to 20 MeV***", Nuclear Science and Engineering, 174, 188–201, (2013).
  - R.Dagan, B. Becker, Y. Danon, "***A complementary Doppler Broadening formalism and its impact on nuclear reactor simulation***", Kerntechnik 3, Page 185-189, (2011).
  - Frank J. Saglime III, Yaron Danon, Robert C. Block, Michael J. Rapp, Rian M. Bahran, Greg Leinweber, Devin P. Barry, Noel J. Drindak, and Jeffrey G. Hoole, "***A system for differential neutron scattering experiments in the energy range from 0.5 to 20 MeV***", Nuclear Instruments and Methods in Physics Research Section A, 620, Issues 2-3, Pages 401-409, (2010).
- **Conference Proceedings**
  - Y. Danon, "**Experiments with Neutron Induced Neutron Emission from U-235, Pu-239, and Graphite**", 2019 International Conference on Nuclear Data for Science and Technology (ND2019), Beijing China, May 2019.
  - Daskalakis, Adam, Blain, Ezekiel, Leinweber, Gregory, Rapp, Michael, Barry, Devin, Block, Robert and Danon, Yaron, "**Assessment of beryllium and molybdenum nuclear data files with the RPI neutron scattering system in the energy region from 0.5 to 20 MeV**", EPJ Web Conf., vol. 146, pp. 11037, 2017
  - R. Capote, A. Trkov, M. Sin, M. W. Herman, P. Schillebeeckx, I. Sirakov, S. Kopecky, D. Bernard, G. Noguere, A. Daskalakis and Y. Danon, "**U-238 evaluation and validation of the neutron induced reactions up to 20 MeV**", ND 2016 International Conference on Nuclear Data for Science and Technology, Bruges, Belgium,, 11-16, September 2016
  - K. Mohindroo, E. Blain, Y. Danon, S. Mosby and M. Devlin, "**Quasi-differential neutron induced neutron emission reaction measurements at WNR**", ransactions of the American Nuclear Society, vol. 115, pp. 701-703, 2016
  - A. M. Daskalakis, E. J. Blain, B. J. McDermott, R. M. Bahran, Y. Danon, D. P. Barry, G. Leinweber, M. J. Rapp, R. C. Block, "***Separation of Neutron Inelastic and Elastic Scattering Contribution from Natural Iron using Detector Response Functions***", 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015.
  - Amanda E. Youmans, J. Brown, A. Daskalakis, N. Thompson, A. Welz, Y. Danon, B. McDermott, G. Leinweber, M. Rapp, "***Fast Neutron Scattering Measurements with Lead***", 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp '15), Washington D.C., November 2015
  - Y. Danon, L. Liu, E.J. Blain, A.M. Daskalakis, B.J. McDermott, K. Ramic, C.R. Wendorff, D.P. Barry, R.C. Block, B.E. Epping, G. Leinweber, M.J. Rapp, T.J. Donovan, "***Neutron Transmission, Capture, and Scattering Measurements at the Gaerttner LINAC Center***", Transactions of the American Nuclear Society, Vol. 109, p. 897-900, Washington, D.C., November 10–14, 2013
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  - Frank J. Saglime III, Yaron Danon, Robert C. Block, Michael J.Rapp, and Rian M. Bahran, Devin P. Barry, Greg Leinweber, and Noel J. Drindak, "***High Energy Neutron Scattering Benchmark of Monte Carlo Computations***", International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, May 3-7, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009).
  - Frank J. Saglime III, Yaron Danon, Robert Block, "***Digital Data Acquisition System for Time of Flight Neutron Beam Measurements***", The American Nuclear Society's 14th Biennial Topical Meeting of the Radiation Protection and Shielding Division, p. 368, Carlsbad New Mexico, USA. April 3-6, 2006.