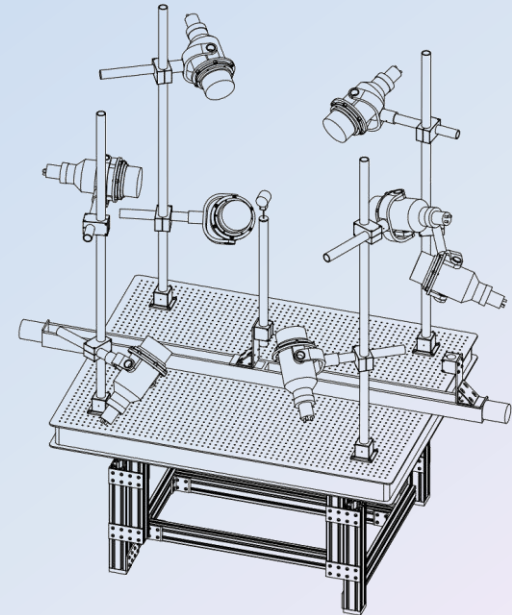


# Measurement of Neutron Scattering as Benchmark for Nuclear Data Evaluations

*Y. Danon*

**Gaerttner LINAC Center**


***Rensselaer Polytechnic Institute, Troy, NY, 12180***



WPEC Meeting, SG-35, May 22, 2013



**Rensselaer**  
Mechanical, Aerospace and Nuclear Engineering

**linac**   
The Gaerttner LINAC Center 1

# Collaboration



- **RPI**

- Faculty:

- Dr. Y. Danon, Dr. E. Liu

- Staff

- P. Brand - Technical Manager
- M. Gray, M. Strock, A. Kerdoun - Linear Accelerator Technicians

- **Graduate Students** (in the Nuclear Data group):

- **A. Daskalakis**, R. Bahrn, D. Williams, J. Thompson, Z. Blain, B. McDermott,, S. Piela

- **KAPL**

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



# Objectives

- 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



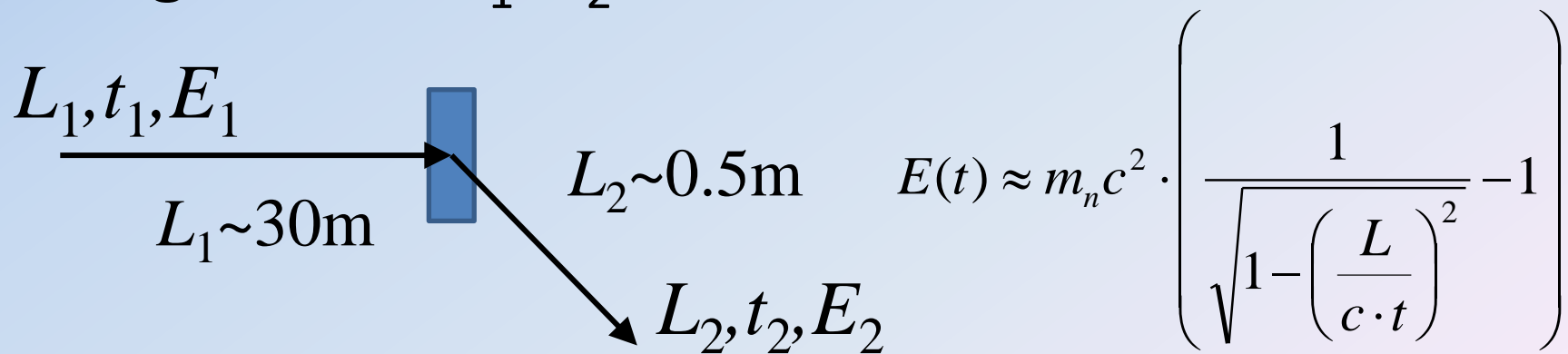
# Methodology

- Measure the scattering yield at several angles around the sample.
  - Use TOF to measure the neutron incident energy
  - Use detectors that are insensitive to (capture/inelastic/background) gamma
- Compare the measurements to detailed simulations of the system with different cross section libraries
  - Characterize the incident neutron flux
  - Characterize the neutron detection efficiency
- Identify energy/angle regions where improvement is needed.



# 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  $t_1 \gg t_2$  and  $E_1 \sim E_2$  then for presentation the incident neutron energy  $E_1$  is calculated using  $t$  and  $L=L_1+L_2$



# First Order Approximation of the Scattering Yield

**Detector Efficiency**

Probability to Interact

**Incident Flux**

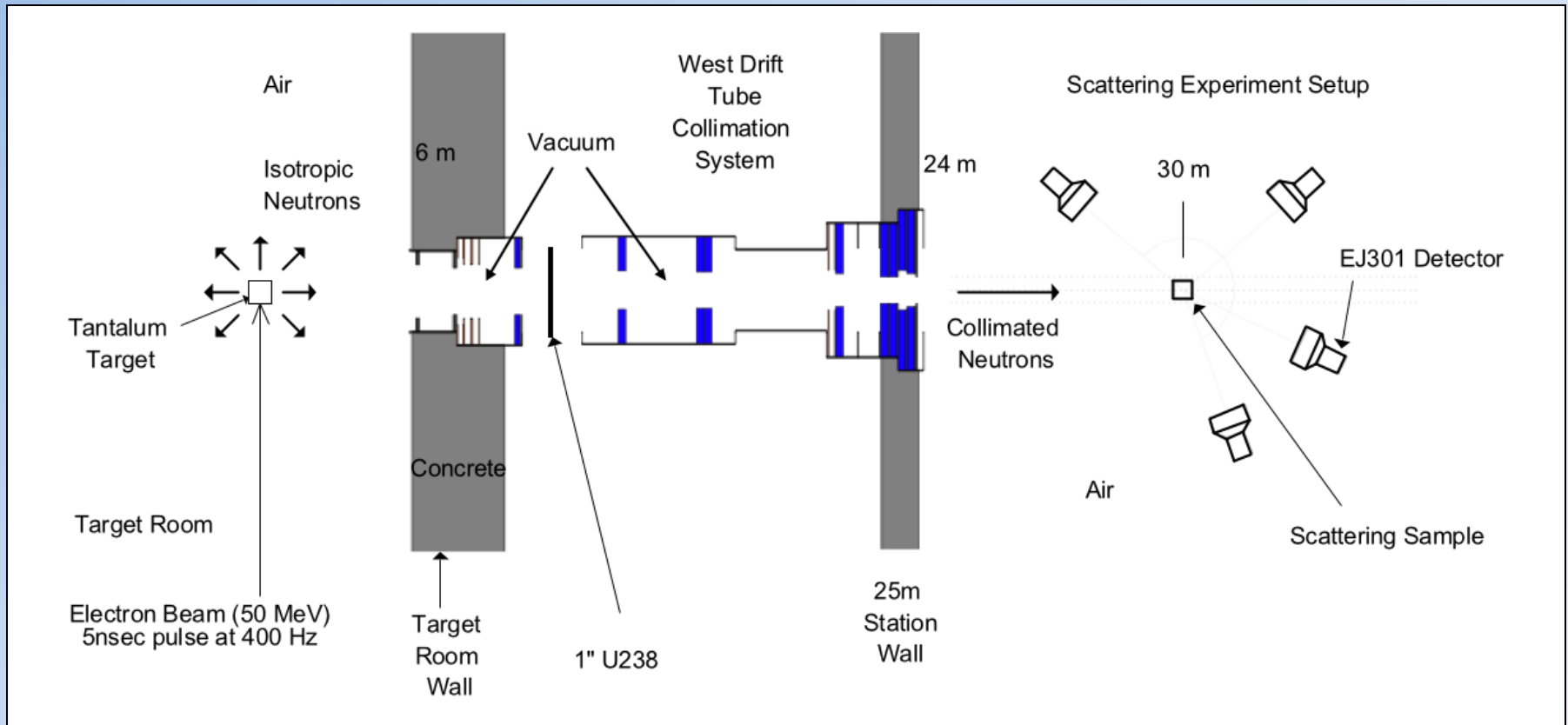
Probability to Scatter in direction  $\phi$

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

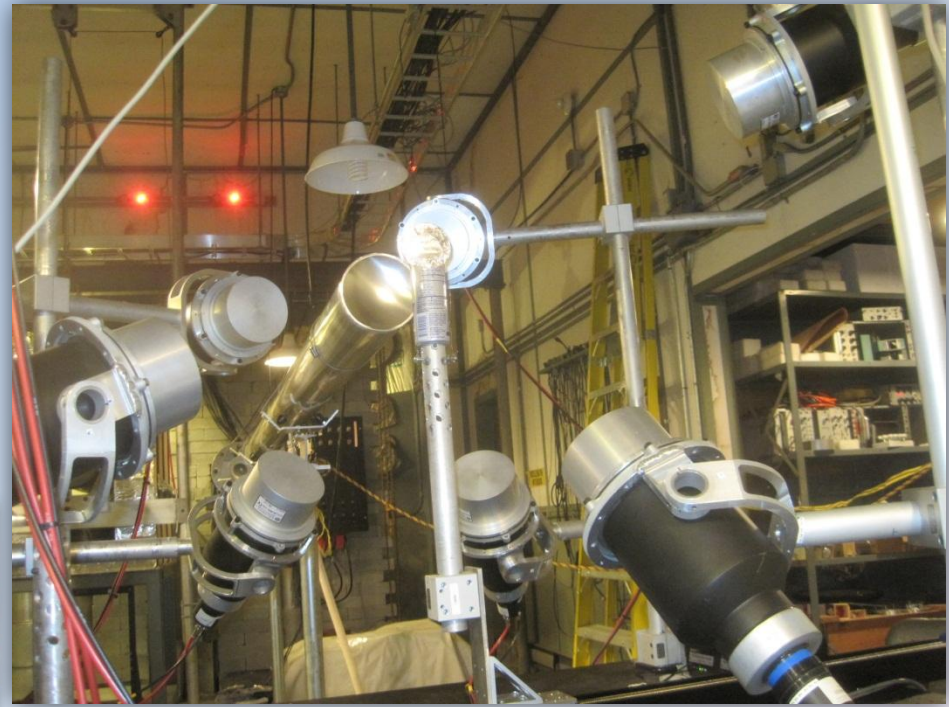
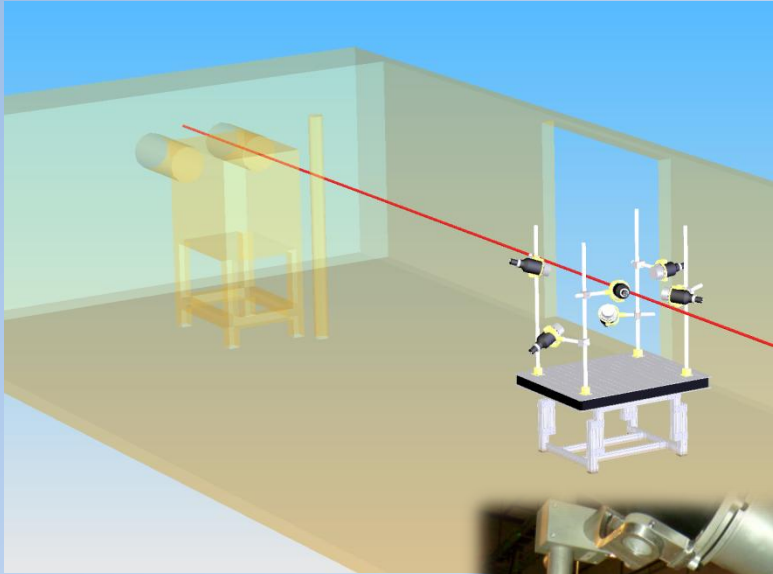
*In this approximation - multiple scattering is ignored*



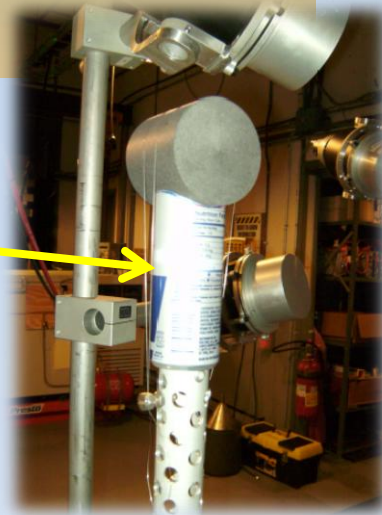
# Experimental Setup Overview



# Scattering Detection System: Experimental Setup

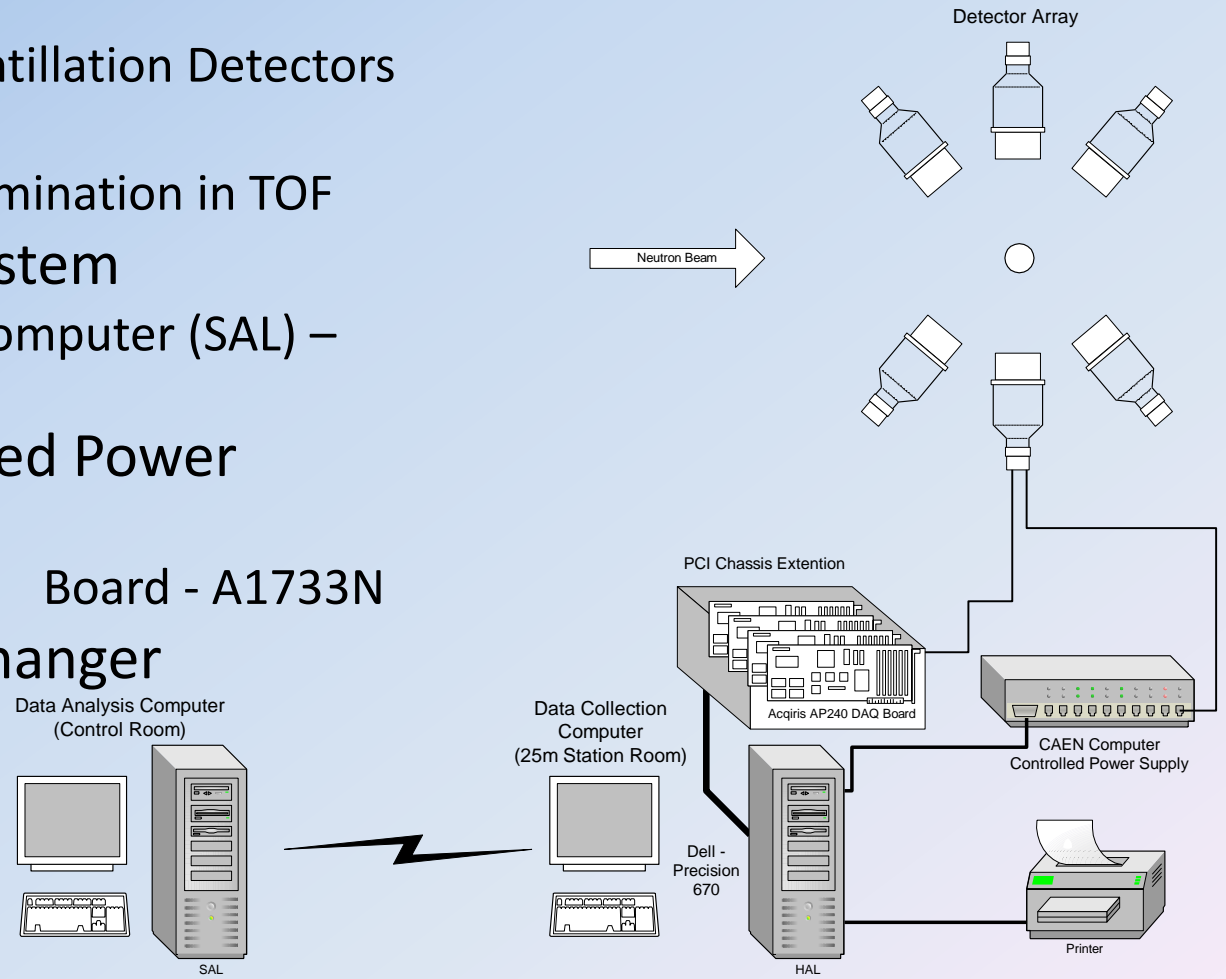


*Pioneered the use of Red Bull can for nuclear physics (as low mass sample holder)*



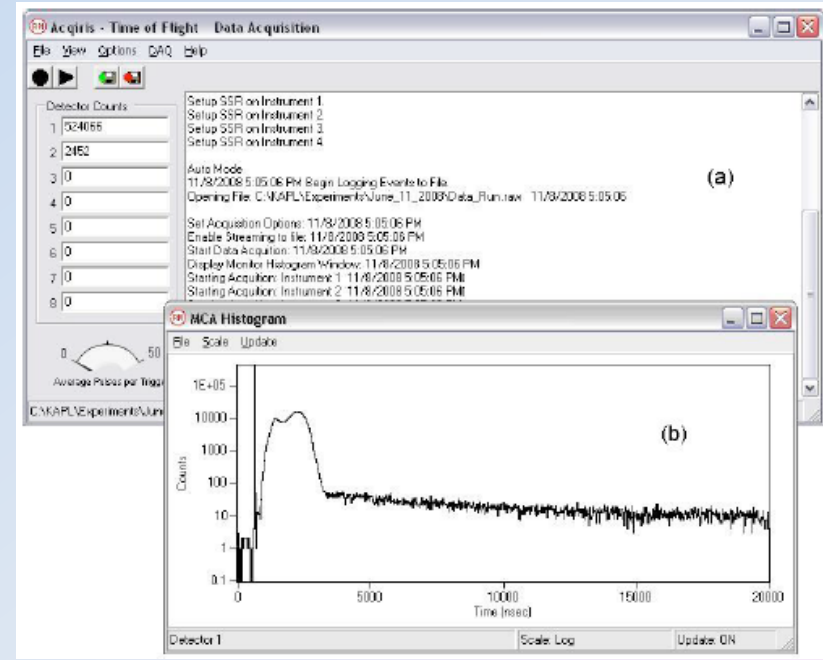
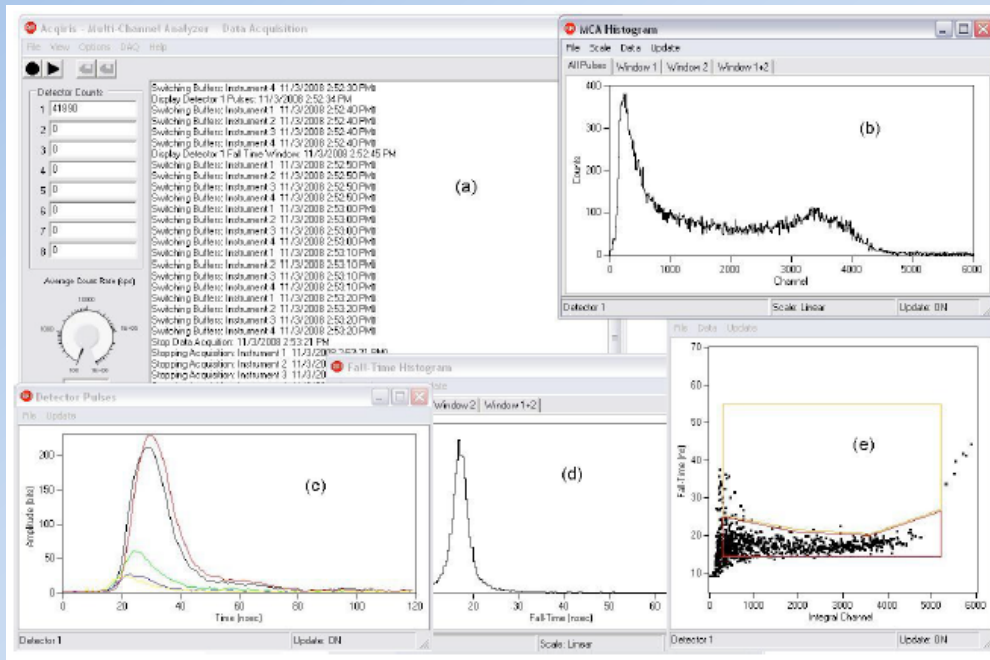
# Scattering Detection System: Experimental Setup

- Detector Array
  - 8 EJ301 Liquid Scintillation Detectors
  - 8 A/D channels
  - Pulse Shape discrimination in TOF
- Data Processing System
  - Data Processing Computer (SAL) – Control Room
- Computer Controlled Power Supply
  - Chassis - SY 3527 Board - A1733N
- Sample Holder / Changer



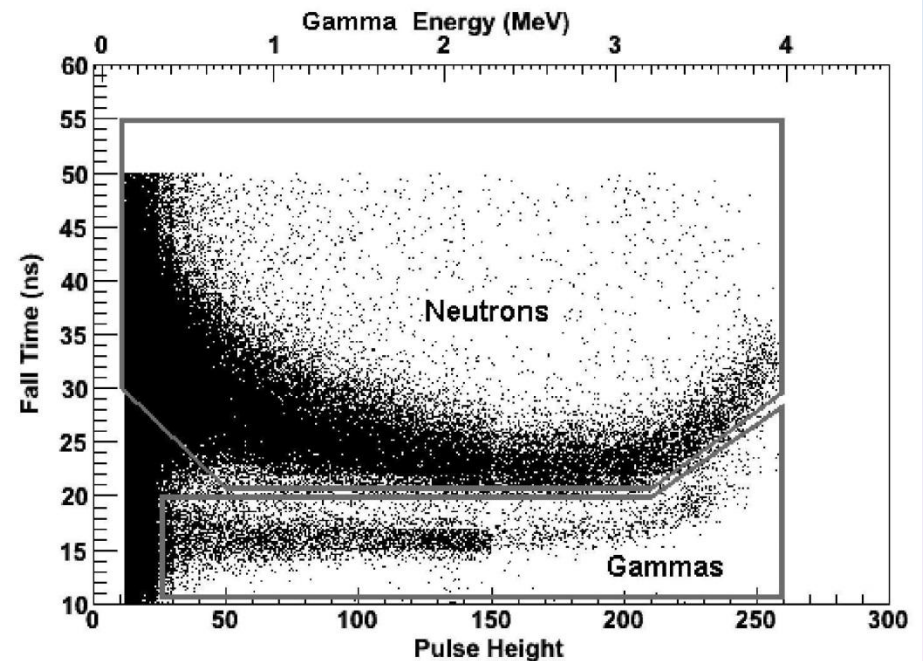
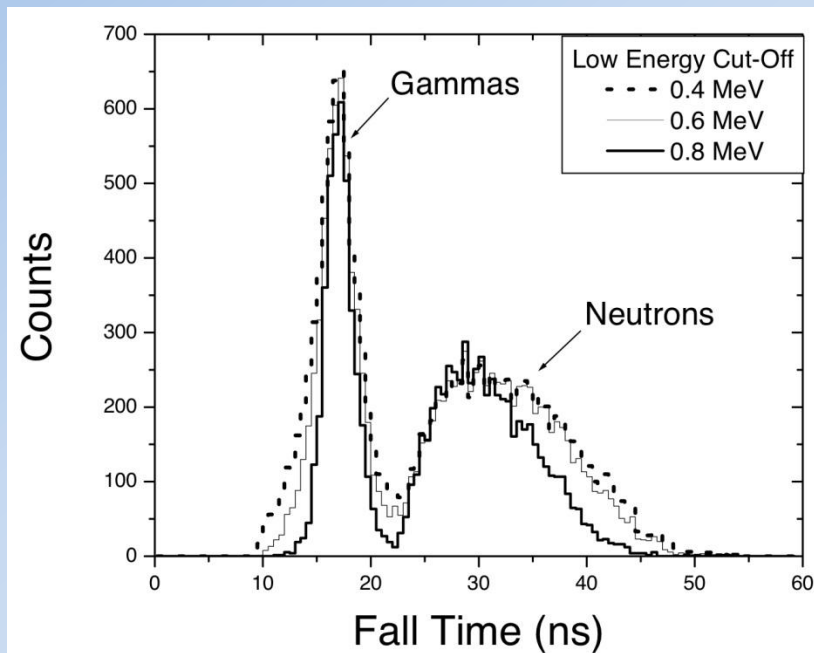
# DAQ system

- All DAQ is automated using script based software running under Windows
- Alternate between sample, graphite and open (background) measurements
- Each position is measured for about 10 min
- Fission chamber monitors are used to normalize beam intensity fluctuations.
- Detector/system gain is periodically aligned using  $^{22}\text{Na}$



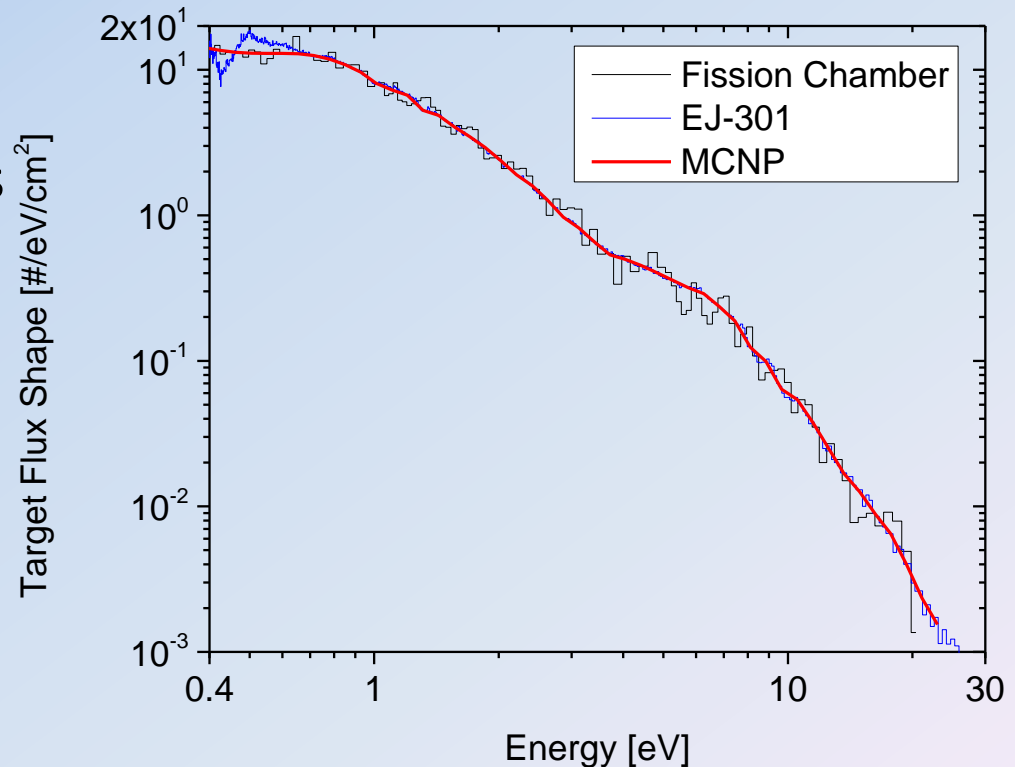
# Neutron Gamma Separation with Pulse Shape Analysis

- Digitize 120 ns to get all the event-generated detector pulses
- Use pulse shape analysis to discriminate gammas
- Works effectively for  $E > 0.4$  MeV

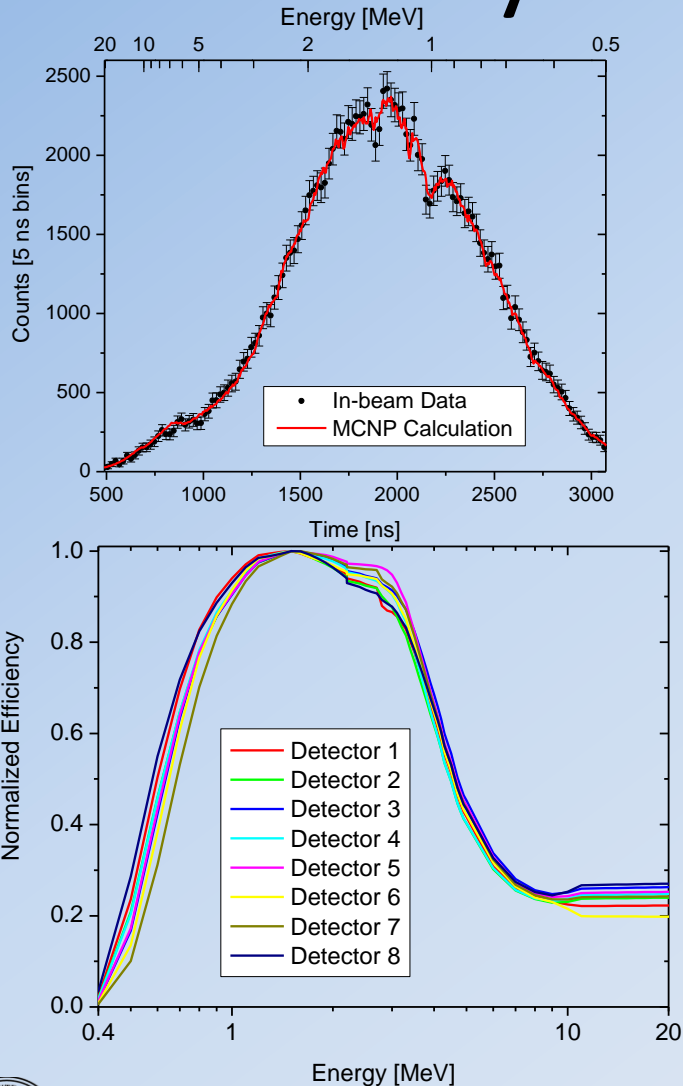


# Flux Shape Measurement

- Use a fission chamber with  $\sim 391$  mg  $^{235}\text{U}$  in the sample position
- Use ENDF/B 7.1 fission cross section for  $^{235}\text{U}$
- 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



# Efficiency as a Function of Energy

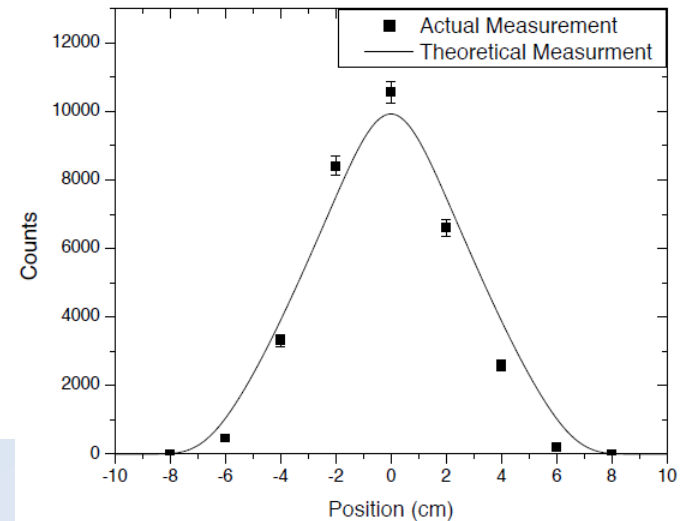
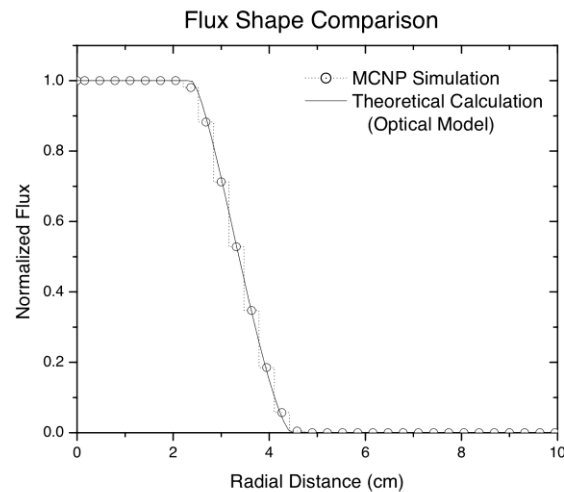
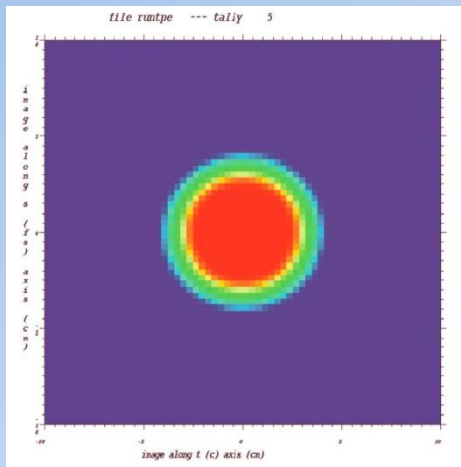


- Objective:
  - MCNP simulation of EJ301 response in the sample position must precisely agree with the measurement
- Methodology:
  - Use the measured flux as a source in MCNP simulation of the in-beam detector response
  - In MCNP set the detector efficiency  $\eta=1$  (tally only the neutron flux 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.



# Neutron Beam Collimation

- Characterize the collimation system
  - Ensure beam diameter agrees with sample diameter of 7.62 cm
  - Verify measurements and calculations agree



# Data Reduction

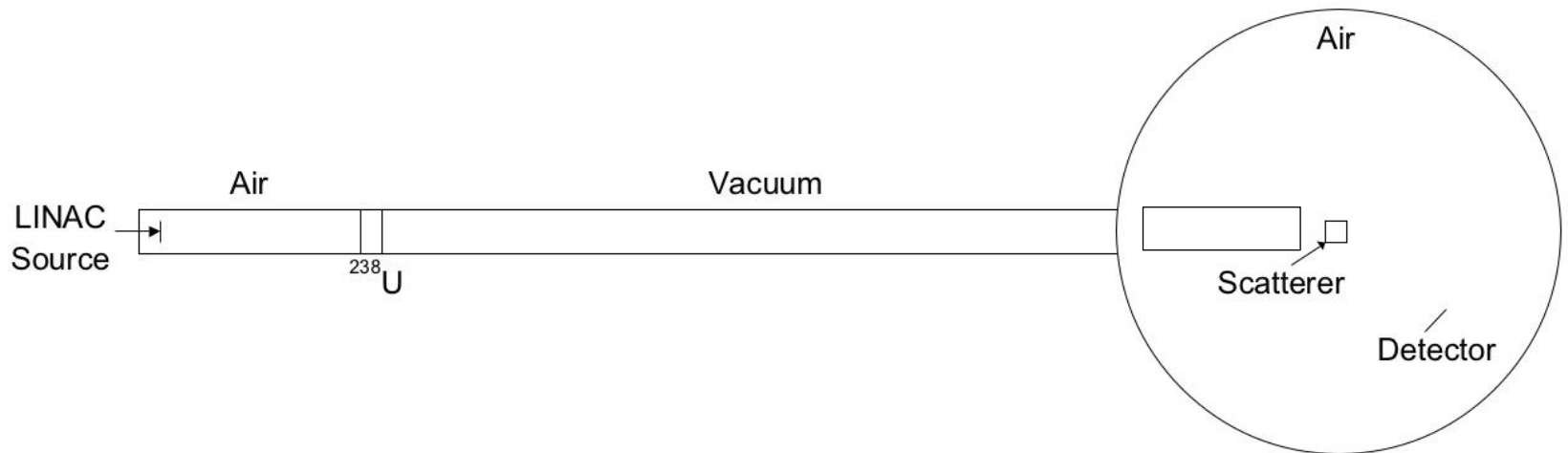
- Sum all files and dead-time correct.
- The experimental count rate corrected for background,  $R_i$ , was obtained by subtracting monitor normalized open data,  $R_i^O$ , by sample data,  $R_i^S$ , for each channel,  $i$ :

$$R_i = R_i^S - \frac{M^S}{M^O} \cdot R_i^O$$



# 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
- Include windows (AI)
- Include recent improvements of vacuum tube near the sample

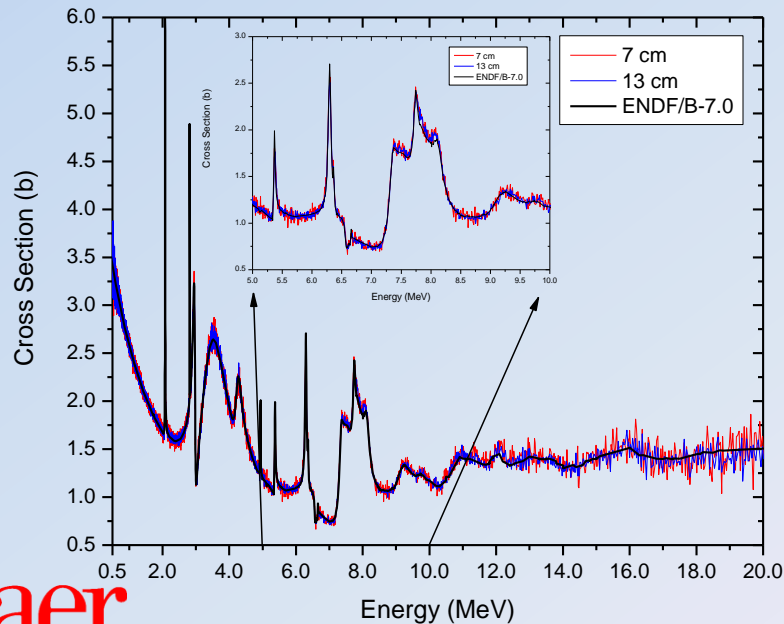
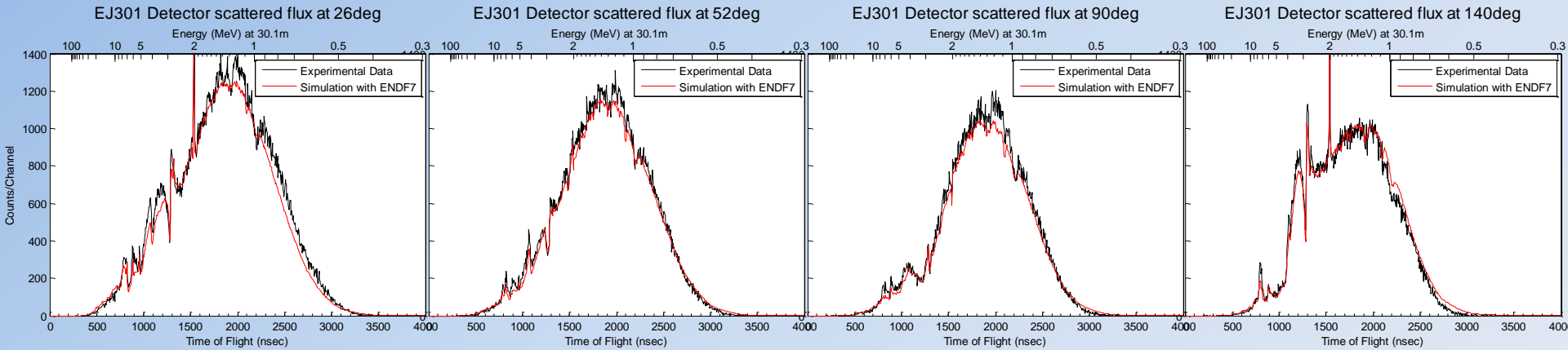


# Data Analysis

- Compare the shape (as a function of TOF) between the measurements and simulations
- Use graphite as a reference in all measurements
  - Differences between the measurement and simulation of graphite are considered systematic errors
- Measurements of Be, Mo and Zr
  - The efficiency was derived from SINCFUL calculations
  - Neutron flux shape based on a fit to in-beam measurements with EJ-301 and Li-Glass
  - Used **individual detector normalization** of the simulation to the experimental data based on graphite measurement
- For  $^{238}\text{U}$  and  $^{56}\text{Fe}$  experiment
  - Flux was derived from  $^{235}\text{U}$  and EJ301 in-beam measurements
  - The efficiency was adjusted to match the MCNP calculations to the in-beam measured data
  - Use **one normalization** factor for all detectors (global normalization)



# Carbon Experimental Results for Be measurement

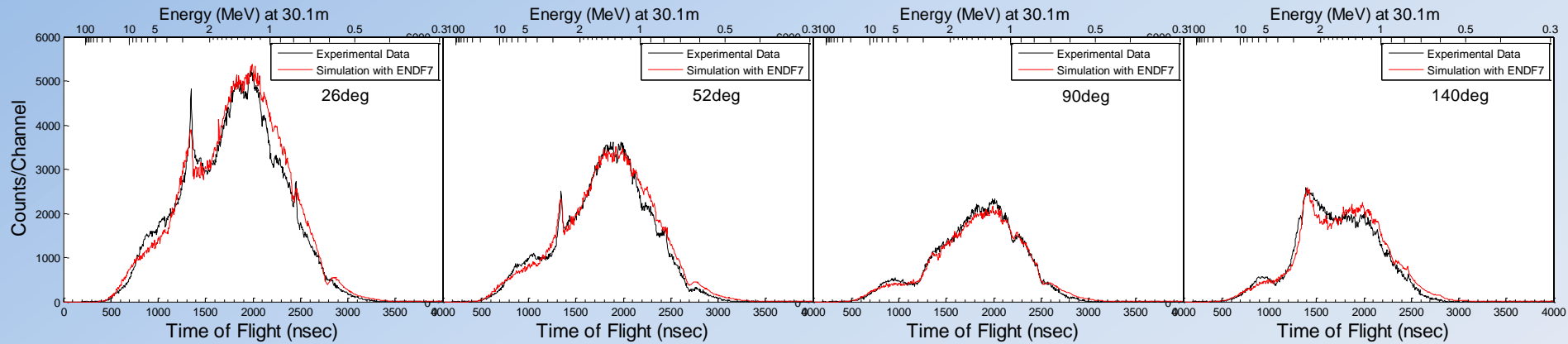


Total cross section

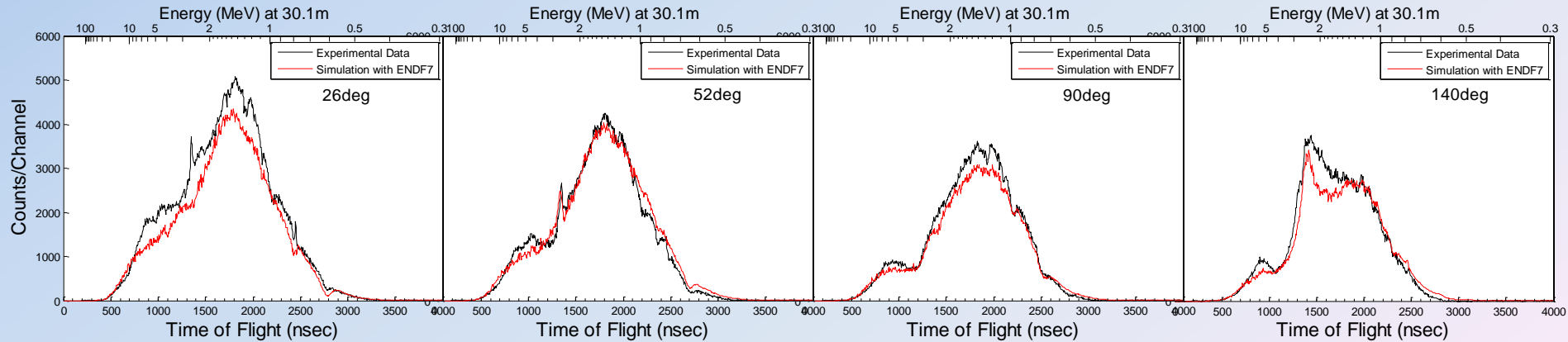


# Beryllium Experimental Results

## 4cm

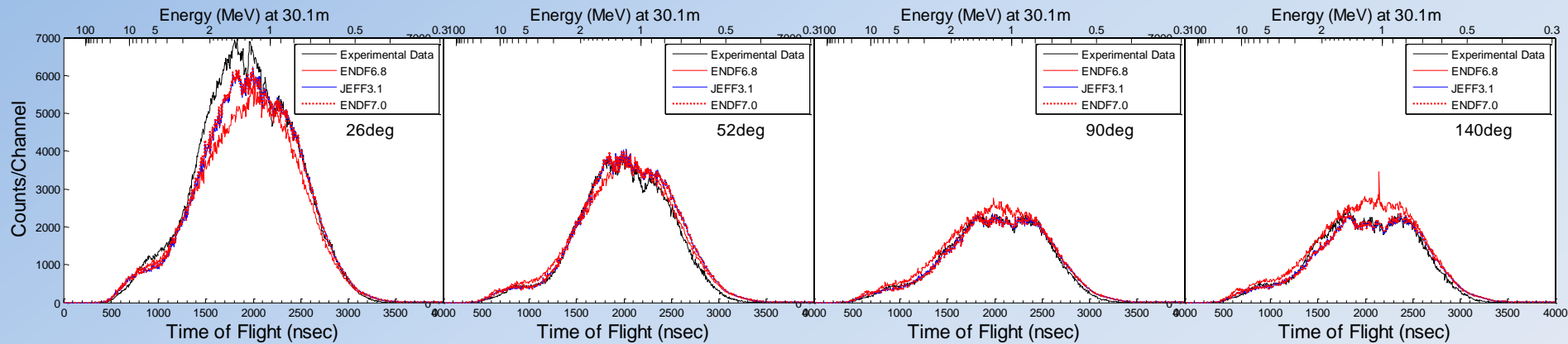


## 8cm

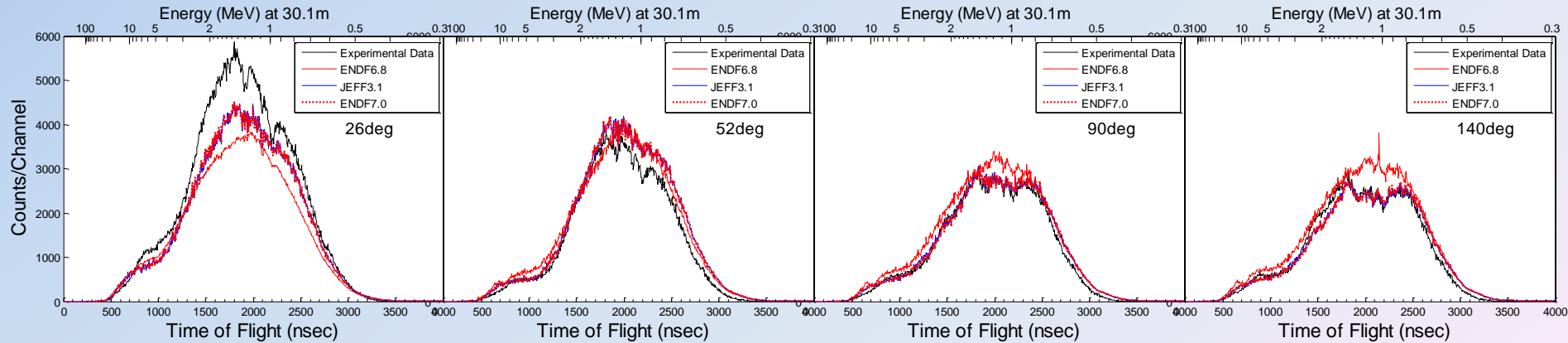


# Molybdenum Experimental Results

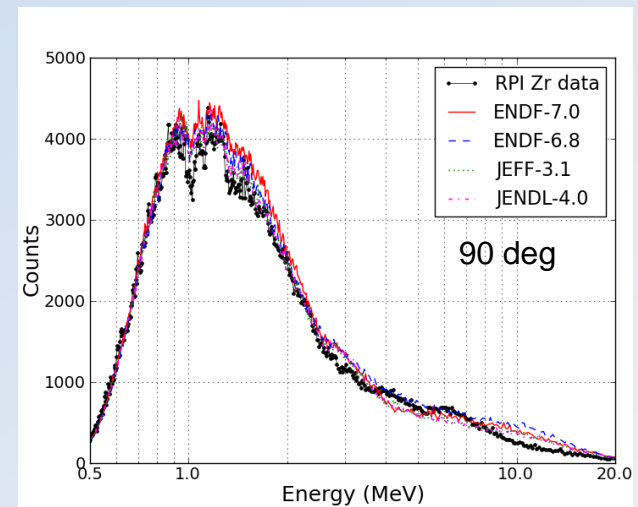
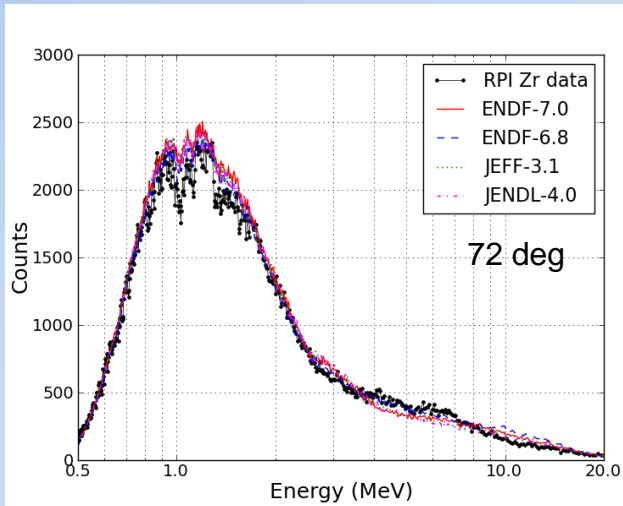
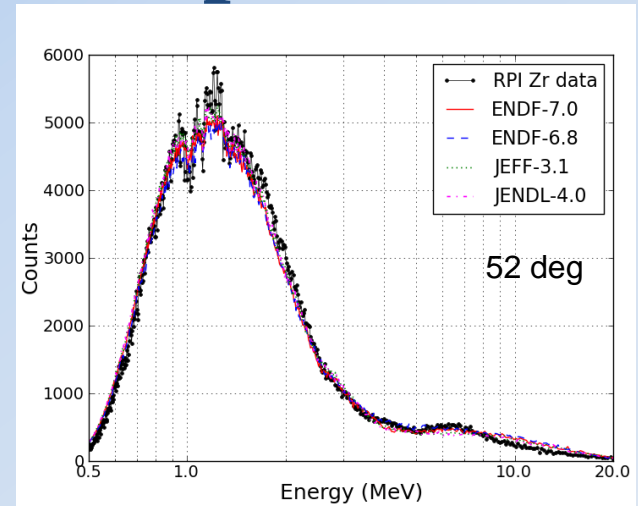
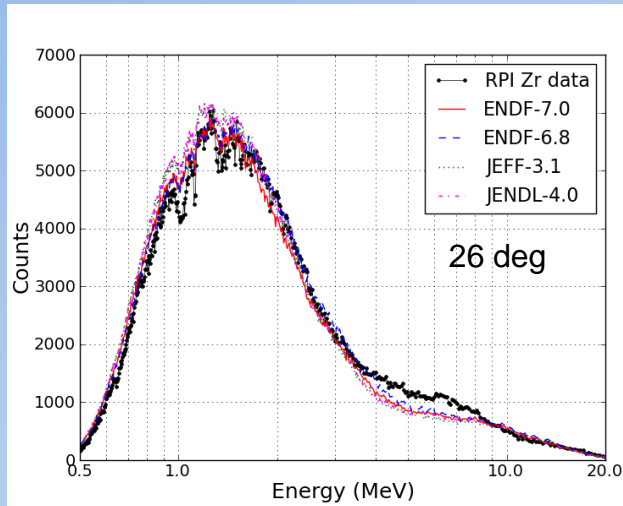
5cm



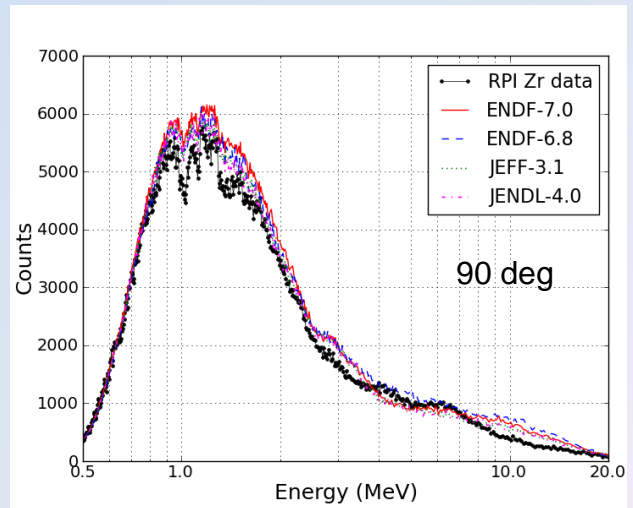
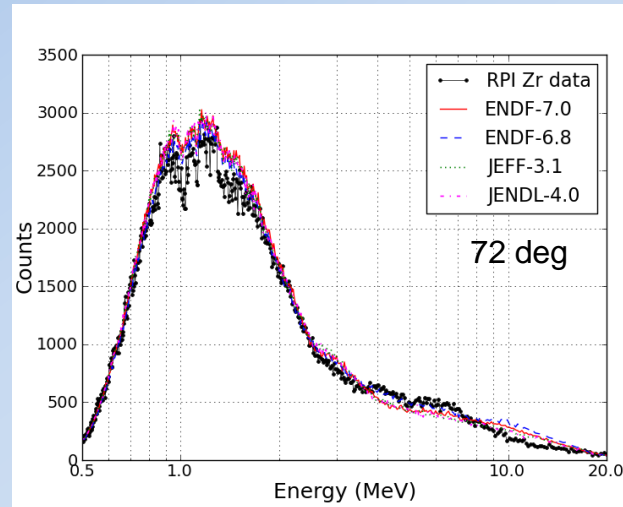
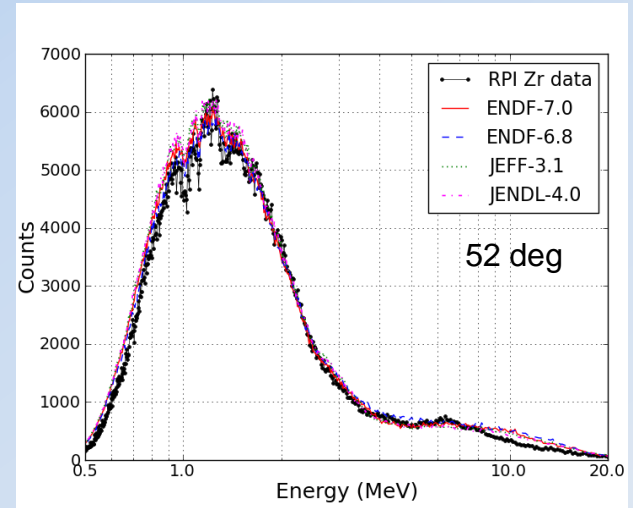
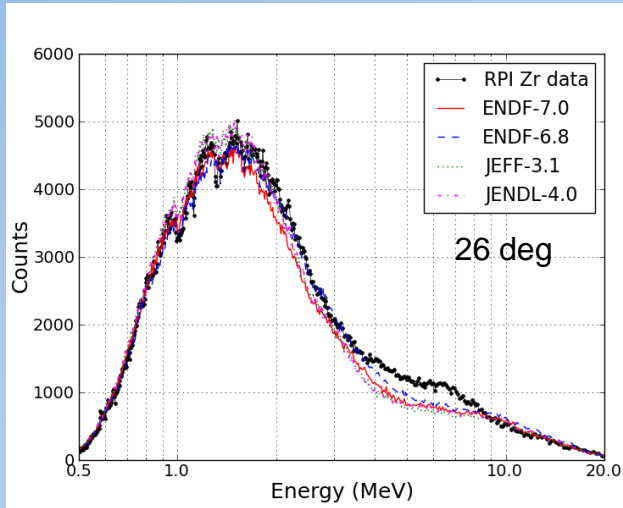
8cm



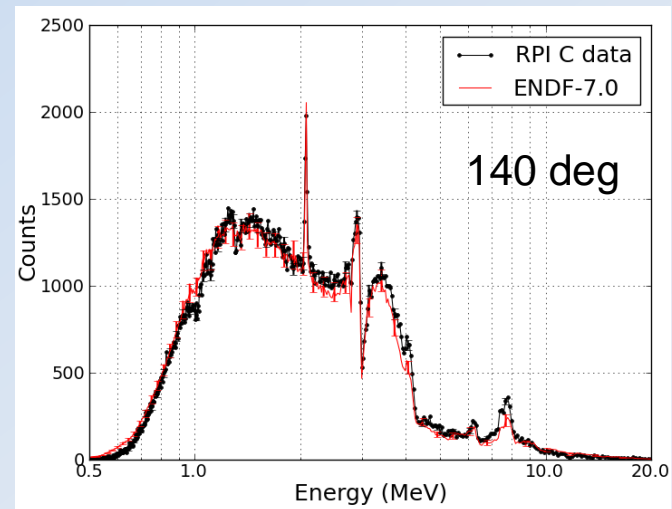
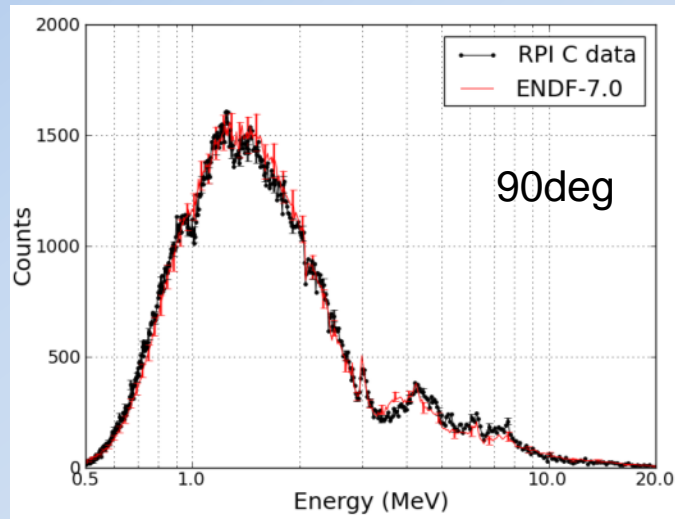
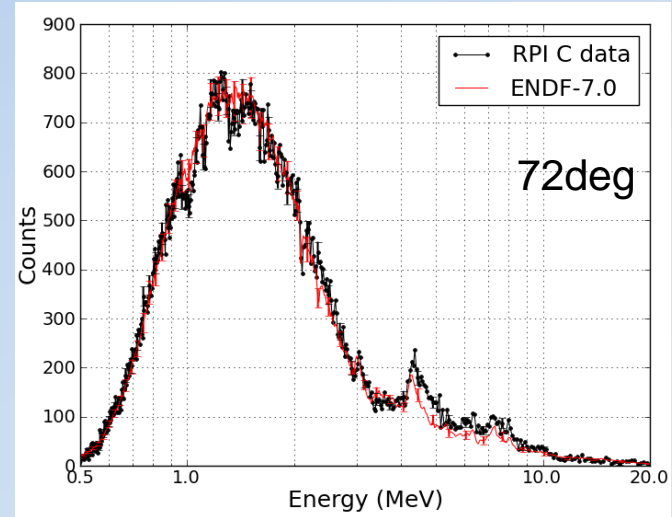
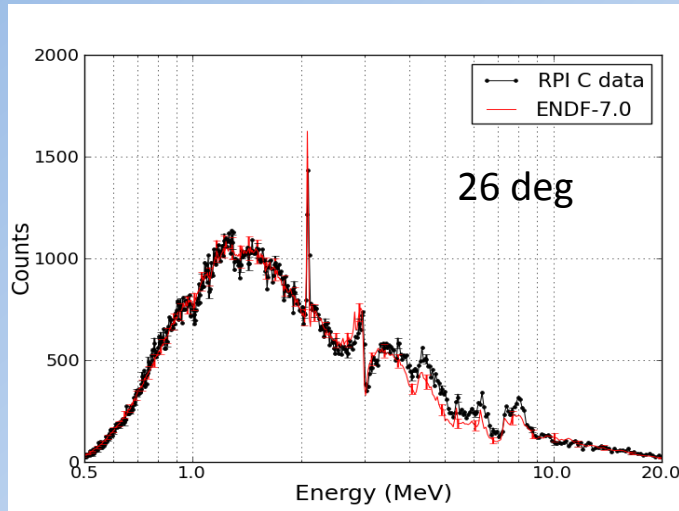
# Zr – 6 cm Thick Sample



# Zr – 10 cm Thick Sample



# Carbon Standard For Zr Experiment

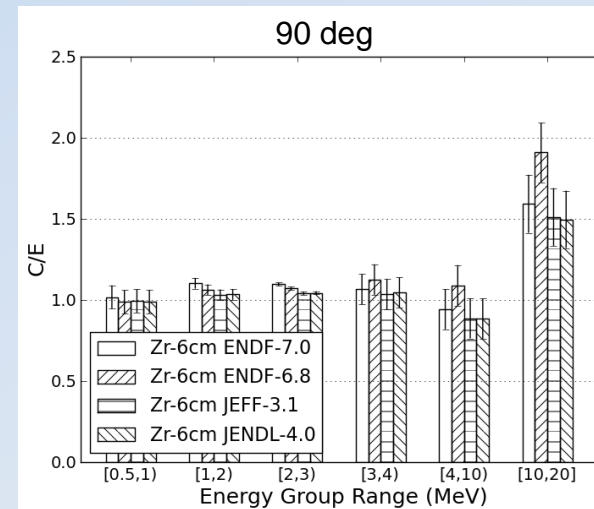
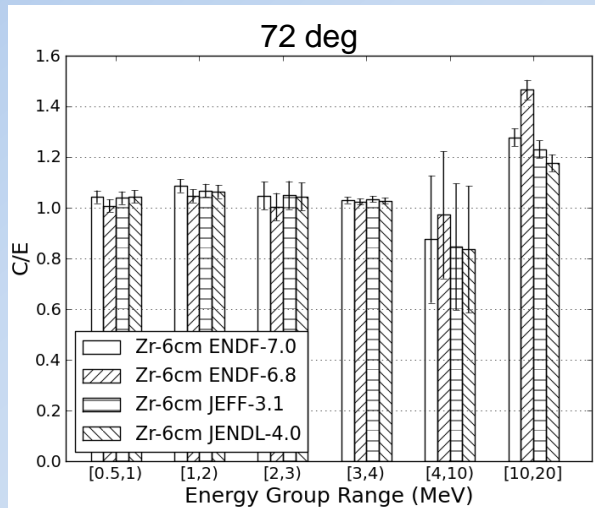
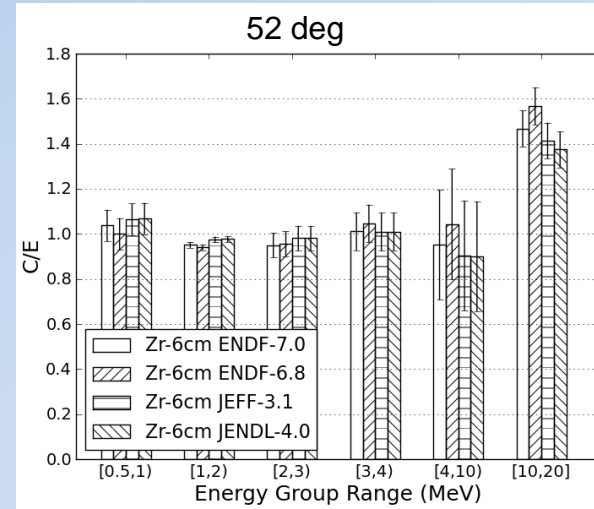
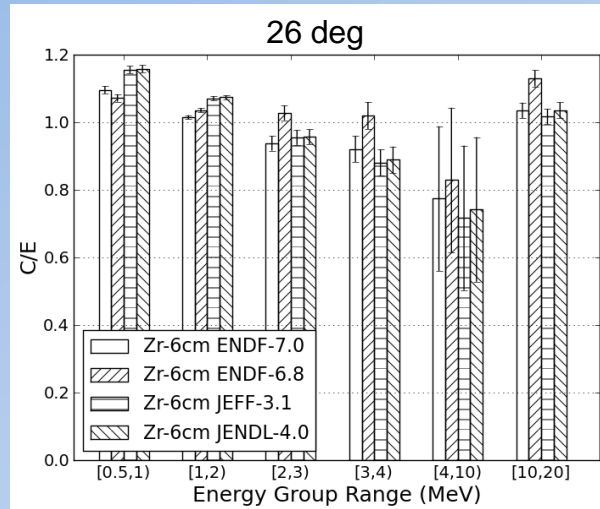


# Comparing Experiments and Evaluations

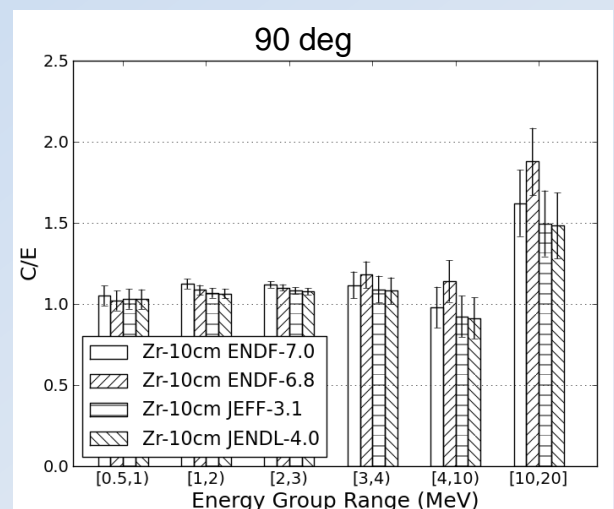
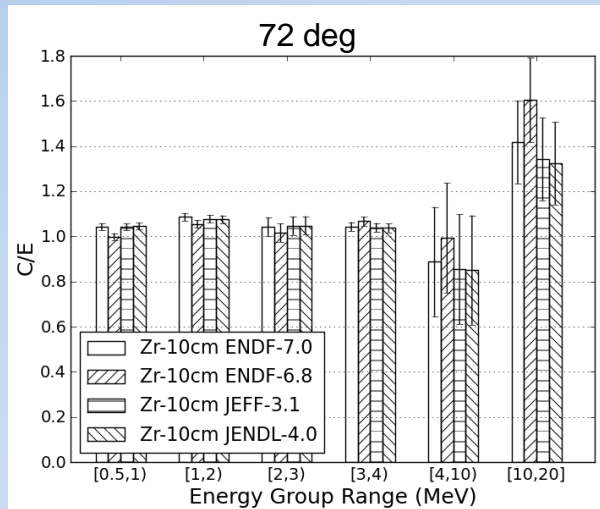
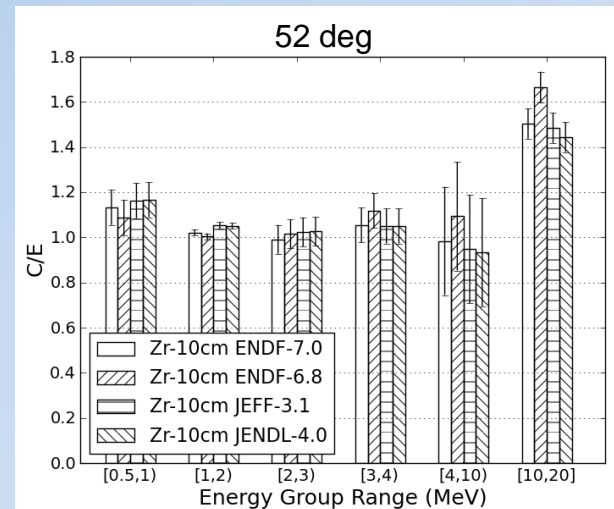
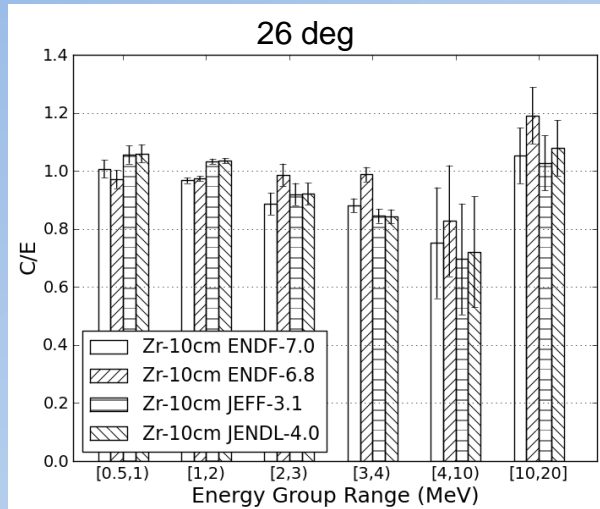
- The MCNP calculations and experimental data were used to calculate  $C/E$  values in several different scattering angles and energy regions between 0.5 MeV and 20 MeV.
- Differences between MCNP simulations of the carbon standard and the experiment were treated as systematic errors



# C/E for 6 cm Zr sample



# C/E for 10 cm Zr sample

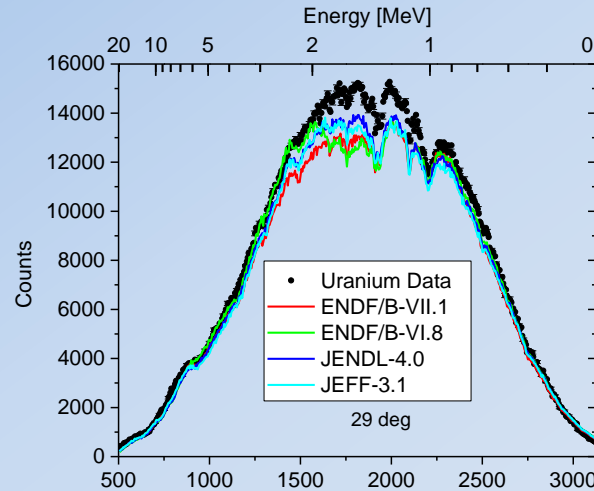
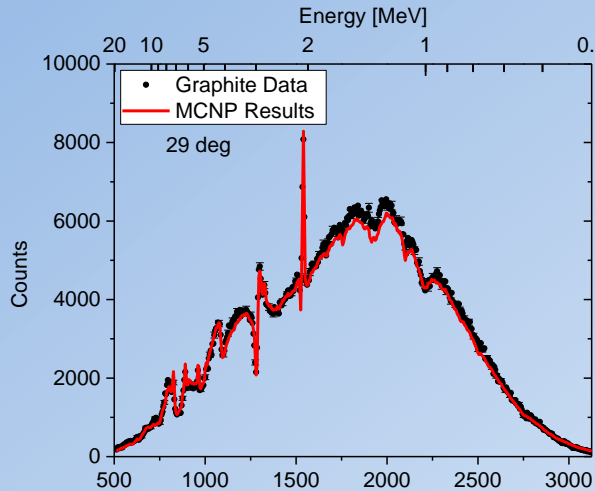


# Observations for Zr

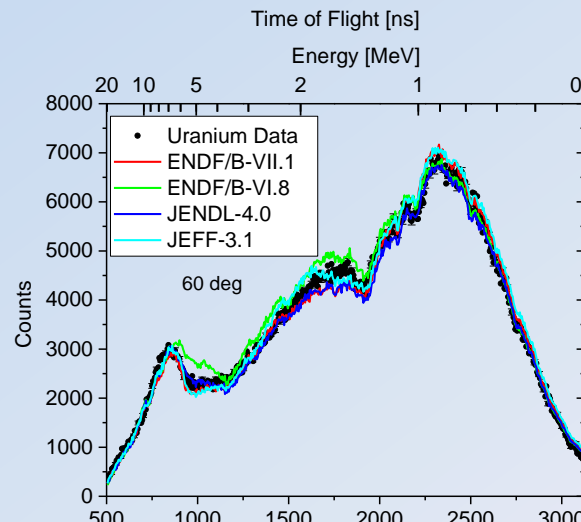
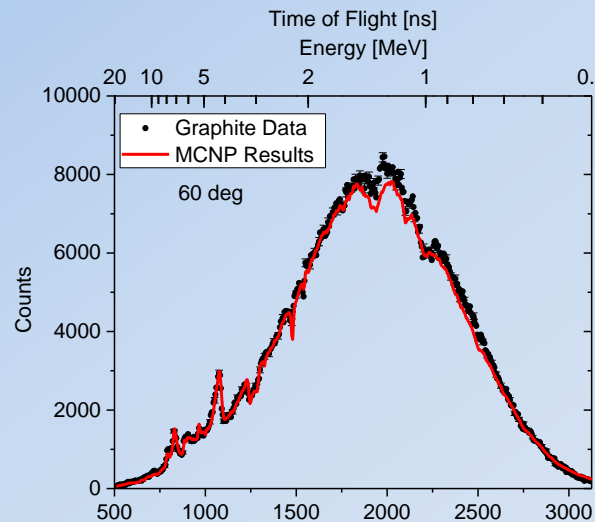
- Overall there is good agreement between the experiments and calculations.
- For the energy group of 10 MeV to 20 MeV the C/E values for all libraries were significantly greater than unity, indicating that the experimentally observed differential scattering cross section is less than the one used in the evaluated library.



# $^{238}\text{U}$ Scattering - Forward Angles

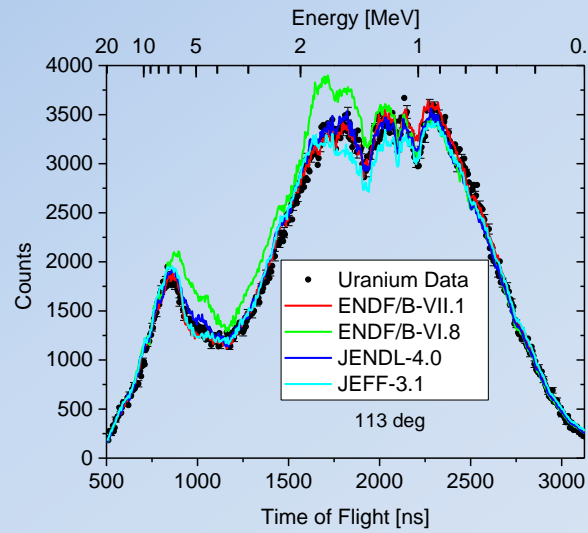
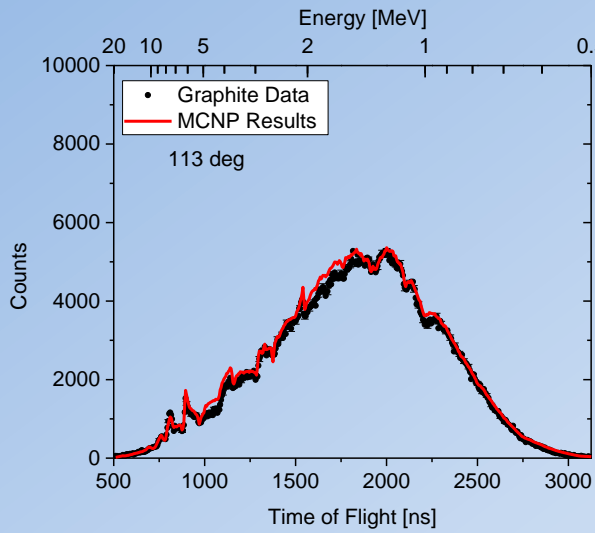


Library	$\chi^2$
ENDF/B-VII.1	2.6
ENDF/B-VI.8	1.9
JENDL-4.0	1.7
JEFF-3.1	2.0

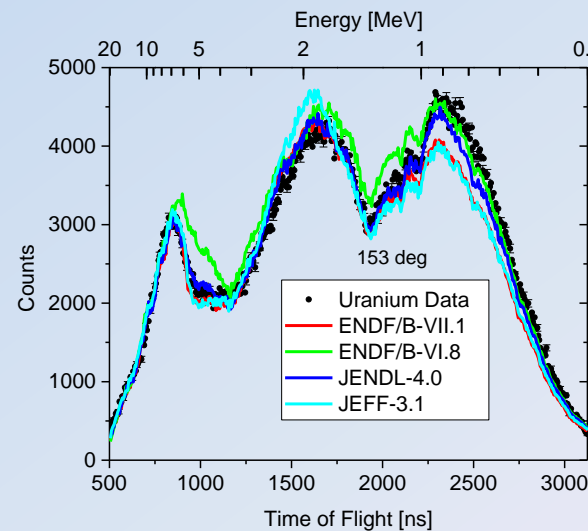
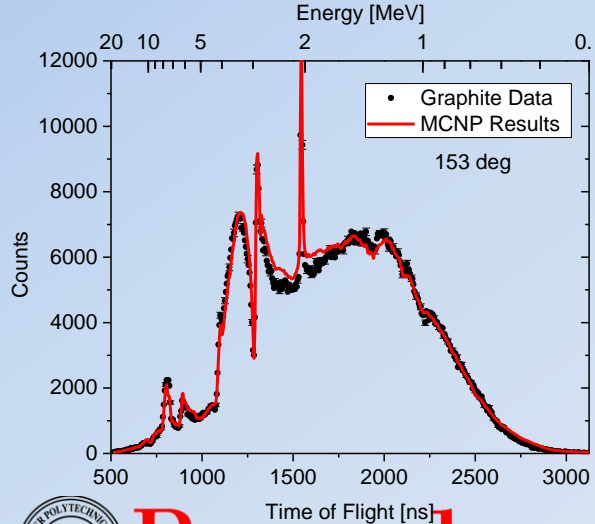


Library	$\chi^2$
ENDF/B-VII.1	1.6
ENDF/B-VI.8	3.7
JENDL-4.0	1.2
JEFF-3.1	2.1

# $^{238}\text{U}$ Scattering – Back Angles



Library	$\chi^2$
ENDF/B-VII.1	0.4
ENDF/B-VI.8	2.7
JENDL-4.0	0.5
JEFF-3.1	0.9



Library	$\chi^2$
ENDF/B-VII.1	3.7
ENDF/B-VI.8	4.9
JENDL-4.0	1.2
JEFF-3.1	4.7



# Observations for $^{238}\text{U}$

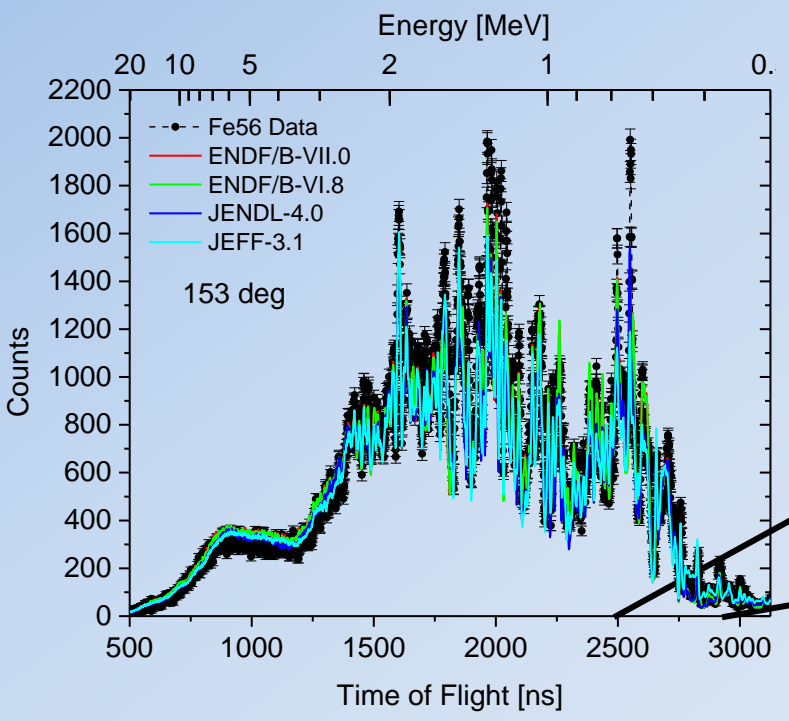
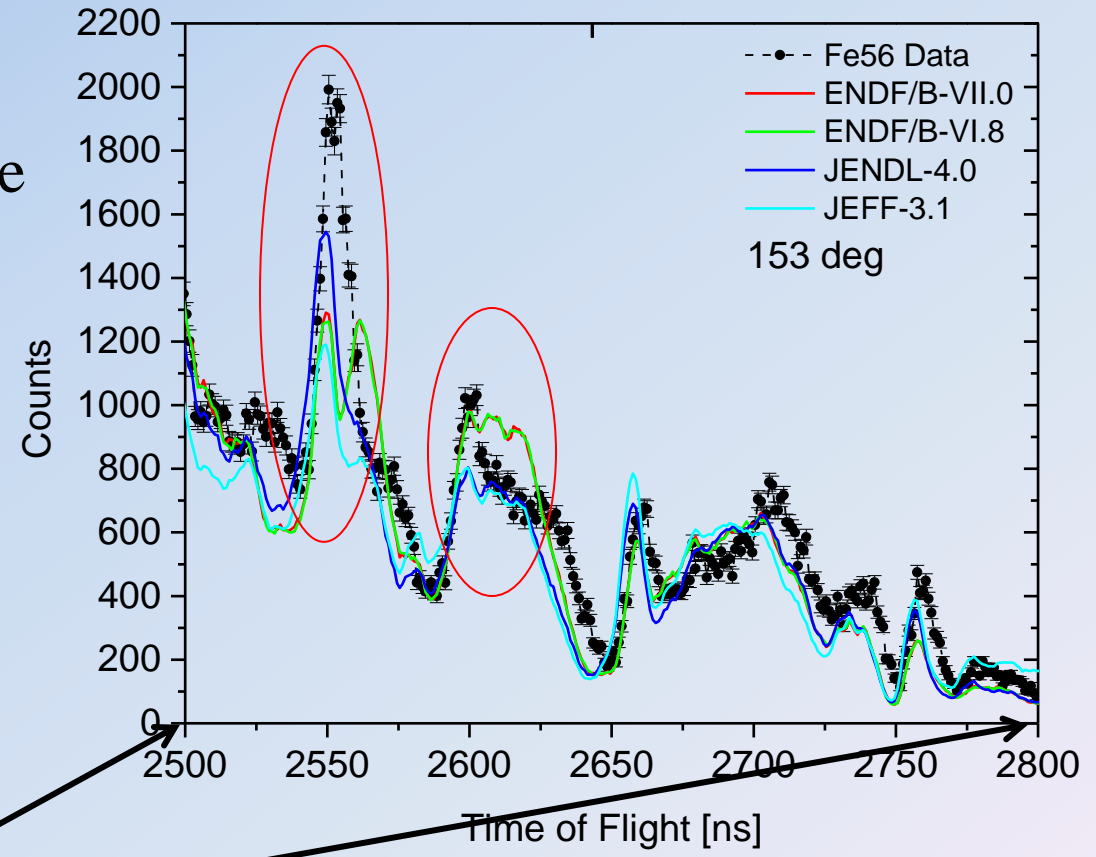
- Differences between the evaluations are visible and exceed the experimental errors.
- To get better agreement the evaluation need to be adjusted mostly at back angles.
- Overall JENDL 4.0 has has the lowest  $\chi^2$



# $^{56}\text{Fe}$ Scattering Measurement – Results $153^\circ$

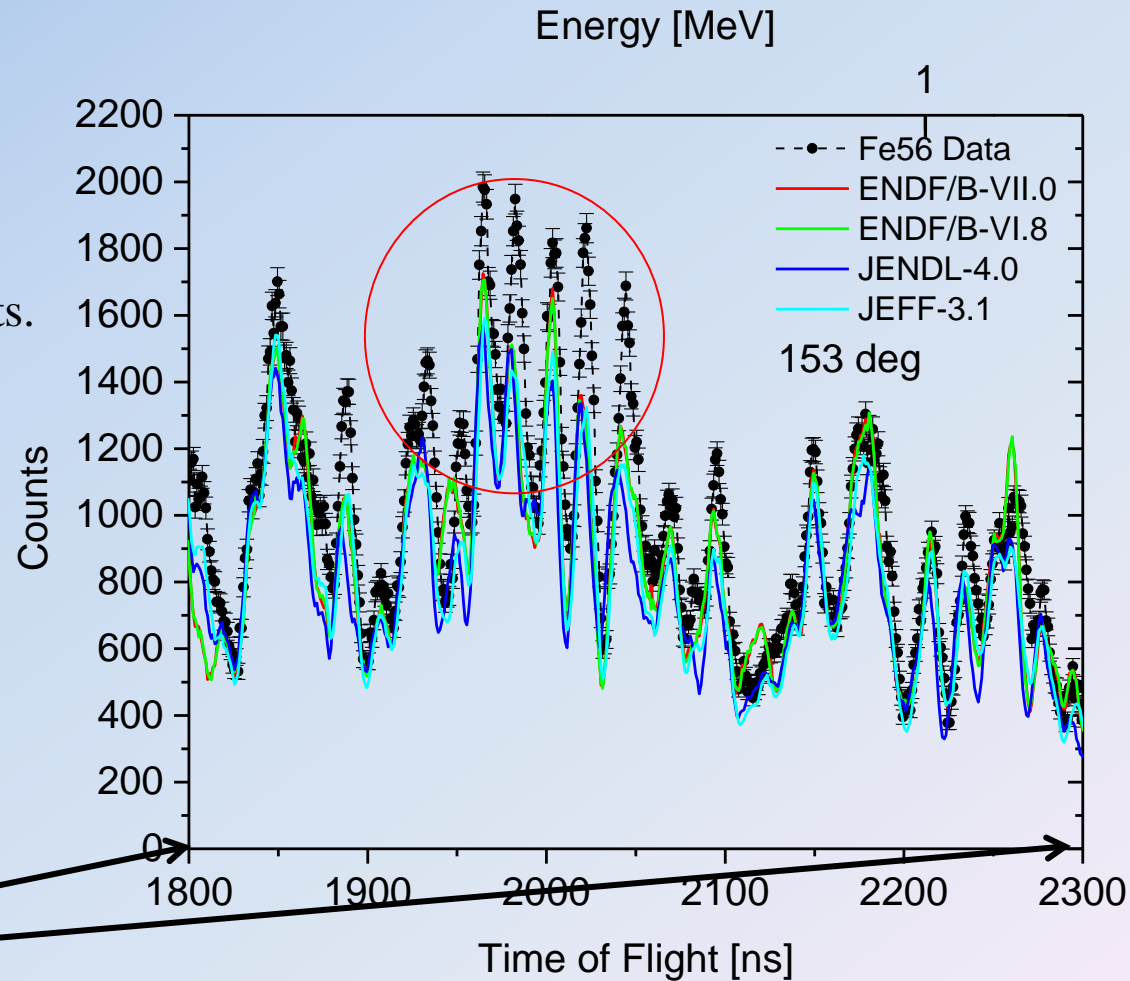
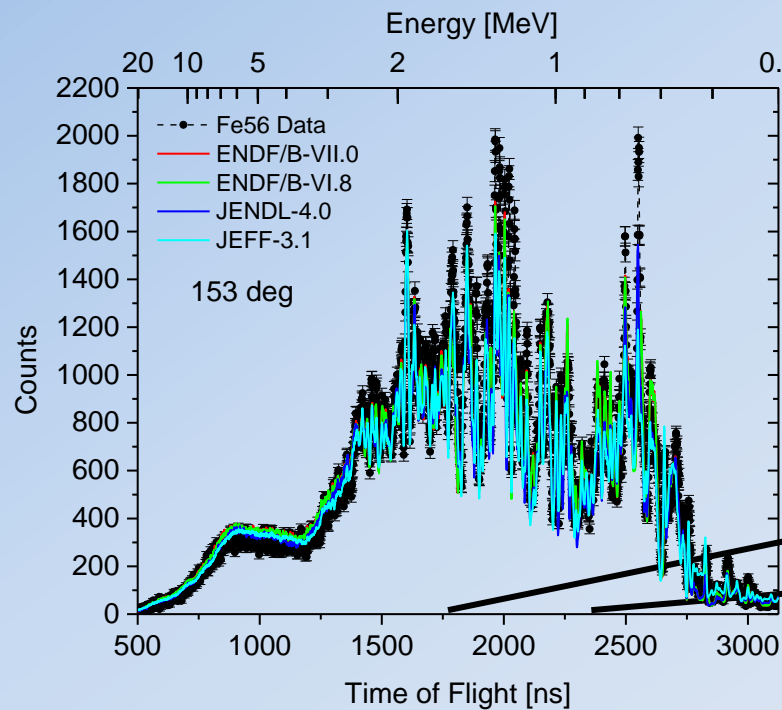
Energy [MeV]

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



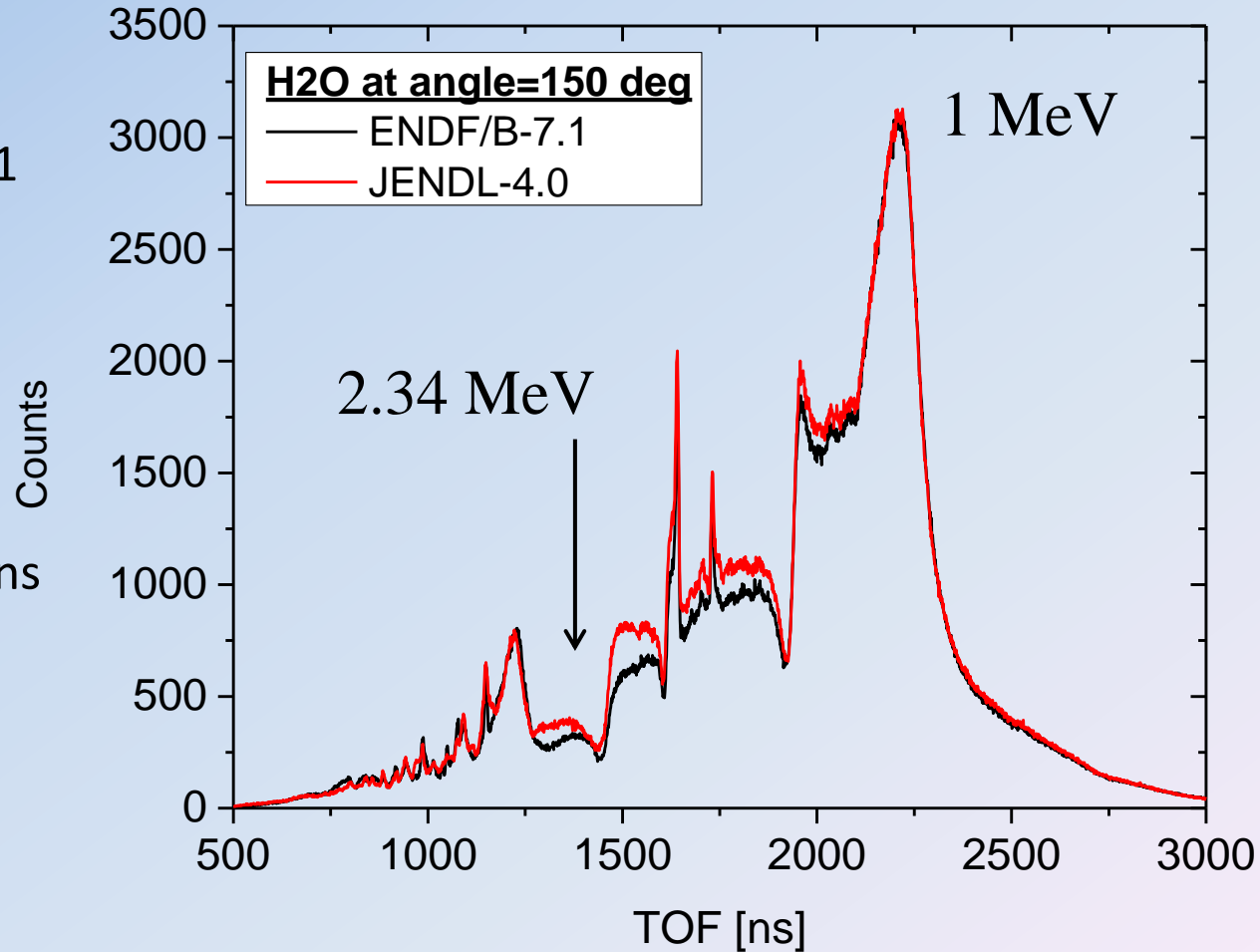
# Fe-56 Scattering Measurement – Results 153°

- 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.



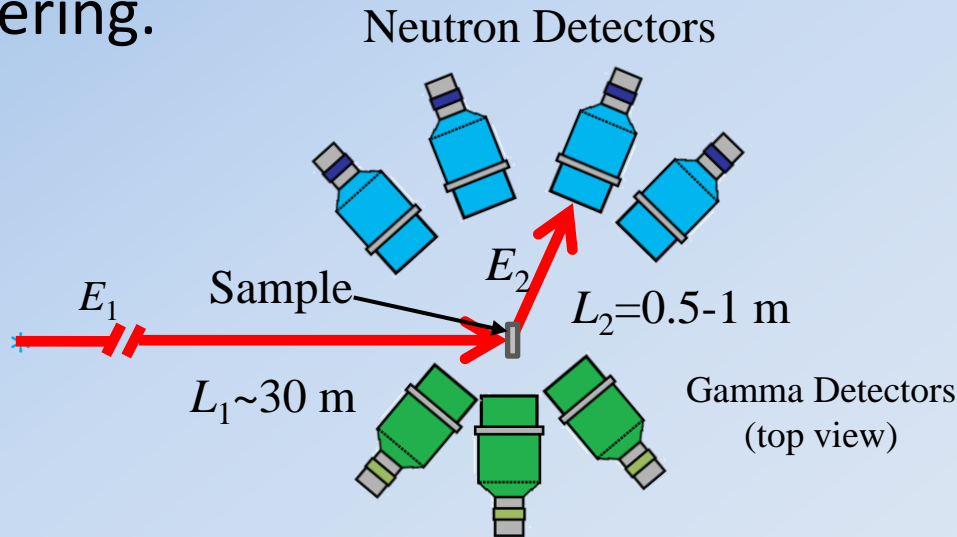
# O-16 in a Water Sample

- A Scoping calculation showing H<sub>2</sub>O scattering calculate using ENDF/B-7.1 and JENDL 4.0
- Differences are visible at back angle between 2-3 MeV
- Easy normalization of the experiment and simulations at the 1 MeV resonance
- D<sub>2</sub>O might be a better sample because of lower contribution from the D



# Future Development

- Use an array of BaF<sub>2</sub> detectors to provide a gamma tag
  - Enables separation of inelastic scattering from elastic scattering.



- Use Filtered beams to measure inelastic scattering
- Use thin samples to obtain double differential scattering cross section.



# Conclusions

- The system developed at RPI measures the neutron scattering yield and fission neutron emission from a sample
- Simulation of the system with different libraries shows differences from the experimental data
- The accuracy of the experiments provides:
  - A recommendation of which evaluated library is best for treatment of neutron scattering
  - Pinpoint the differences in angle and energy and provide information to evaluators.



# Related Publications

- Devin P. Barry et al., “Quasi-differential Neutron Scattering in Zirconium from 0.5 MeV to 20 MeV”, *Nuclear Science and Engineering*, Accepted For Publication (2012).
- Adam M. Daskalakis, Rian M. Bahran, Ezekial J. Blain, Brian J. McDermott, Sean Piela, Yaron Danon, Devin P. Barry, Greg Leinweber, Robert C. Block, Michael J. Rapp, “Quasi-Differential Neutron Scattering Measurements of  $^{238}\text{U}$ ”, ANS Winter Meeting and Nuclear Technology Expo, American Nuclear Society, San Diego CA. November 11-15, 2012.
- 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).
- 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, High Energy Neutron Differential Scattering Measurements For Beryllium And Molybdenum, PhD dissertation, Rensselaer Polytechnic Institute, Troy, NY 12180, June 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.

