The Nuclear Data Program at Rensselaer

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Collaboration

- Rensselaer Polytechnic Institute, Troy, NY, USA
  - Faculty:
    - Dr. Y. Danon
  - PhD. Students:
    - Z. Blain
    - R. Bahran
    - M. Rapp
    - J. Thompson
    - D. Williams
- Bechtel Marine Propulsion Corporation, Knolls Atomic Power Laboratory
  - Dr. G. Leinweber
  - Dr. D.P Barry
  - Dr. R.C Block
  - J. Hoole

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Outline

- The Facility
- Resonance Region
  - Neutron Transmission Measurements
  - Neutron Capture Measurements
  - Capture to Fission Ratio
  - Neutron Resonance Scattering
- High Energy (0.5 MeV- 20 MeV)
  - Neutron Transmission Measurements
  - Neutron Scattering Measurements
- Filtered Beam Measurements
- The Lead Slowing Down Spectrometer

The RPI LINAC Facility

- Started operation in 1961
- 60 MeV electron LINAC
- Pulsed width from 5 ns to 5 ms
- Neutron production by (g,n) reactions in Ta
- Flight Paths lengths ranging from 15m to 250m

Graduated over 160 student who utilized the LINAC as part of their PhD theses research.

The RPI LINAC Facility

- ~4 X 10^{13} neutrons/sec
- 1- 500 Hz
- 6-5000ns pulse width

250m 100m 15-35m

LSDS

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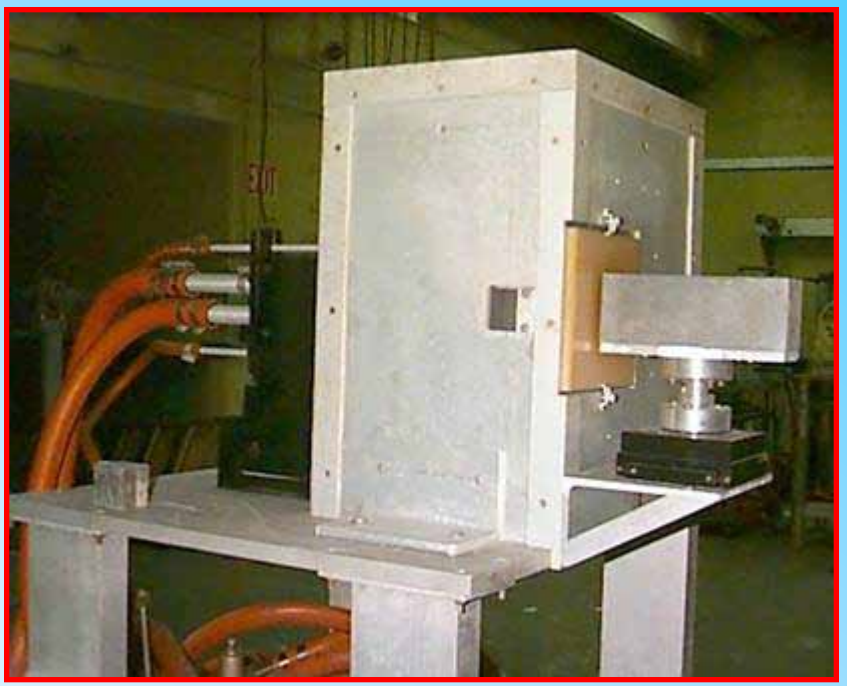
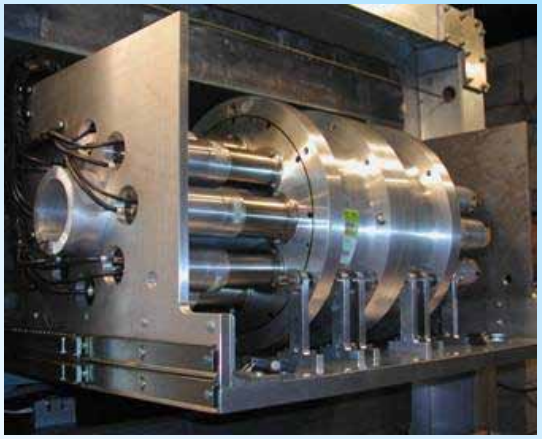
Neutron Producing Targets

"Bare Bounce Epithermal Target"

"Enhanced Thermal Target"



Detectors



Capture/multiplicity
25m

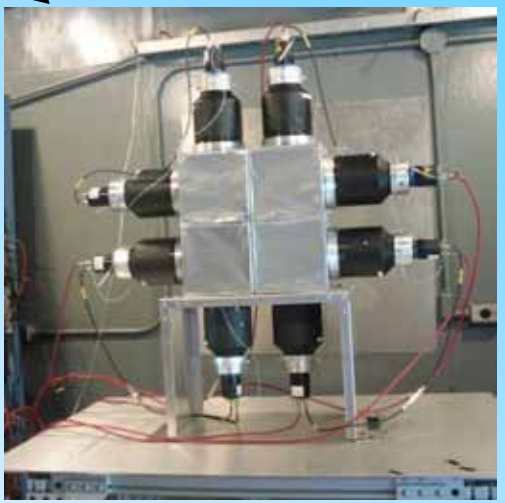
25m- 30m

Transmission

250m

100m

Scattering
30m



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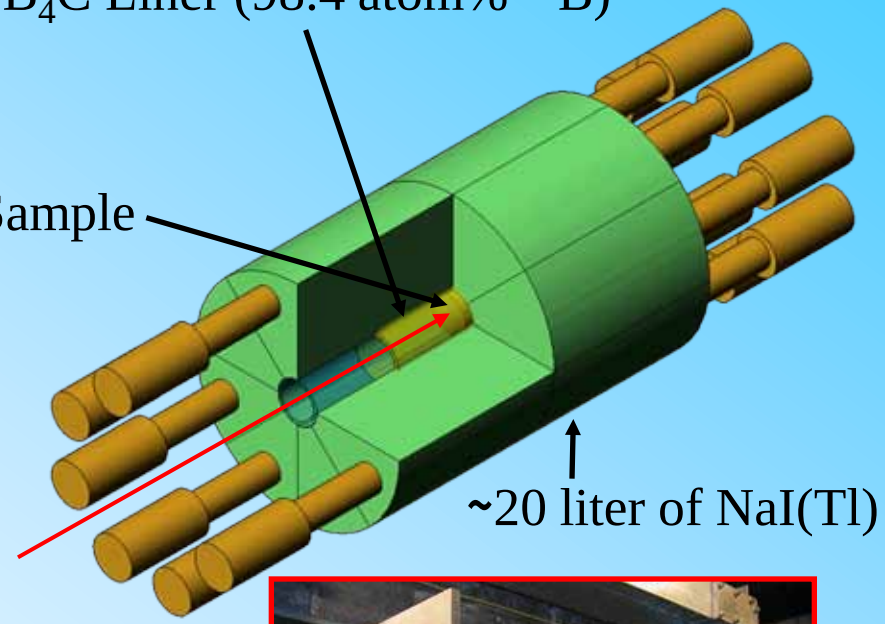
Current Activity

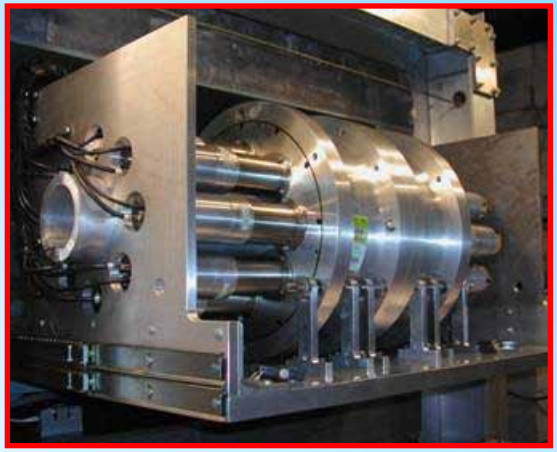
- Time of flight measurements
  - Resonance Region
    - Capture (0.01 eV – 2 keV)
    - Transmission (0.001 eV – 100 KeV)
    - Capture to fission ratio (alpha)
  - High energy (0.4-20MeV)
    - Scattering (30 m flight path)
    - Transmission (100m and 250m flight path)
    - Fission spectra and nubar
  - High accuracy total cross section measurements using filtered beams
  - Resonance scattering
- Lead Slowing Down Spectrometer
  - Simultaneous measurement of fission cross sections and fission fragment mass and energy distributions using the RPI lead slowing down spectrometer
  - Measurements of energy dependent (n,p) and (n,a) cross sections of nanogram quantities of short-lived isotopes. (collaboration with LANL).

Resonance Region Detectors

Li-Glass Detector at 25m

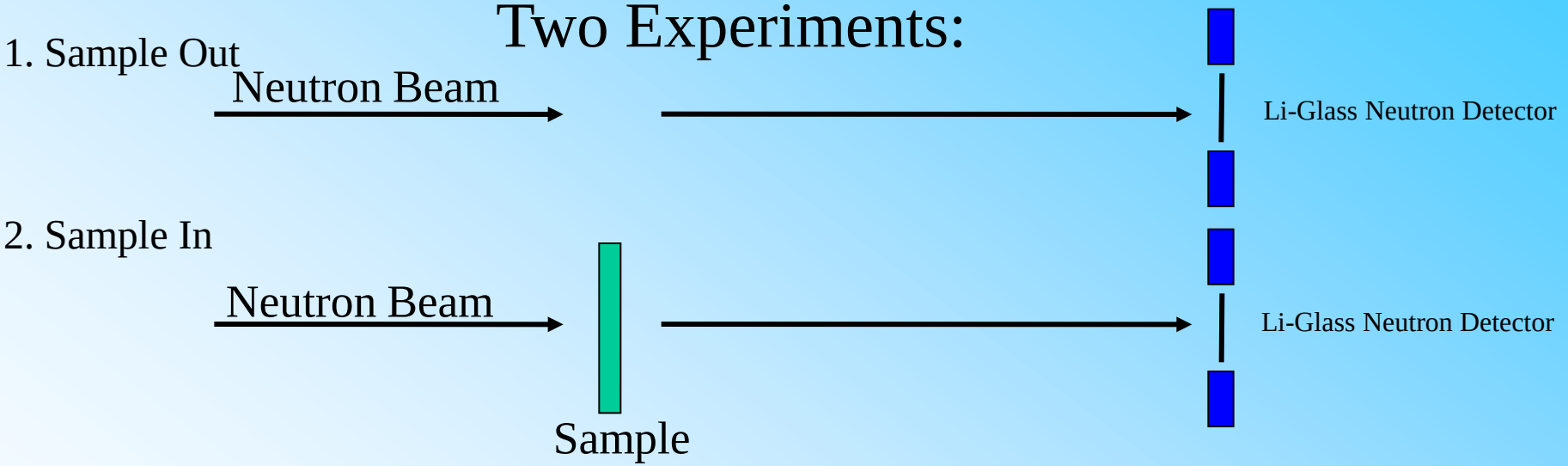
2 cm B_4C Liner (98.4 atom% ^{10}B)





Transmission Experiment

Two Experiments:

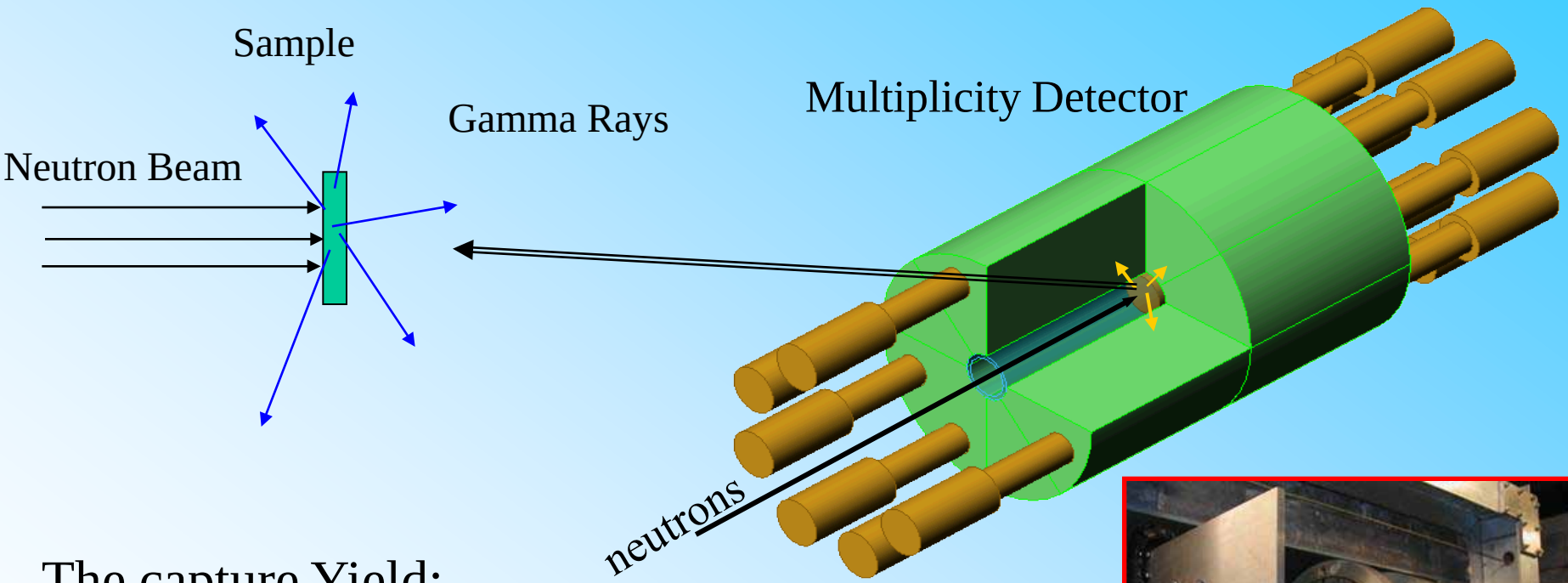


$$T = \frac{C_{\text{Sample In}}}{C_{\text{Sample Out}}} = \exp(-Ns_t)$$

N – Number density [atoms/barn]

s_t – Total cross section

Capture Experiments

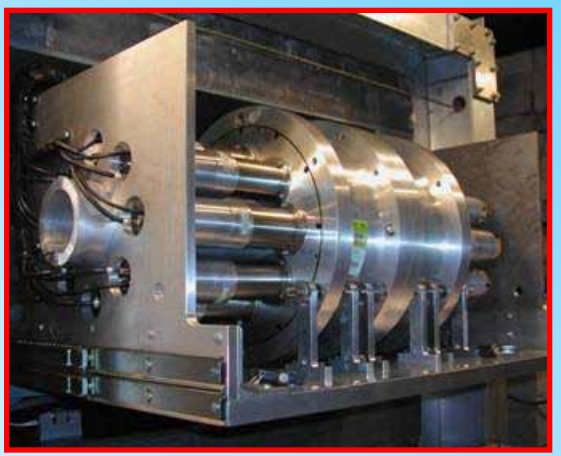


The capture Yield:

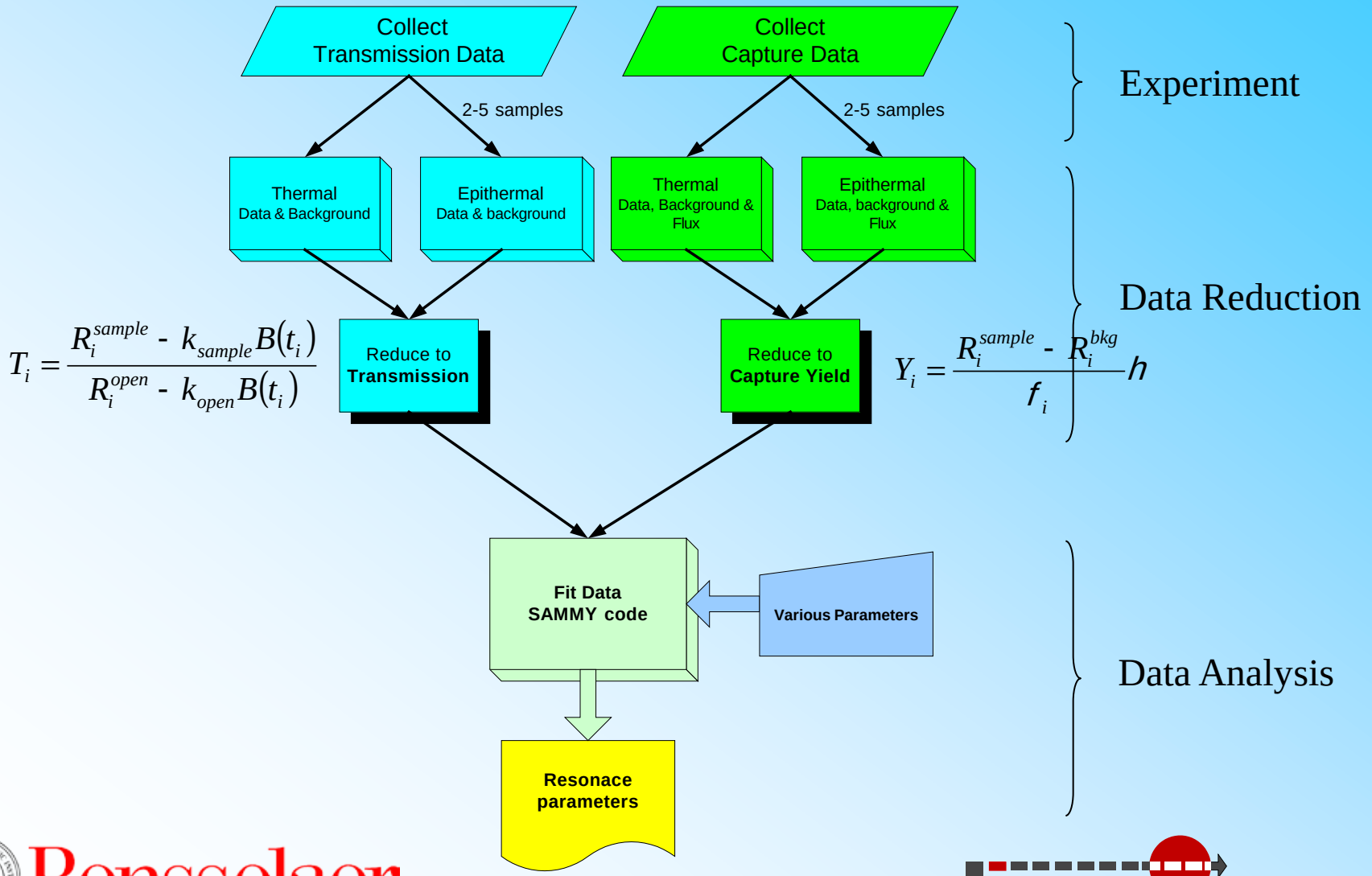
f – neutron flux
h – detection efficiency

$$Counts = fYh$$

$$Y = \left(1 - \exp(-Ns_t)\right)\frac{s_g}{s_t} + Y_{ms}$$



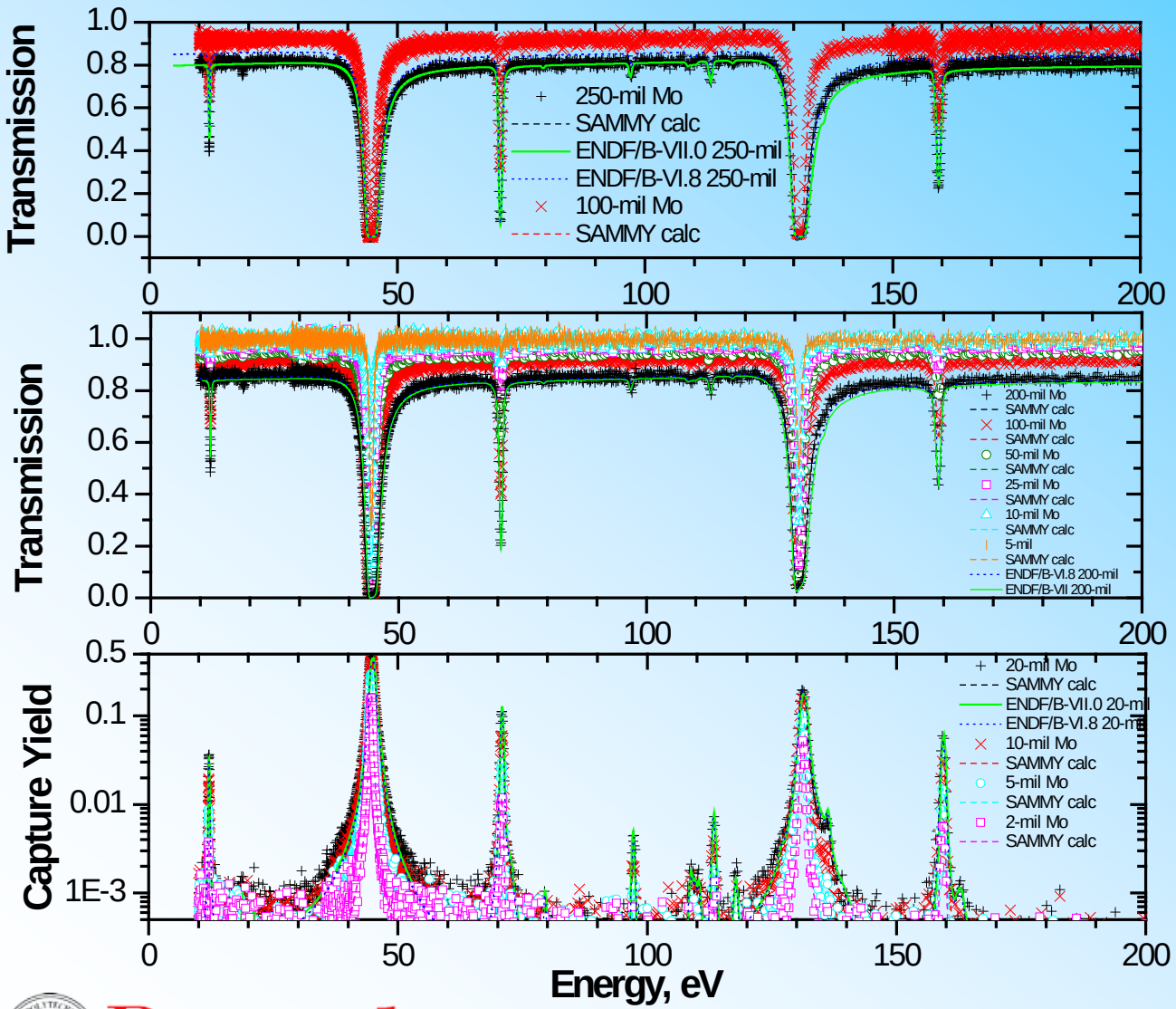
Resonance Cross Section Measurements and Data Analysis



$$T_i = \frac{R_i^{sample} - k_{sample} B(t_i)}{R_i^{open} - k_{open} B(t_i)}$$

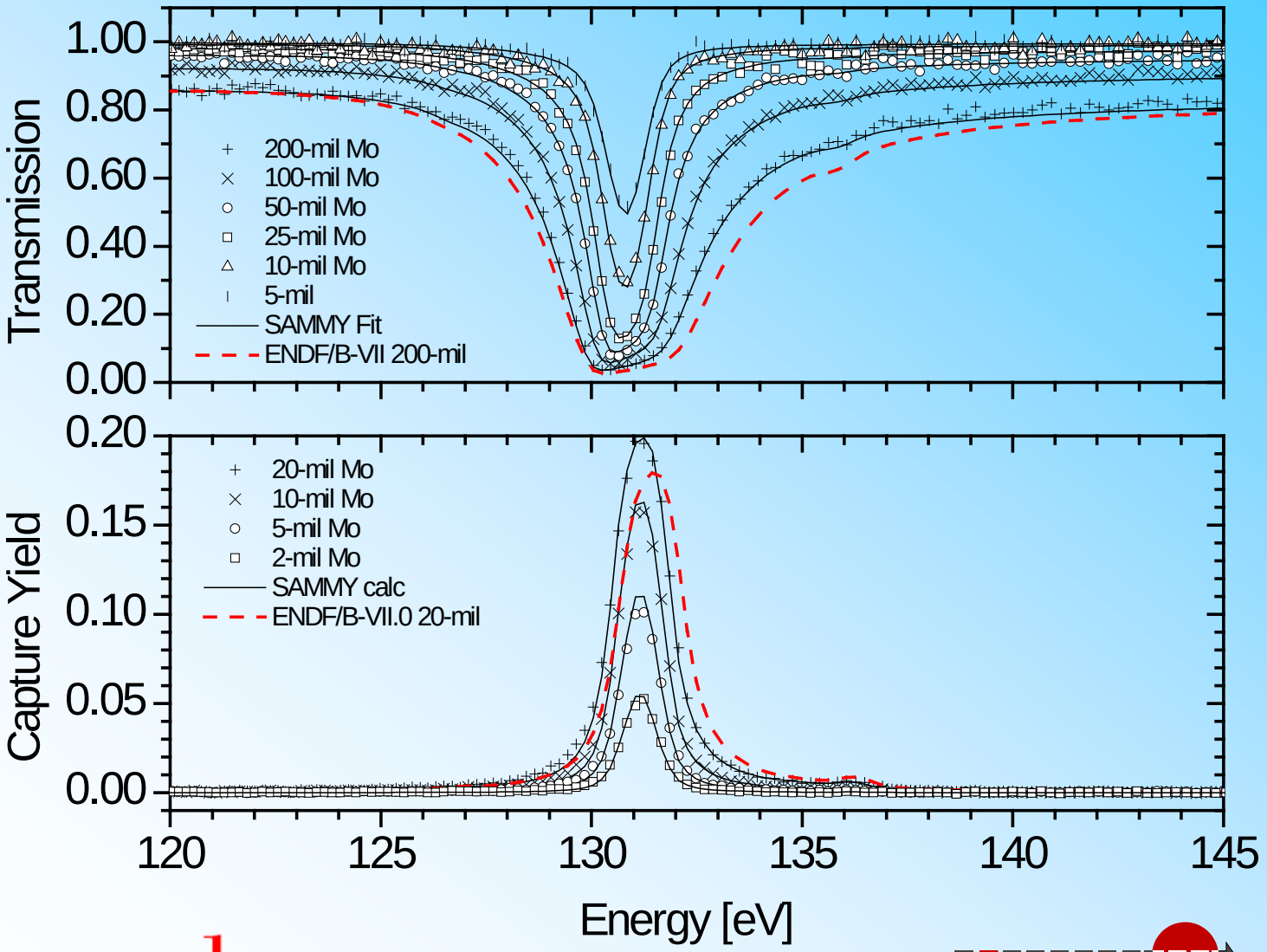
$$Y_i = \frac{R_i^{sample} - R_i^{bkg}}{f_i} h$$

Elemental Molybdenum

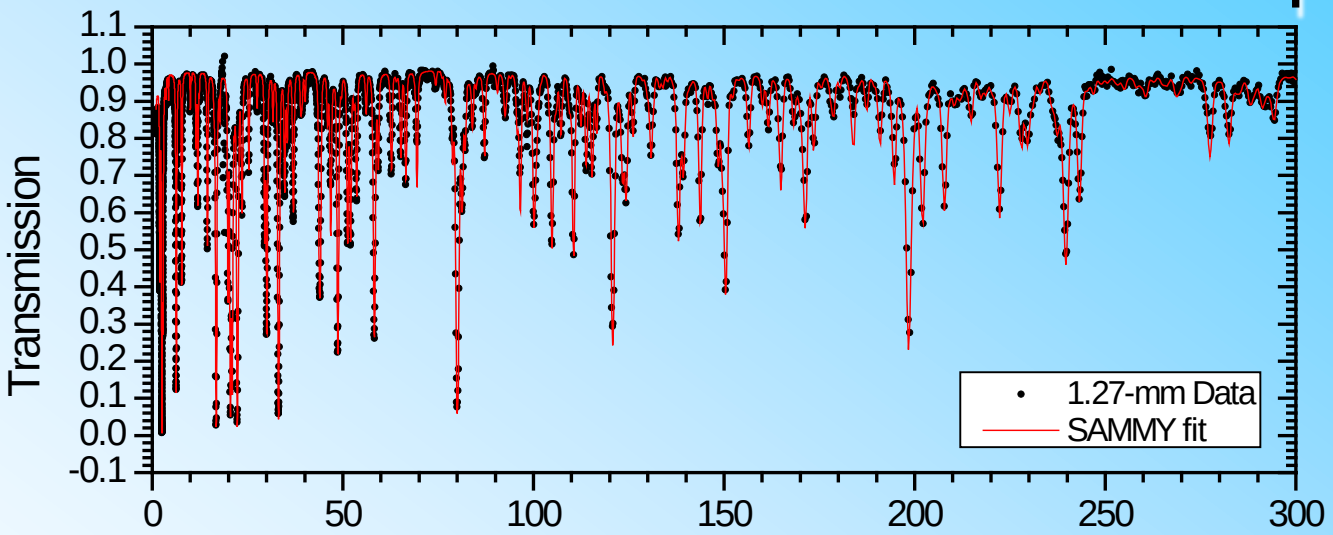


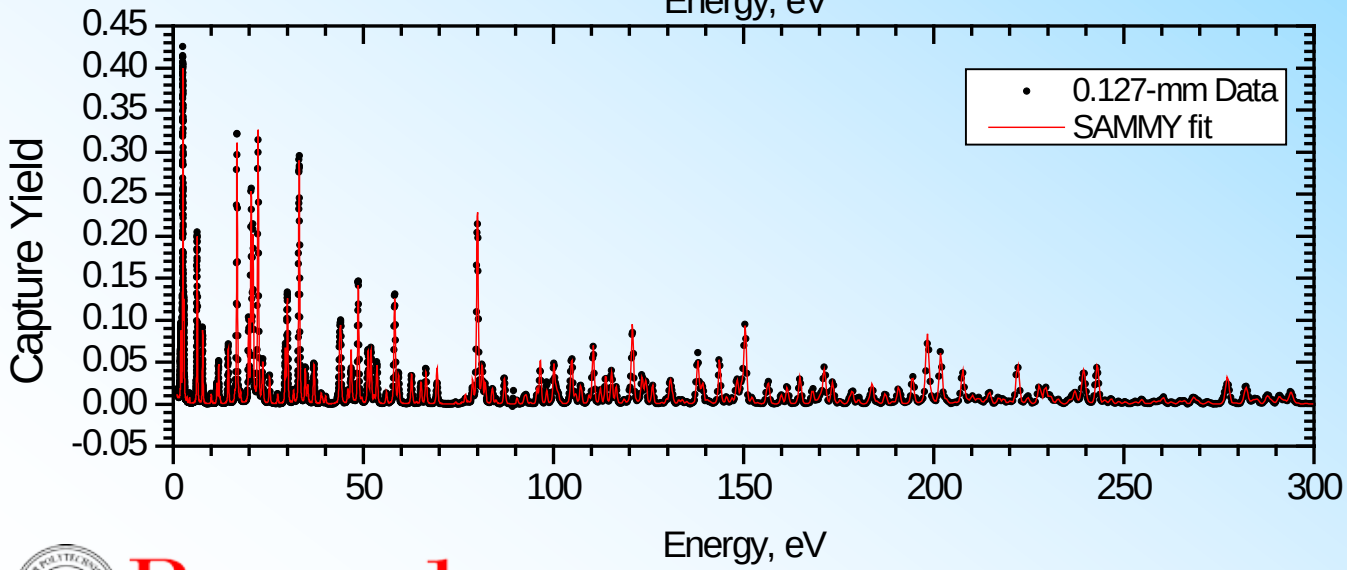
G Leinweber, DP Barry, JA Burke, NJ Drindak, RC Block, Y Danon, BE Moretti, "Resonance Parameters and Their Uncertainties Derived from Epithermal Neutron Capture and Transmission Measurements of Elemental Molybdenum", Nuclear Science And Engineering, **164**, 287-303, (2010)

Elemental Molybdenum 120 eV - 145 eV



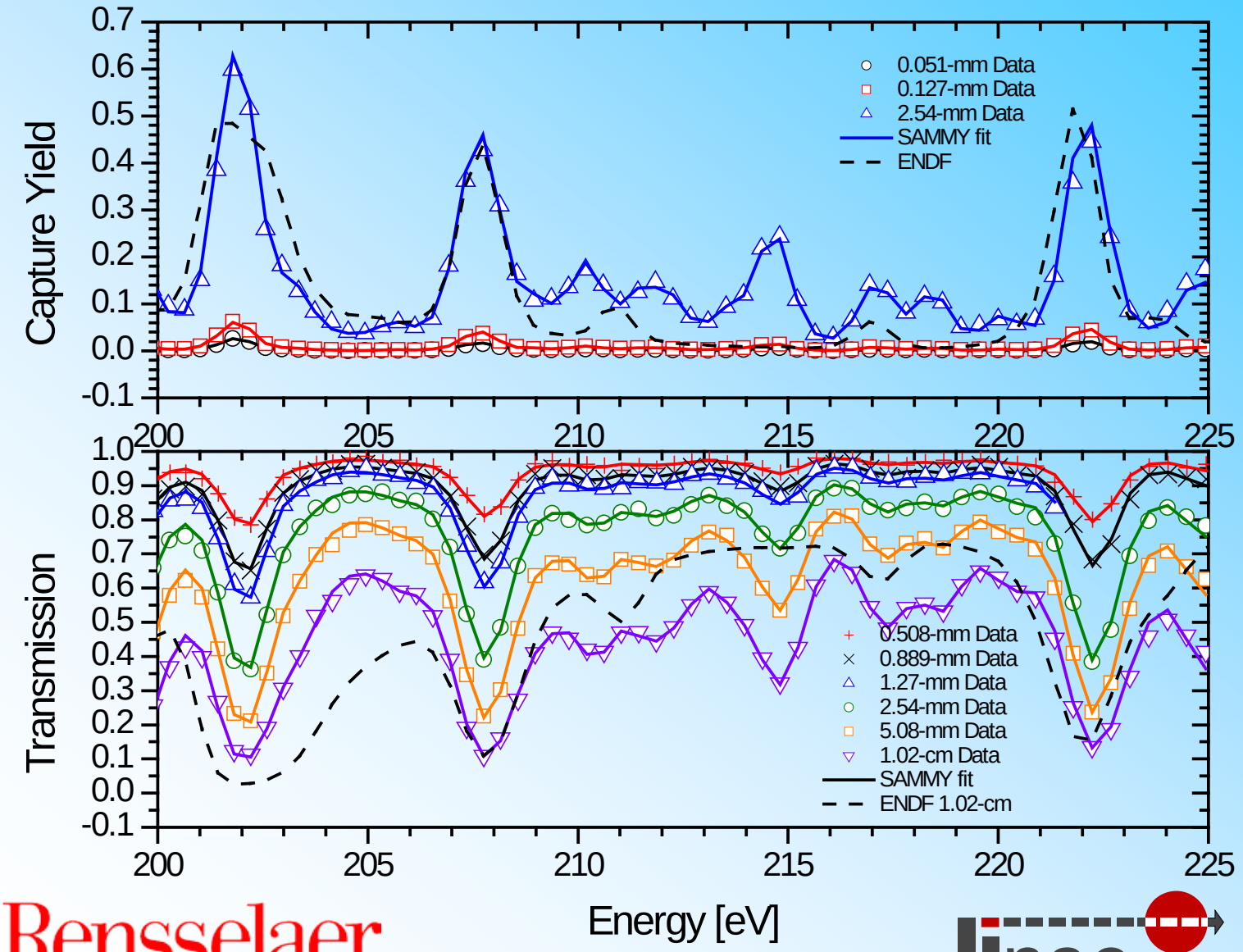
Gd Transmission and Capture



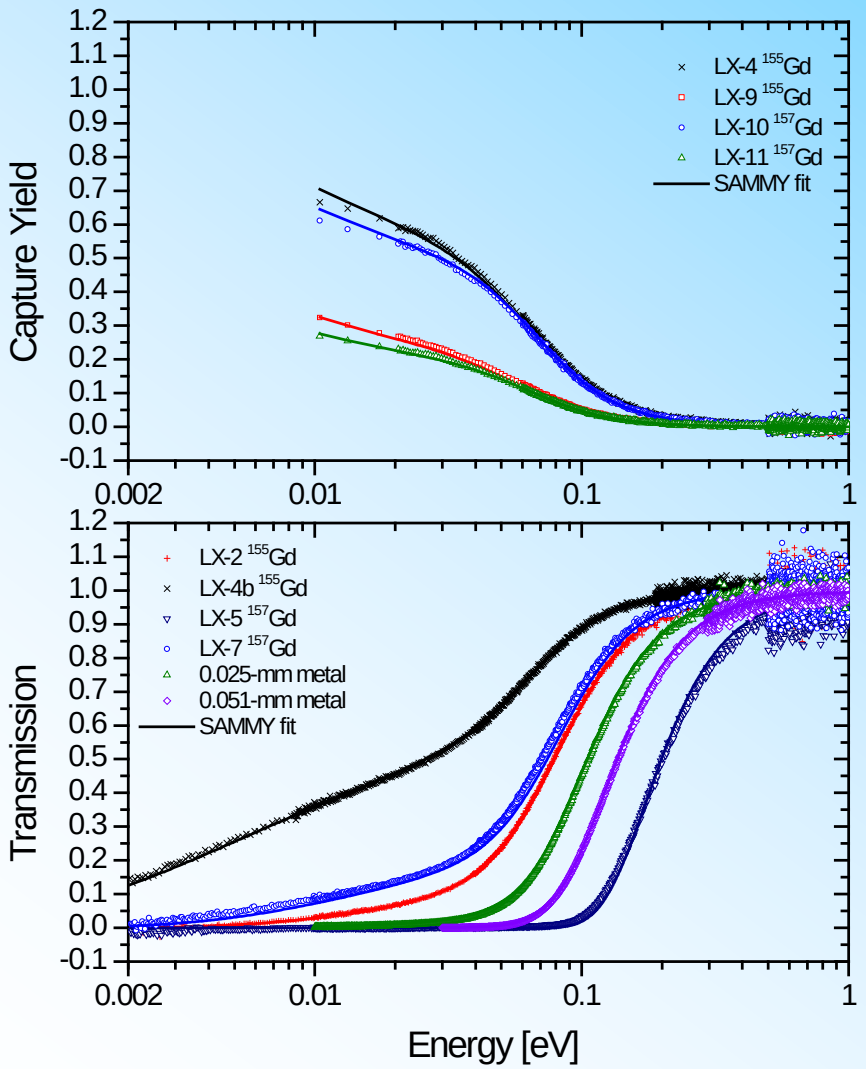


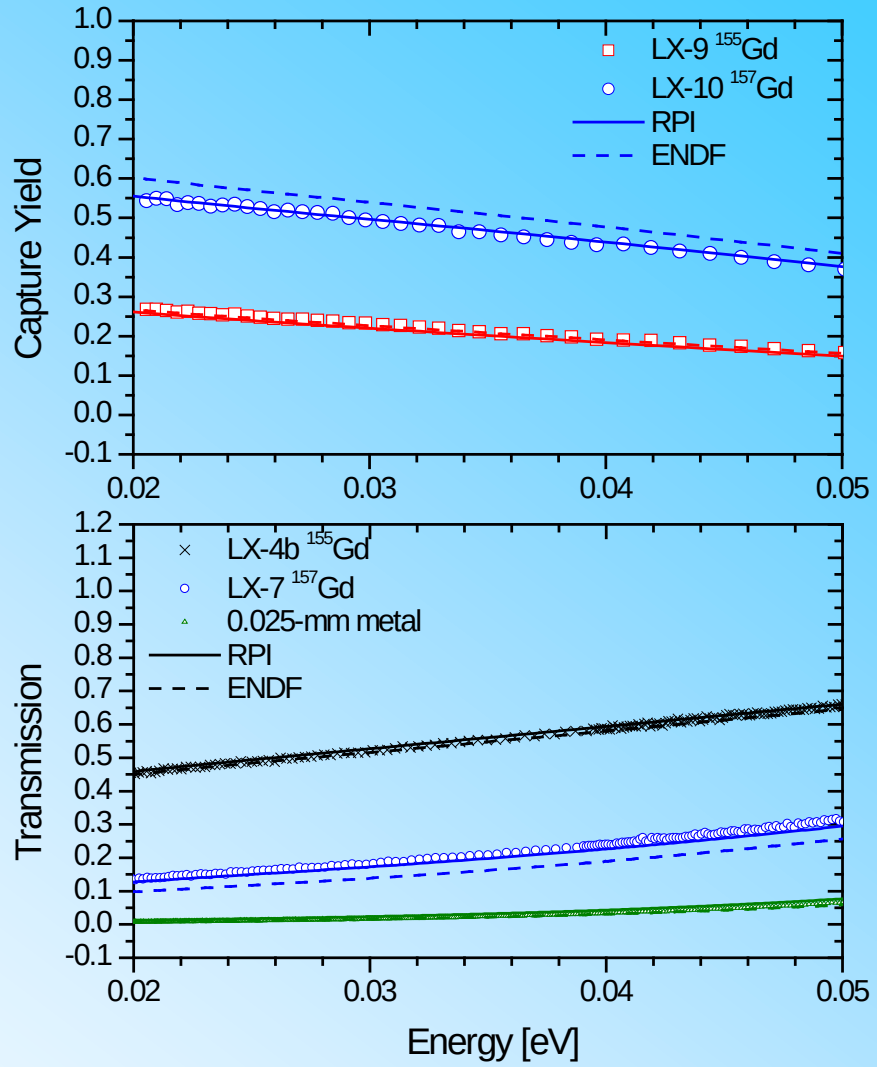
G. Leinweber, D.P. Barry, M.J. Trobovich, J.A. Burke, N.J. Drindak, , HD Knox, RV Ballad, R.C. Block, Y. Danon, L.I. Severnyak, "Neutron Capture and Total Cross-Section Measurements and Resonance Parameters of Gadolinium",. *Nuc. Sci Eng.* **154**, 261-279 (2006).

New Gd Resonances



^{155,157}Gd Thermal Region - Separated Isotopes





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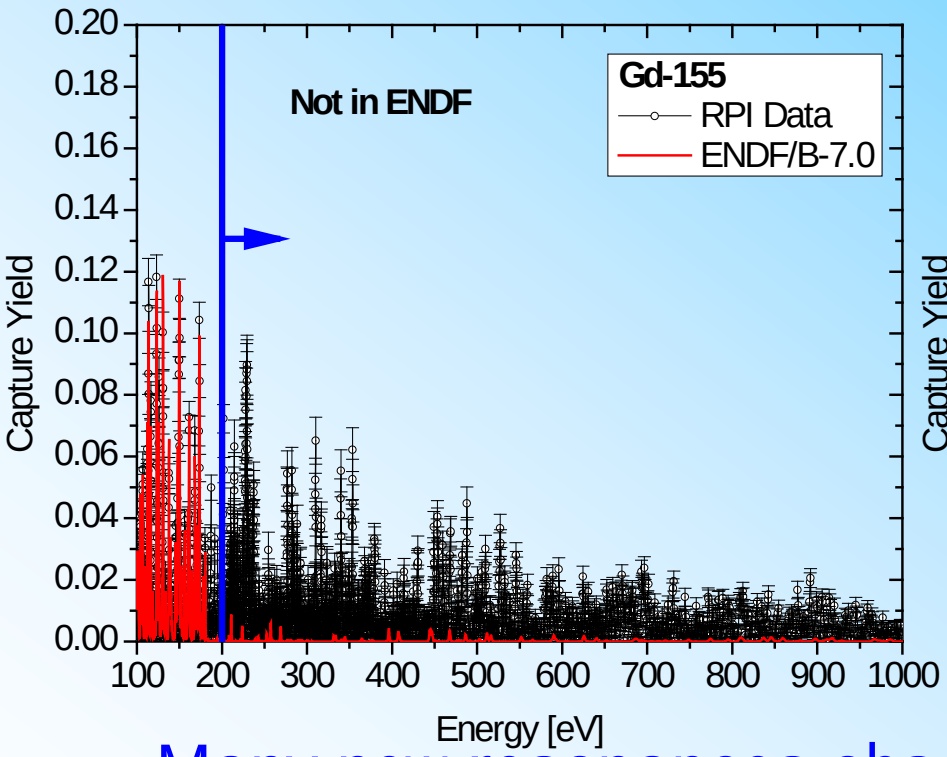
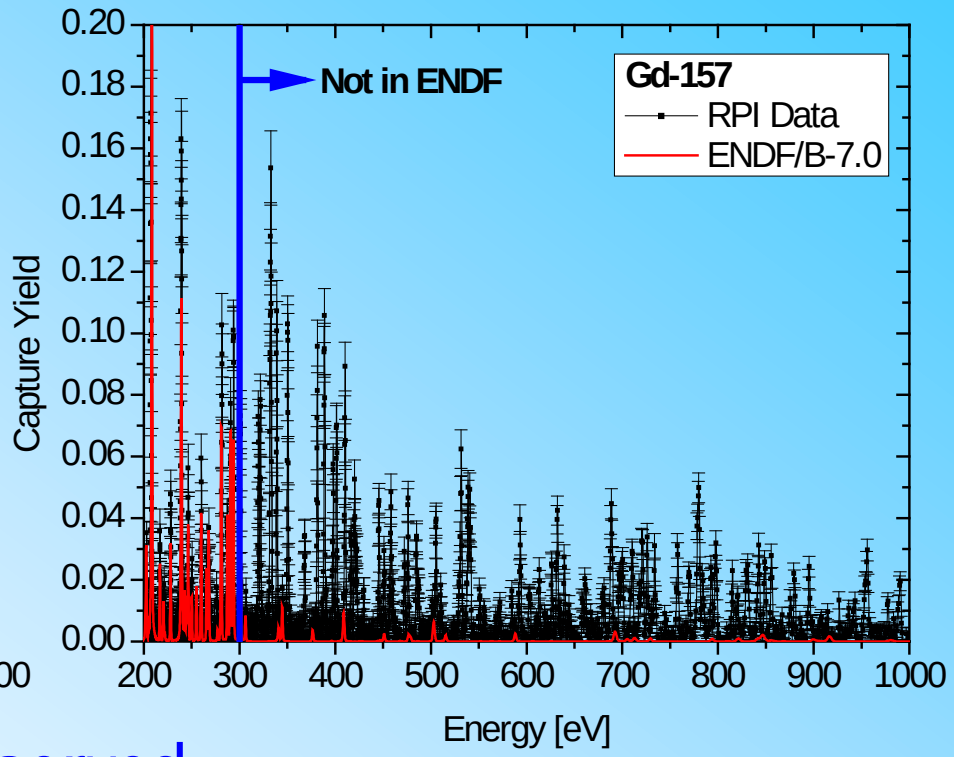
New ^{155,156,157,158,160}Gd Capture Measurements

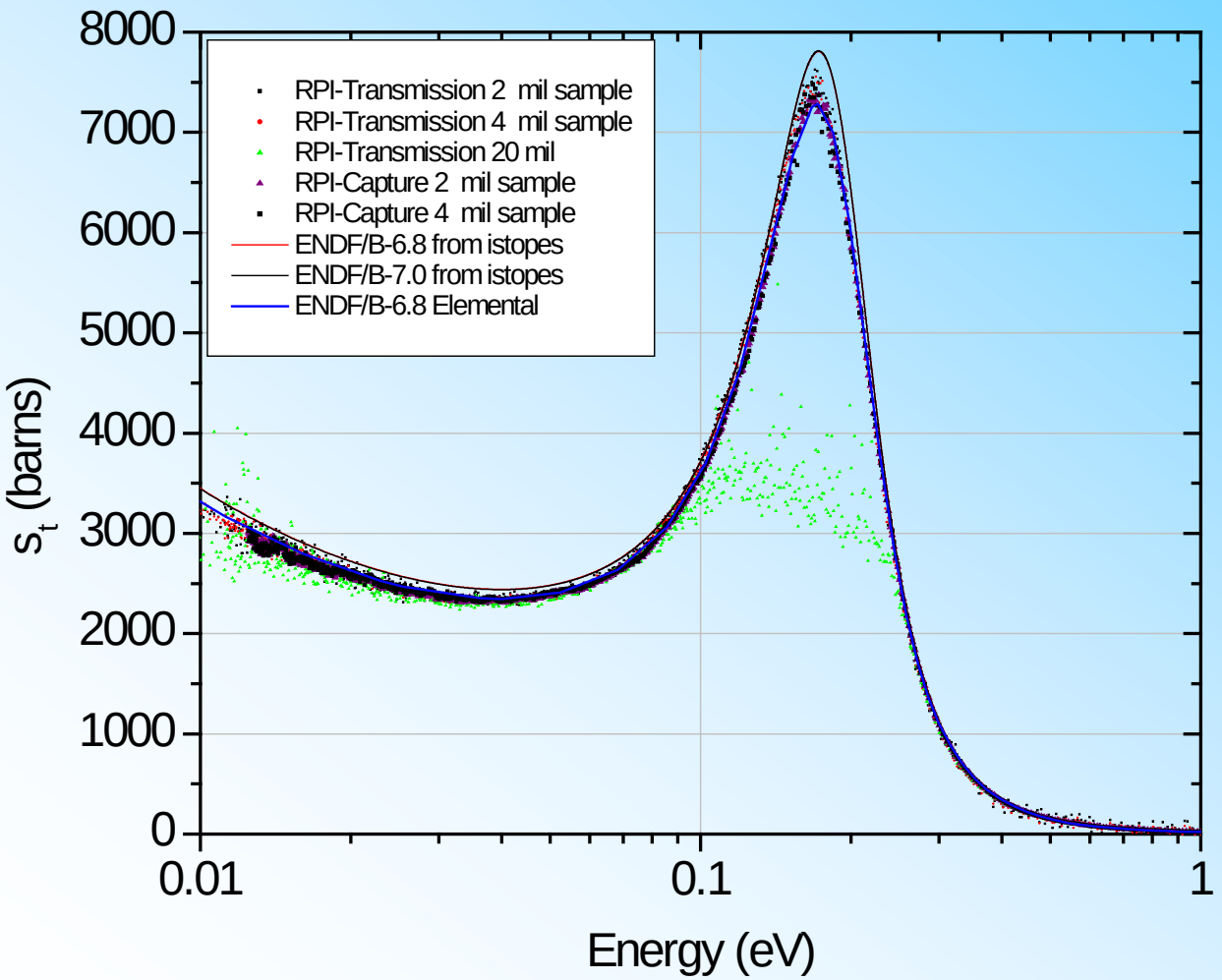




- Many new resonances observed

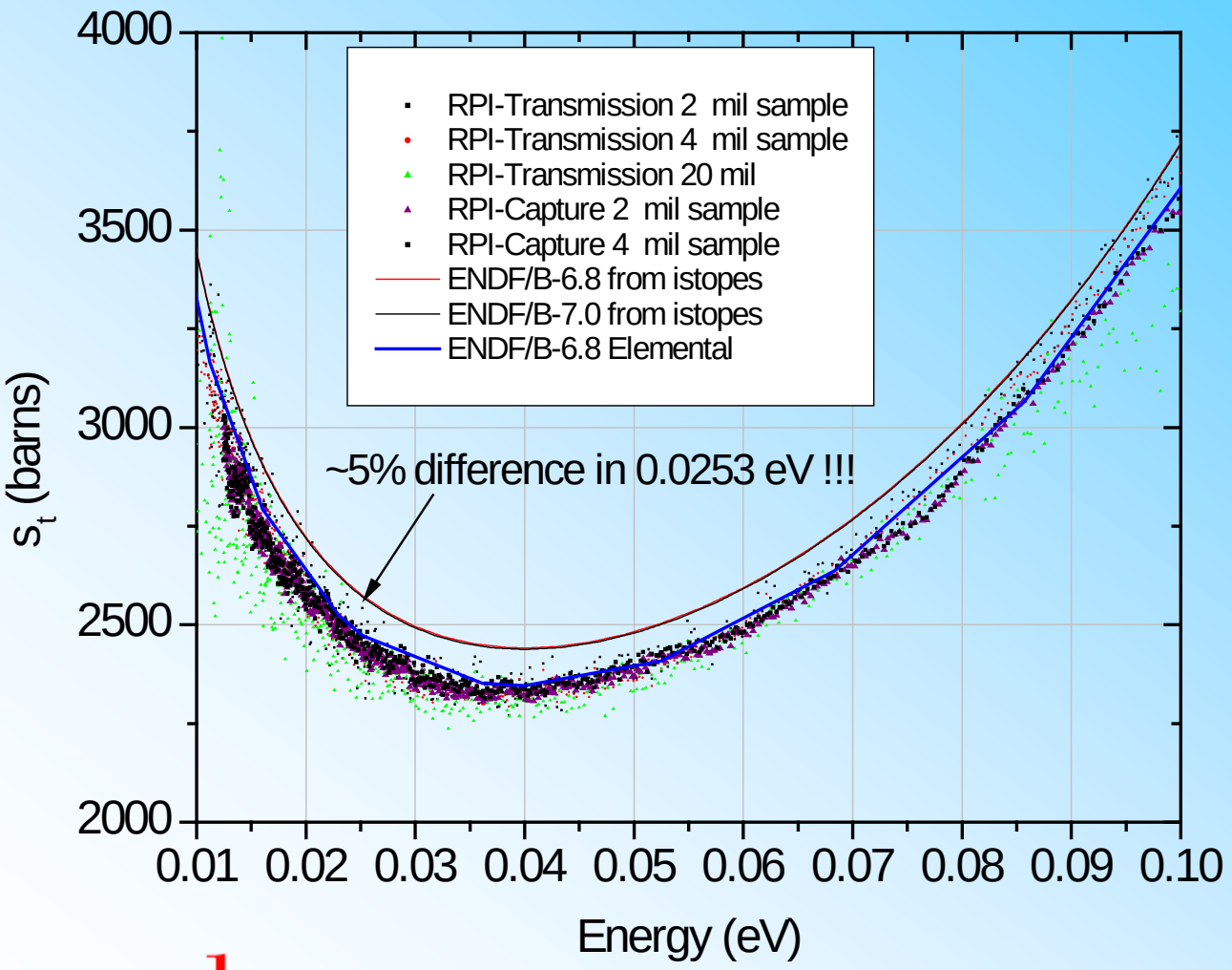
Yeong-Rok Kang, Tae-TK Ro, Taofeng Wang, Sung-shul Yang, Manwoo Lee, Guinyun Kim, Jong-Hwan Lee, Robert Block, Devin Barry and Yaron Danon, "Neutron Capture Measurements and Parameters of Gadolinium", International Conference on Nuclear Data for Science and Technology (ND2010), Korea, 26-30 April, 2010

Thermal Total Cross Section of Natural Cd - I

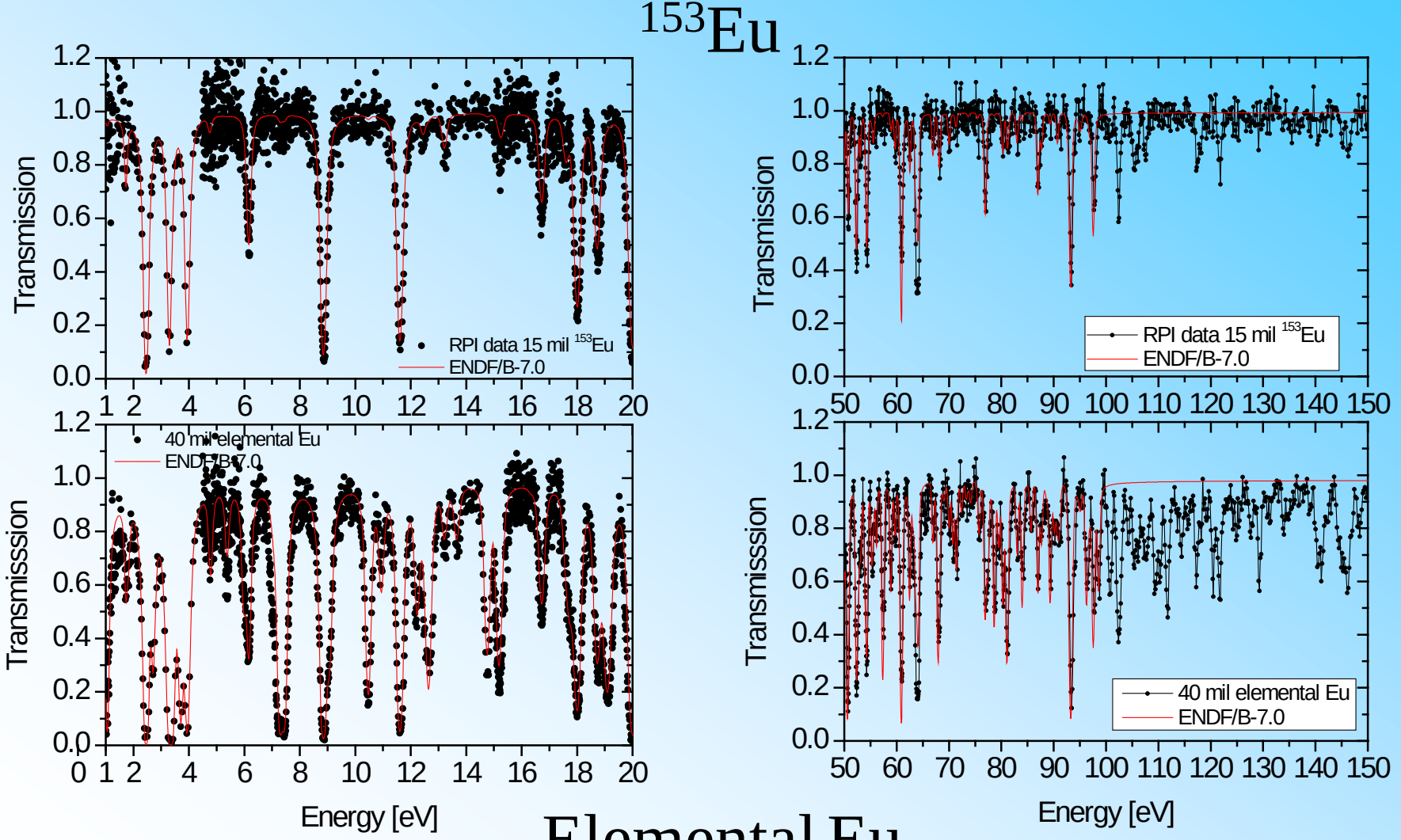


- The transmission and capture data are in very good agreement
- The data is in good agreement with ENDF/B-VI.8 elemental but not with the isotopic ENDF/B-VI.8 and ENDF/B-VII.0
- Surprisingly there are not many measurements of the thermal value.

Thermal Total Cross Section of Natural Cd - II



Eu Transmission compared to ENDF/B-7.0



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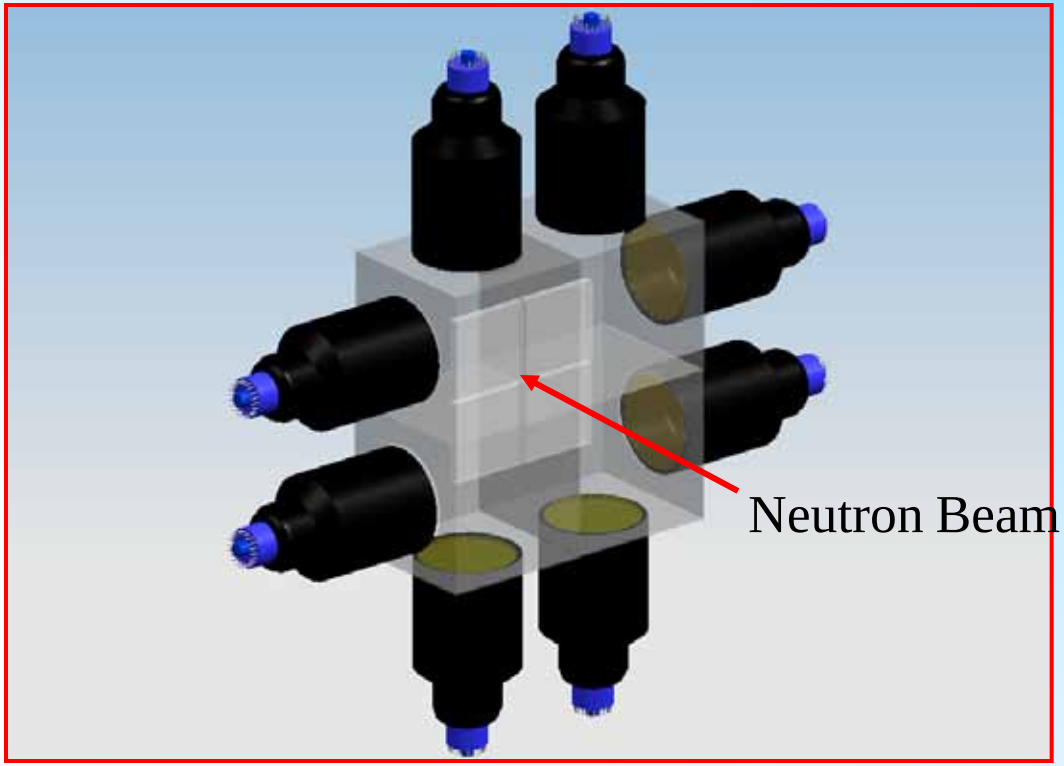
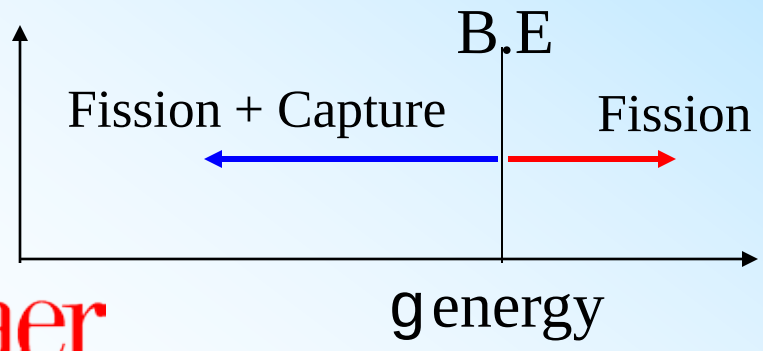
High Resolution Transmission Detector

- Modular Li-Glass detector at 100m flight path
  - Extends our capabilities to the unresolved resonance region
  - Qualification measurements in progress.

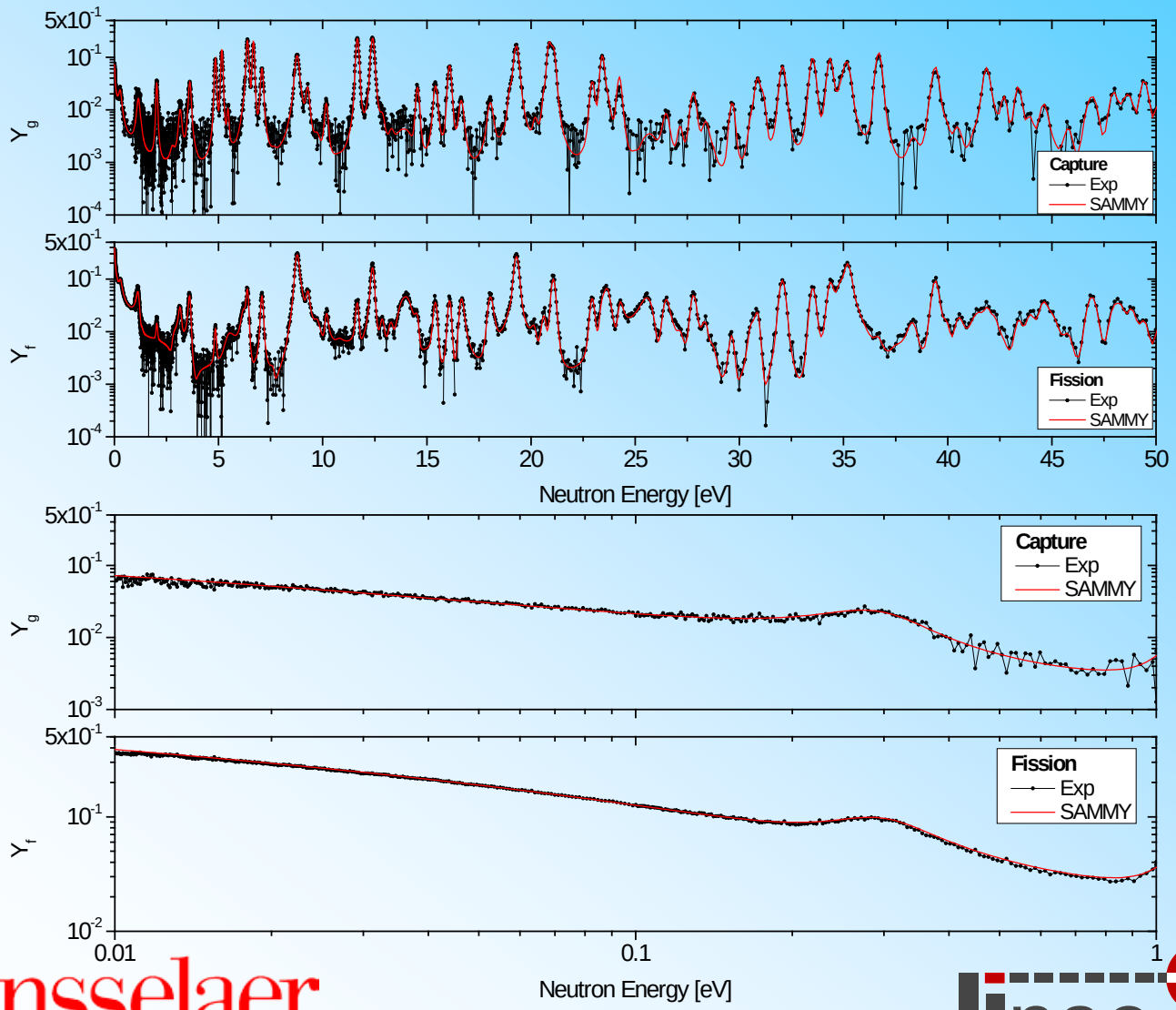


^{235}U Alpha Measurements

- Place a ^{235}U sample in the multiplicity detector
- Measurements with ^{235}U samples
  - Use the multiplicity information
  - Use data above and below neutron binding energy

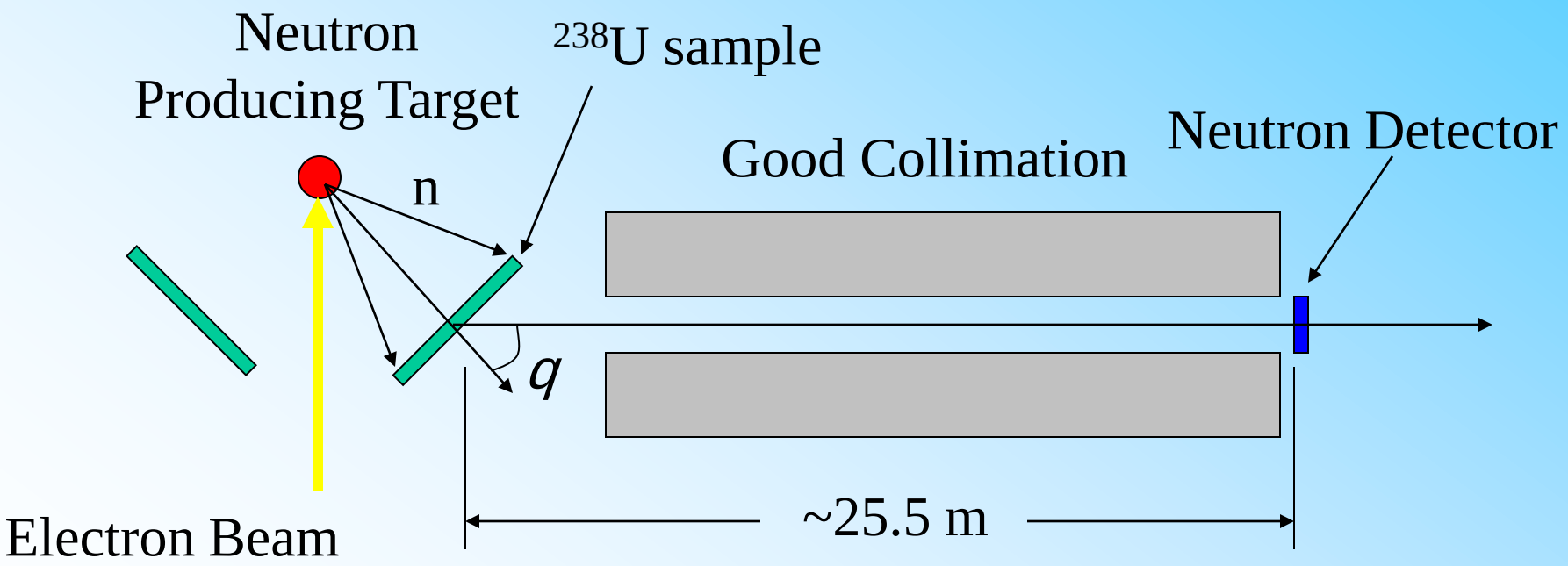


Simultaneous Measurement of the Fission And Capture Cross Section of ^{235}U

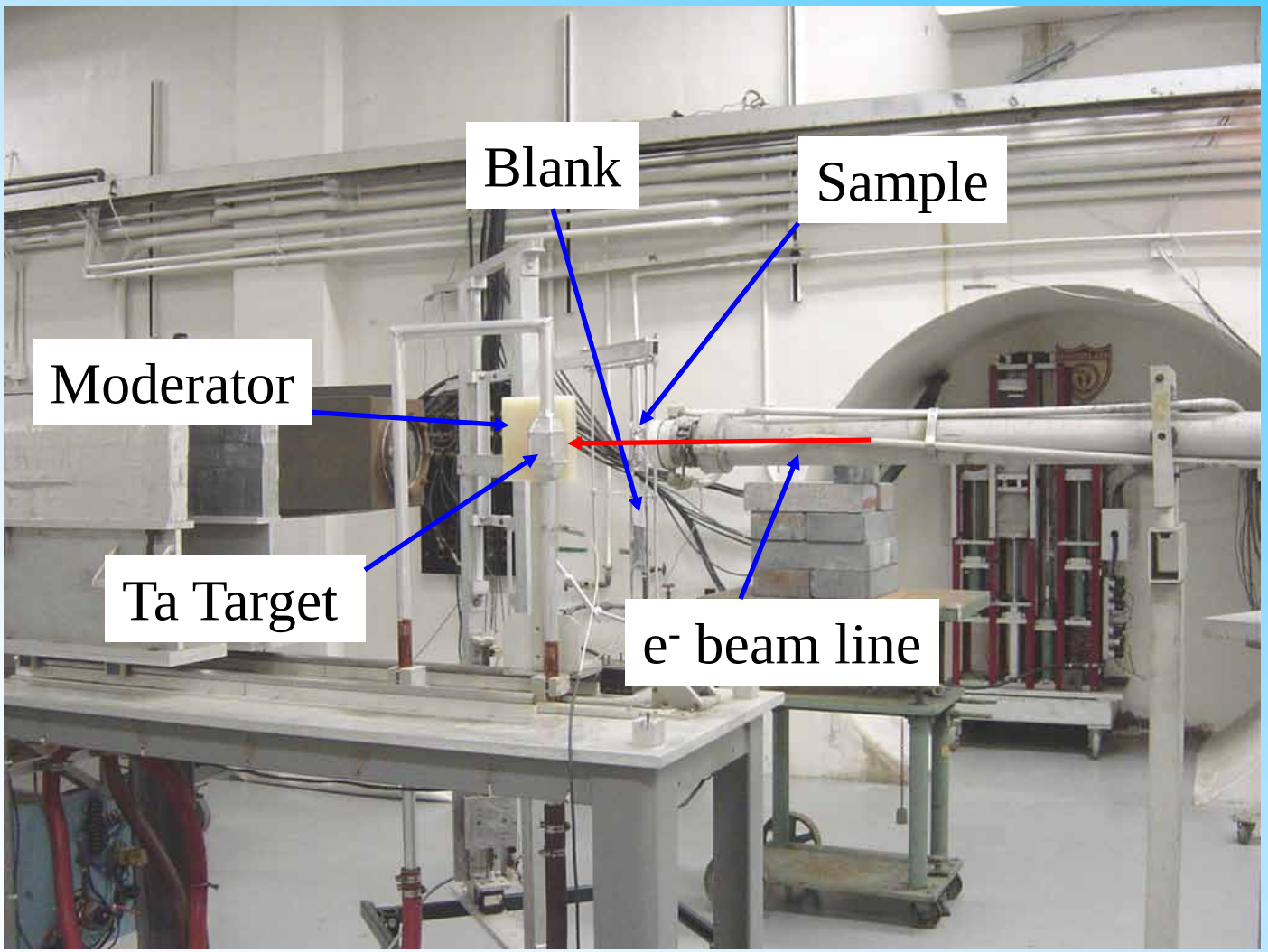


Resonance Scattering Experiment

- Motivation – Provide a benchmark to the model Developed by Dagan et al.
  - Current MC codes have a poor approximation of the scattering kernel in the vicinity of a resonance.
- Use the Time-Of-Flight (TOF) method
  - The TOF will correspond to the scattered neutron energy
  - Scattering in forward and backward scattering angles can be measured

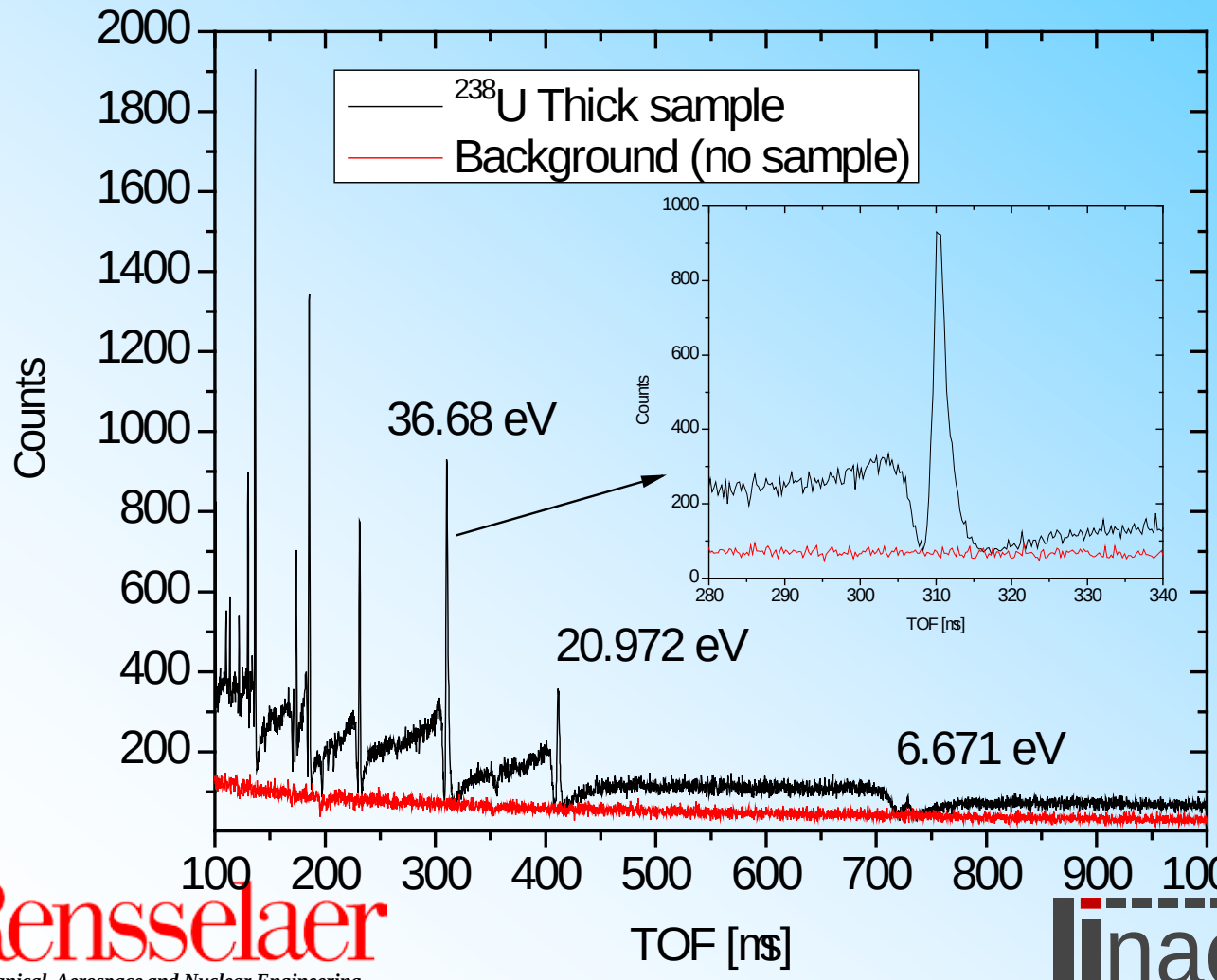


Experimental Setup

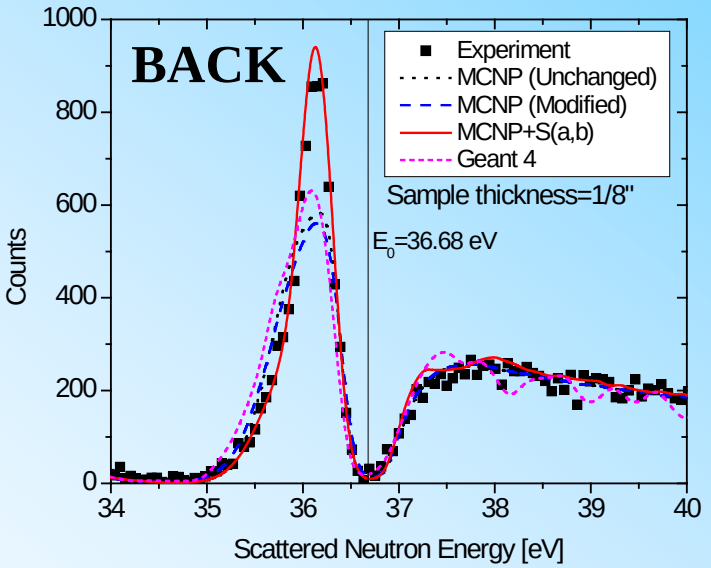


Measured Data

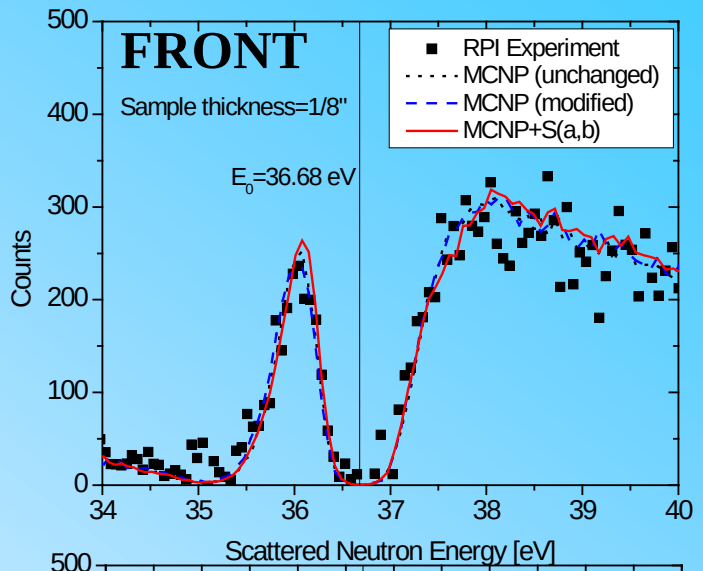
- Thick Sample time-of flight spectrum forwards scattering

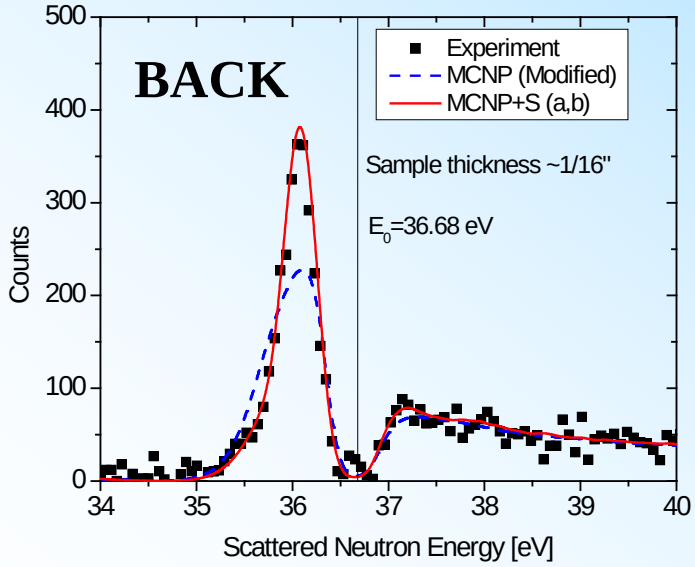


Results - ^{238}U Scattering

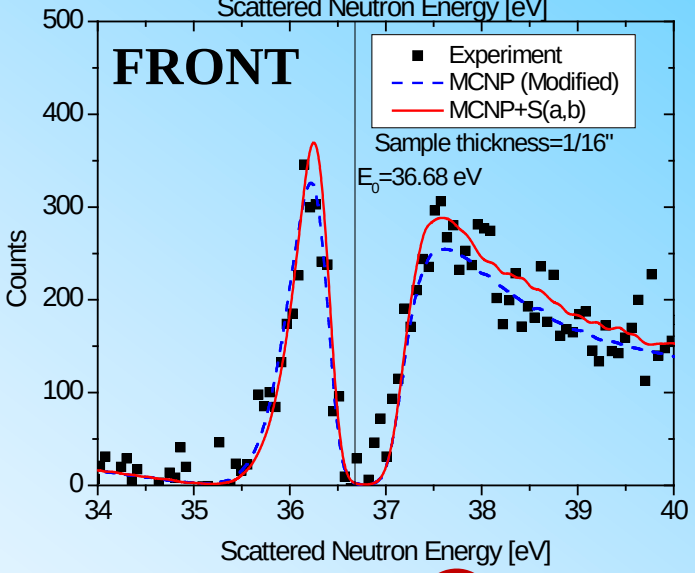


Thick Sample





Thin Sample



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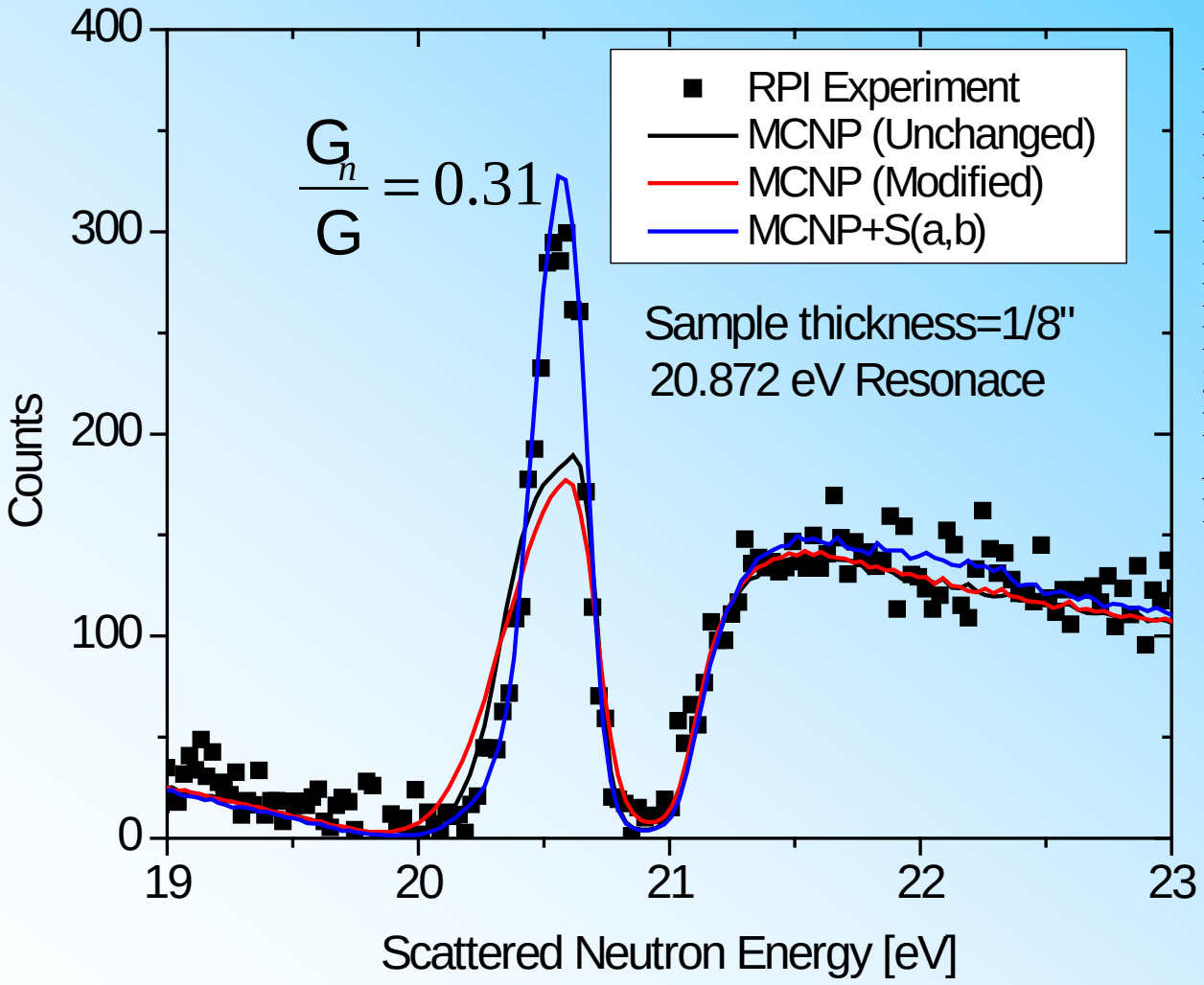
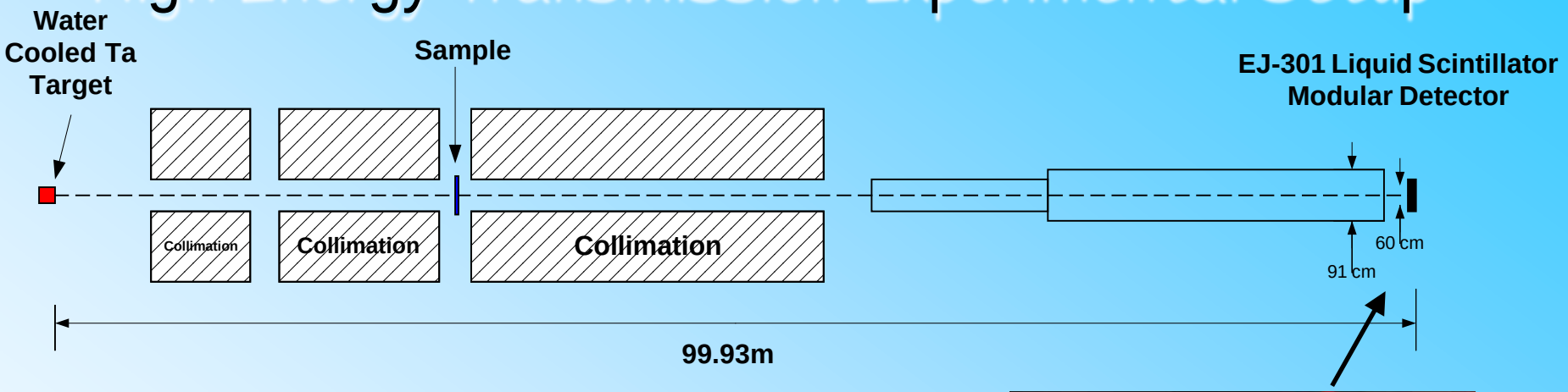
Other Resonances (Back Scattering)

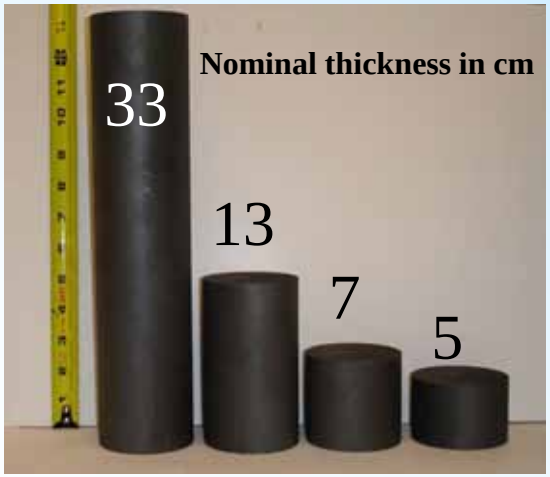


Y. Danon, E. Liu, D. Barry, T. Ro, R. Dagan, "Benchmark Experiment of Neutron Resonance Scattering Models In Monte Carlo Codes", International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, May 3-7, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009).

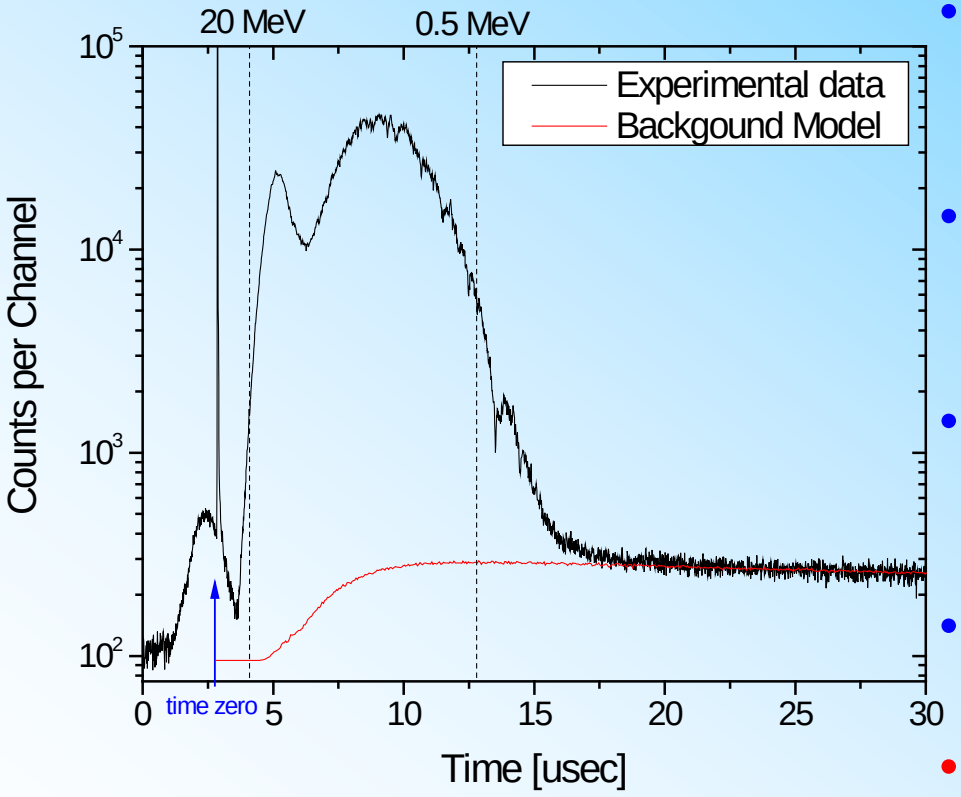
High Energy Transmission Experimental Setup



Graphite Samples

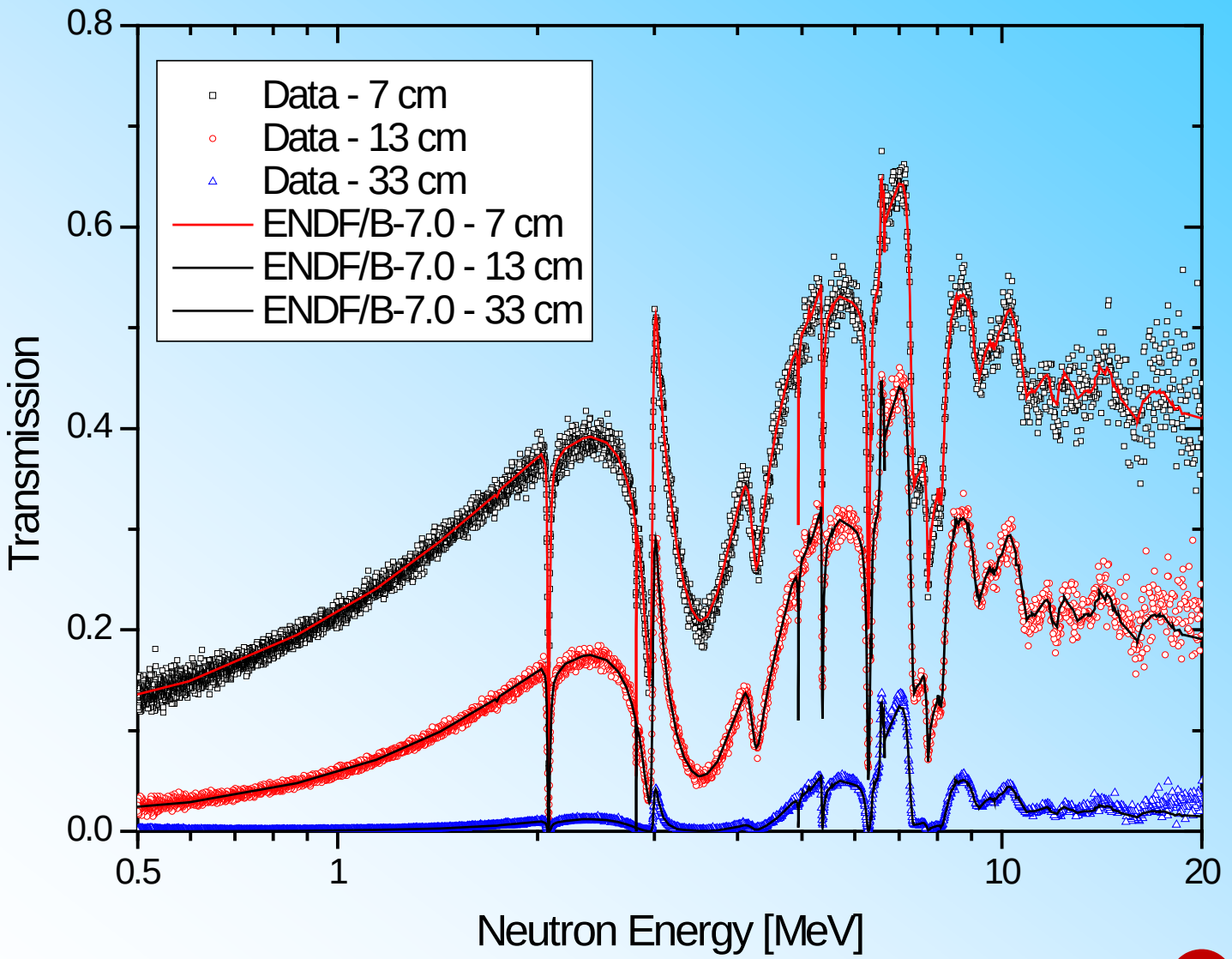


Background Determination

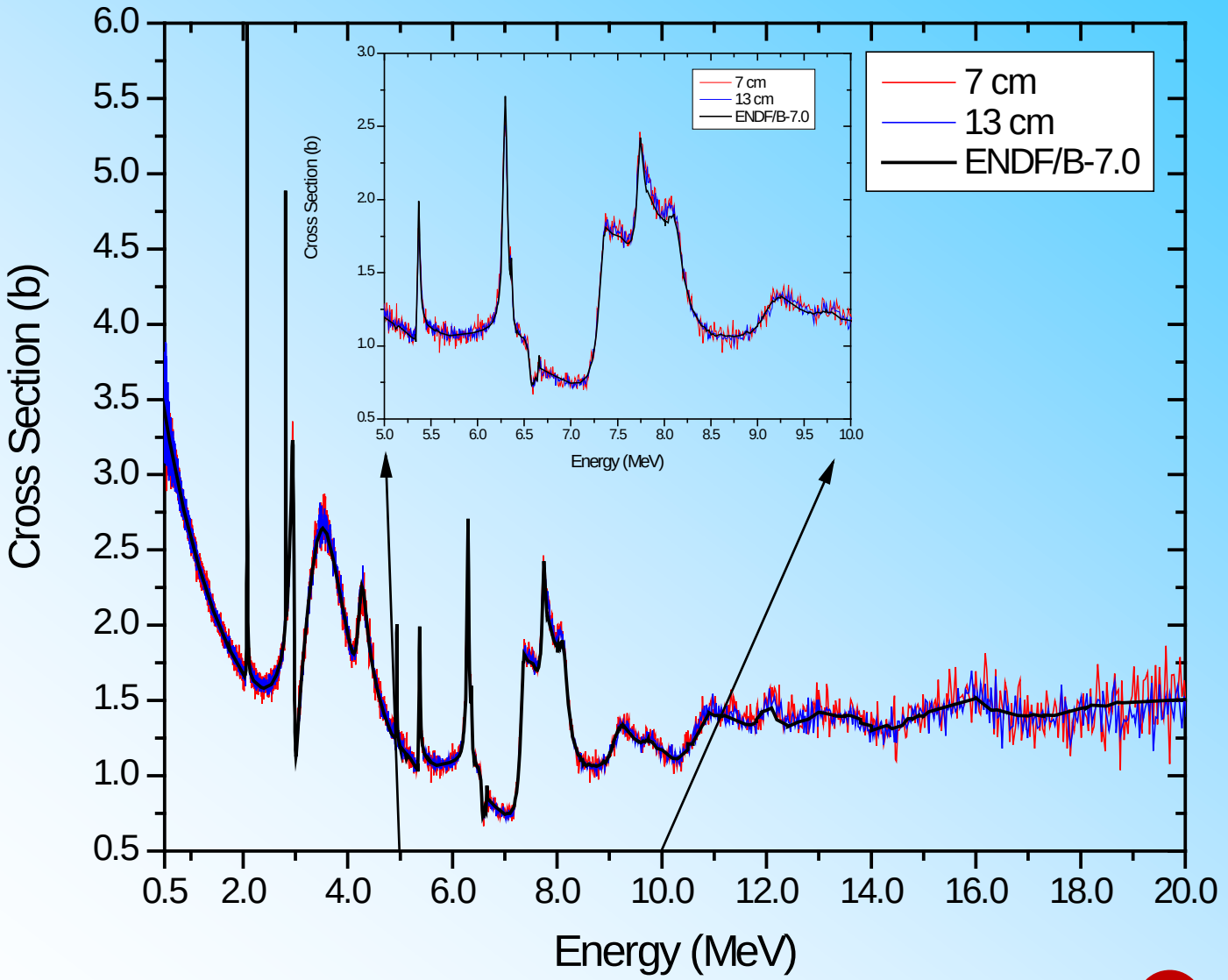


- MCNP was used to simulate background due to neutron capture interactions with the detector
- 2.2 MeV photons from hydrogen neutron capture were tallied in the detector volume as a function of time
- The MCNP tally was normalized to the exponentially decaying portion of the collected data (t>20 ms)
- The MCNP results were fitted to a pulse shape curve
- 18<(Sig-Bkg)/Bkg <200

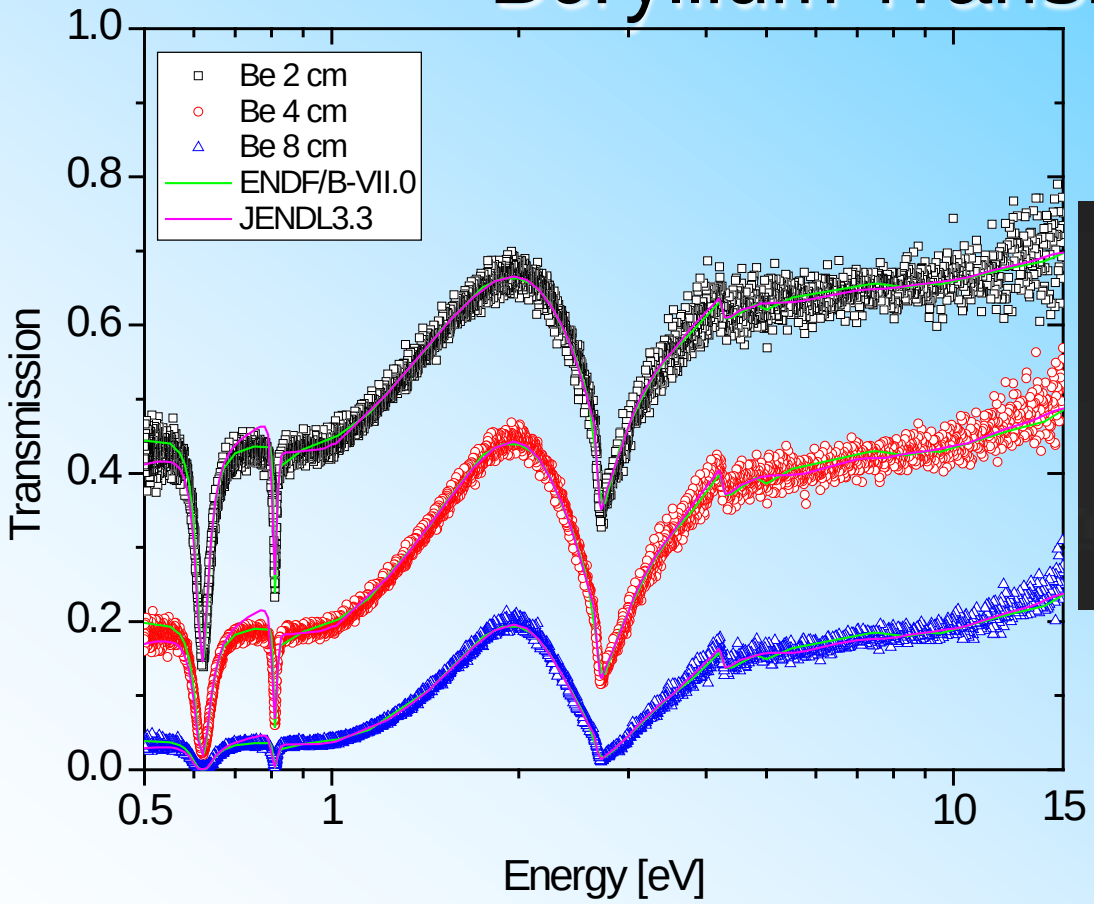
Graphite Transmission



Results – Carbon Total Cross Section



Beryllium Transmission



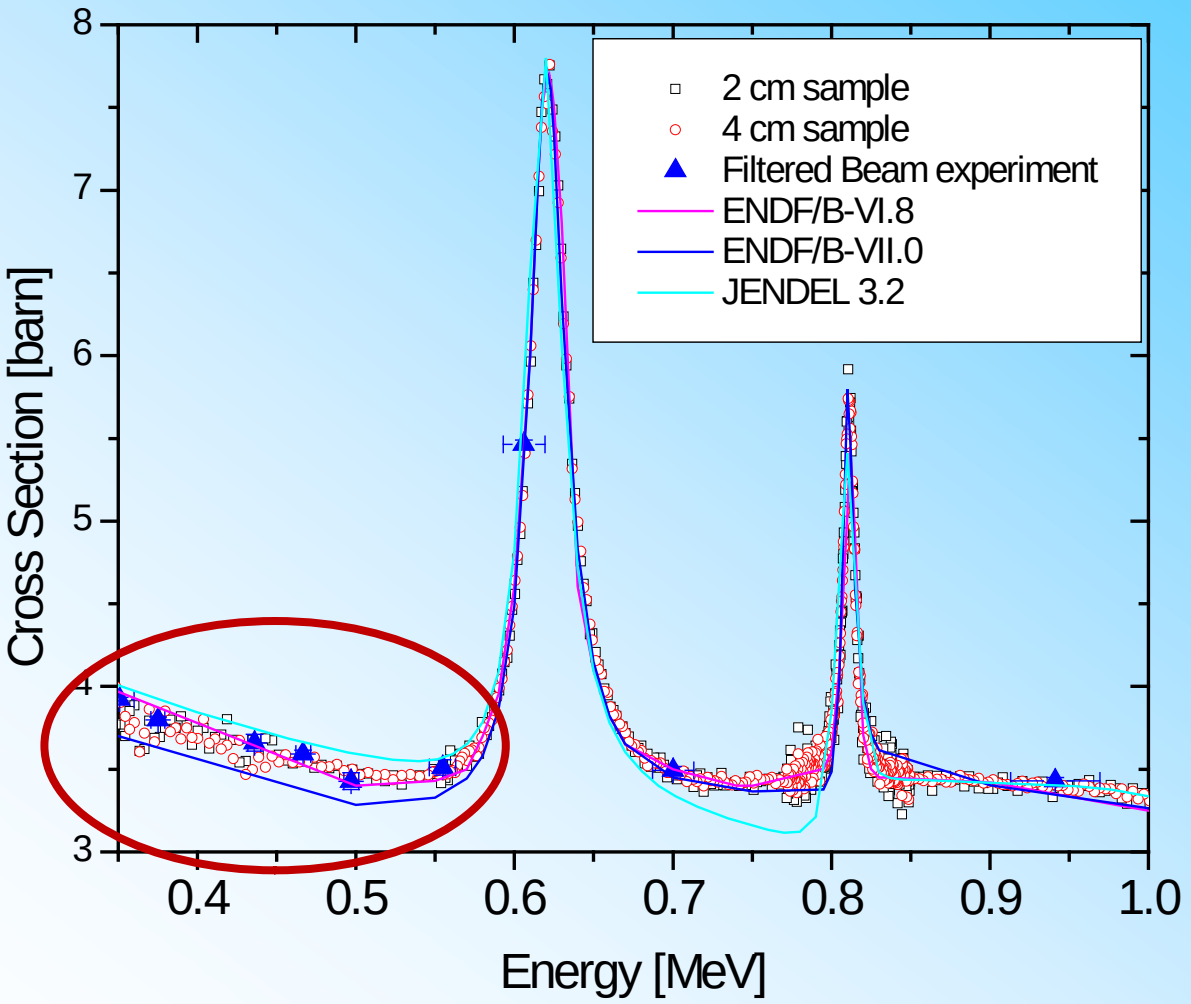
Beryllium samples

Sample thickness is given in cm

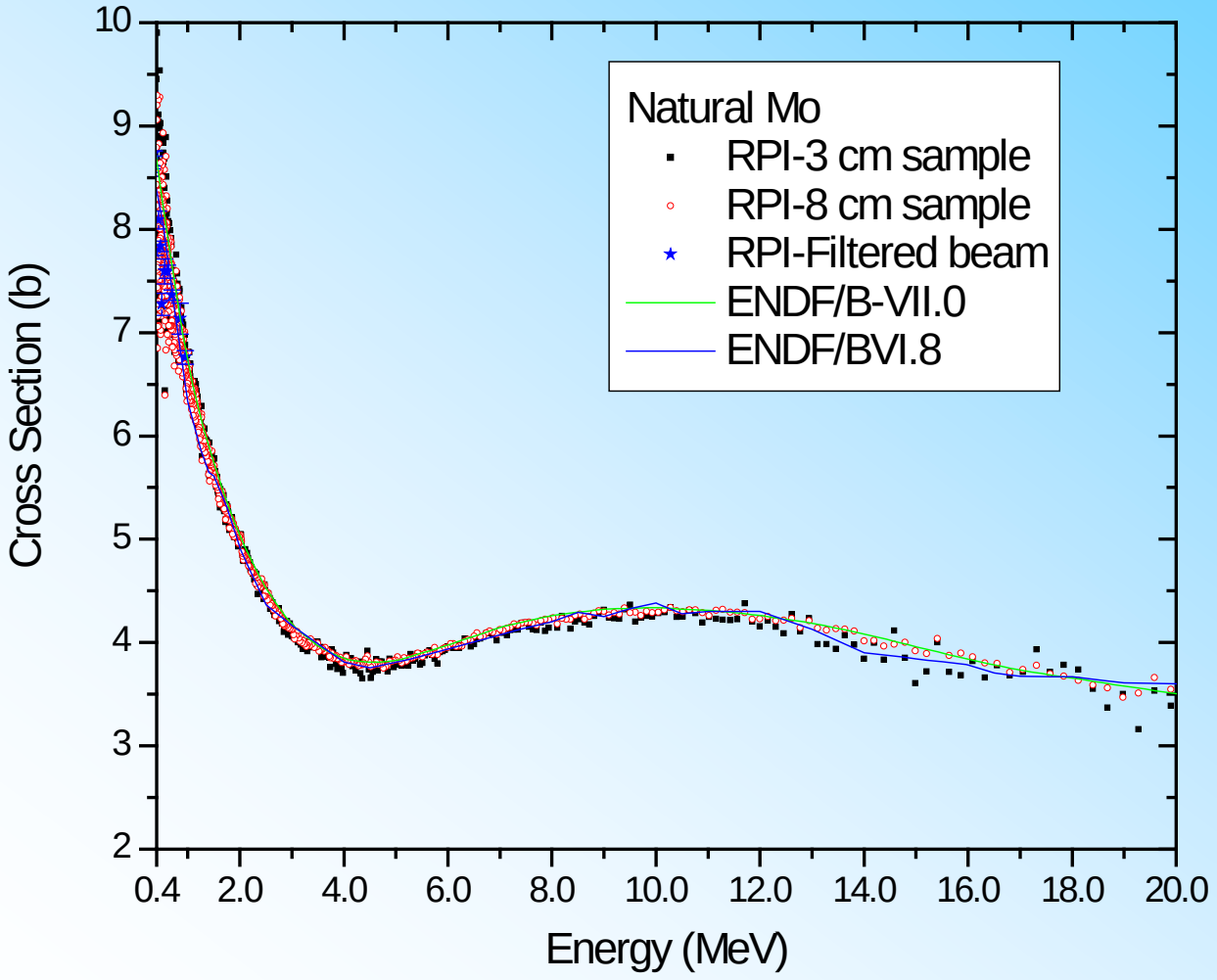
Reconfigured the detector with two units to reduce background

M. Rapp, Y. Danon, R. C. Block, F. Saglime, R. Bahran, G. Leinweber, D. P. Barry, N. Drindak, "High Energy Neutron Time of Flight Measurements of Carbon and Beryllium Samples at the RPI LINAC", 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)

Beryllium Total Cross Section (Low Energy)

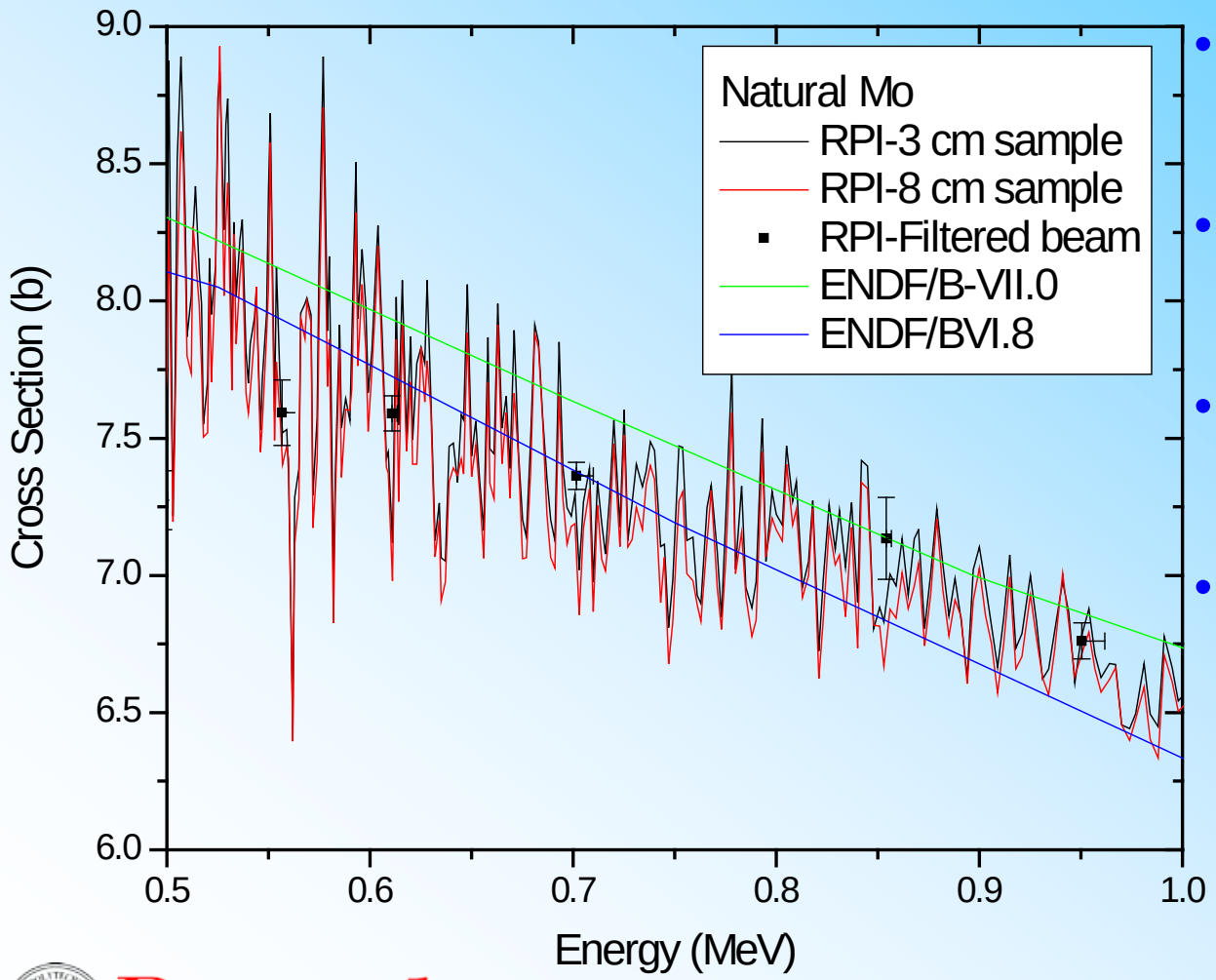


Mo Total Cross Section



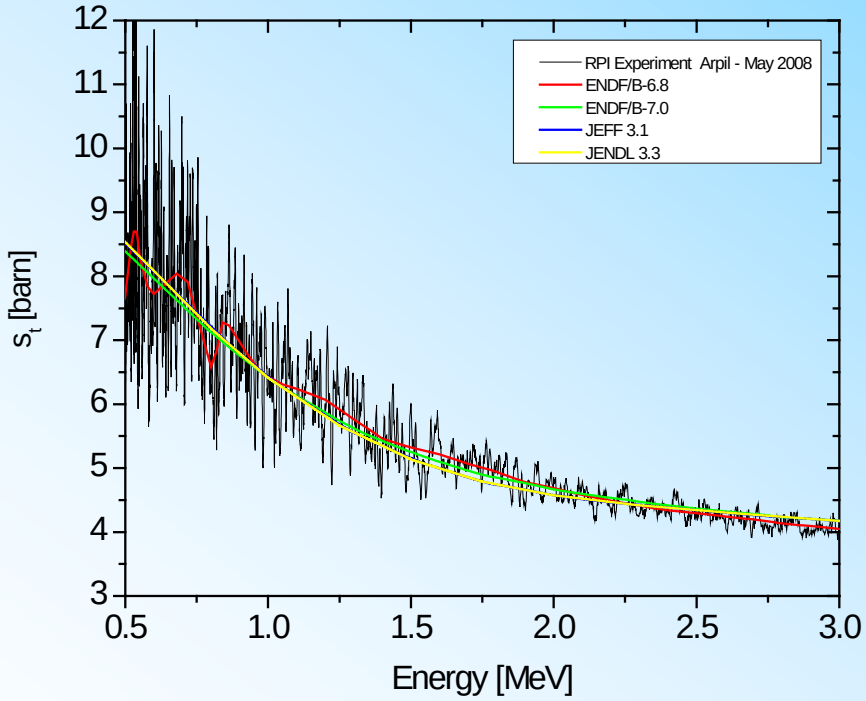
M. Rapp, Y. Danon, F. Saglime, Rian Bahran, Robert Block, Greg Leinweber, Devin Barry, Jeff Hoole, "Molybdenum and Zirconium Neutron Total Cross Section Measurements in the Energy Range of 0.5 to 20 MeV", International Conference on Nuclear Data for Science and Technology (ND2010), Korea, 26-30 April, 2010

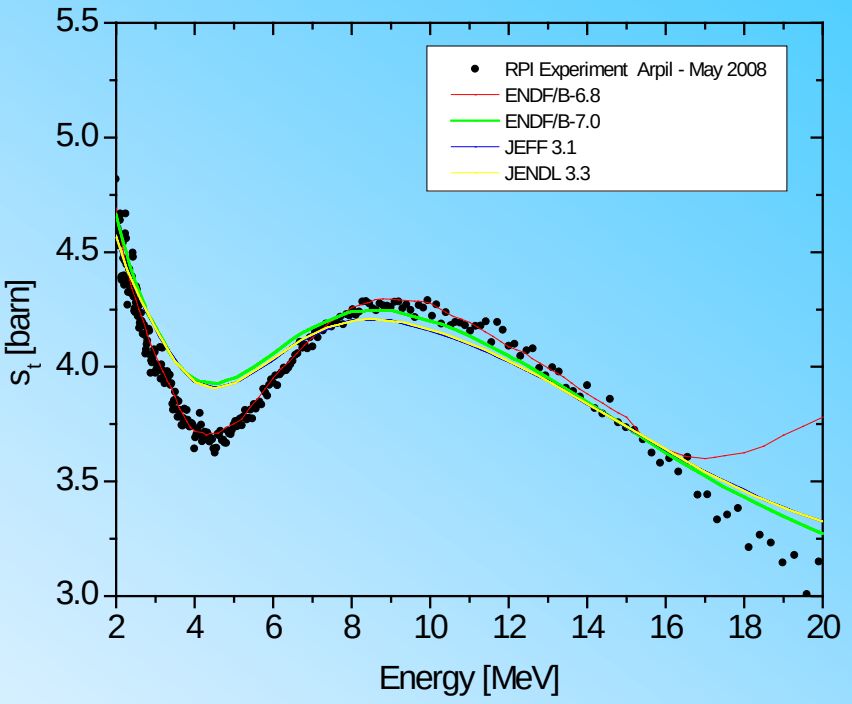
Mo Total Cross Section Below 1 MeV



- Notice the visible structure in the cross section
- Better agreement with ENDF/B-VII.0. below 0.8 MeV
- Should ENDF evaluations include some of this structure ?
- The filtered beam transmission data is in good agreement with the transmission data

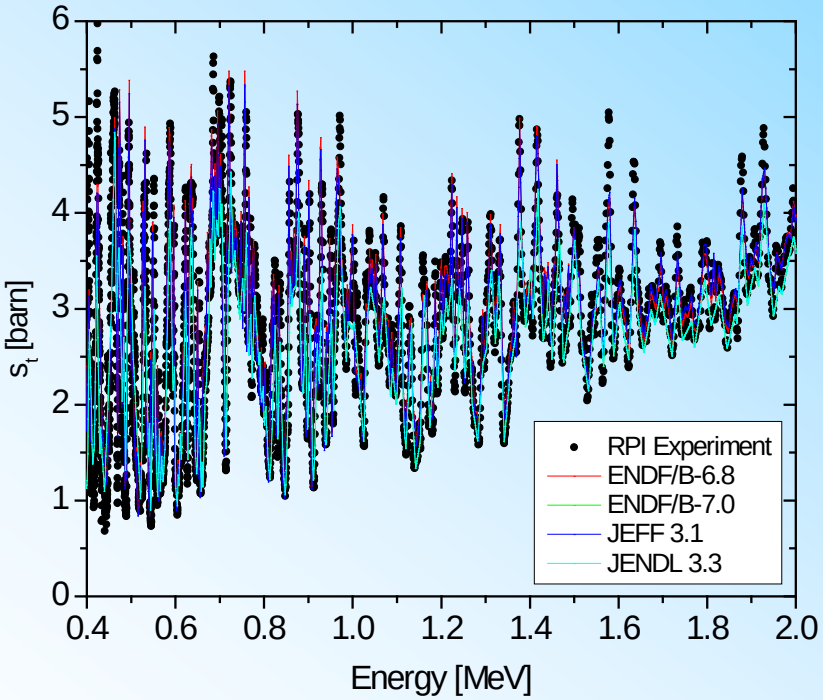
Zr Total Cross Section Measurements (0.5-20 MeV)

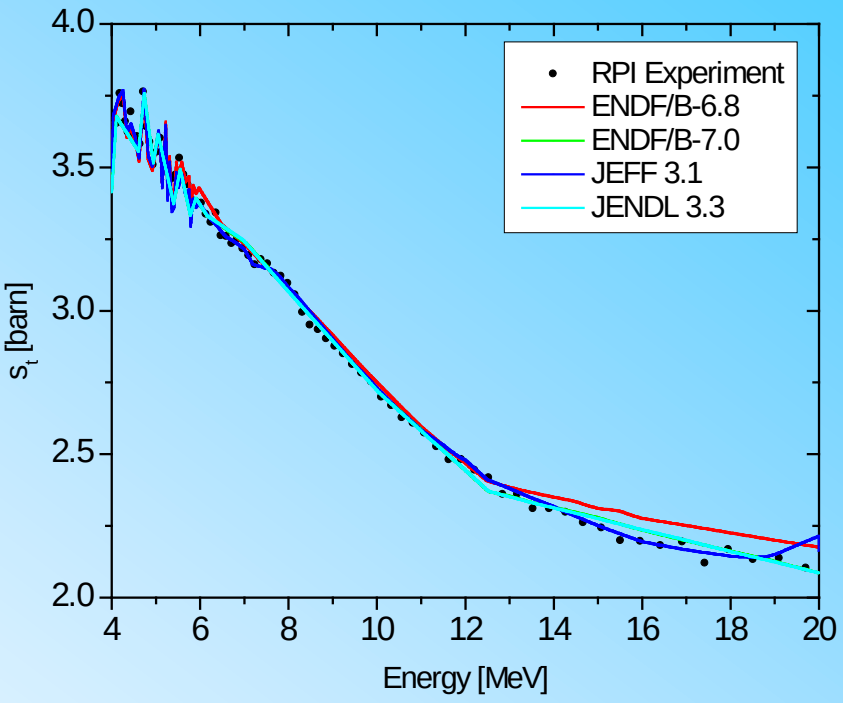




- Used low Hf (less than 100 ppm) Zr metal
- ENDF/B 6.8 seems like a better fit for E<16 MeV
- New partially resolved structure below 2.0 MeV
- Data can be used to improve the unresolved resonance region evaluation

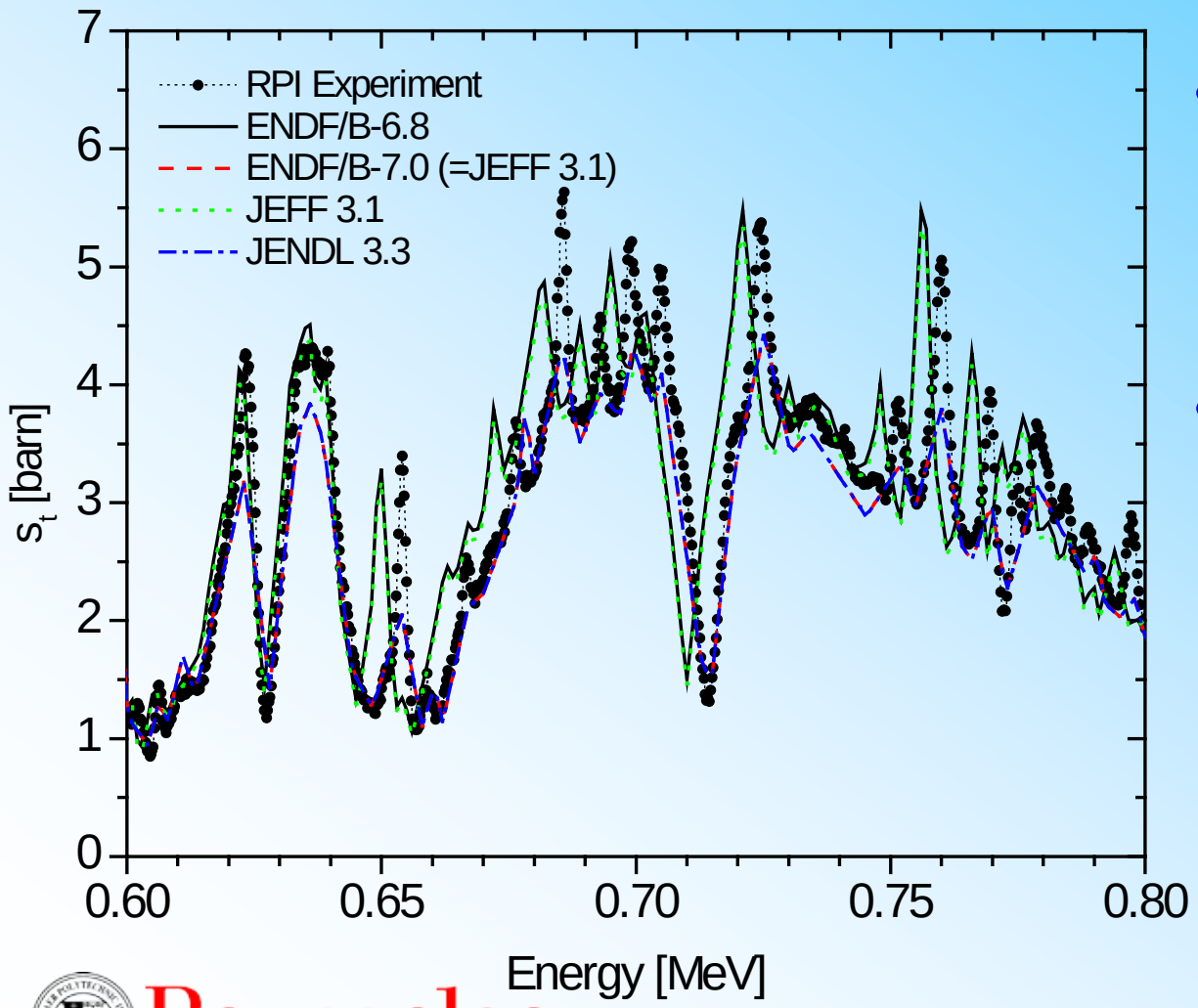
Ti Total Cross Section Measurements (0.5-20 MeV)





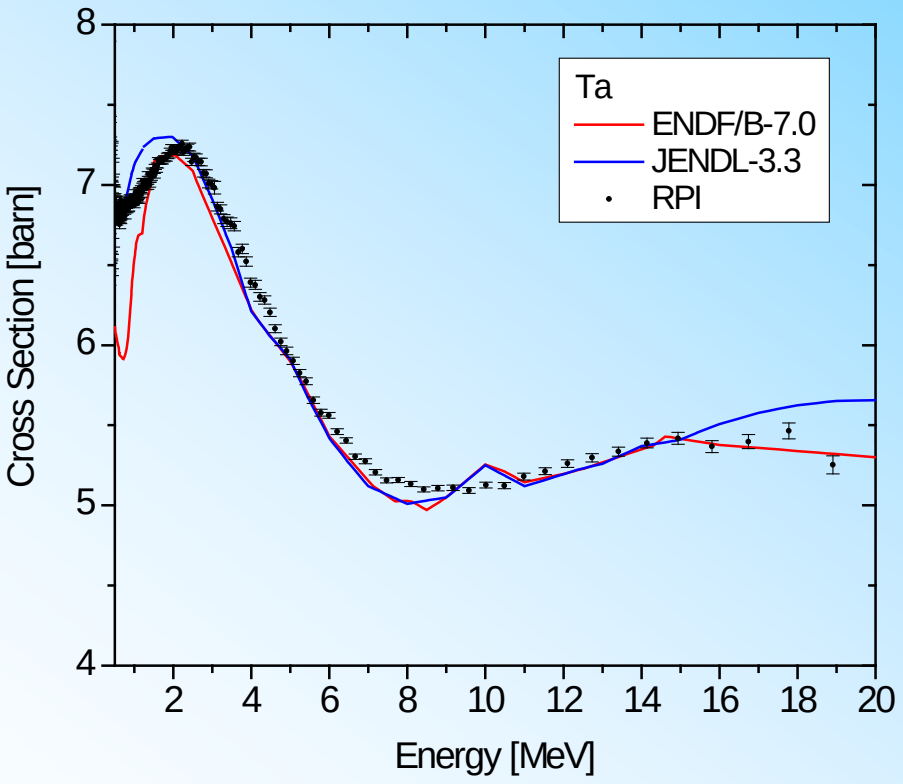
- The evaluation are generally in good agreement with the data
- Below 2 MeV the data has better energy resolution than the evaluation

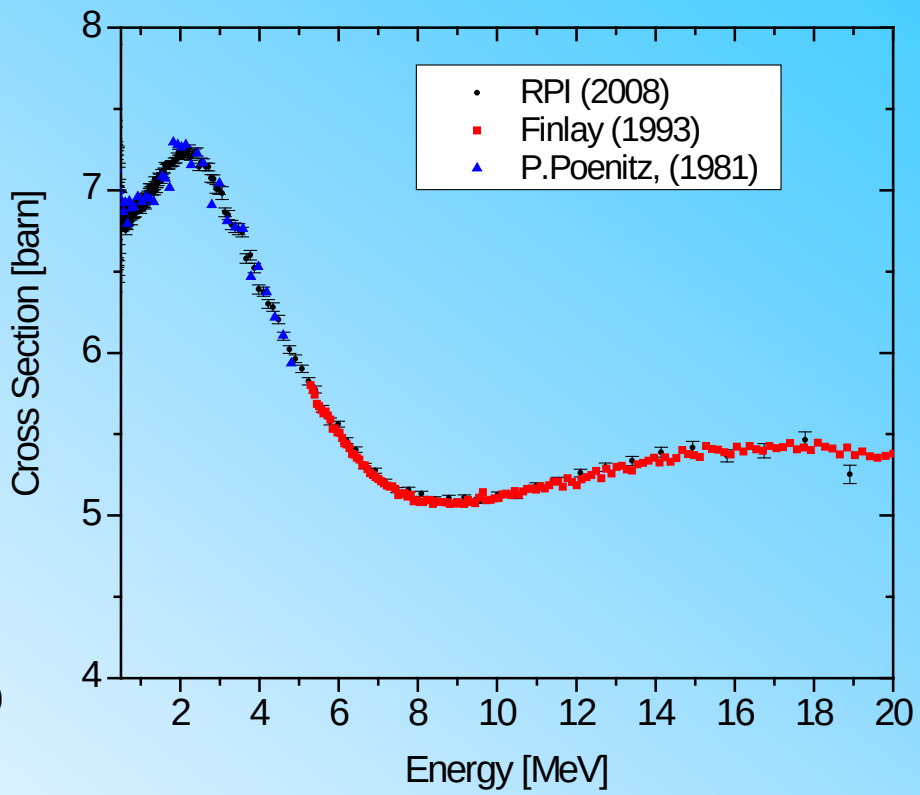
Ti Total Cross Section Measurements
0.5-1 MeV energy region



- The ENDF/B 6.8 and JEFF3.1 evaluations seem to have an energy shift.
- ENDF/B-7.0 and JENDL 3.3 are similar and seem to be based on low resolution measurements

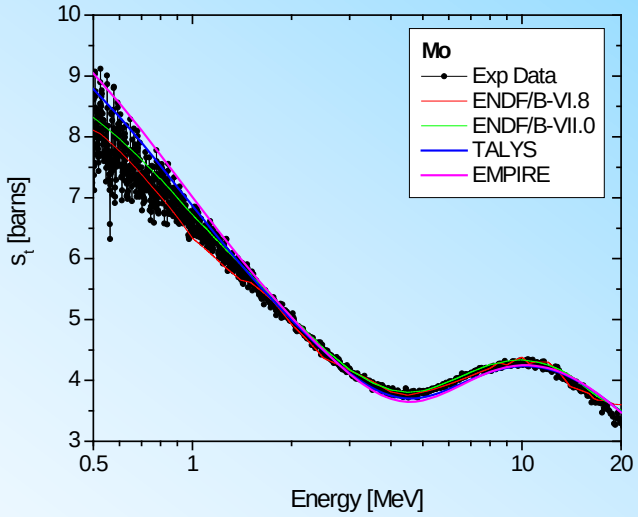
Tantalum

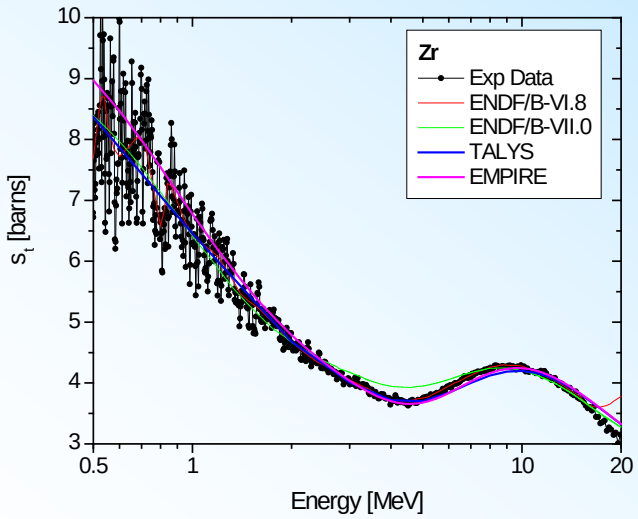


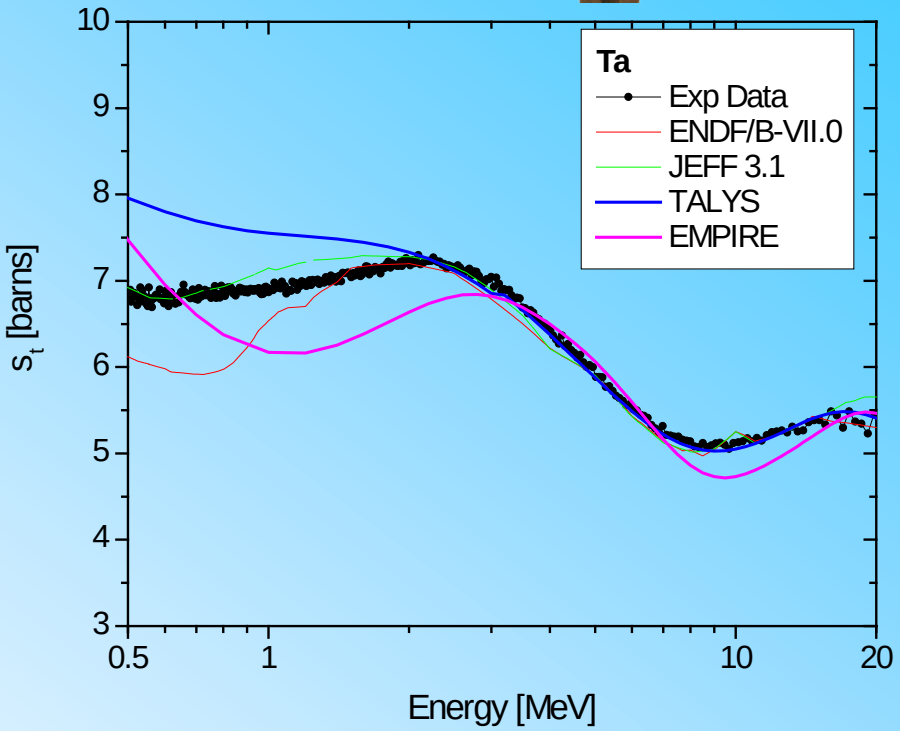


- Deviations from ENDF/B-7.0 and JENDL-3.3 below 3 MeV
- RPI measurement agrees with other experimental data

TALYS vs EMPIRE

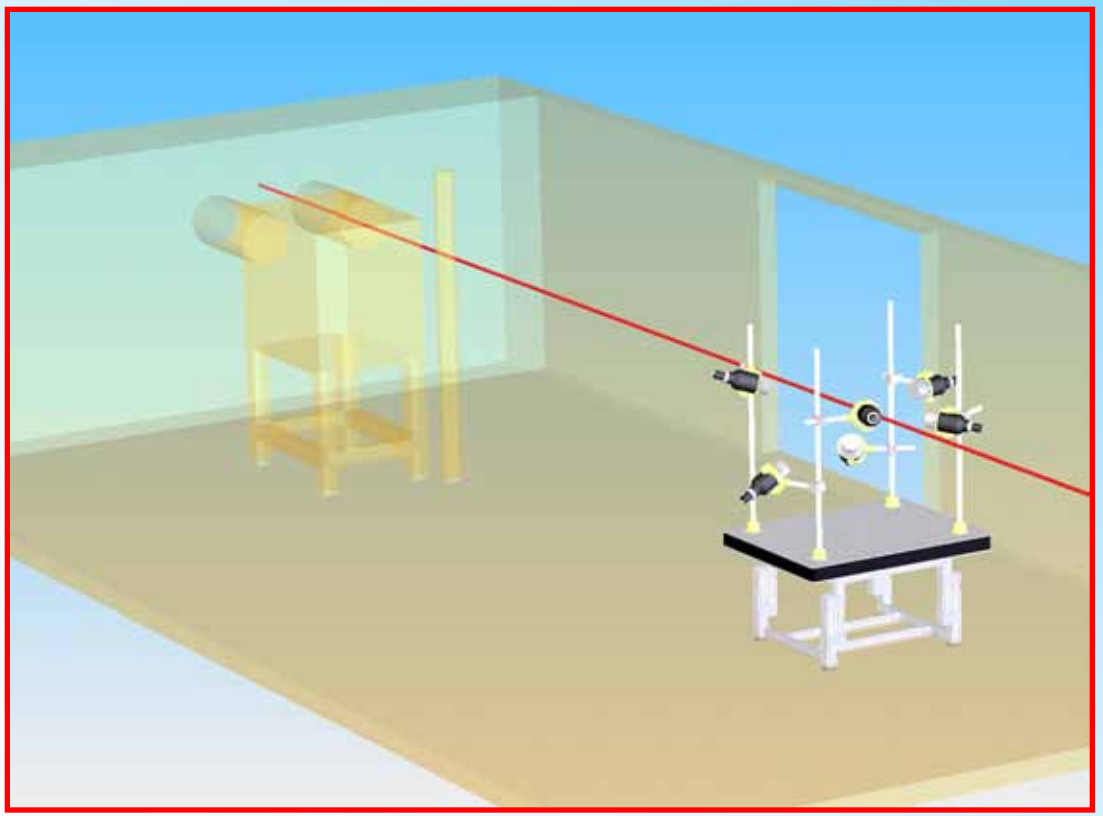






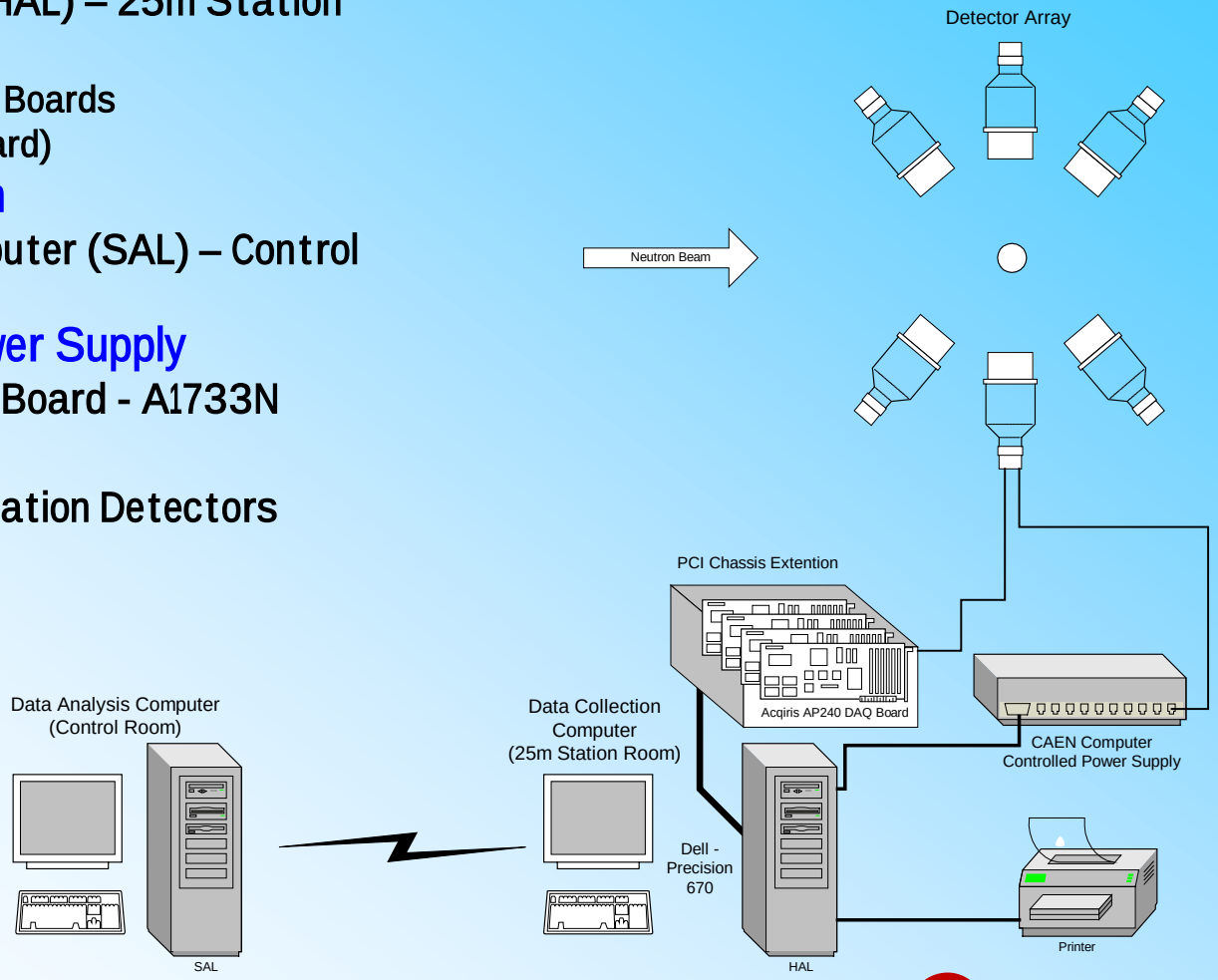
- TALYS and EMPIRE calculations with default parameters for Zr and Mo are in agreement with the data
- For Ta and E<3 MeV the codes disagree.
  - Shades some light on the disagreements of the data with the evaluations.

Fast Neutron Scattering Detector Array

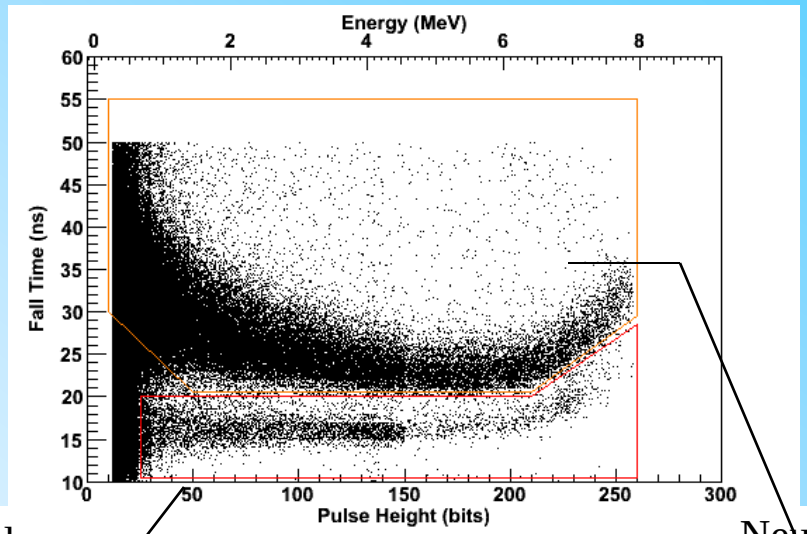


Scattering Detection System: Experimental Setup

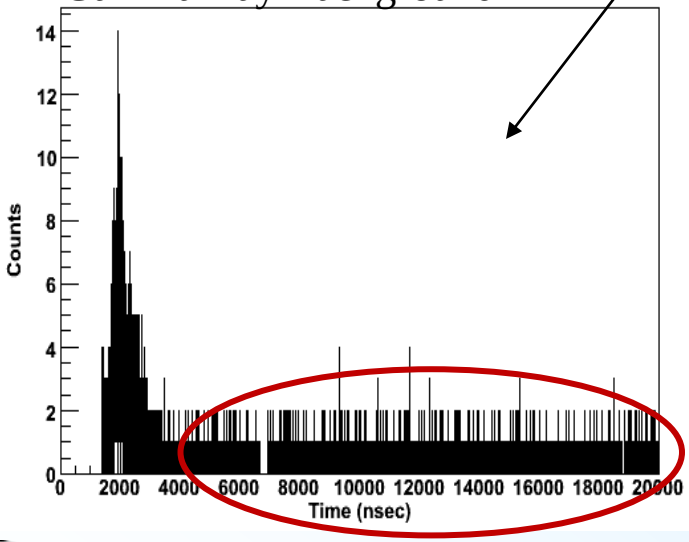
- **Data Acquisition System**
  - Main DAQ Computer (HAL) – 25m Station
  - PCI Extension Chassis
    - Acqiris AP240 DAQ Boards (2 Channels per Board)
- **Data Processing System**
  - Data Processing Computer (SAL) – Control Room
- **Computer Controlled Power Supply**
  - Chassis - SY 3527 Board - A1733N
- **Detector Array**
  - 8 EJ301 Liquid Scintillation Detectors
  - Detector Stands
- **Sample Holder / Changer**



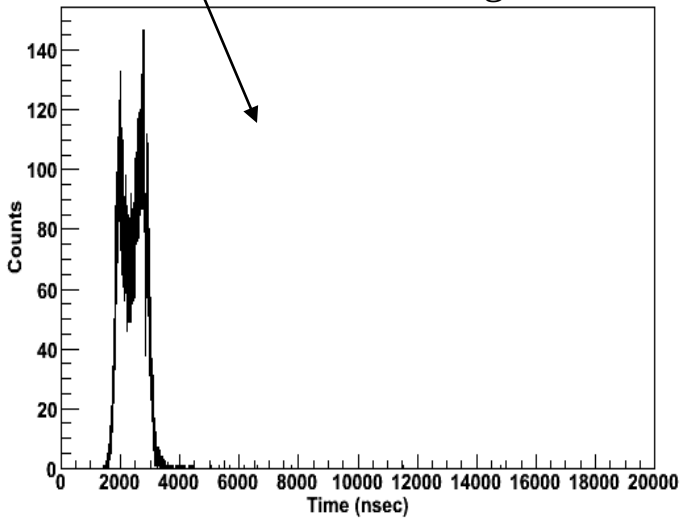
Gamma Background Reduction by Pulse Shape Analysis



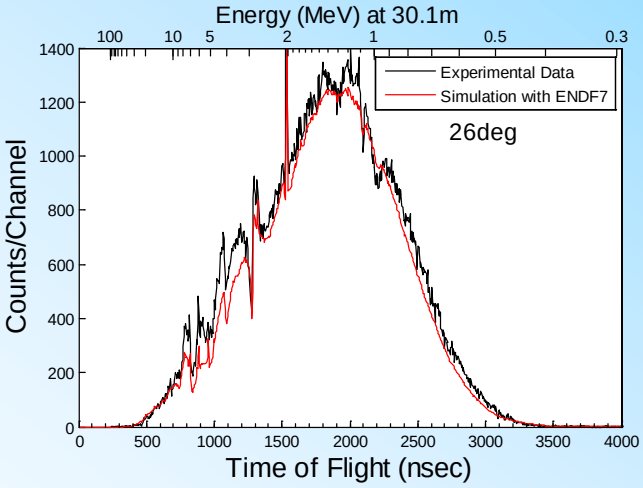
Gamma Ray Background

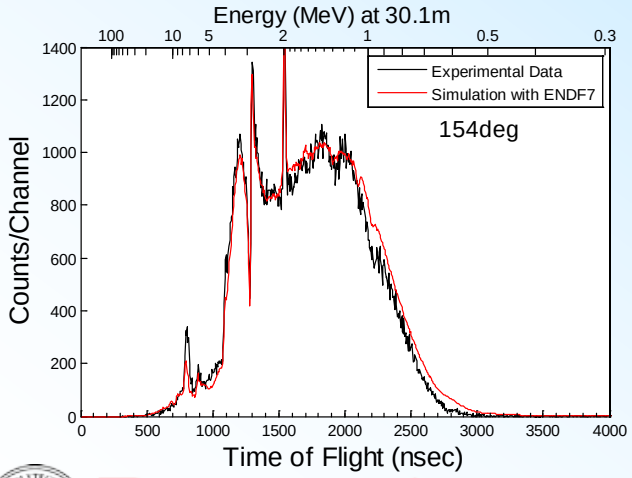


Neutron Time of Flight



Scattering Setup Illustration



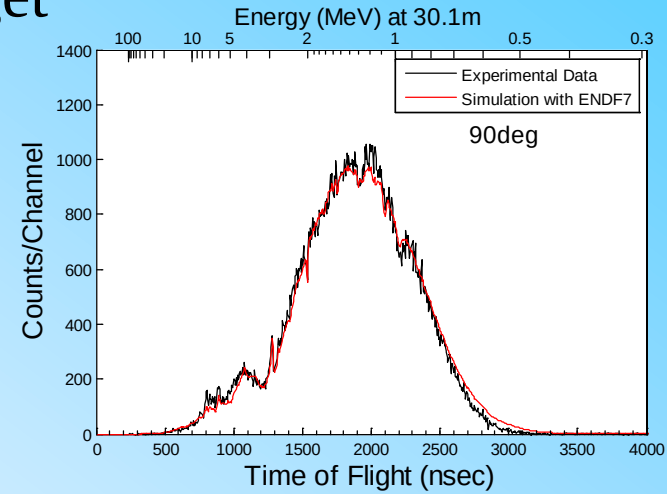


7 cm thick
Graphite Target

26°

154°

90°



Pulsed Neutron
Beam

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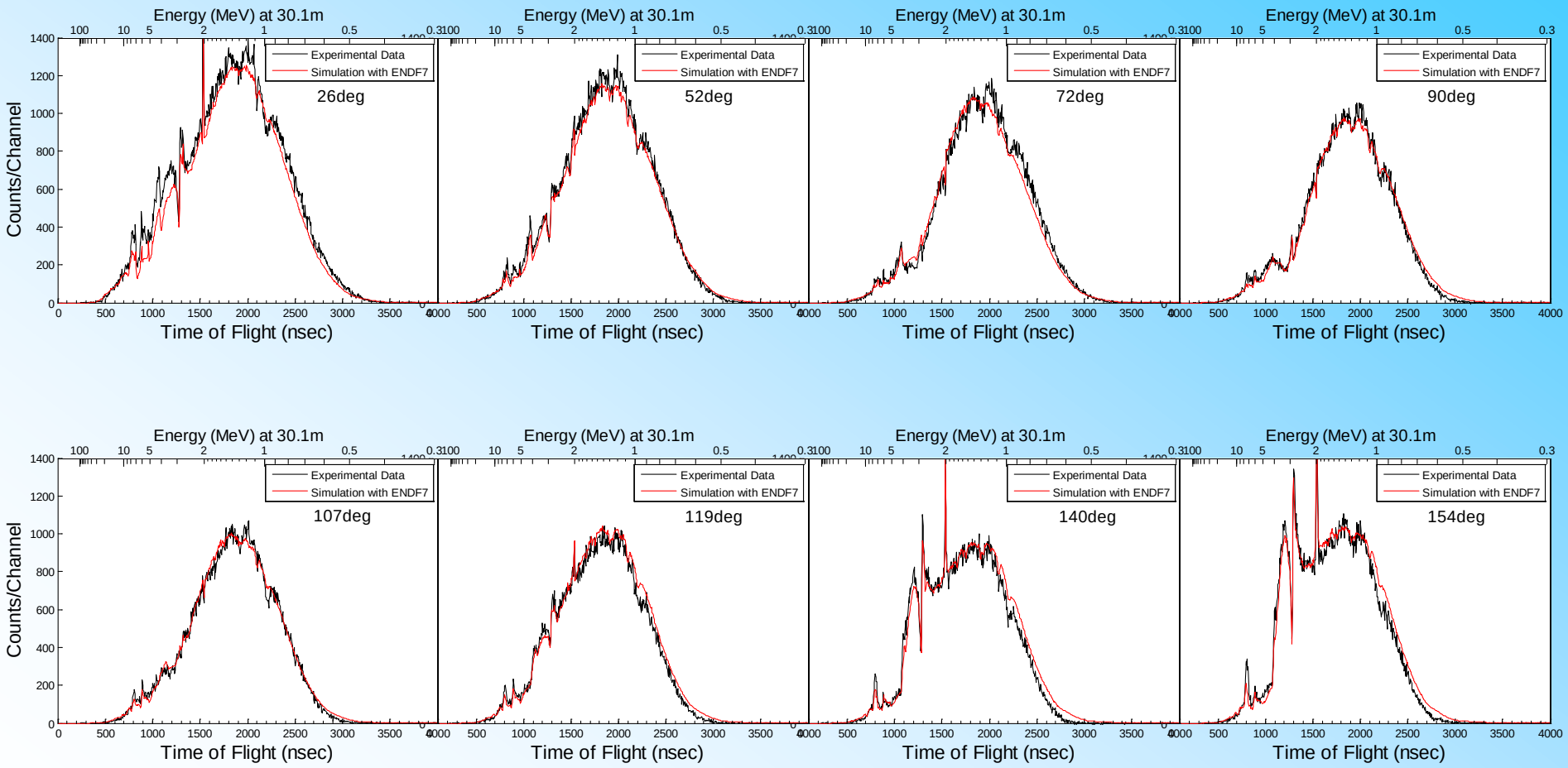
Carbon Experimental Results (Validation)

7cm



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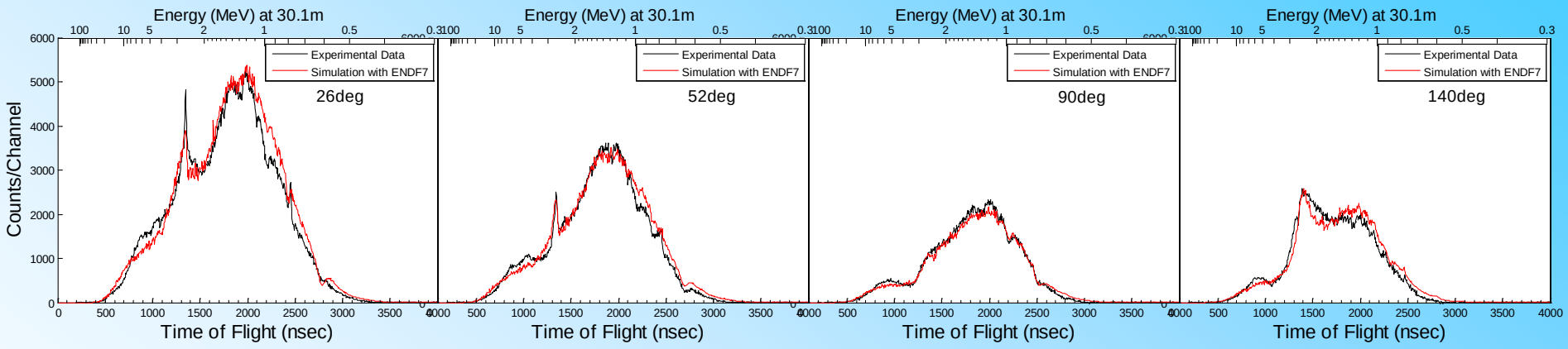
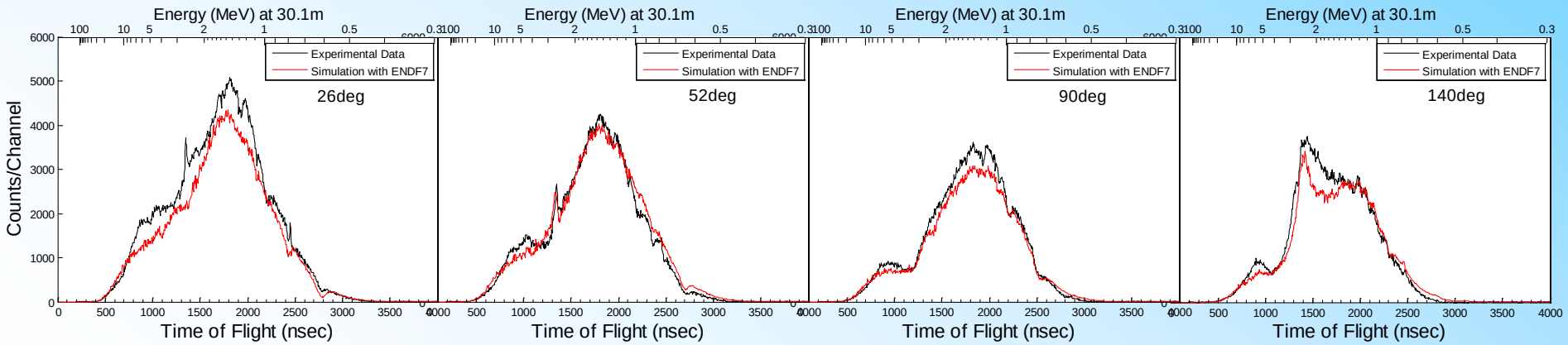
Beryllium Experimental Results

4cm

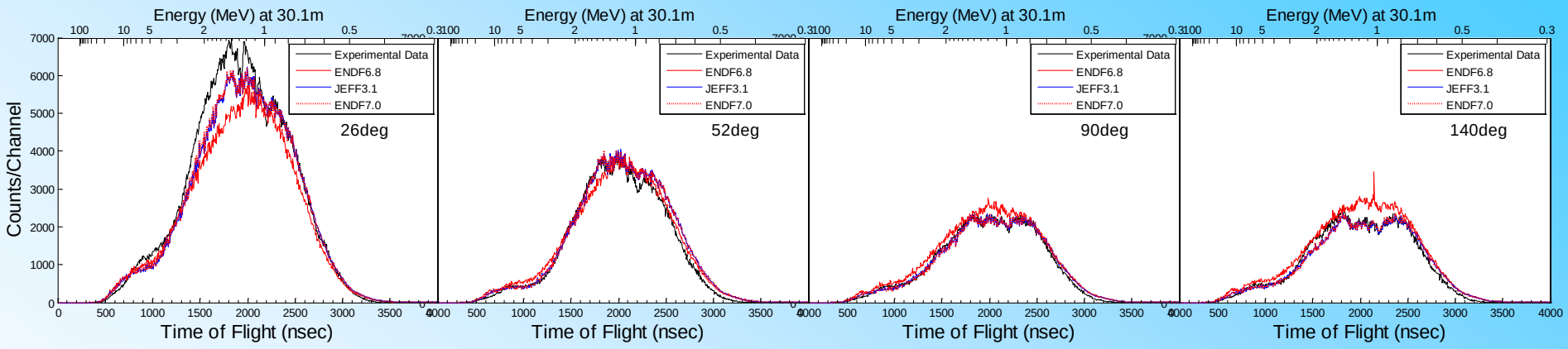


8cm

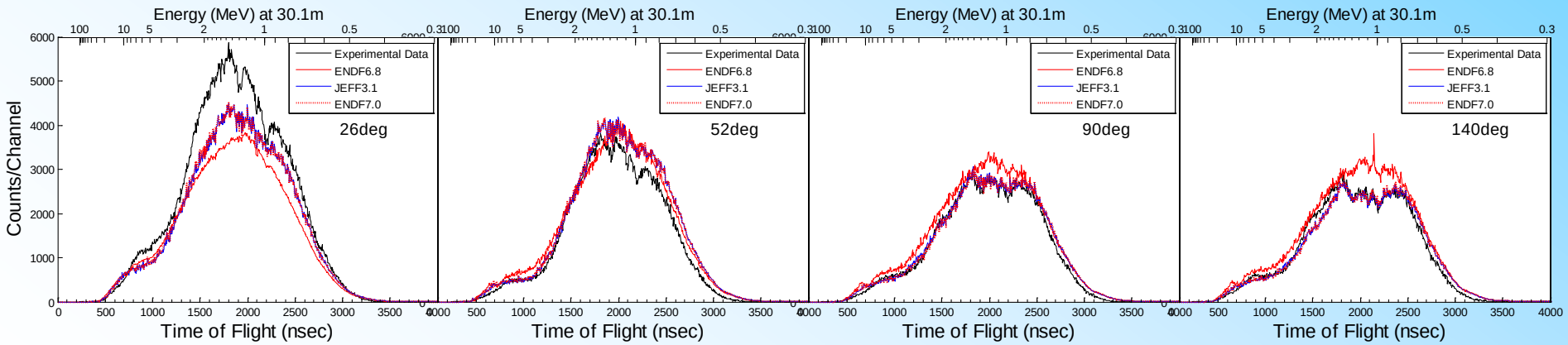


Molybdenum Experimental Results

5cm



8cm



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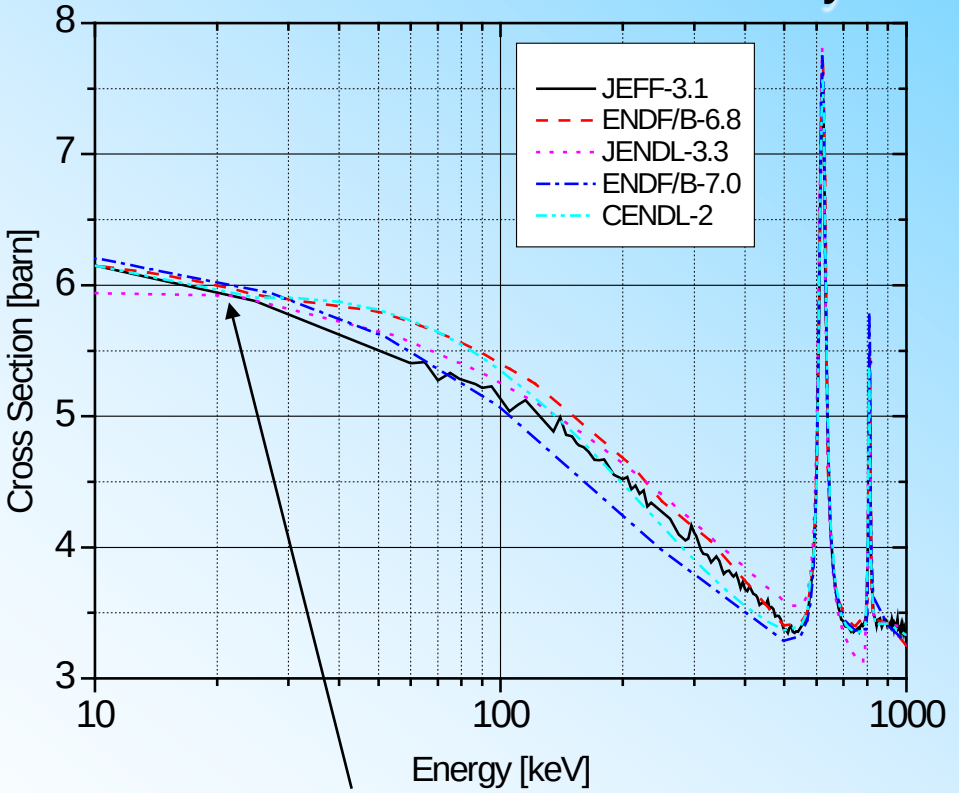
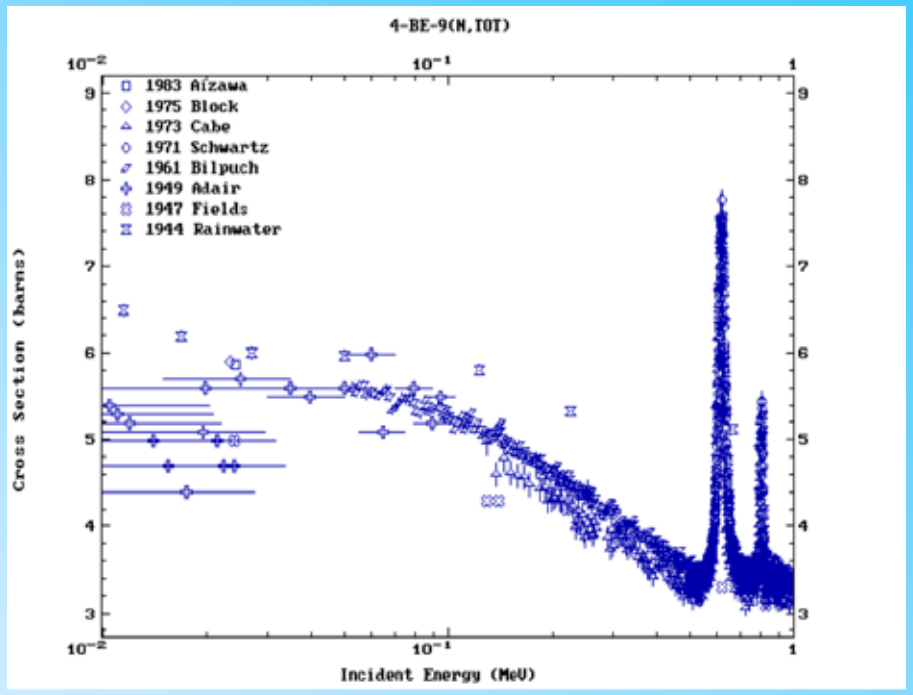
High Precision Cross Section Measurements Using Filtered Beams
Motivation - Beryllium Total Cross Section

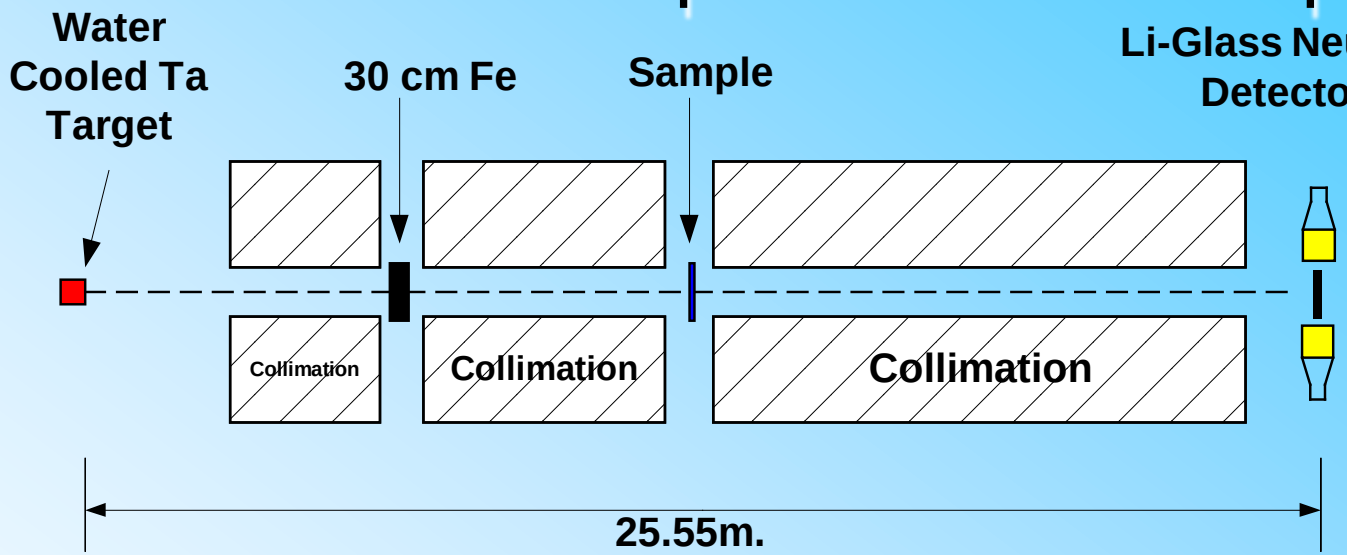




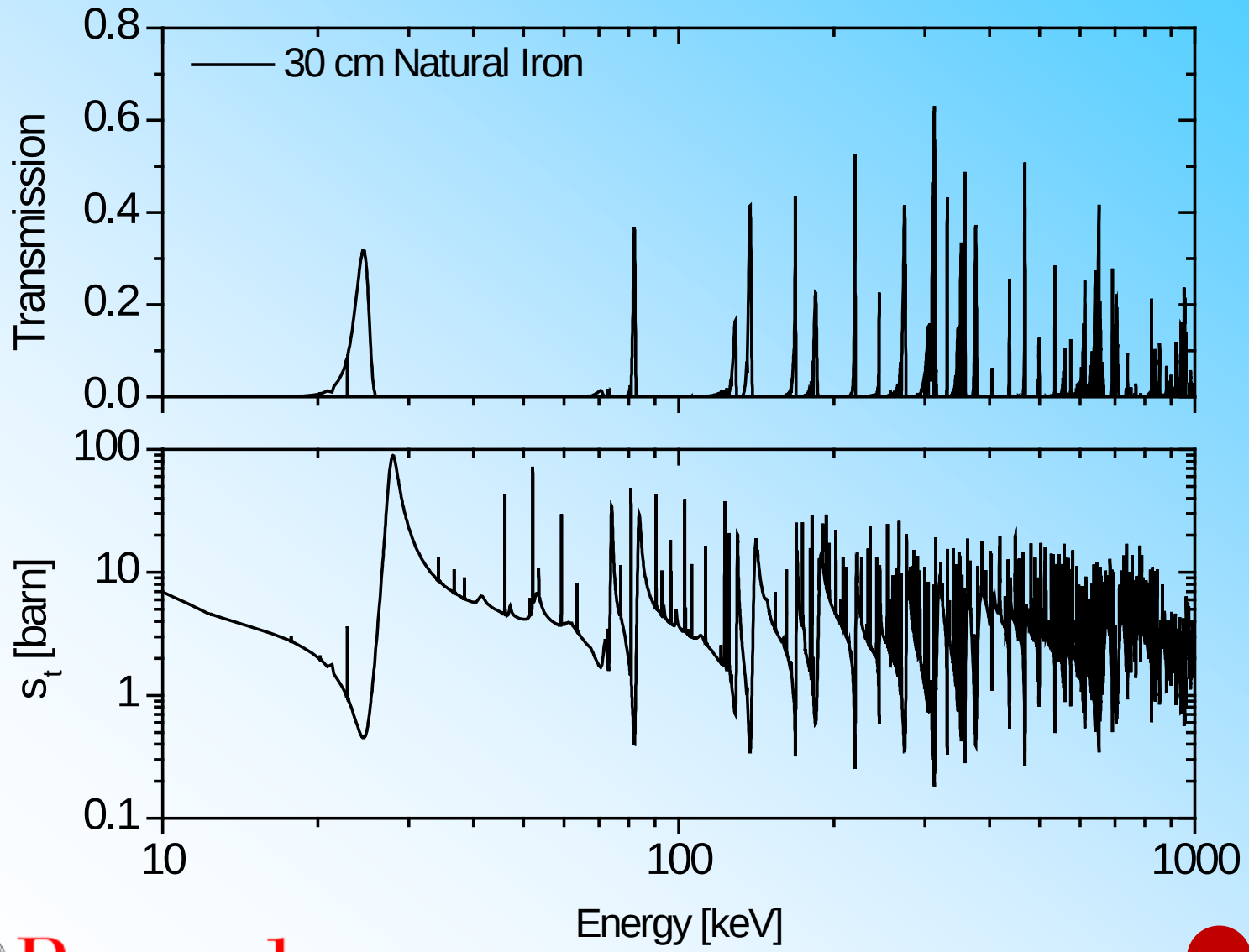
Notice the evaluations were forced through the 24 KeV point of Block et al.

R.C.Block, Y.Fujita, K.Kobayashi, T.Oosaki, Precision neutron total cross-section measurements Near 24 kev, *J. of Nuclear Science and Technology*, Tokyo Vol.12, p.1, 1975

Iron Filter Experimental Setup

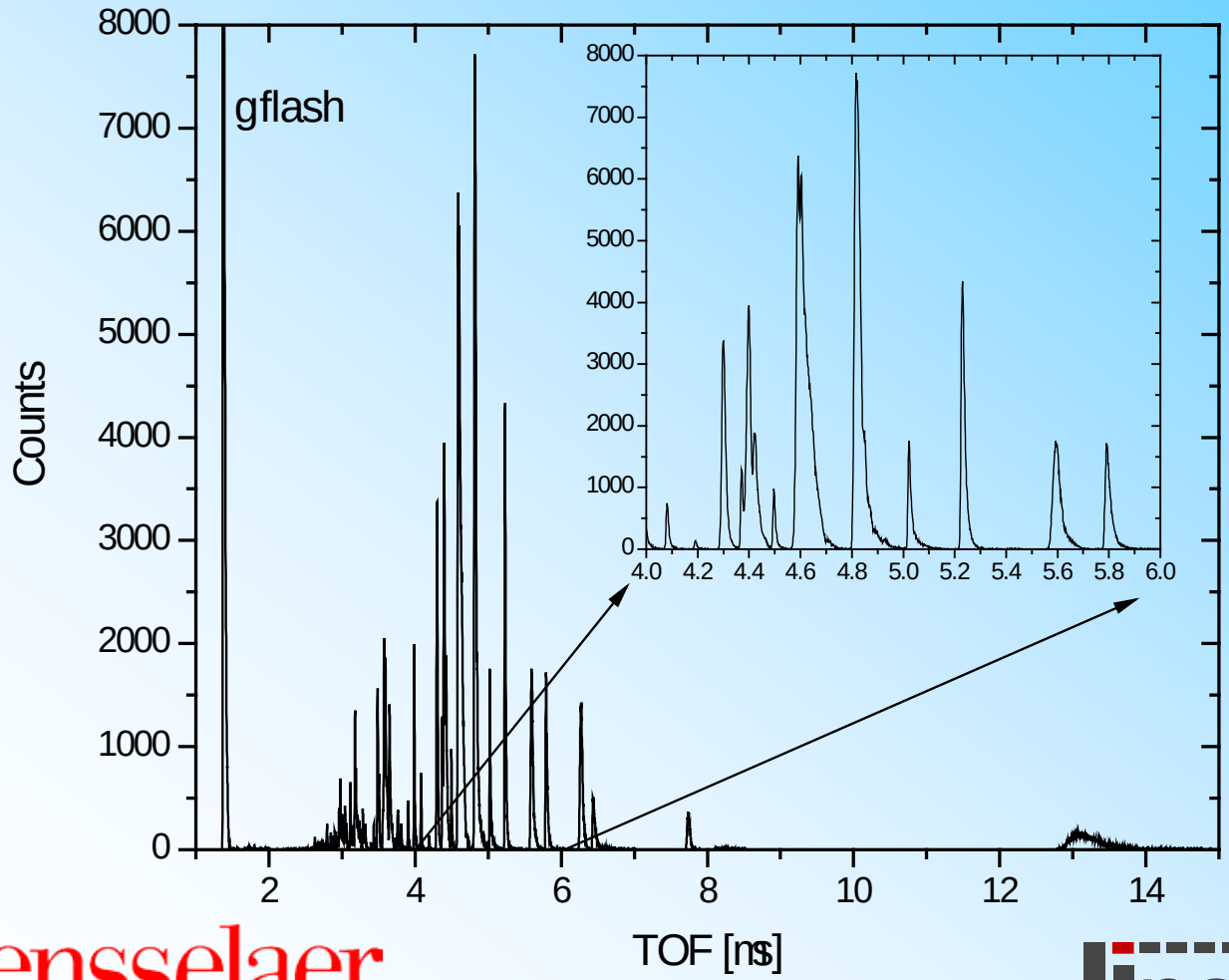


Natural Iron Filter

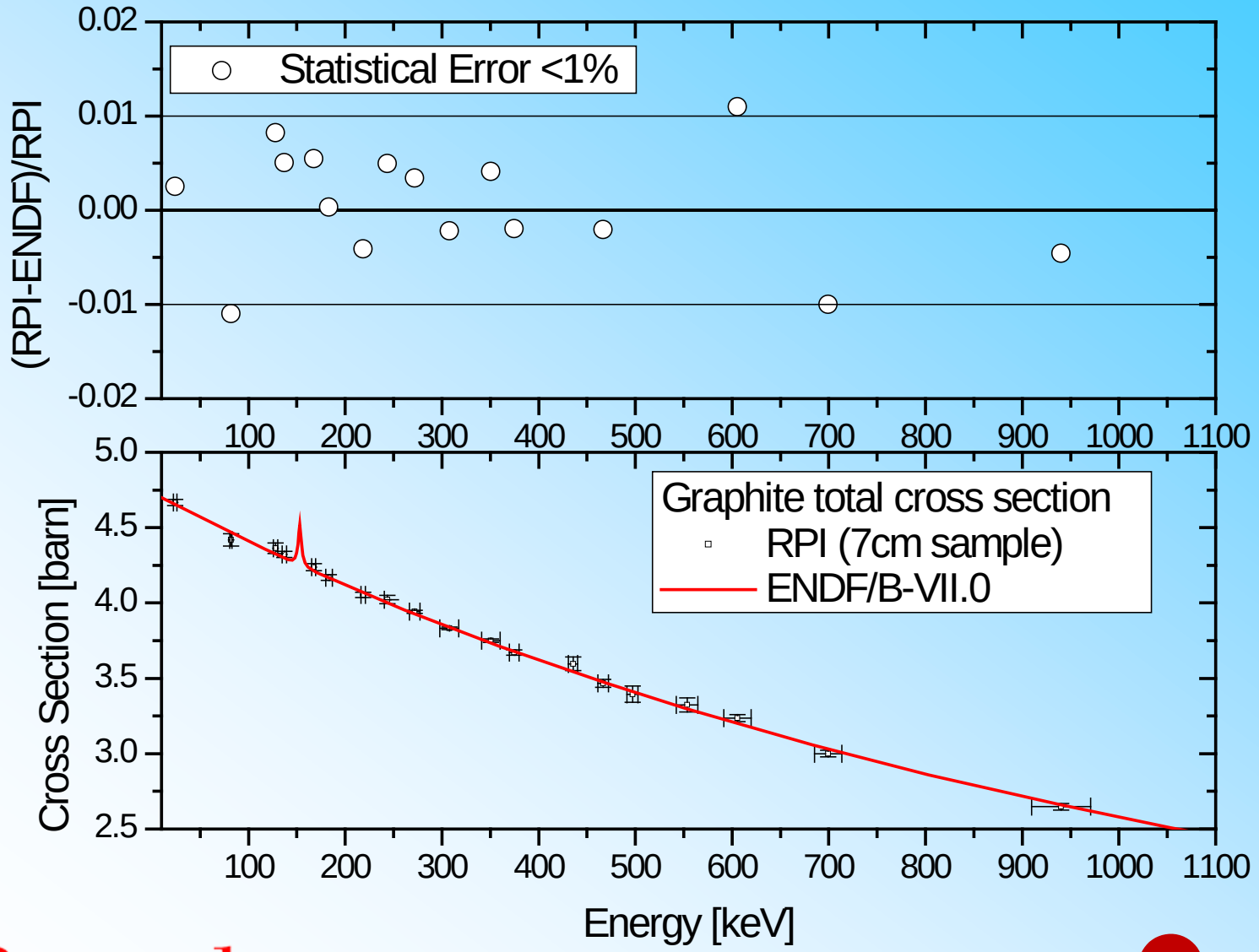


Experimental Data

- Iron filtered beam data
  - Peaks are broadened by the TOF resolution function
  - High signal-to-background ratio



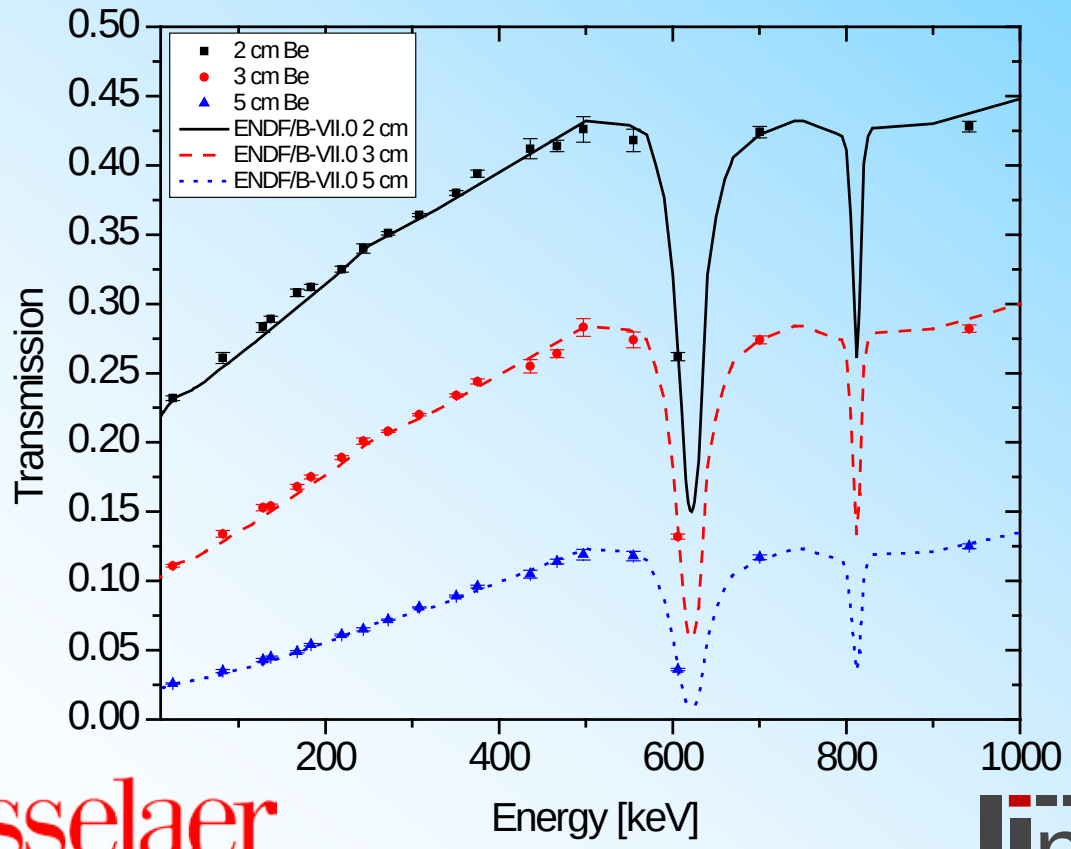
Results - Graphite



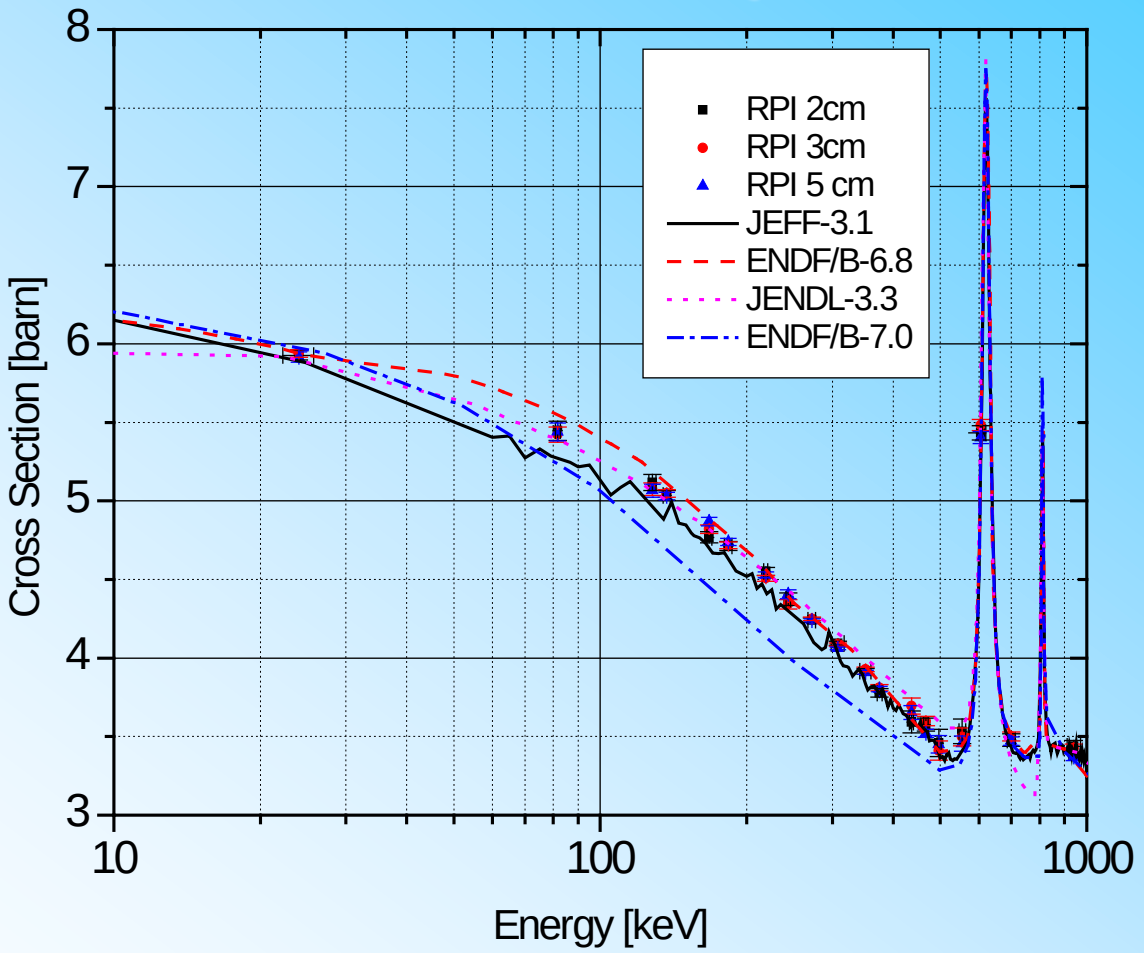
Be Transmission

Sample thickness and time split was selected according to:

Yaron Danon and R. C. Block, "Minimizing The Statistical Error of Resonance Parameters and Cross Sections Derived from Transmission Measurements", Nuclear Instruments and Methods A, Vol. 485, 585-595 June, (2002).

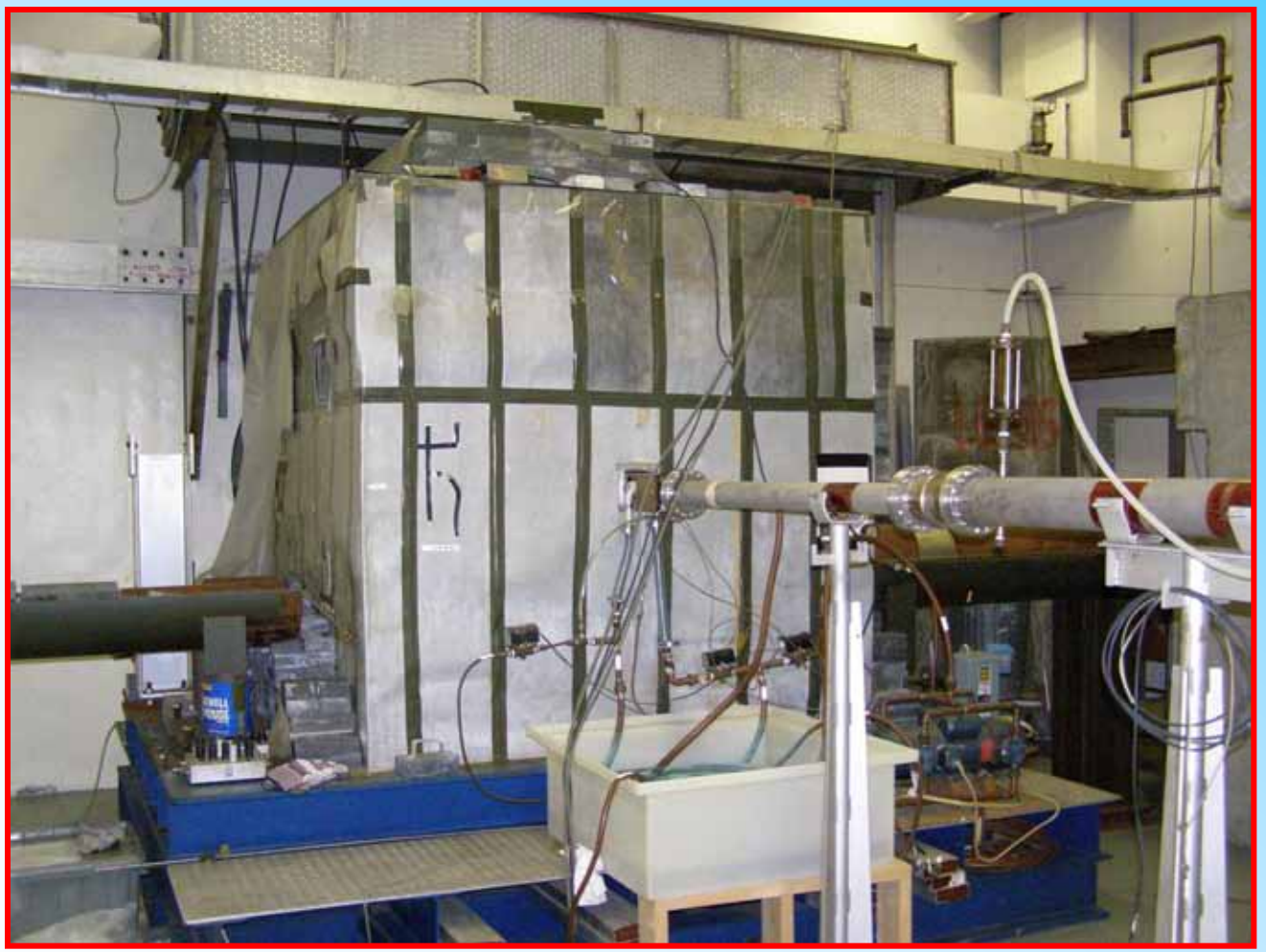


Results - Beryllium



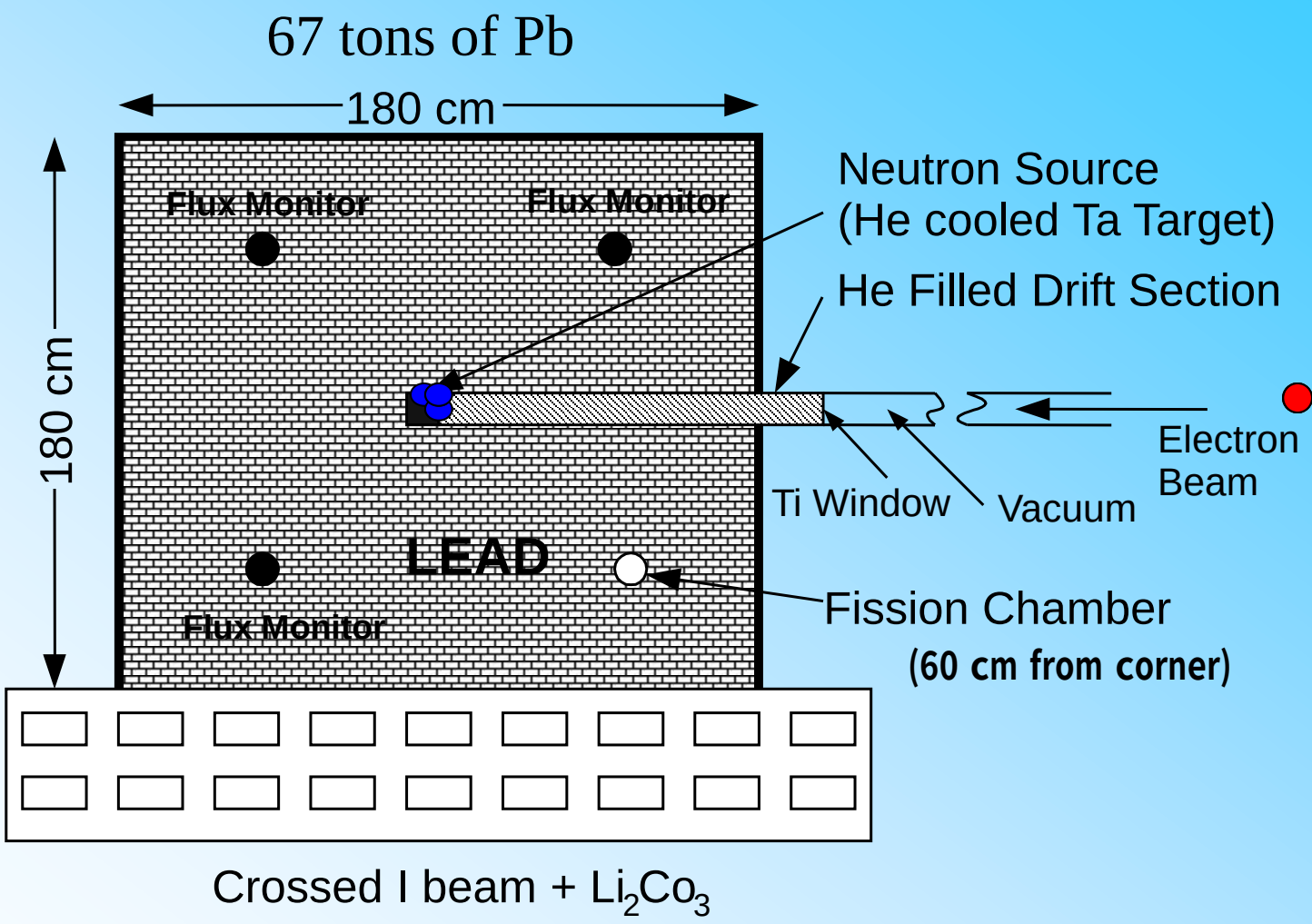
Y. Danon , R. C. Block, M. J. Rapp, and F. J. Saglime, G. Leinweber, D. P. Barry, N. J. Drindak and J. G. Hoole, "Beryllium and Graphite High Accuracy Total Cross-Section Measurements in the Energy Range from 24 keV to 900 keV", Nuclear Science And Engineering, **161**, 321–330, (2009).

Lead Slowing Down Spectrometer



Lead Slowing-down Spectrometer at RPI

- Tantalum target in the center produces neutrons.
- Neutrons scatter elastically with the Pb.
- Neutrons can pass through the same position several times.
- About 10^3-10^4 times higher flux than an equivalent flight path TOF experiment (5.6m).

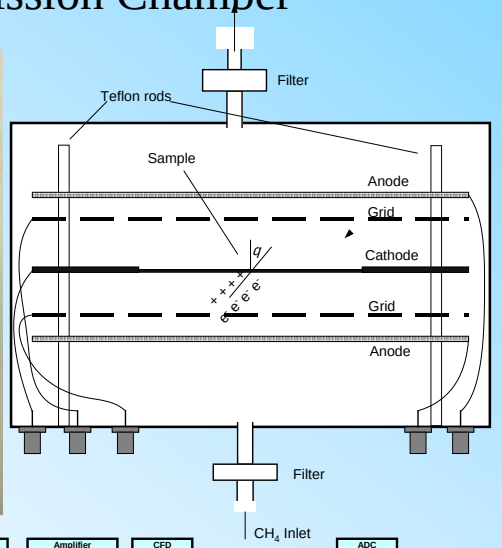


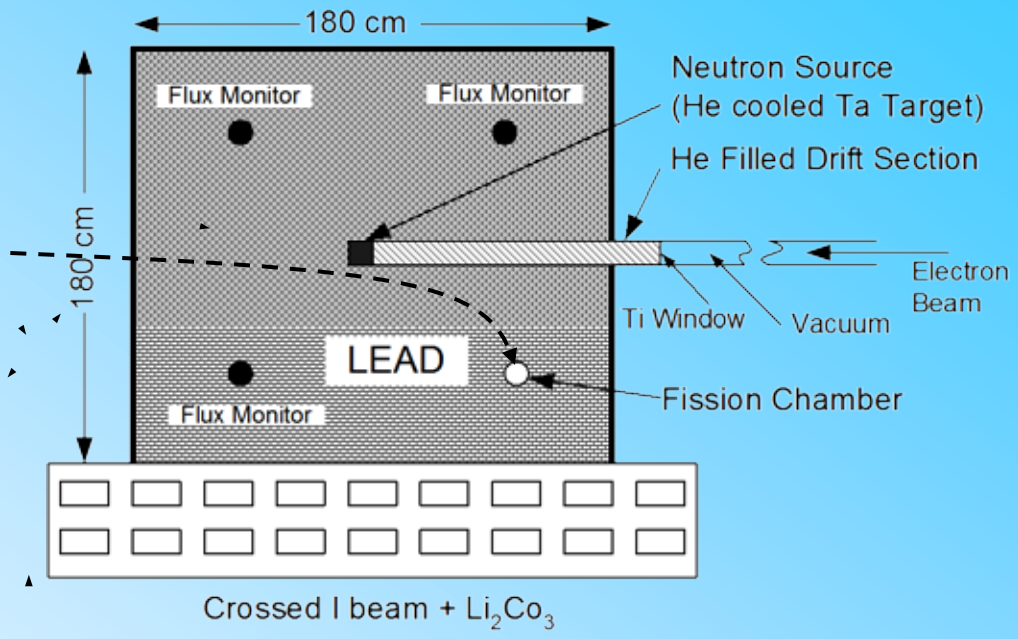
Fission Fragment Kinematics

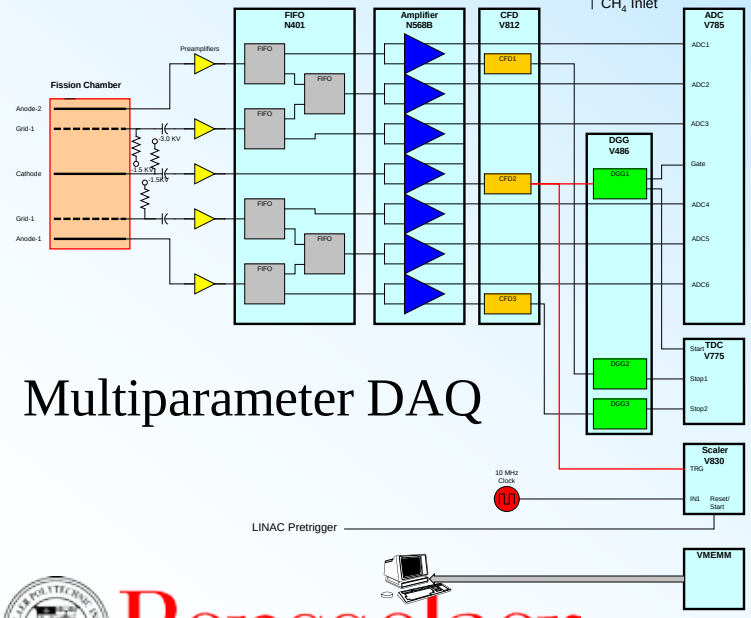
- **Objectives**
  - Simultaneous measurement of the fission cross section and fission fragment mass and energy distributions of small samples (~nanograms).
  - Use the RPI lead slowing down spectrometer and a double gridded fission chamber.
  - Samples are deposited on very thin backing (120 nm thick polyimide with 15 nm gold coating)

SETUP

Double Gridded Fission Chamber







Multiparameter DAQ

In collaboration with LANL and BRC

- ^{237}U Fission cross sections.
- (n,a), (n,p) measurements on small samples.

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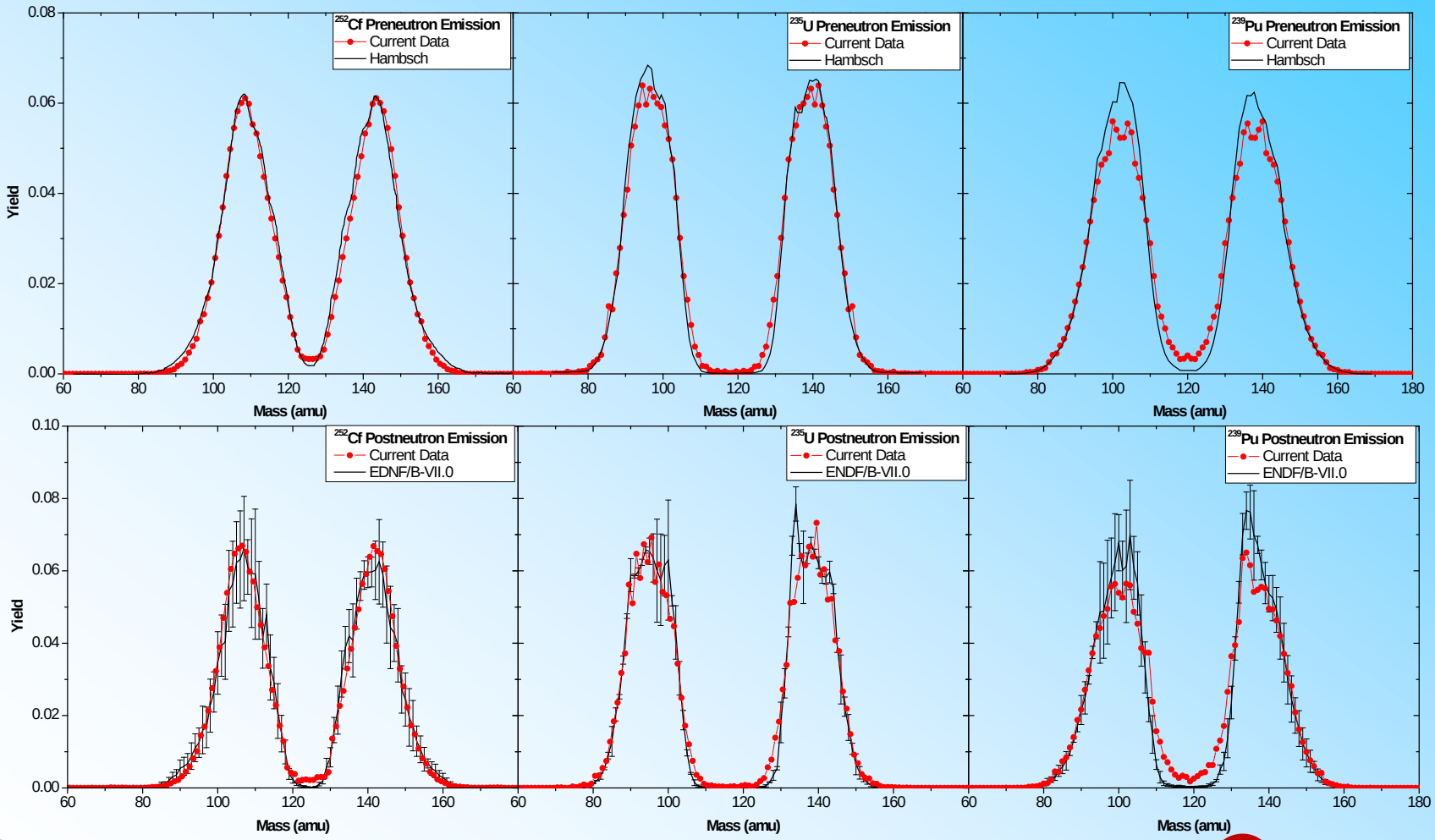
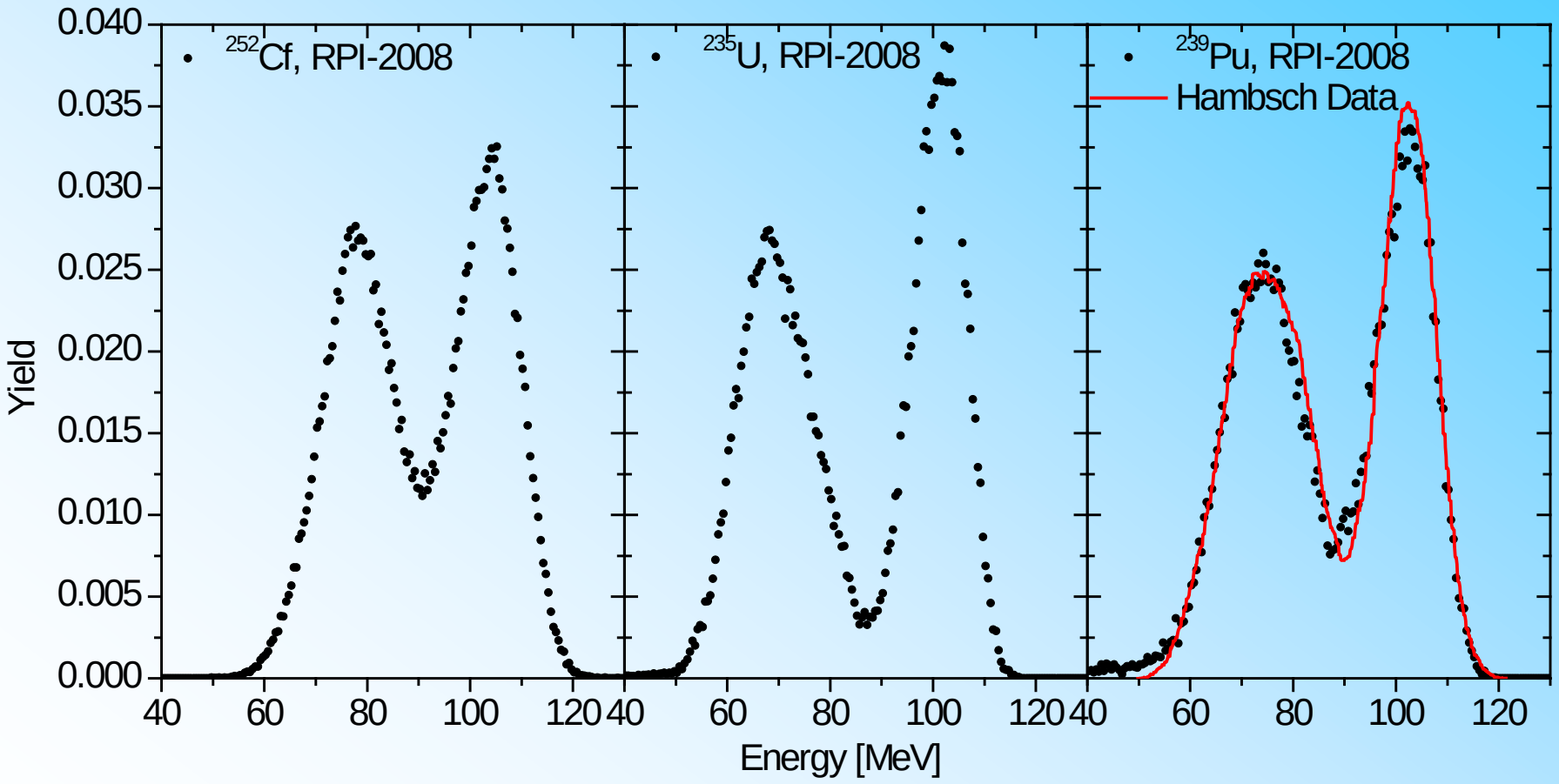
Results – Fission Fragment Mass distribution E_n<0.1 eV

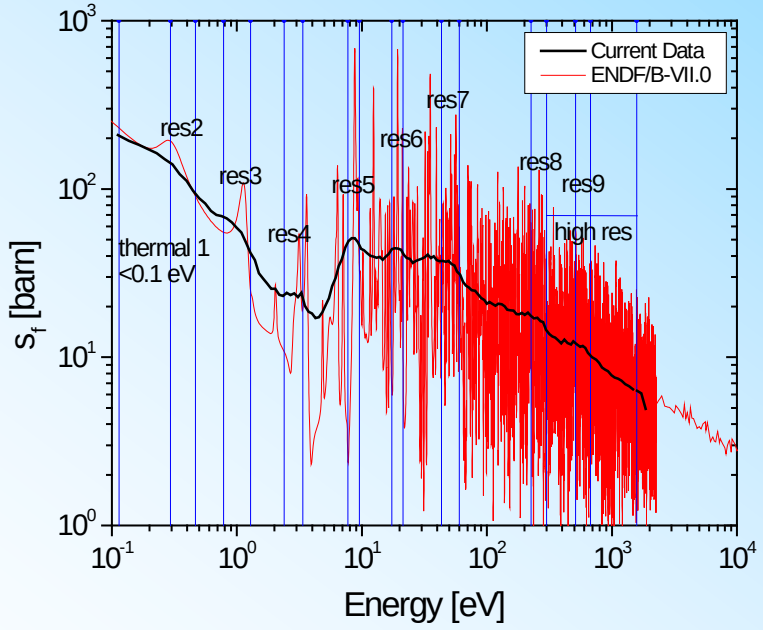
^{252}Cf ^{235}U ^{239}Pu

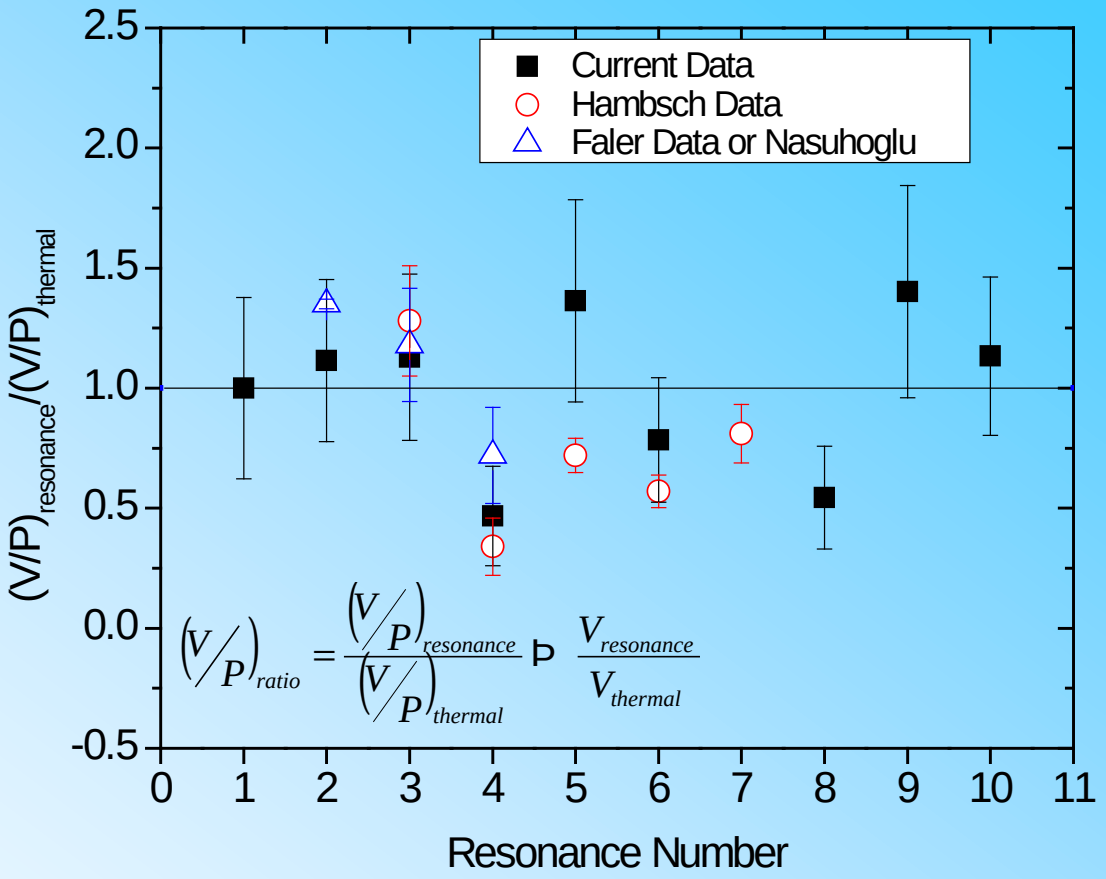


Results – Fission Fragment Energy Distribution
E_n<0.1 eV



^{235}U Fission symmetry in resonance clusters

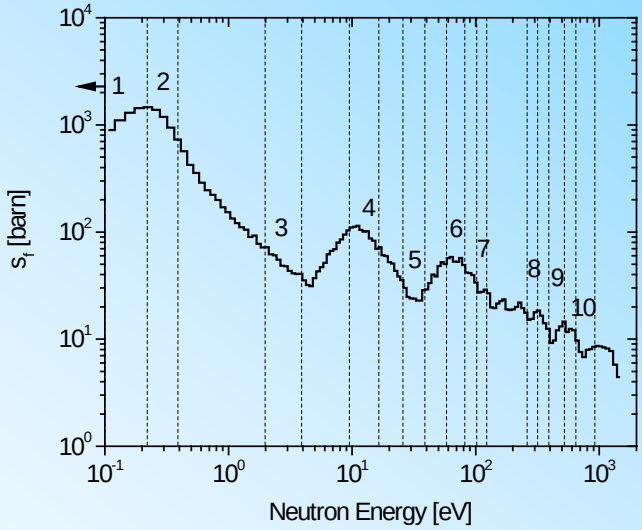


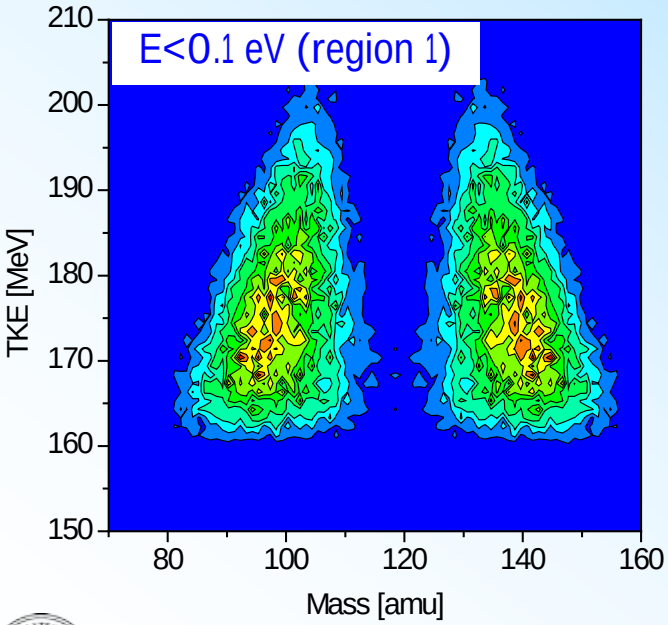


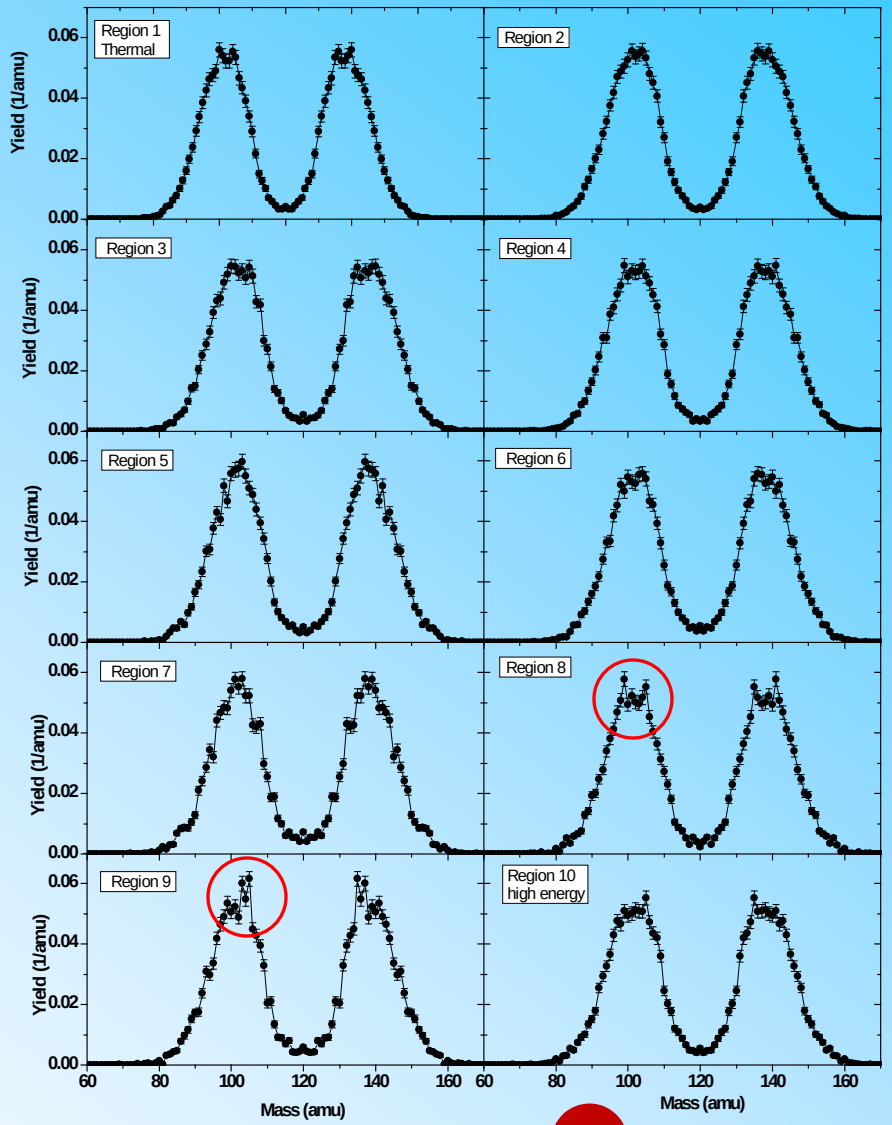
K. T. Faler, R. L. Tromp, Phys. Rev. **131,** 1746-1748(1963).
R. Nasuhoglu, et al., Phys. Rev. **108**, 1522 (1957).

V- Valley at mass range 115-121
$P_{resonance}$,$P_{thermal}$ – average of the normalized yield=constant

^{239}Pu - Results







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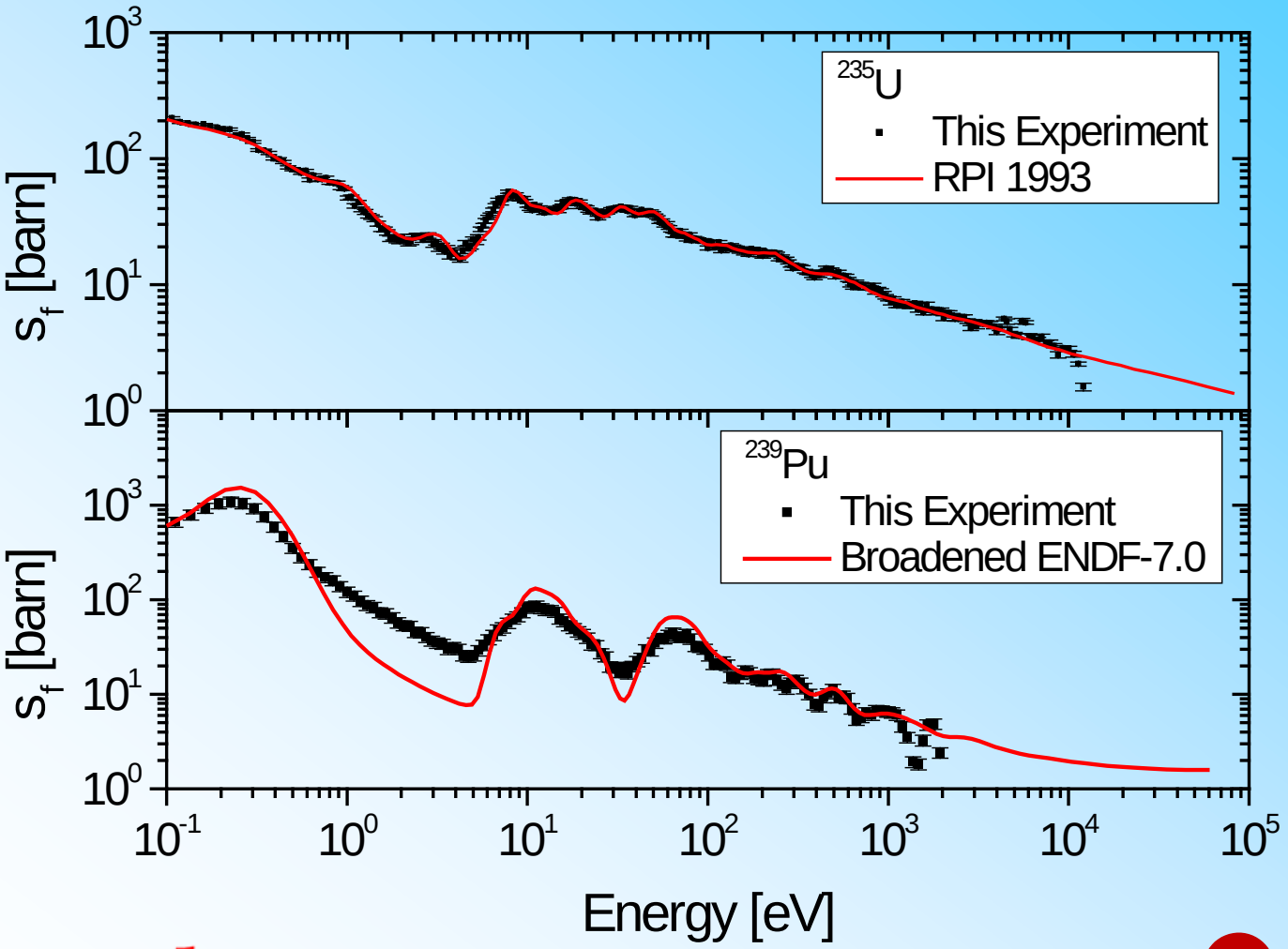
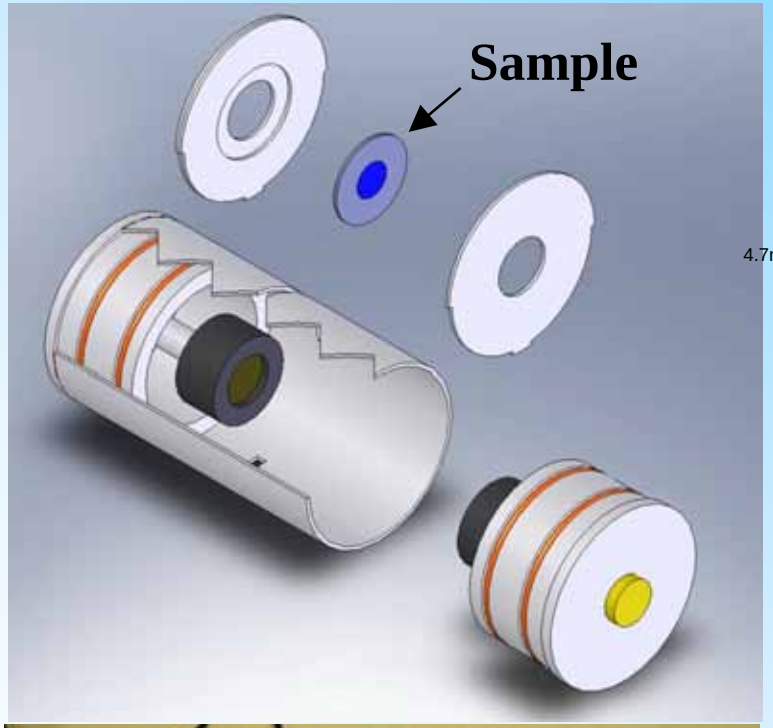
Results – Measured Fission Cross Section

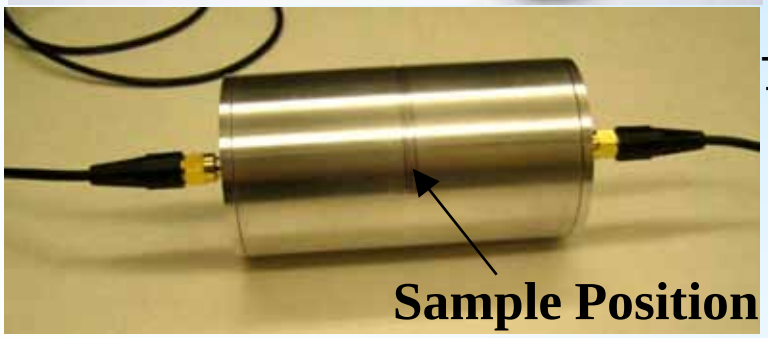


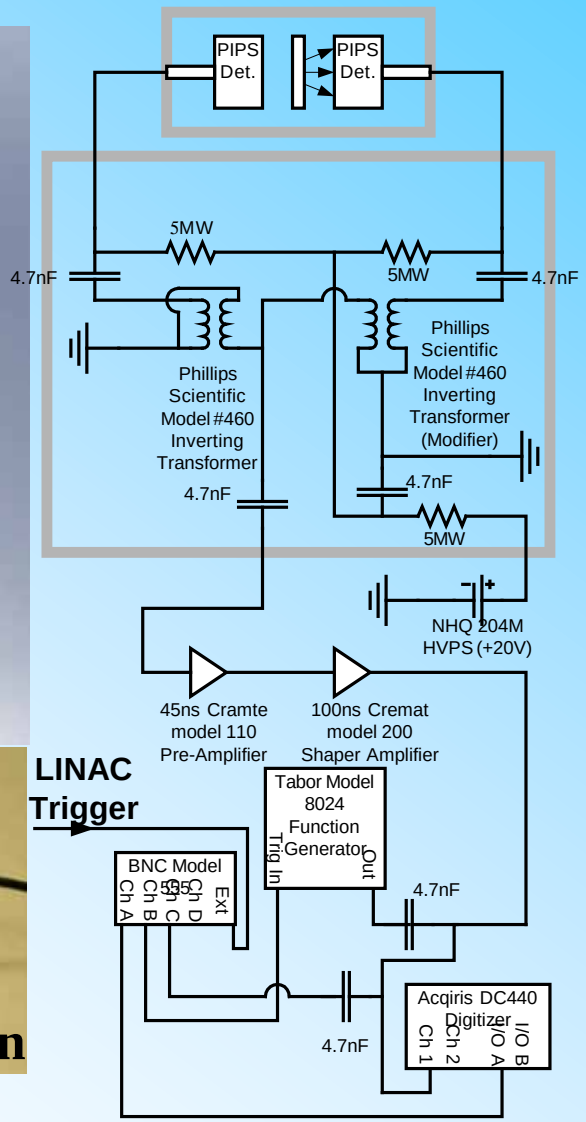
(n,a) and (n,p) Cross section Measurements

- Relevant to astrophysics
  - Can use very small samples (nanograms) or small cross section
  - The energy range and resolution in the LSDS provides data that can be used to produce Maxwellian averaged cross sections.
- Develop a detector
  - **Compensated**, to suppress the effect of the gamma flash
  - **Sensitive** to alpha but can also work in noisy RF environment.
  - **Not sensitive to gamma** background (from inelastic scattering in Pb)

Compensated PIPS Detector

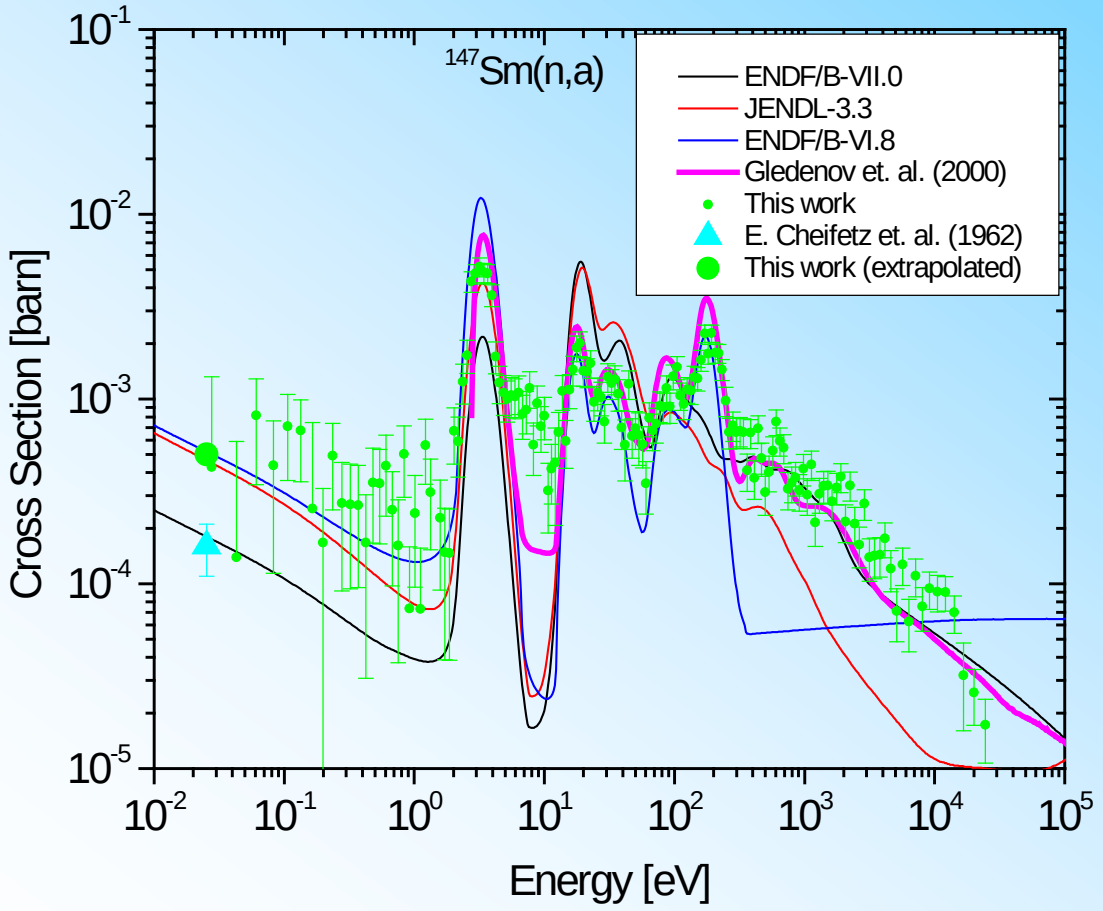






- Gamma discrimination by recording the gamma spectra on two face to face detectors
- Digital DAQ collects a **bipolar signal**
- Correct for background by subtracting the bare detector signal from the sample detector on an event by event basis

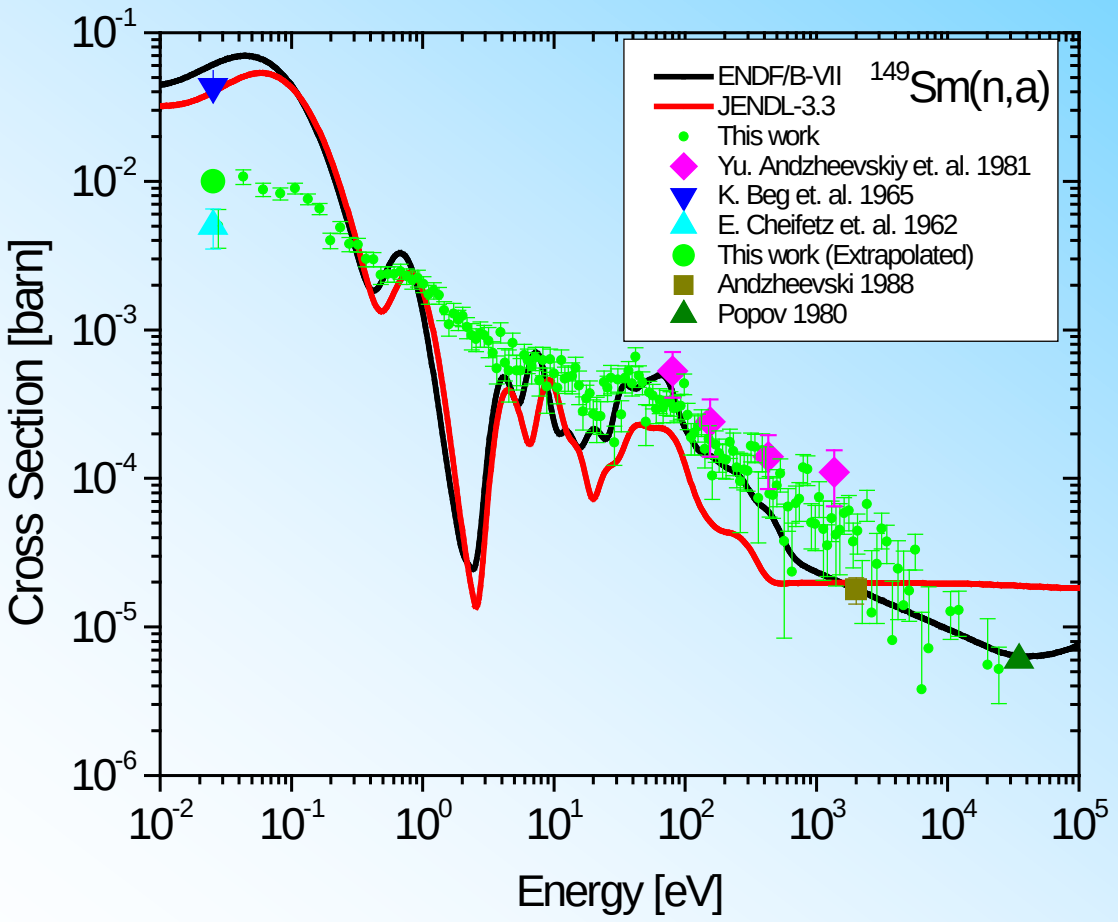
Measurement of (n,a) cross section of ^{147}Sm



- The motivation was to demonstrate the ability to measure small cross section of small sample with the LSDS
- Used 8.25 mg of ^{147}Sm (98.03% enriched Sm)
- Our data agrees with the resolution broadened Gledenov measurement better than ENDF/B 7.0

Gledenov et al., Phys. Rev. C **62**, 042801(R) (2000).

Measurement of (n,a) cross section for ^{149}Sm



- This is the only measured data for this reaction
- Used 7.99mg ^{149}Sm (98.03% enriched Sm)
- The data are in reasonable agreement with the ENDF/B-7.0 estimate
- Extrapolation of the thermal value is in better agreement with the Beg et al. (1965) measurement

Some Recent Measurements

- Fission
  - Ø C. Romano, Y. Danon, R. Block, J. Thompson, E. Blain, E. Bond, "Fission Fragment Mass And Energy Distributions As A Function of Neutron Energy Measured In A Lead Slowing Down Spectrometer", Phys. Rev. C **81**, 014607 (2010)
- Mo Analysis in Progress
  - Ø G. Leinweber, D.P. Barry, J.A. Burke(ret.), N.J. Drindak, R.C. Block, Y. Danon, B.E. Moretti, "Measurements of elemental molybdenum and resonance parameter analysis", International Conference on Nuclear Data for Science and Technology (ND2007), April 22-27, Nice, France, (2007)
  - Ø G Leinweber, DP Barry, JA Burke, NJ Drindak, RC Block, Y Danon, BE Moretti, "Resonance Parameters and Their Uncertainties Derived from Epithermal Neutron Capture and Transmission Measurements of Elemental Molybdenum", Nuclear Science And Engineering, 164, 287-303, (2010).
- C & Be
  - Ø Y. Danon, R.C. Block, M. Rapp, F. Saglime, D.P. Barry, N.J. Drindak, J. Hool, G. Leinweber, "High-Accuracy Filtered Neutron Beam and High-Energy Transmission Measurements at the Gaerttner Laboratory", submitted to the International Conference on Nuclear Data for Science and Technology, April 22-27 2007, Nice, France
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- Rh – Analysis in progress
- Re – Analysis in progress
- Gd-155,156,157,158,160 Capture analysis in progress
- Dy-161,162,163,164 – Capture analysis in progress.
- Eu-nat, Eu-153 – Capture and Transmission analysis in progress