Report on U.S. Experimental Activities

WPEC 2016

Yaron Danon

Rensselaer Polytechnic Institute, Troy, NY 12180, USA

CSEWG measurements committee chair

WPEC May 12-13, 2016, OECD Paris, France

Introduction

- **The US experimental effort reported is mostly based the CSEWG meeting reports during November 2015.**
- **Reports from different laboratories:**
  1. Nuclear Data Experiments at LANSCE: Brief Highlights 2015, (LANL).
  2. ORNL Neutron Cross-Section Measurements Activities (ORNL).
  3. Update on Nuclear Data Research at RPI (RPI).
  4. NIST Measurements and Standards including Related Work at Other Facilities, Carlson, Allan (NIST).

- **This report represents only part of the U.S. nuclear data activity.**

Los Alamos National Laboratory

- **Capture measurement with DANCE (Detector for Advanced Neutron Capture Experiments)**
  - $^{236,238}U(n,\gamma)$ Relative to $^{235}U(n,f)$ – mixed target, E > 10 keV (M. Jandel DOE ECR)
  - $^{238}U(n, \gamma)$ showing importance of M1 strength
  - $^{235}U(n, \gamma)$ Capture isomers (requires fission tagging)
  - ^{242}Pu Spontaneous fission – gamma-ray spectra (with LLNL)
  - $^{67,68}Zn(n, \gamma)$ Astrophysics (with LSU)
  - $^{136}Xe(n, \gamma)$ Double-Beta decay backgrounds and physics (With IU)
  - $^{161,162}Dy(n, \gamma)$ Strength functions and resonances (with NCSU, Charles U.)
  - $^{173,174}Lu(n, \gamma)$ Radioactive samples! (With CEA)
  - $^{191,193}Ir(n, \gamma)$ Capture data > 10 keV
- **GEANIE – (GErmanium Array for Neutron Induced Excitations)**
  - $^{187}Re(n,xn)$ with Jeff Carroll (NRL) and David Matters (AFIT)
  - $^{109}Ag(n,2n)^{108}Ag$ isomer population
  - $^{136}Xe(n,xn)$ for $0\nu\beta\beta$ backgrounds with Josh Albert, Lisa Hoffman, etc (IU)
  - Neutron-induced γ-ray standard measurements: ^{56}Fe, Cr, B, Ti (n,n') γ-ray comparisons as a function of E_n
  - The detector was retired for unknown period of time.

LANL (continued)

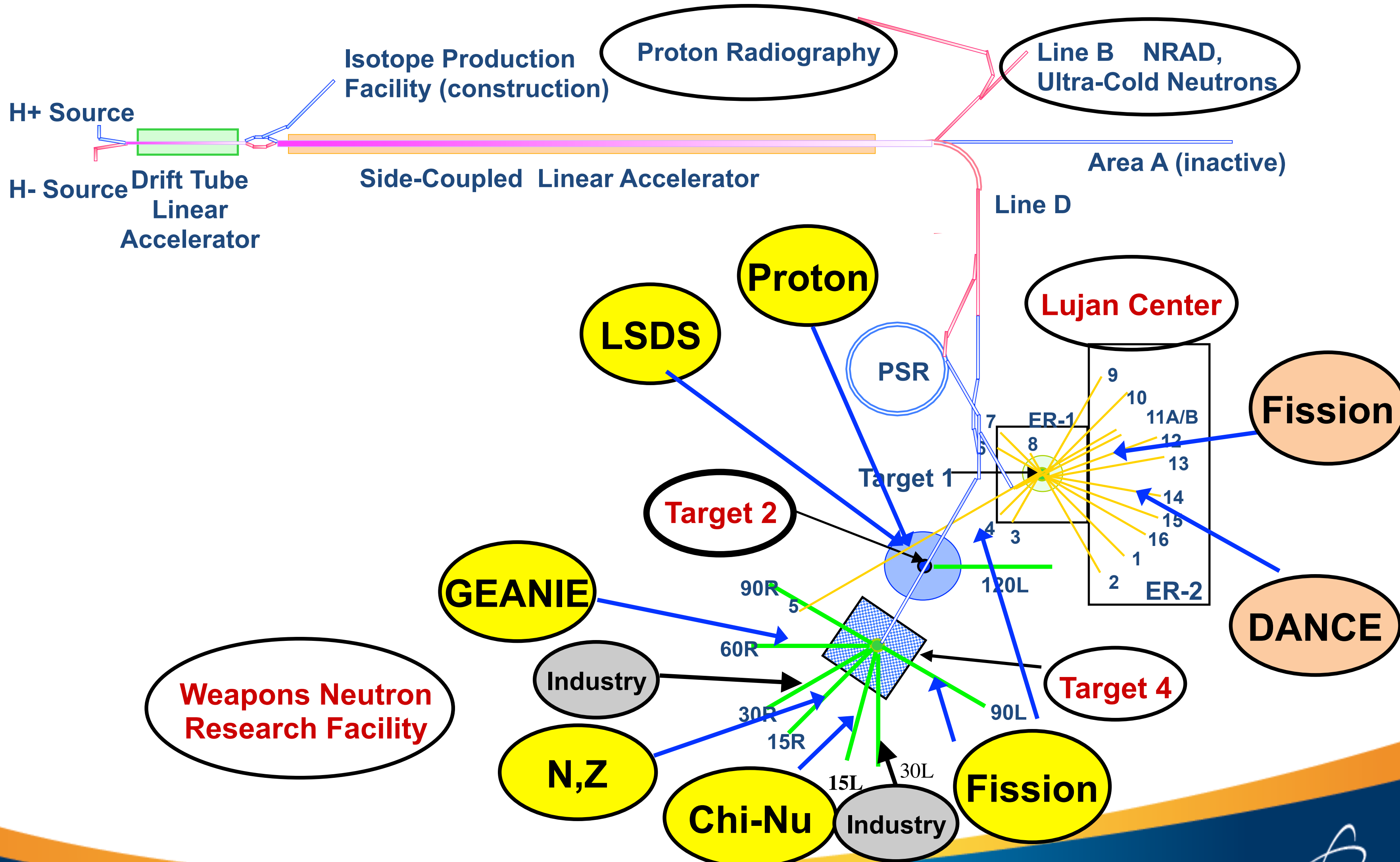
- **Neutron-Induced Fission Fragment Tracking Experiment (NIFFTE) project**
  - MICROMEGAS detector with segmented anode planes, 5952 hexagonal pads, 3D particle tracking, 4π solid angle coverage, custom electronics, sustained 60 MB/s.
  - Results of preliminary ^{235}U Fission Fragment Anisotropy measurements were presented as a function of neutron energy from 0.1 to 100 MeV.
- **SPectrometer for Ion DEtermination in fission Research (SPIDER)**
  - 2E2v instrument for high mass resolution fission product yields
  - Thermal neutron fission fragment mass distribution for ^{252}Cf, ^{235}U and ^{239}Pu were presented.
  - For ^{235}U and ^{239}Pu good agreement with England and Rider was observed.
- **TKE and mass distributions with a Frisch-gridded ionization chamber**
  - TKE as a function of incident neutron energy (<30 MeV) were presented for $^{235,238}U$ and ^{239}Pu. The data is in good agreement with the evaluation of Lestone et al 2011.
- **Chi-Nu - Prompt fission neutron spectra**
  - PFNS was measured using the Li-Glass detector array. Preliminary results for ^{235}U were presented covering the energy range from 0.02-1 MeV. Below 0.1 MeV the new data is slightly higher the ENDF/B-VII.1 but both agree within experimental uncertainty.

Nuclear Data Experiments at LANSCE: Brief Highlights 2015

Robert Haight
for P-27 and colleagues
Los Alamos National Laboratory

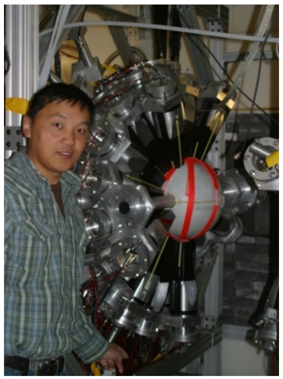
Cross Section Evaluation Working Group Meeting
Brookhaven National Laboratory
November 2-4, 2015

Nuclear data experiments use neutrons at the Lujan Center, Target 2 and Target 4

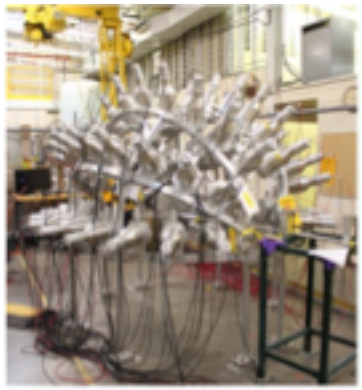


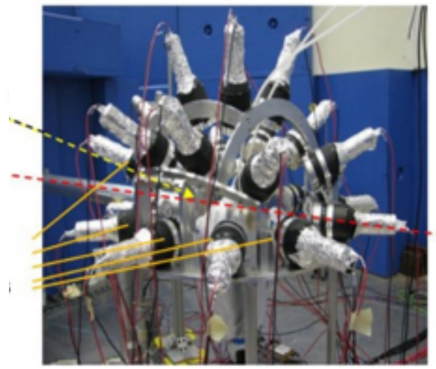
Nuclear data measurements at LANSCE are made with many different instruments

DANCE (n,γ)



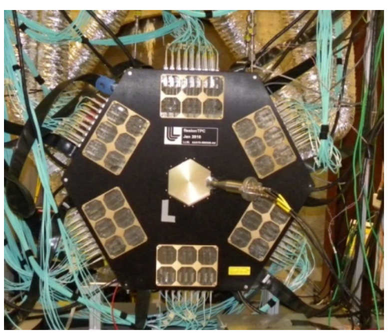
Chi-Nu – PFNS and (n,xn)



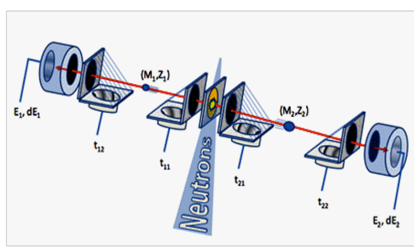


LENZ

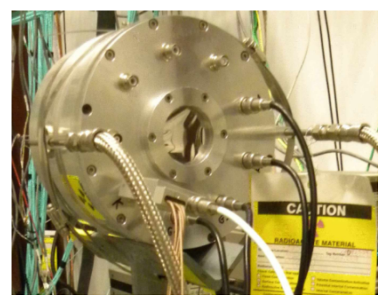
TPC



SPIDER



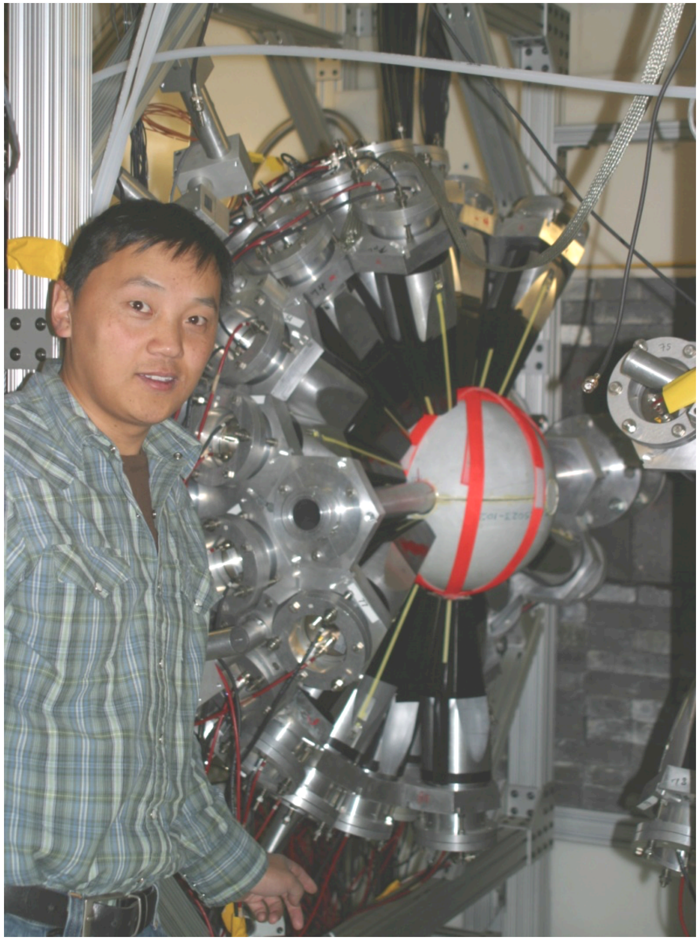
Double gridded ion chamber (IRMM)



Lead Slowing-Down Spectrometer

Note: GEANIE (n,xγ) is now disassembled

DANCE (n,γ)

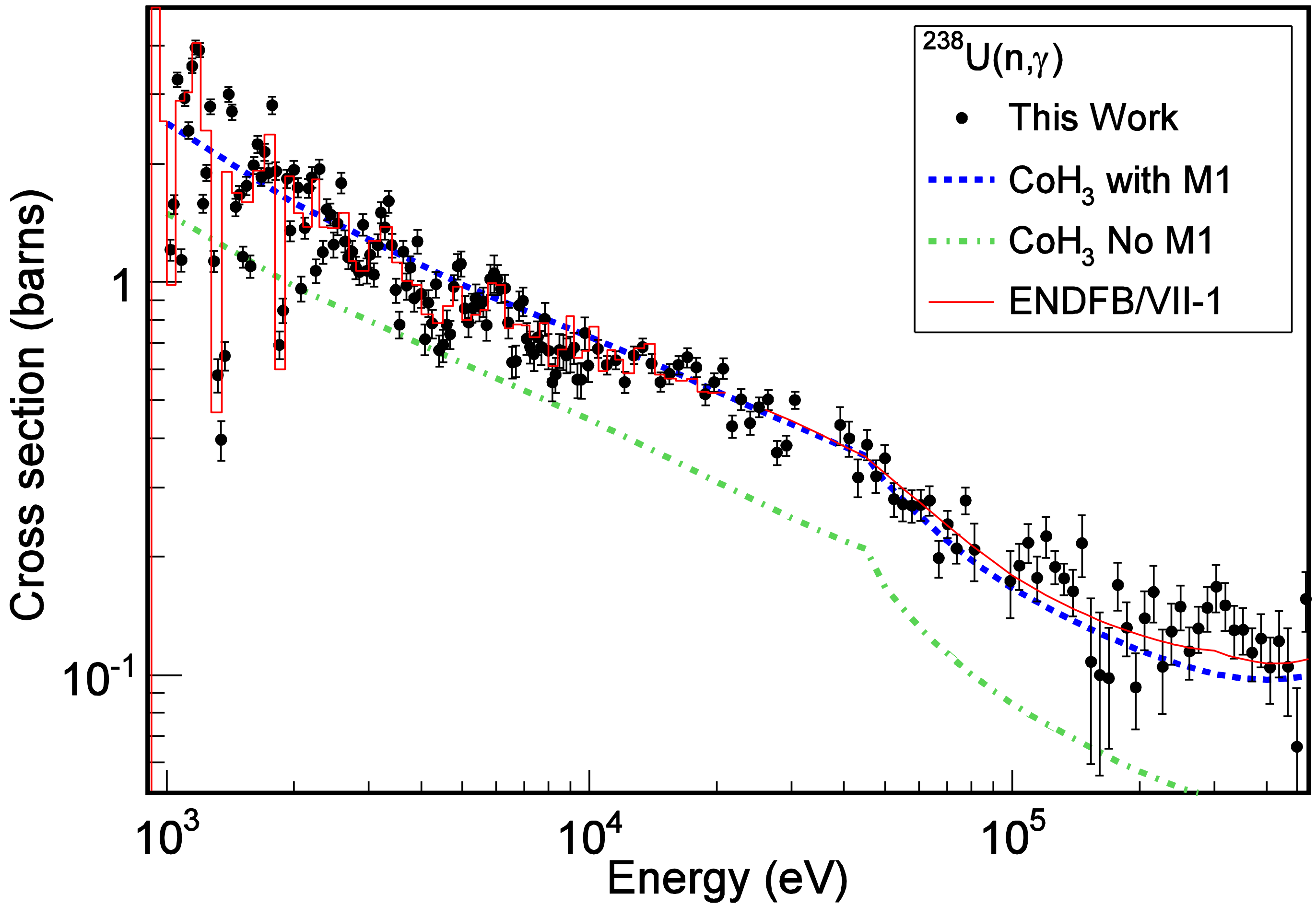


Contacts:
John Ullmann
Aaron Couture
Marian Jandel

Major DANCE Experiments 2014/2015

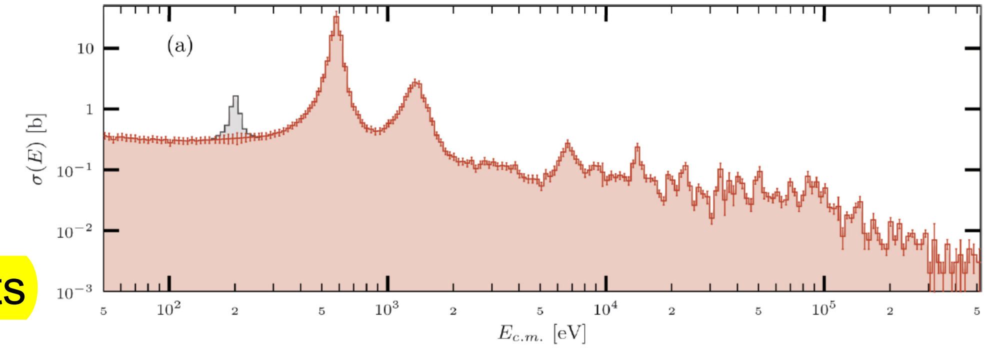
- ^{236,238}U(n,γ) relative to ^{235}U(n,f) – mixed target
  Data > 10 keV (M. Jandel DOE ECR)
- ^{238}U(n,γ) showing importance of M1 strength
- ^{235}U(n,γ) capture to isomers (requires fission tagging)
- ^{242}Pu spontaneous fission and (n,f) – gamma-ray spectra (LLNL)
- ^{67,68}Zn(n,γ) astrophysics (with LSU)
- ^{136}Xe(n,γ) Double-Beta decay backgrounds and physics (with IU)
- ^{161,162}Dy(n,γ) Strength functions and resonances (with NCSU, Charles U.)
- ^{173,174}Lu(n,γ) radioactive samples! (CEA)
- ^{191}Ir(n,γ) and ^{193}Ir(n,γ) Capture data > 10 keV

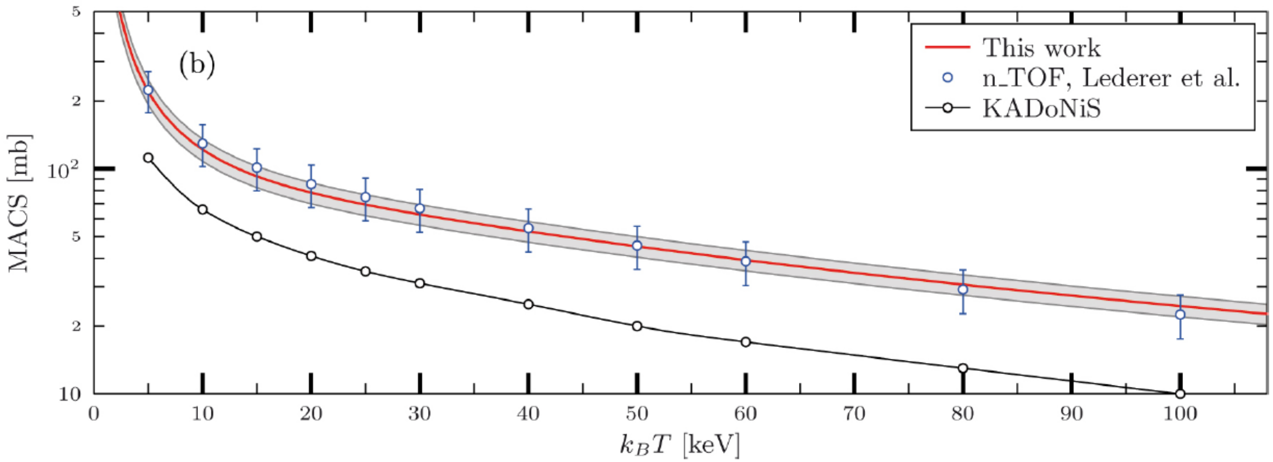
^{238}U capture shows importance of M1 strength



DANCE Measurement of ^{63}Ni(n,γ)

- ^{63}Ni radioactive $t_{1/2}$ = 101.2 y
- The neutron capture cross section was measured up to several 100 keV
- The deduced MACS increased by a factor of 2 from prior predictions
- The new capture cross section results in a 30% reduction in the production of s-only ^{63}Cu in the weak s-process, the primary production site for ^{63}Cu





Data and Figures from Weigand *et al.*, PRC, accepted

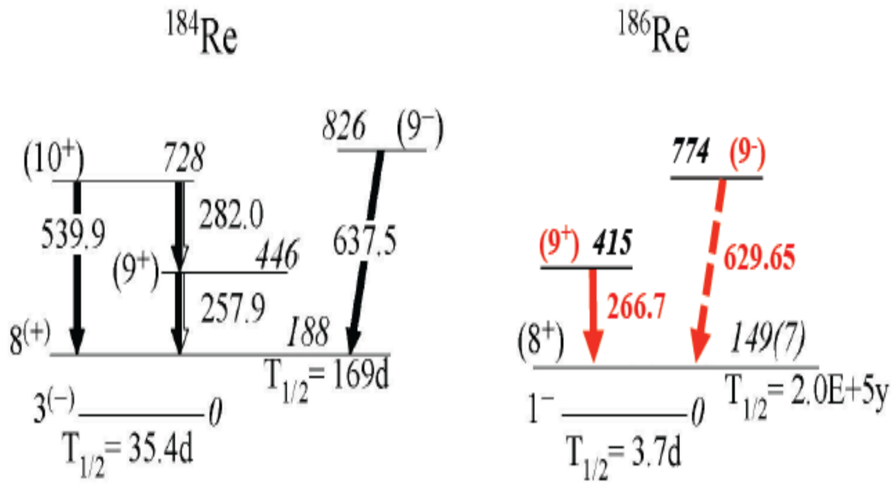
GEANIE $(n,x\gamma)$

Contacts:
Ron Nelson
Nik Fotiades
Matt Devlin

GEANIE is now dismantled but data analysis continues

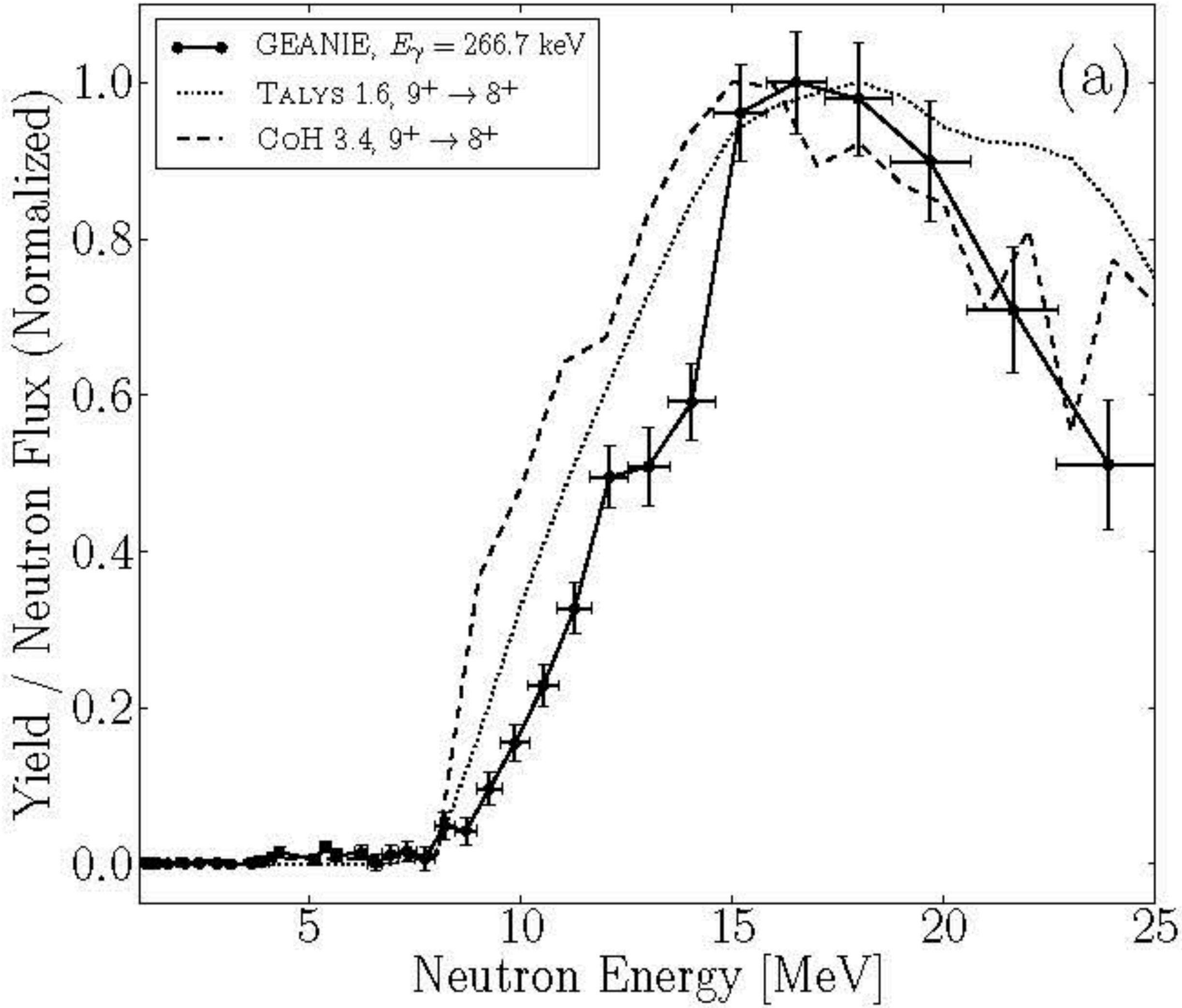
Measurements of (n,x) reactions feeding isomers

- ^{187}Re(n,xn) with Jeff Carroll (ARL) and David Matters (AFIT)



New γ-rays feeding the isomer in ^{186}Re, observed with GEANIE from the ^{187}Re(n,2n) reaction. From D. Matters, Master's Thesis, Air Force Institute of Technology (2015)

Excitation function of transition leading to isomer can be compared with calculations



Other GEANIE measurements

- Population of isomer in $^{109}Ag(n,2n)^{108}Ag$
- $^{136}Xe(n,xn)$ for $0\nu\beta\beta$ backgrounds with Josh Albert, Lisa Hoffman, et al. (IU)
- Neutron-induced γ-ray standard measurements: ^{56}Fe, Cr, B, Ti (n,n') γ-ray comparisons as a function of E_n

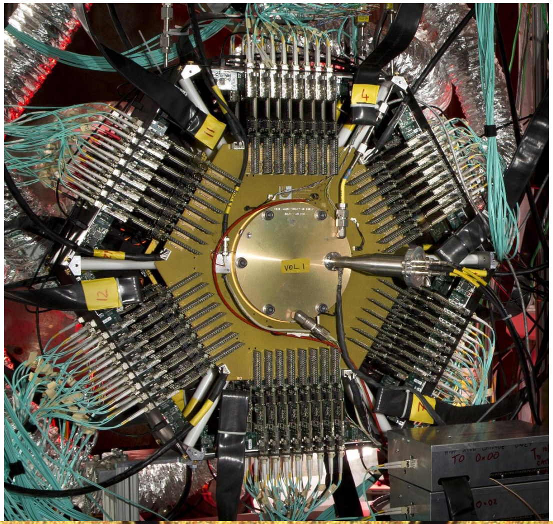
Fission Cross Sections
Fission Product Angular Distributions
Fission Total Kinetic Energy
Fission Product Yields

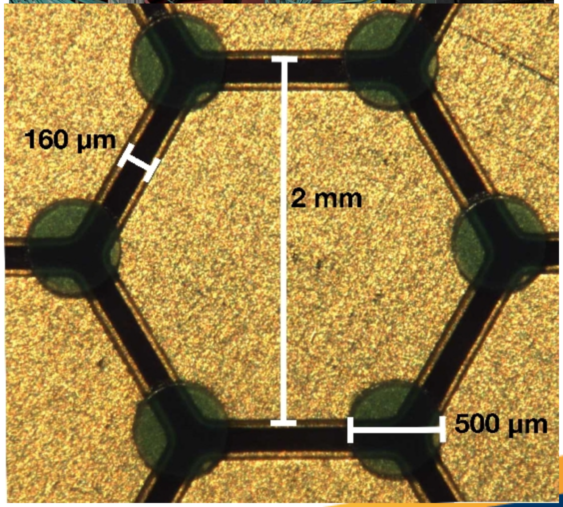
Contact:
Fredrik Tovesson

The NIFFTE TPC

NIFFTE = Neutron-Induced Fission Fragment Tracking Experiment

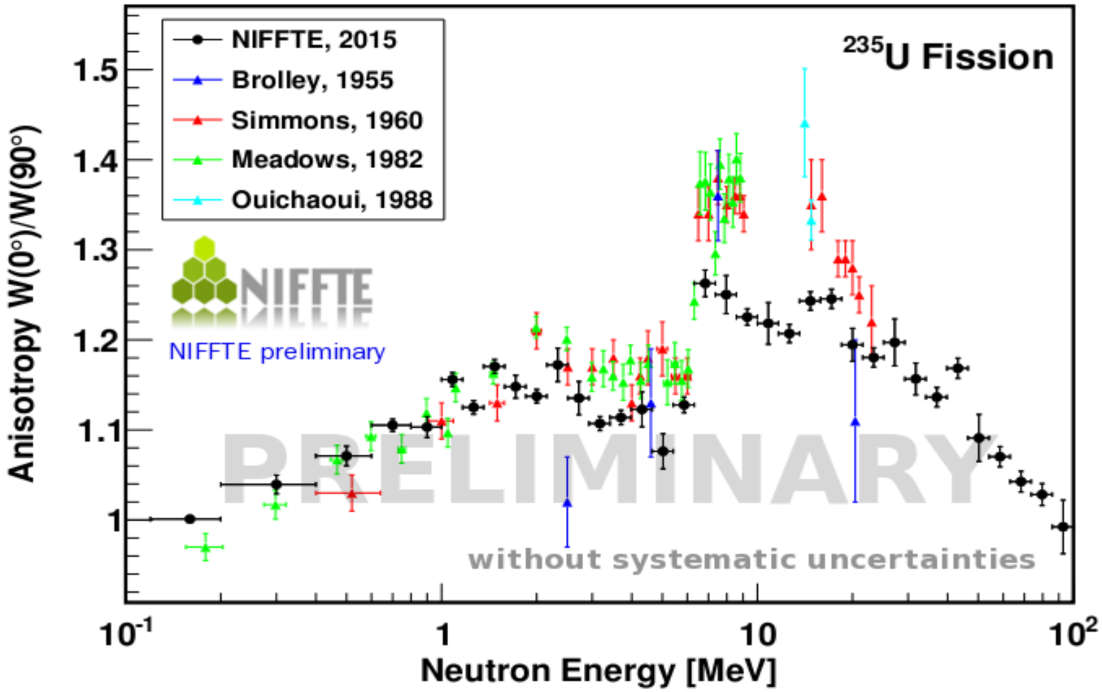
- MICROMEGAS detector
- Segmented anode planes
  - 5952 hexagonal pads
- 3D particle tracking
- ~4π solid angle coverage
- Custom electronics
  - Sustained 60 MB/s





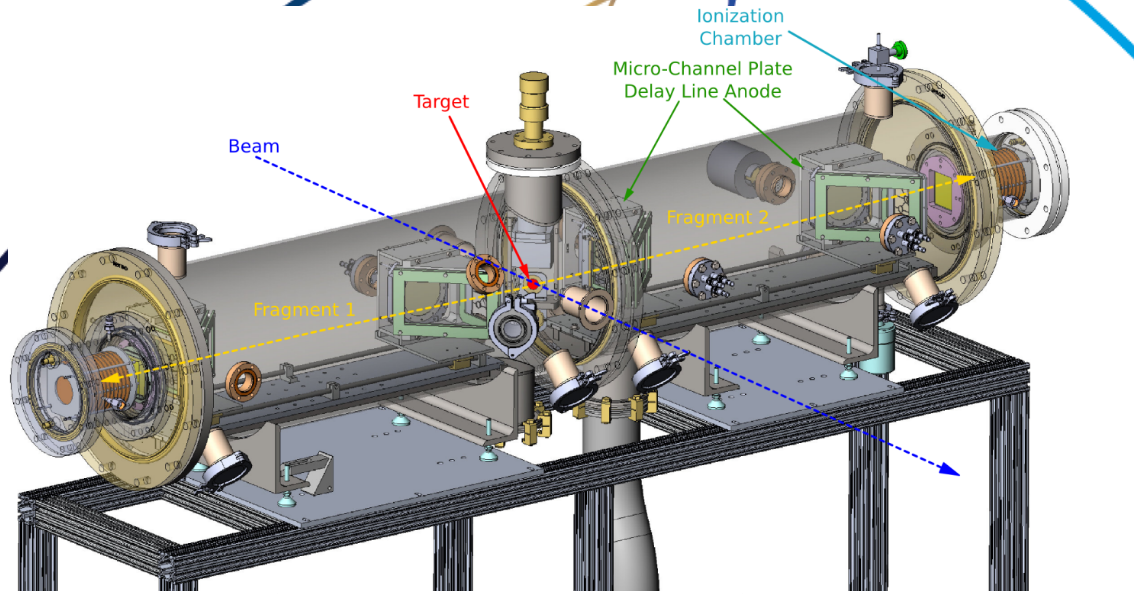
Preliminary ^{235}U Fission Fragment Anisotropy

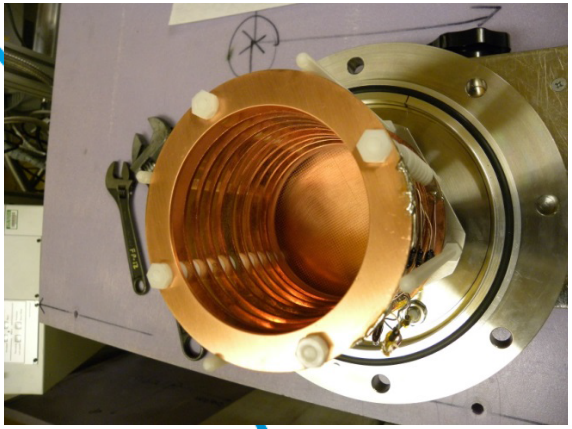
- Thesis work of Verena Kleinrath
- Fit angular distributions bin-by-bin with even Legendre polynomials
- Statistical uncertainties shown
- ^{239}Pu anisotropy analysis ongoing



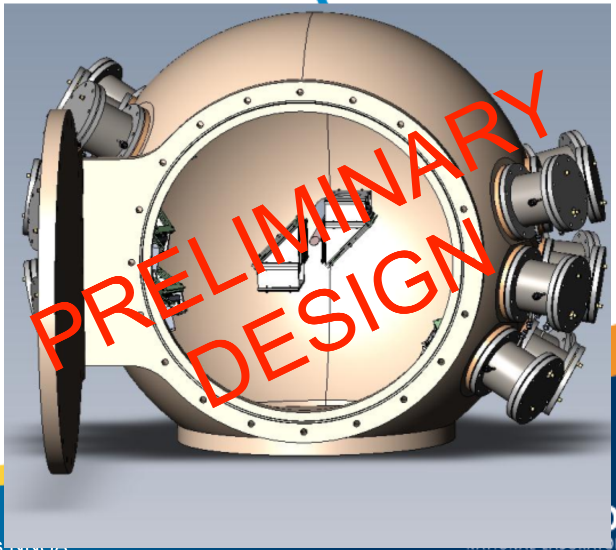
SPIDER Instrument:

SPectrometer for Ion DEtermination in fission Research

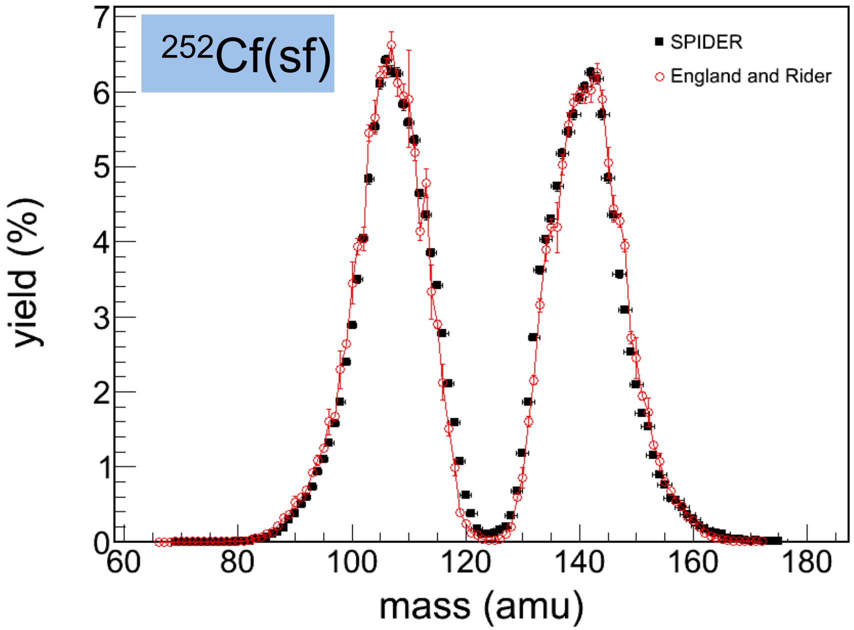


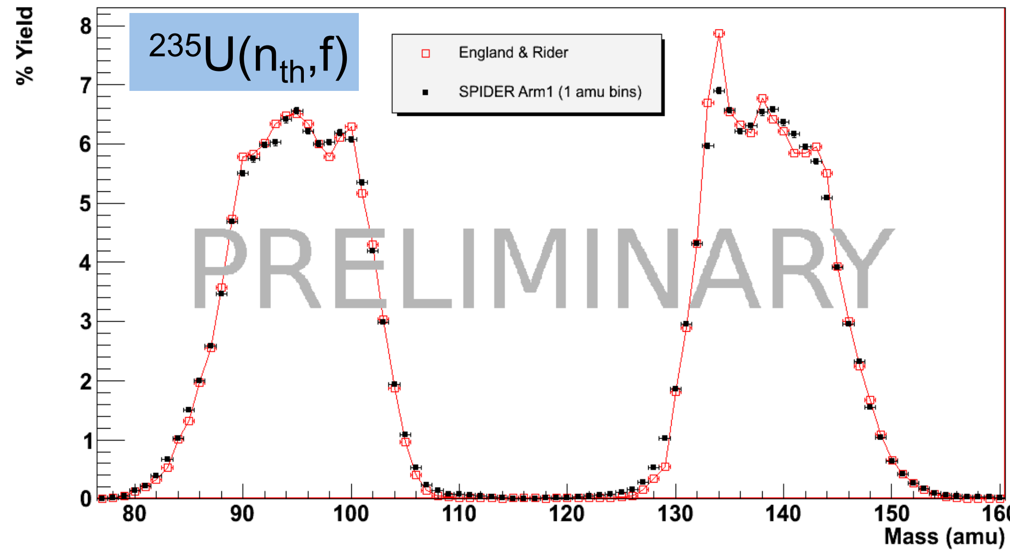


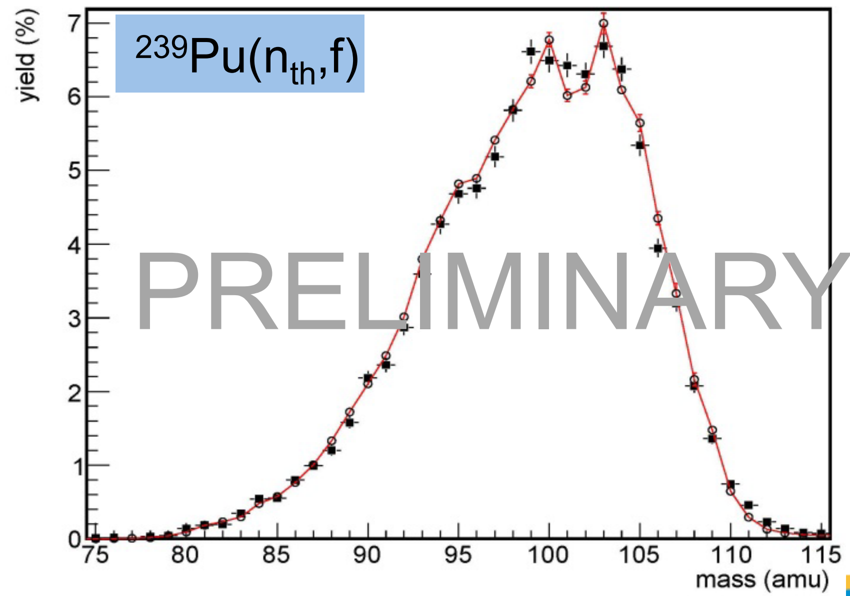
- 2E2v instrument for high mass resolution fission product yields
- Particle energy measured with ionization chambers
  - -200 nm SiN entrance window, isobutane fill gas
- Particle velocity measured with ToF assemblies
  - -Micro-channel plates for fast timing (75 mm diameter)
    - C. W. Arnold *et al*., Nucl. Instr. and Meth., **764**, 53 (2014)
  - - Delay line anode for particle trajectory corrections
- A scale-up beyond the dual-arm will notably enhance detection efficiency and experimental capabilities



Recent SPIDER Fission Product Yield Results







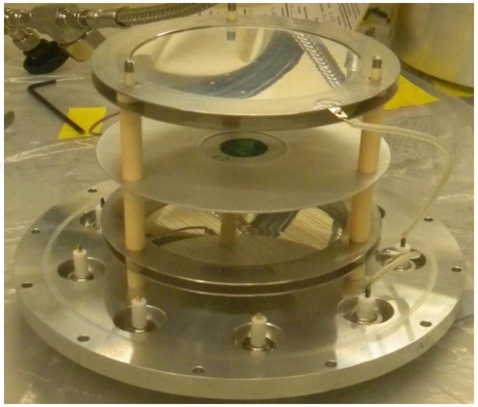
- Experimental data from 2014 – 2015
  - ^{252}Cf(sf), ^{235}U(n_{th},f) and ^{239}Pu(n_{th},f)
  - Comparison to England and Rider Evaluation LA-UR-94-3106, ENDF-349
  - -^{252}Cf results published in NIM: K. Meierbachtol *et al*., Nucl. Instr. and Meth., **788**, 59 (2015)

TKE and mass distributions with an Frisch-gridded ionization chamber

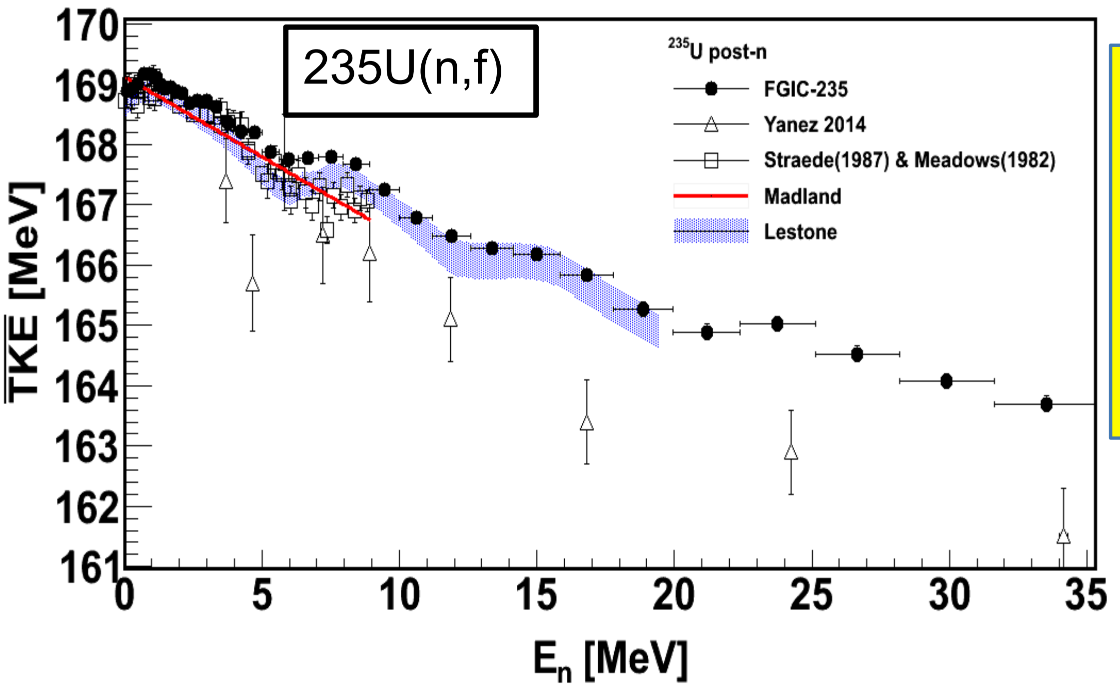
- The FGIC has been optimized for fission measurements.
  - ~0.5% energy resolution
  - 4-5 AMU mass resolution (using 2E method)

<ins>Experiments</ins>

- 2012 : ^{238}U (TKE and mass) [**D. Duke,** Ph.D. Thesis, Nov. 2015]
- 2013 : ^{235}U (TKE and mass) Publications in progress.
- 2014 : ^{239}Pu (TKE) [**Meierbachtol, K. et al.**, Publication in process.]

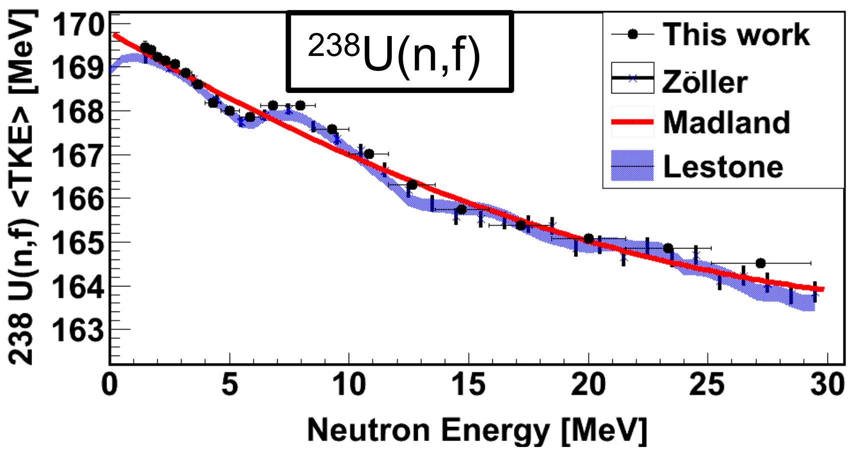


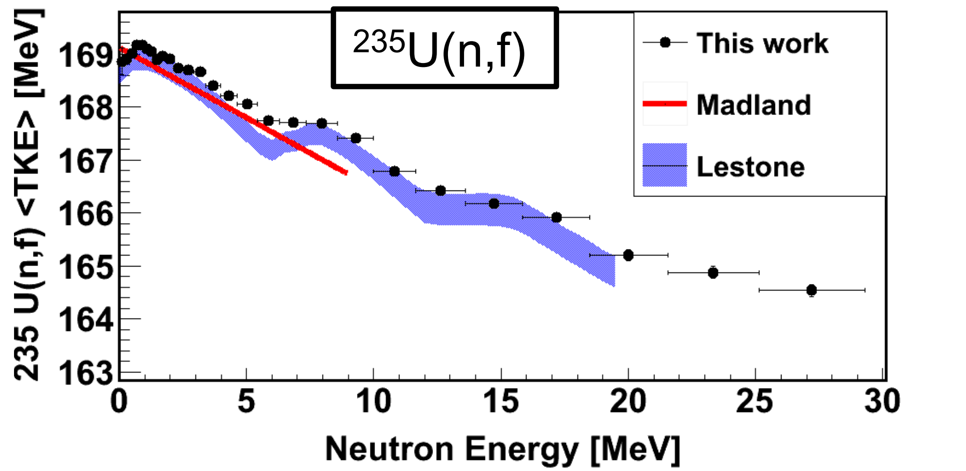
[**S. Mosby et al.,** *NIM A.* 2014, 757, 75]

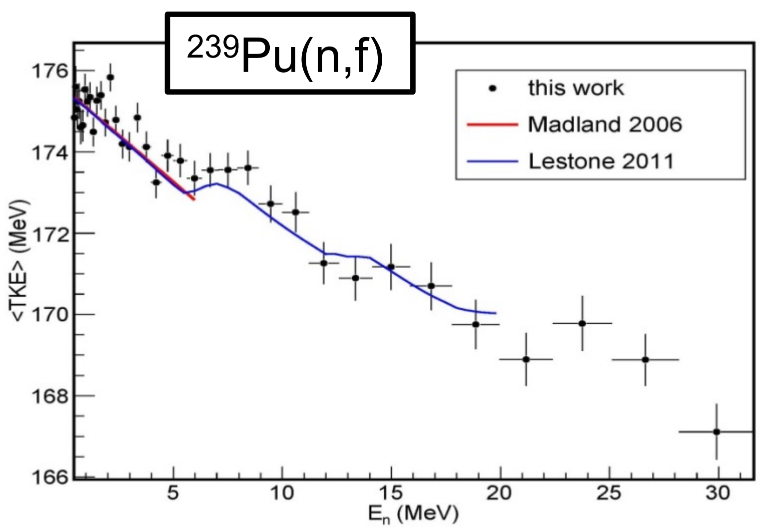


- TKE shape validates model.
- 235U Data exhibit the turnover behavior at low E_n = 0 - 3 MeV.
- Structure corresponding to multichance fission thresholds.

TKE experimental results are consistent with calculations by Lestone et al.

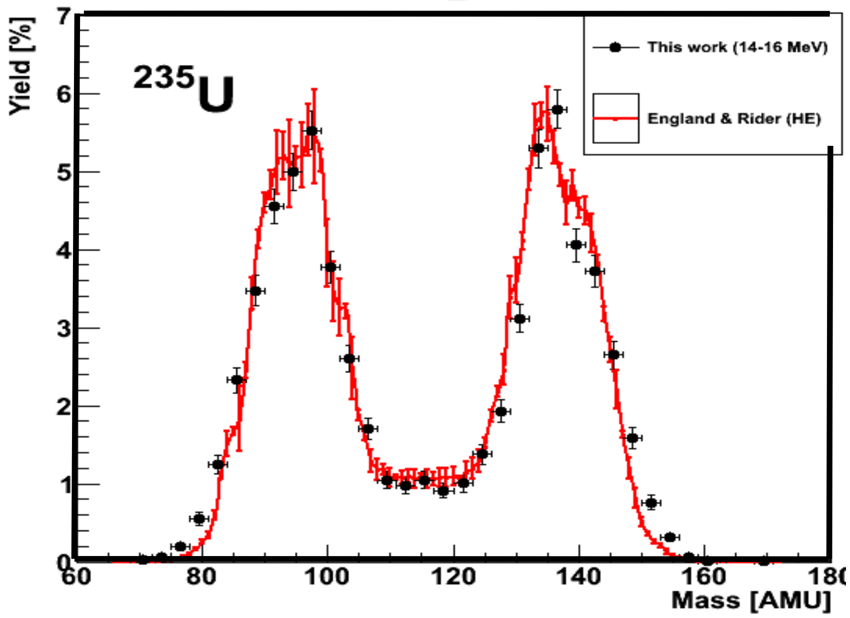




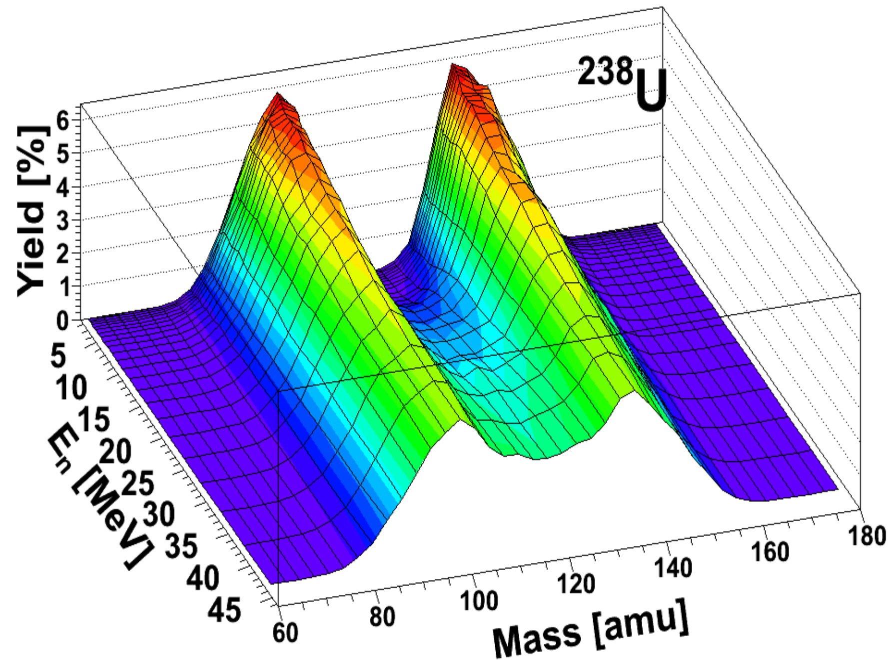


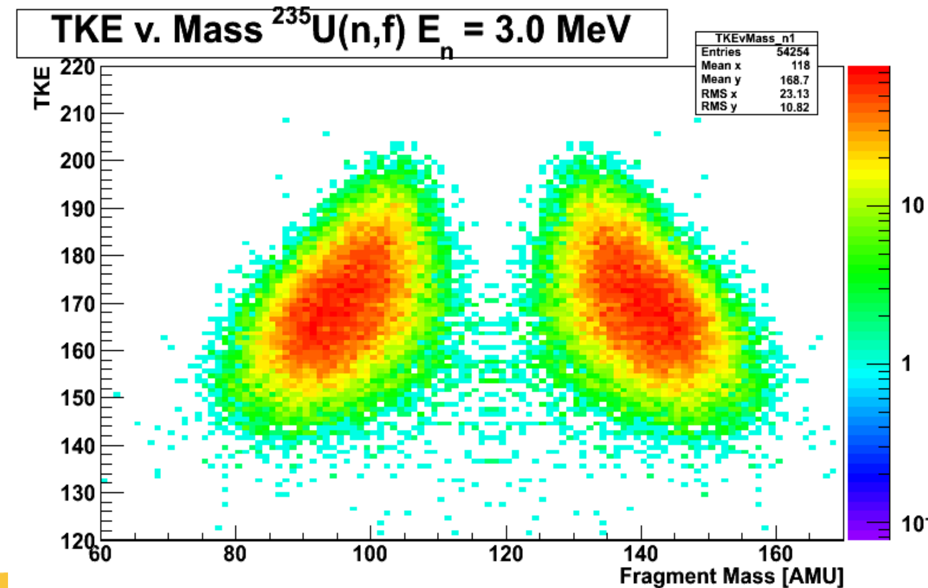
- **Zöller data for U-238 extends > 30 MeV**
  - For U-235 no previous data above 9 MeV
  - For Pu-239 no data beyond 5 MeV
- **Madland evaluation is fit to experimental data**
  - Not intended for extrapolation
  - ENDF values for 14 MeV never the less are extrapolations
- **Semi-empirical modeling by Lestone et al. in close agreement with new data**

Mass Distributions



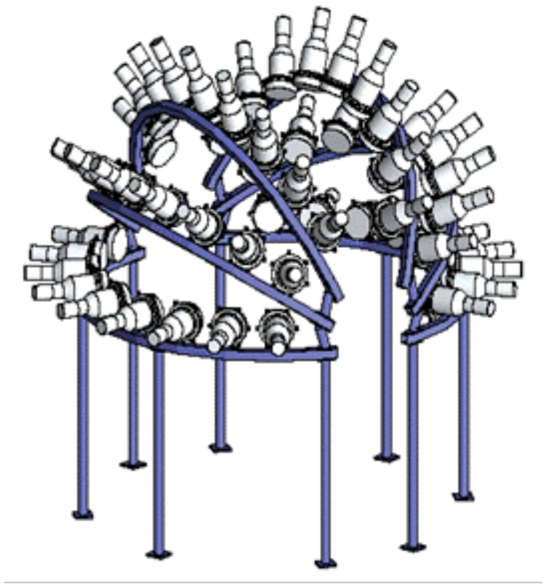
[England, T. R. & Rider, B. F. ENDF-349. October 1994]

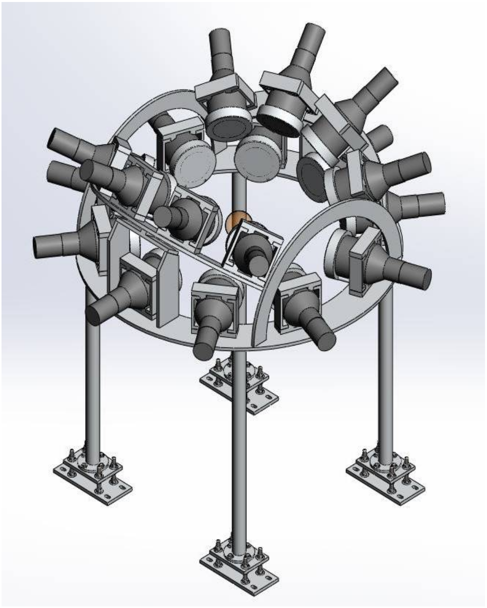




- Fission fragment mass distributions for 238U and 235U are available at for a wide range of Einc.
- Correlated mass and energy information is also available.

Chi-Nu - Prompt fission neutron spectra





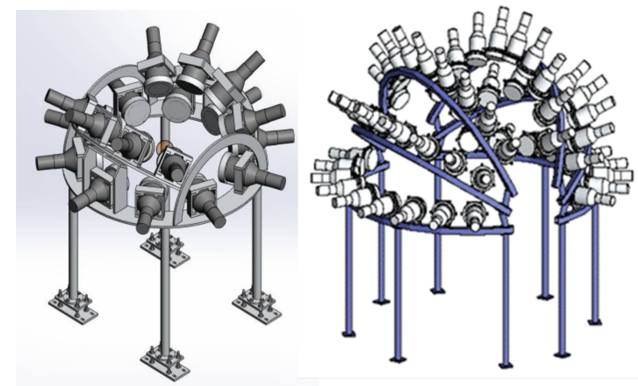
Contacts:
LANL:
Bob Haight
Hye Young Lee
Shea Mosby
Matt Devlin
LLNL:
Ching-Yen Wu

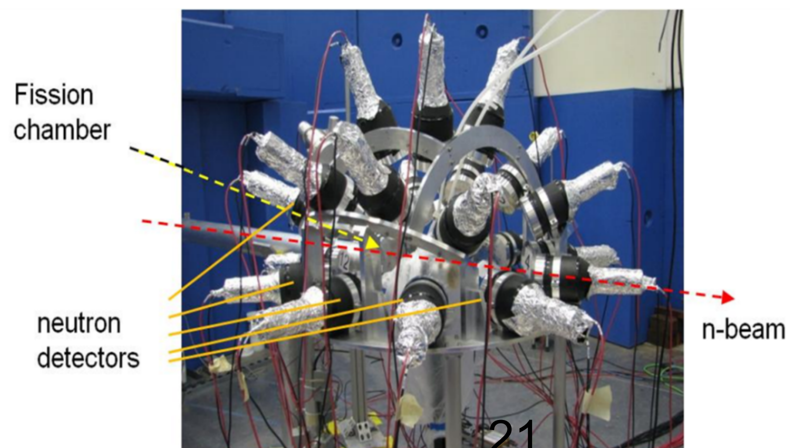
Approach – fast fission counter, two types of neutron detector arrays to cover fission neutron energy range

- WNR/LANSCE spallation neutron source – all neutron energies from 0.5 to 30 MeV and higher
- New building from LANS support
- Double time-of-flight
  - LANSCE spallation source to fission chamber → incident neutron energy
  - Fission chamber to neutron detector → fission neutron energy
- Multi-year project – thru FY2017
- Goal: a significant result for stockpile stewardship (i.e. with respect to the current nuclear data evaluations)

LLNL fission chamber

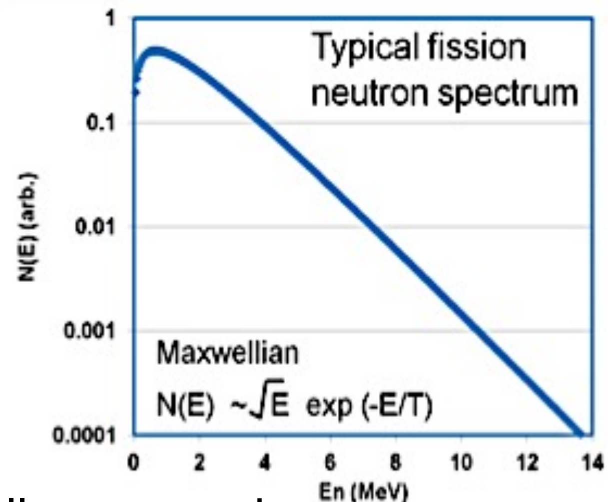
Two LANL neutron detector arrays

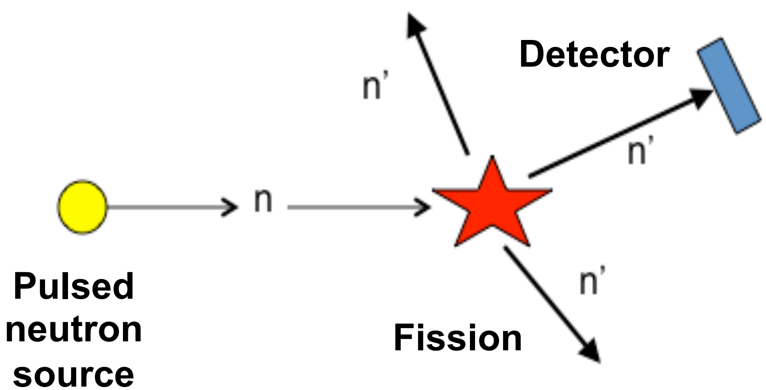




Measuring fission neutron spectra by time of flight is straightforward in principle

- Detect fission
- Measure PFNS by time of flight to a detector
- We also measure incident neutron energy by TOF

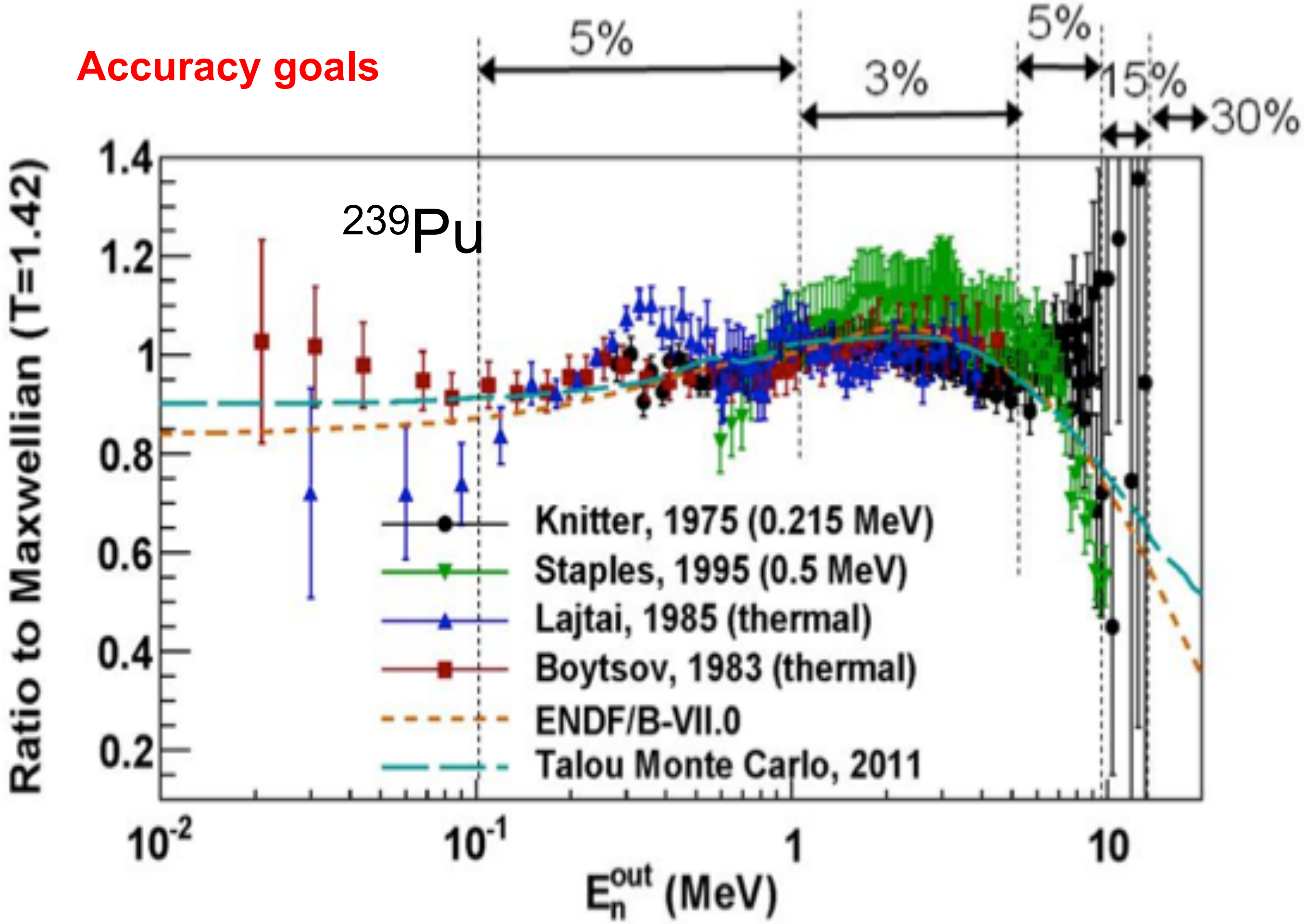




Challenges are in:

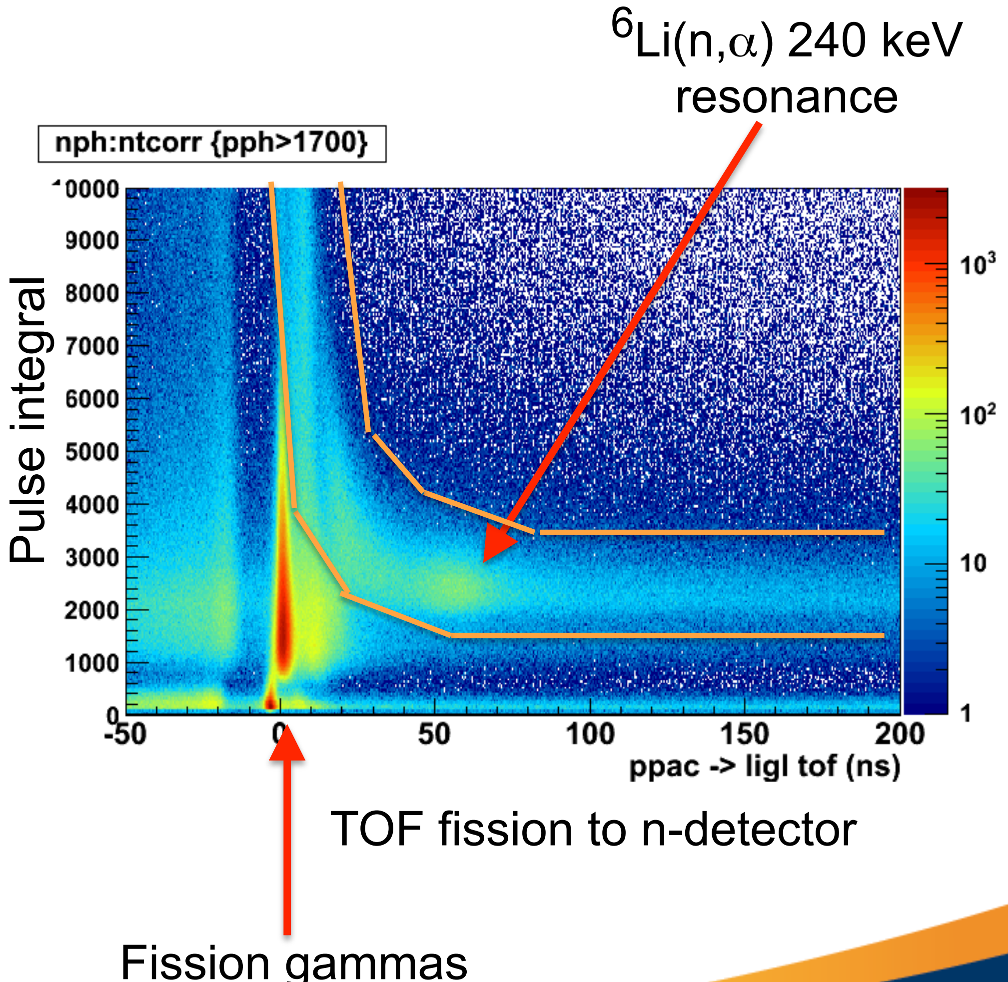
- neutron scattering
  - fouls up path length
  - neutrons scatter to lower energy
- detector response (efficiency 5-30%)
- few neutrons at high energies
- n-gamma separation
- good timing (ns)

Goal for Chi-Nu is measurements that will impact evaluations – shape and uncertainties



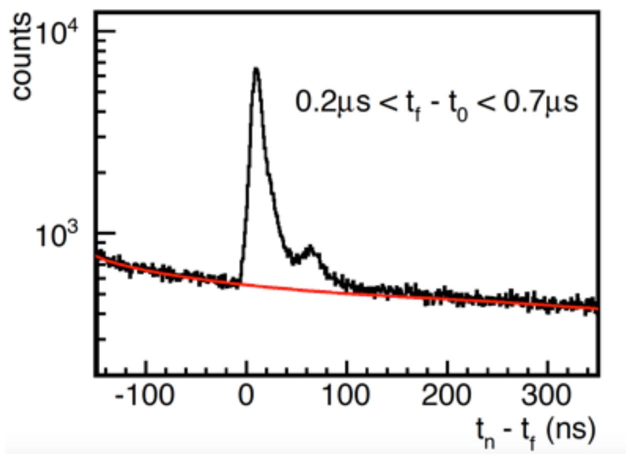
^{6}Li-glass neutron detectors give pulse-height versus time of flight from the fission counter to the detector

- Reaction: $^6Li(n,alpha)^3H$
  Q-value = 4.8 MeV
- Efficiency good at low En
- Good separation of neutrons and gamma rays for low En

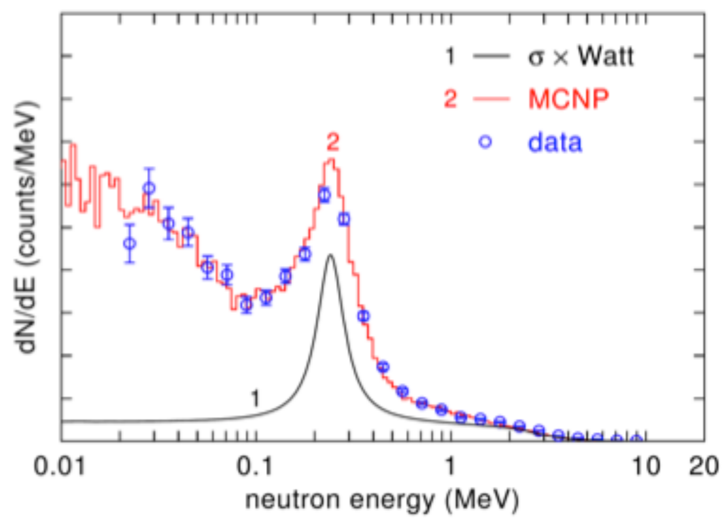


Then we need to subtract background and transform to "equivalent" fission energy

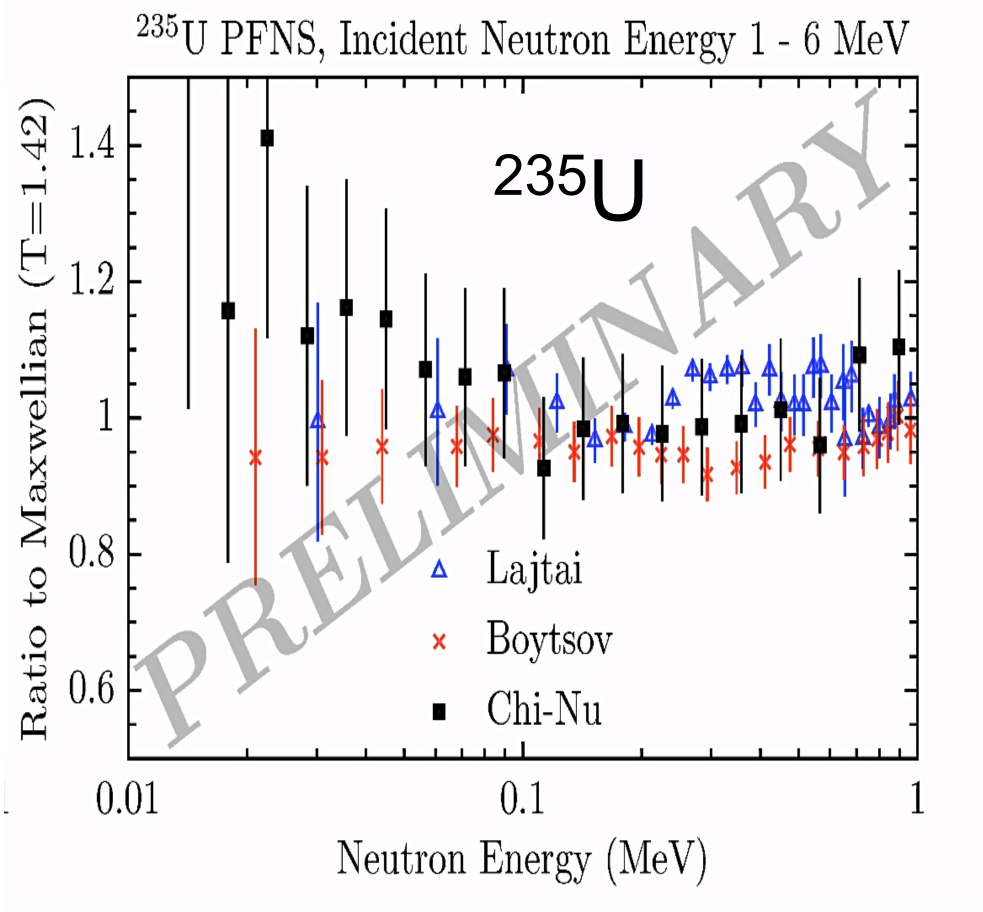
TOF- Bkg



"Equivalent" fission energy

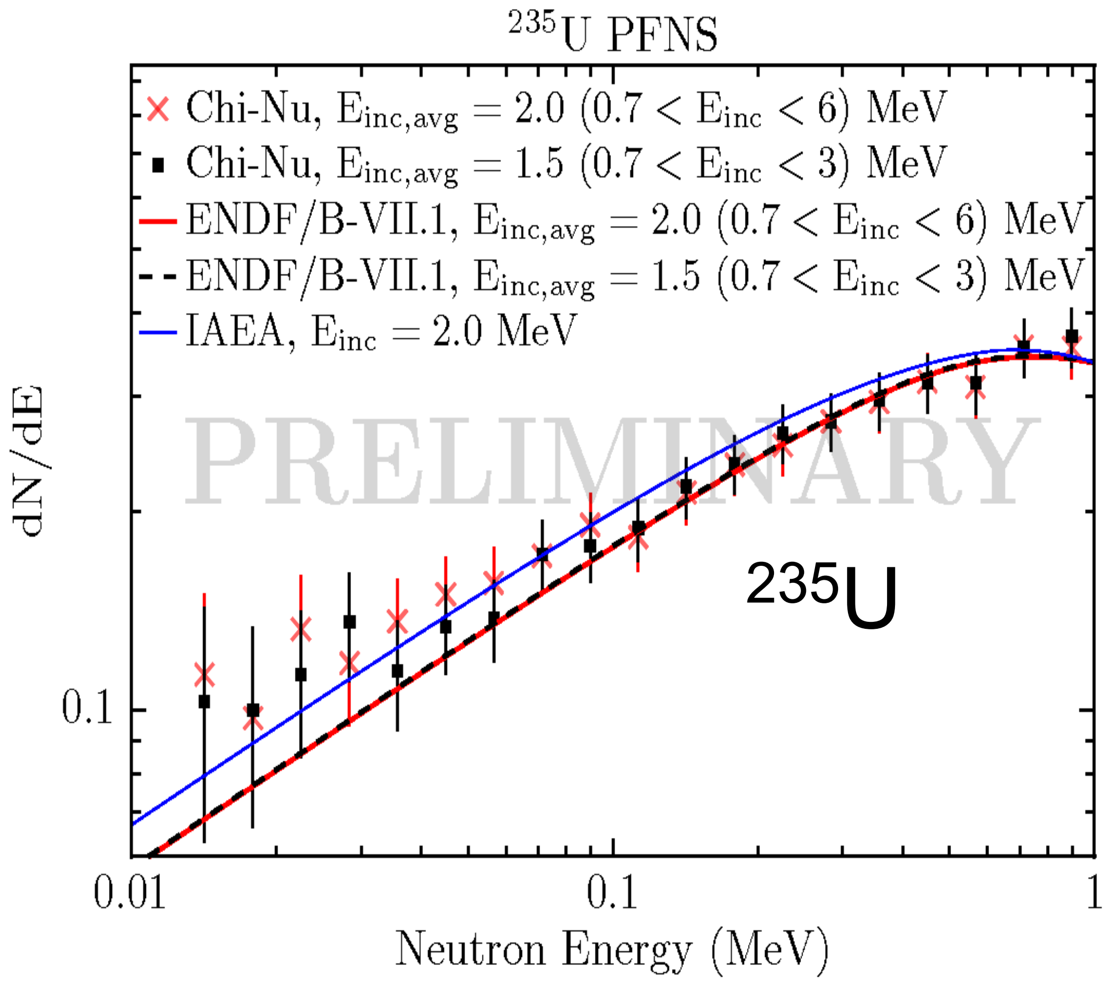


First, preliminary results on low energy part of PFNS for $^{235}U(n,f)$ can be compared with literature values



- MCNP calculations moved to High Performance Computers
- Results good down to 0.1 MeV (our goal) and probably even lower
- Error bars include both statistical and systematic errors
- General agreement with data taken at thermal energy

The preliminary results for ^{235}U compare rather well with evaluations

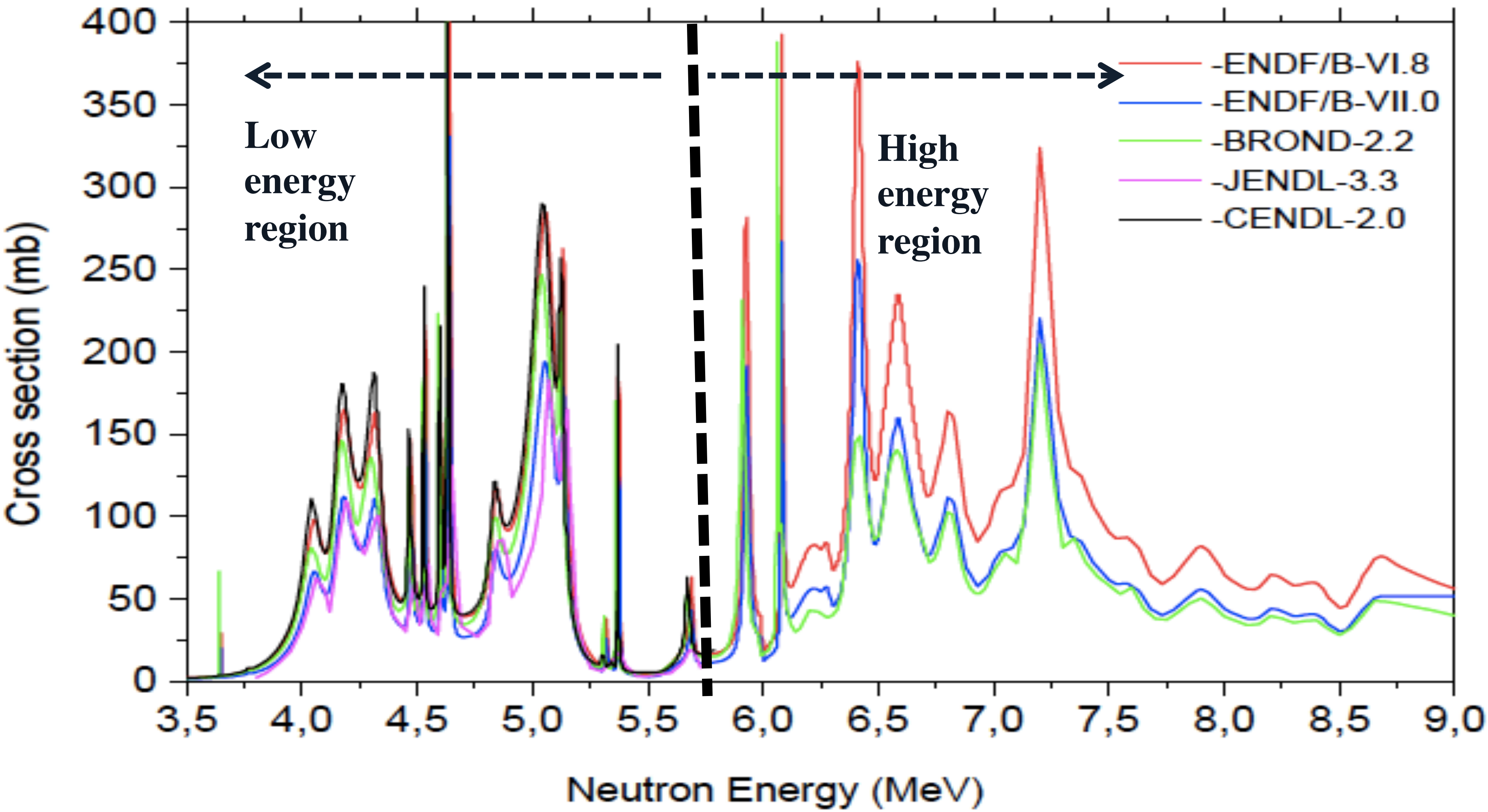


No significant discrepancy with evaluations for ^{235}U from our ratio-of-ratios analysis

LANL (continued)

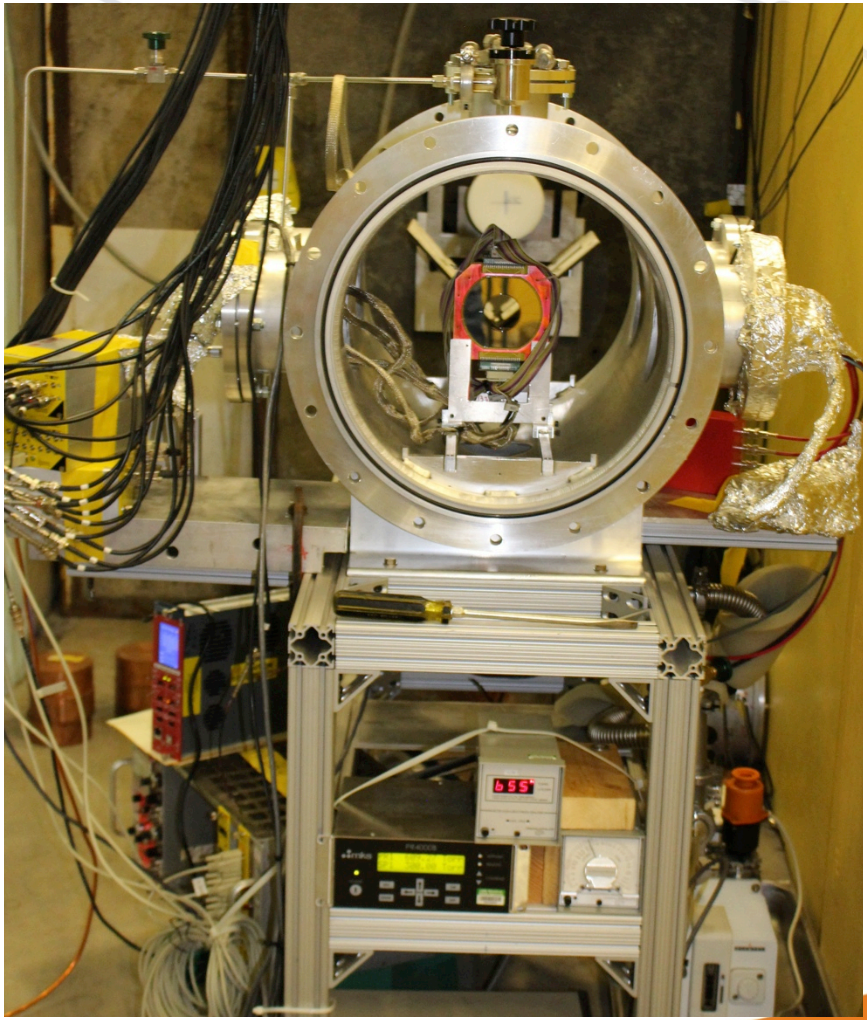
- **Planned new activity**
  - **$^{16}O(n,\alpha)$ measurement at LANSCE**
    - LENZ uses: twin Frisch grid ionization chamber, multi-target wheel system, at forward angles, silicon strip detectors measures angles and charged particles as a telescope.
    - The detector will be used at LNSCE with a white neutron spectrum.
    - Plan to use solid Ta_2O_5 target also with ratio to Li_2CO_3. Total uncertainty is estimated at about 12%
  - Neutron Array at DANCE (NEUANCE)
    - DANCE hardware upgrade, provides new measurements on correlated data between neutrons and gammas in neutron-induced fissions with high efficiency. Work is in progress.

Evaluation of $^{16}O(n,\alpha)$ reaction : differ by up to 30-50 %



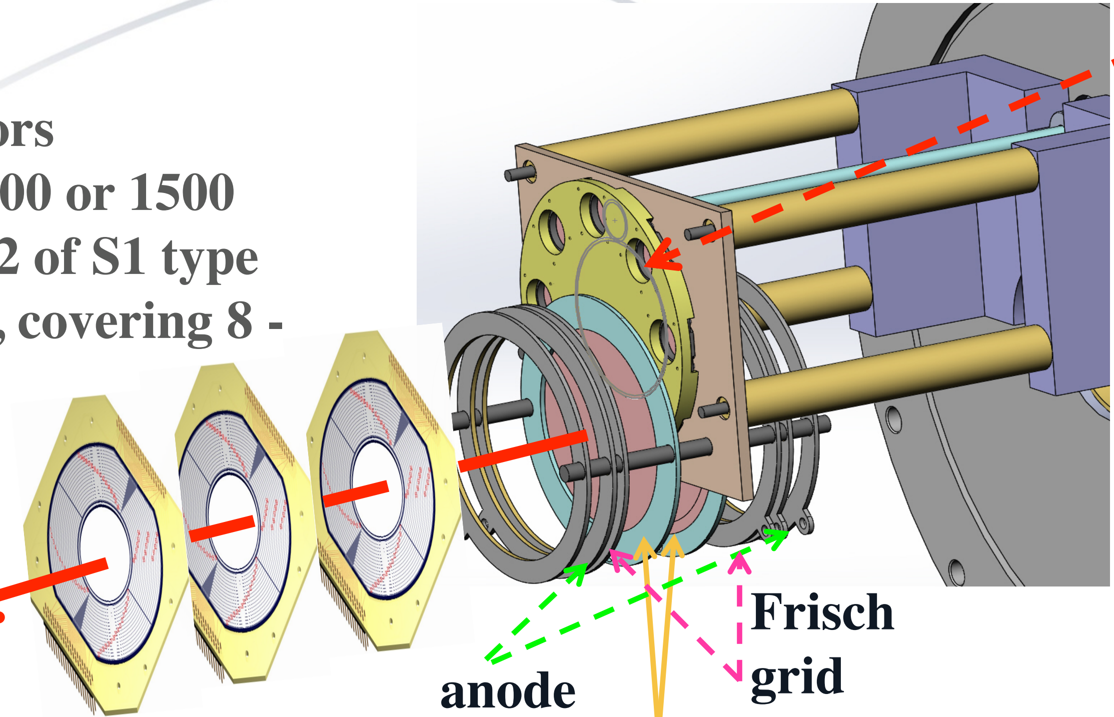
LENZ : upgrade of NZ chamber

- Designed for measuring (n,z) reactions with a large solid angle and low detection threshold for especially alphas
- Twin Frisch grid ionization chamber
- Multi-target wheel system
- At forward angles, silicon strip detectors measures angles and charged particles as a telescope
- Digitizers provide wavelet information as post processing for improving signal-to-noise ratio and timing resolution with no dead time



LENZ configuration for $^{16}O(n,\alpha)$ reaction

E : silicon detectors
rest energy in 1000 or 1500 μm thick DSSD (2 of S1 type and 1 of S3 type), covering 8 - 60 degrees



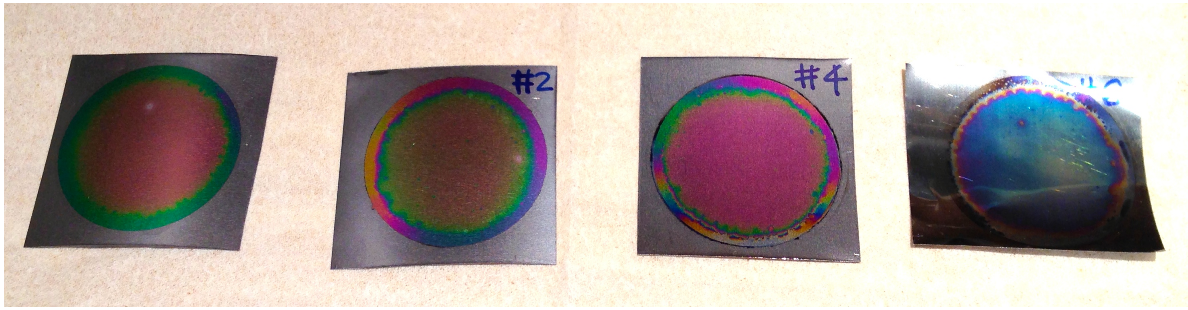
ΔE : ionization chamber
energy loss in 97% Xe + 3%CO2 or in P10 gas mixture

○Maximize the solid angle and minimize the low energy alpha's energy loss

○Minimize the detection thresholds in anodes and timing resolution in cathodes

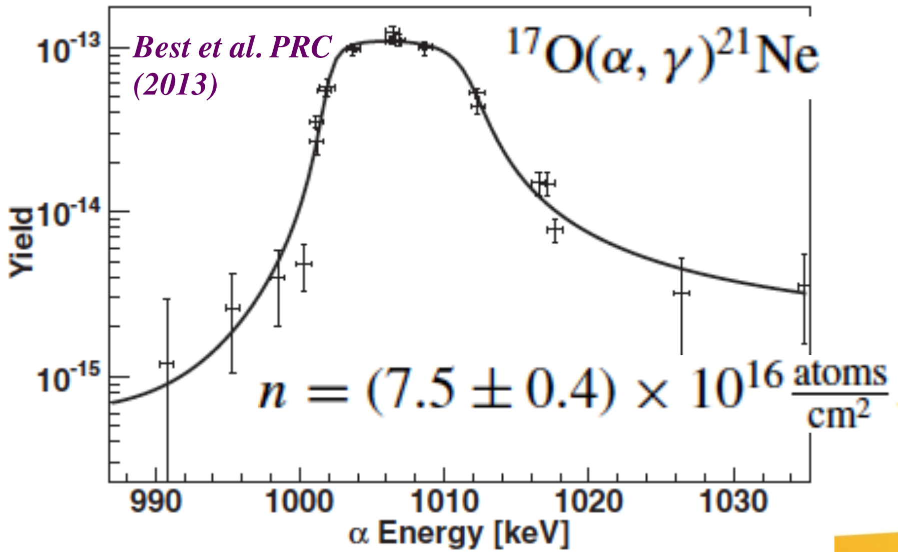
Solid ^{16}O target for LANSCE measurements

- For better control of the target amount and ease of manufacturing in house, we plan to use a solid oxygen target
- Tantalum backing was anodized to produce Ta_2O_5 with ~ 4000 Å

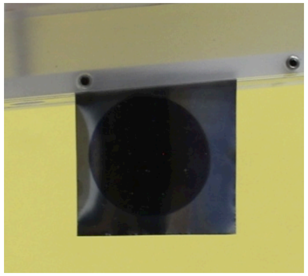


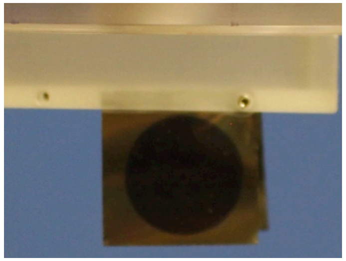
Vermilyea, Acta Metallurgica (1953)

Thickness (Å)	Error (Å)
200-500	1
500-2500	5
2500-5000	8

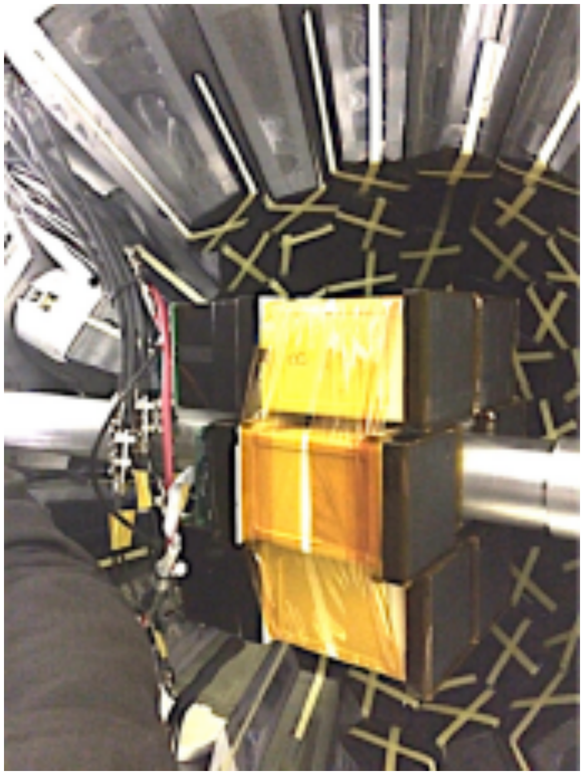


- For the ratio measurement, Li_2CO_3 targets were made



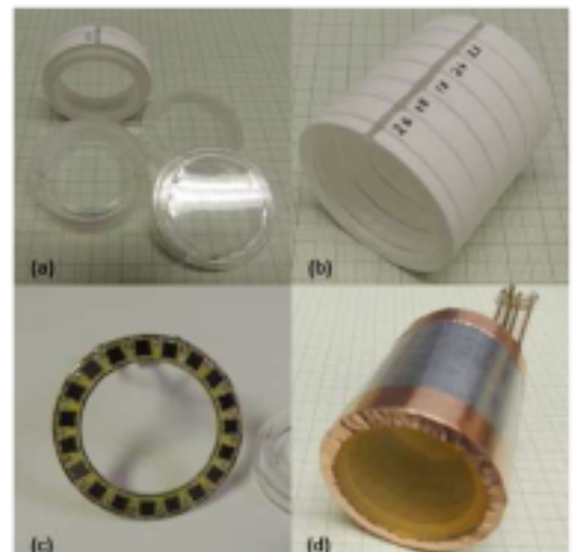


4. Enhanced DANCE Capability at LANSCE, led by M. Jandel (DOE-Early Career)



DANCE hardware upgrade, NEUANCE (Neutron Array at DANCE), provides new measurements on correlated data between neutrons and gammas in neutron-induced fissions with high efficiency

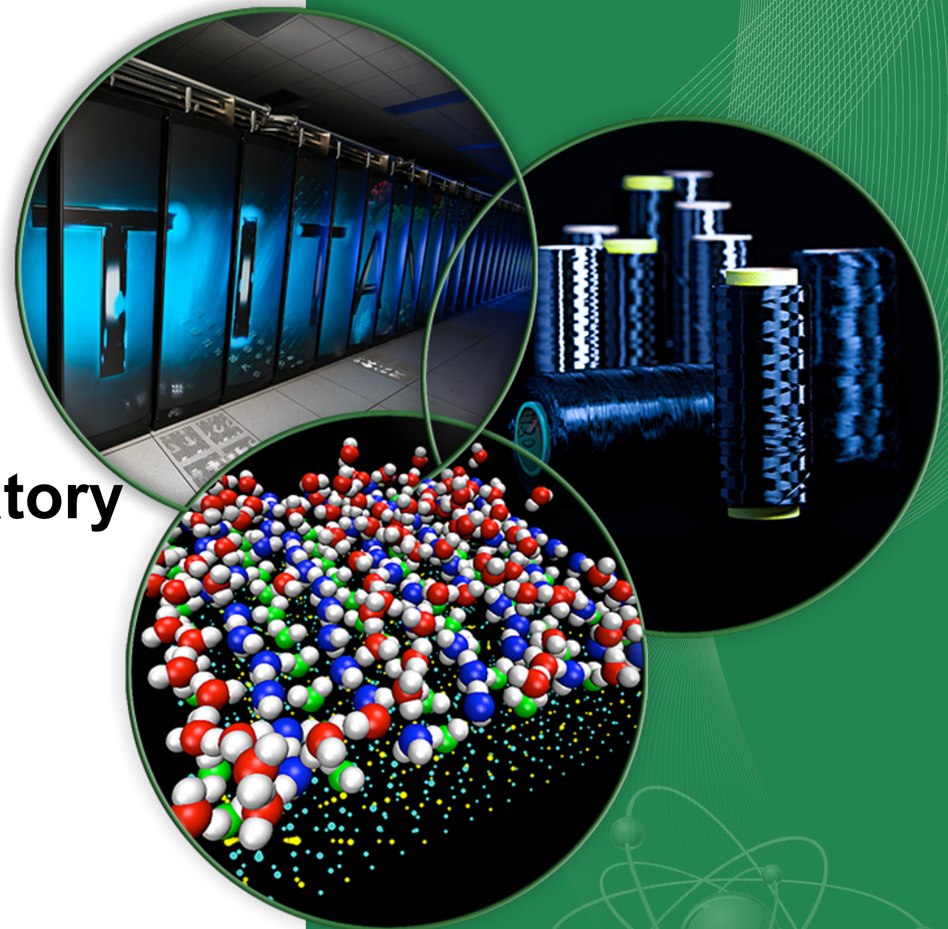
Fission fragment tagging with thin scintillator foils is composed of multiples films from a solution of liquid scintillator, for the studies of gamma-ray cascades leading to the isomeric states in U-236



Oak Ridge National Laboratory

- **Resonance Region Measurements**
  - **Ce** - Measurements of Ce using natural metallic samples
    - The samples are in Al canning due to reactivity with air
    - Transmission experiments with different sample thickness are scheduled using FP4, 50 m
    - Neutron capture using detector system at FP14, 60 m
  - **V** - Measurements using metallic samples of different thickness
    - Neutron capture using detector system at FP14, 60 m
    - Neutron Transmission experiments with different samples are scheduled using FP4, 50 m

ORNL Neutron Cross-Section Measurements Activities



K. H. Guber

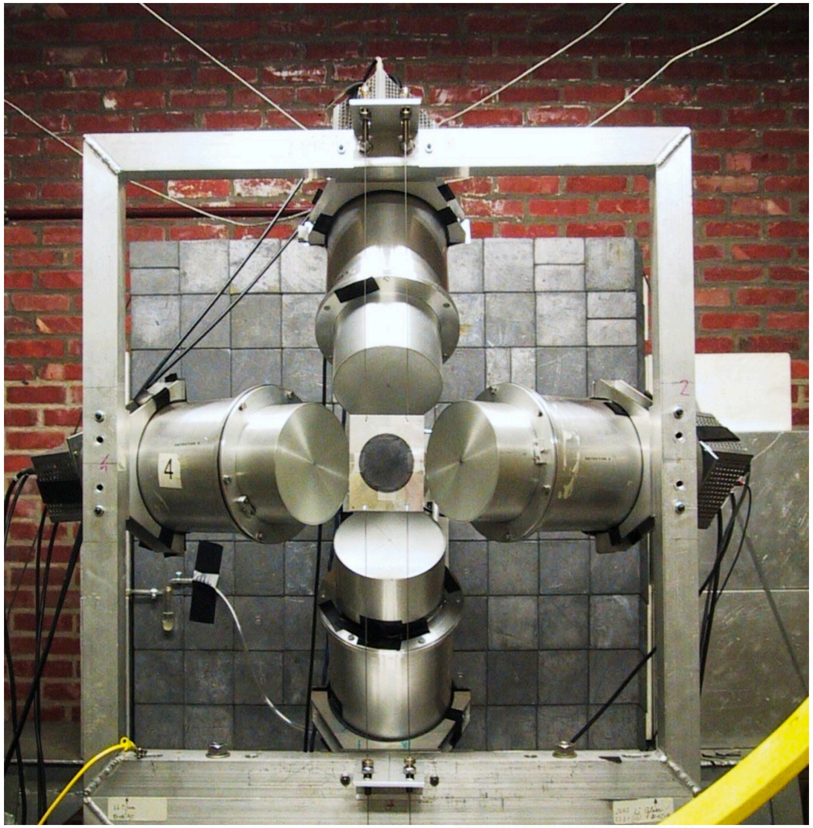
Oak Ridge National Laboratory

Oak Ridge, TN, USA

CSEWG Meeting 2015

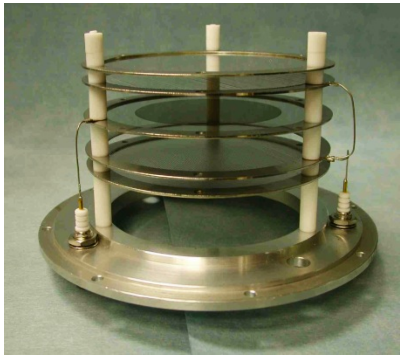
Capture Cross-Section Measurements at GELINA

L = 10 m, 30 m and 60 m



Total energy detection

- C_6D_6 liquid scintillators
  - 125°
  - PHWT
- Flux measurements (IC)
  - $^{10}B(n,\alpha)$
  - $^{235}U(n,f)$

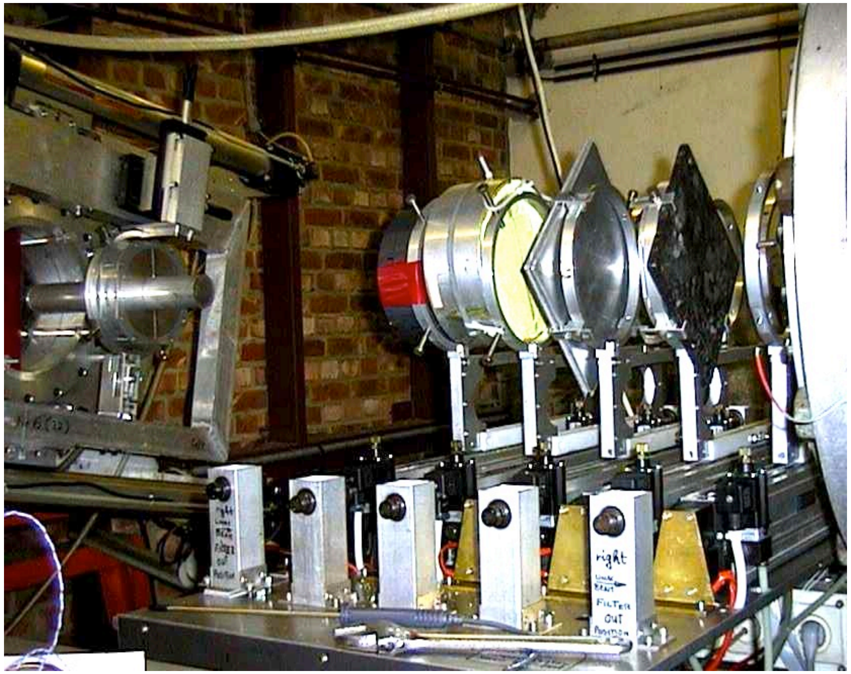


$$Y_{exp} = N\sigma_{\varphi} \frac{C_w - B_w}{C_{\varphi} - B_{\varphi}}$$

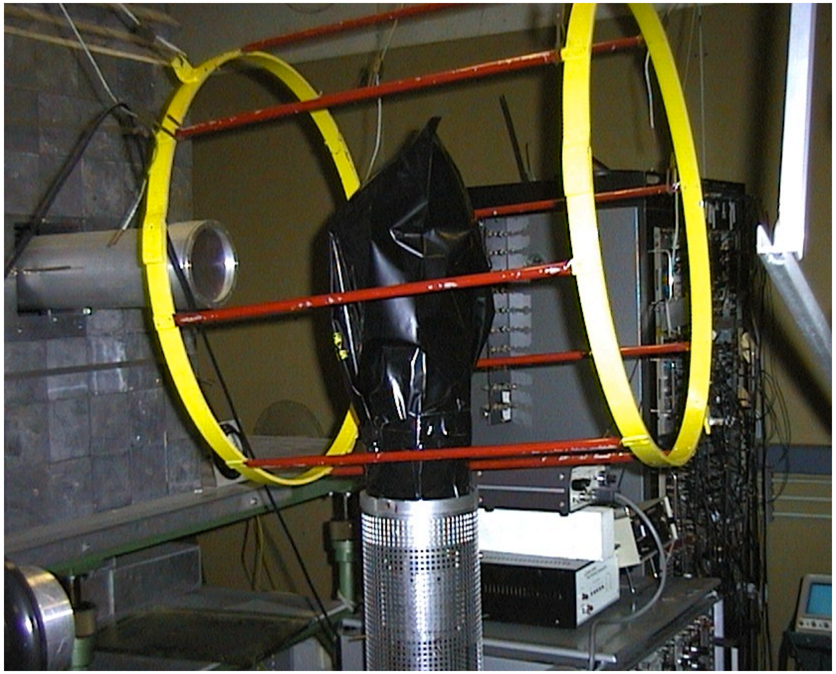
OAK RIDGE National Laboratory

Transmission Measurements

Sample & Background Filters



Detector



Detector stations
Moderated: L= 30 m,50 m,(100 m,200 m)
Fast: L= 400 m

Low energy : $^{6}Li(n,t)\alpha$ Li-glass

High energy : H(n,n)H Plastic scintillator

$$T = \frac{C_{in}}{C_{out}} \cong e^{-n\sigma_{tot}}$$

Oak Ridge National Laboratory

ORNL Measurement Activities for Cerium

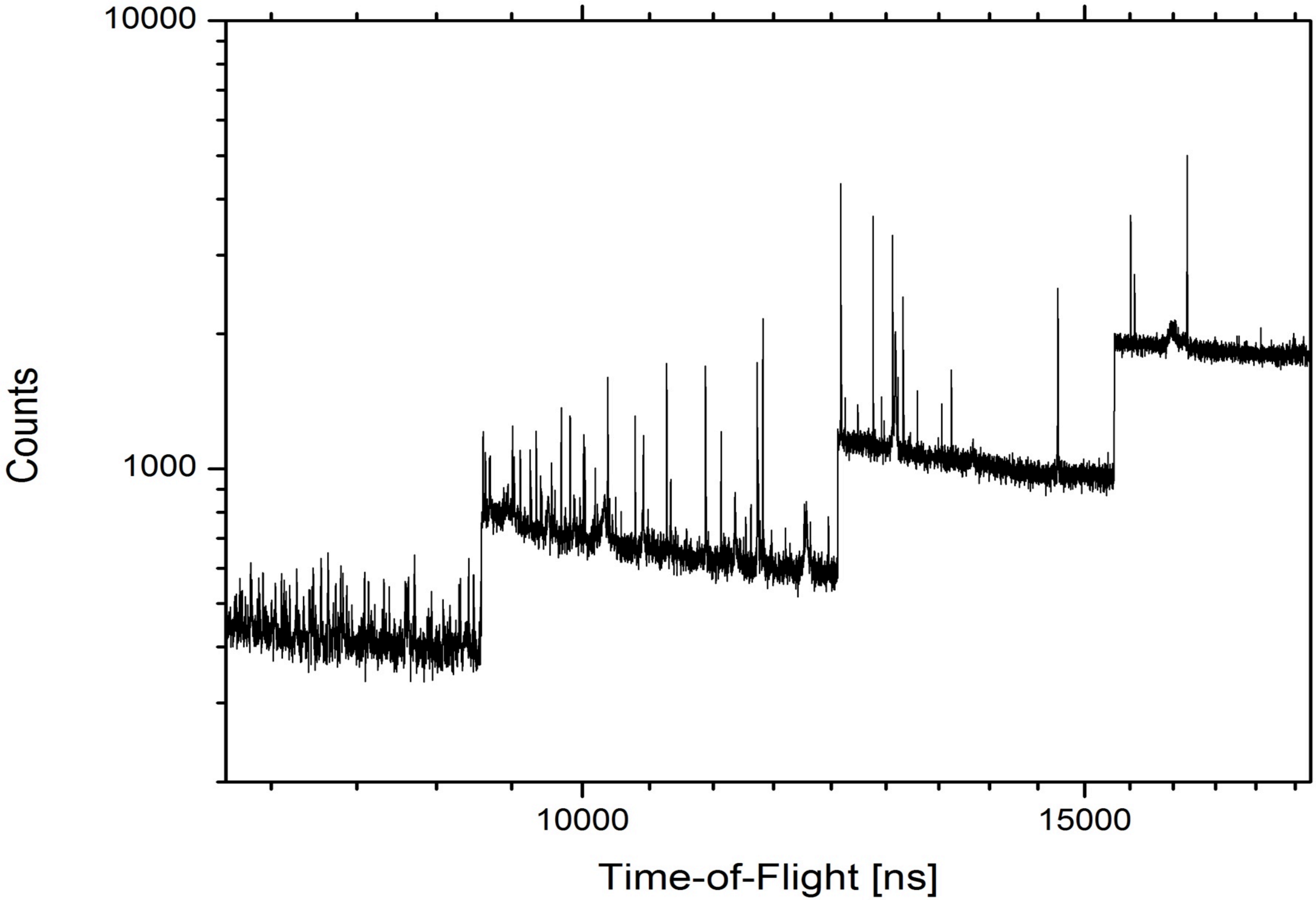
- Measurements of Ce using natural metallic samples.
- The samples are in Al canning due to reactivity with air.
- Old experiments used $CeCO_3$ samples.
  - For each Ce atom there are 4 atoms which only scatter neutrons due to their small capture cross section.
  - Produce unwanted prompt neutron background in capture experiment, within the width of the resonance.

OAK RIDGE
National Laboratory

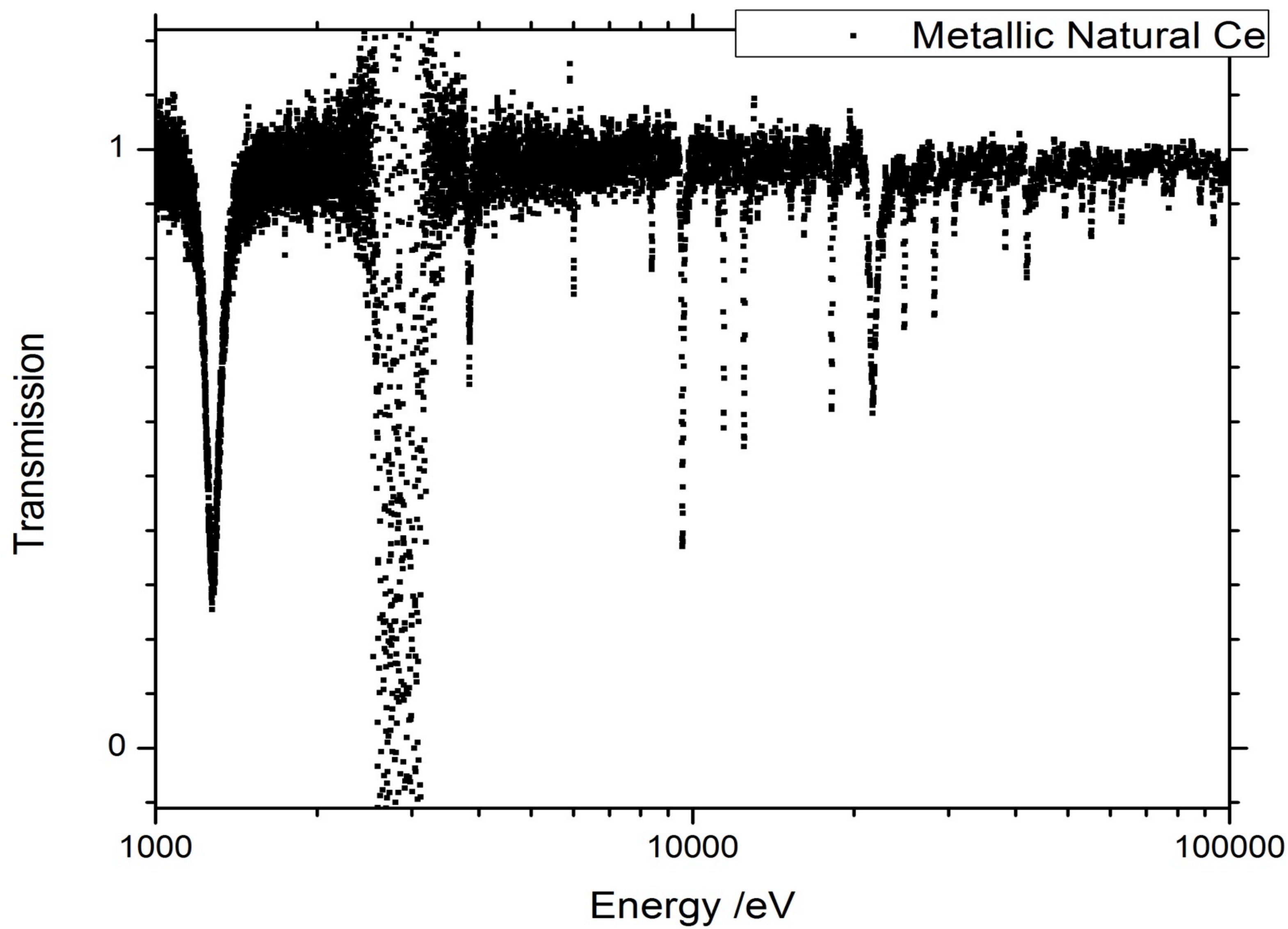
ORNL Measurement Activities for Cerium

- Transmission experiments with different sample thickness were performed using FP4 50 m station.
- Neutron capture using detector system at FP14, 60 m.
- Experiments performed with different background filter combinations.
- Transmission and capture experiments using enriched Ce142 oxide sample are planned. Waiting on DOE decision for new lease policy.

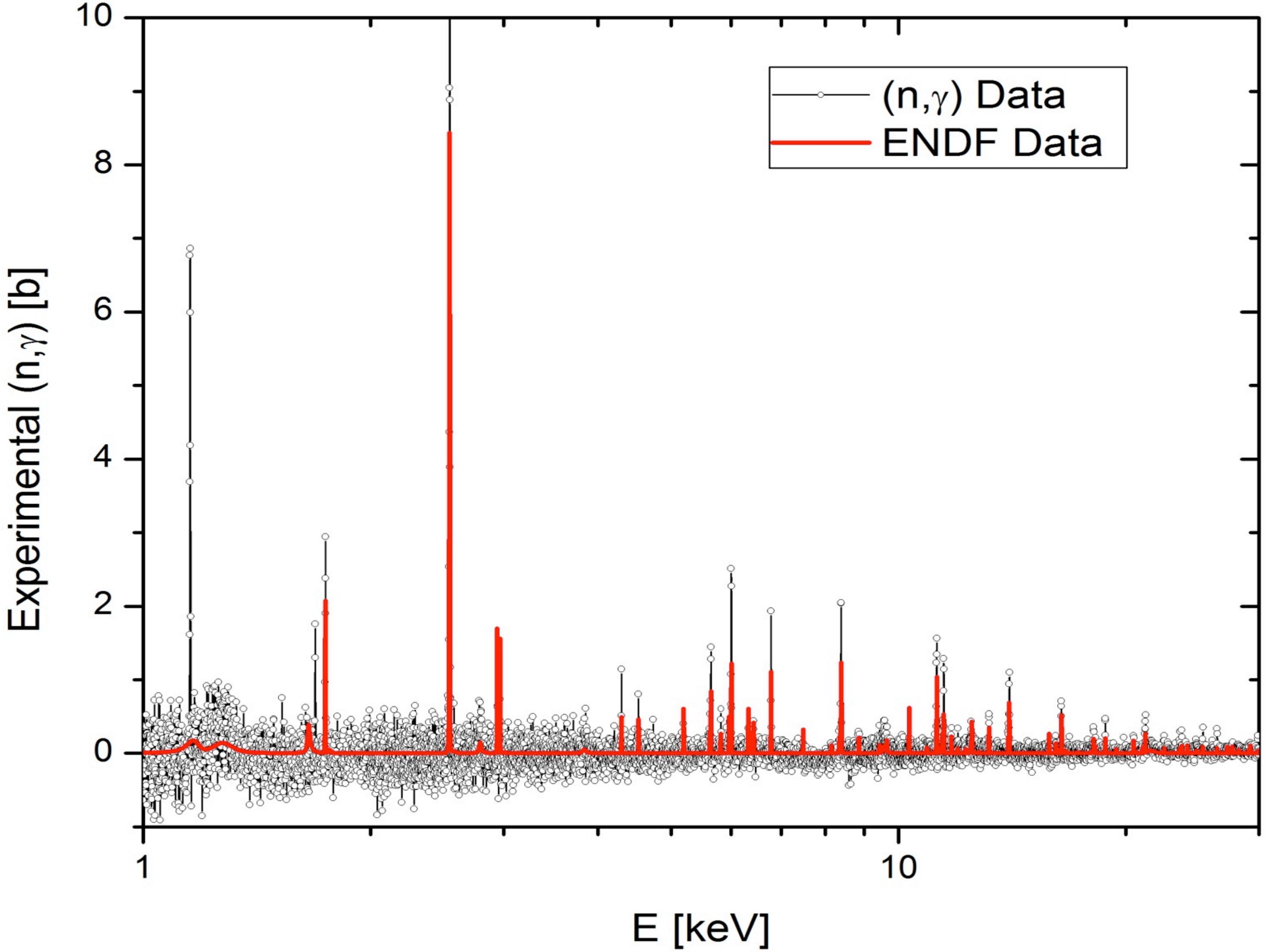
Natural Ce (n,γ) Raw Data
Resolving Resonances above 200 keV



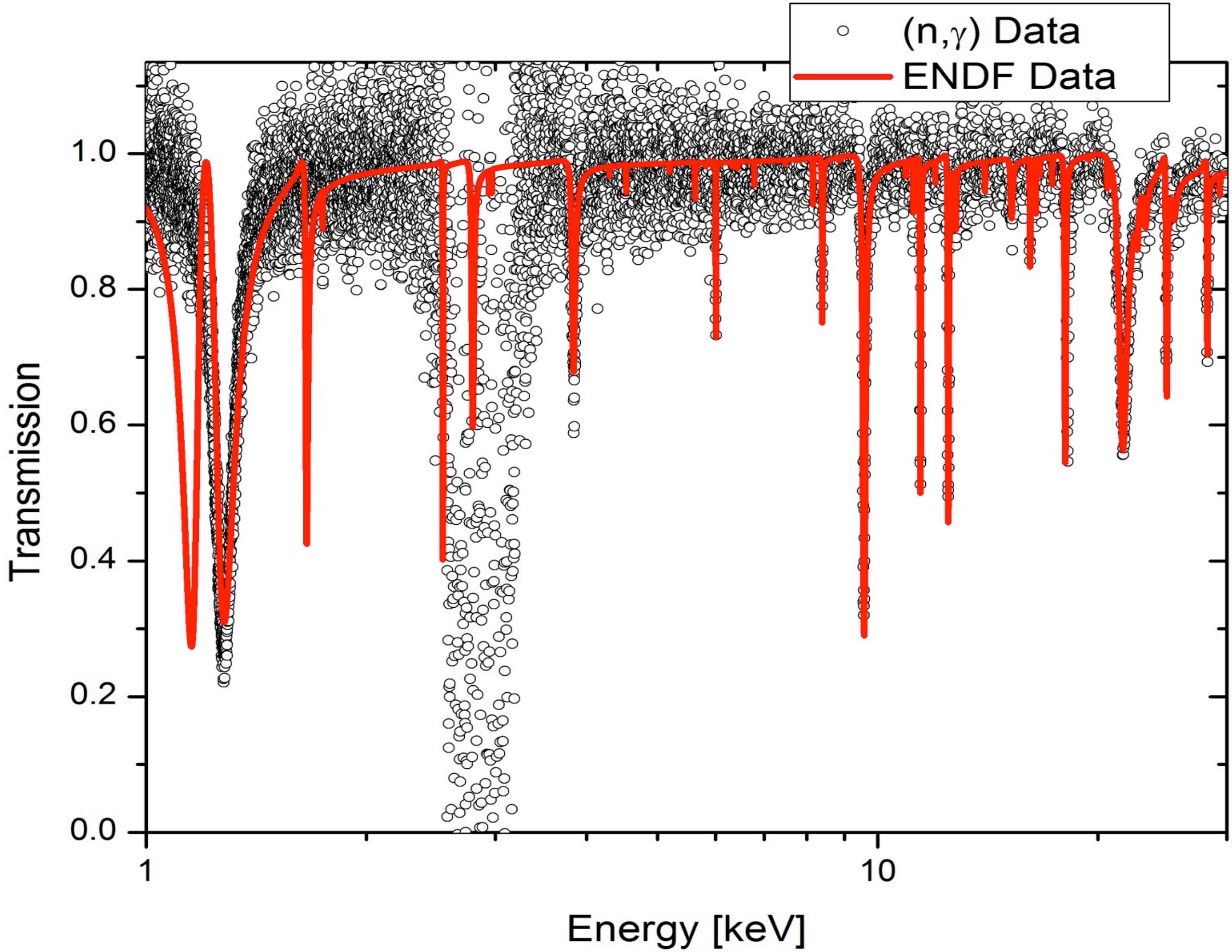
Transmission of Thin Natural Ce Sample



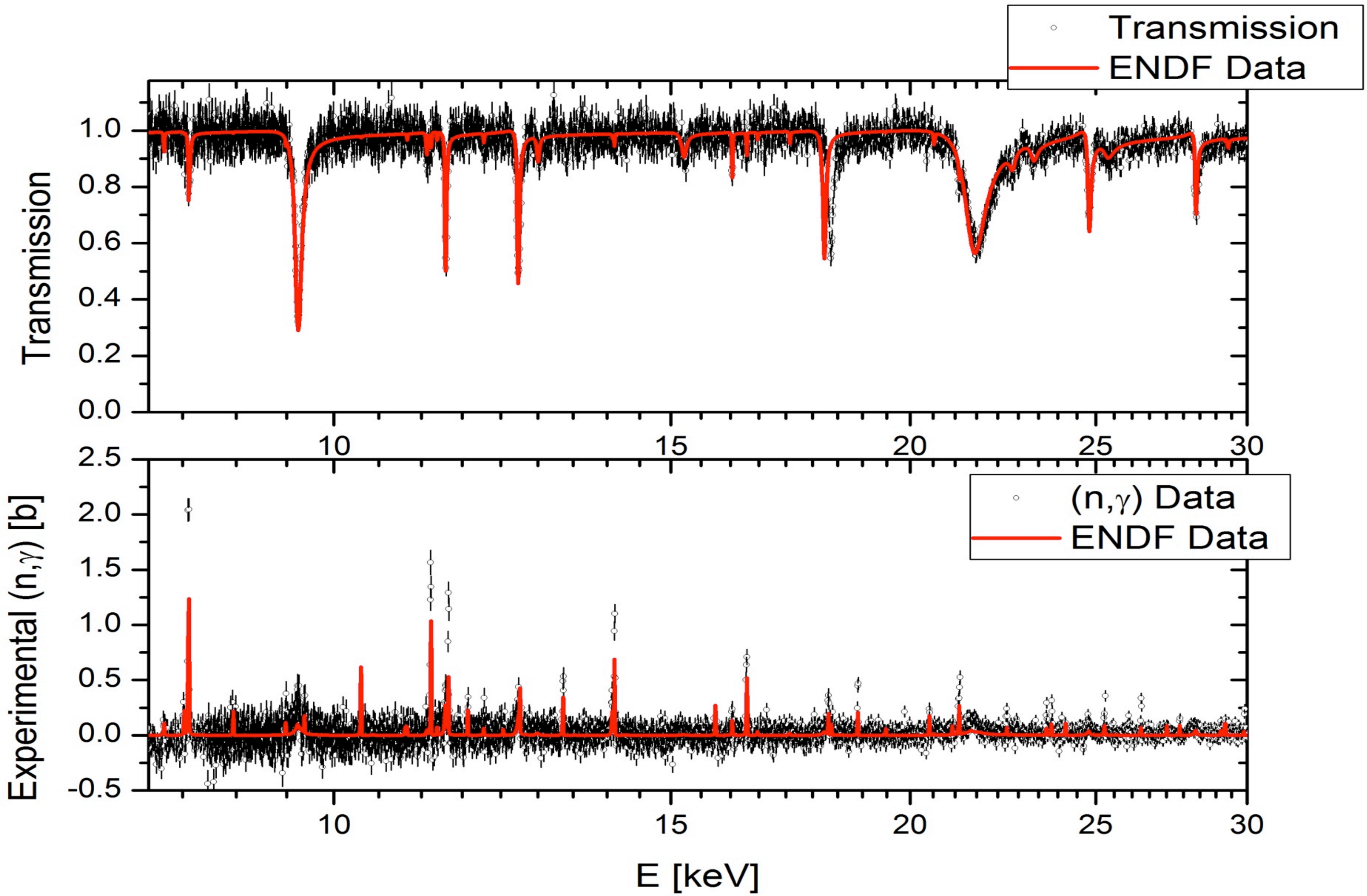
Ce (n,γ) Data compared to ENDF/B-VII.1



Ce Transmission Data compared to ENDF/B-VII.1



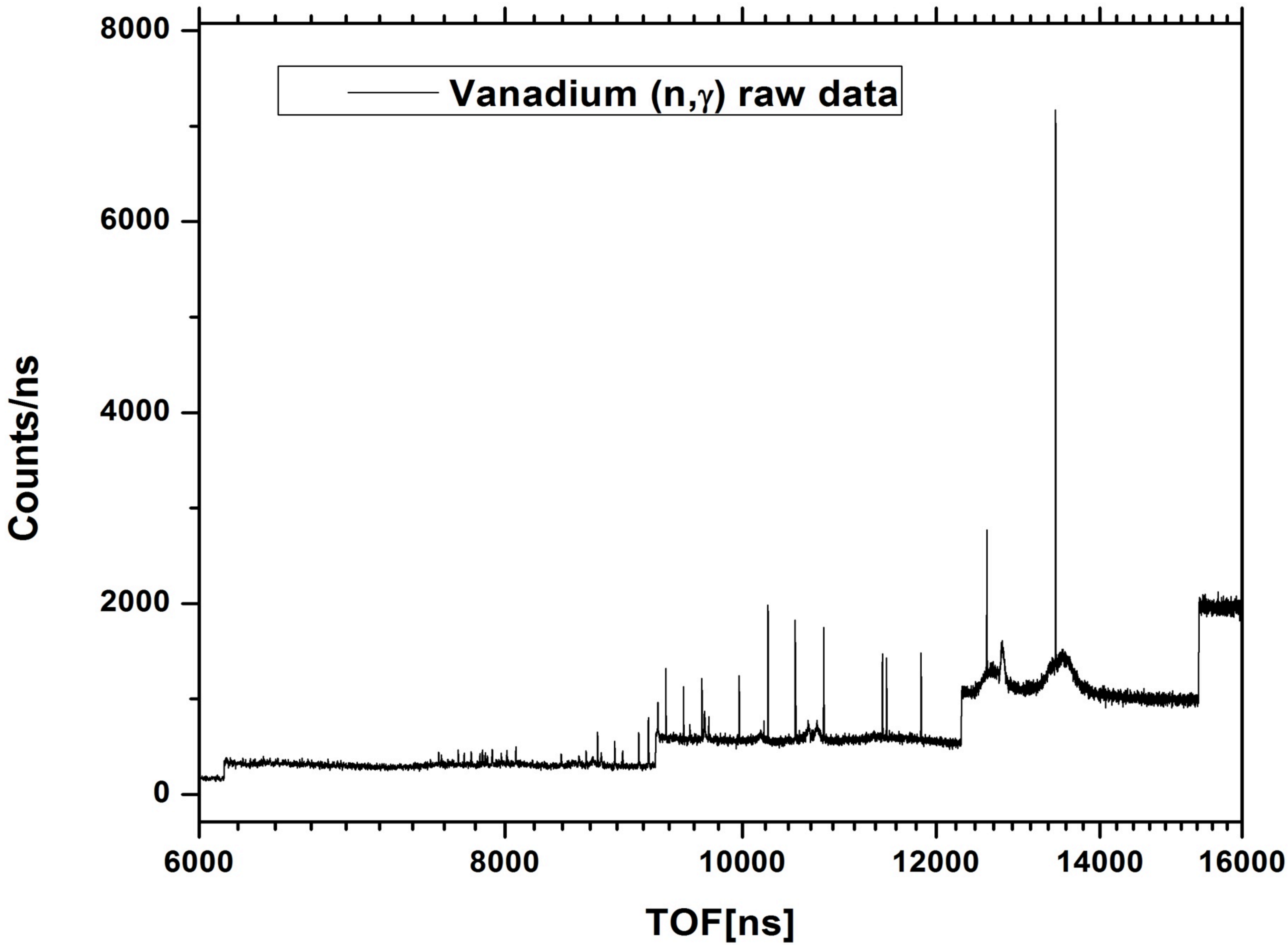
Ce Transmission and (n,γ) Data compared to ENDF/B-VII.1



ORNL Measurement Activities for Vanadium

- V is mono-isotopic, non reactive in air.
- Measurements using metallic samples of different thickness
- Transmission experiments with different samples are performed using FP4, 50 m station
- Neutron capture using detector system at FP14, 60 m.
- Experiments performed with different background filter combinations.
- Capture and transmission experiments performed in FY15.

V (n,γ) Raw Data for Thin Sample



Status of Experiments at GELINA

	Ca	Ce	V
Sample	metallic disks nat Ca	Metallic disks Nat Ce, Ce-142	metallic disks mono isotopic
Experiments GELINA	60m (n,γ) transmission	Nat Ce 60m (n,γ) Nat Ce transmission	60m (n,γ) transmission
Data Sorting	finished 60m Transmission	In progress Data for 2mm sample	
Reduced to Cross section	X-section transmission	2mm X-section 2mm transmission	
Data Testing	Data ready for evaluation	In progress	
Analysis and Evaluation	Started		

Rensselaer Polytechnic Institute
Recent Measurements

- **Transmission**
  - W, Pb H_2O - 0.5-20 MeV, 250m flight path
  - Capture
  - Fe - 500 eV - 500 keV, 45m flight path
  - Ta – 4 eV – 20 eV, 500 eV – 1 MeV, 45m flight path
- **Scattering**
  - Pb – 0.5 – 20 MeV
  - Zr <0.5 MeV in development
- **Neutron Capture**
  - ^{56}Fe,^{nat}Fe Ta – few eV to 2 MeV using C_6D_6 array.
- **Thermal neutron scattering**
  - Polyethylene at temperatures of 295 K and 5 K.

Update on Nuclear Data Research at RPI

Report to CSEWG

Y. Danon, E. Liu, E. Blain, A. Daskalakis, B. McDermott, K. Ramic, C. Wendorff

Rensselaer Polytechnic Institute, Troy, NY, 12180

and

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

KAPL, Bechtel Marine Propulsion Corporation, Schenectady, NY ,12301-1072

CSEWG meeting, November 3, 2015 at BNL

Rensselaer

linac The Gaertner LINAC Center

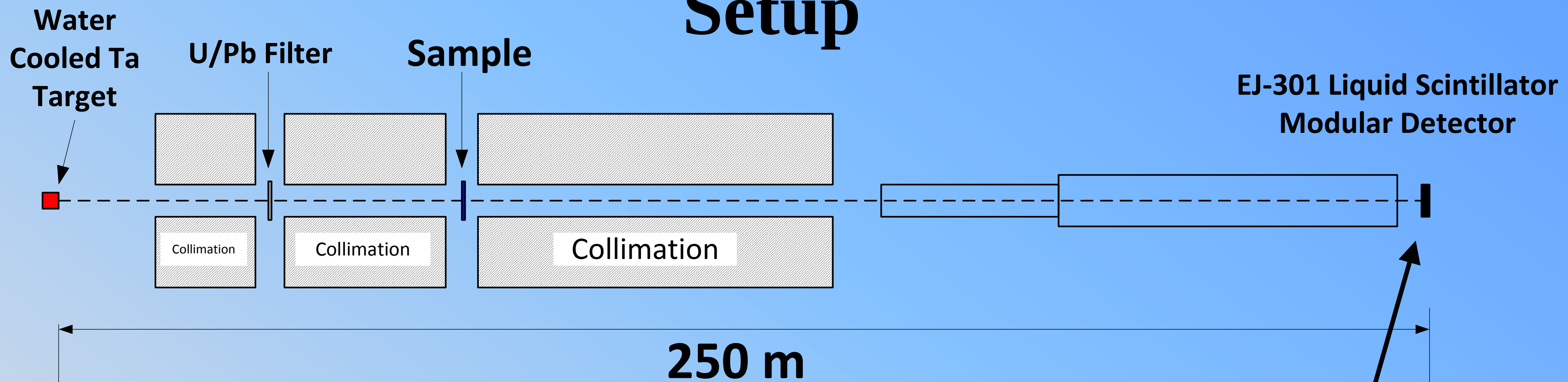
Data Analysis

Measure	Sample	Status
High Energy	Fe, Ti, Ta, Cu, Zr, $^{92/94,95,96,98,100,nat}Mo$	High energy (0.5-20MeV) transmission, publication in preparation
RRR and URR	Cs, Rh , Re, Fe, Ta $^{161,162,163,164}Dy$ ^{236}U $^{155,156,157,158,160}Gd$ $^{153,nat}Eu$ $^{92/94,95,96,98,100,nat}Mo$	Resonance analysis in progress Resonance analysis in progress, ^{164}Dy - publication in internal review ^{236}U – published in nuclear energy Gd isotopes – published, NSE Vol. 180, Number 1, May 2015. Eu – published , Annals of Nuclear Energy, Vol. 69, pp. 74-89, 2014. ^{95}Mo URR – Published in Phys. Rev. C in 2015
Scattering	^{238}U Fe Pb	^{238}U – published, Annals of Nuclear Energy, Vol. 73, pp. 455-464, 2014. Fe – analysis near completion Pb – analysis in progress
Thermal Scattering	H_2O, polyethylene, quartz	Analysis in progress

Rensselaer

linac The Gaertner LINAC Center

High Energy Transmission Experimental Setup



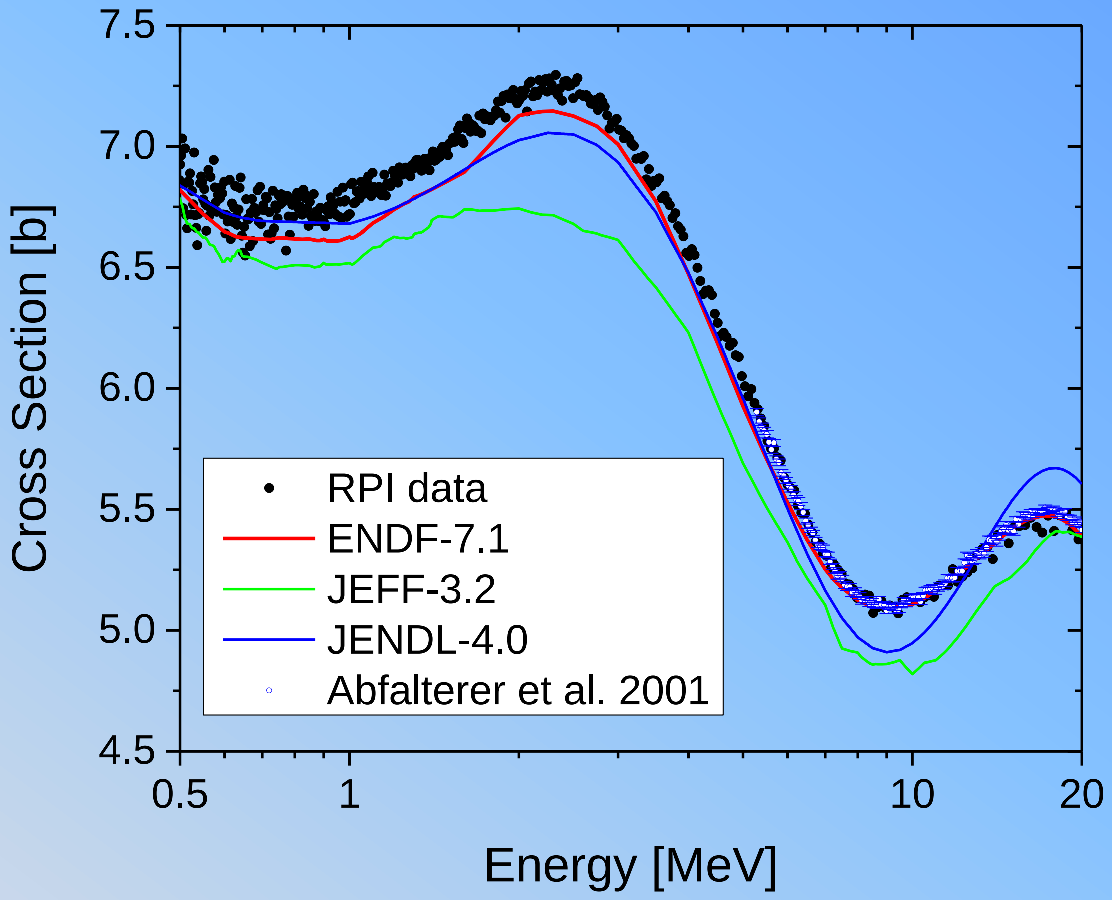
Graphite Samples

Rensselaer

linac The Gaertner LINAC Center

Total cross section of ^{nat}W

- Used 250m flight station with 2 modules of EJ-301 detector
- Measured two sample thicknesses: 4.5 and 5.5 cm
- ENDF/B-7.1 is in good agreement above 8 MeV
- The RPI data agree well with the Abfalterer et al. 2001 experimental data
- Below 8 MeV the evaluations need improvement.

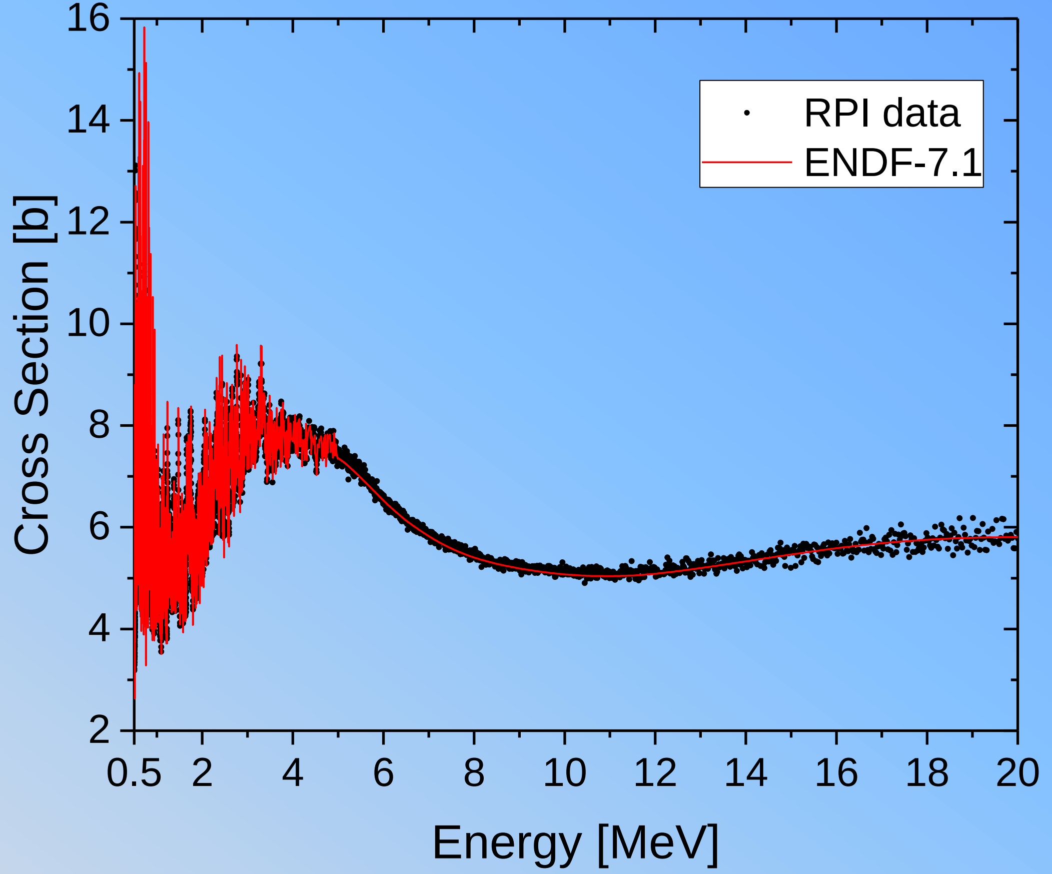


Rensselaer

The Gaertner LINAC Center

Total Cross Section of ^{nat}Pb

- Was measured to supplement a Pb Scattering measurement
  - No anomalies were observed in the sample material
- Measured two sample thicknesses: 9 and 12 cm
- The data are in good agreement with ENDF/B-7.1
- Resonance structure is evident below 5 MeV



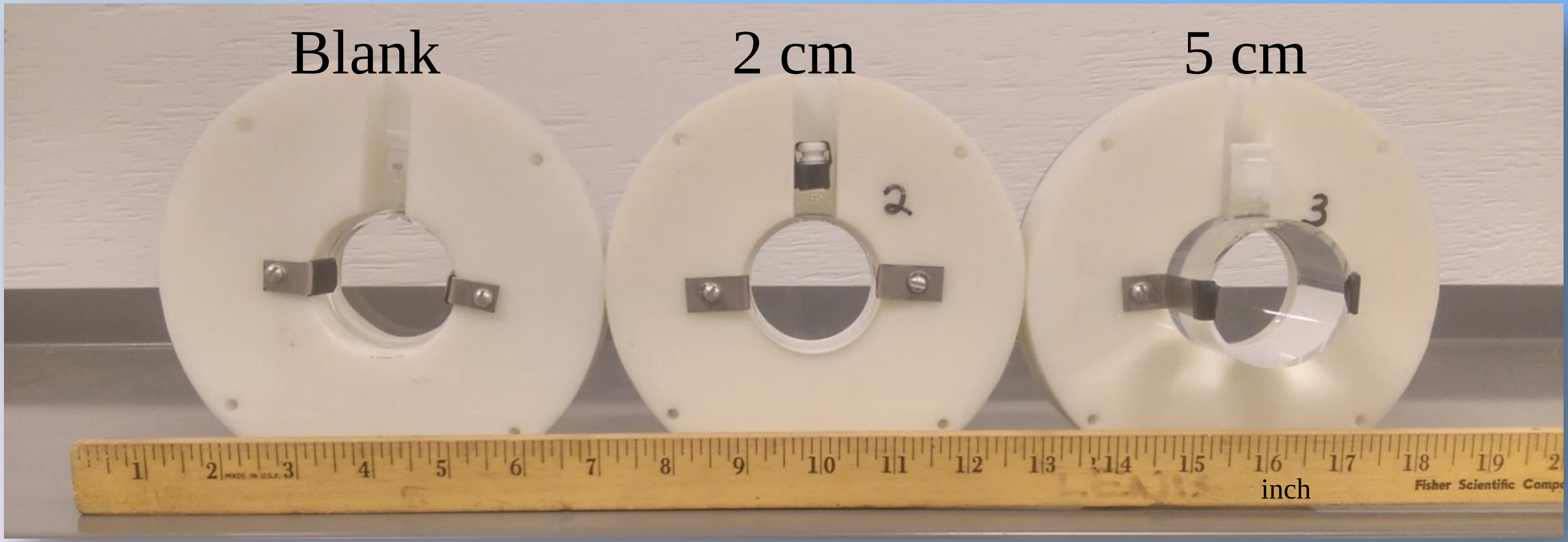
Rensselaer

linac The Gaertner LINAC Center

Update on Oxygen total cross section

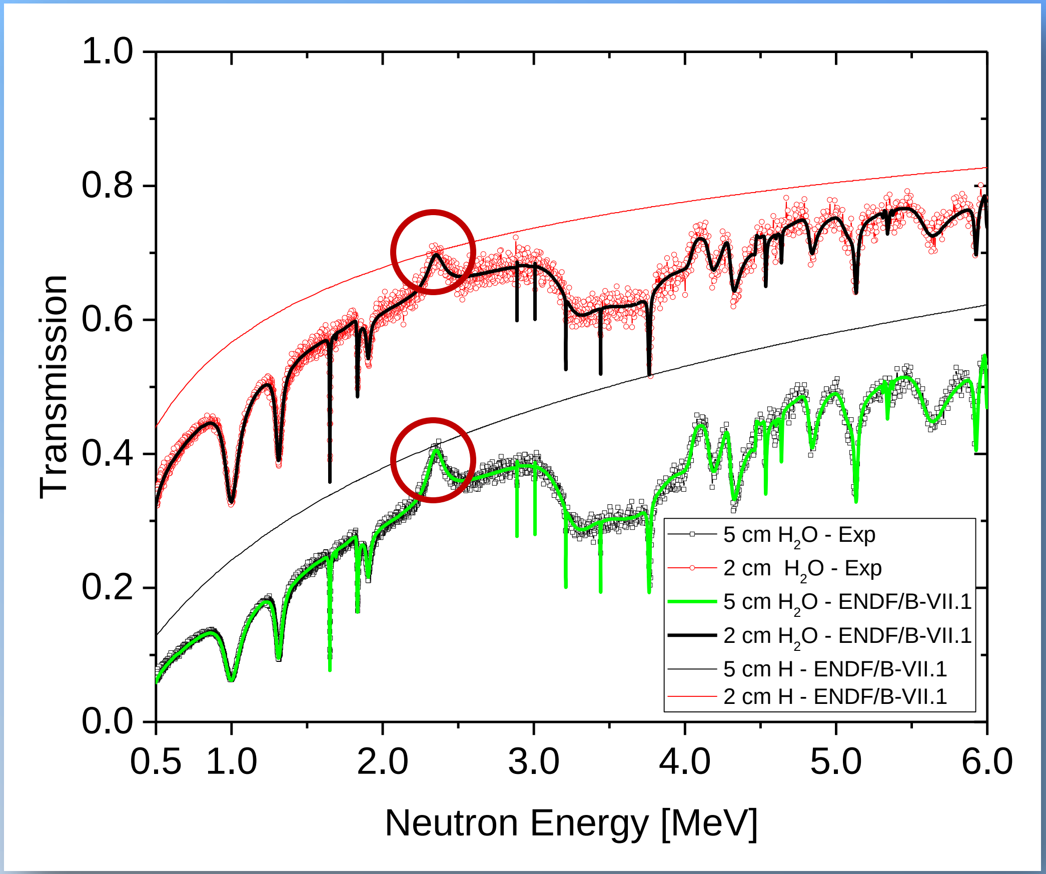
H_2O Samples

- Used a spectroscopic quartz cell to contain research grade water
  - Outgas the water by drawing vacuum for ~1 minute.
  - Mounted the cells in a polyethylene holder
  - Made sure there was no air bubble in the cell
  - Monitored the sample using a camera to make sure air bubbles were not formed
  - Monitored the room temperature to characterized the variations (±1.5° C)
- Used two cell thicknesses: 2 cm and 5 cm, about 5 cm diameter.
- Measured an empty cell as an open beam
- 13 cm thick graphite sample was used for verification and energy calibration



H_2O transmission measurement

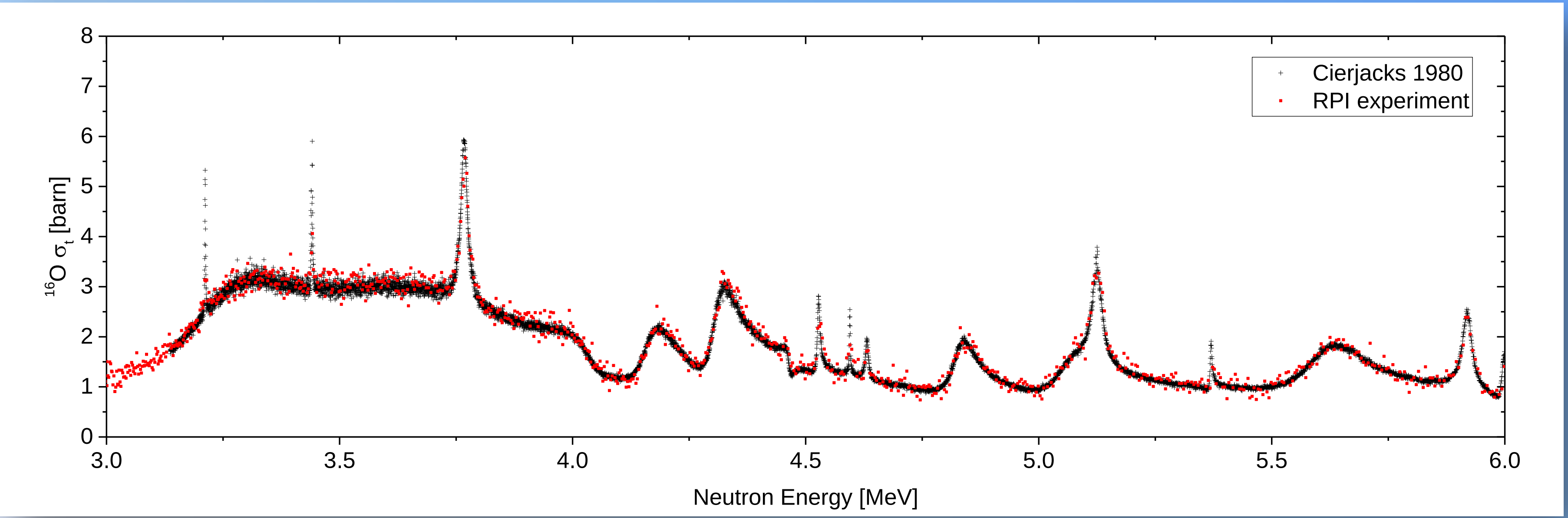
- Measurements of 2 cm and 5 cm thick H_2O in thin walled quartz optical cells.
- Used 250 m TOF and 10 ns pulse width.
- Used 3 fission chambers as beam monitors.
  - The experiment requires "good" monitor normalization
- In the ^{16}O cross section minima at 2.34 MeV mostly H_2 was measured
  - **Provides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



Rensselaer

linac The Gaertner LINAC Center

Comparing Normalization with Other Data Sets



Energy range 3.2 MeV < E < 6 MeV	C/E_{RPI}	C/E_{RPI} 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
Cierjacks 68	1.009	±0.002
Johnson 74	**0.996**	±0.002

Normalization uncertainty:

$$\frac{\sigma_{\exp}^{H}}{\sigma_{ENDF}^{H}} = 0.996 \pm 0.003^{*}$$

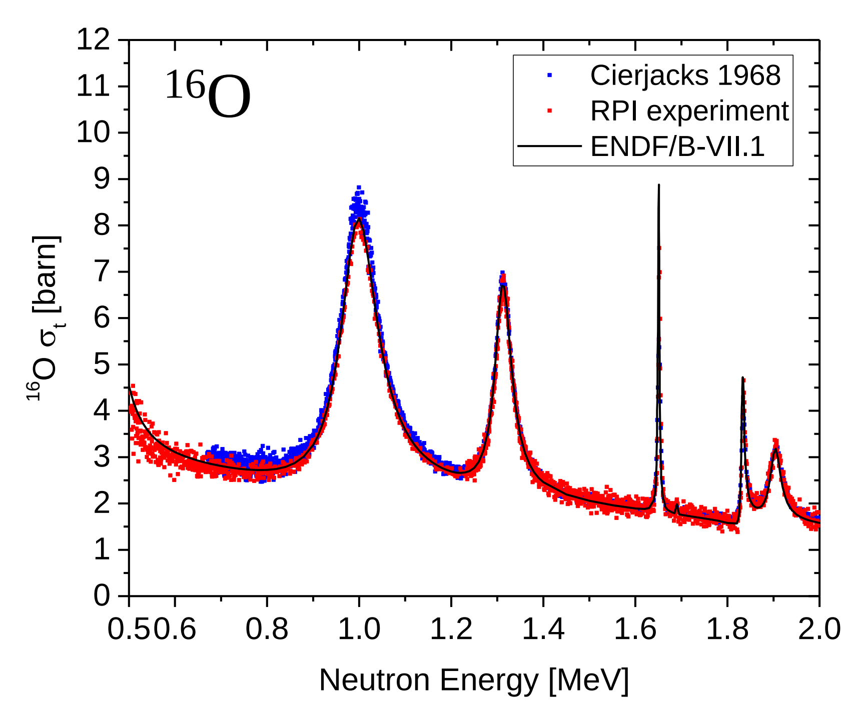
*Statistical

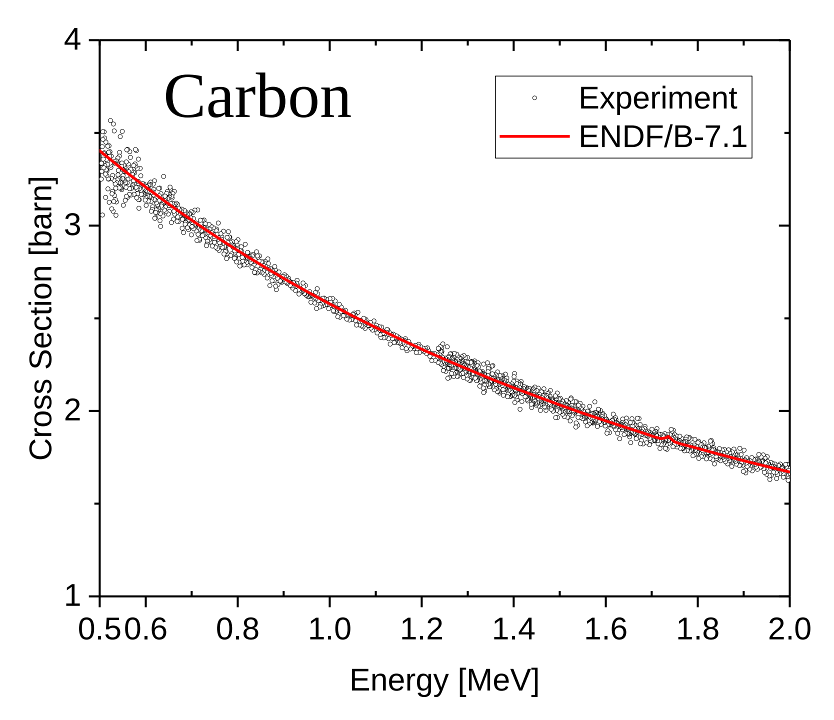
Rensselaer

linac The Gaertner LINAC Center

Other ^{16}O observations

- RPI energy resolution is better than Cierjacks 68
- There is some disagreement at the peak of the 1 MeV resonance
- Carbon transmission measured at the same experiment shows good agreement with the evaluation



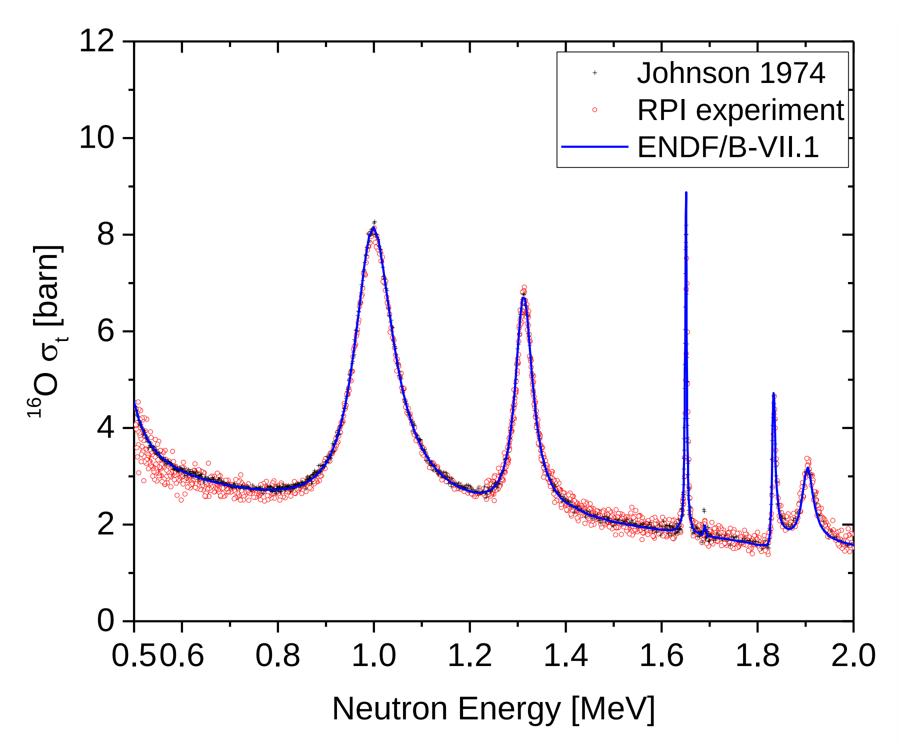


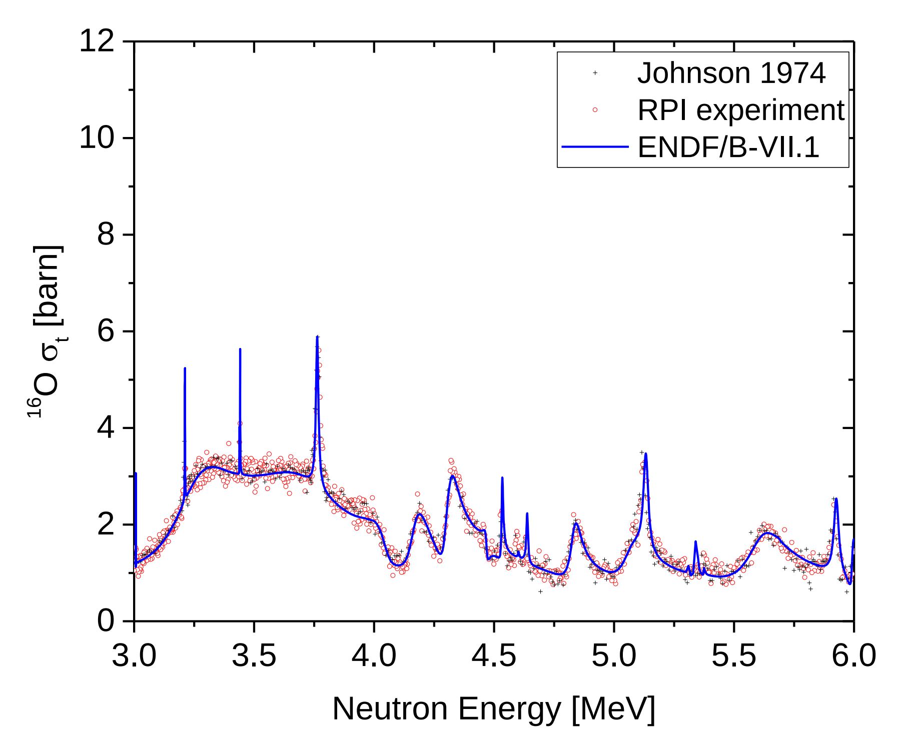
Rensselaer

linac The Gaertner LINAC Center

RPI and Johnson 74

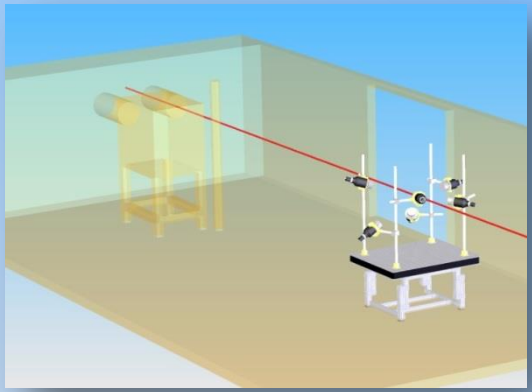
- Overall good agreement
  - Good agreement in the 1 MeV resonance.
  - ENDF is based on the Johnson data
- The Johnson 74 data has slightly better energy resolution.
- There is a slight energy shift between the two experiments





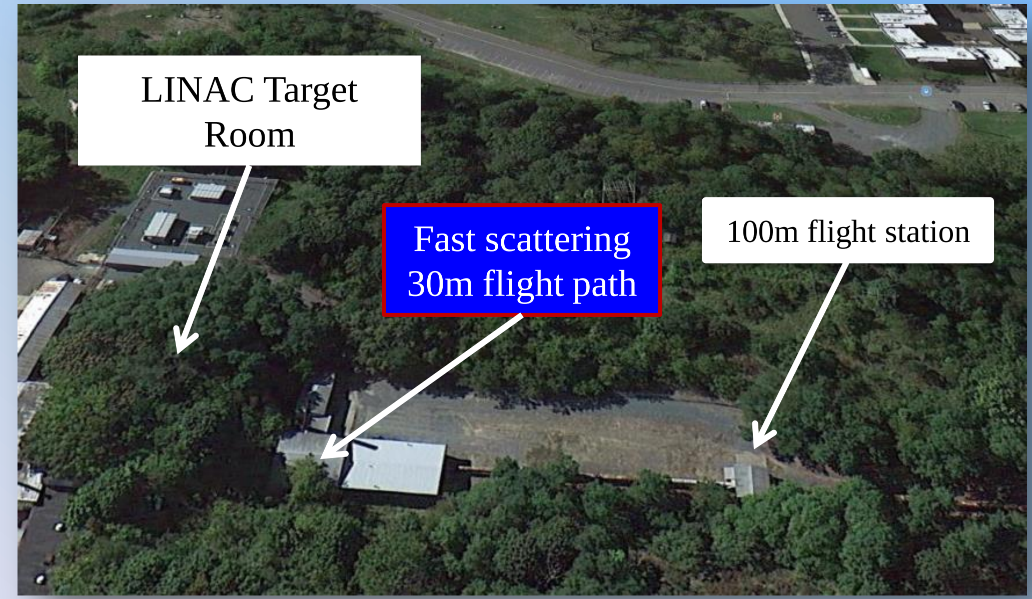
Rensselaer

linac The Gaertner LINAC Center



Fast Neutron Scattering

Quasi-differential neutron scattering and angular distributions.

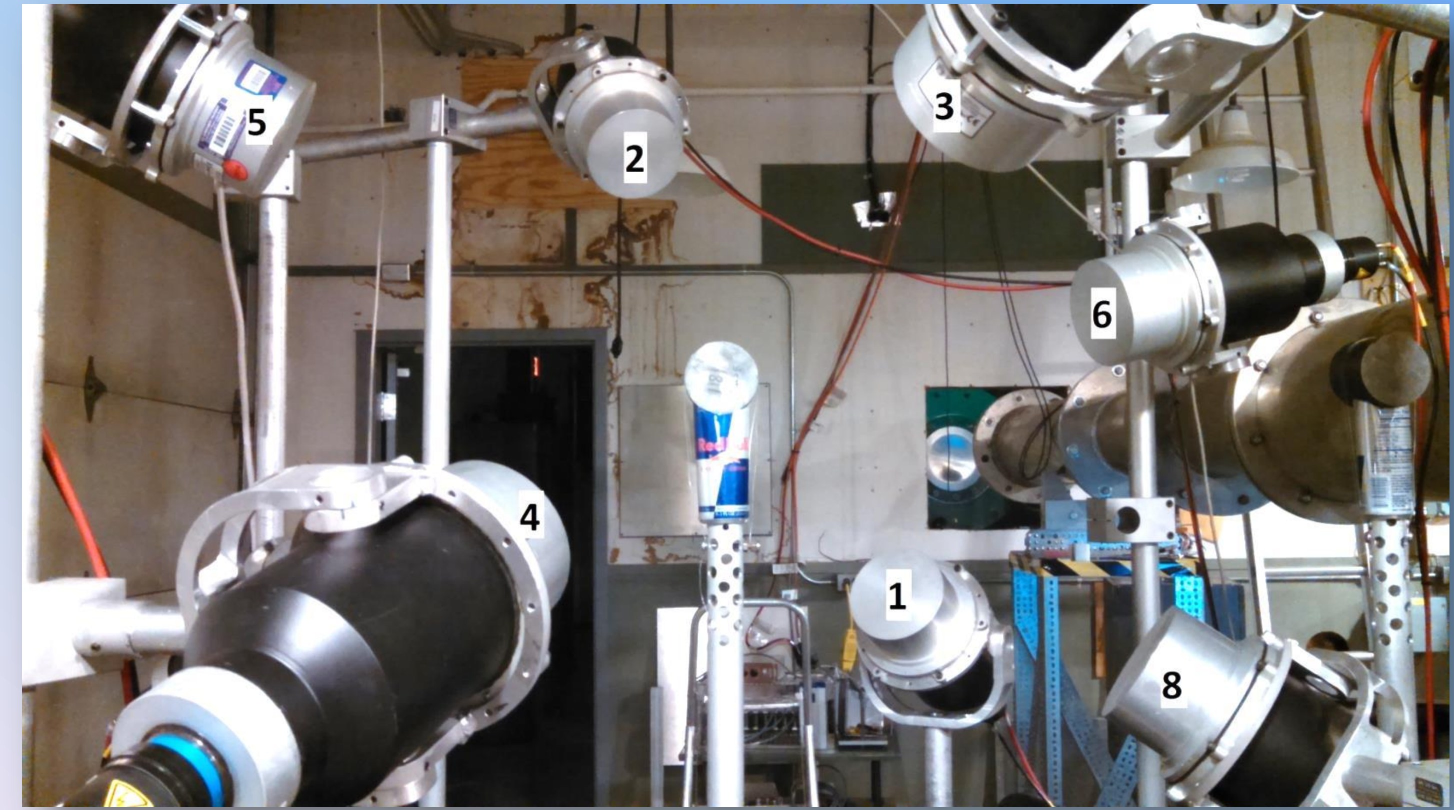


Rensselaer

The Gaertner LINAC Center

Angle Set 1 (45, 70, 100, 150 degrees)

- Use 8 liquid scintillators, 2 are always at the same angle
- Total of 7 different angles (one pair of detectors is stationary)

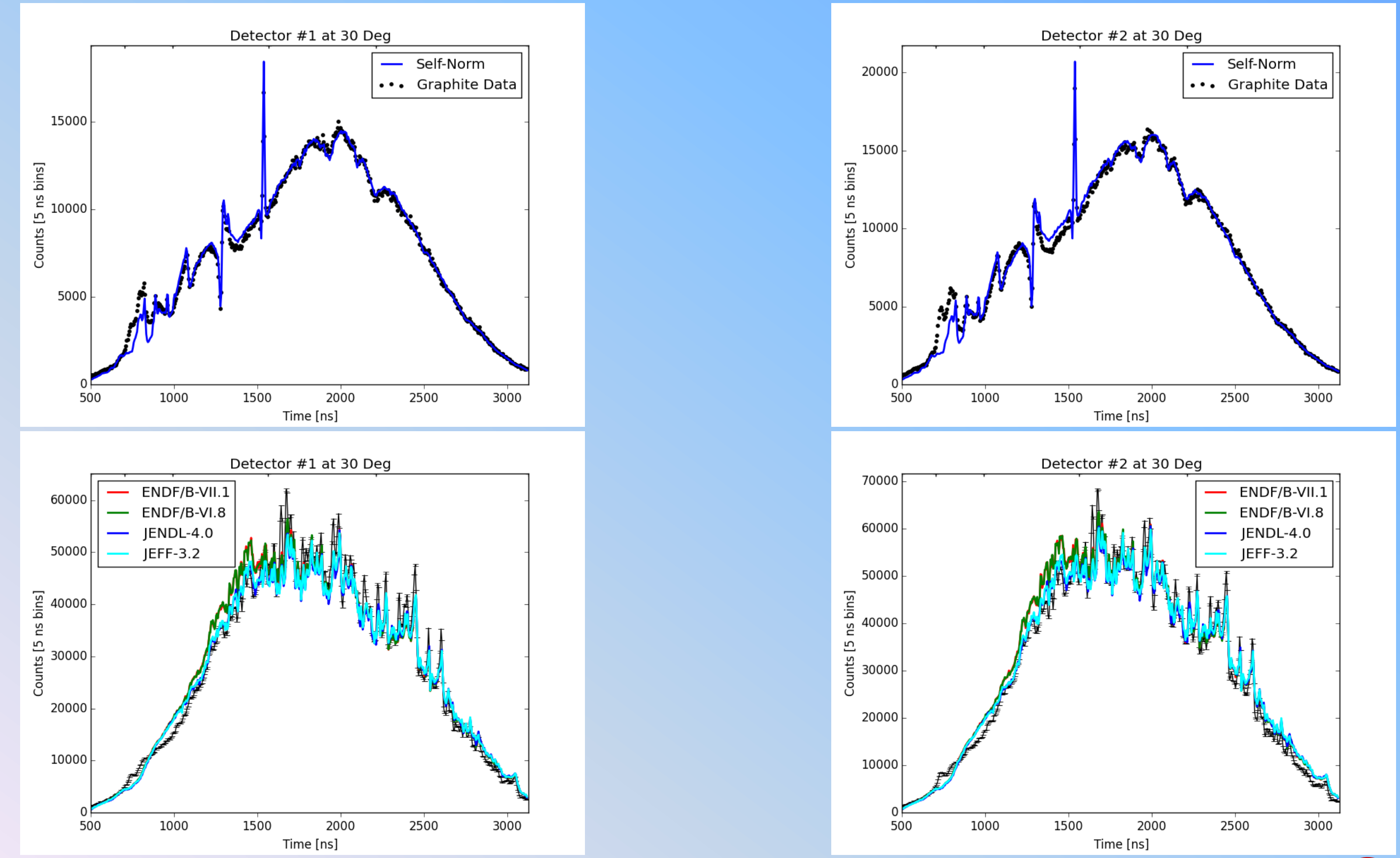


Rensselaer

linac The Gaertner LINAC Center

Pb Scattering at 30 deg

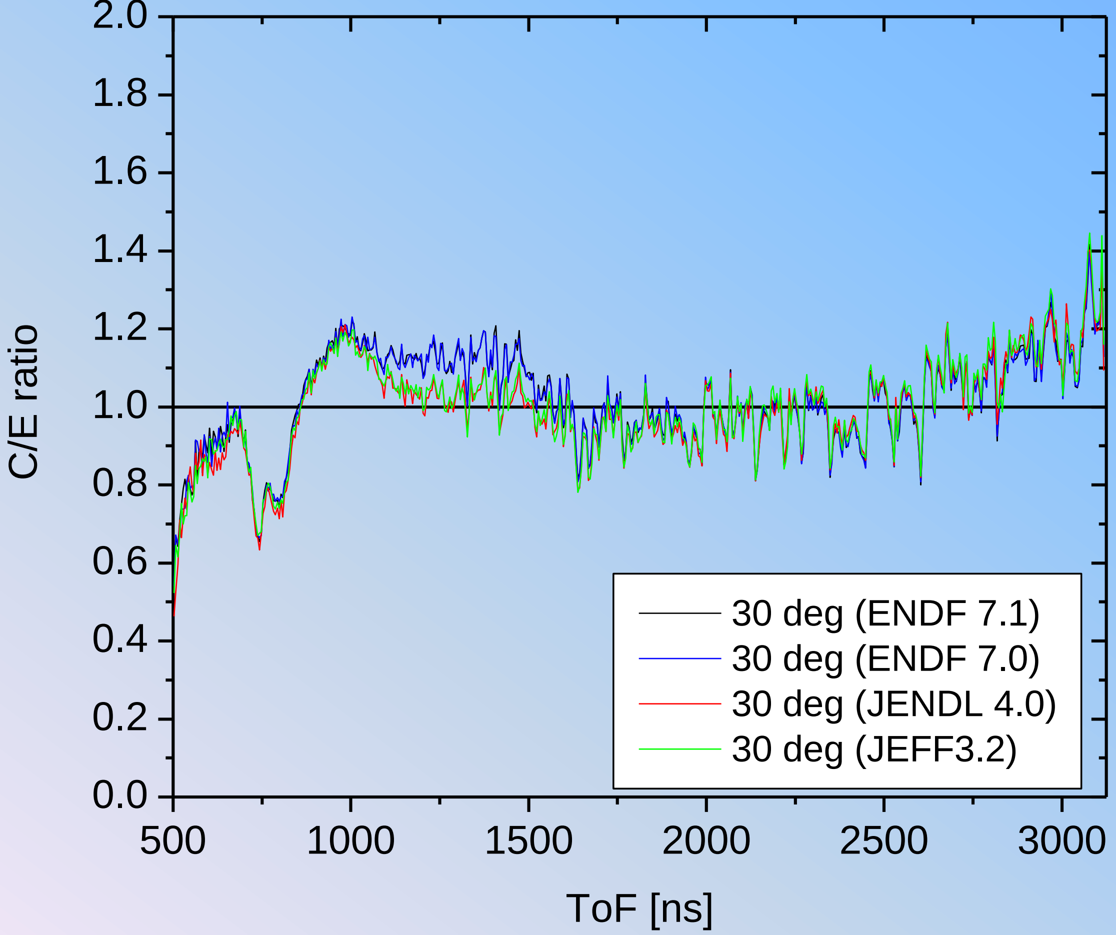
- Experiment and evaluation are in good agreement for both C and Pb



Rensselaer

linac The Gaertner LINAC Center

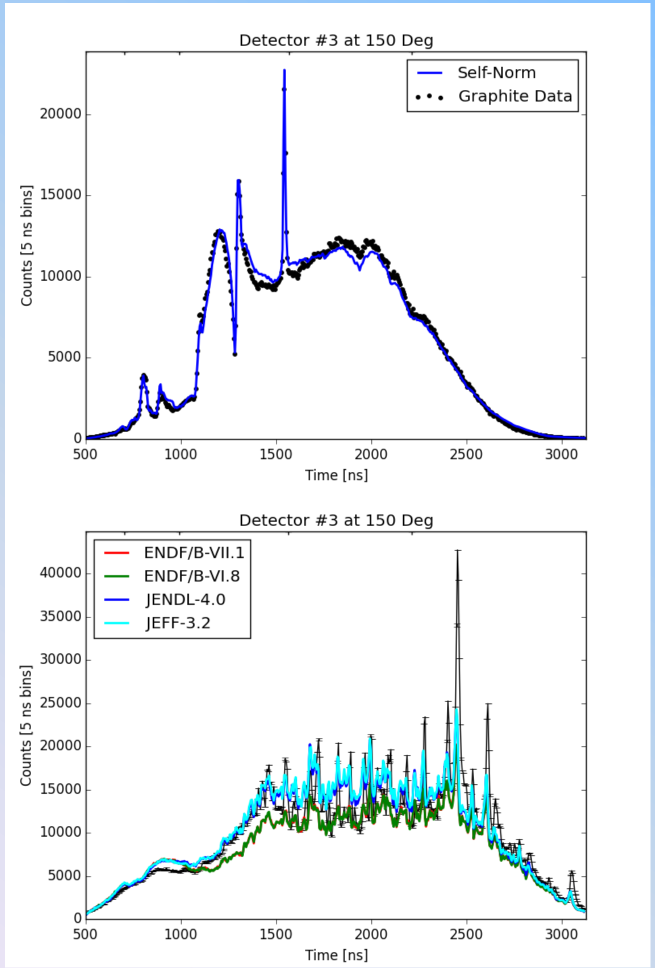
C/E values as a function of ToF

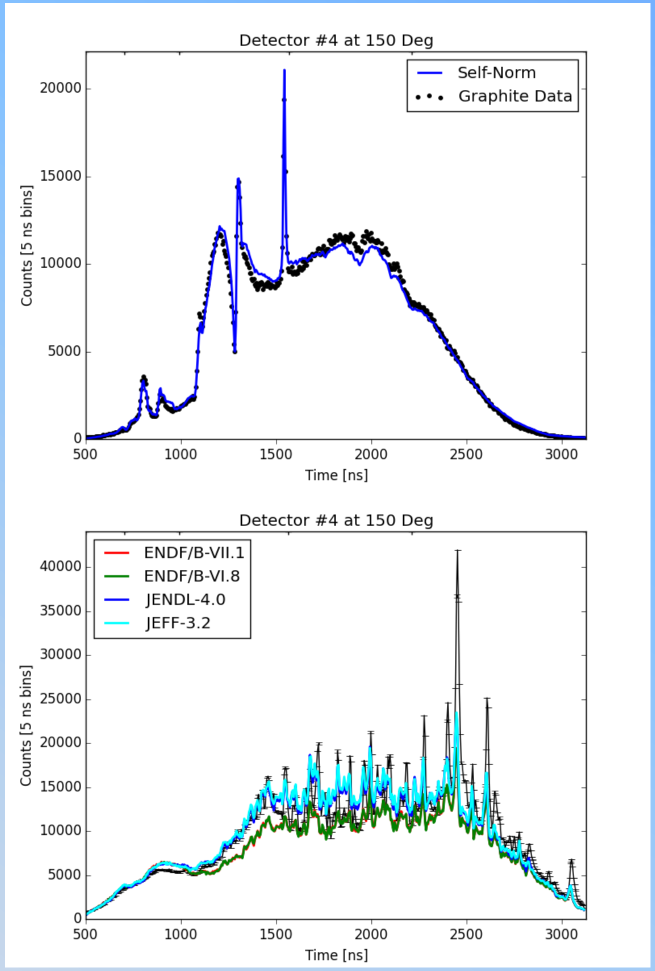


- Relatively good agreement between experiment and evaluations
  - Discrepancies at low and high energy

Pb results at 150 deg

- Carbon measurements agree with simulation
- For Pb, ENDF underpredicts the experiment



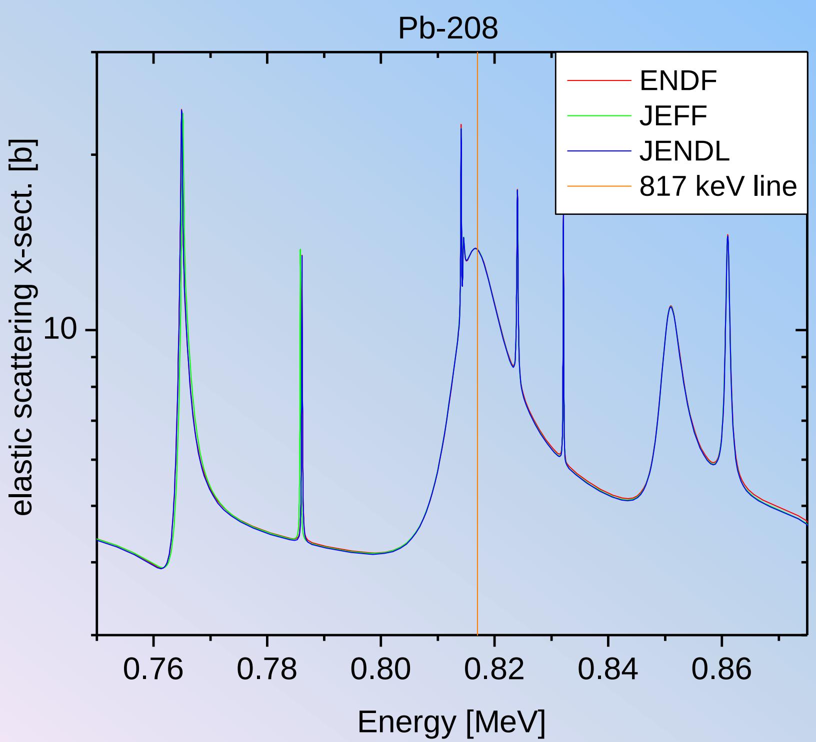


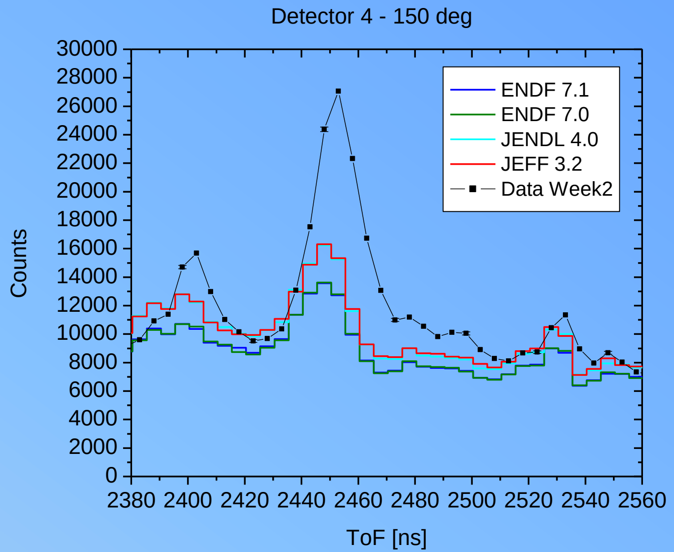
Rensselaer

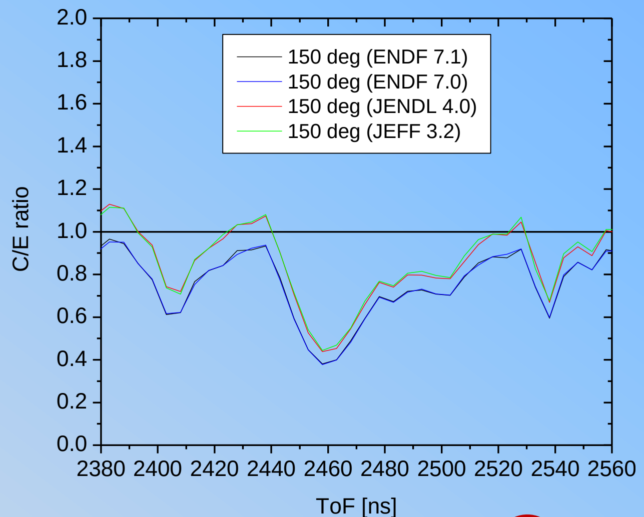
linac The Gaertner LINAC Center

Resonance in Pb-208 at 817 keV

- Some resonances show disagreement at different angles
  - Could be related to spin or angular momentum assignment.





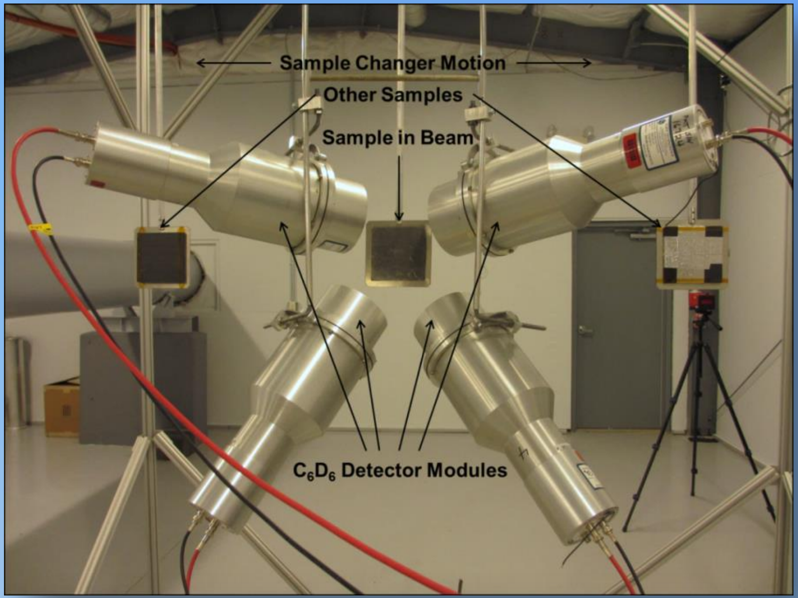


Rensselaer

The Gaertner LINAC Center

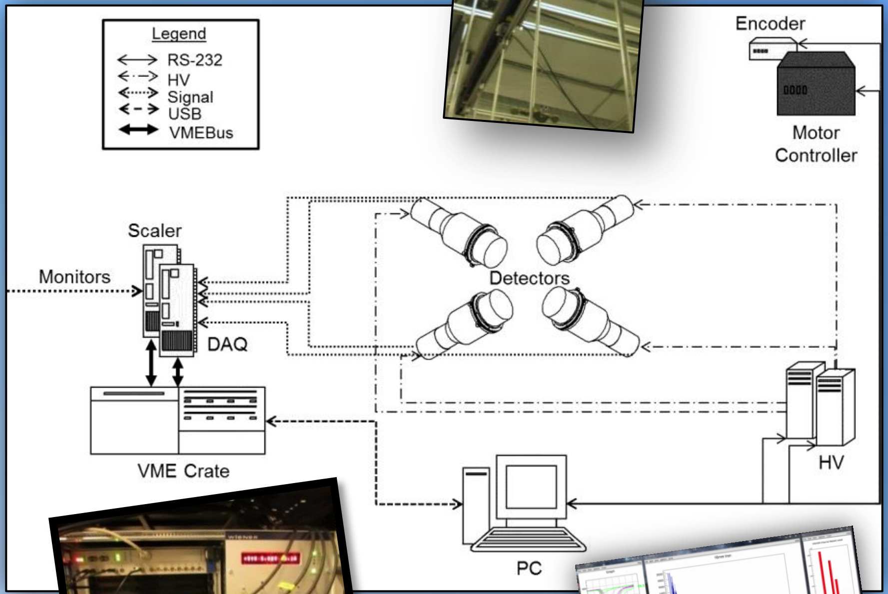
Mid-Energy Capture Detector System Overview

- 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
  - Use fission chambers as monitors
- **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

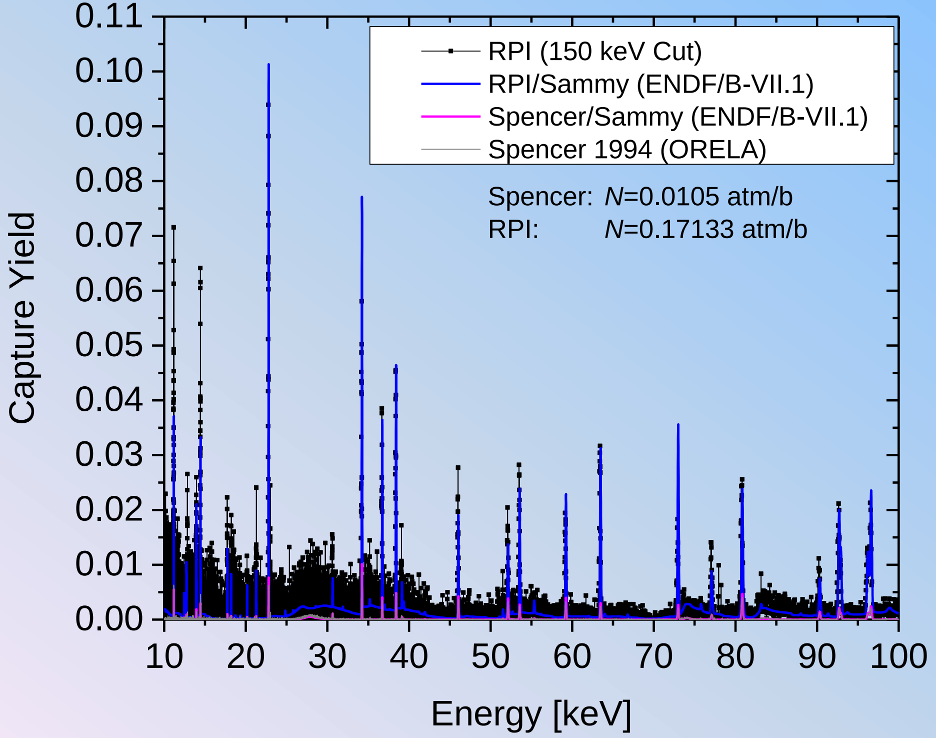


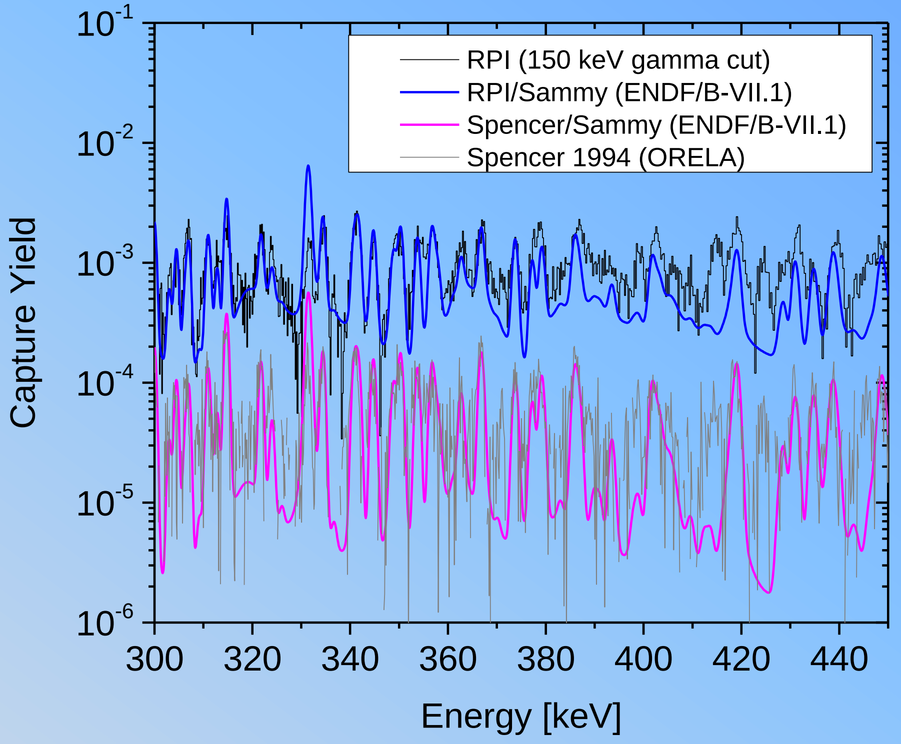
Rensselaer

linac The Gaertner LINAC Center

^{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)



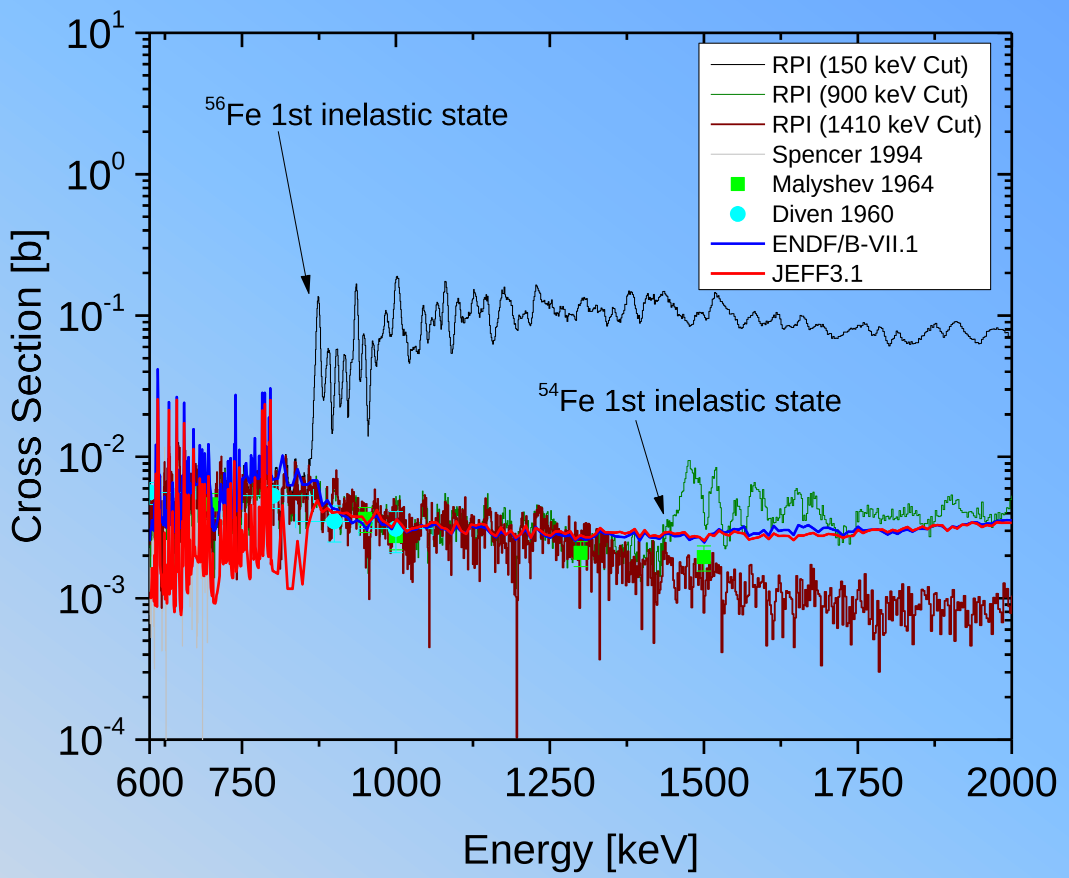


Rensselaer

The Gaertner LINAC Center

^{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
- Above 1400 MeV, the data are lower than the evaluations

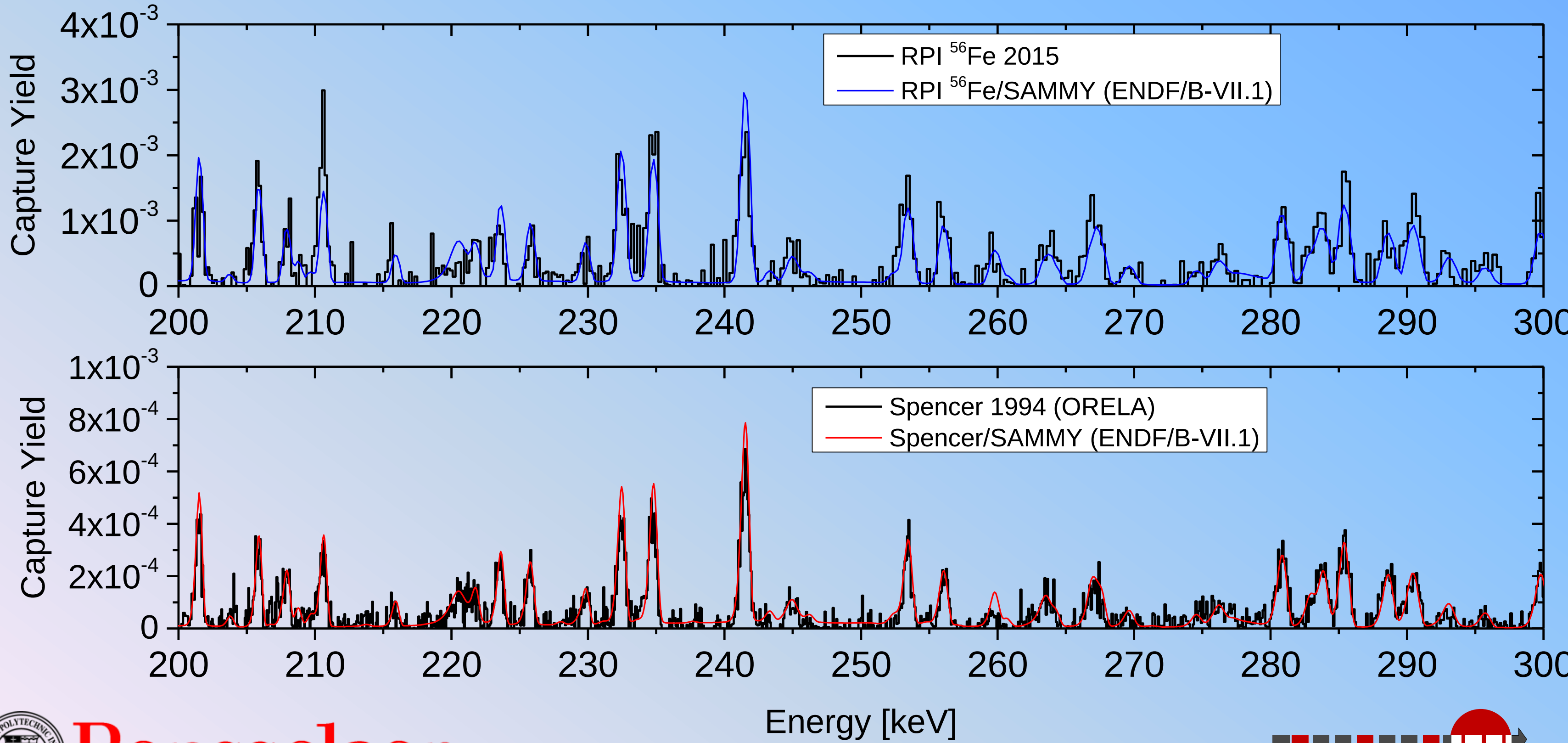


Rensselaer

linac The Gaertner LINAC Center

^{56}Fe Capture measurement

- ^{56}Fe sample was 7mm thick.
  - Data was collected up to 2 MeV
- The data is in good agreement with the Spencer Data (was used to generate ENDF/B-VII.1)
  - Although there are some differences
- The statistical accuracy is not sufficient yet.

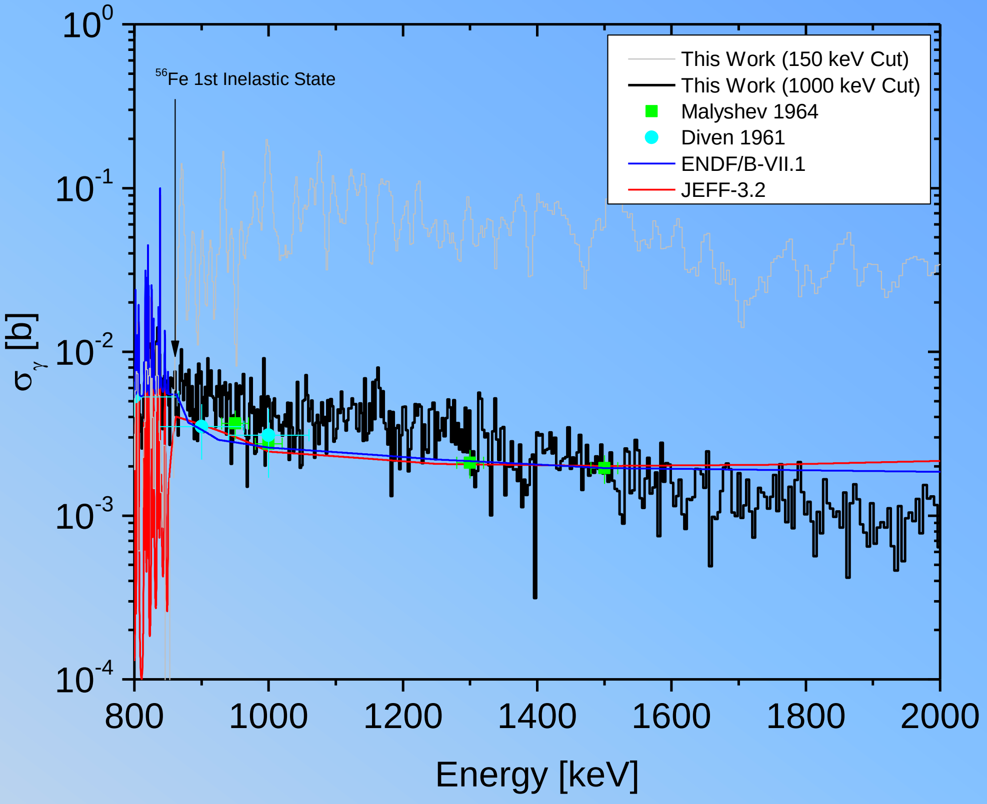


Rensselaer

linac The Gaertner LINAC Center

^{56}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 seems slightly higher that our ^{nat}Fe results
- Above 1400 MeV, the data are lower than the evaluations

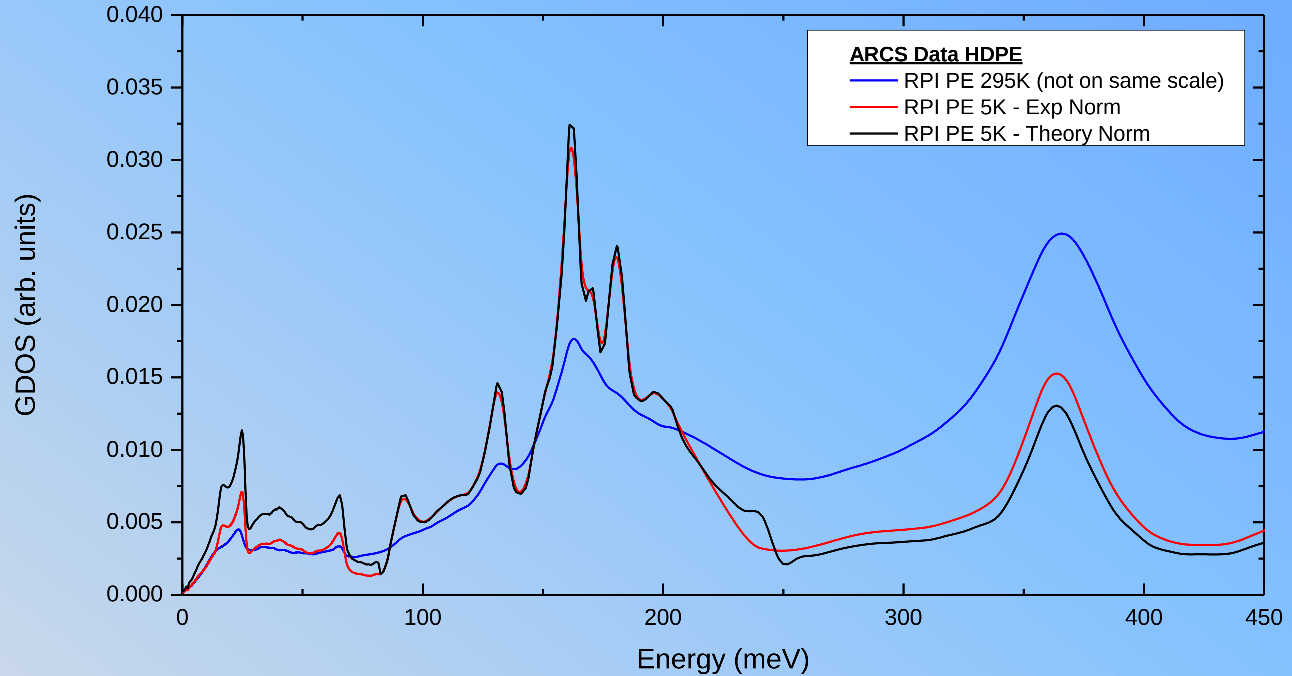


Thermal Scattering

Thermal Scattering Overview

- Preformed measurements at SNS
  - SEQUOIA
    - Water
    - Medium Density Polyethylene (MDPE)
  - ARCS
    - High Density Polyethylene (HDPE) 295 °K and 5 °K
    - Quartz (SiO_2) at 20, 300 550, 600 °C
  - VISION (measures S(ω))
    - Lucite, Lexan, Polyethylene at 5 °K and 295 °K
- The double differential scattering data (DDSD) can be used to benchmark thermal scattering evaluations
- Method to generate S(α,β) from the experimental data are under development:
  1. Convert the data (S(Q,ω)) to phonon spectrum (use low values of Q to limit multiple phonon scattering)
  2. Remove the elastic peak from the DDSD and convert the inelastic part directly to S(α,β)
- Developed capabilities to use LAMMPS code to calculate the phonon spectrum and scattering kernel.

Phonon spectrum from measured *S*(*Q*,*E*)



- Low temperature measurements are essential in order to resolve the structure.
- Convert the measured $S(Q,E)$ data for phonon spectrum using the SNS DAVE code:

$$S(Q,E) = \frac{\hbar^2 Q^2}{6ME} \exp(-\langle u^2 \rangle Q^2) G(E)[n(E,T)+1] \qquad n(E,T) = \frac{1}{\exp\left(\frac{E}{k_B T}\right)-1}$$

$G(E)$ - generalized phonon density-of-states(GDOS),

Q - wave vector transfer,

$S(Q,E)$ - structure dynamics factor,

M - mass of the atom,

$\langle u^2 \rangle$ - mean square displacement.

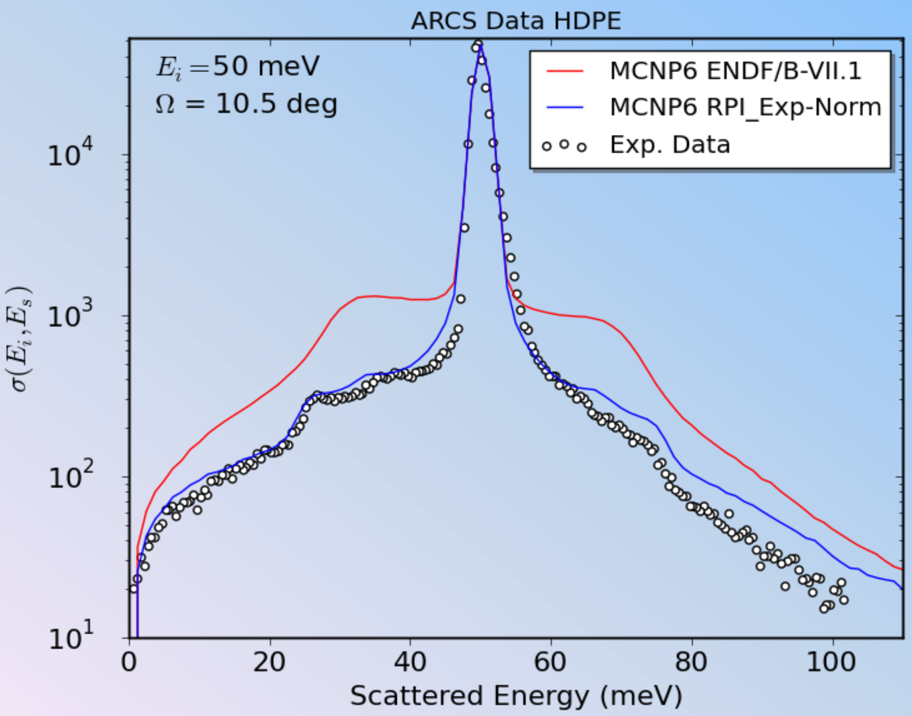
Rensselaer

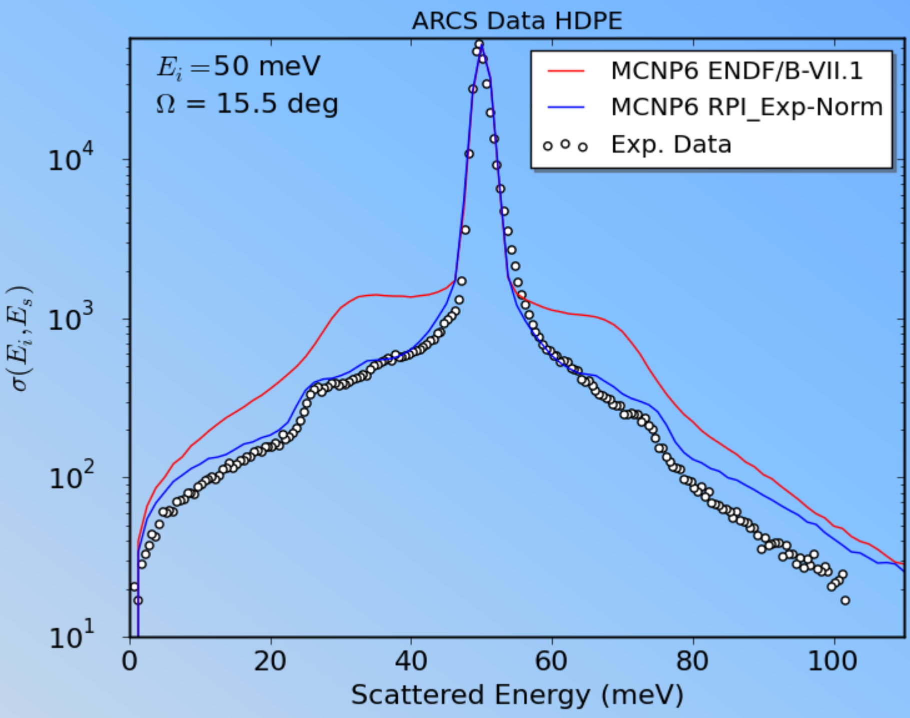
linac The Gaertner LINAC Center

Example for HDPE

Experiment Normalized GDOS

- The phonon spectrum was processed with NJOY 2012
- The experimental response simulated with MCNP 6
- The agreement with the experiment is improved



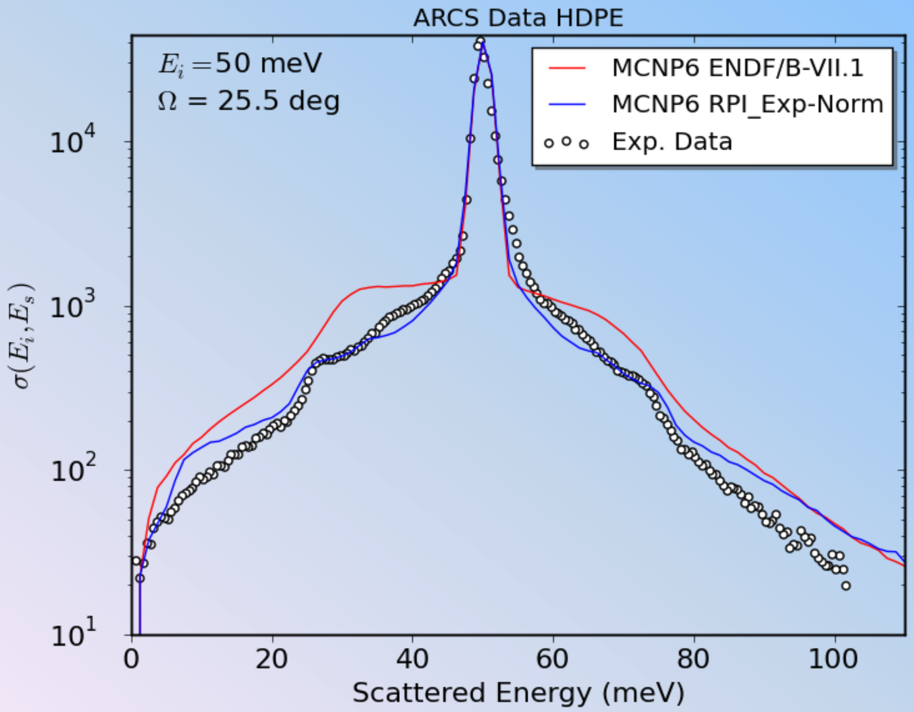


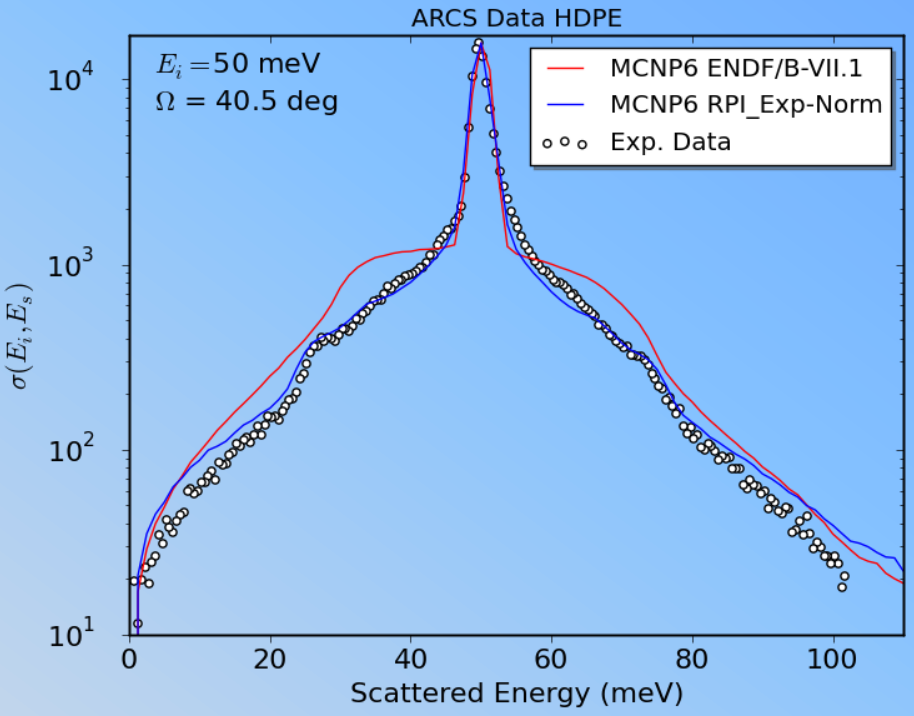
Rensselaer

linac The Gaertner LINAC Center

Example for HDPE other angles Experiment Normalized GDOS

- Similar improvements
- Other incident energies and angels available



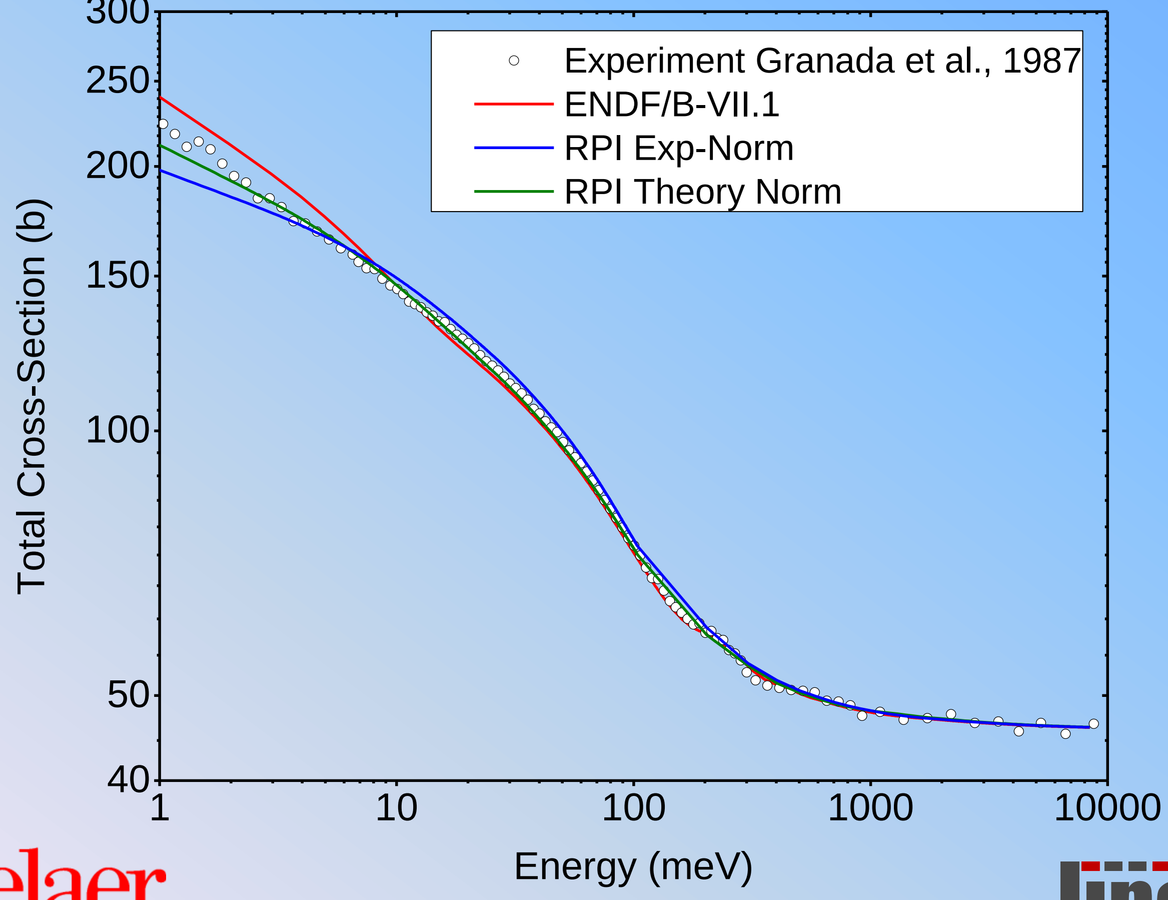


Rensselaer

linac The Gaertner LINAC Center

Polyethylene Total Cross Section

- The experimentally derived phonon spectrum is in good agreement with the total cross section measurement.
- The Experimental vs theory driven measurement give slightly different results



Rensselaer

linac The Gaertner LINAC Center

NIST Measurements and Standards including Related Work at Other Facilities(NIST).

- **Discussion on all standards**
  - Review some new related measurements done in the US
  - For more information see CSEWG 2015 minutes at: https://indico.bnl.gov/getFile.py/access?resId=0&materialId=minutes&confId=1291

NIST Measurements and Standards Including Related Work at Other Facilities

Allan D. Carlson
Neutron Physics Group
National Institute of Standards & Technology

Presented at
The CSEWG Meeting
BNL
November 3, 2015

Motivation

➢ In order to improve the standards, it is essential to maintain an active program of measurements concerning the standards. Much of this work is supported under the IAEA Nuclear Data Development Project "Maintenance of the Neutron Cross Section Standards".

➢ Several libraries including ENDF/B and JEFF, will soon be producing new versions of their libraries. New and improved standards are needed for them.

➢ We have broadened the standards research effort by considering, in addition to the traditional activities related to standards, extending the energy ranges of the standards, including "reference data" that are not as well known as the standards but can be very useful in certain types of measurements, and certain neutron spectra data.

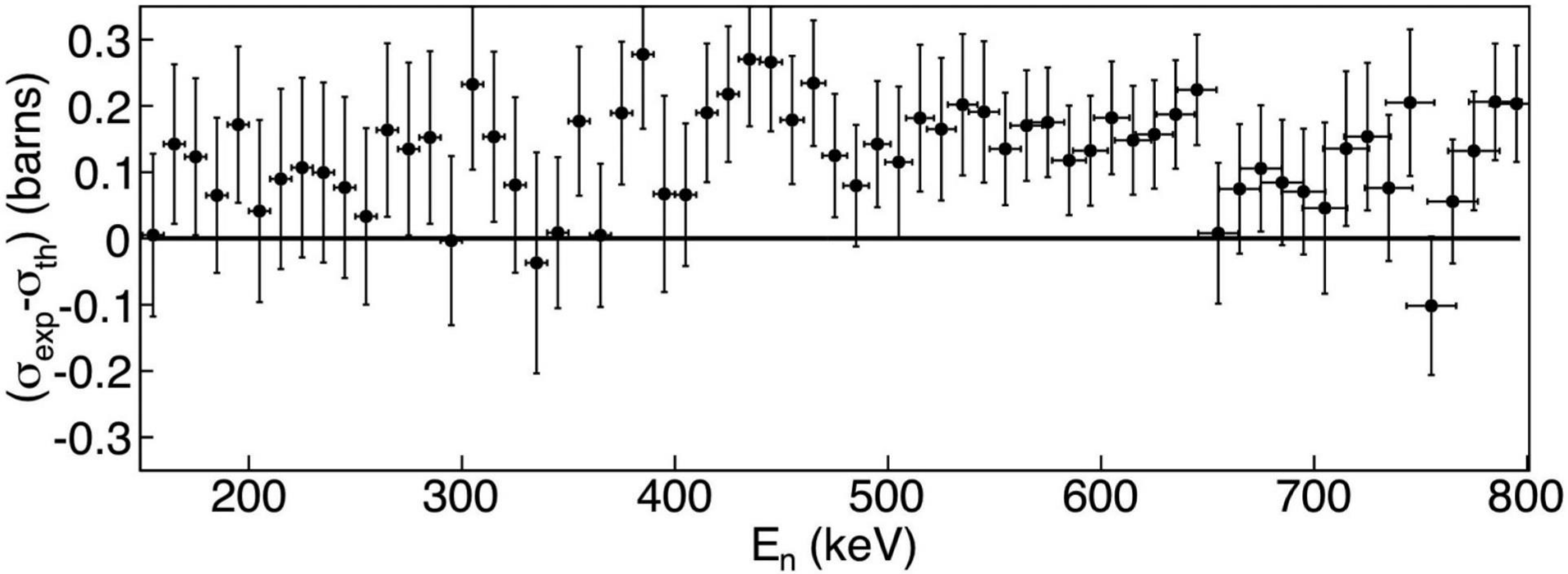
THE NEUTRON CROSS SECTION STANDARDS

Reaction	Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	thermal to 50 keV
^{6}Li(n,t)	thermal to 1 MeV
^{10}B(n,α)	thermal to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	thermal to 1 MeV
C(n,n)	1 keV to 1.8 MeV
^{197}Au(n,γ)	thermal, 0.2 to 2.5 MeV
^{235}U(n,f)	thermal, 0.15 to 200 MeV
^{238}U(n,f)	2 to 200 MeV

H(n,n)H Standard Measurements

- Concerns about the hydrogen total scattering cross section at low neutron energies led to work at the University of Kentucky Van de Graaff by Daub *et al*. from 150 keV to 800 keV. The results are systematically slightly larger than the ENDF/B-VII values but generally within their uncertainties of 1.1 to 2%. (Phys Rev C87, 014005 (2013)). Including these data in the new hydrogen being done by Hale and Paris will cause a slight increase in the evaluated cross section. This would then lead to a somewhat better agreement with the Arndt evaluation. The Arndt evaluation is larger than ENDF/B-VII by about 0.1% at low energies and about 1% at about 12 MeV. Gerry however has found EDA normalizes these data down about 2%.

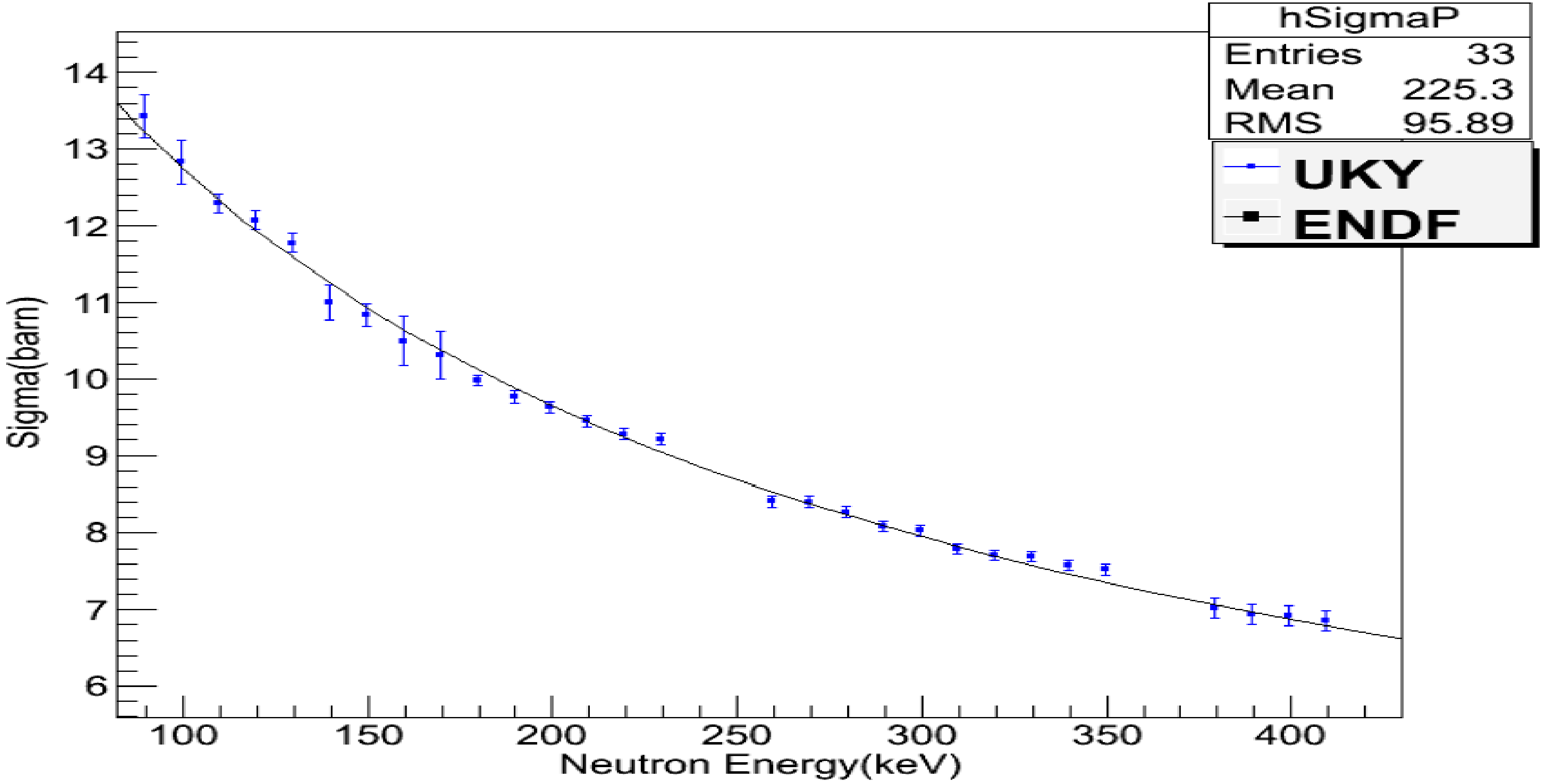
Daub *et al.* Hydrogen Total Cross Section-ENDF/B-VII Evaluation



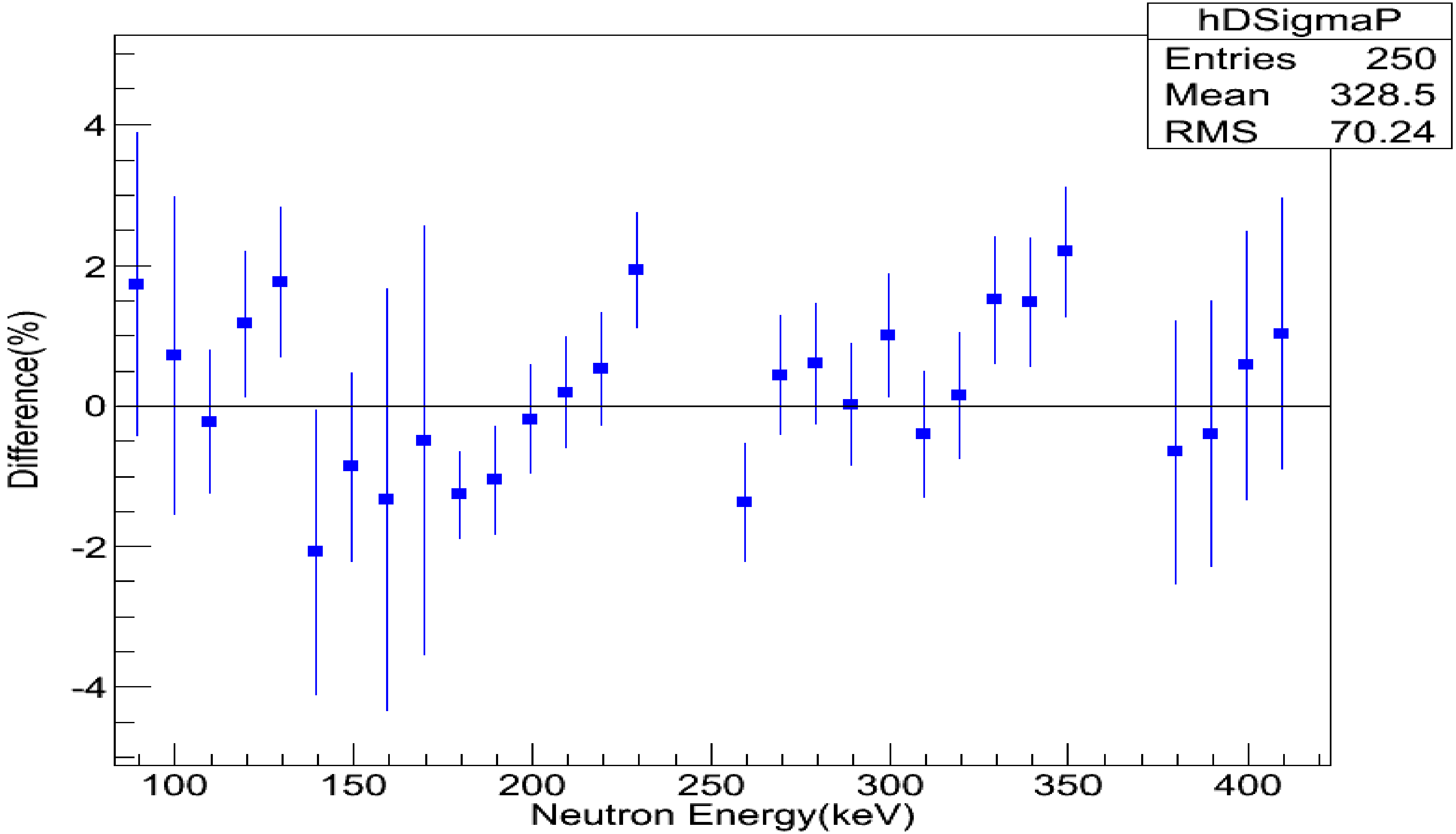
H(n,n)H Standard Measurements

- Additional total cross section work at Kentucky was done byYang as a thesis Project that was recently completed. The focus was getting to even lower energies than that obtained by Daub *et al*. The Van de Graaff data were obtained from 90 keV to 1.8 MeV with generally smaller uncertainties than those obtained by Daub *et al*. For these data it is not clear that the cross sections are slightly higher than ENDF/B-VII as was observed by Daub *et al*.

Yang Hydrogen Total Cross Section



Yang Hydrogen Total Cross Section-ENDF/B-VII Evaluation



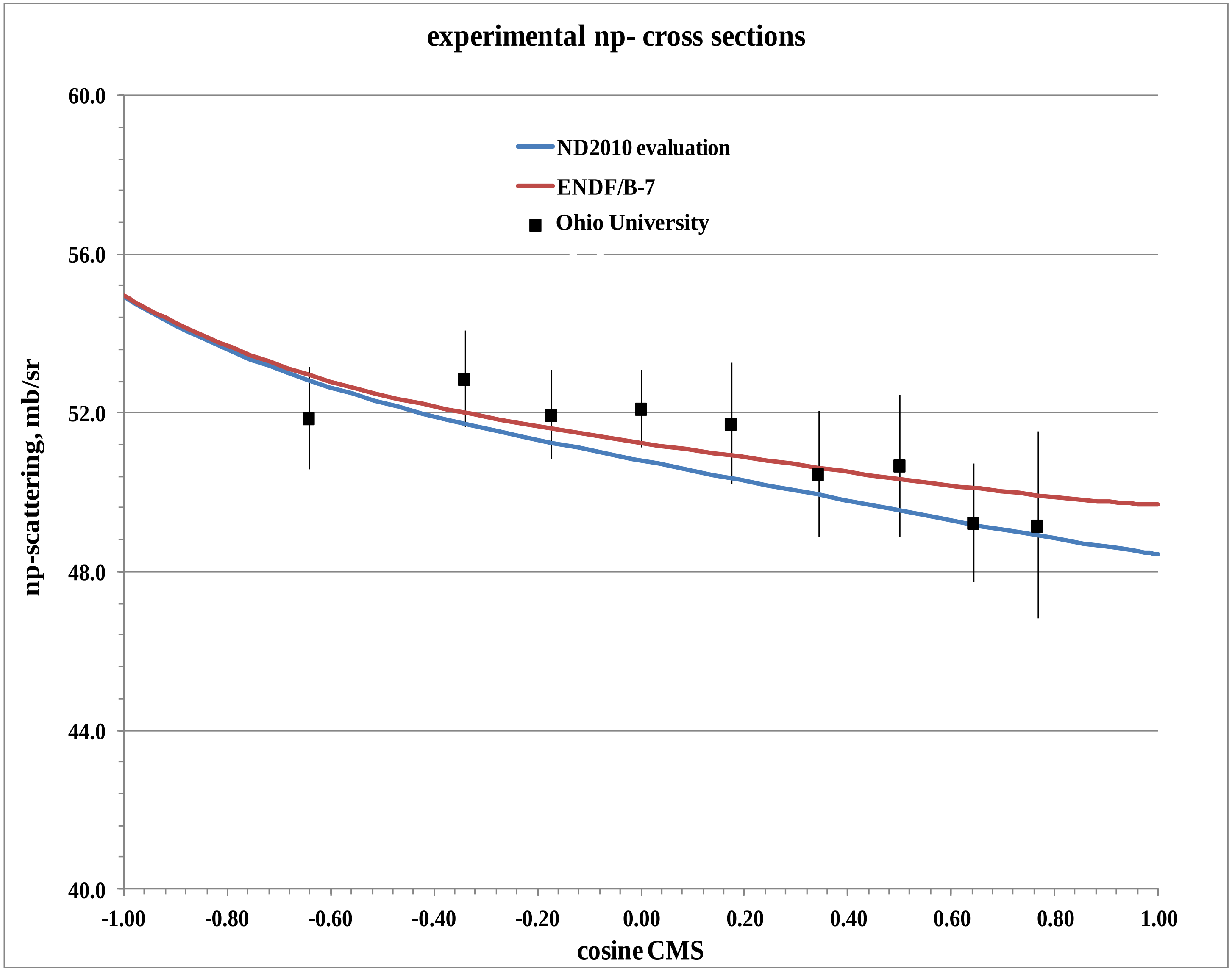
H(n,n)H Angular Distribution Measurements

- There is a problem with the quality of data at small CMS angles for hydrogen scattering. In order to improve the database of measurements at smaller scattering angles an experiment has been designed where the primary objective is detection of the scattered neutron instead of the scattered proton.

- The work was done at the Ohio University accelerator facility. Preliminary measurements have been made at laboratory neutron scattering angles from 20 degrees to 65 degrees in 5 degree steps for 14.9 MeV incident neutrons. The plan is to increase the accuracy of the measurements and extend the angular range so that data are obtained from 15 to 70 degrees. Plans have also been made to do similar measurements for 10 MeV neutrons. For this work the ^{252}Cf neutron spectrum standard was used to determine the efficiency of the neutron detector.

(collaboration of Ohio University, NIST, LANL and the University of Guelma)

14.9 MeV Hydrogen Angular Distribution Measurements



H(n,n)H Angular Distribution Measurements

- To obtain the higher accuracy needed for this work, the neutron detector efficiency must be determined more accurately.

- For our work, the detector efficiency is well known below about 6 MeV. For neutron detector efficiency determinations above that energy, a technique using reactions where the projectile and target are identical is being used. Because they are identical, the angular distribution **must** be symmetrical in the CMS. So the neutron yield at an angle Θ must be the same as that at 180- Θ in the CMS. But the energies of the neutrons are different in the LAB system. Thus in the LAB system, for a bombarding energy such that the backward portion of the angular distribution falls in the energy range below 6 MeV where the efficiencies are well known, we can deduce the efficiency for the higher energy group in the forward hemisphere.

- Many possible reactions were studied. D(d,n) turned out to be the best reaction and will be used for 10 MeV neutrons. A gas cell will be used. The Q value of 3.3 MeV will allow data to be taken at small angles for 10 MeV neutrons.

- Studies using MCNP in an effort to optimize the experiment are now underway.

(collaboration of Ohio University, NIST, LANL and the University of Guelma)

^{6}Li(n,t) Measurements

- At the NIST Neutron Center for Neutron Research a measurement was made by Yue *et al.* of the ^{6}Li(n,t) cross section standard. The value obtained is 2563.3 ± 7.7 b for a neutron energy of 3.3245 ± 0.0016 meV.

- This is the first direct and absolute measurement of this cross section in this neutron energy range using monoenergetic neutrons.

- A primary effort was focused on measuring the neutron fluence accurately. It was determined with an uncertainty of 0.06%.

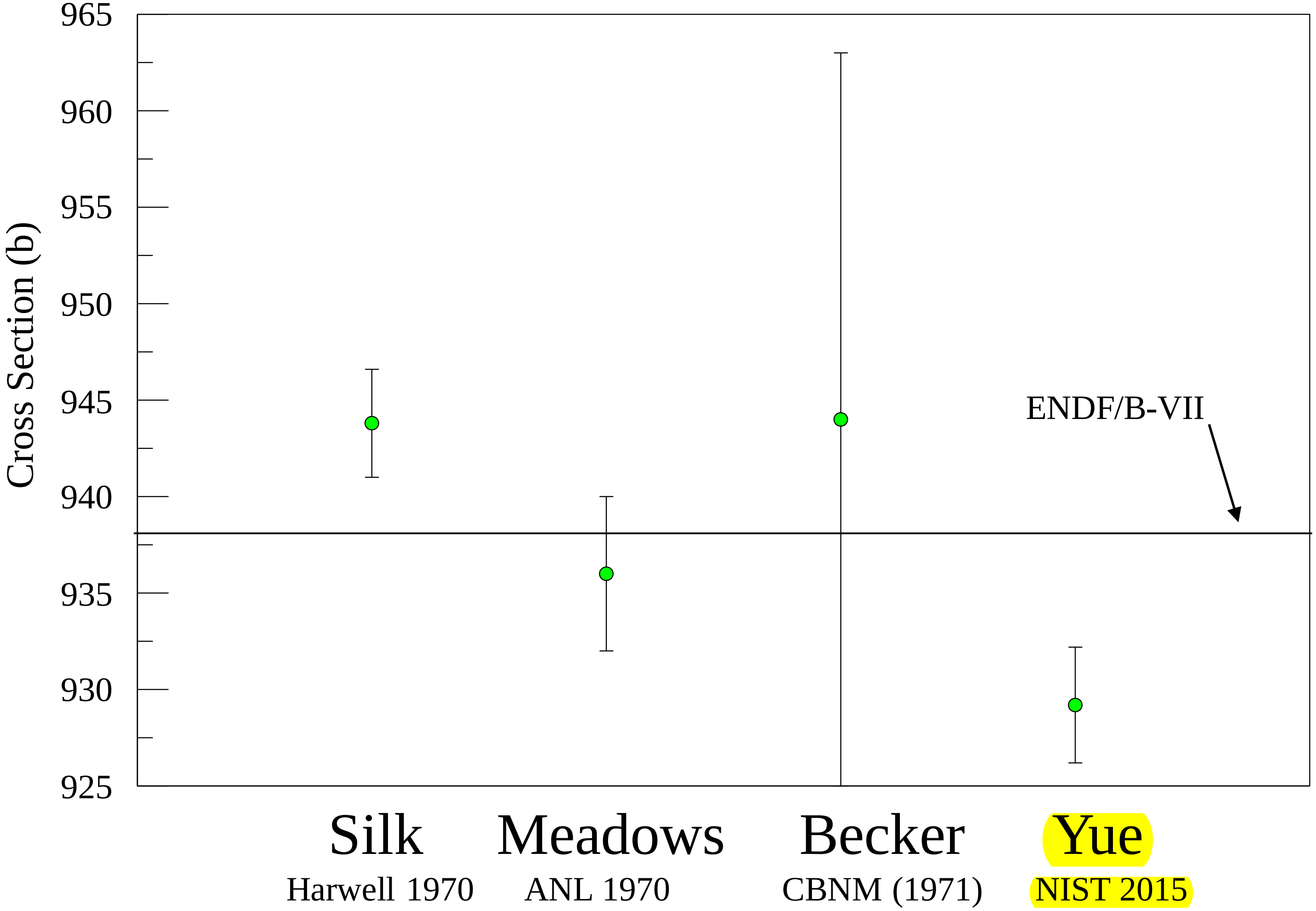
- Much investigation has gone into the uncertainty of this result. The uncertainty is mainly from the uncertainty in the ^{6}Li mass. The initial value obtained was in excellent agreement with the ENDF/B-VII standards evaluation. It was recently found that the mass reported by IRMM was in error. Using the new mass value produces a cross section value with an uncertainty of 0.3% that is 1% lower than the ENDF/B-VII value.

- **The low energy (thermal) cross section ENDF/B-VII value is largely determined by measurements made in 1970-1971.**
  - It is not clear how well they determined their ^{6}Li masses.

(collaboration of NIST with the University of Tennessee and Tulane University)

Thermal Measurements of the $^{6}Li(n,t)$ cross section

(The Yue value is converted to thermal energy)



$^{6}Li(n,t)$ Measurements

- Measurements have been made of the $^{6}Li(n,t)$ cross section by Devlin et al. at LANL. This work was initiated to improve the cross section in the 2 MeV energy region where the uncertainties in this cross section are large. This work includes angular distribution data obtained from 0.2 to 10 MeV at eight laboratory angles using four E-ΔE telescopes. These data are absolute ratios to the $^{235}U(n,f)$ cross section and also the hydrogen scattering cross section. The uncertainties are about 5%. These data have been added to the existing R-matrix database used by Hale for a new "independent evaluation" of the $^{6}Li(n,t)$ cross section. The new Hale evaluation is consistent with the Devlin et al. data.

^{6}Li(n,t) Measurements (cont.)

- It should be noted that the ENDF/B-VII.0 evaluation for the ^{6}Li(n,t) cross section up to 2.6 MeV is obtained from the international standards evaluation. But the cross section is a standard only up to 1 MeV. The result from the new "independent evaluation" by Hale including the results from the Devlin et al. data is about 4% higher than ENDF/B-VII.0 at 2 MeV.

- Thus the Devlin et al. data had an important impact on the new Hale evaluation.

- At 1 MeV, the highest energy where ^{6}Li(n,t) is a standard, the uncertainty is 1%. The difference between the "independent evaluation" by Hale and the previous standards evaluation is about 3%.

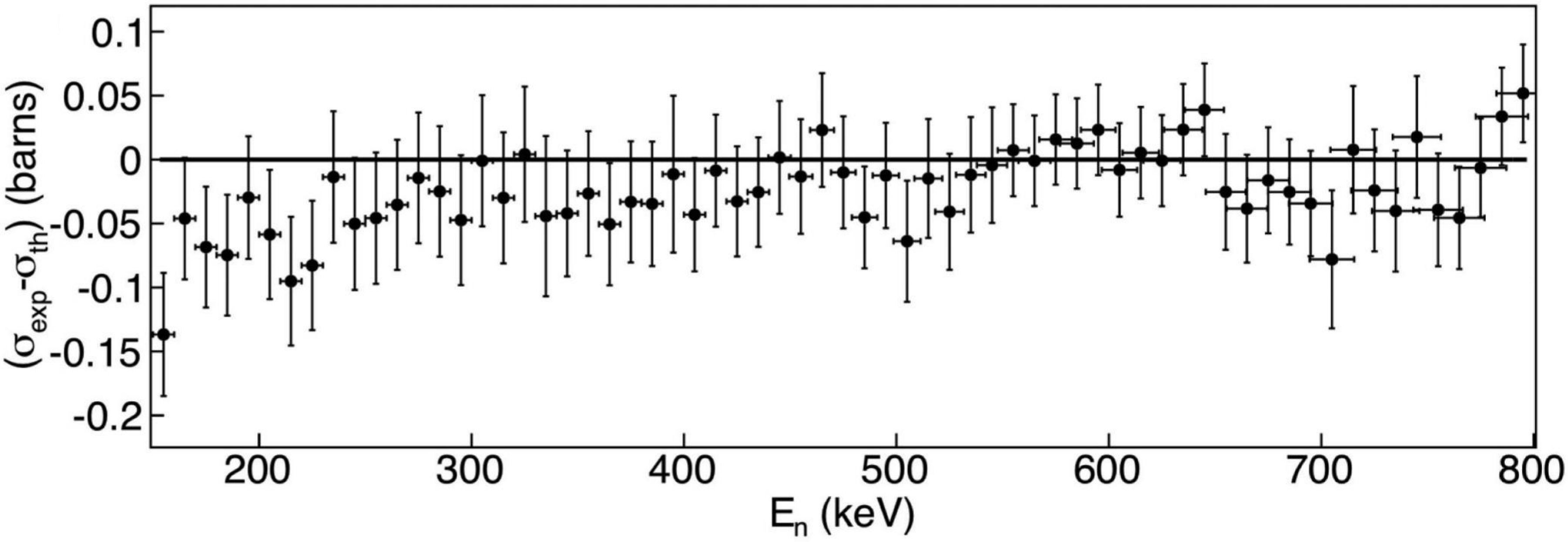
- It is still not clear what result will come from the present evaluation process but we must be concerned when very large changes occur relative to uncertainties for the standards!

C(n,n) Data

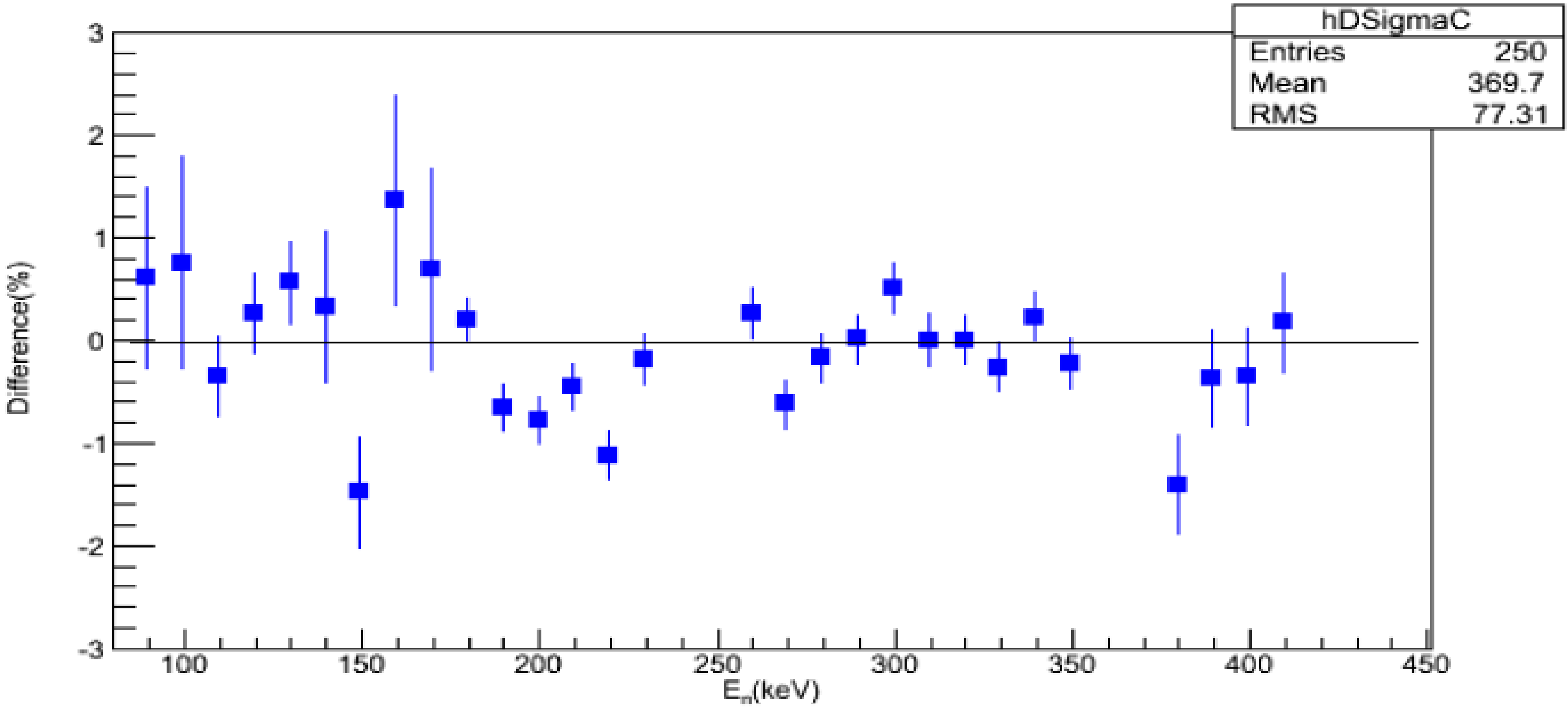
- In addition to their work on the hydrogen total cross section, Daub *et al.* also made very accurate measurements of the carbon total cross section from 150 keV to 800 keV. The results were systematically very slightly lower than the ENDF/B-VII values values but generally within their uncertainties of 1.1 to 2%.

- Additional total cross section work at Kentucky was done by Yang as a thesis Project that was recently completed. The focus was getting to even lower energies than that obtained by Daub *et al.* The Van de Graaff data were obtained from 90 keV to 1.8 MeV with generally smaller uncertainties than those obtained by Daub *et al.* For these data it is not clear that the cross sections are slightly lower than ENDF/B-VII as was observed by Daub *et al.*

Daub *et al.* Carbon Total Cross Section



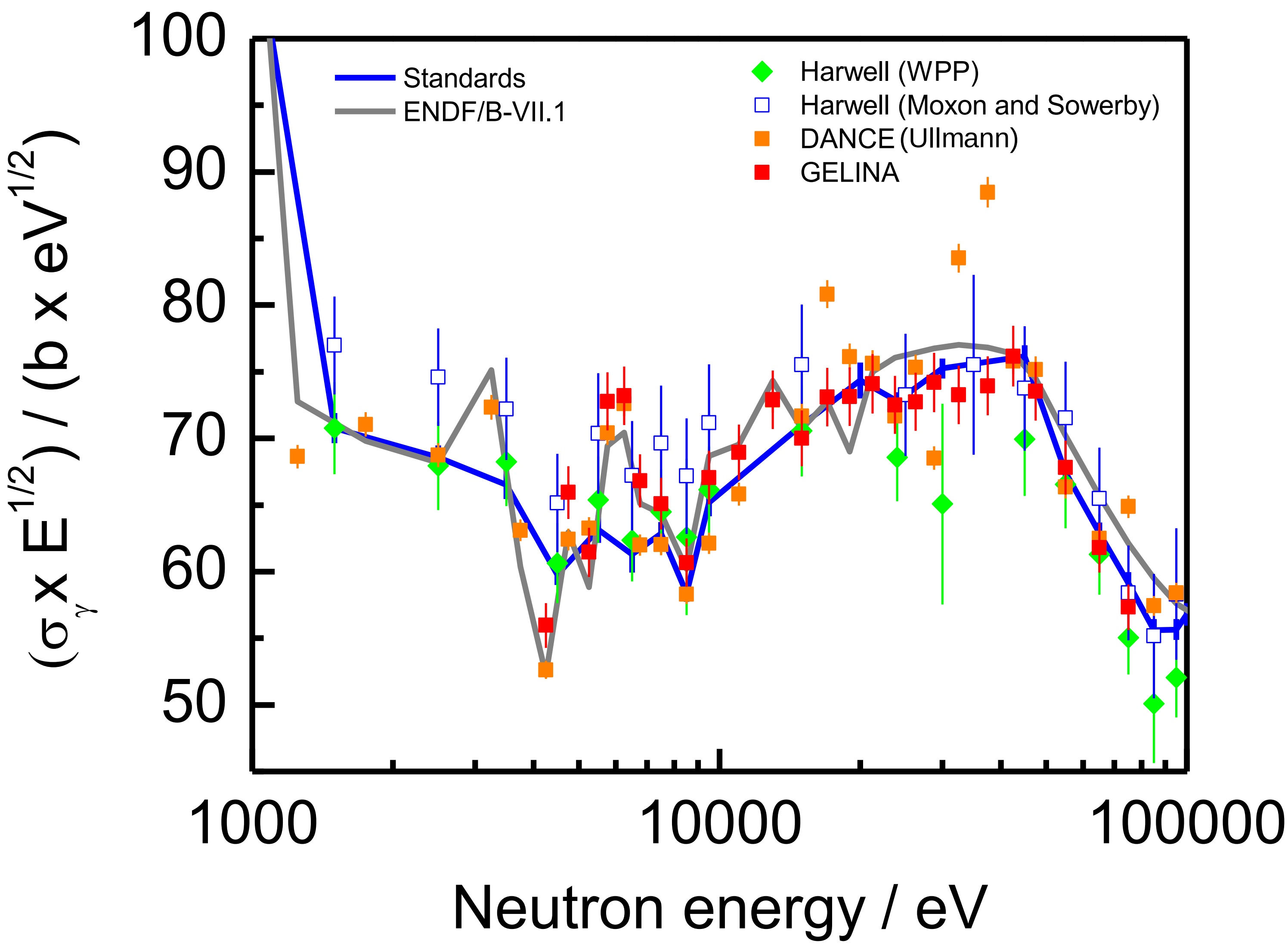
Yang Carbon Total Cross Section - ENDF/B-VII Evaluation



$^{238}U(n,\gamma)$ Measurements

- Ullmann et al. made measurements of the $^{238}U(n,\gamma)$ cross sections using the DANCE (160 BaF_2 crystals) detector at LANSCE. The neutron beam was monitored with a ^{235}U fission chamber, a BF_3 counter, a ^{6}Li F detector and a ^{3}He detector. Small ^{238}U samples could be used due to the high neutron intensity at DANCE. This reduces the uncertainty due to multiple scattering. Though the data could be made absolute, they are normalized to capture in the 80 and 145 eV resonances. Since the data are normalized in this manner, not to a standard set of reactions, they will be used as shape data in the evaluation. They associate a 2 percent uncertainty to this normalization. The energy range is 10 eV to 500 keV. In the evaluation, the data will be used up to 10 keV and above 200 keV because of an apparent contribution from aluminum resonances from the encapsulation of the sample.

Measurements of the $^{238}U(n,\gamma)$ Cross Section



^{238}U(n,f) Measurements

- Measurements have been completed and analyzed by Miller from the University of Kentucky of the ^{238}U(n,f) cross section relative to hydrogen scattering. The absolute data are shape measurements extending from 100 to 300 MeV. The data were obtained at the LANL WNR facility. There may be some very minor changes to the Data.

Measurements of the $^{238}U(n,f)$ Cross Section by Miller