Update on CIELO Related Measurements at RPI

Y. Danon

Gaerttner LINAC Center, Rensselaer Polytechnic Institute, Troy, NY 12180

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RPI Nuclear Data Group

RPI Faculty

Prof. Yaron Danon - LINAC Director

Prof. Li Liu – Thermal Scattering

KAPL

Dr. Greg Leinweber

Prof. (Emeritus) Robert C. Block

Dr. Devin Barry

Dr. Michael Rapp

Dr. Tim Donovan

Mr. Brian Epping

Dr. John Burke

Technical Staff

Dr. Ezekiel Blain

Peter Brand

Michael Bretti

Matt Gray

Azeddine Kerdoun

Graduate Students

Adam Daskalakis

Brian McDermott

Adam Weltz

Nicholas Thompson

Kemal Ramic

Carl Wendorff

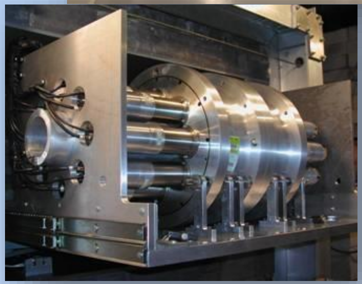
Amanda Youmans

Jesse Brown

The Nuclear Data Program at the Gaerttner LINAC Center

- Driven by a 60 MeV pulsed electron LINAC ~$\mathbf{10^{12}}$ **n/s**
- **Neutron transmission**
  - Resonance region: 0.001 eV- 1000 keV,
  - High energy region: 0.4- 20 MeV
- **Neutron Capture**
  - Resonance region: 0.01-1000 eV
  - New detector array at 45m: 1 keV ~ 500 keV
- **Neutron Scattering**
  - High energy region: 0.4 MeV- 20 MeV
- **Prompt Fission neutron spectrum**
- **Lead Slowing Down Spectrometer**
  - Fission cross section and fission fragment spectroscopy.
  - (n,α), (n,p) and (n,γ) cross sections on small (radioactive) samples.



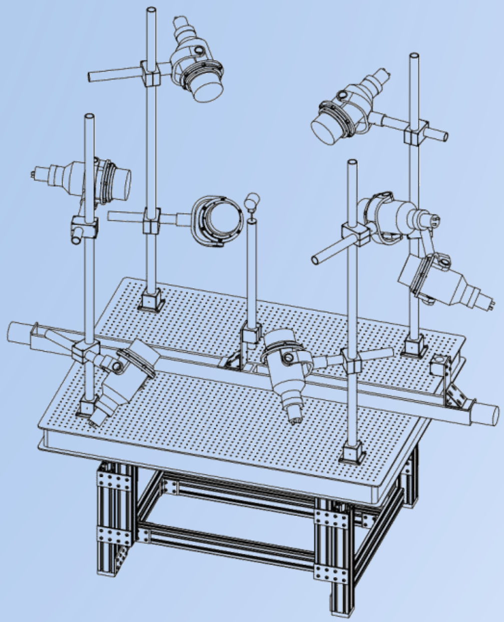



Recent CIELO Related Activity

- U-238
  - Neutron scattering 0.5 MeV $<E_n<$20 MeV
    - Data on ^{238}U published (ANE, Vol 73, P. 455-464, Nov. 2014).
- Fe
  - ^{nat}Fe Neutron scattering 0.5 MeV$<E_n<$20 MeV.
    - Publication in preparation
  - ^{nat}Fe neutron capture 1 keV$<E_n<$2 MeV
  - High resolution transmission on Fe and ^{56}Fe, 0.5 MeV$<E_n<$20 MeV. Data was delivered to Leal (ORNL) for inclusion in the evaluation.
- O-16
  - Measurement of H_2O neutron transmission 0.5 MeV$<E_n<$20 MeV using a 250m flight station.

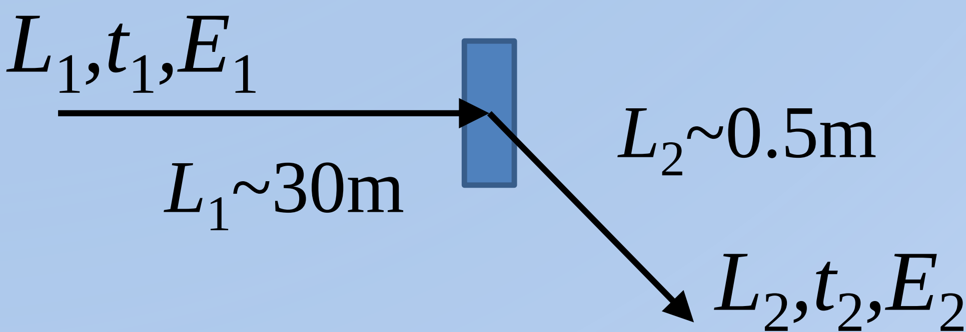
Neutron Scattering

- Provide accurate benchmark 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
- Design a flexible system: now also used for fission neutron spectra measurements



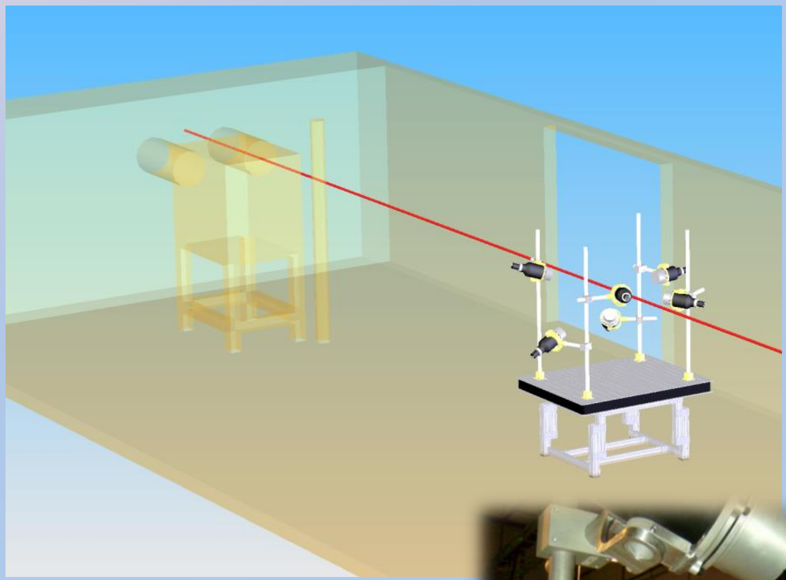
TOF Scattering Yield Measurement

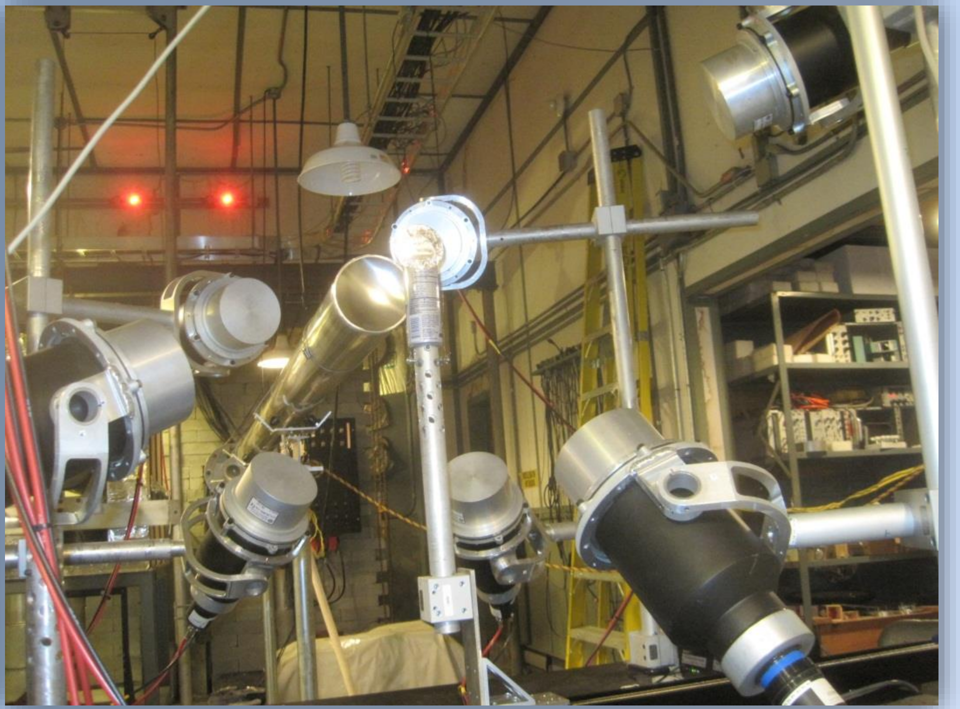
- Measure the total TOF $t=t_1+t_2$
- For all scattering events $E_2<E_1$
- In most cases the energy loss is small $E_1 \sim E_2$
- Since $t_1>>t_2$ and $E_1 \sim E_2$ then for presentation the incident neutron energy E_1 is calculated using t and $L=L_1+L_2$



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

Scattering Detection System: Experimental Setup

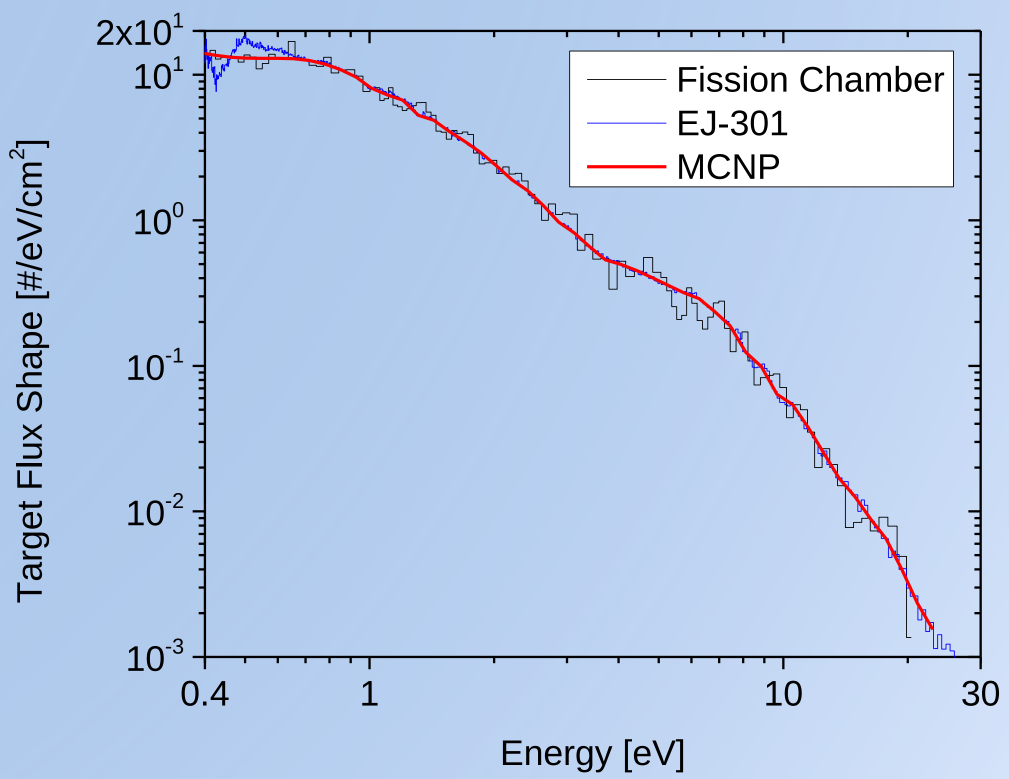




Low mass sample holder

Flux Shape Measurement

- Use a fission chamber with ~391 mg ^{235}U in the sample position
- Use ENDF/B-VII.1 fission cross section for ^{235}U
- 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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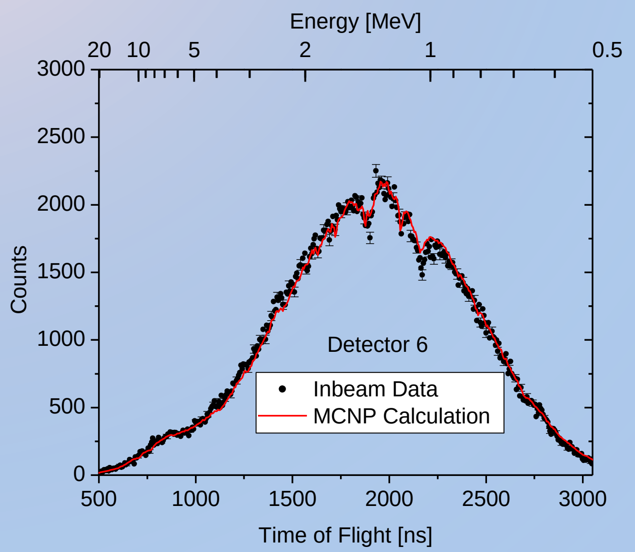
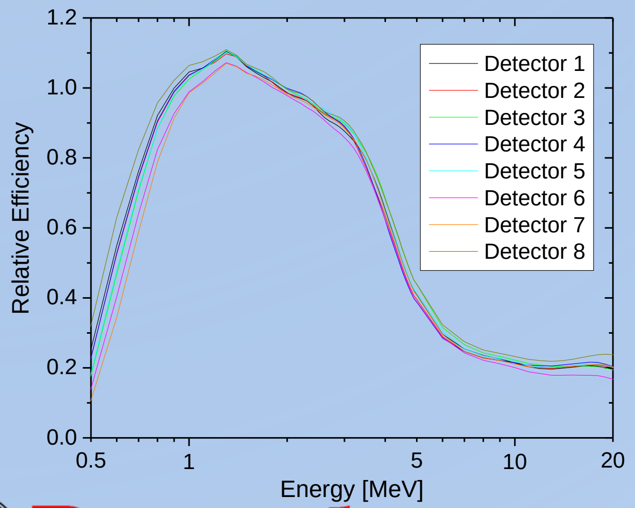
Efficiency as a Function of Energy





- Objective:
  - MCNP simulation of EJ301 response in the sample position must precisely agree with the measurement
- Methodology:
  - 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 $\eta(E)$ for each detector
  - During the experiment periodic gain calibrations are done to minimize gain shift.

Data Reduction

- Sum all files and dead time correct.
- The experimental count rate corrected for background and false neutrons:

$$Rn_i = Rn_i^s - fn_i^s - \frac{M^S}{M^O} \cdot \left(Rn_i^o - fn_i^o \right)$$

Rn_i^s, Rn_i^o - Sample and open neutron counts at TOF channel *i*

fn_i^s, fn_i^s - Sample and open false neutron counts for TOF channel *i*

M^S, M^O - Open and sample monitor counts for the run

The false neutron correction: $$fn_i = \sum_{j=1}^{n_\gamma} f(A_j)$$

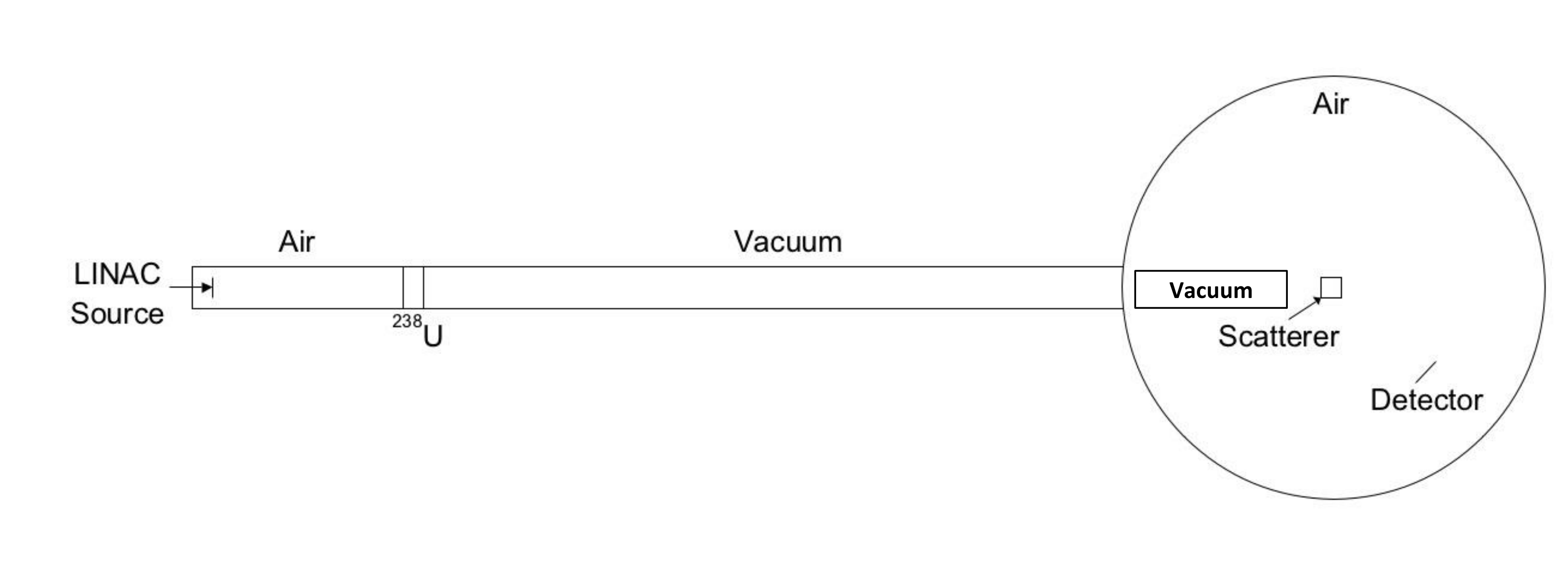
~2% effect for ^{238}U
For E_n~6 MeV

n_γ - Number of gammas in TOF channel *i*

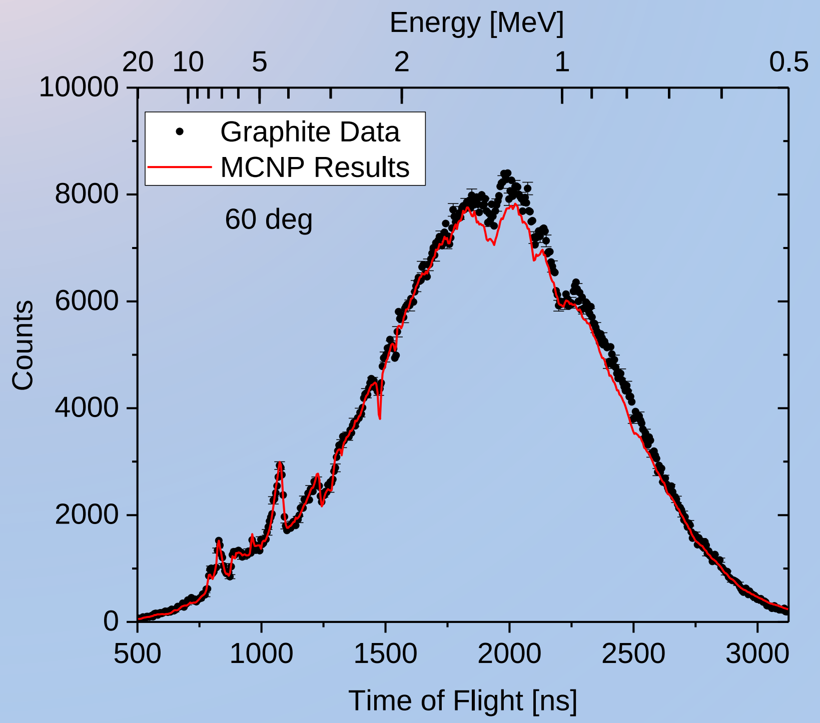
$f(A_j)$ - False neutron correction factor for pulse area A_j

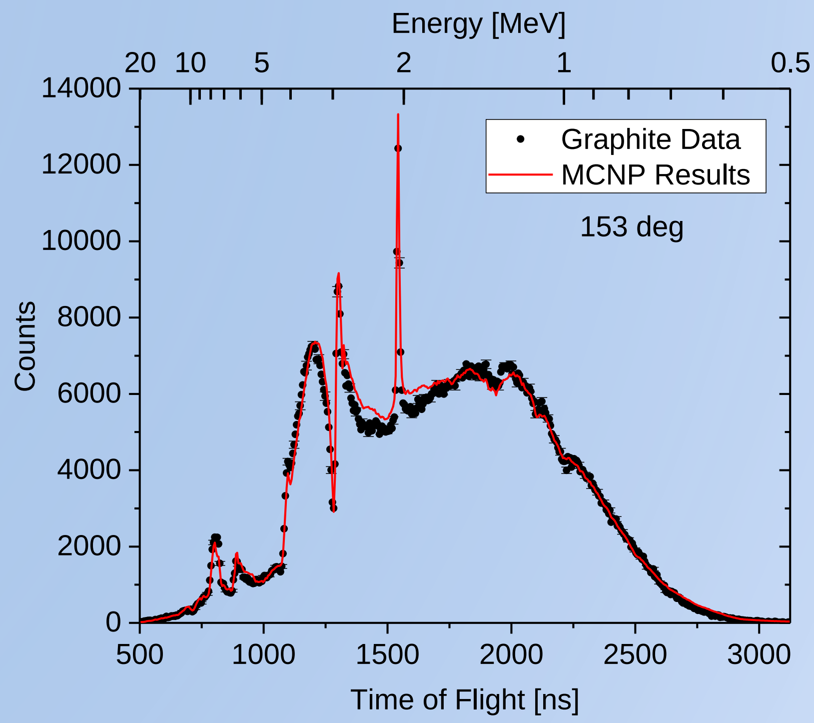
MCNP Simulation Geometry

- Use ASAP (As Simple As Possible) approach
- Use array of point detector tally F5 to model the EJ301 detector
  - Convolute the tally with the detector efficiency
- Include:
  - ¾" Depleted U filter in the simulation
  - windows (Al) and Mylar windows
  - Optical Table
  - Concrete floor
  - Adjacent aluminum vacuum flight tube



Graphite Reference Results





- Differences between experimental data and MCNP calculations (ENDF/B-VII.1/JEFF-3.2) used to estimate systematic uncertainties

$$FOM_i = \frac{1}{n} \cdot \sum_{j=0.5MeV}^{n=20MeV} \frac{\left(C_{i,j} - MC_{i,j}\right)^2}{\varepsilon_{i,j}^2}$$

n – Total number of energy bins
C – Total neutron counts
MC – Normalized MCNP Results
i – Detector #
j – Energy bin
ε – uncertainty including experimental and simulation

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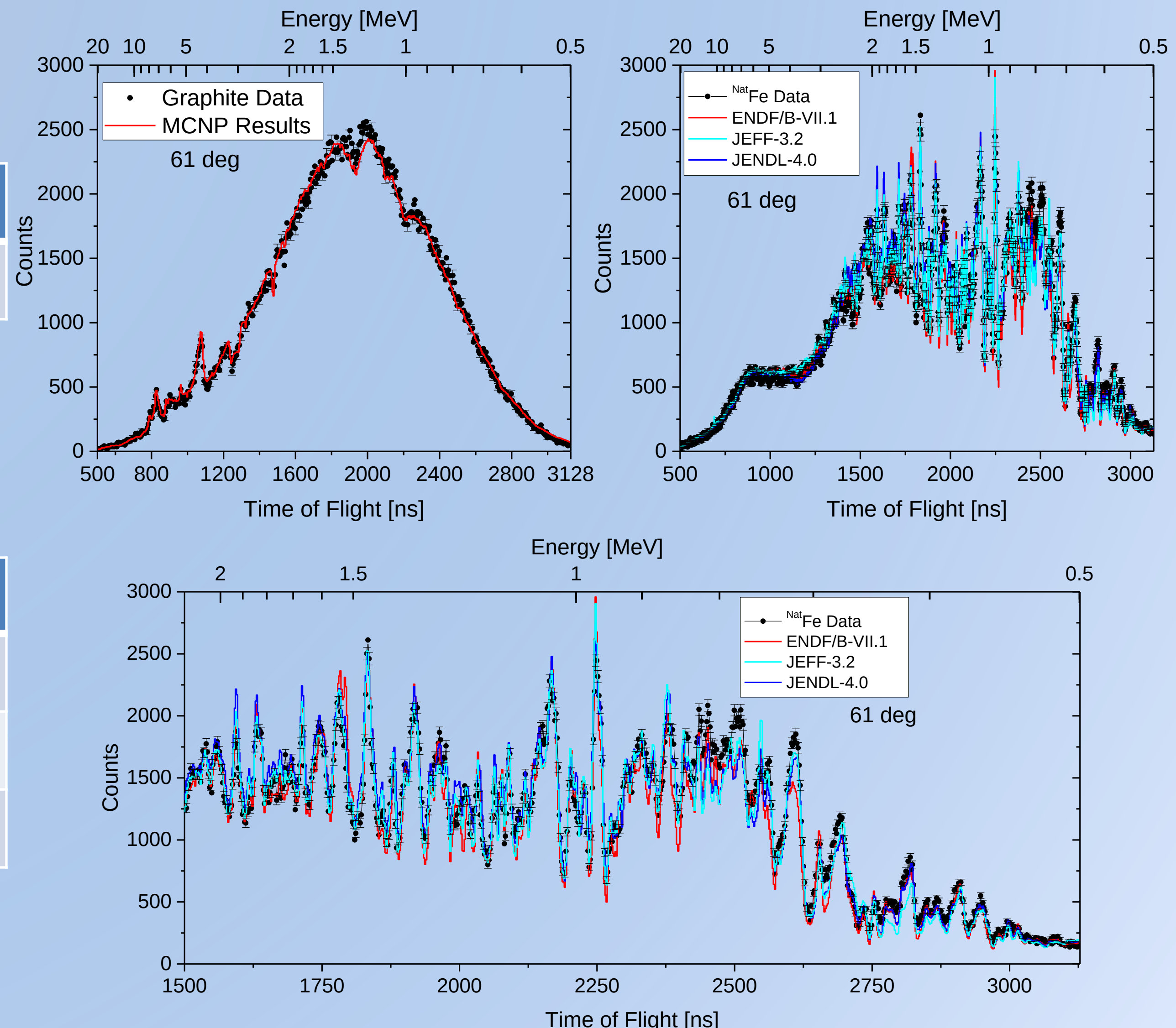
Iron Scattering

^{nat}Fe Scattering - 61°

Reference	FOM
Graphite	1.3

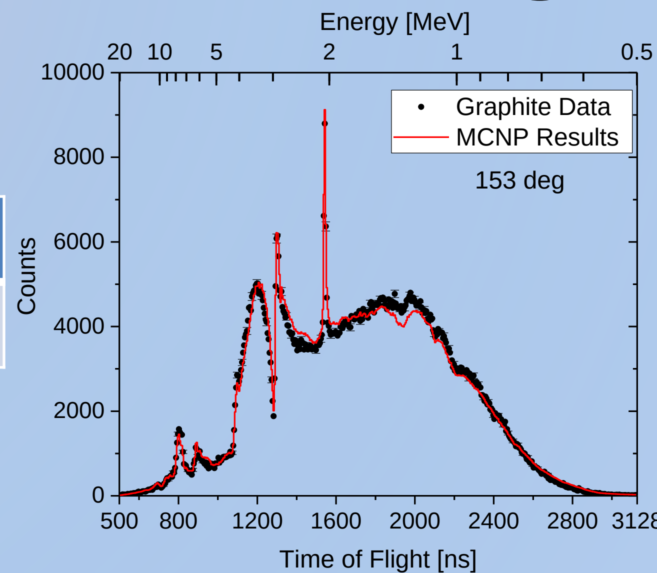
Library	FOM
ENDF/B-VII.1	9.5
JEFF-3.1	9.5
JENDL-4.0	8.4

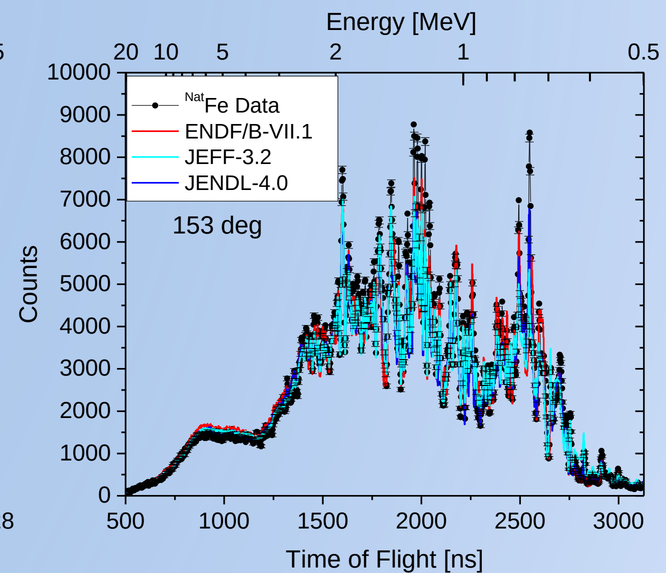


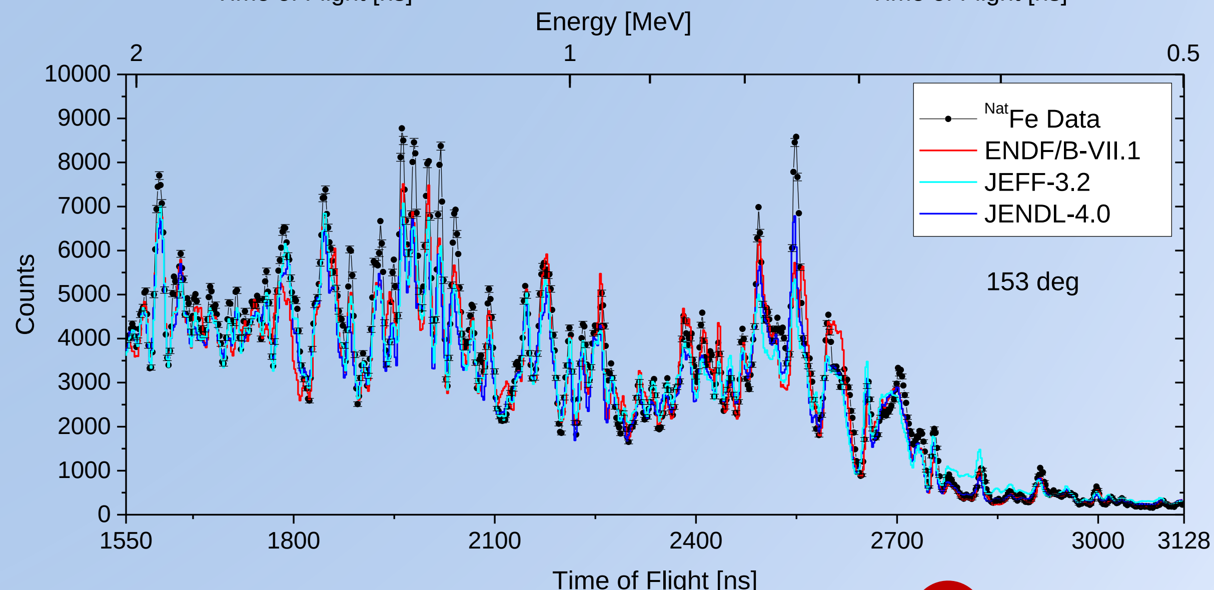
^{nat}Fe Scattering - 153°

Reference	FOM
Graphite	4.9

Library	FOM
ENDF/B-VII.1	25.9
JEFF-3.1	39.8
JENDL-4.0	23.4







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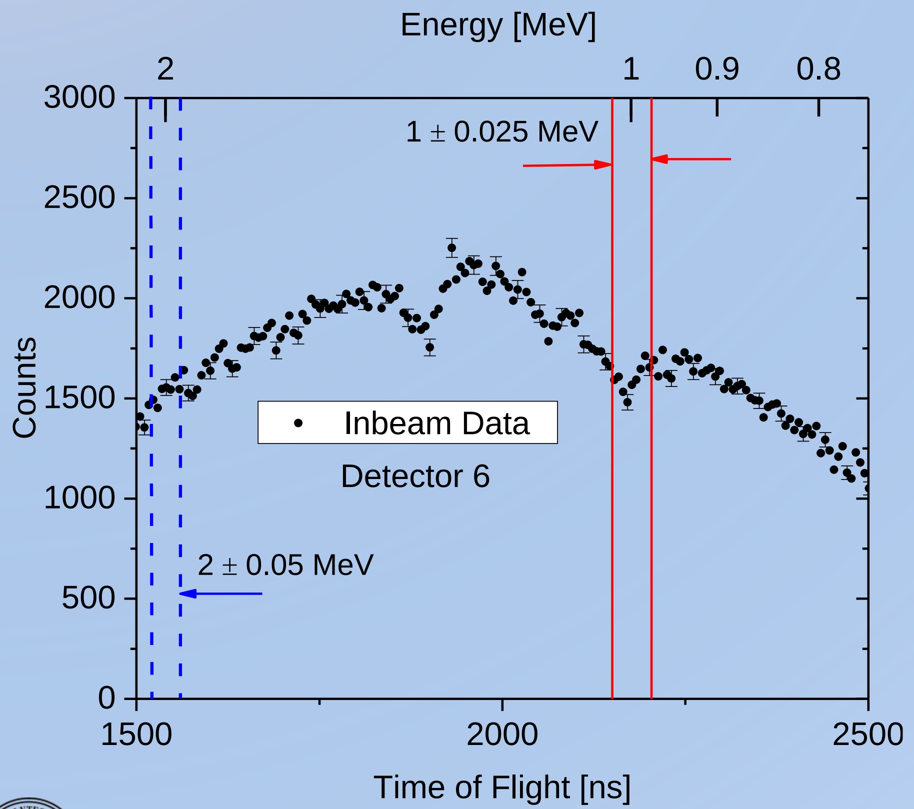
Observations for ^{nat}Fe

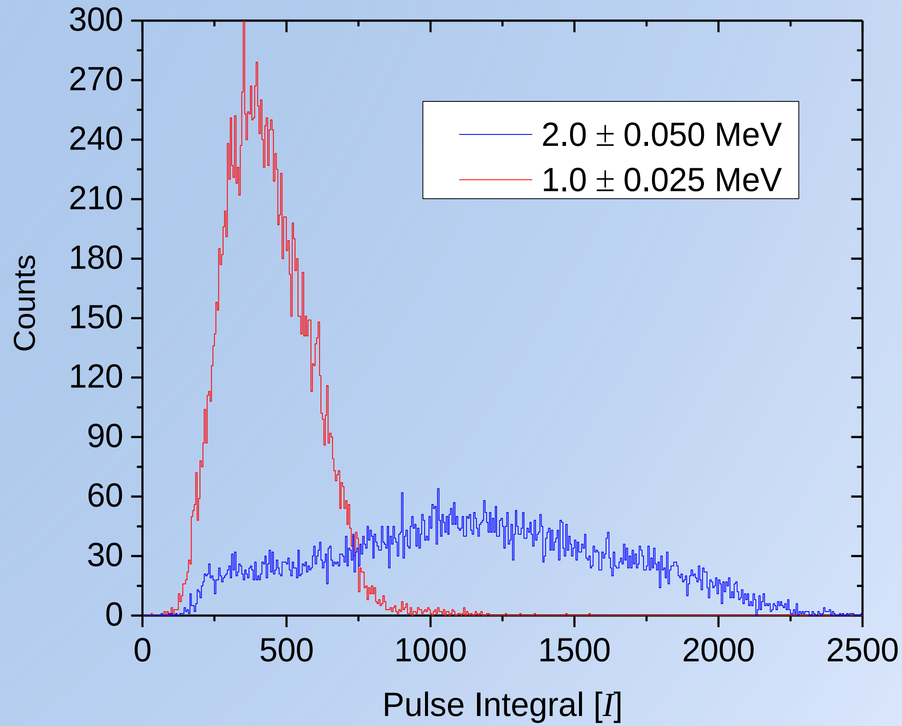
- The JENDL-4.0 evaluation had best overall agreement with experimental data from 0.5 to 20 MeV for all angles.
- Experimental data can be analyzed further to provide:
  - Inelastic to Elastic Scattering Ratios
  - Elastic (only) Scattering Contribution

Inelastic to Elastic scattering Ratio

EJ-301 Response Functions

- Detector in-beam measurements were used to develop response functions for energies 0.4 < *E*(*t*) < 2.0 MeV





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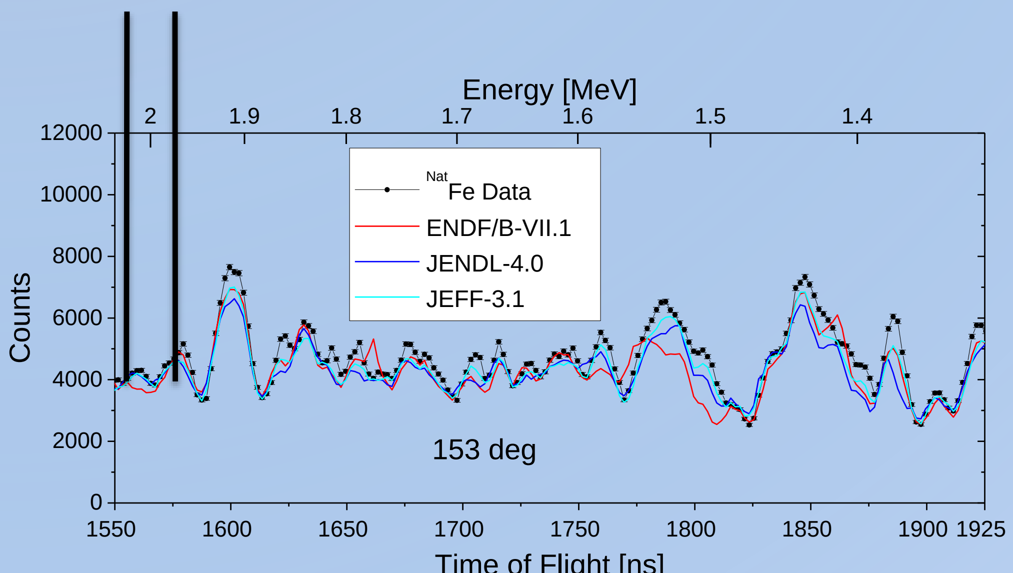
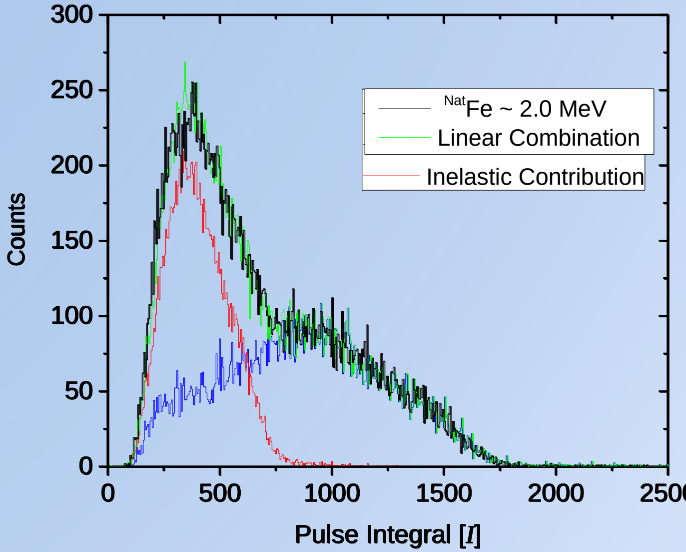
Inelastic to Elastic Ratio ^{nat}Fe

- Select an energy region (shown between the two black vertical)
- Fit in-beam response functions, $f_{el}(I)$ and $f_{inl}(I)$, to known levels

$$R(I) = A \cdot f_{el}(I) + (1 - A) \cdot f_{inl}(I) \qquad \text{Ratio} = \frac{(1 - A)}{A} \qquad A - \text{Fitted elastic fraction}$$





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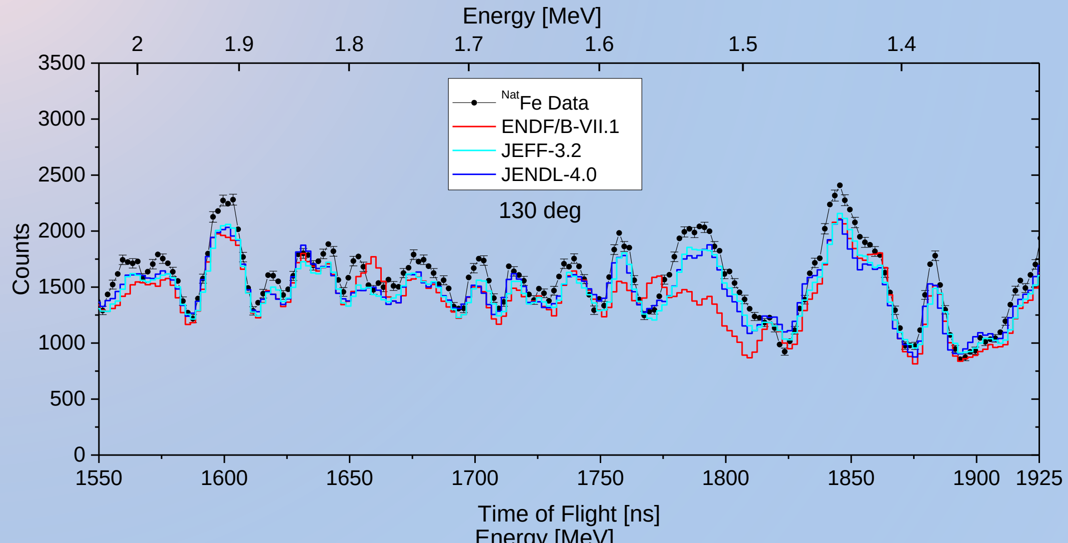
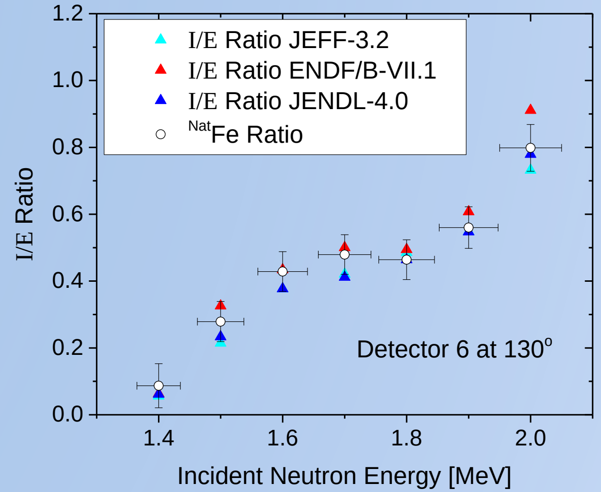
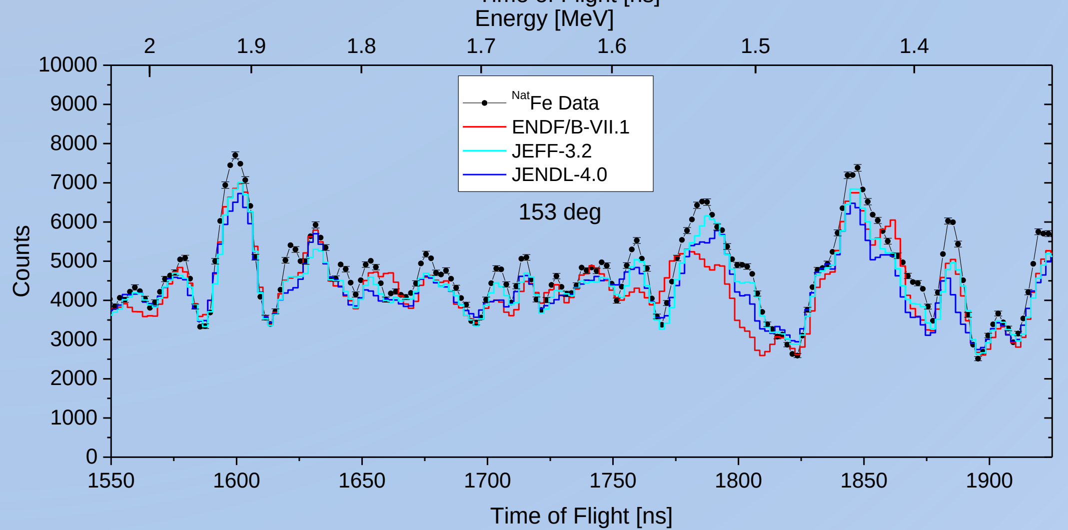
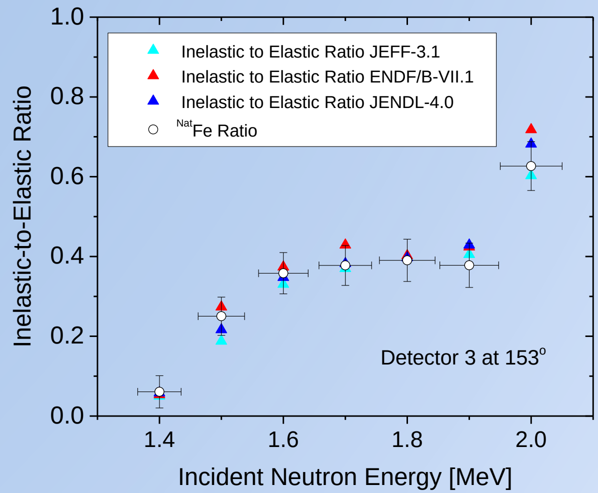
Inelastic to Elastic Ratio





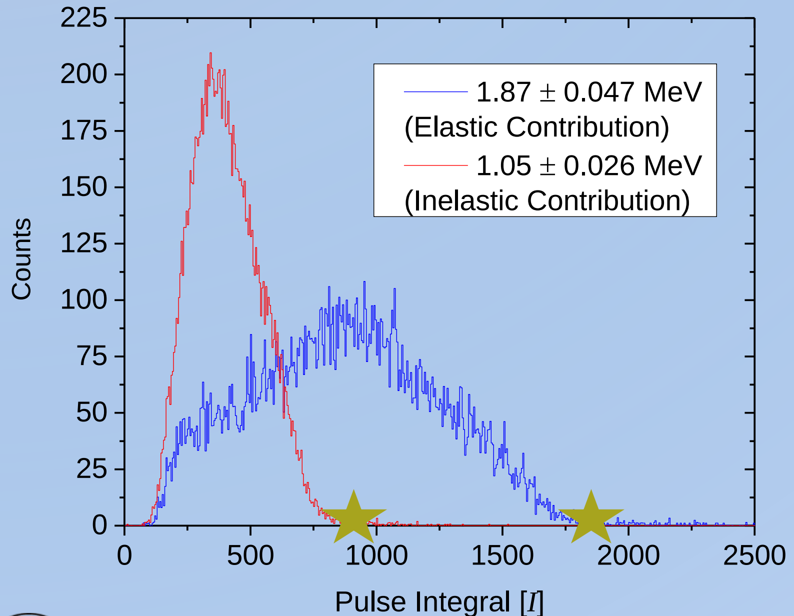


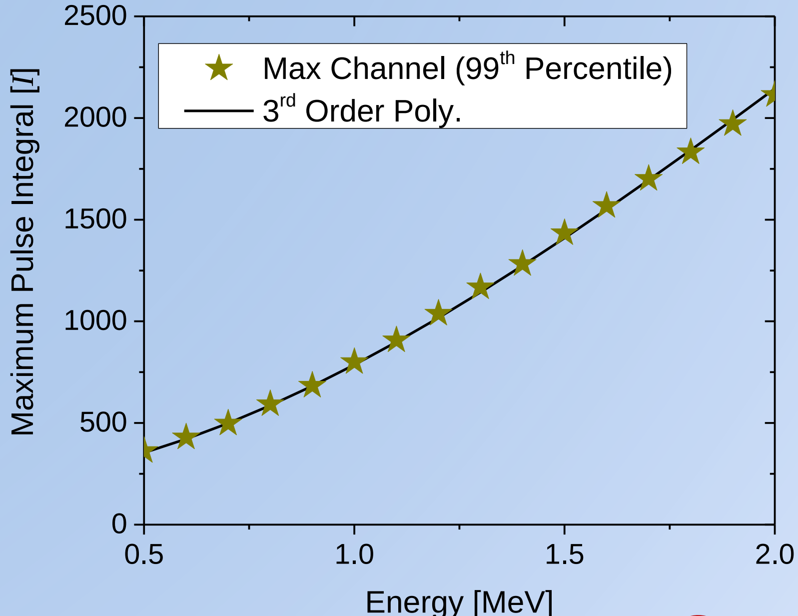


- Multiple scattering effects included in MCNP simulations
- Statistical and systematic uncertainties included in analysis

Elastic Scattering Contribution

- The response function fitted method does not easily extend to high energy resolution data and a new method was developed
- The goal is to isolate only the elastic scattering:
  - Cut pulses with integral less than the discrimination.
  - Correct for the elastic shape that was discriminated.
  - Method is insensitive to inelastic to elastic ratios.





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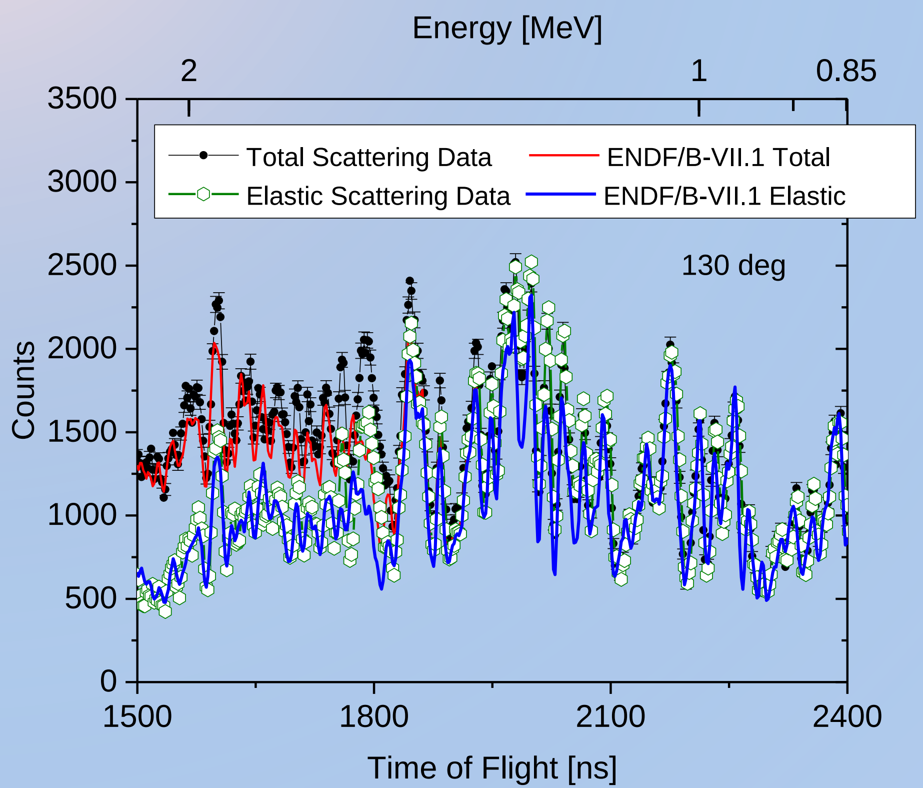
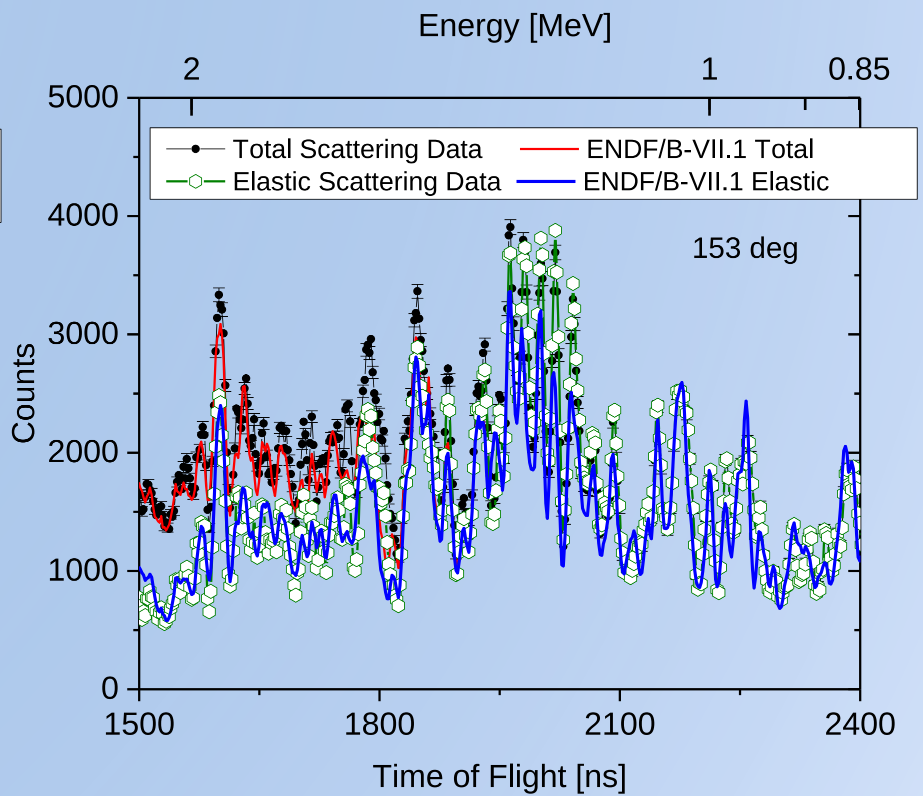
Elastic Scattering vs MCNP simulation

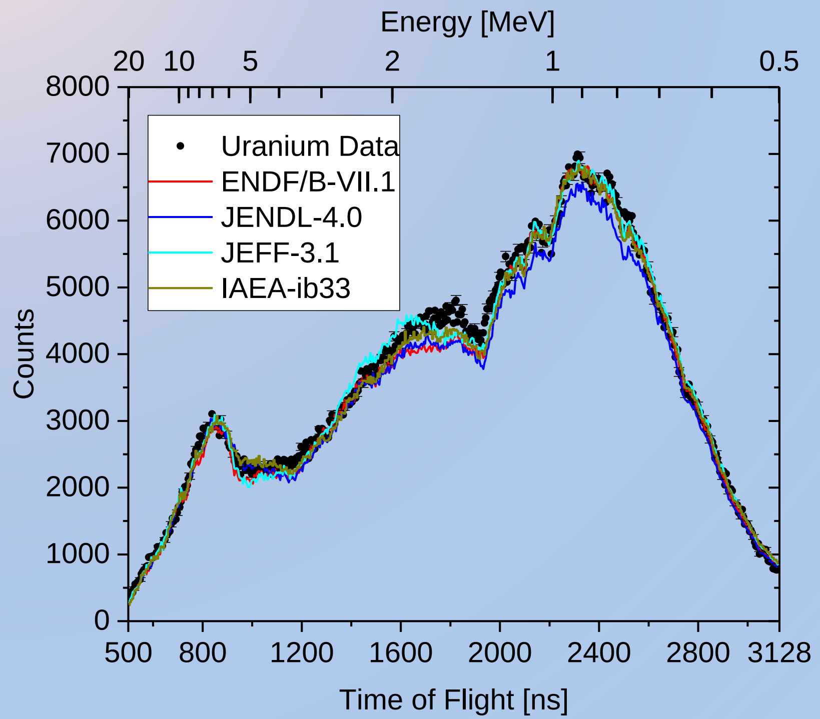


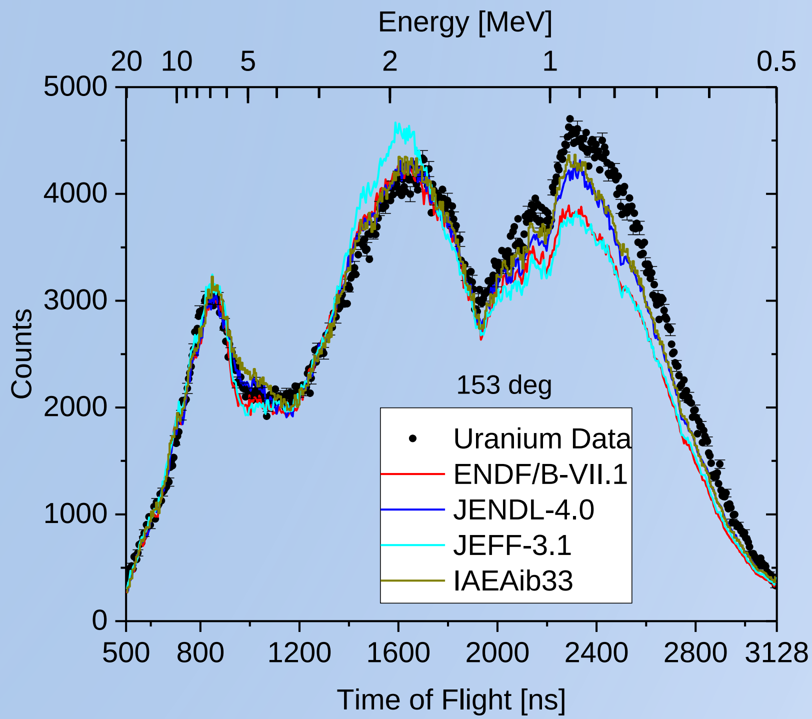


- Elastic scattering can be measured from 0.5 to 2.0 MeV
- Only elastic scattering contribution measured and simulated
- Collaborating with ORNL to improve new ^{56}Fe evaluation

^{238}U

^{238}U Scattering Measurement

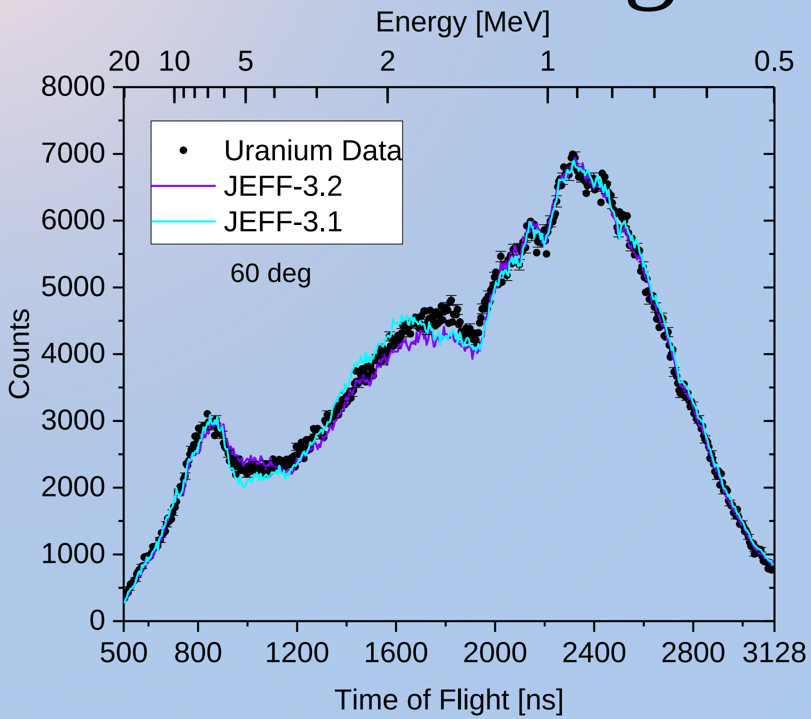


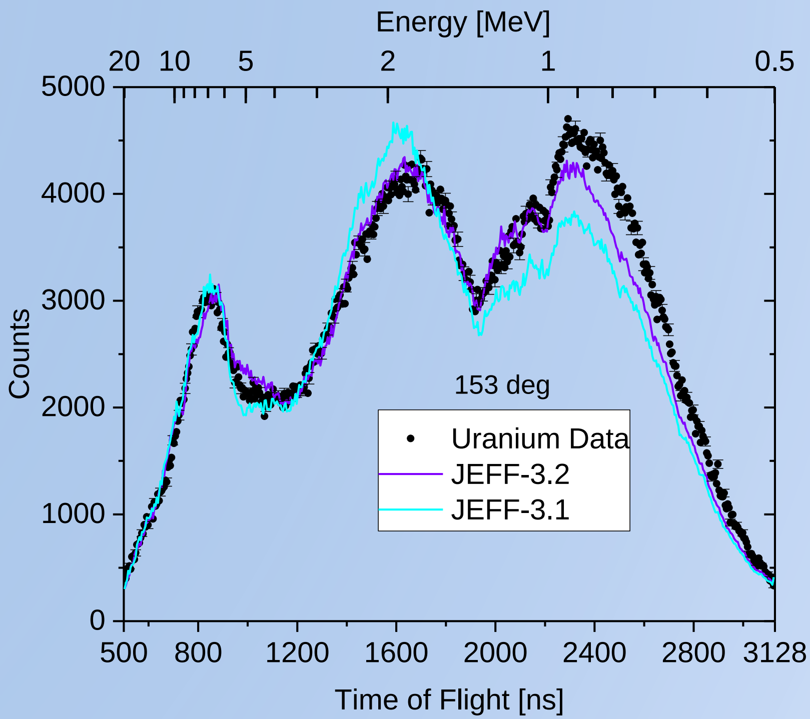


Library	FOM
ENDF/B-VII.1	3.8
JEFF-3.1	3.0
JENDL-4.0	5.5
IAEA-ib33	3.5

Library	FOM
ENDF/B-VII.1	18.8
JEFF-3.1	20.4
JENDL-4.0	7.7
IAEA-ib33	7.0

^{238}U Scattering Measurement - JEFF 3.2





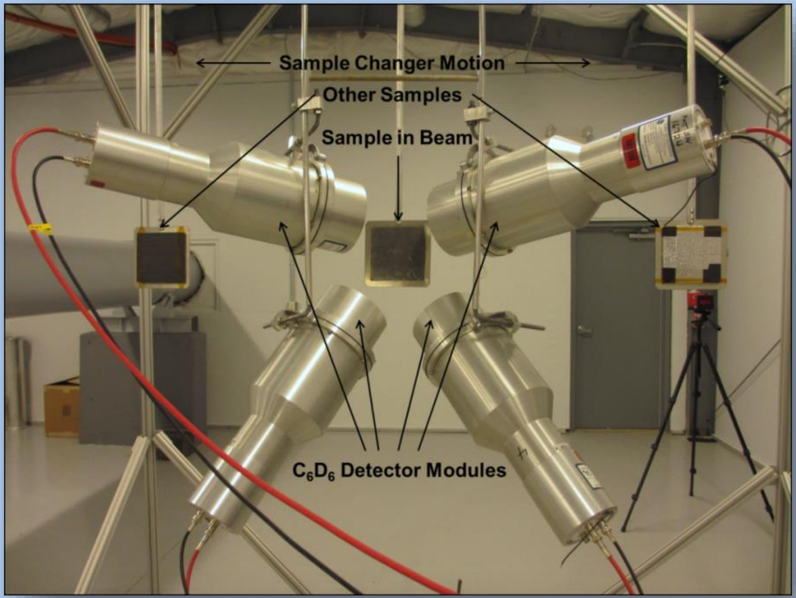
Library	FOM
JEFF-3.1	3.0
JEFF-3.2	2.8

Library	FOM
JEFF-3.1	20.4
JEFF-3.2	7.9

- Significant improvement in JEFF3.2

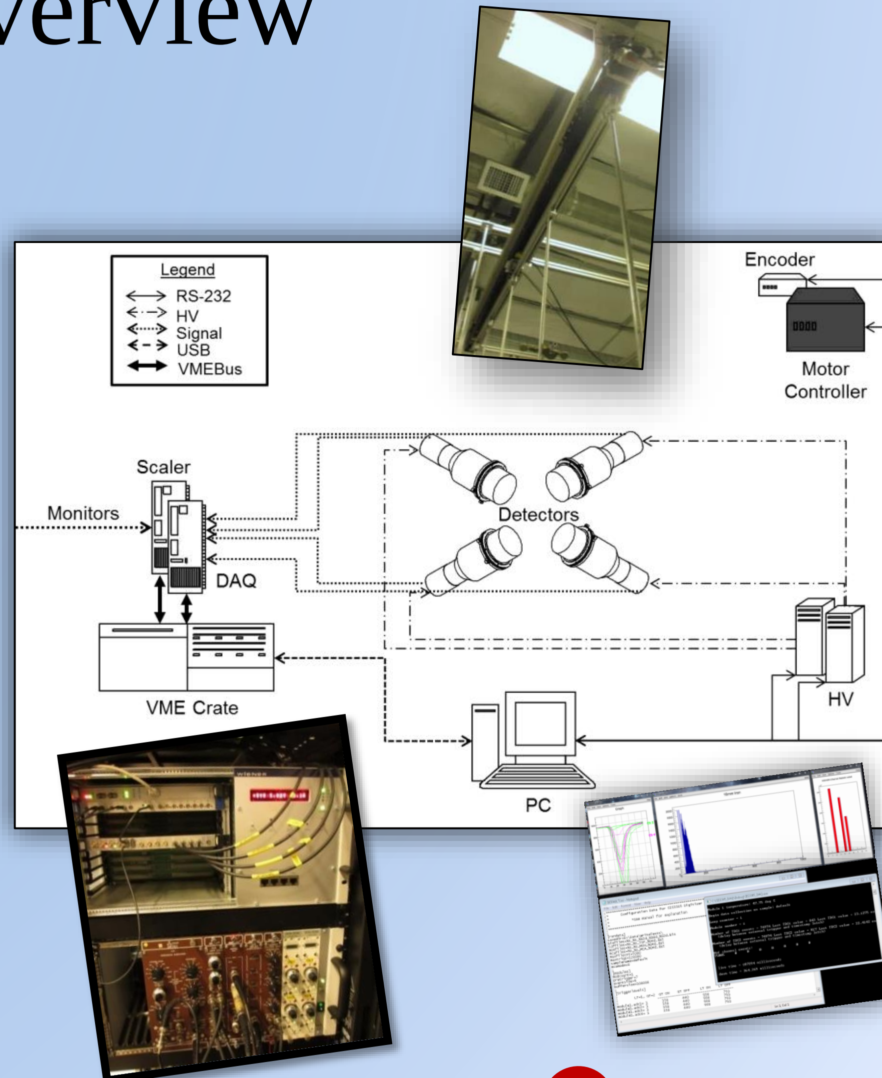
Mid-Energy Capture Detector System Overview

- 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

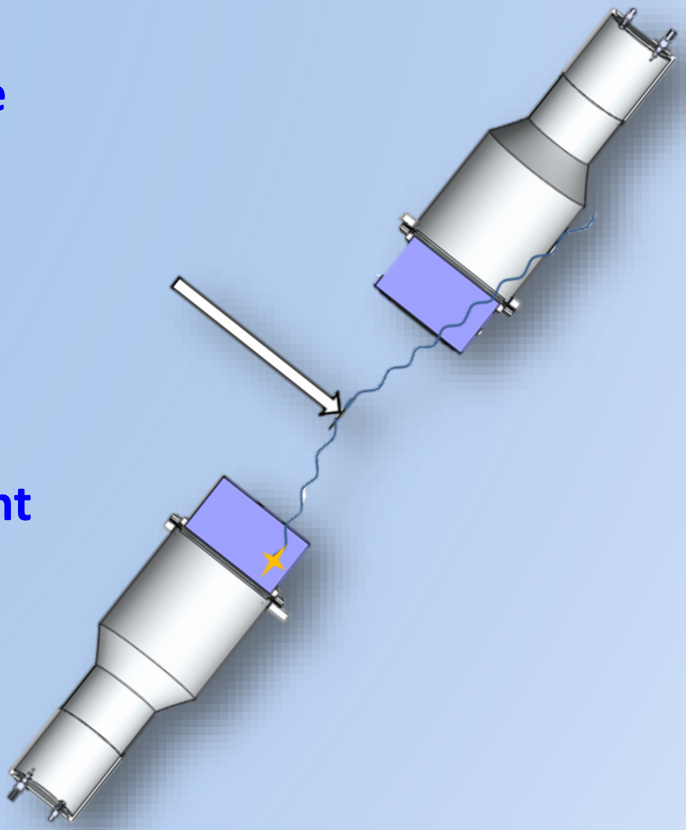
- **Sample Changer**
  - Velmex BiSlide linear translation table w/ stepper motor and magnetic position encoder
- **Data Acquisition**
  - 8-channel SIS3305 digitizer w/ 10-bit, 1.25GHz functionality
- **Beam Flux Monitoring**
  - 8-Channel MDGG-8 Flexible Delay/Gate Generator & Scaler
- **Detector Bias**
  - 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:

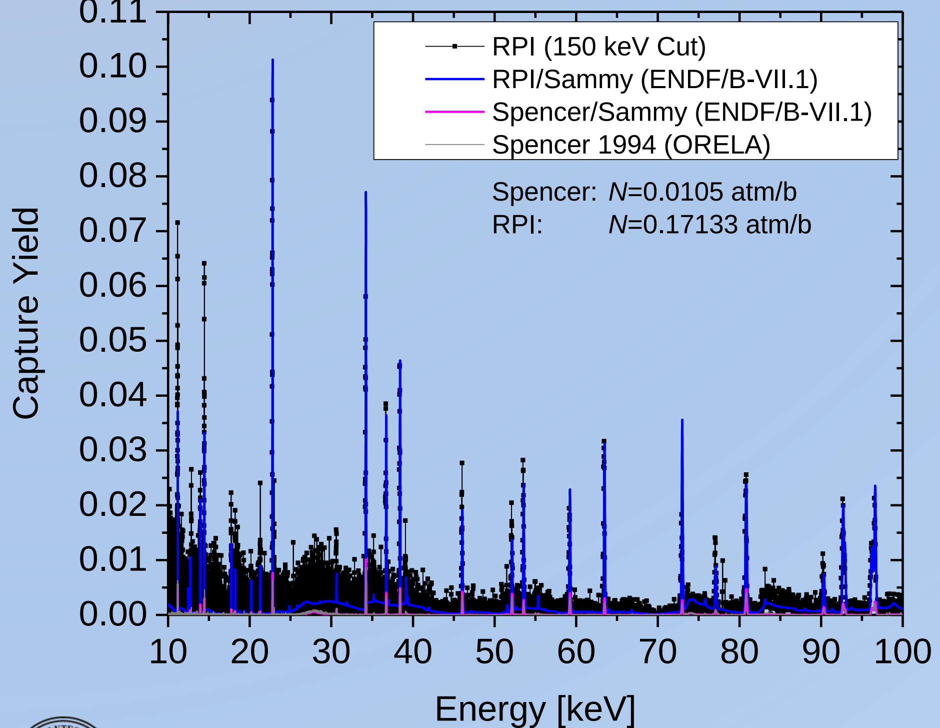
1. Detect only a **single photon per capture** cascade
2. Assert that the detection **efficiency is proportional** to the incident photon energy
3. Given 1 and 2, it can be shown that the total **efficiency to detect a capture event is proportional to the total excitation energy** of the compound nucleus,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

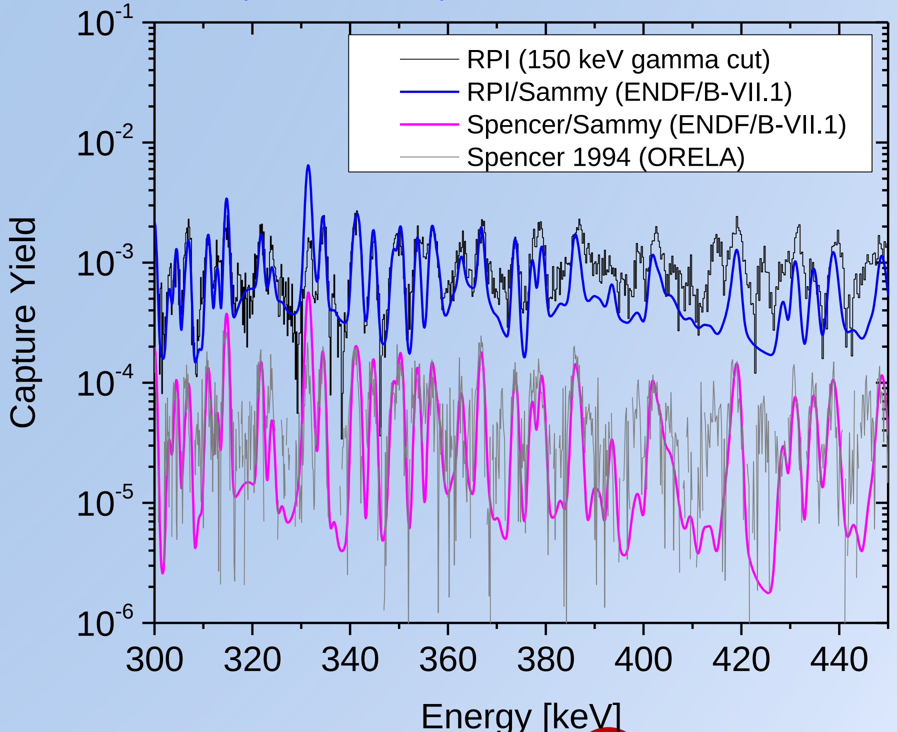


Requires a weighting function

^{nat}Fe Capture Measurement

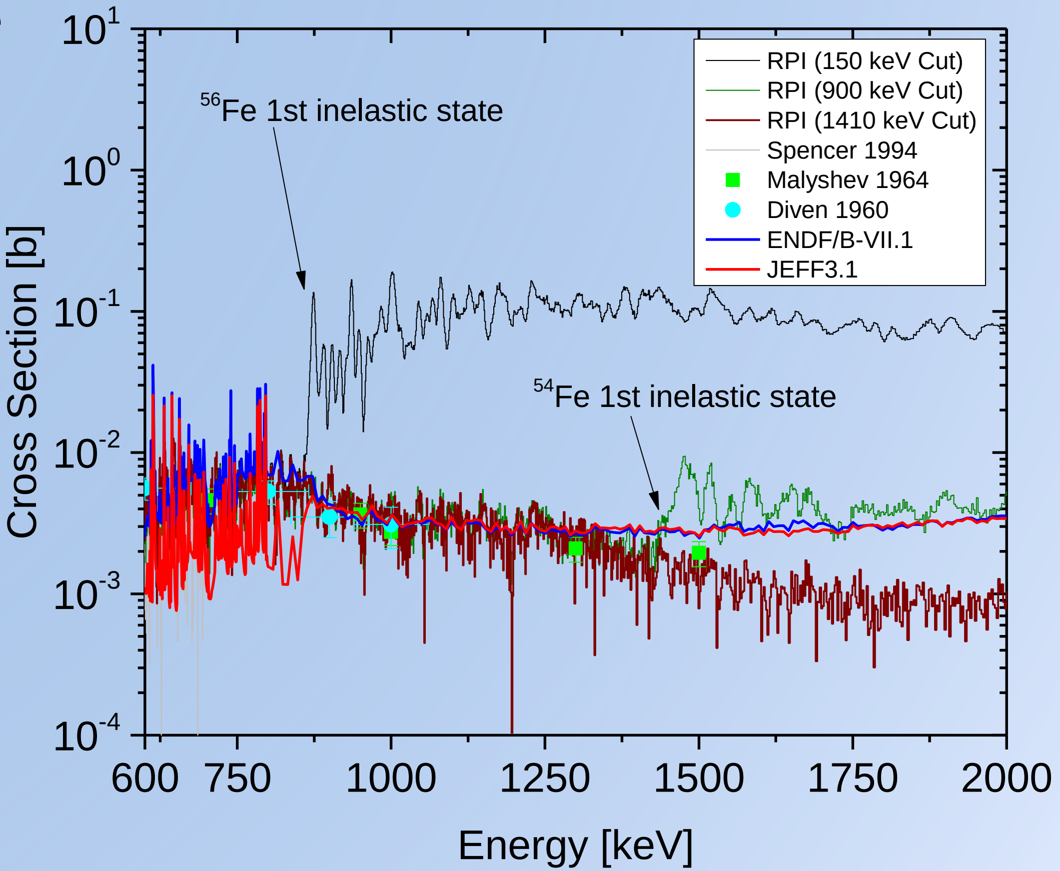
- ^{nat}Fe was used as a test to compare with evaluations and other measurements
  - The RPI data (45m flight path) has good energy resolution compared to the Spencer ORELA data (40m flight path)
  - The RPI data provide information above 700 keV (next slide)





^{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
- The data are lower than the evaluations above 1400 MeV



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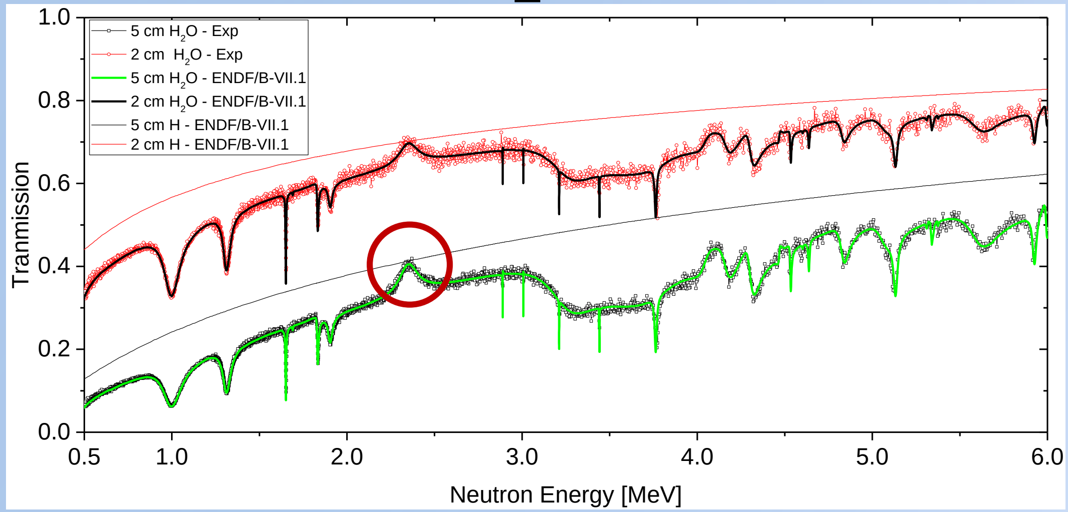
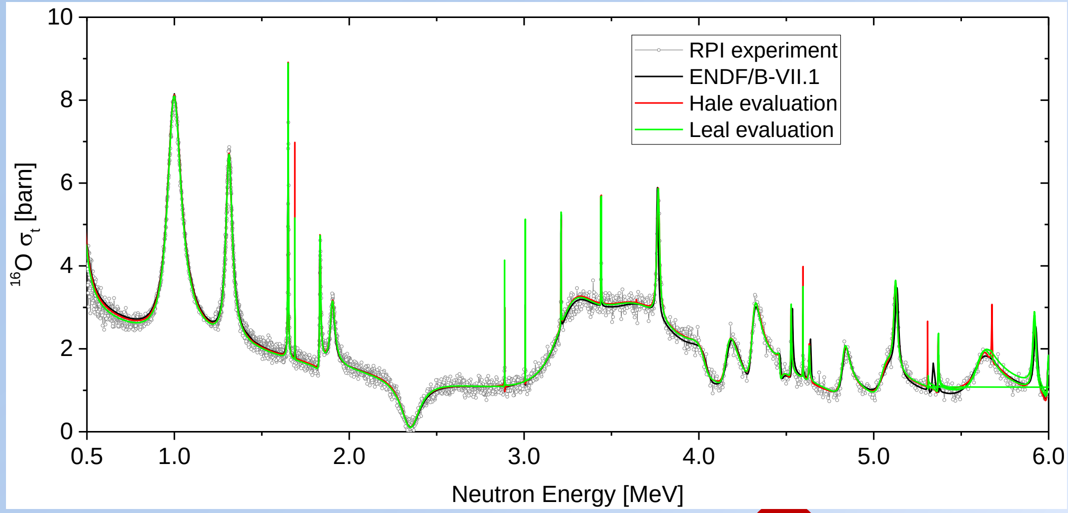
Feasibility of ^{16}O total cross section measurement using H_2O

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





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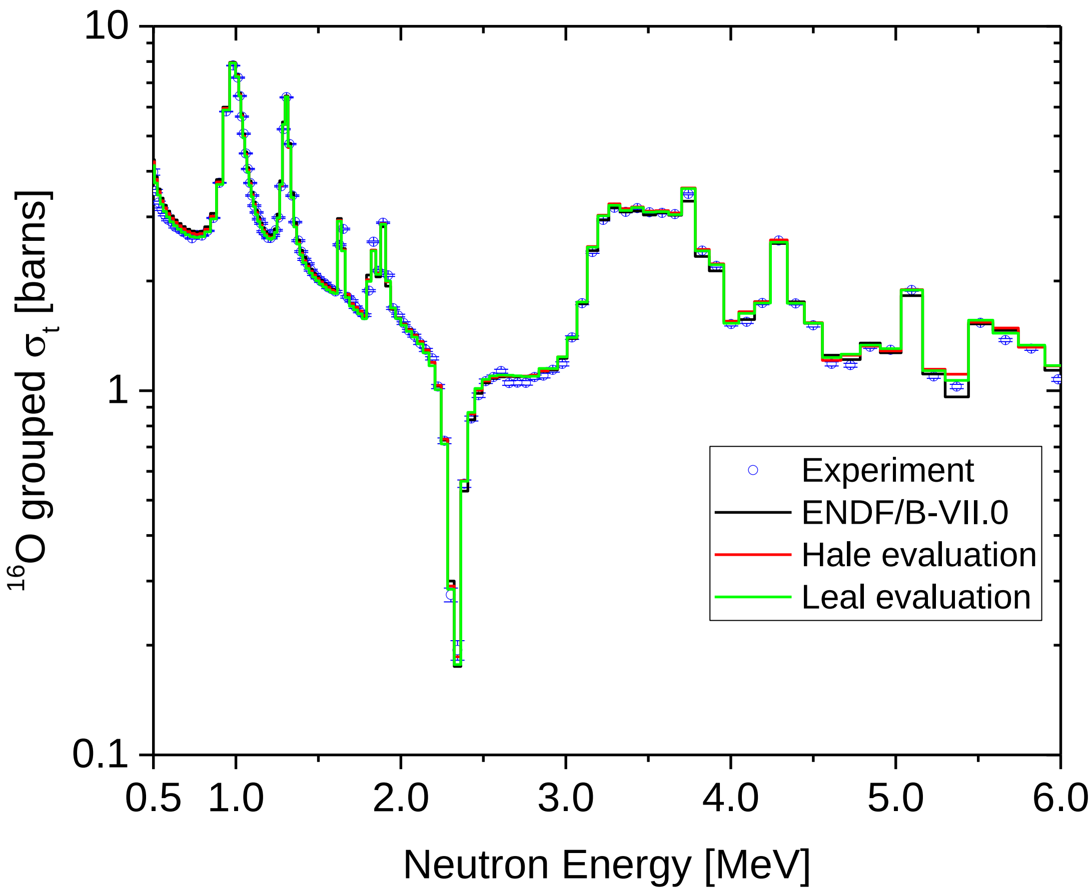
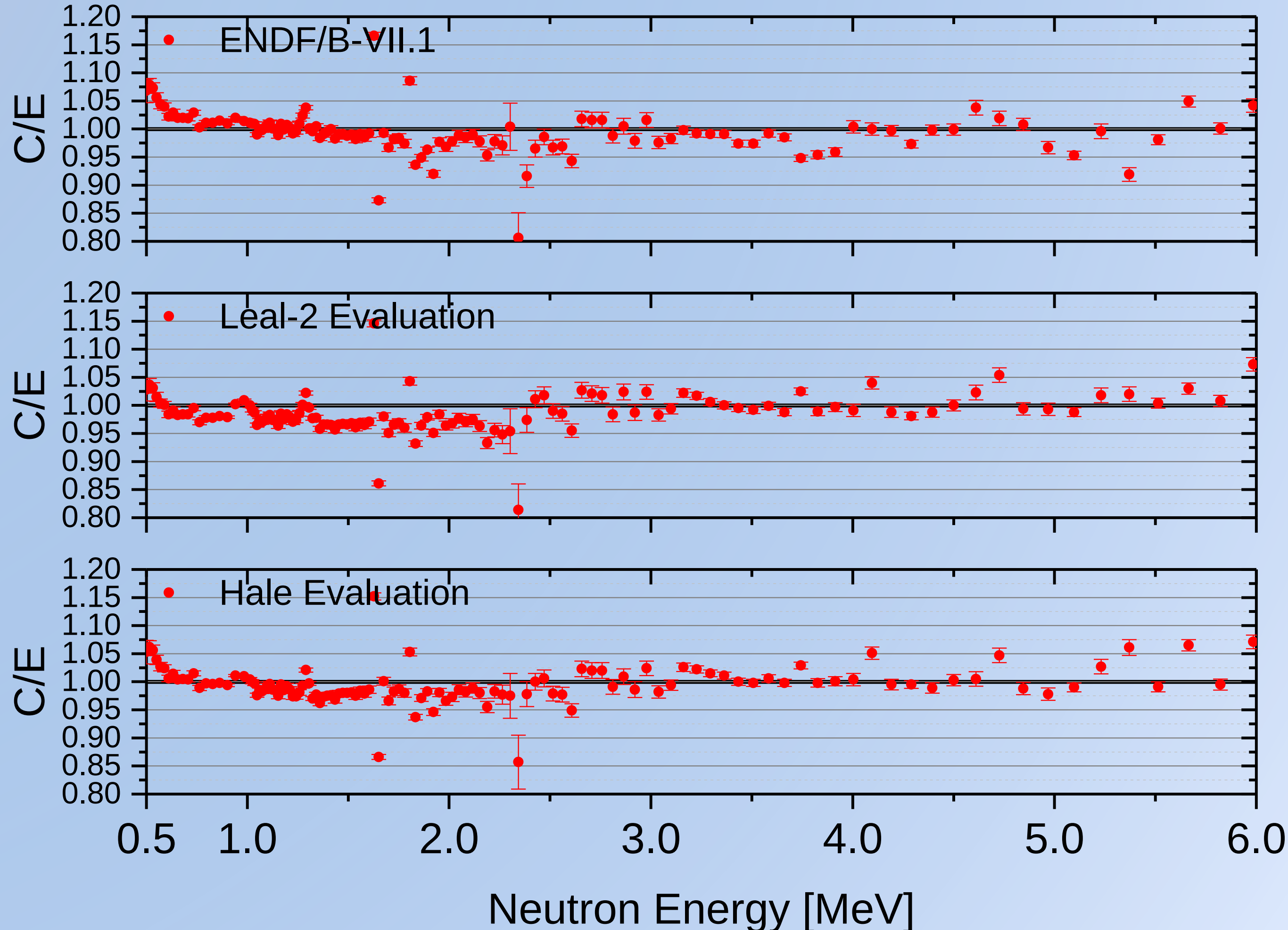
To compare the experiment with evaluation both were grouped

- Grouping reduces the statistical uncertainty
- Grouping preserves the number of neutrons transmitted through the sample
- Grouping can be done in two ways:
  - Group the cross section
  - Group the transmission and then compute the effective cross section
- Both options gave similar results
  - **The grouped cross section is shown**

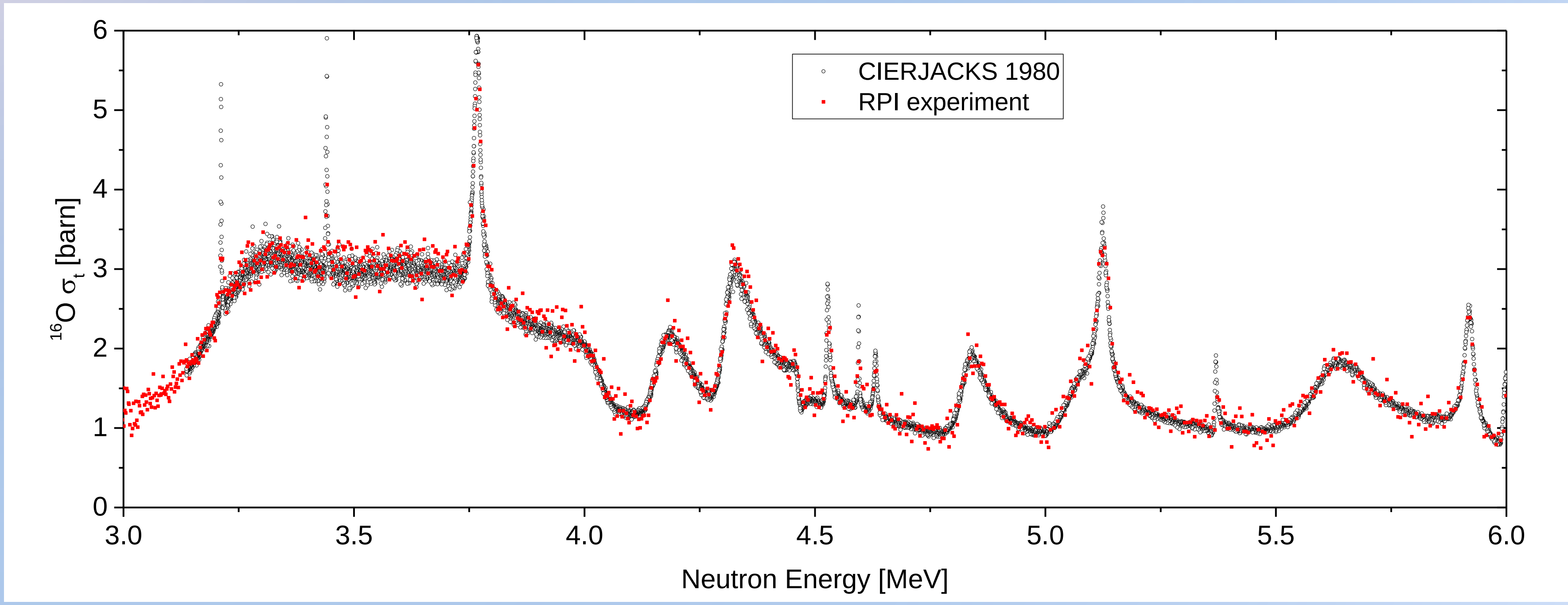


^{16}O – total cross section C/E

- Below 3 MeV the evaluation are lower.
- Below ~0.7 MeV there are large differences
  - carbon sample measured at the same time does not have this problem
- Between 3.2-6 MeV ENDF/B-VII.1 matches the experiment within ~1.2%
- H normalization is better than 1%
- It is feasible to provide new information on ^{16}O normalization
  - Normalization of the experiment is critical



Comparing to CIERJACKS 1980



3.2 MeV < E < 6 MeV	C/E	C/E 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

Normalization uncertainty:

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

*Statistical

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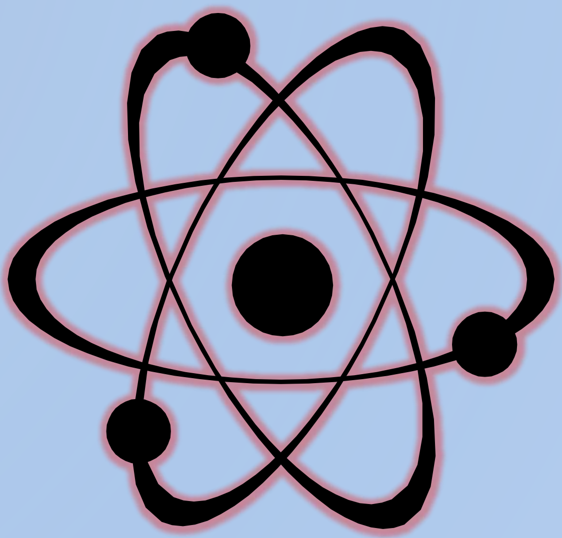

Thank You