

Report on U.S. Experimental Activities

WPEC 2017

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CSEWG measurements committee chair

WPEC, May 15-19, 2017, OECD Headquarters, Paris, France

Introduction

- **This presentation is based on presentations during the November 2016 CSEWG meeting.**
- **A min-CSEWG meeting was held on May 4-5 at BNL**
 - Mostly to discuss ENDF/B-VIII.0.
- **Reports from different laboratories:**
 1. Los Alamos National Laboratory
 2. Oak Ridge National laboratory
 3. Lawrence Berkeley National Laboratory
 4. University of Kentucky
 5. Rensselaer Polytechnic Institute
 6. National Institute of Standards

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

Los Alamos National Laboratory

- **Neutron-capture study at DANCE**
 - $^{236}\text{U}(n,\gamma)$ results
 - $^{63}\text{Cu}(n,\gamma)$ results
 - $^{239}\text{Pu}(n,\gamma)$ results
- **Photon Strength Function _{γ} Study for unstable nuclei :Apollo at ANL**
 - • $^{96}\text{Zr}(d,p\gamma)$ updates
 - • $^{57}\text{Fe}(d,p\gamma)$ updates
- **NZ study : LENZ status**
 - $^{16}\text{O}(n,\alpha)$ updates
 - $^{95}\text{Mo}(n,p)$ $^{52}\text{Cr}(n,\alpha)$ reactions
 - $^{60,61,62}\text{Ni}(n,p)$ reaction

The Progress on LANSCE Experimental Activity



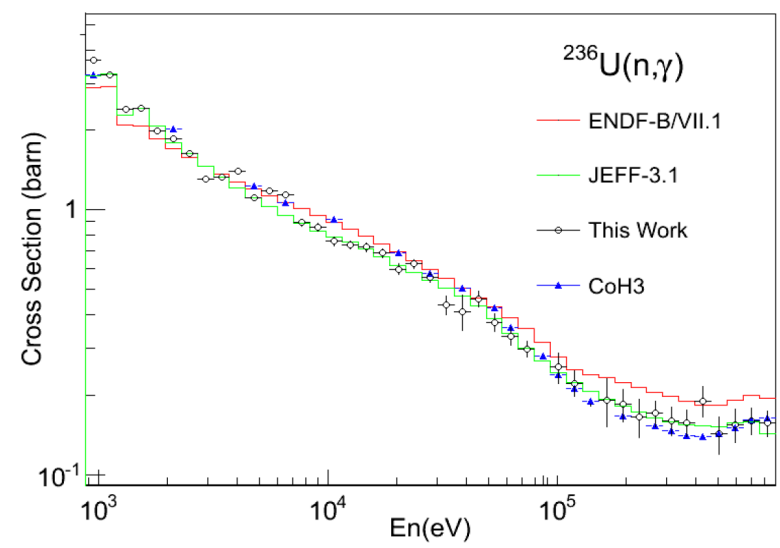
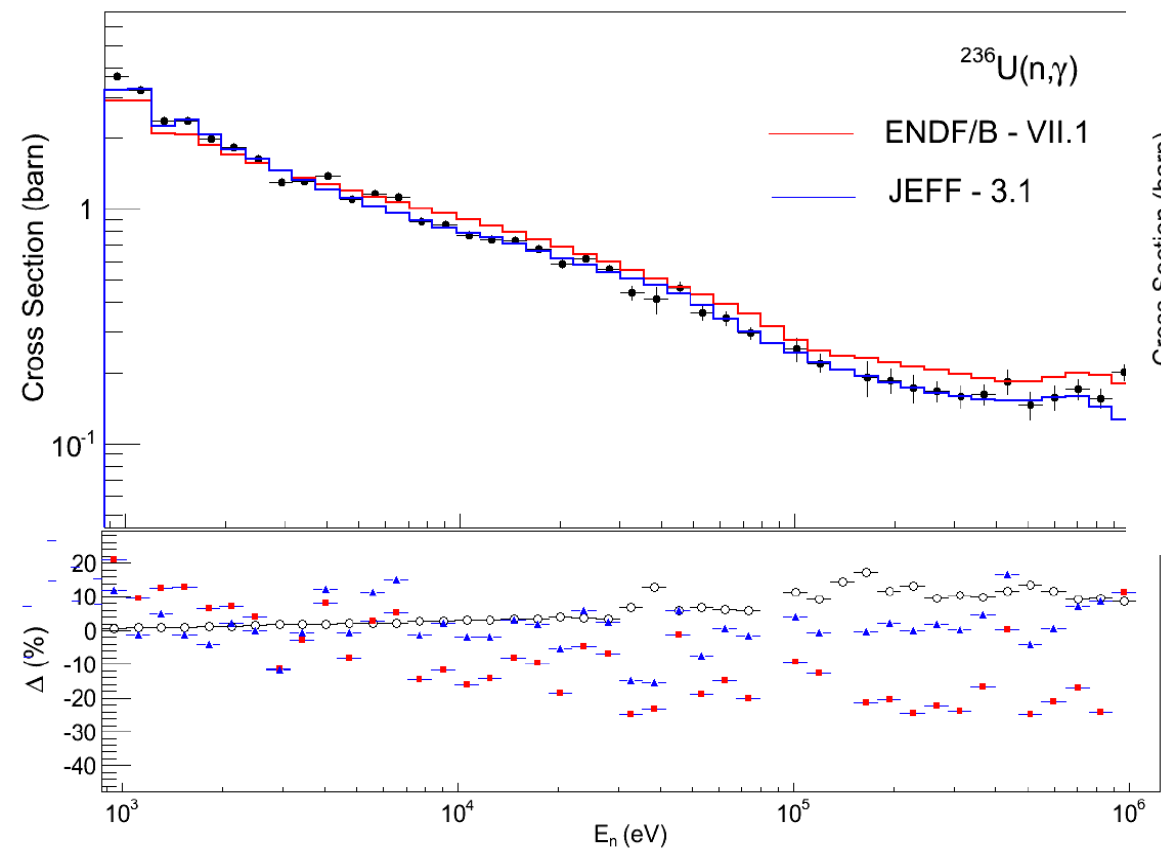
Hye Young Lee
Physics Division

*Cross Section Evaluation Working
Group : Measurement, US National
Nuclear Data Week 2016, Nov. 14-18*

Outline

- **Neutron-capture study : DANCE Status and Upgrade of NUANCE**
 - $^{236}\text{U}(n,\gamma)$ results
 - $^{63}\text{Cu}(n,\gamma)$ results
 - $^{239}\text{Pu}(n,\gamma)$ results
- **Photon Strength Function Study for unstable nuclei : Apollo at ANL**
 - $^{96}\text{Zr}(d,p\gamma)$ updates
 - $^{57}\text{Fe}(d,p\gamma)$ updates
- **NZ study : LENZ status**
 - $^{16}\text{O}(n,\alpha)$ updates
 - $^{95}\text{Mo}(n,p)$ $^{52}\text{Cr}(n,\alpha)$ reactions
 - $^{60,61,62}\text{Ni}(n,p)$ reaction

Dance : $^{236}\text{U}(n,\gamma)$ result led by B. Baramsai

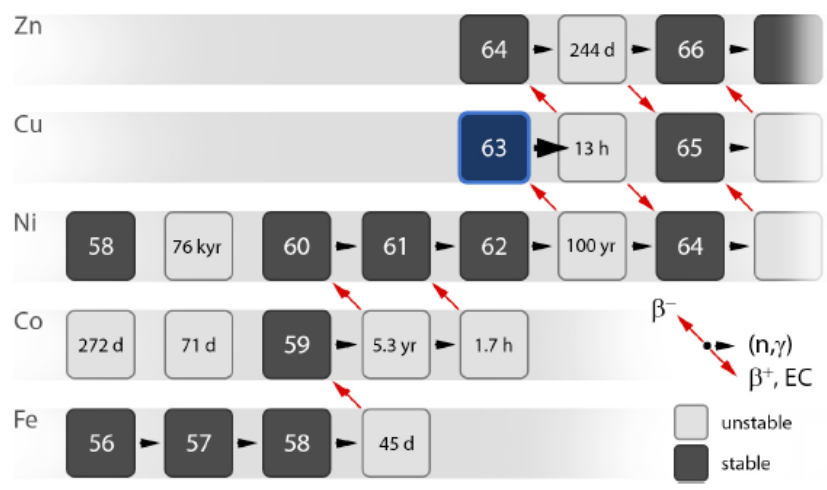


Systematic uncertainties (1-100 keV)

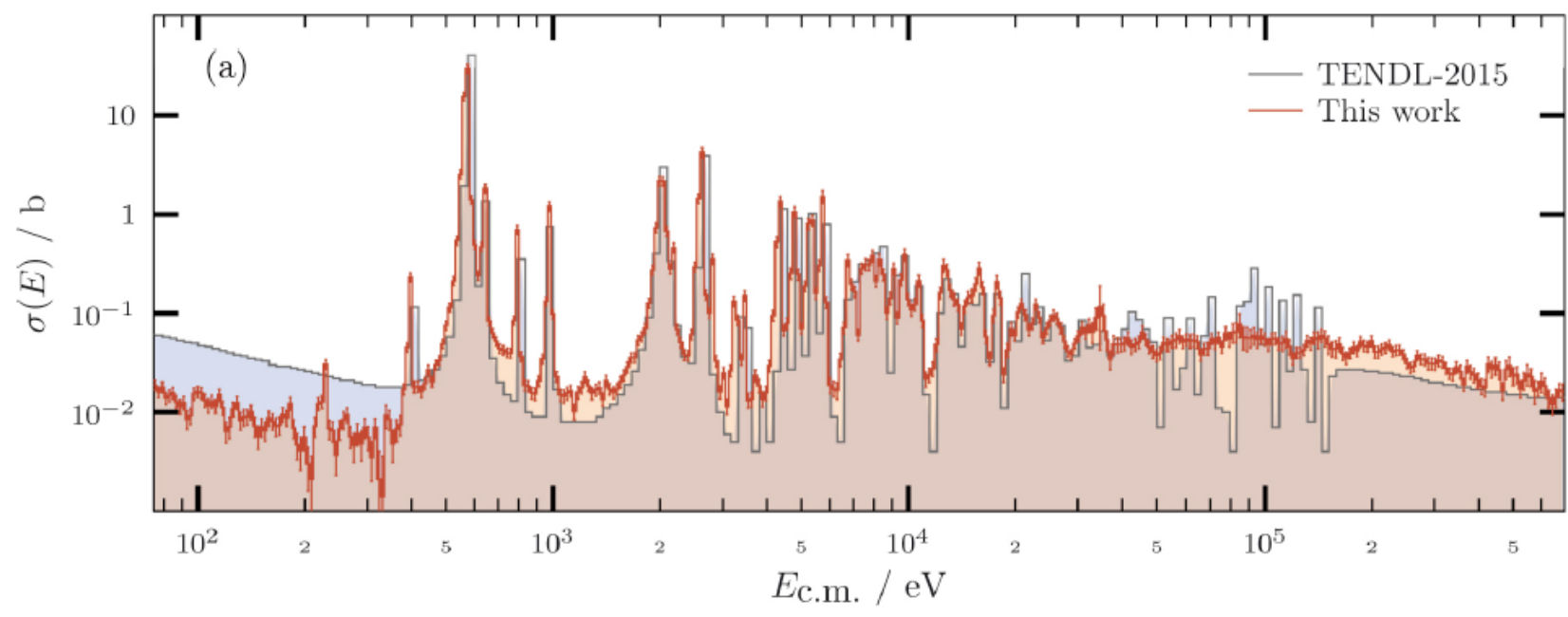
Uncertainty Source	dX / X
Statistical	<0.1-3 %
Background Subtraction	~1.7 %
Experimental Corrections	~2.2 %
Width fluctuation	1.7%
Reference CS (^{235}U)	1%
Total	4-8%

$^{236}/^{235}\text{U}$ (89%/10%) targets with each mass of 64 μg and 30 mg, so ^{235}U cross section was used as a reference

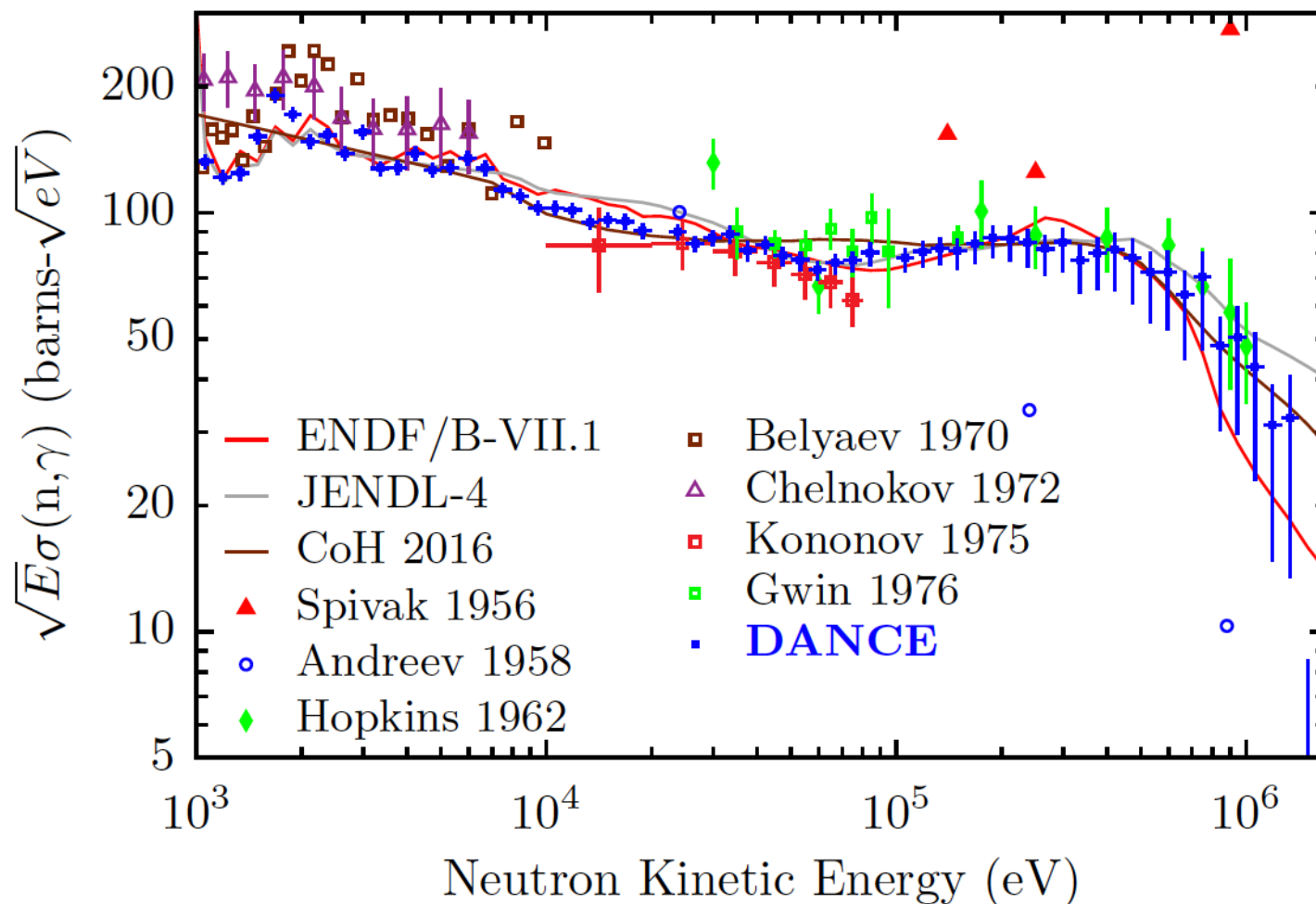
Dance : $^{63}\text{Cu}(n,\gamma)$ cross section



Copper isotopes are important for weak s-process nucleosynthesis, in particular neutron capture on ^{63}Cu produces the unstable ^{64}Cu . β^+ decayed ^{64}Ni shields ^{64}Zn from the contributions of the r-process



Dance : $^{239}\text{Pu}(n,\gamma)$ cross section led by S. Mosby

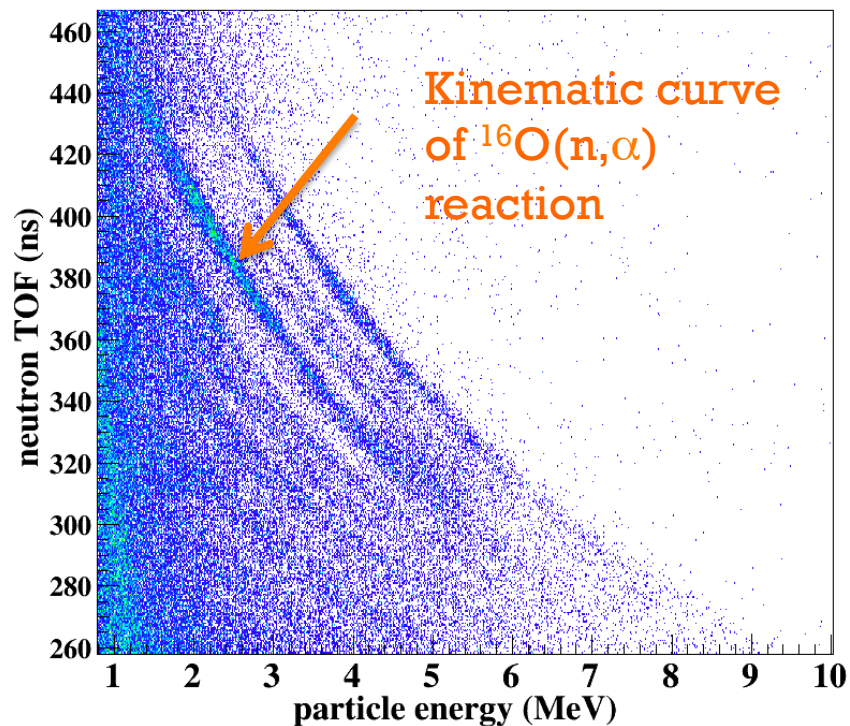


- **DANCE**
Uncertainty is dominated by systematic uncertainty
- **Thick target measurement with a beam time less than 14 days**
- **No fission tagging, so only γ -ray multiplicity = 7&8 was used for identifying fissions**

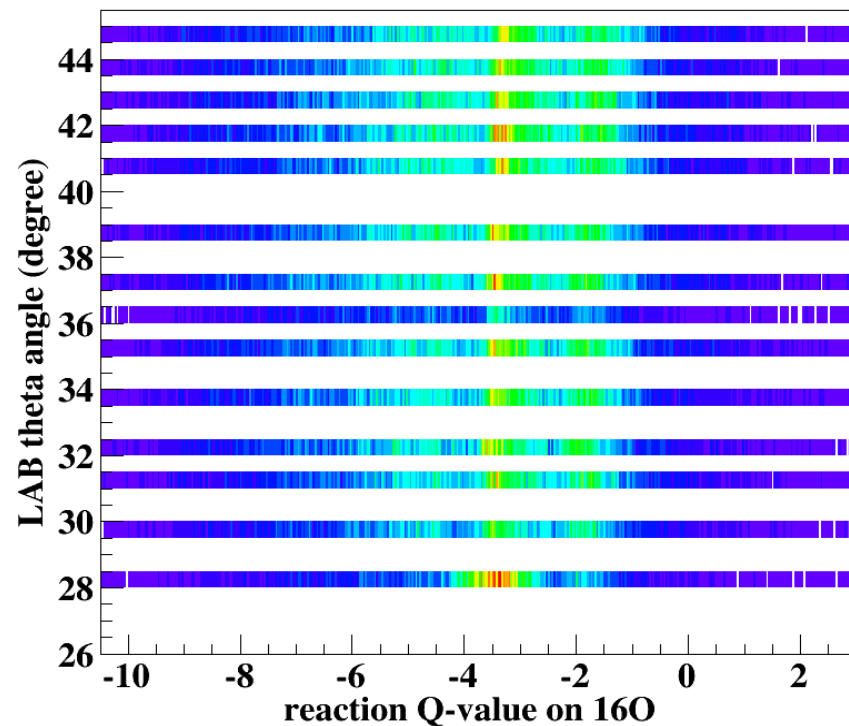
Thin ^{239}Pu target DANCE measurement by S. Mosby et al. PRC 89, 034610 (2014)

$^{16}\text{O}(n,\alpha)$ measurement updates

Detected particle energy vs.
neutron Time-of-Flight



Reaction Q-value vs. detected
LAB angles



Cross section is being deduced from the experimental yields by applying corrections and normalizations for the amount ^{16}O and a beam flux

Los Alamos National Laboratory

Chi-Nu

- **ChiNu matrix**
 - 0.5-100 MeV Ein
 - PPAC fission detector
 - Derive background from chance coincidence
- **Results (preliminary)**
 - ^{235}U
 - ^{239}Pu



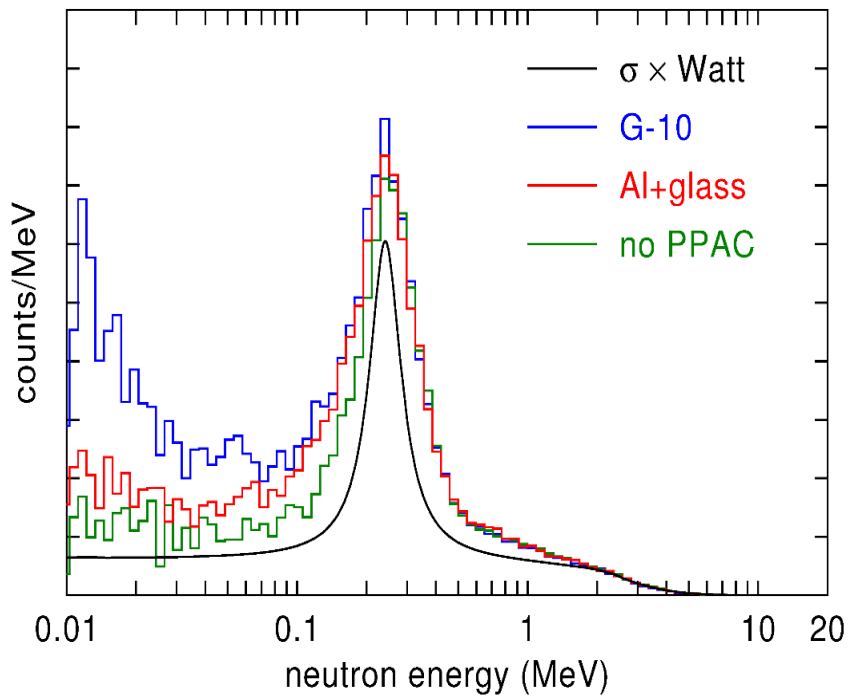
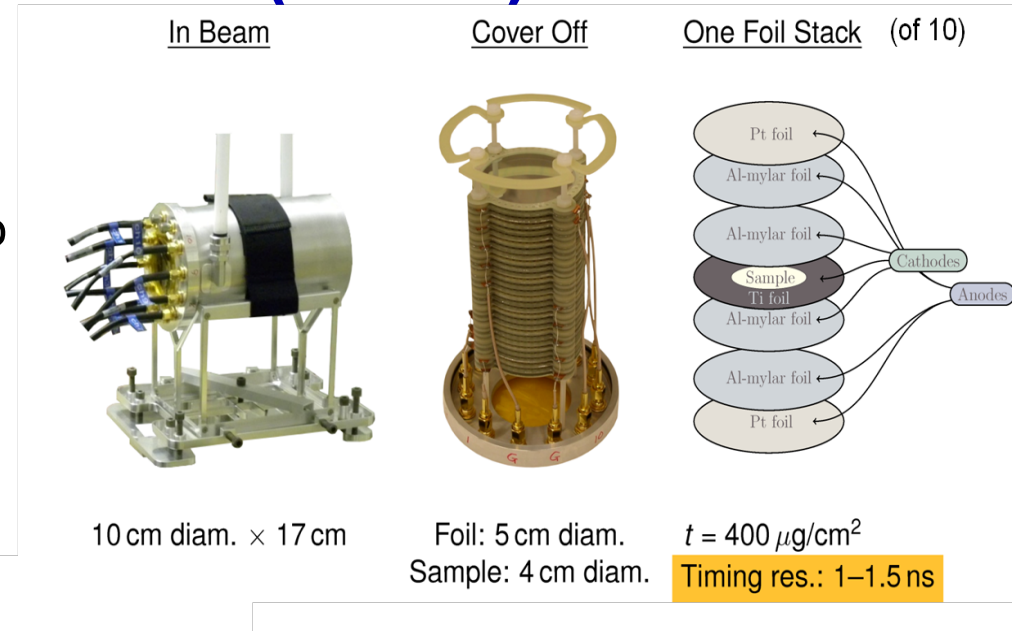
Measurements of the Prompt Fission Neutron Spectra of ^{235}U and ^{239}Pu at Chi-Nu

K.J. Kelly, M. Devlin, R.C. Haight, J.A. Gomez, H.Y. Lee, T.N. Taddeucci,
S.M. Mosby, J.M. O'Donnell, N. Fotiades, D. Neudecker, P. Talou,
M.E. Rising, M.C. White, C.J. Solomon, (LANL)
and
C.Y. Wu, B. Bucher, M.Q. Buckner, R.A. Henderson (LLNL)

CSEWG 2016
November 14, 2016
LA-UR-16-28935

Fission Detection: Parallel-Plate Avalanche Counter (PPAC)

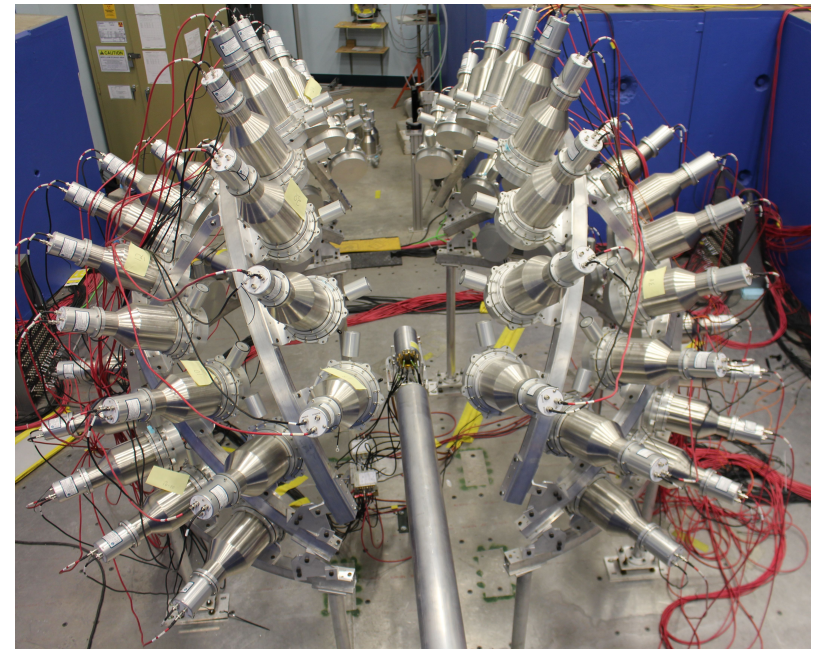
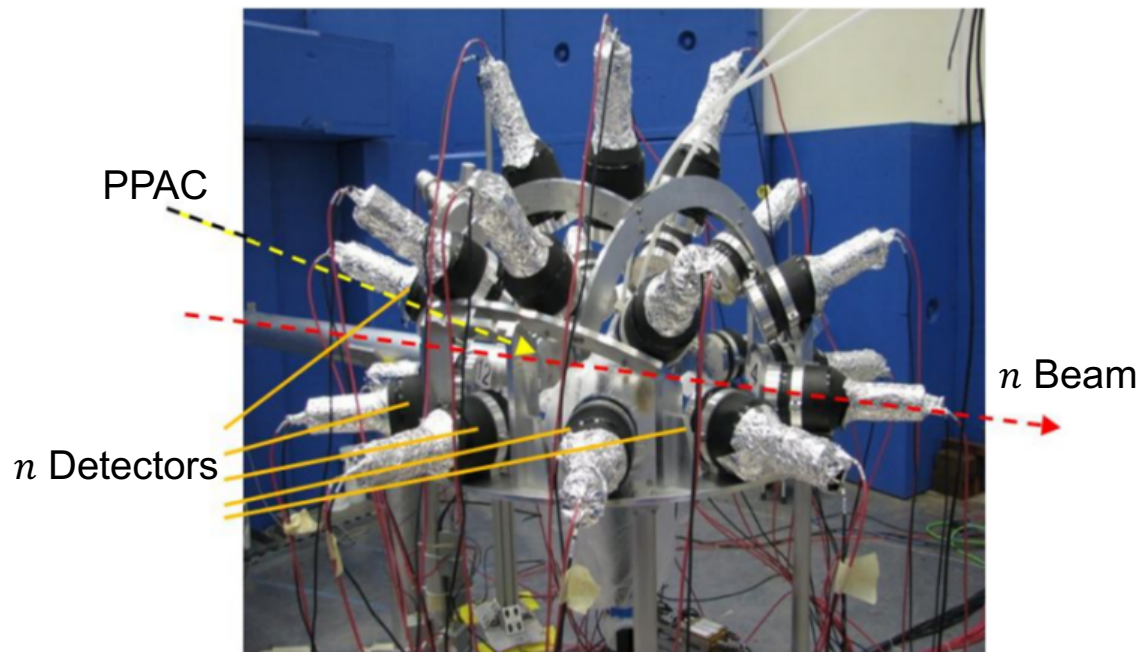
- 6 Total PPACs:
 - ^{252}Cf : Two, with different activities
 - ^{235}U : One, with 50 mg total mass
 - ^{239}Pu : Three, one with 50 and two with 100 mg total mass
- ^{235}U and ^{239}Pu PPACs contain 10 Ti target foils



- Significant modifications made to initial PPAC design to reduce n scattering
 - G-10 is an issue
 - Change from G-10 to Al and glass improved PPAC performance
 - Other H-rich materials have also been reduced

Outgoing Neutron Detection: Chi-Nu n -Detector Arrays

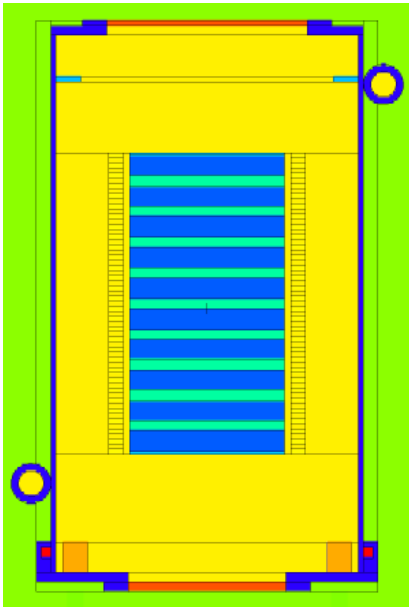
- Low E_n^{out} : 22 ${}^6\text{Li}$ -glass (LiGI) Detectors
 - $E_n^{out} \leq 1 \text{ MeV}$
 - Operate via ${}^6\text{Li}(n, \alpha)t$ reaction
- High E_n^{out} : 54 Liquid Scintillators
 - $E_n^{out} \geq 0.5 \text{ MeV}$
 - Good PSD for n - γ separation



Overlap region allows for a high- and low-energy measurements to be combined into a single PFNS result

Detailed Models of the Chi-Nu Experiment

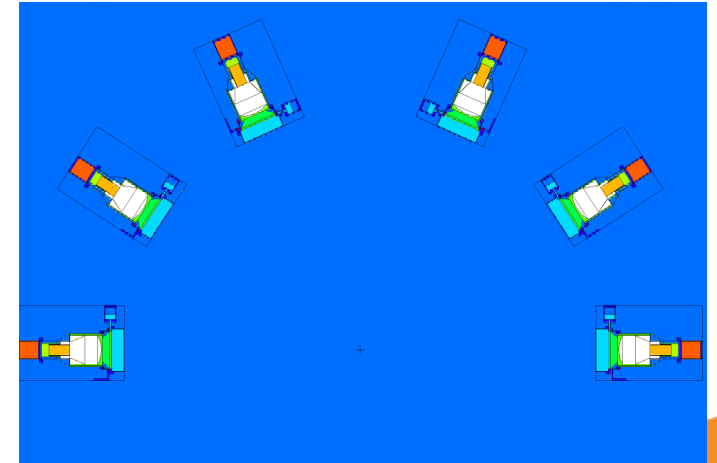
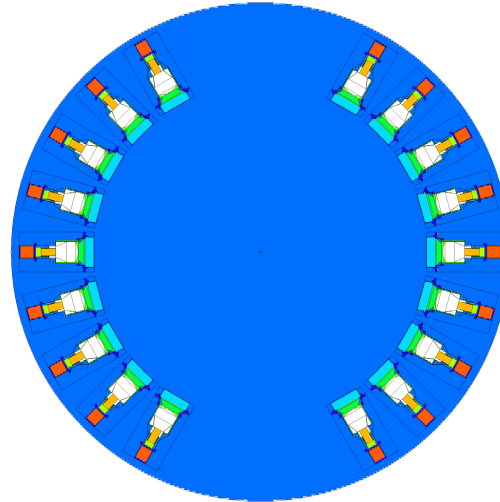
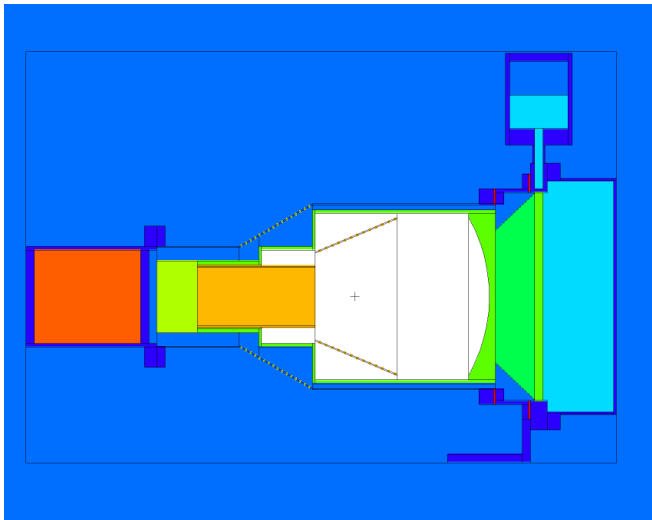
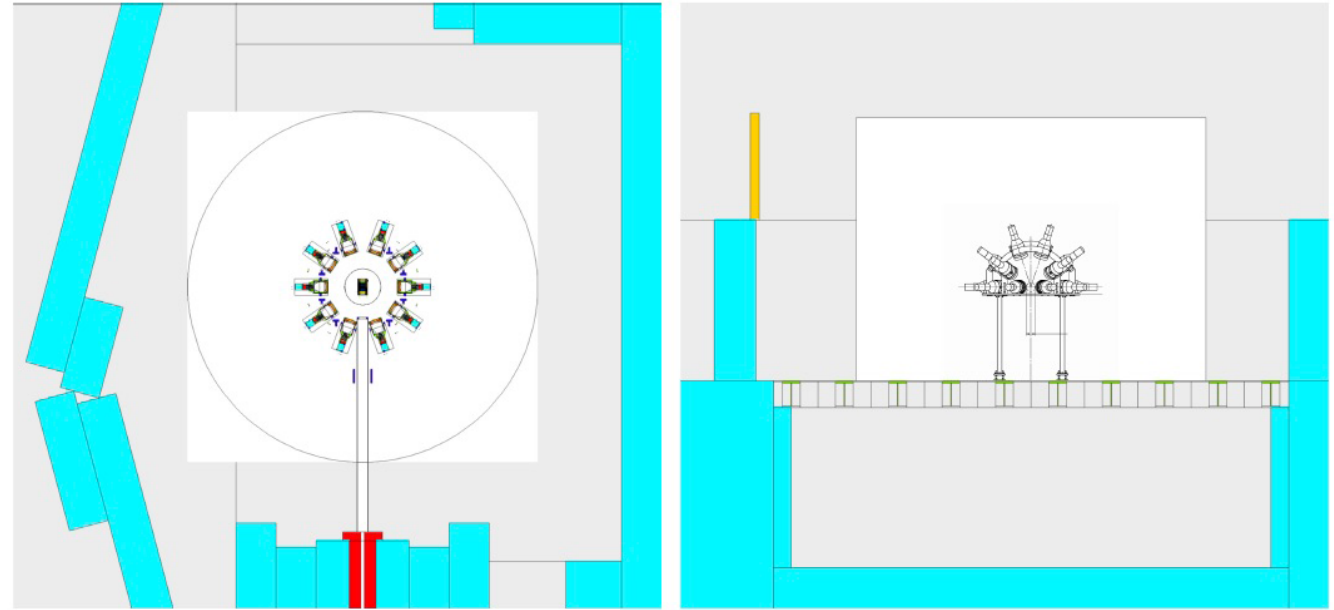
PPAC



^6Li -glass Array

top view

front view



Liquid Scintillator Array

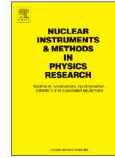
Time-Dependent Background Measurements



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in
Physics Research A

journal homepage: www.elsevier.com/locate/nima



A new method to reduce the statistical and systematic uncertainty of chance coincidence backgrounds measured with waveform digitizers

J.M. O'Donnell

Los Alamos National Laboratory, Los Alamos, NM 87544, USA

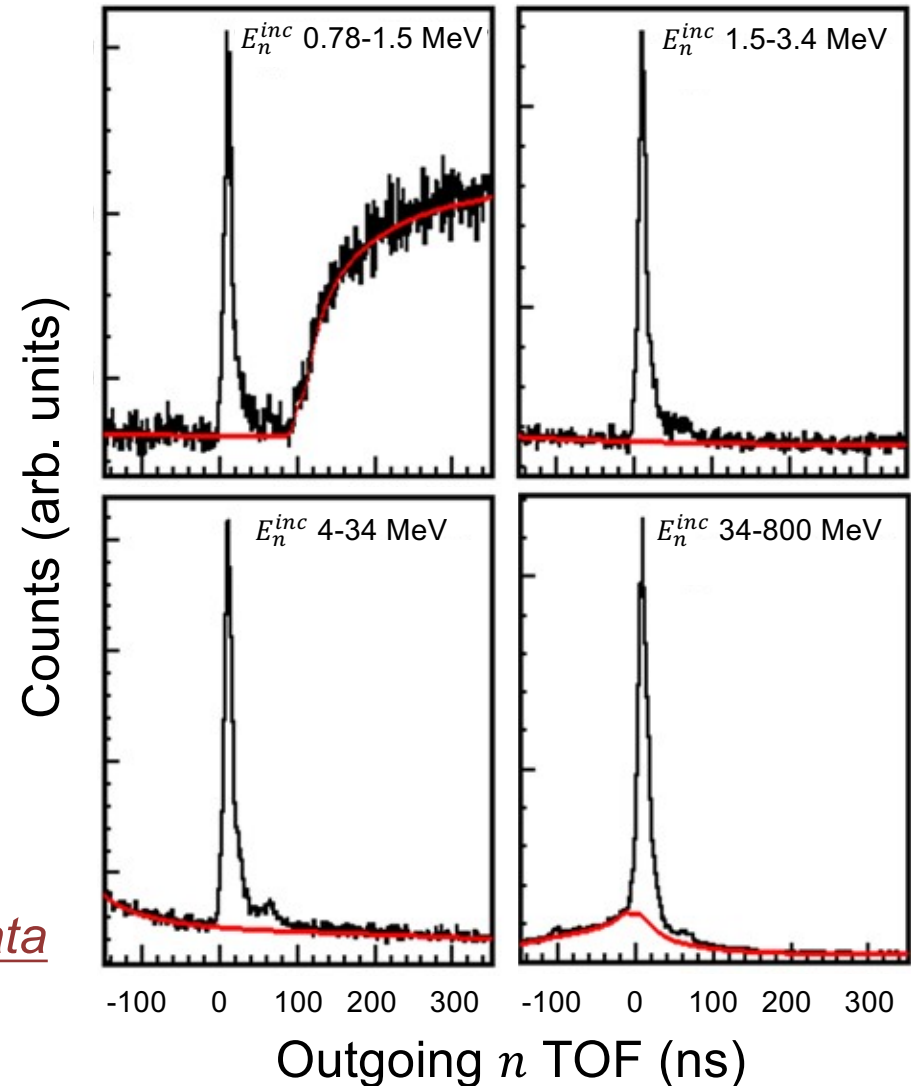
J.M. O'Donnell, Nucl. Instrum. and Methods **A 805** (2016), 87

- Background changes shape based on the chosen E_n^{inc}
- Chance coincidence rate is measured using the *singles* rates of the PPAC and n detectors

No Need to Collect Separate Background Data

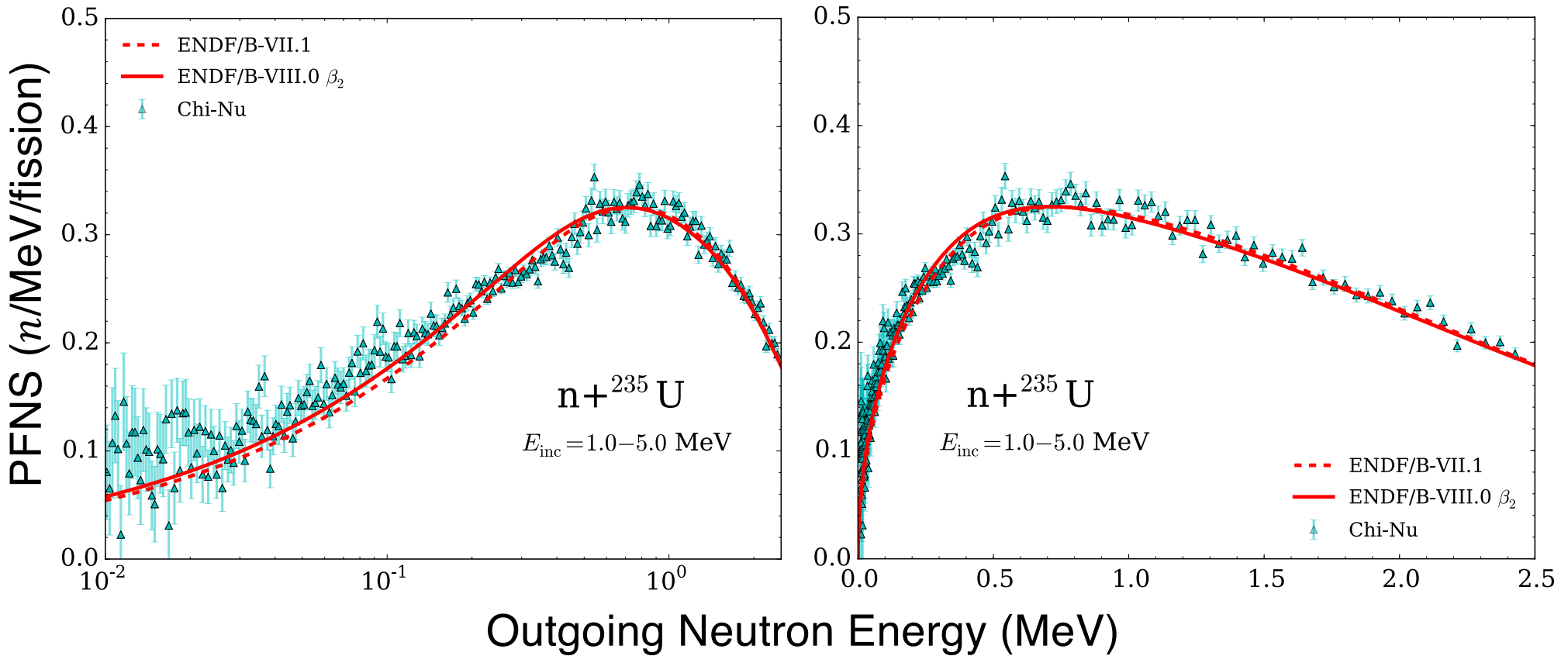
Collect Background as Data are Taken

Factor of 4 Improvement in use of Beam Time

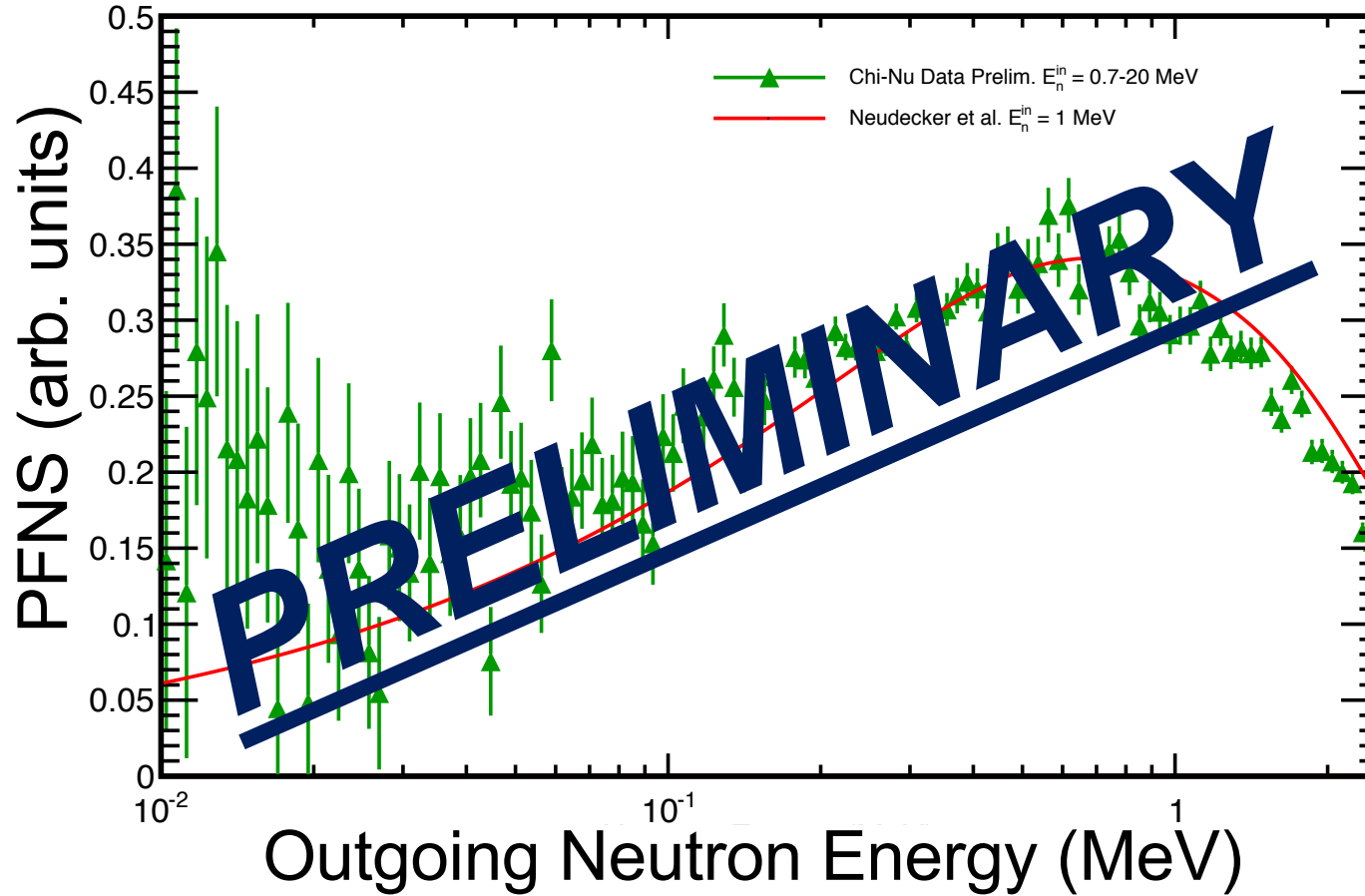


Preliminary Low-Energy ^{235}U Results

PRELIMINARY



Preliminary Low-Energy ^{239}Pu Results



Only 1 Week of Low-Energy Data

- High α -background rate is a serious problem
- Techniques have been developed to ensure that the highest precision result is obtained

Los Alamos National Laboratory

TPC and SPIDER

- **NIFFTE Time Projection Chamber**
 - ^{238}U fission cross section normalized at 14 MeV
 - ^{235}U fission fragment anisotropy $W(0^\circ) / W(90^\circ)$
- **Dual Frisch-gridded Ionization Chamber (TKE)**
 - $^{235, 238}\text{U}$
 - ^{239}Pu TKE and FP mass distribution
- **SPIDER 2v2E Mass Spectrometer**
 - ^{239}Pu FP mass distribution (thermal neutrons)
 - ^{235}U FP mass distribution (thermal neutrons)



NIFFTE Time Projection Chamber

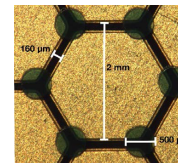
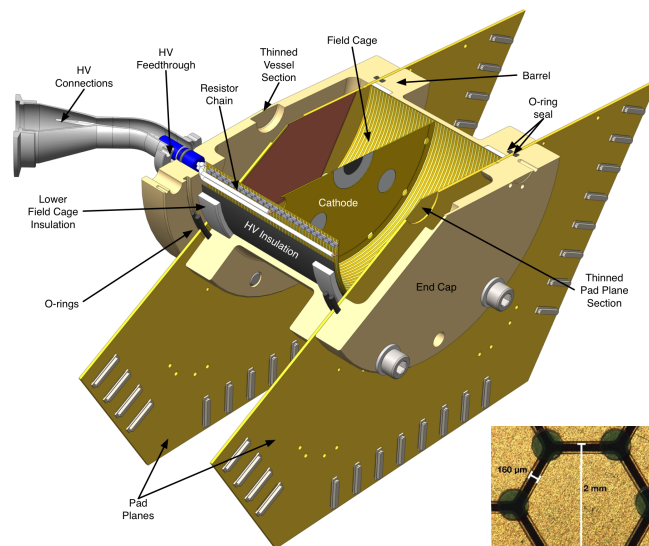
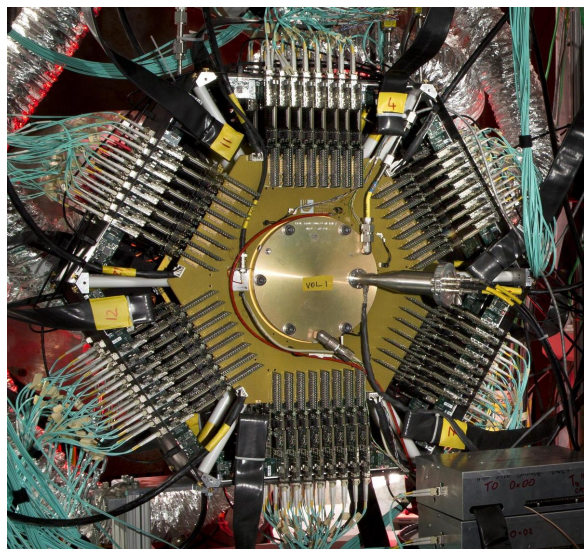
(Neutron-induced Fission Fragment Tracking Experiment)

NIFFTE fissionTPC – Time Projection Chamber

- Cross section datasets have uncertainties of 3-5% in the fast region
- Uncertainties of $\leq 1\%$ are needed for applications
- NIFFTE seeks to study sources of uncertainties effecting prior works

Sources of uncertainty

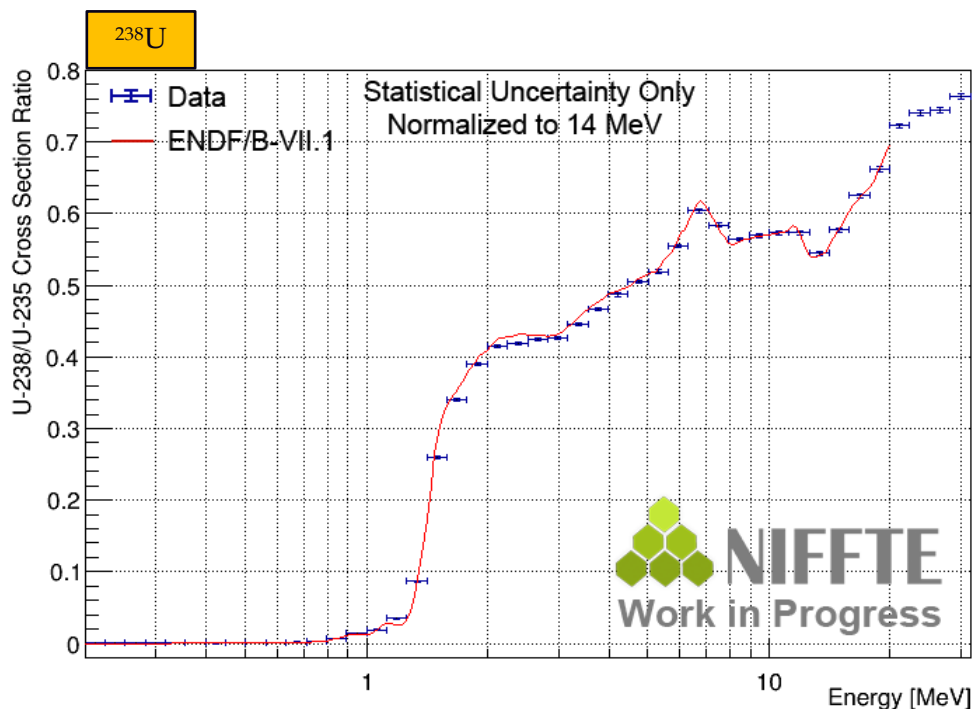
- Particle ID, alpha/fission fragment separation
- ^{235}U reference
- Energy loss in target
- Neutron beam profile
- Neutron beam energy-position correlations
- Beam spreading and attenuation
- Neutrons scattering back in (room return)
- Target contamination
- Non-uniform density (target and backing)
- Complete fragment loss (detector efficiency)



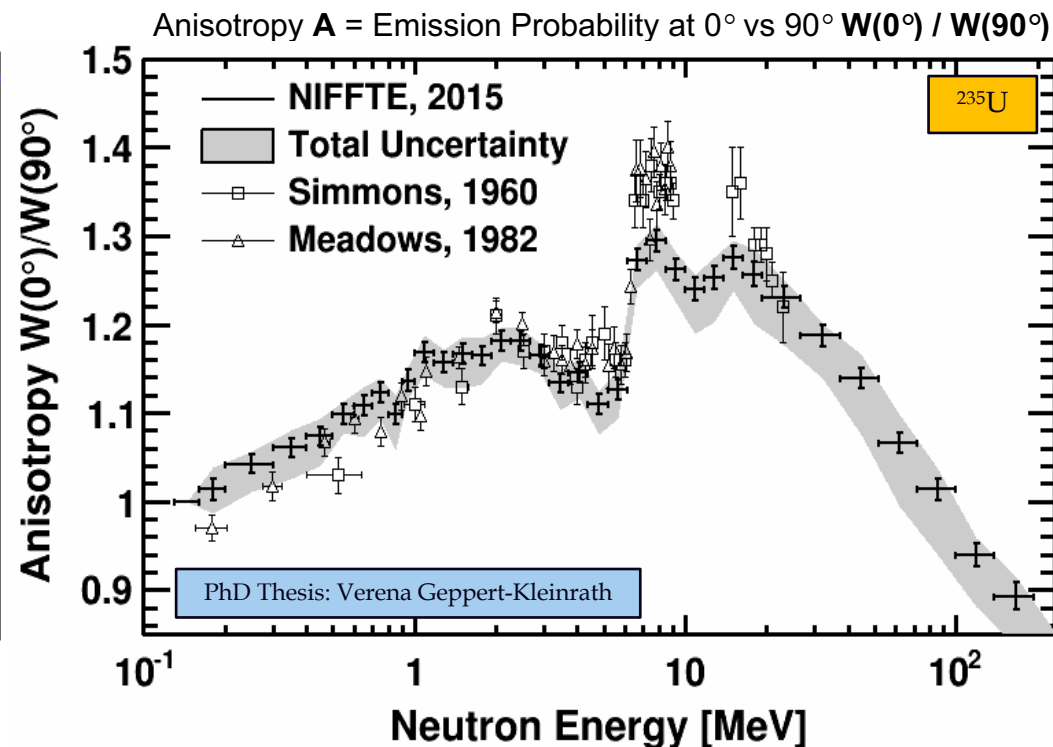
fissionTPC Features:

- Two-chamber design
- Compact, 4π Detector
- Particle tracking
- Segmented MicroMegas
- ~ 6000 independent channels

NIFFTE fissionTPC – Time Projection Chamber



• Analysis of ²³⁹Pu/²³⁵U cross section ratio in progress

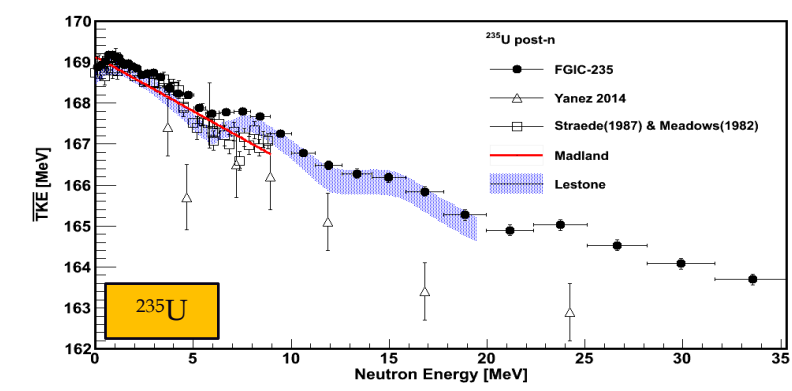
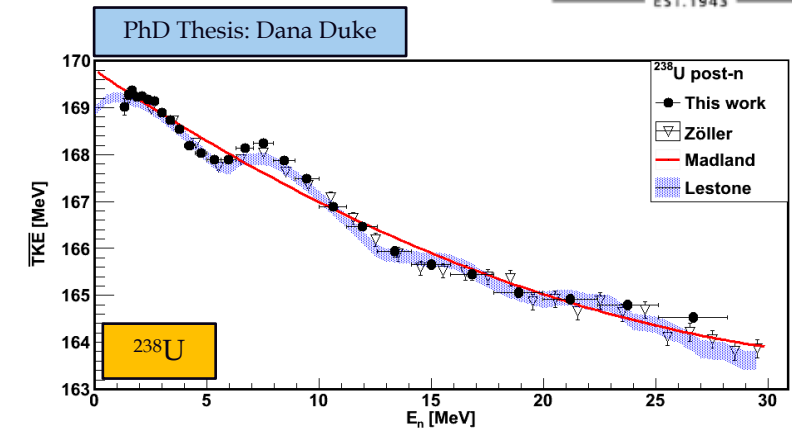
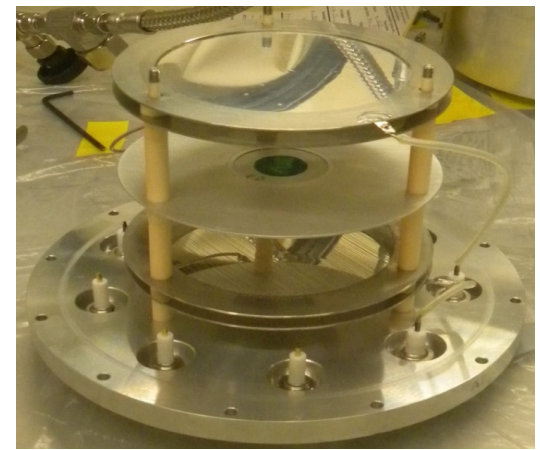
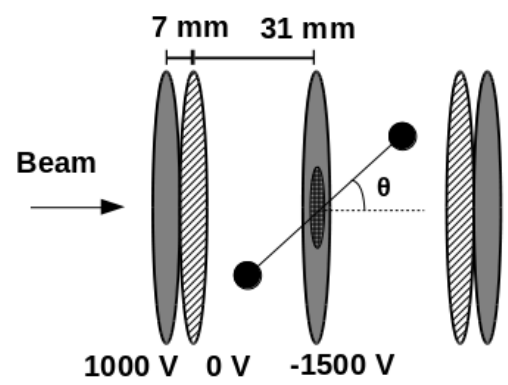


Dual Frisch-gridded Ionization Chamber

(TKE - Total Kinetic Energy)

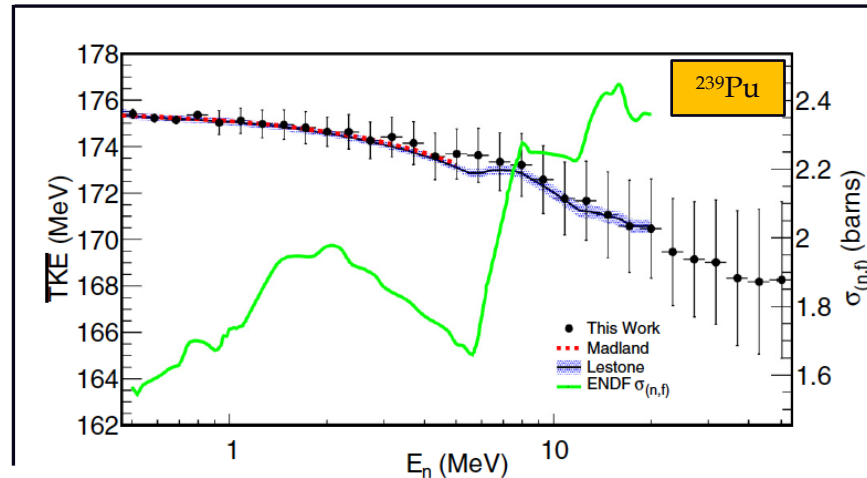
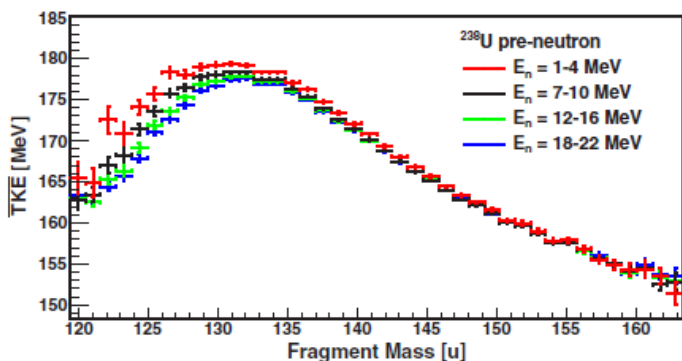
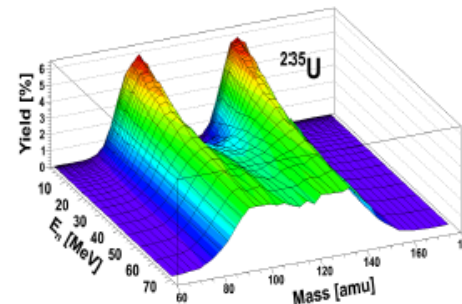
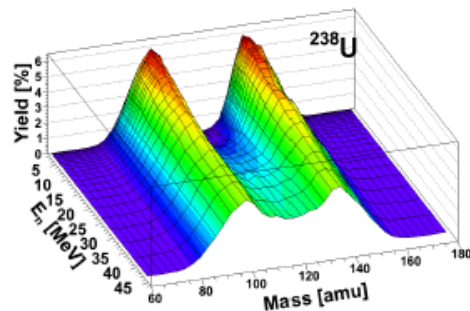
Dual Frisch-gridded Ionization Chamber

- TKE represents most of the energy released in fission
- A key observable to model and application communities
- Evolution of fission observables with increasing E_n
 - Benchmark for state-of-the-art fission models



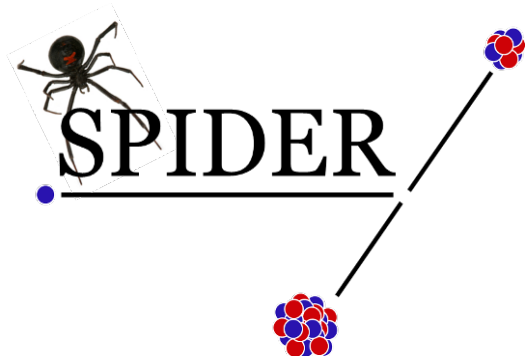
Dual Frisch-gridded Ionization Chamber Experiment

FPYs (E_n)
Resolution: 3-5 amu



Run Cycle 2016 Data

- ^{232}Th (collected)
- ^{233}U (in progress)
- ^{237}Np (planned)

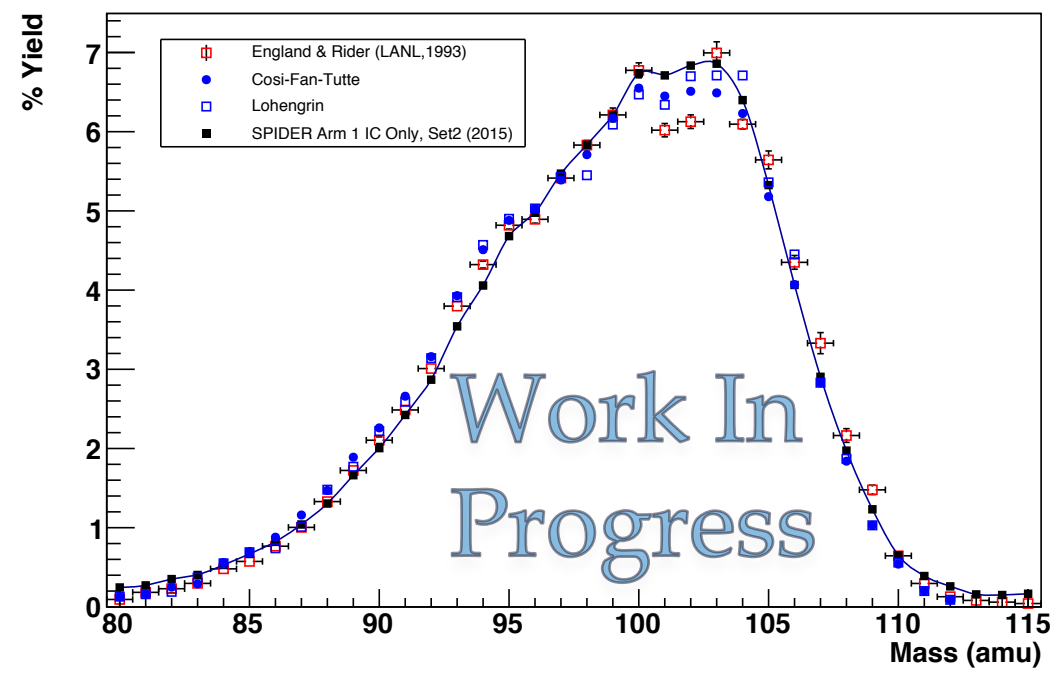


SPIDER – $2\nu 2E$ Mass Spectrometer

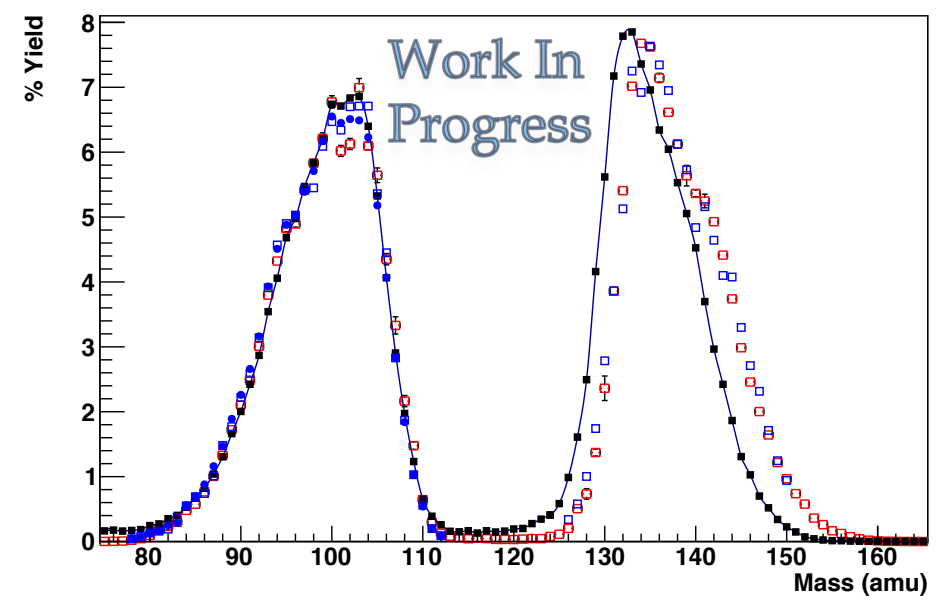
(Spectrometer for Ion Determination In Fission Research)

SPIDER Results: ^{239}Pu Thermal Fission ($1\nu1E$)

Pu239t Fission Product Yield

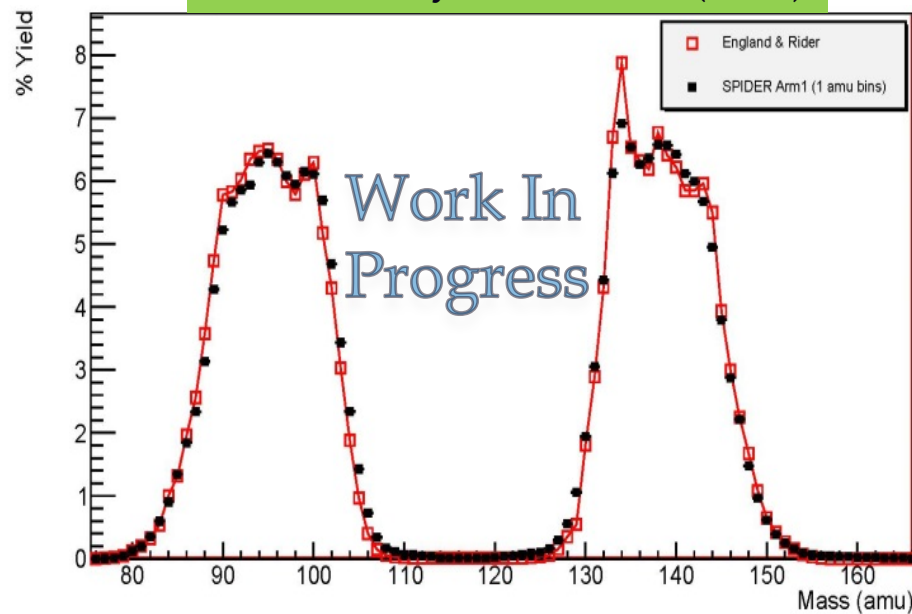


Pu239t Fission Product Yield

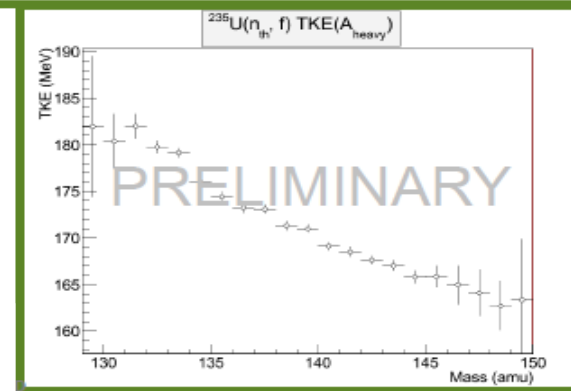
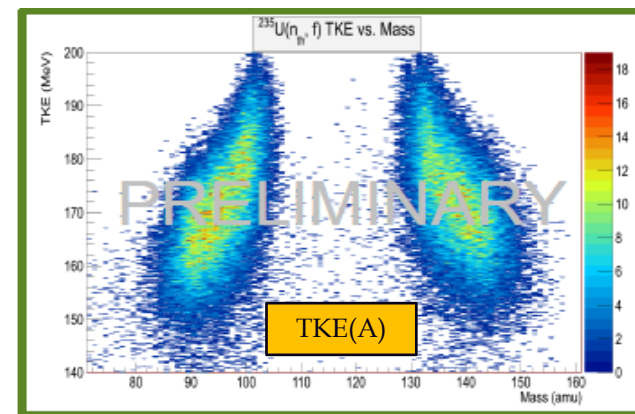


SPIDER Results: ^{235}U Thermal Fission ($2\nu 2E$)

Data Courtesy of D. Shields (CSM)



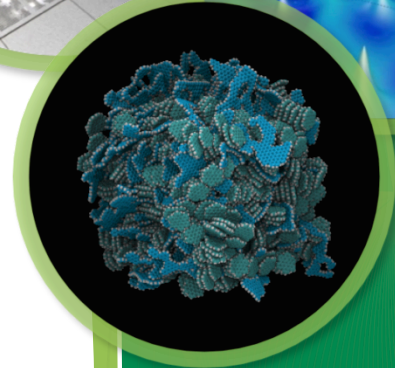
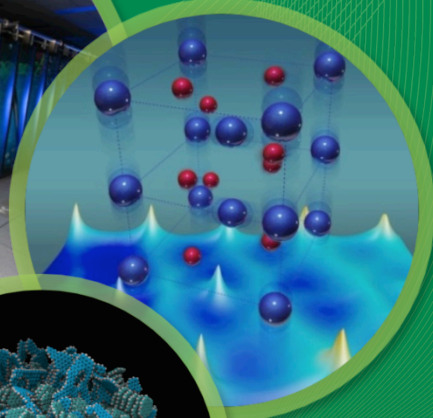
- ^{235}U FPY distribution exhibits pronounced features
- Preliminary data, but demonstrates high-resolution



Oak Ridge National Laboratory

- **Resonance Region Measurements at GELINA**
 - **Ce** - Measurements of Ce using natural metallic samples
 - Transmission experiments with different sample thickness are scheduled using FP4, 50 m
 - Neutron capture using detector system at FP14, 60 m
 - **^{51}V** - Measurements using metallic samples of different thickness
 - Neutron Transmission experiments at FP4, 50 m
 - Neutron capture at FP14, 60 m

ORNL NEUTRON CROSS SECTION MEASUREMENTS FOR NCSP



K. Guber, I. Gauld, C. Celik

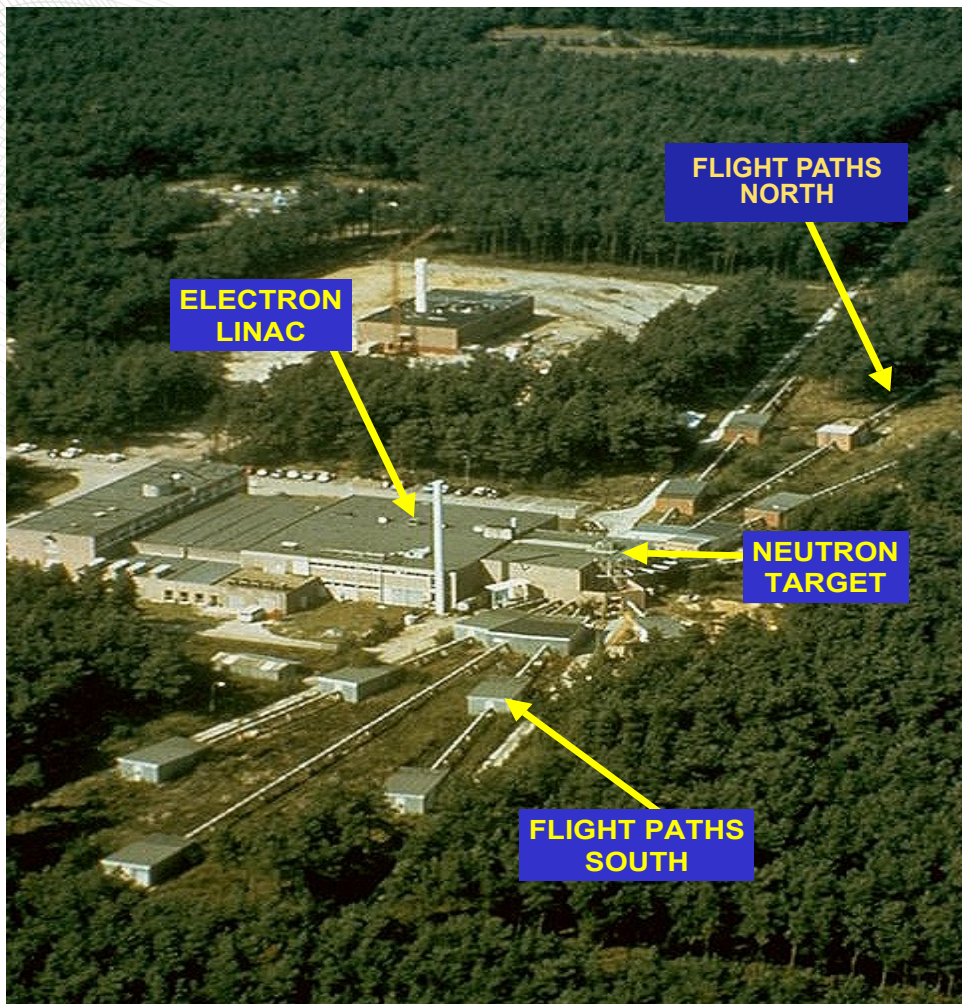
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Y. Danon, G. Leinweber

Rensselaer Polytechnic Institute, Troy, NY, 12180, USA

C. Paradela, S. Kopecky, J. Heyse,
P. Schillebeeckx, and P. Siegler

Nuclear Physics Unit, EC-JRC Geel, Retieseweg 111,
2440 Geel, Belgium



GELINA

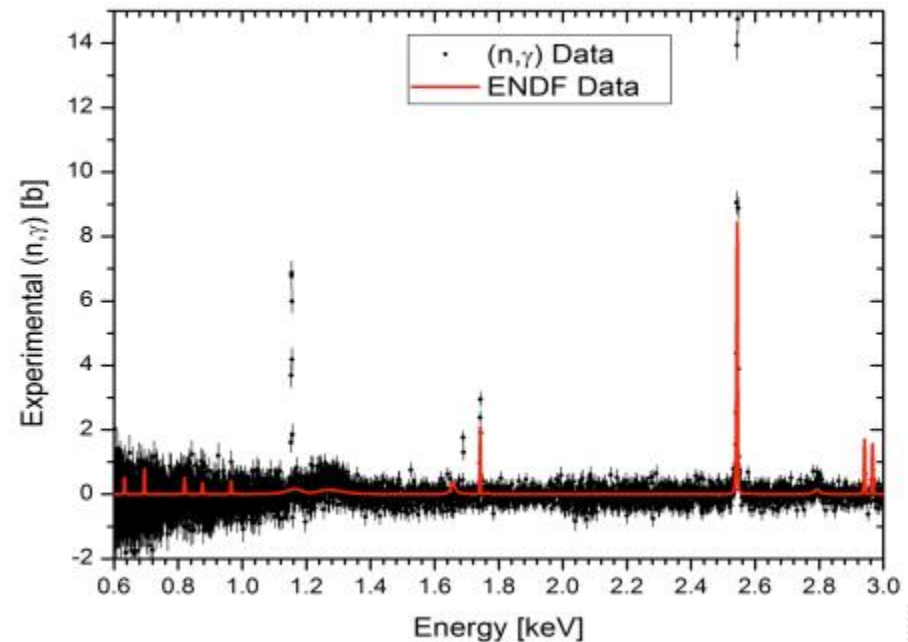
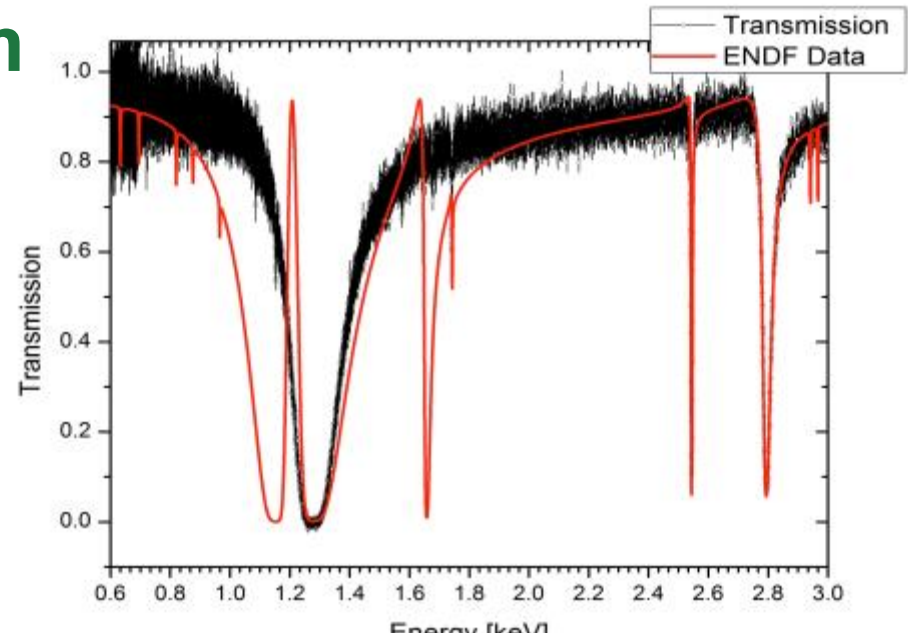


- **Time-of-flight facility**
- **Pulsed white neutron source**
($10 \text{ meV} < E_n < 20 \text{ MeV}$)
- **Multi-user facility with 10 flight paths (10 m - 400 m)**
- **The measurement stations have special equipment to perform:**
 - Total cross section measurements
 - Partial cross section measurements

Pulse Width : 1ns
 Frequency : 40 Hz – 800 Hz
 Average Current : $4.7 \mu\text{A} - 75 \mu\text{A}$
 Neutron intensity : $1.6 \cdot 10^{12} - 2.5 \cdot 10^{13} \text{ n/s}$

Observations For Cerium

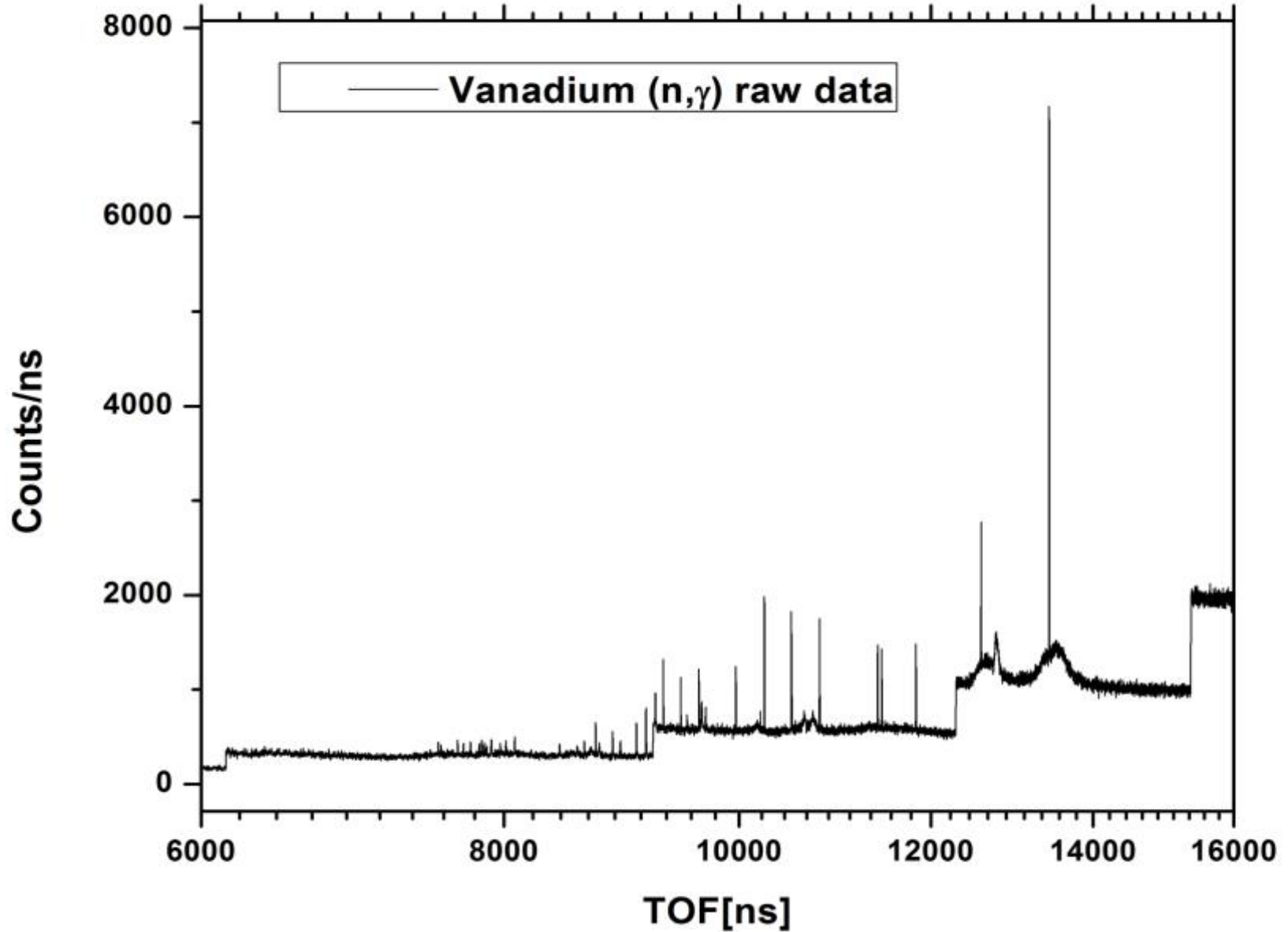
- ENDF/B-VII shows for the (n,γ) and (n,tot) data serious discrepancies compared to our data and literature.
- Resonances are misassigned or missing.
- Investigation indicate that after the reevaluation of WPEC SG23 (fission products) those wrongly assigned resonances made it into ENDF/B VII.1
- Sometimes a reevaluation without new data and consulting the literature does not seem to be a good idea.



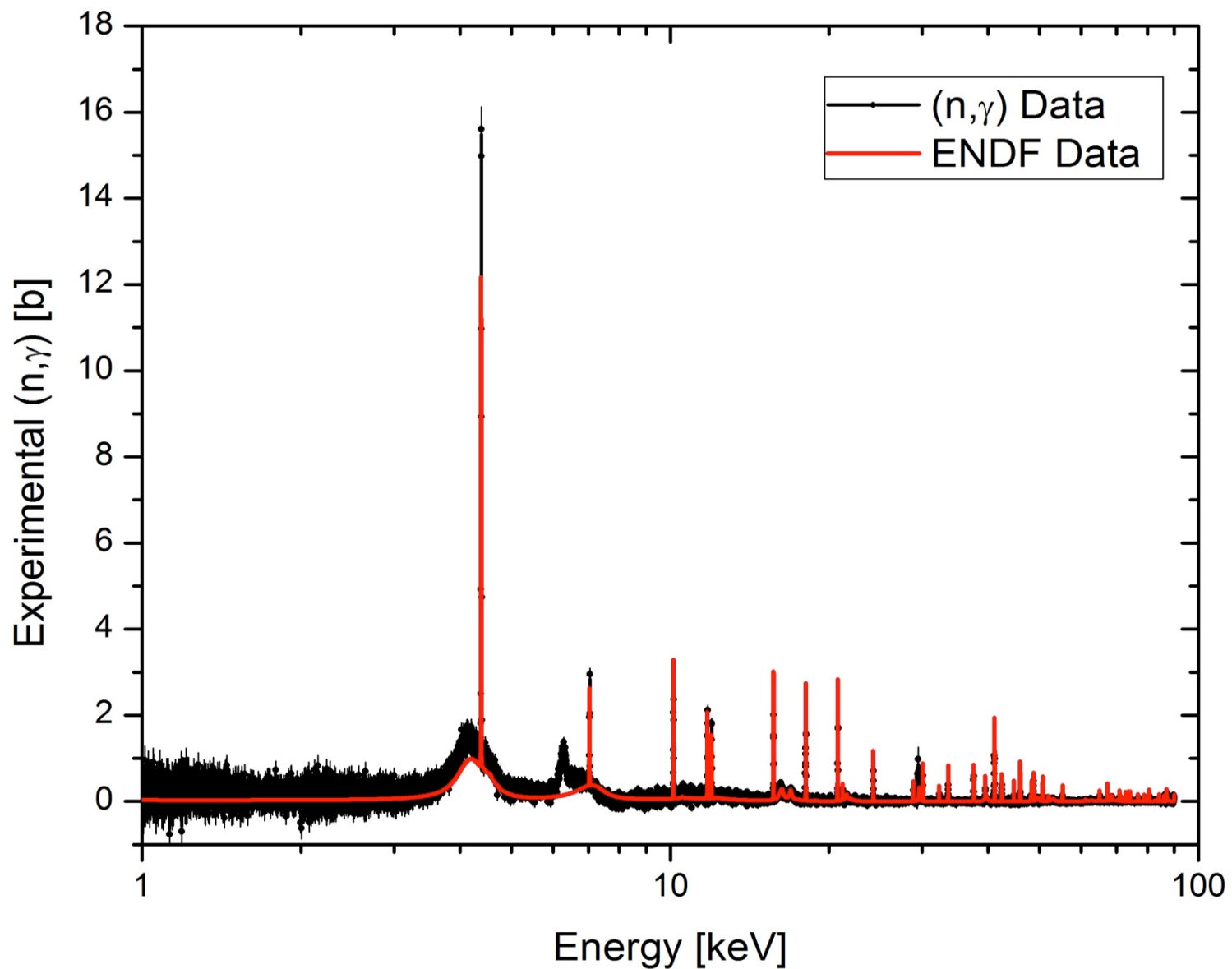
ORNL Measurement Activities for Vanadium

- ^{51}V 99.75% natural abundance. V is 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 at FP14, 60 m.
- Experiments performed with different background filter combinations.
- Capture and transmission experiments performed in 2015/2016. Need to be finalize.

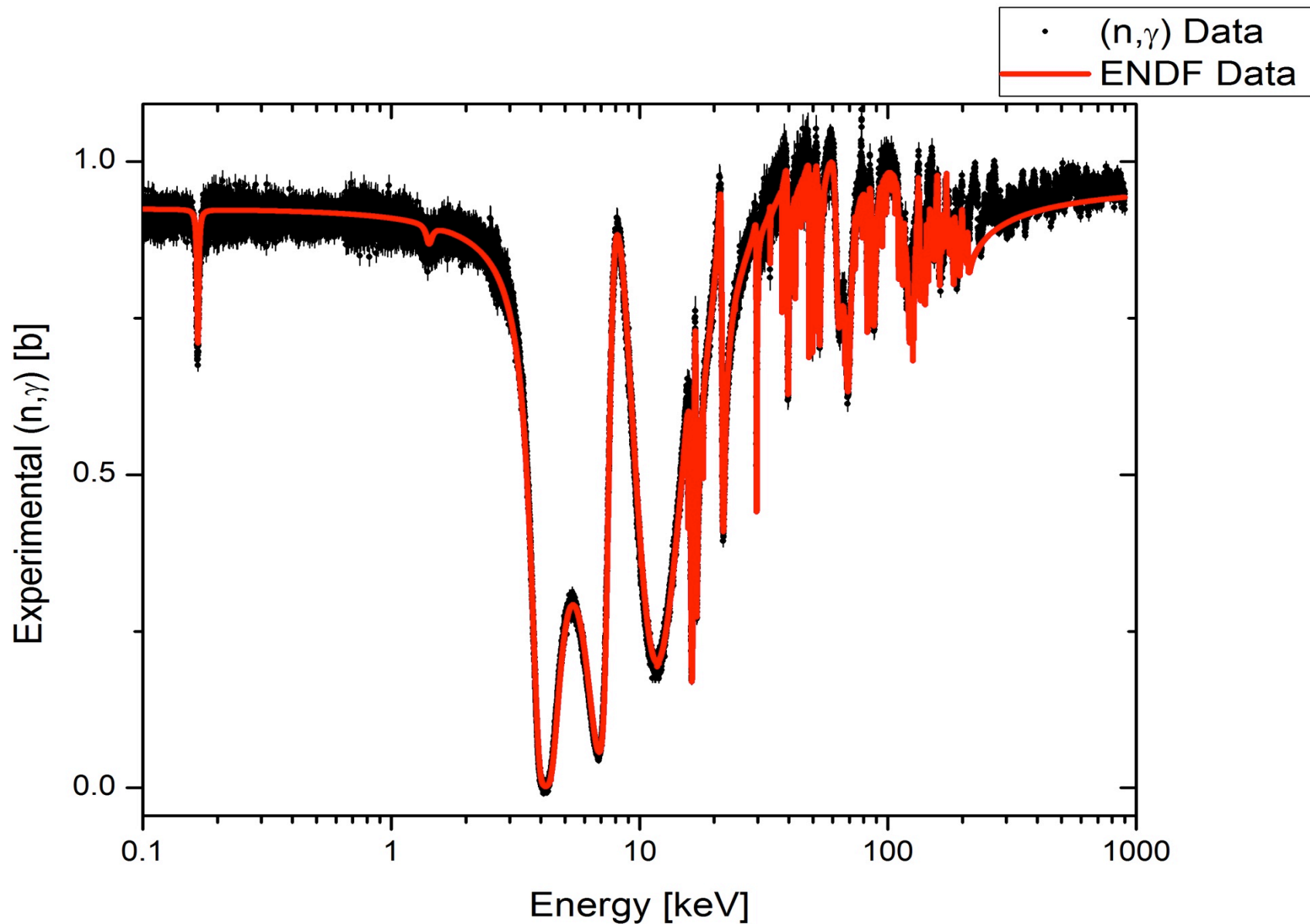
V (n,γ) Raw Data for Thin Sample



(n,γ) of 0.35mm Vanadium sample

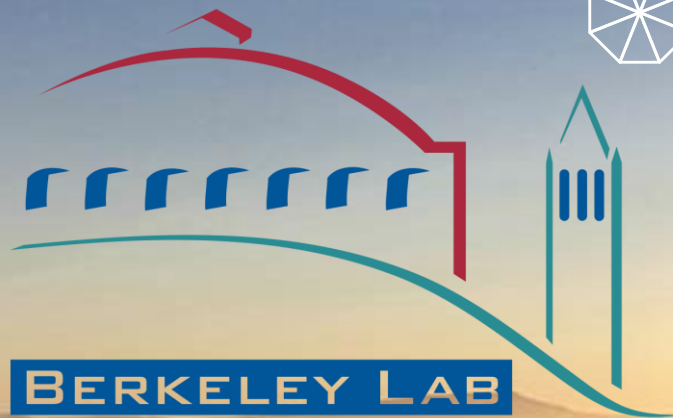


Transmission of 2mm Vanadium sample



Experimental Activities in Berkeley (LBL)

- **^{64}Cu and ^{47}Sc (n,p) Cross-Section for medical applications (2.54 MeV neutrons)**
- **Improvement of Fe (p,p γ) level scheme**



Experimental Activities in Berkeley

Andrew S. Voyles

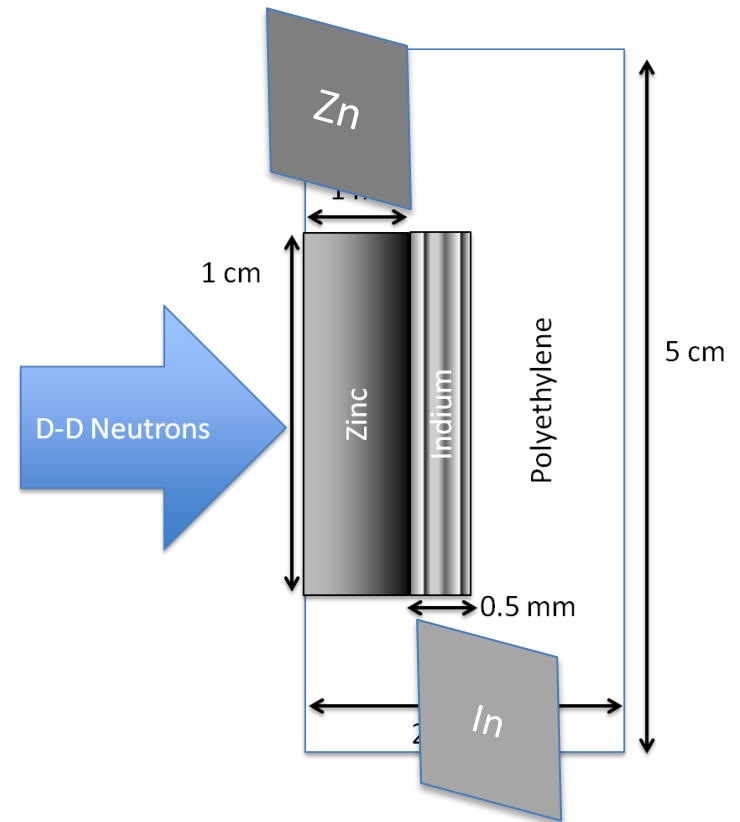
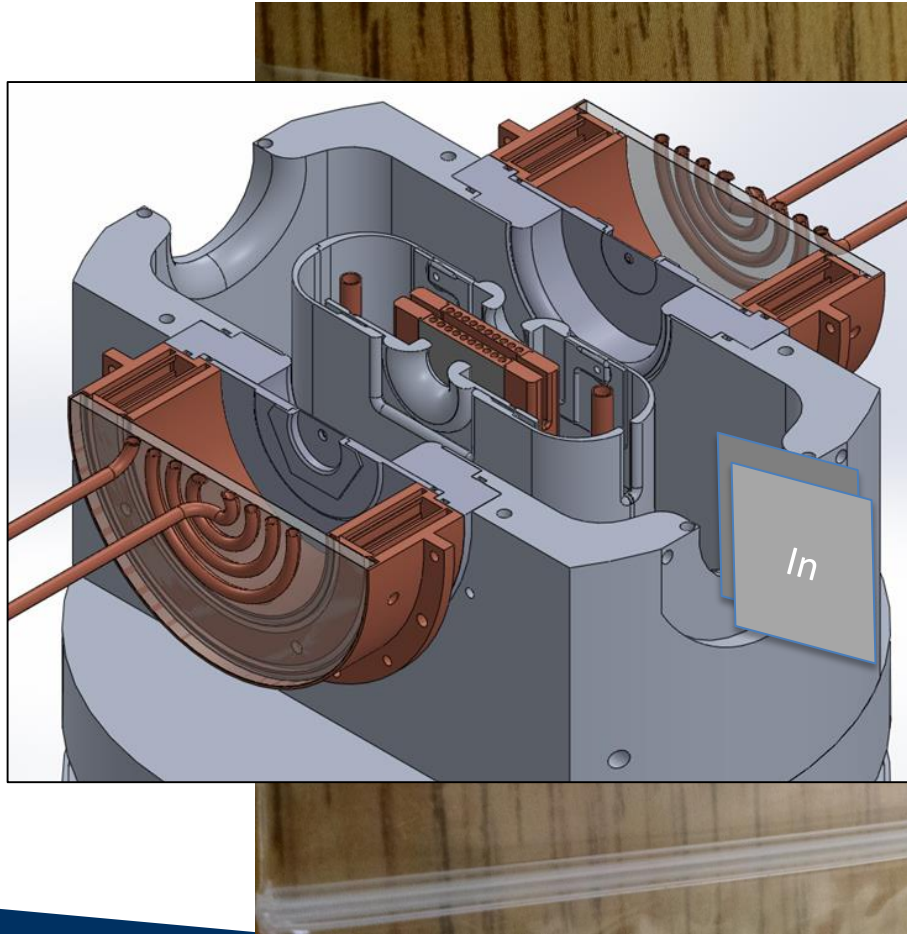
14 November 2016

Nuclear Data Week 2016 - CSEWG

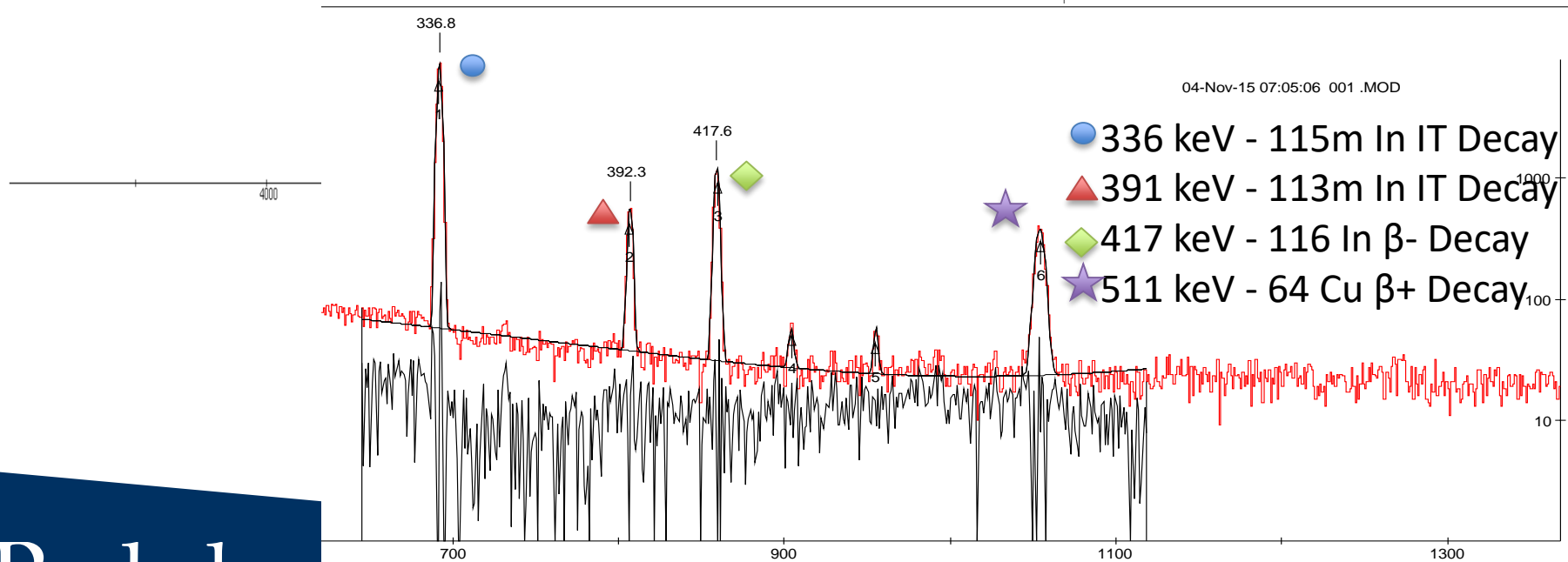
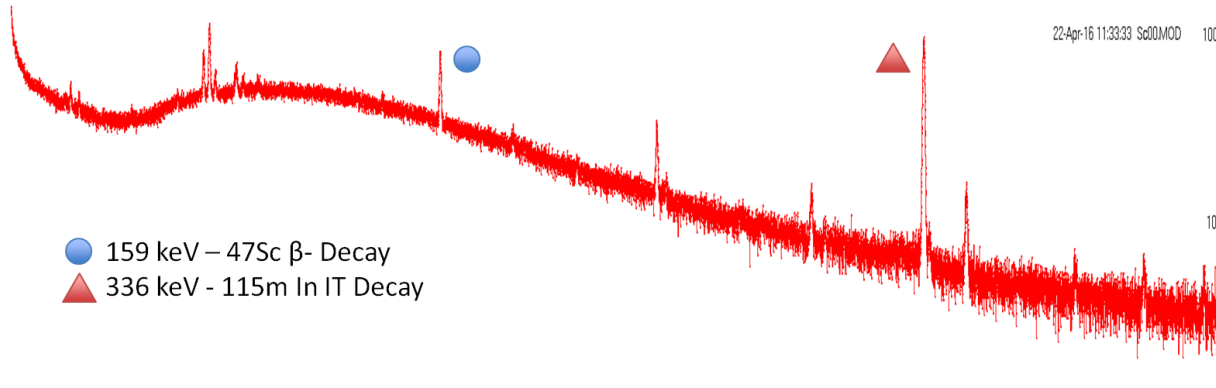
^{64}Cu and ^{47}Sc (n,p) Cross-Section Measurements for Medical Radionuclide Production

UCB

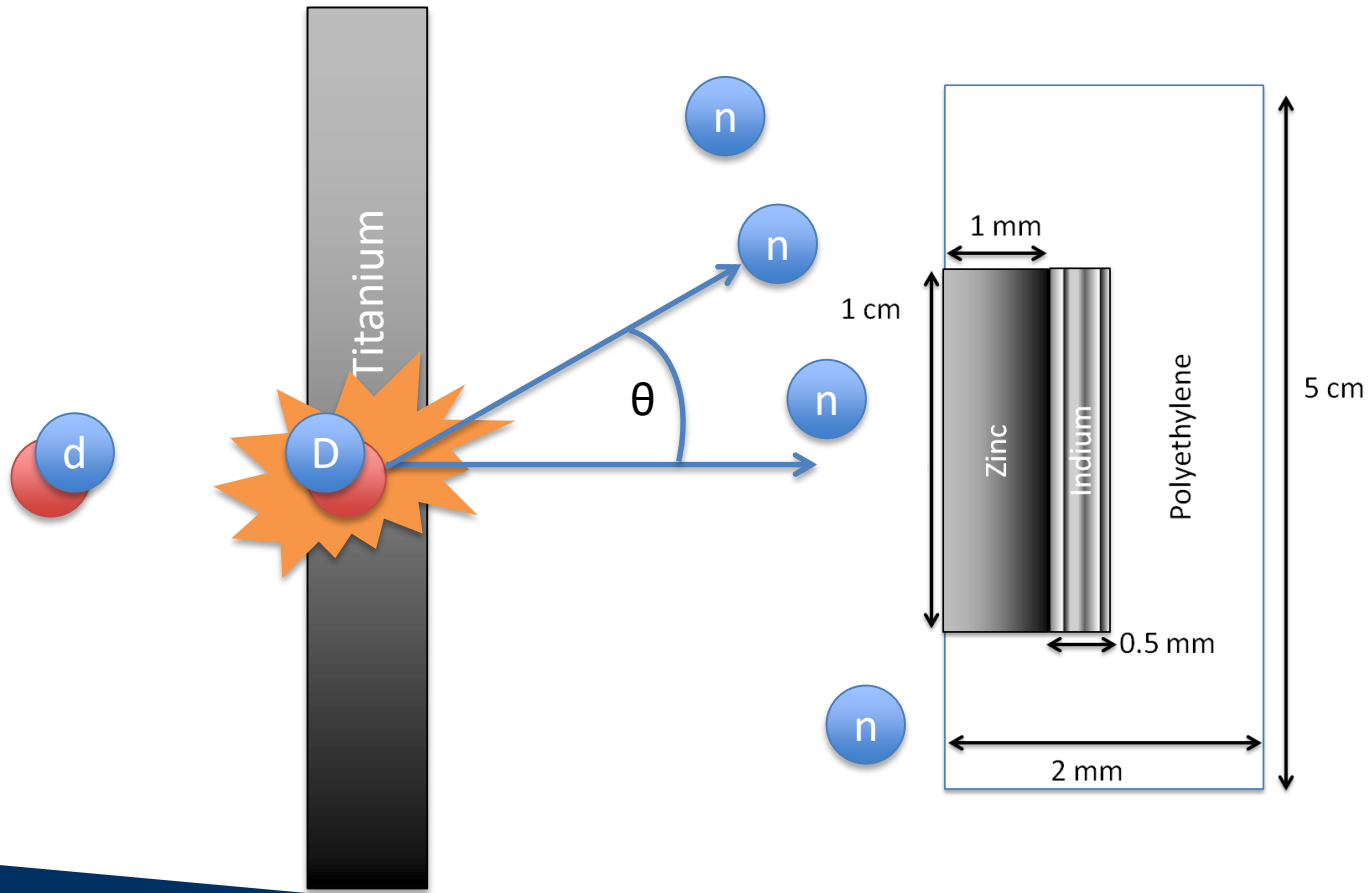
The UC Berkeley High Flux Neutron Generator



Relative Activation Measurements



Neutron Energy Spread



Neutron Energy Spread

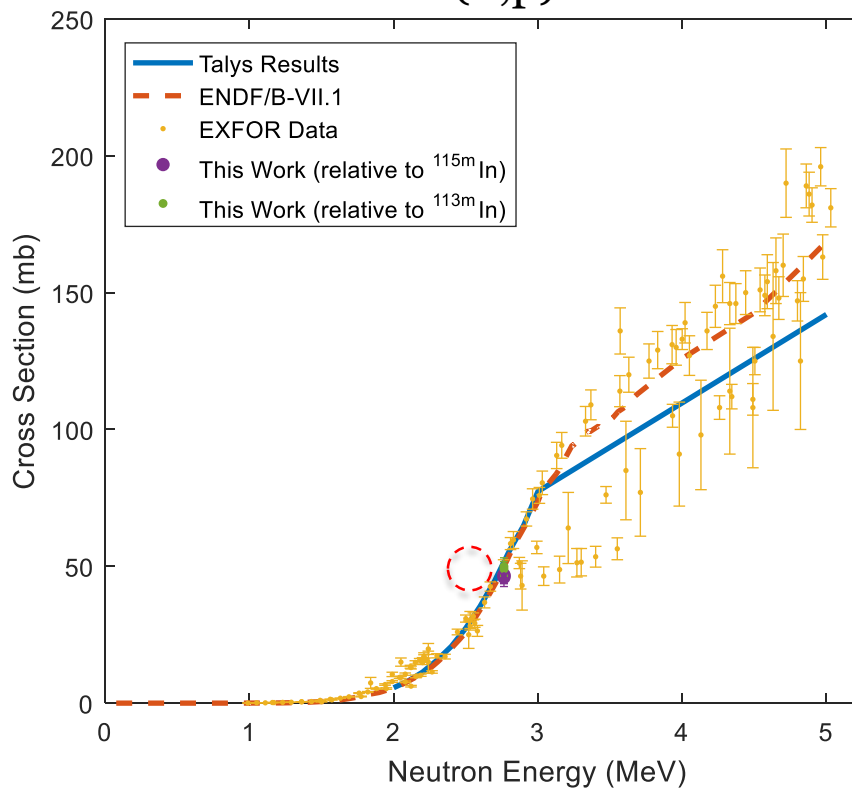
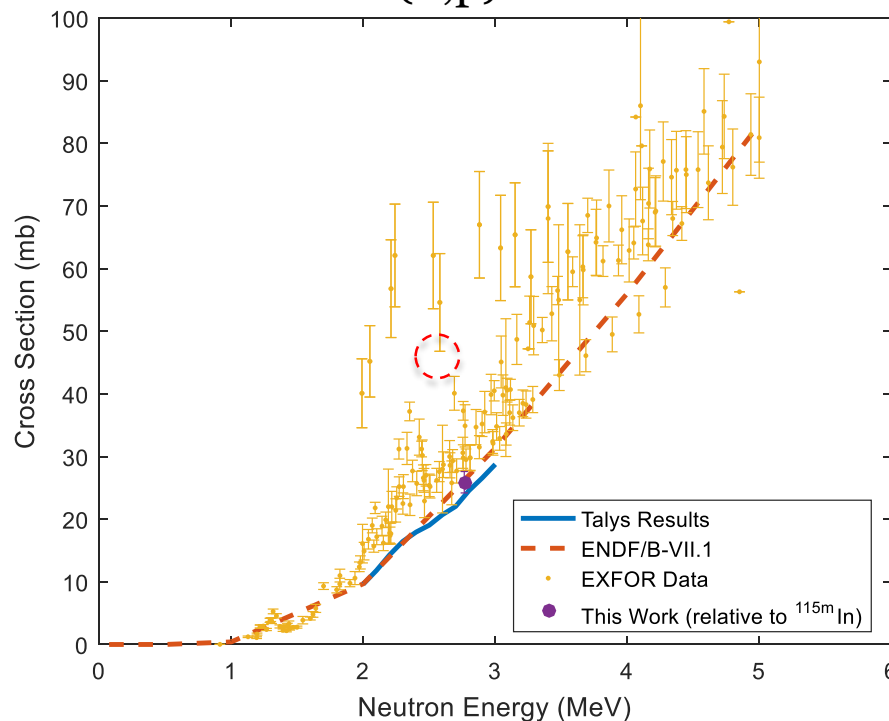


Table 3. Results of cross section measurement.

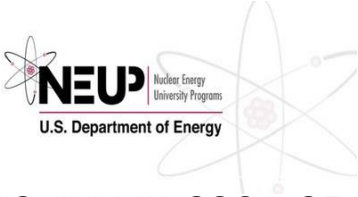
Reaction	$\sigma(E_n = 2.7645 \text{ MeV})$ (mb)
$^{64}\text{Zn}(n,p)^{64}\text{Cu}$ (relative to ^{113}In)	$45.953 \pm 3.351,$ $46.493 \pm 2.805,$ 46.9 ± 3.189
$^{64}\text{Zn}(n,p)^{64}\text{Cu}$ (relative to ^{115}In)	$49.716 \pm 3.335,$ $49.011 \pm 2.698,$
$^{47}\text{Ti}(n,p)^{47}\text{Sc}$ (relative to ^{115}In)	$25.901 \pm 1.7089,$

After!



Recent Measurements on Carbon and Iron at the University of Kentucky

- Fe-56 (n,n₀), (n,n₁) angular distributions
- Fe-54 (n,n₀)
- ¹²C (n,n₁) cross section



NU12-KY-UK-0201-05

- the Univ Kentucky Accelerator Lab
- Measurement Techniques
- Status of Current Projects: ^{54}Fe , ^{12}C , ^{28}Si , ^{18}O , ^{24}Mg , ^7Li , ^2H
- Examples
 - ^{54}Fe requires OMP surface absorption rather than volume
 - Can γ -ray excitation functions be converted to cross sections?
 - ^{56}Fe γ -ray spectroscopic information & level cross sections
 - Student tests of PMT-DAQ system stability
 - Student $^{12}\text{C}(n,n_1)$ results
- Summary



Tungsten wedge

$3\text{H}(p,n)$ $Q = -0.76$ MeV

$2\text{H}(d,n)$ $Q = 3.3$ MeV

$3\text{H}(d,n)$ $Q = 17.6$ MeV

Neutron detector

Beam line

Gas cell

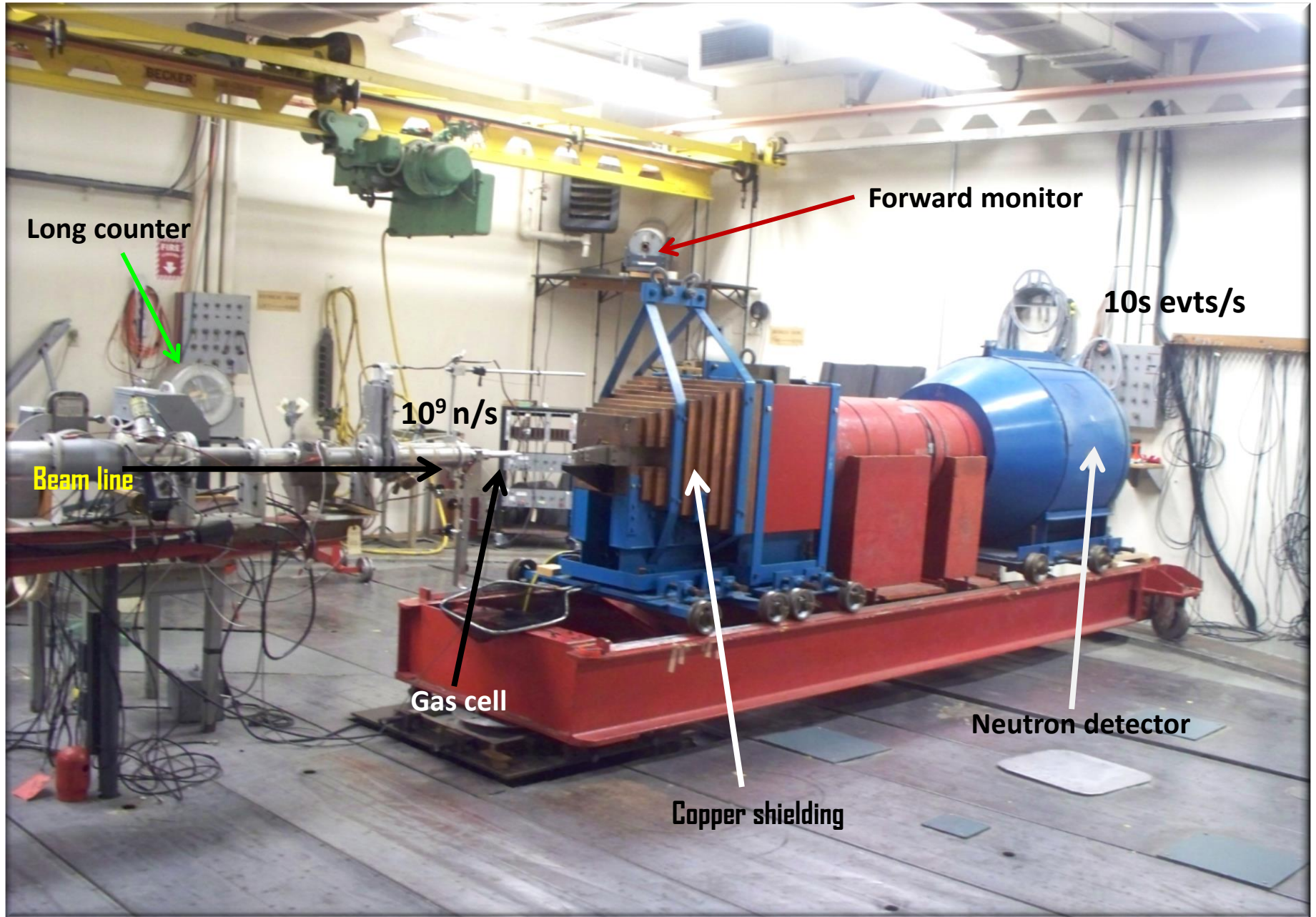
Na sample

Typical adjustment of wedge with cell and sample

1 - 4.5 MeV with pT,

4.5 - 9 MeV dD,

15 - 20 MeV dT



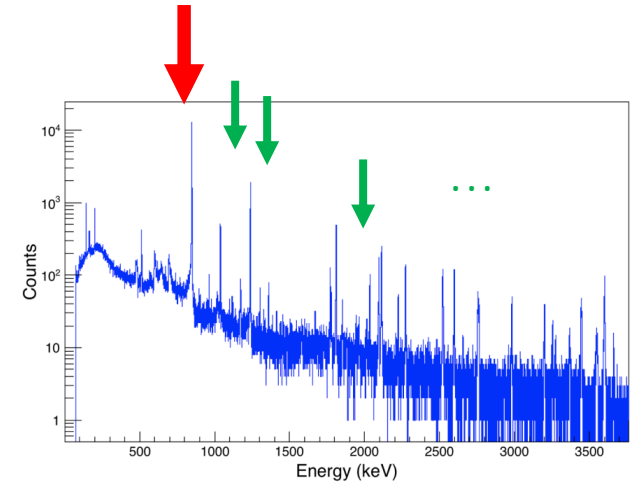
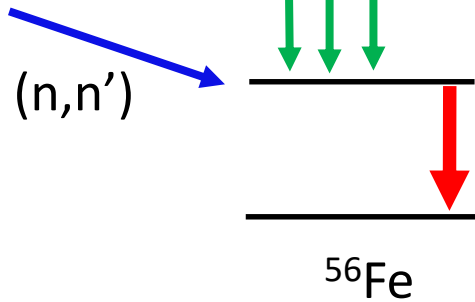
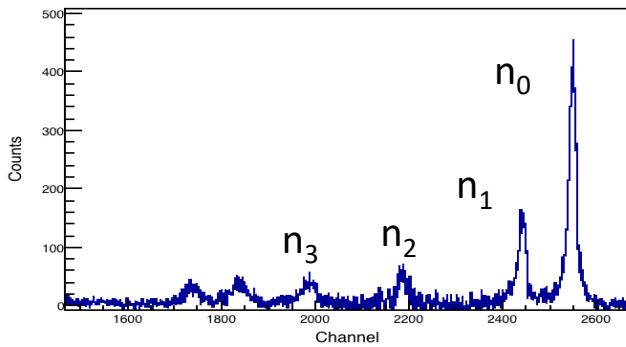
(n,n') TOF Setup



BGO Compton Shield

(n,n'γ) TOF Setup

TYPES OF MEASUREMENTS



(n,n') Angular Distributions

-- measure $\text{yield}_n(\theta)$ at fixed E_n

Advantages:

- Single incident neutron energy
- Obtain reaction mechanism details
- Fit to Leg polyn to get XS
- No 'feeding' issues
- Obtain reaction mechanism details

Disadvantages:

- Poor final level resolution
- 3-4 days per incident energy

(n,n'\gamma) Angular Distributions

-- measure $\text{yield}_\gamma(\theta)$ at fixed E_n

Advantages:

- Single incident neutron energy
- Obtain structure information J^π , br, δ , τ , B(XL)
- Excellent energy level resolution
- Short measurement times per energy.

Disadvantages:

- 3 days per incident energy

(n,n'\gamma) Excitation Functions

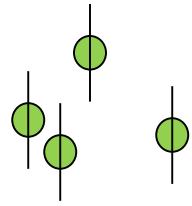
-- measure $\text{yield}_\gamma(E_n)$ at fixed θ

Advantages:

- Single incident neutron energy
- 4 days for 1 to 5 MeV range.
- Feeding is known & easy to subtract.
- Excellent energy level resolution
- 4-5 days for 1 to 5 MeV.

Disadvantages:

- Requires a_4P_4 small ←
- ΔE_n step ~ 100 keV.



Uncertainties



Issue	
Counting Statistics n_0, n_1	<1%
Ability to Extract Yield from Peaks in Spectra (elas)	~1-2% usually
Ability to Extract Yield from Peaks in Spectra (inel)	...hum
Monitoring Neutron Production	<1%
Sample Mass	<<1%
H(n,n) reference XS	<0.5%
Detector Efficiency	
$^3\text{H}(p,n) \ d\sigma/d\Omega$	~3%

Issue	
Atten & Mult Scat	
$n\sigma$	0.3 %
sample radius	0.3 %
sample-Tcell dist	0.2 %
method	<5%

Overall during ^{23}Na runs: elastics ~8-10%
 inelastics ~13-18%

Overall during ^{54}Fe runs: elastics ~7-10%
 inelastics ~10%

Measurement Status

Measurements	Status
$^{54}\text{Fe}(n,n)$	<ol style="list-style-type: none"> 1. Final XS values sent to S.H. 2. Paper to NPA in <31 Dec 3. Angular distributions indicate OMP Absorption strongly focused at surface, very weak volume component
$^{56}\text{Fe}(n,n)$	<ol style="list-style-type: none"> 1. Final XS values sent to S. H. (well, in the next couple days) 2. Paper sent to PRC (well, in the next couple days) 3. Two Additional $^{56}(n,n_k)$ @ 6.5-8.5 MeV
$^{54,56,\text{nat}}\text{Fe}(n,n'\gamma)$	<ol style="list-style-type: none"> 1. Preliminary XS values sent to S.H. 2. Angular distributions & DSAM lifetimes measured
$^{12}\text{C}(n,n)$	<ol style="list-style-type: none"> 1. Have many quick measurements of ELAS ang distrib (2009-2015) 2. Initial Measurements of (n,n_1) @ 5.7 – 6.3 MeV support ENDF values 3. Repeating 2-5 MeV elastic ang distrib with longer runs
$^{12}\text{C}(n,n'\gamma)$	<ol style="list-style-type: none"> 1. Measuring γ-ray ang distributions above n_1 threshold to obtain inelastic cross sections (Nov2016: 5.6-7.2MeV)

Measurement Status

Measurements	Status
$^{18}\text{O}(n,n)$ & $(n,n'\gamma)$	<ol style="list-style-type: none"> 1. Have some older data with slightly uncertain conditions. 2. (n,n) @ 6.0, 8.5, 9.3 MeV 3. γ-ray peaks significantly Doppler broadened, new analysis technique under development. <p>2. Plan to take additional data.</p>
$^{28}\text{Si}(n,n)$ & $(n,n'\gamma)$	<ol style="list-style-type: none"> 1. Enriched ^{28}Si not available from Isotope Sales (nat is 92%) 2. Measurements starting January 2017, we hope.
$^{24}\text{Mg}(n,n)$ & $(n,n'\gamma)$	<ol style="list-style-type: none"> 1. 4 gm of enriched metal available for \$9250 <i>large deformation</i>
$^7\text{Li}(n,n)$ & $(n,n'\gamma)$	<ol style="list-style-type: none"> 1. Can we measure and extract n_0 & n_1 ? <i>Marcus Nyman GELINA in PRC 93, 2016</i>
$^2\text{H}(n,n)$	<ol style="list-style-type: none"> 1. Have 1+ gm deuterated poly 2. Forward-backward asymmetry in ang distrib is desired

PRELIMINARY RESULTS
not appropriate for public consumption

EXAMPLES

54,56Fe XS show significant jitter <4 MeV

54: btw 2-3 MeV $\langle\sigma\rangle=3.4$ b jitter=0.6 b rms

btw 3-8 MeV $\langle\sigma\rangle=3.6$ b jitter=0.2 b rms

OM treatments can at most hit the average behavior

54 & 56 RESULTS:

good agreement with previous measurements to the extent it's possible to compare

$^{56}\text{Fe}(n, n_0)$

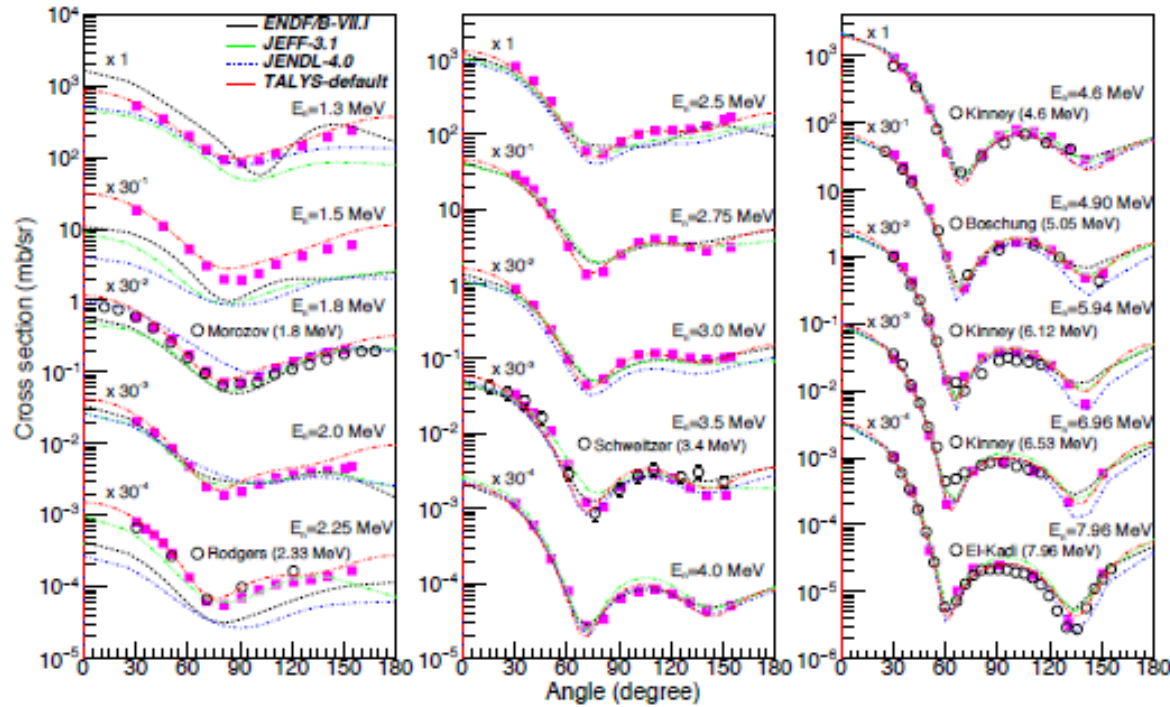


FIG. 3. New experimental neutron elastic scattering differential cross sections for ^{56}Fe (solid points) compared with previously reported data (open points), predictions from evaluation databases (curves) from ENDF/B-VII.1 (black), JEFF-3.1 (green) and JEND-4.0 (blue), and theoretical calculations from TALYS (red).

Results follow

ENDF

JEFF

TALYS-default

nicely

by Anthony Ramirez

PRELIMINARY RESULTS
not appropriate for public consumption

$^{56}\text{Fe}(n, n_1)$

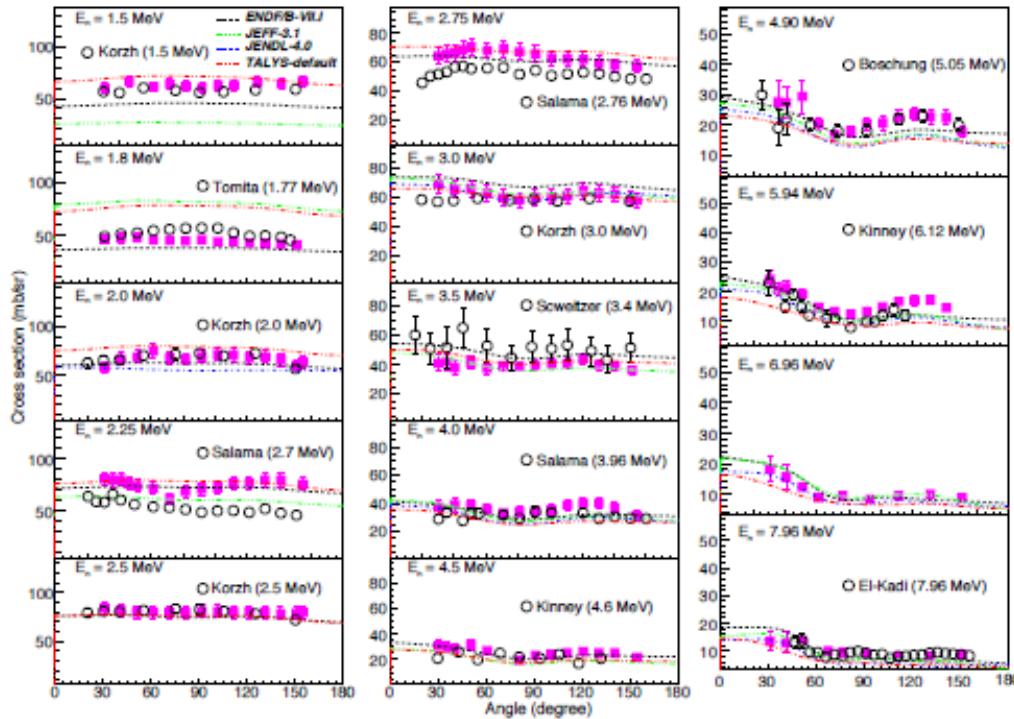


FIG. 4. New experimental neutron differential cross sections for ^{56}Fe for the inelastic scattering populating the 847-keV level. See the caption of Fig. 3 for further details.

by Anthony Ramirez

Flat at low energies

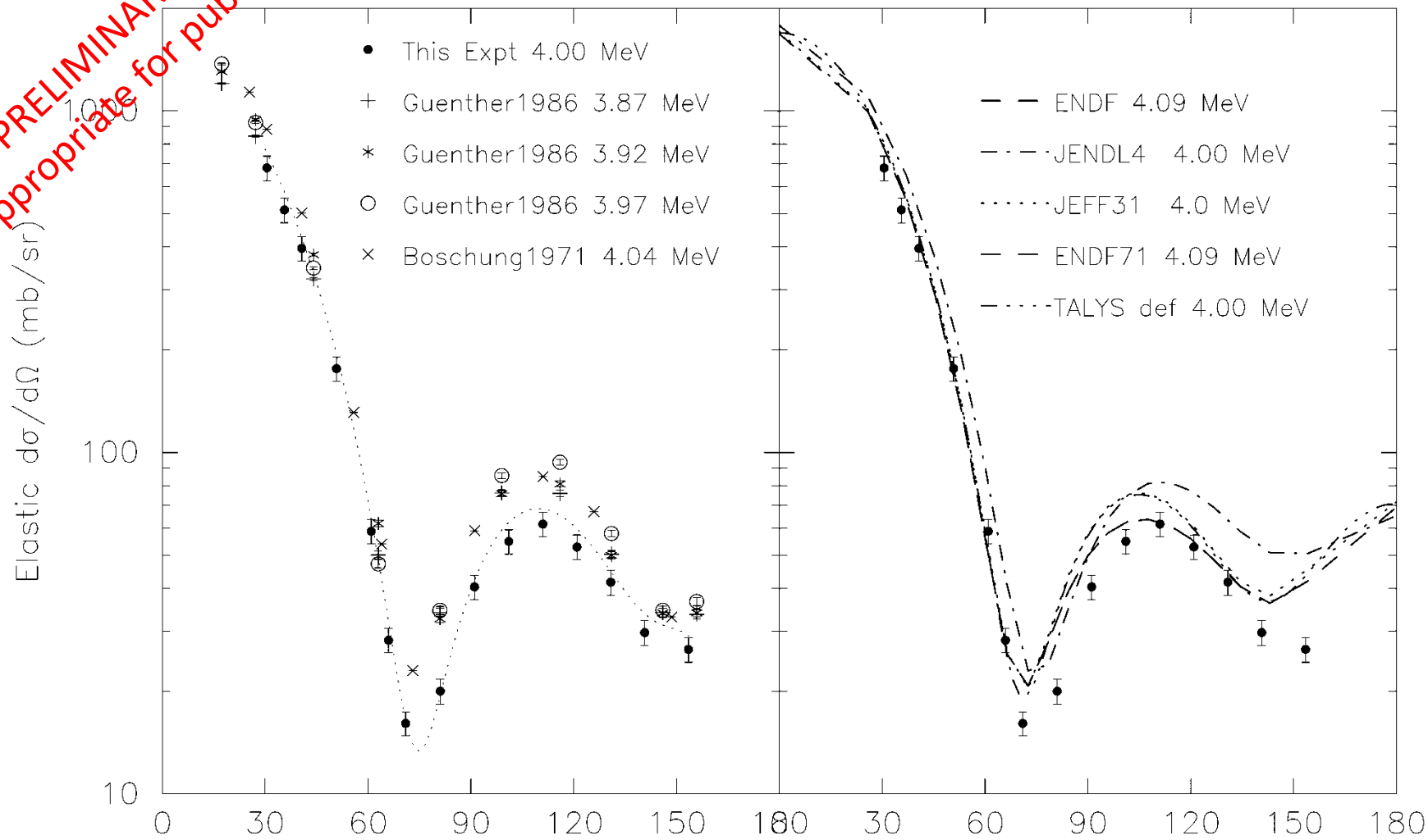
→ n_0 n_1 separation working well

Direct coupling turns on >5 MeV

PRELIMINARY RESULTS
not appropriate for public consumption

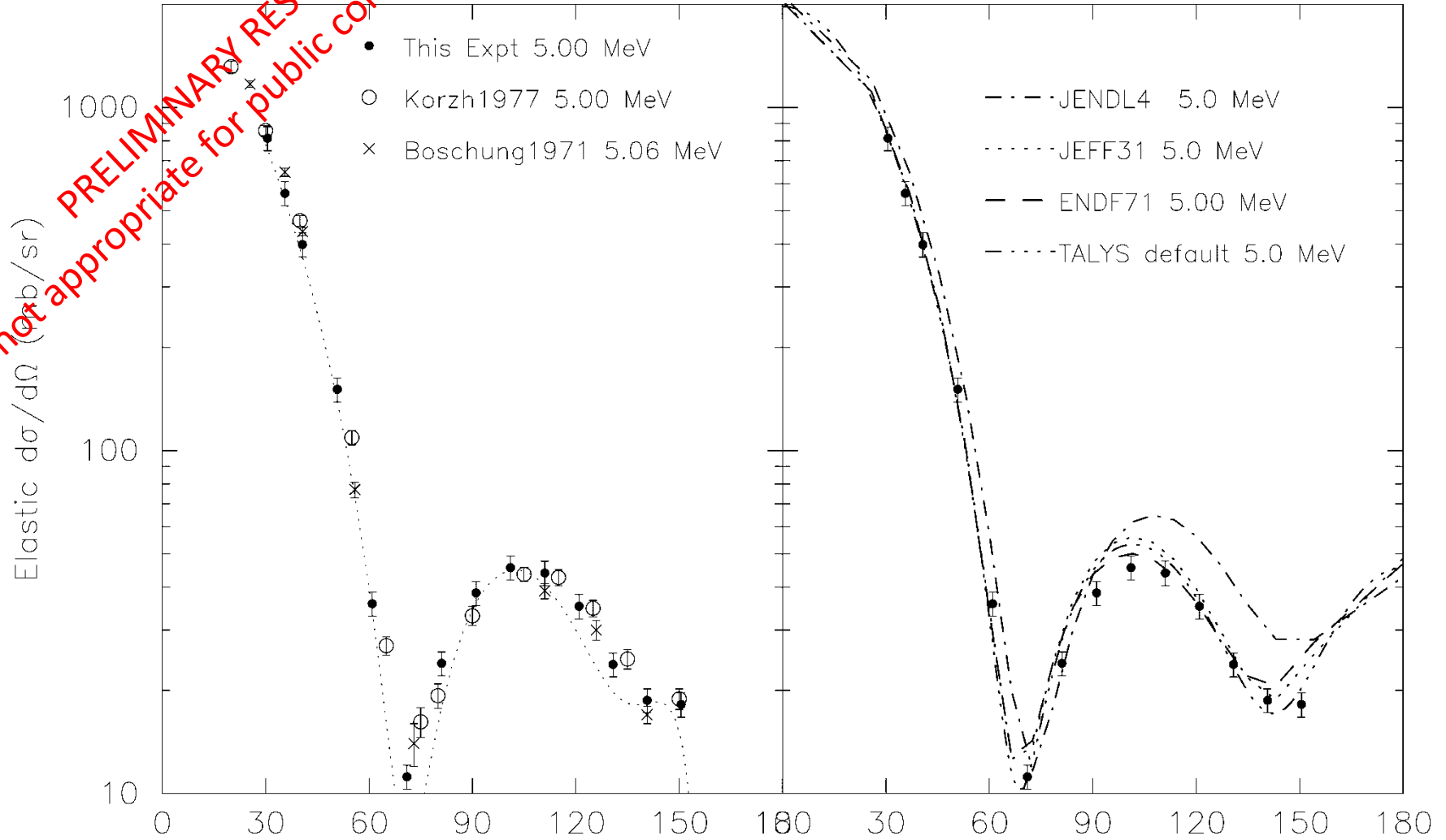
$^{54}\text{Fe}(n,n_0)$

PRELIMINARY RESULTS
not appropriate for public consumption



$^{54}\text{Fe}(n,n_0)$

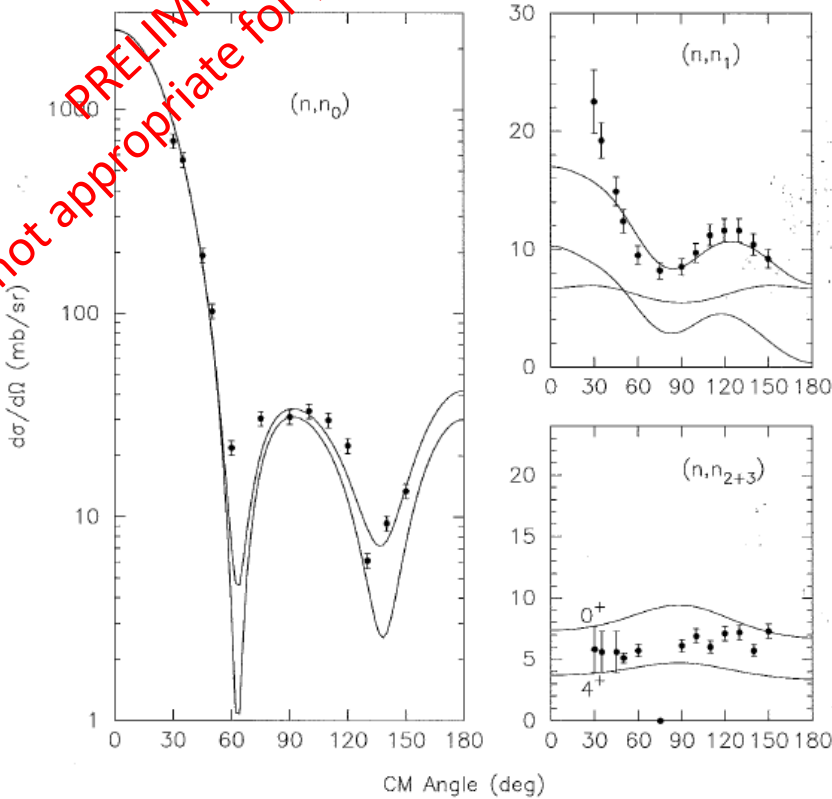
PRELIMINARY RESULTS
not appropriate for public consumption



$^{54}\text{Fe}(n, n_0)$

TALYS default calculation

PRELIMINARY RESULTS
not appropriate for public consumption



by Marcus McEllistrem

Minima are 'off'

Direct coupling starts earlier

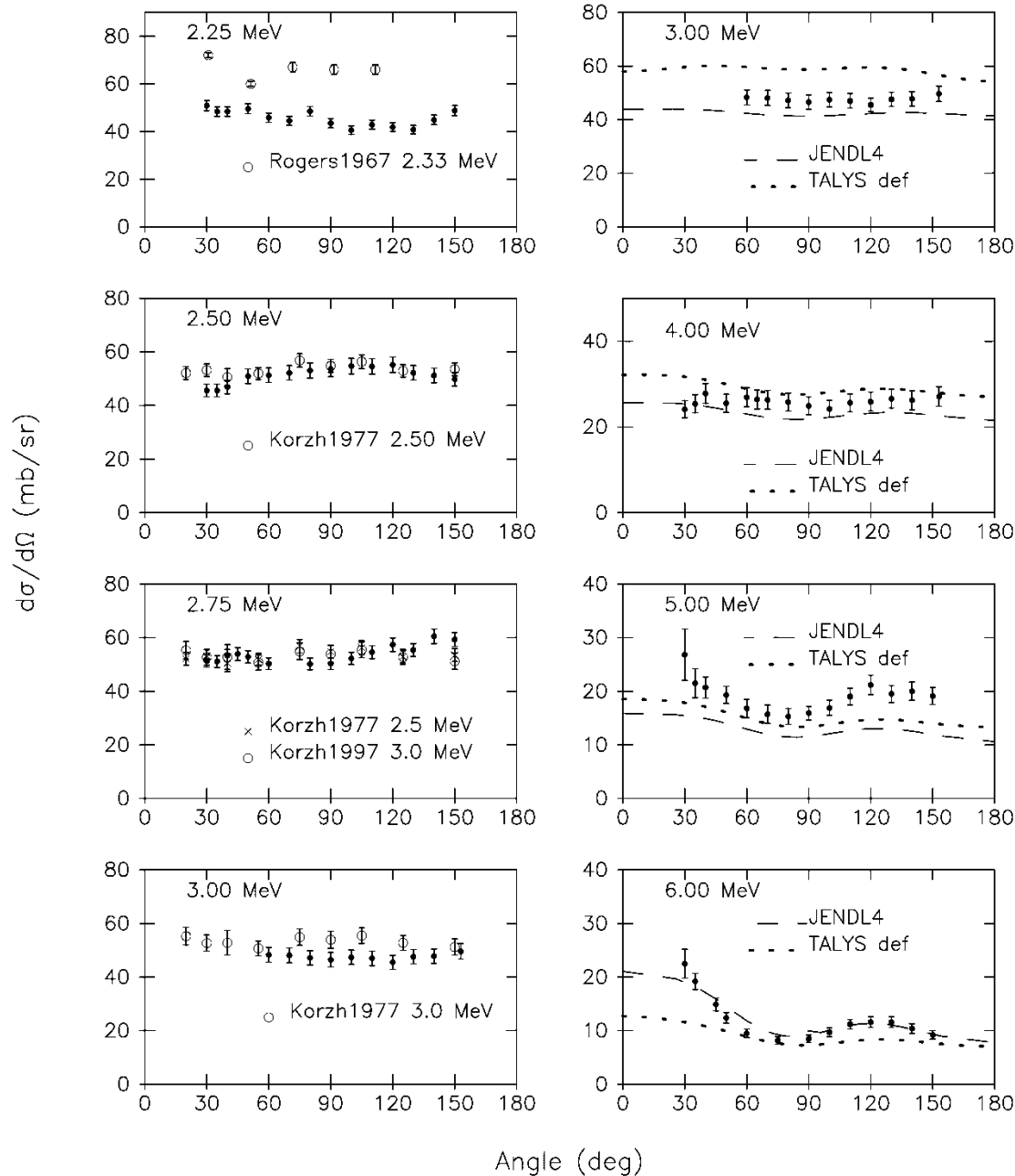
TALYS/ECIS

β_2 Coupling strength of 54 & 56
essentially the same

However electromagnetic BE2: 2-0
for the two nuclei are different by factor 2.5

Can better position the minima by making
OM absorption
strongly surface peaked and enlarging the R_W .

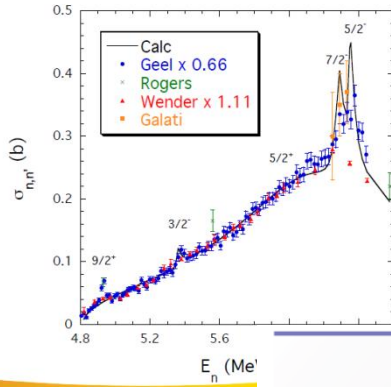
$^{54}\text{Fe}(n, n_1)$



Flat at low energies
→ n_0 n_1 separation working well
Direct coupling turns on suddenly
at ~ 5 MeV

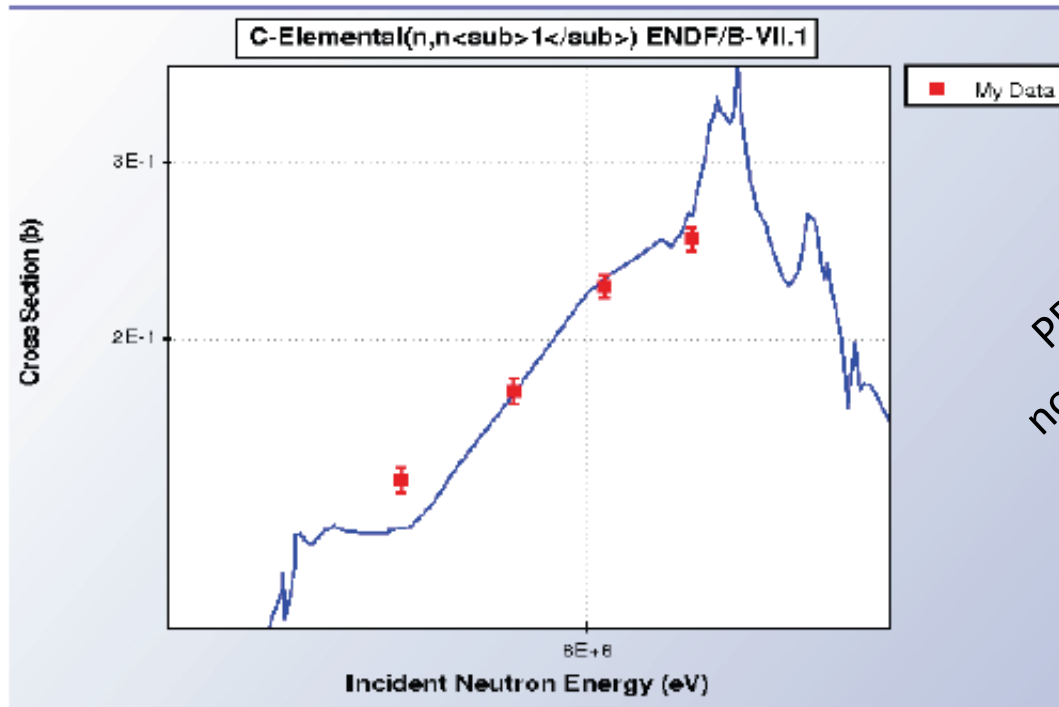
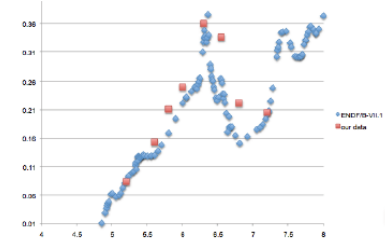
PRELIMINARY RESULTS
not appropriate for public consumption

n+¹²C Inelastic Cross Section



¹²C(n,n₁)

“Back of the Envelope” Analysis of Week-old (n,n’ γ) Data
 -- trends only, not yet normalized--



PRELIMINARY RESULTS
 not fit for public consumption

May 2016 (n,n’) measurements to date support ENDF values.

However accelerator running horrible at the time. Measurements must be repeated.

Nov 2016 (n,n’ γ) angular distribution measurements

Rensselaer Polytechnic Institute

Recent Measurements and Analysis

- **Resonance Region**
 - ^{164}Dy - transmission and capture (0.01 eV - 550 eV)
 - $^{161,162,163,164}\text{Dy}$ – capture (10 eV - 1000 keV)
 - Rh - transmission and capture (0.01 eV – 2 keV)
 - ^{56}Fe , Fe – capture (1 keV -2 MeV)
 - ^{96}Mo – transmission 5 – 20 keV
- **Scattering**
 - Fe
 - Zr <0.5 MeV in development
- **Thermal neutron scattering**
 - Not discussed here

Nuclear Data Research at RPI

Report to CSEWG 2016

Y. Danon, E. Liu, E. Blain, B. McDermott, K. Ramic, C. Wendorff
Gaerttner LINAC Center, Rensselaer Polytechnic Institute, Troy, NY, 12180
and

D. Barry, R. Block, J. Burke, A. Daskalakis, B. Epping, G. Leinweber, M. Rapp, T. Trumbull
Naval Nuclear Laboratory, KAPL, P.O. Box 1072, Schenectady, NY 12301



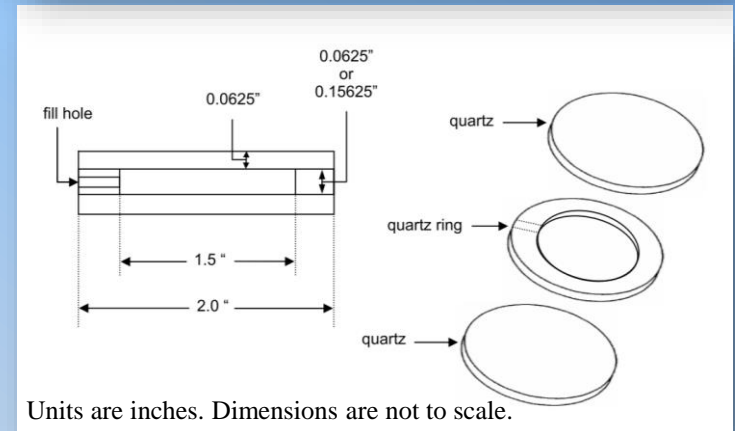
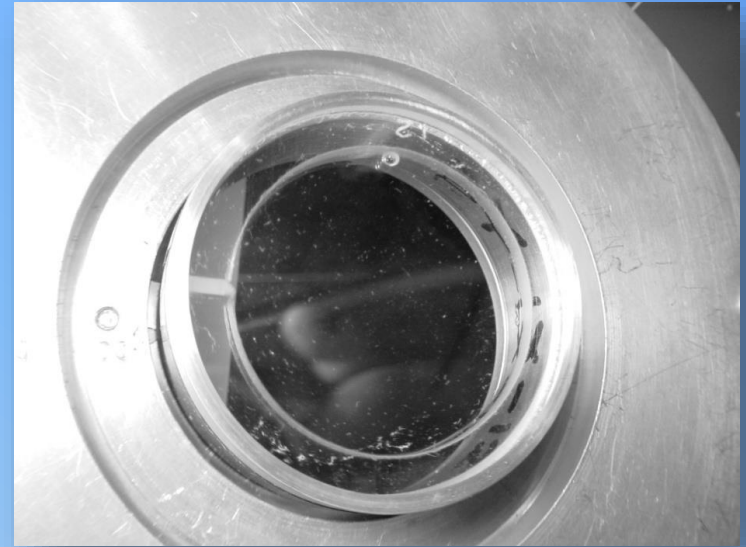
CSEWG meeting, November 14, 2016 at BNL



Rensselaer

^{164}Dy Resonance Region Measurements

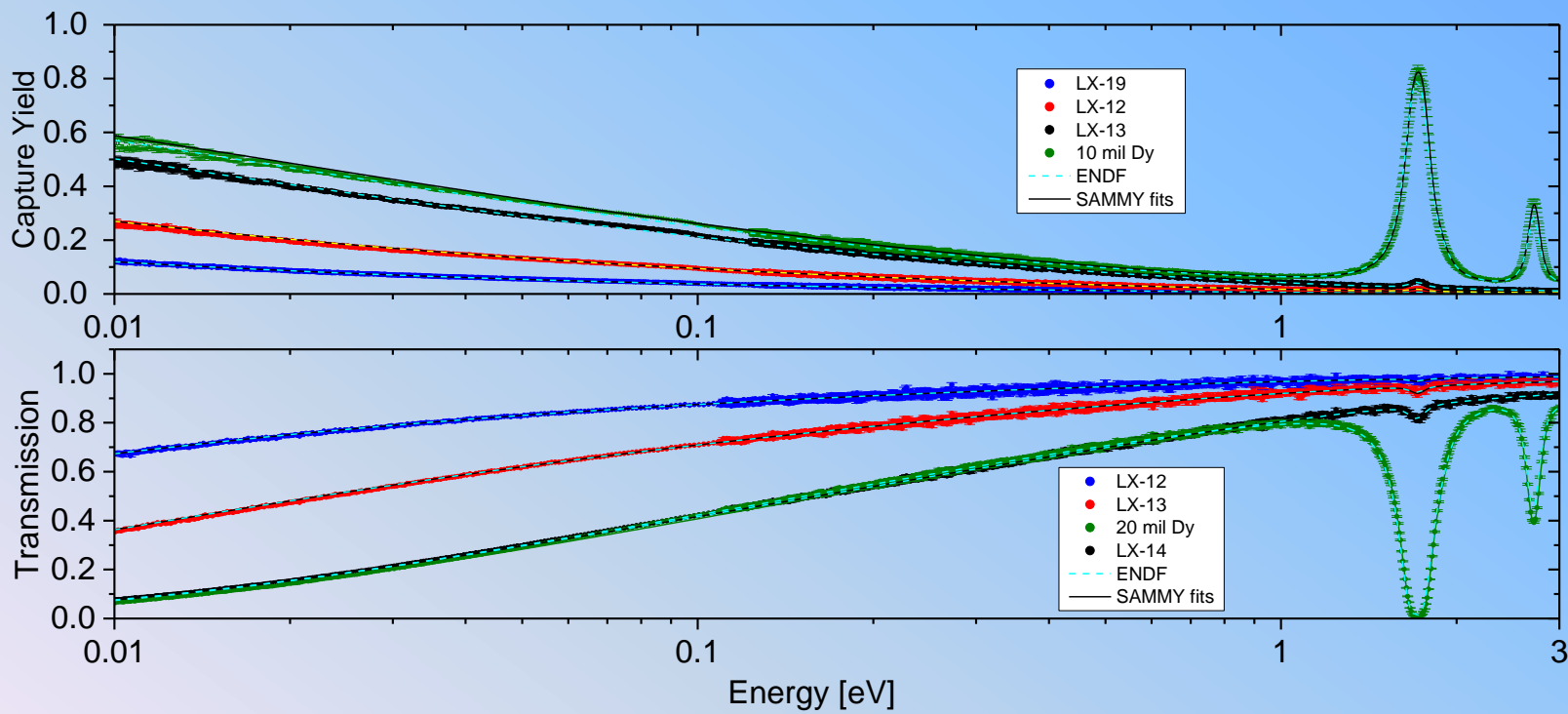
- Enriched ^{164}Dy and elemental samples measured
- Dy solutions in quartz cells used to ensure uniformity in thin samples
 - Equivalent of 0.0254 mm enriched metal
 - Thin and uniform
 - Diluted in D_2O
- The strong 5.44 eV resonance in ^{162}Dy was used for capture flux normalization



Thermal ^{164}Dy Measurements

^{164}Dy Thermal Total Cross Section	
NNL/RPI	ENDF
2980 ± 10 barns	2981 barns

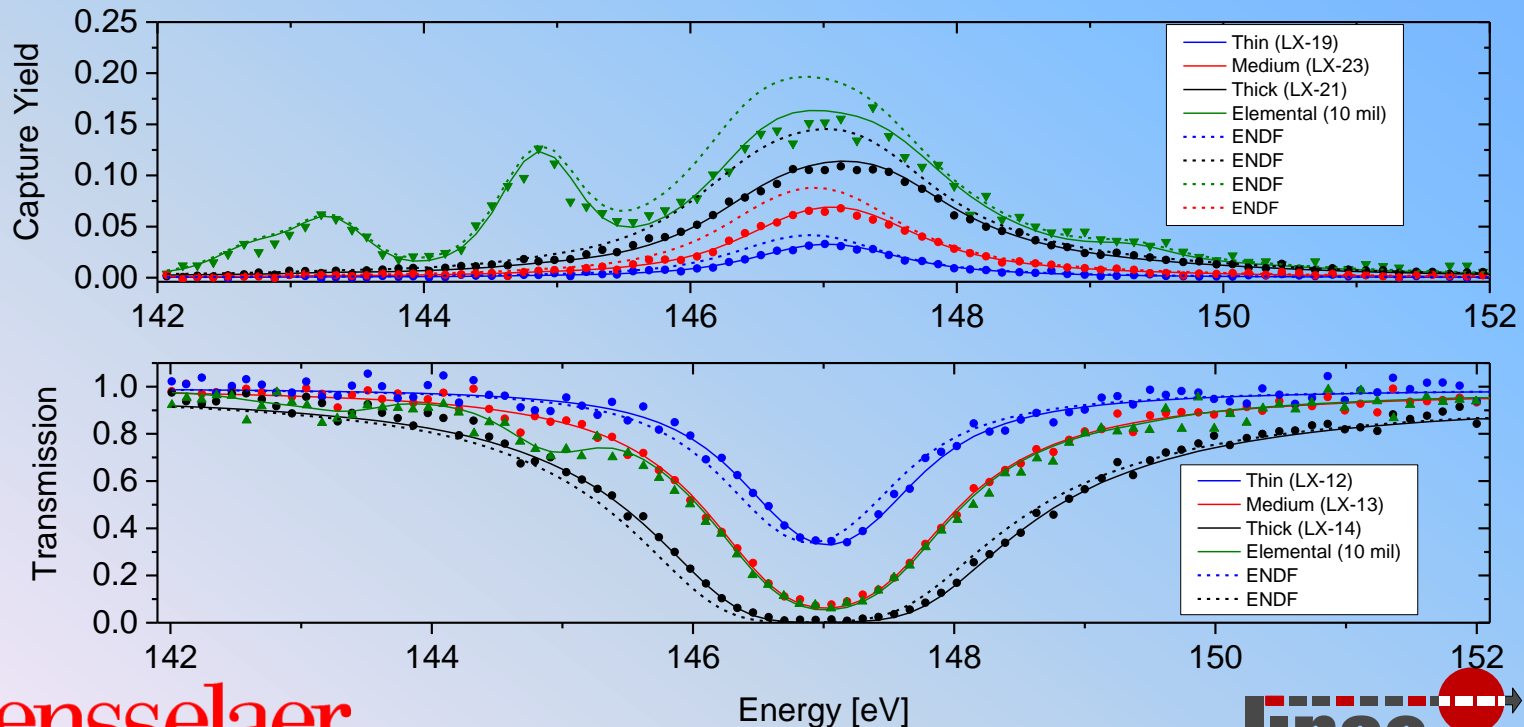
^{164}Dy Capture Resonance Integral	
NNL/RPI	ENDF
338 ± 1 barns	342.2 barns



^{164}Dy Resonance at 147 eV

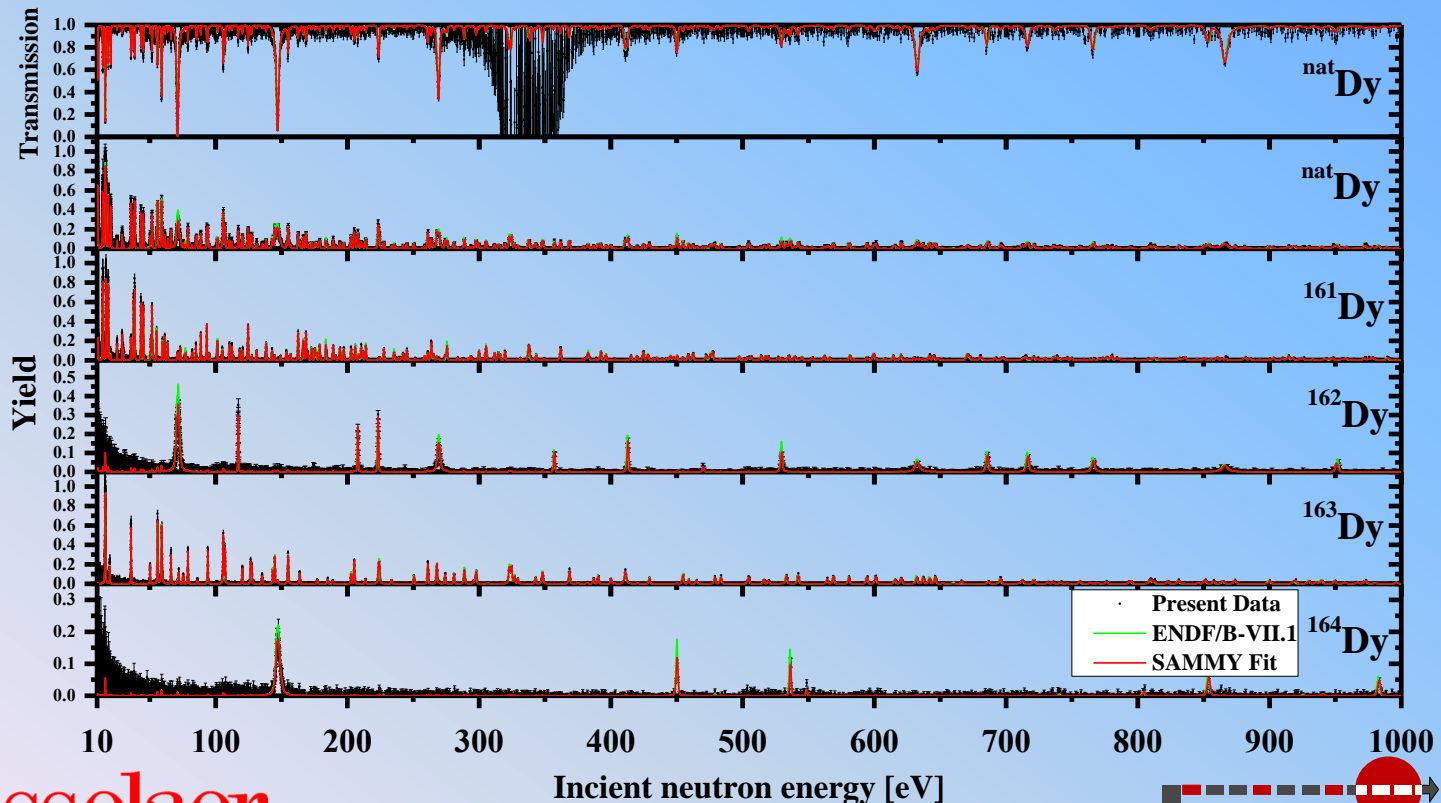
- Lowest positive energy and strongest resonance in ^{164}Dy
- Γ_n within uncertainties of ENDF, but Γ_γ lower, as seen in capture fits

Source	E_0 (eV)	$\Delta E_{o,B}$ (eV)	$\Delta E_{o,ext}$ (eV)	Γ_γ (meV)	$\Delta\Gamma_{\gamma,B}$ (meV)	$\Delta\Gamma_{\gamma,ext}$ (meV)	Γ_n (meV)	$\Delta\Gamma_{n,B}$ (meV)	$\Delta\Gamma_{n,ext}$ (meV)	Iso- tope	J
NNL/RPI	147.105	0.005	0.008	86	2	1	830	8	10	164	0.5
ENDF/B-VII.1	147.97			114.2			820			164	0.5



$^{161,162,163,164}\text{Dy}$ Capture Measurements

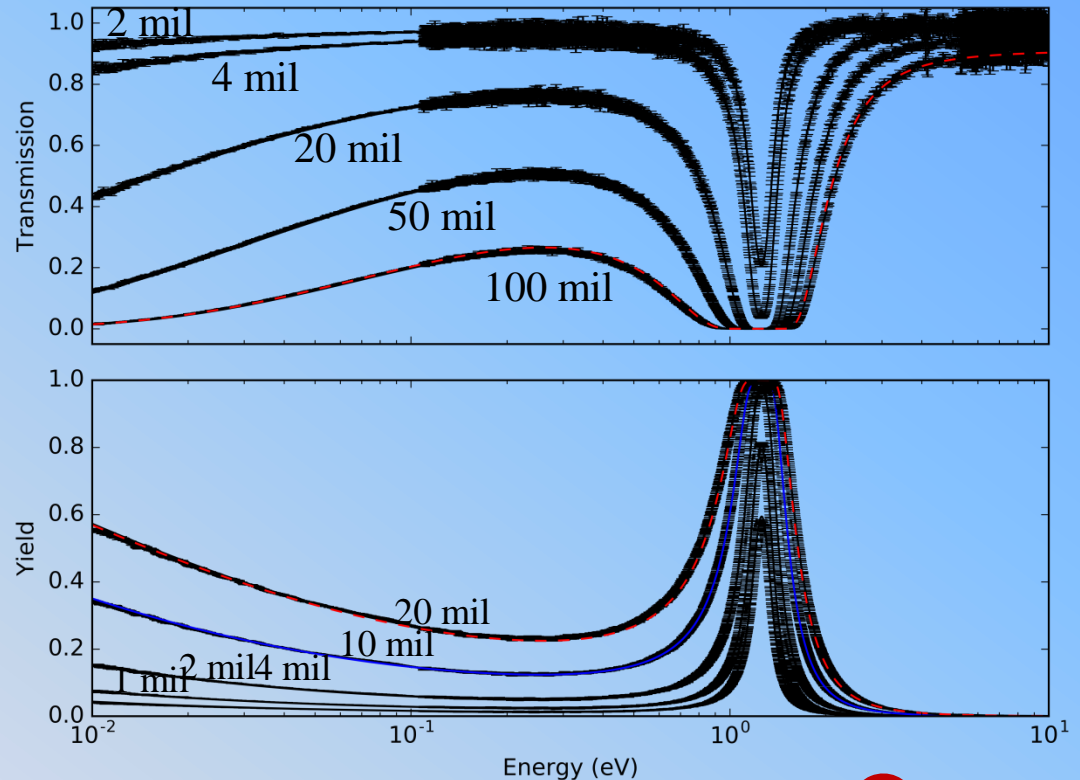
- Publication is in final review and includes all resonance parameters
- New resonances: 29 in ^{161}Dy , 17 in ^{163}Dy .
- ENDF/B-VII.1 resonances not observed: 6 in ^{161}Dy isotope, 2 in ^{163}Dy , 4 in ^{164}Dy .
- $^{\text{nat}}\text{Dy}$ resonance integral was found to be 1405 ± 3.5 , $\sim 0.3\%$ higher than ENDF/B-VII.1



Rh Transmission and Capture in the RRR

Thermal cross section (barns)			
	Total	Capture	Elastic
NNL	149 ± 1	144 ± 1	5.2 ± 0.1
ENDF/B-VII.1	146.3	142	4.3

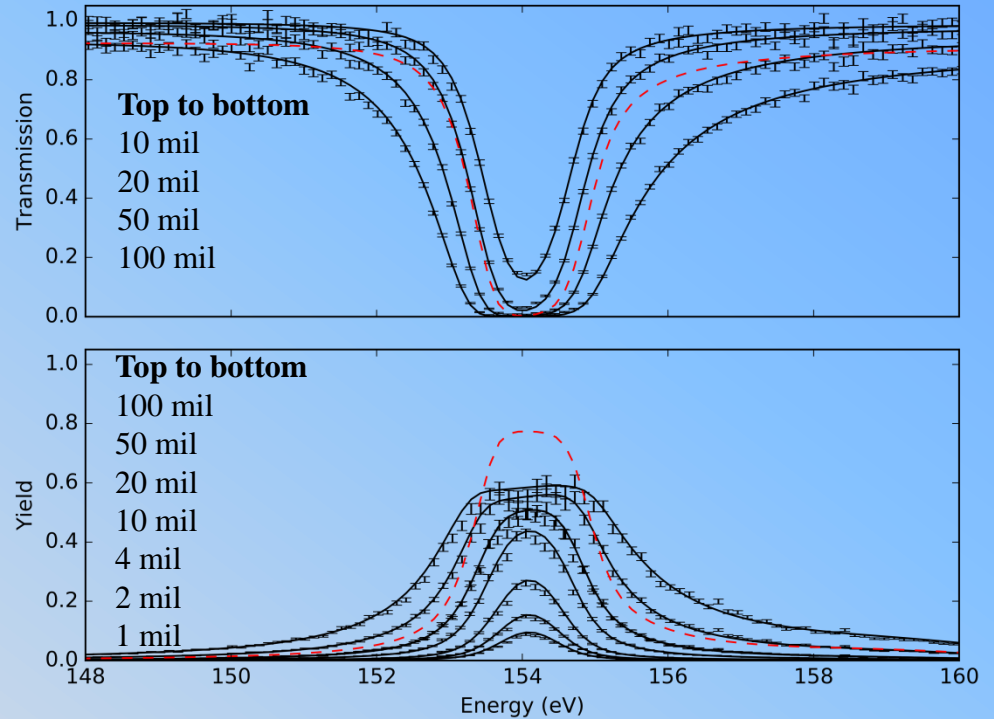
- Measured multiple sample thicknesses in both transmission and capture
 - Transmission at ~ 15 m flight path
 - Capture at ~ 25 m flight path
- Capture slightly higher than ENDF/B-VII.1
- Scattering $\sim 20\%$ higher than ENDF/B-VII.
 - small cross section compared to capture



Rh Transmission and Capture in the RRR

Resonance Integral (barns)			
	Total	Capture	Elastic
NNL	1120 ± 10	990 ± 10	121 ± 1
ENDF-7.1	1084	968	108

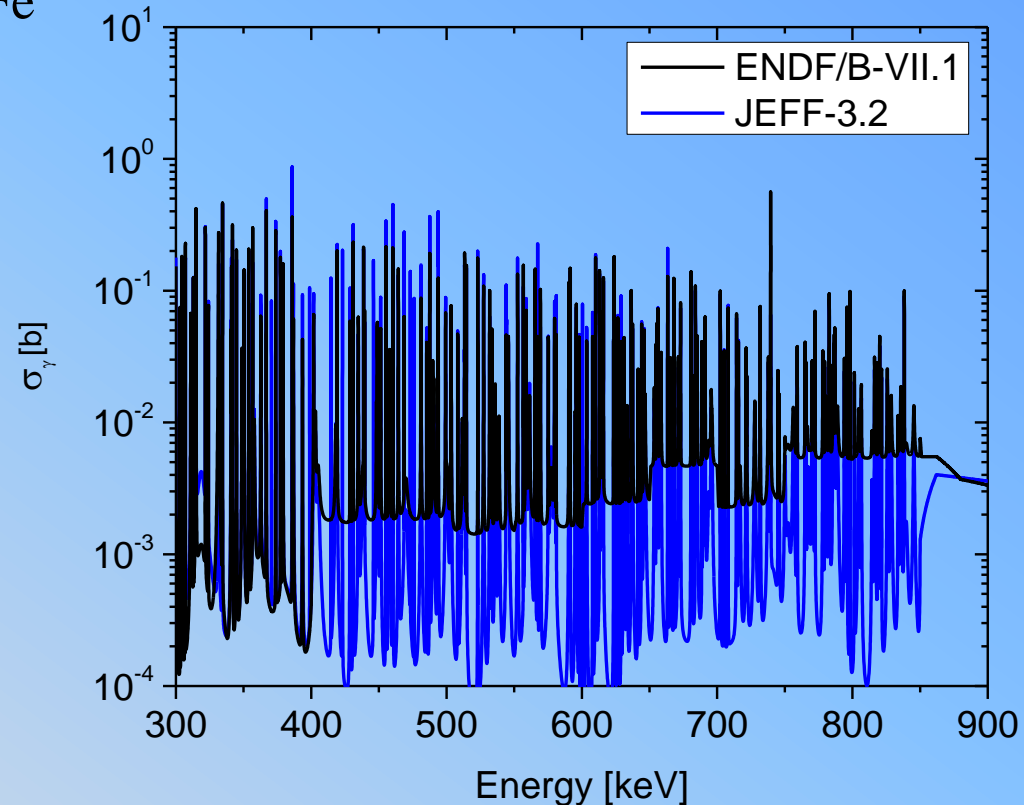
- Measured multiple sample thicknesses in both transmission and capture
 - Both Transmission and Capture at ~ 25 m flight path
- The absorption resonance integral is $\sim 3\%$ higher compared to ENDF/B-VII.1
- Scattering resonance integral is $\sim 12\%$ higher compared to ENDF/B-VII.1



Example of a large difference compared to ENDF/B-VII.1

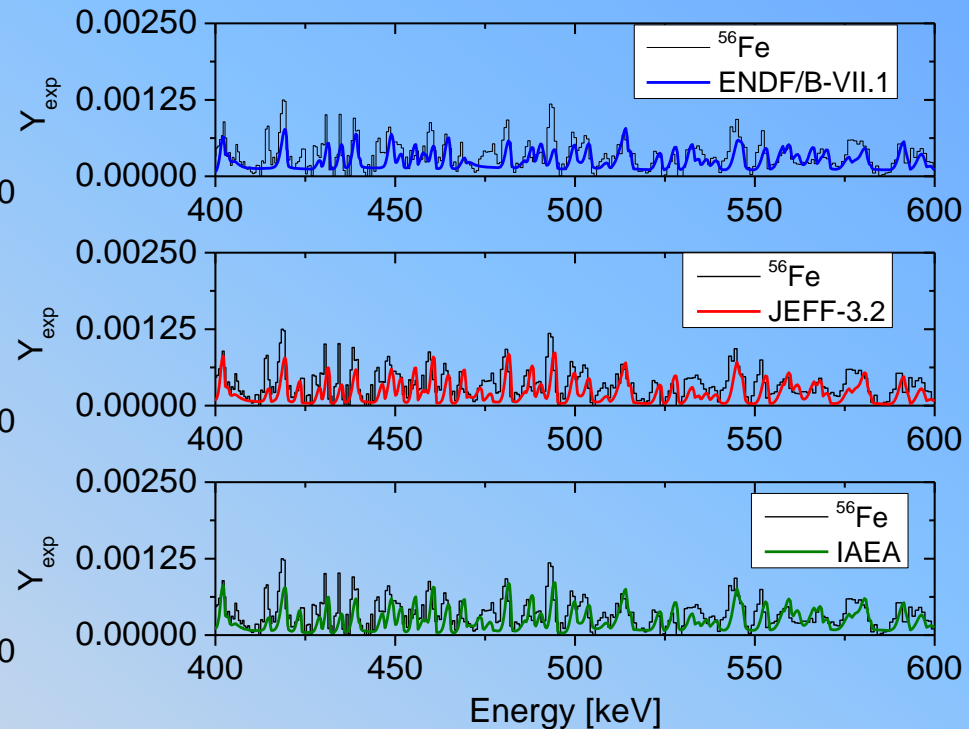
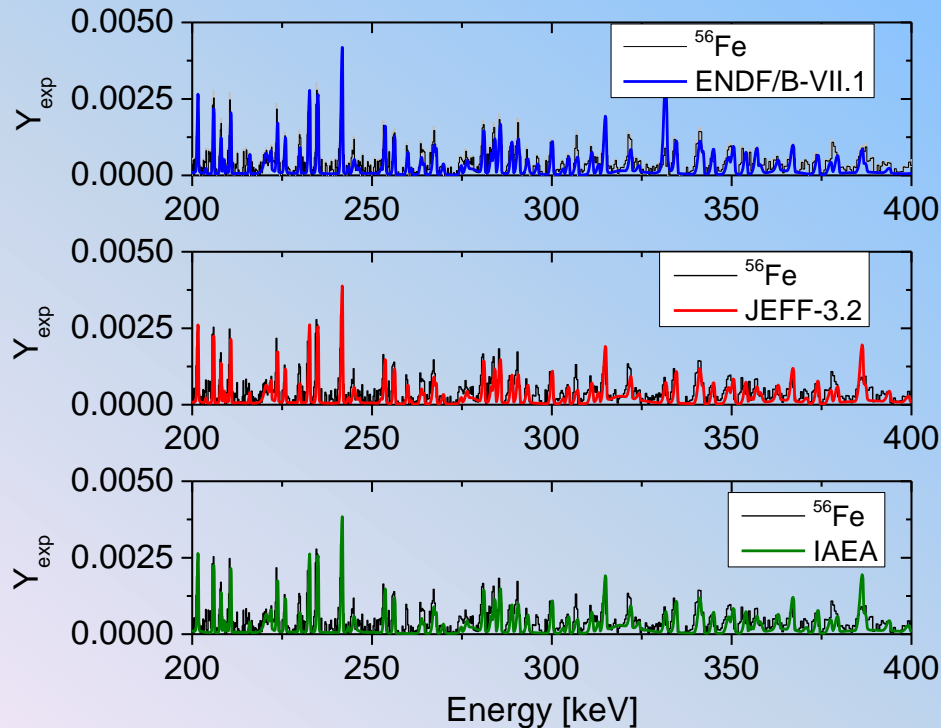
New measurements of ^{56}Fe capture cross section up to 2 MeV

- ENDF/B-VII.1 evaluation for ^{56}Fe has artificial background above 400 keV
- Discrepancies are apparent in MCNP calculations
- Used C_6D_6 detector array for capture measurements



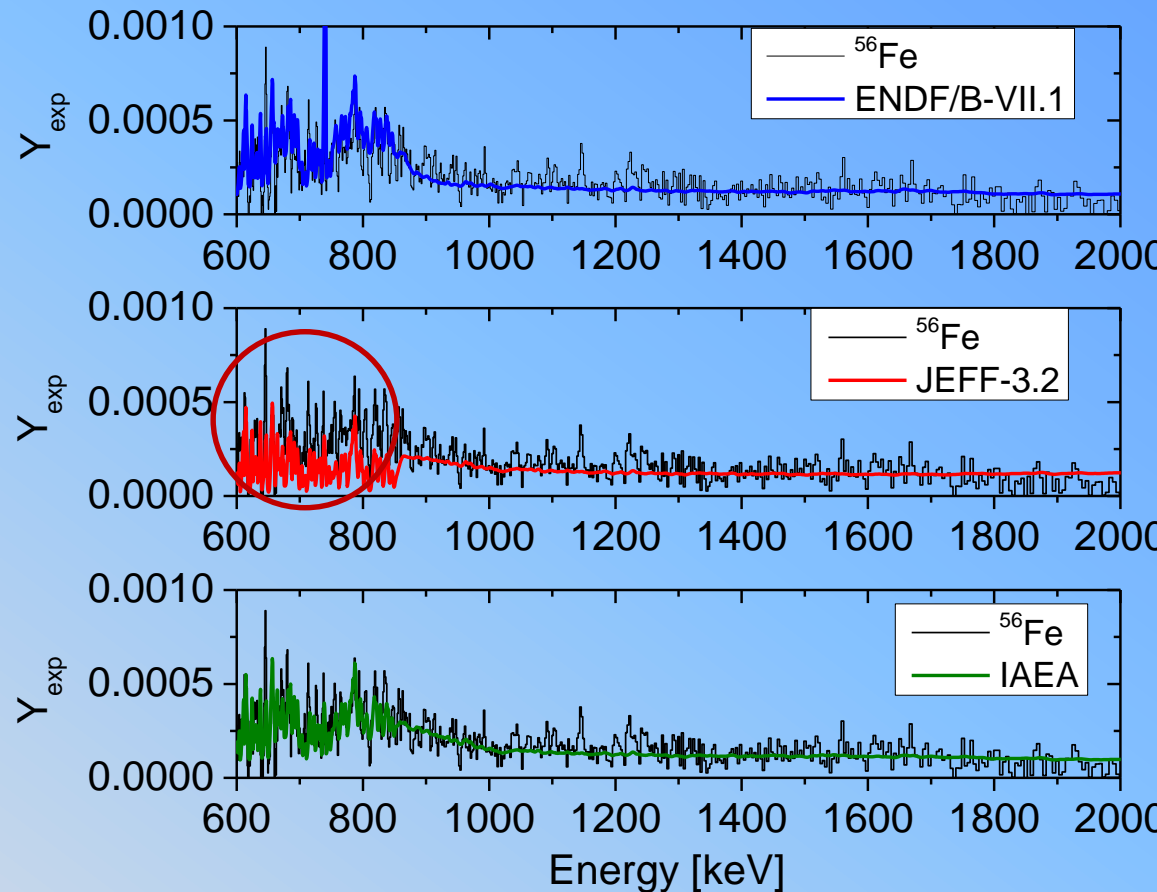
^{56}Fe Results – MCNP Comparison

- Evaluation comparisons among ENDF, JEFF and IAEA were performed using MCNP
- Background in ENDF is apparent above 400 keV
- Differences observed among resonances in the different evaluations



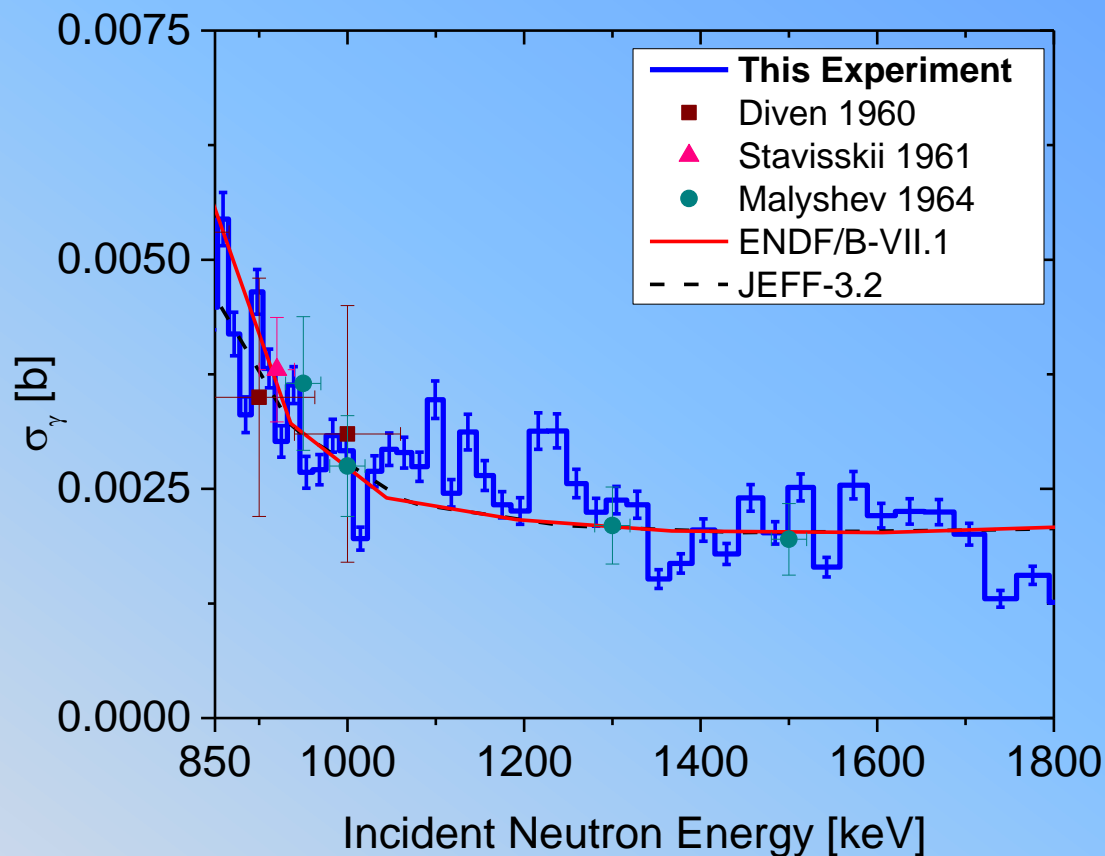
^{56}Fe Results – MCNP Comparison

- Possible unresolved or intermediate structure may account for higher data yields from 600-850 keV (self-shielding)
- ENDF overcompensates with its background treatment, JEFF has no background treatment.
- Above 850 keV, the data agree with the 3 evaluations presented.



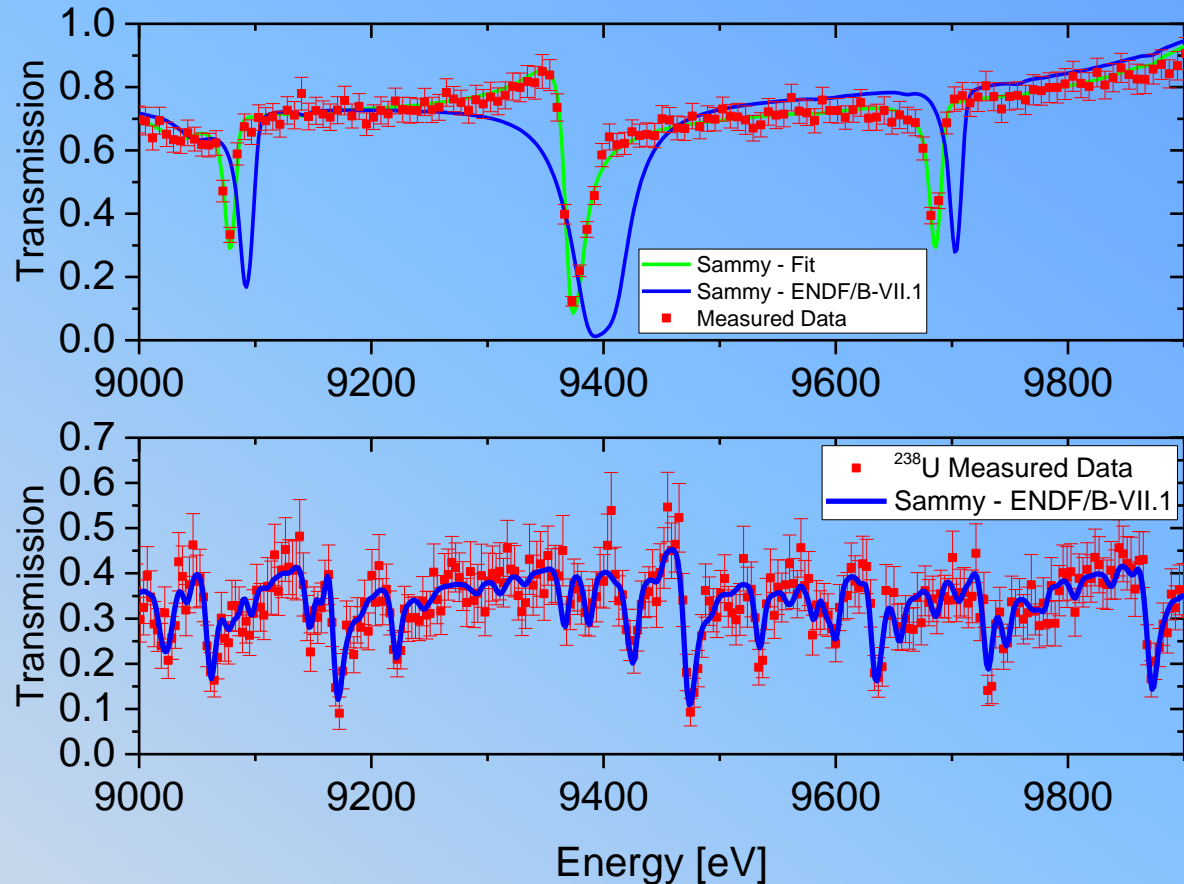
^{56}Fe Results – High Energy – other experiments

- High energy (>850 keV) data are in good agreement with previous experiments
- Data agree with ENDF and JEFF evaluations up to 1725 keV



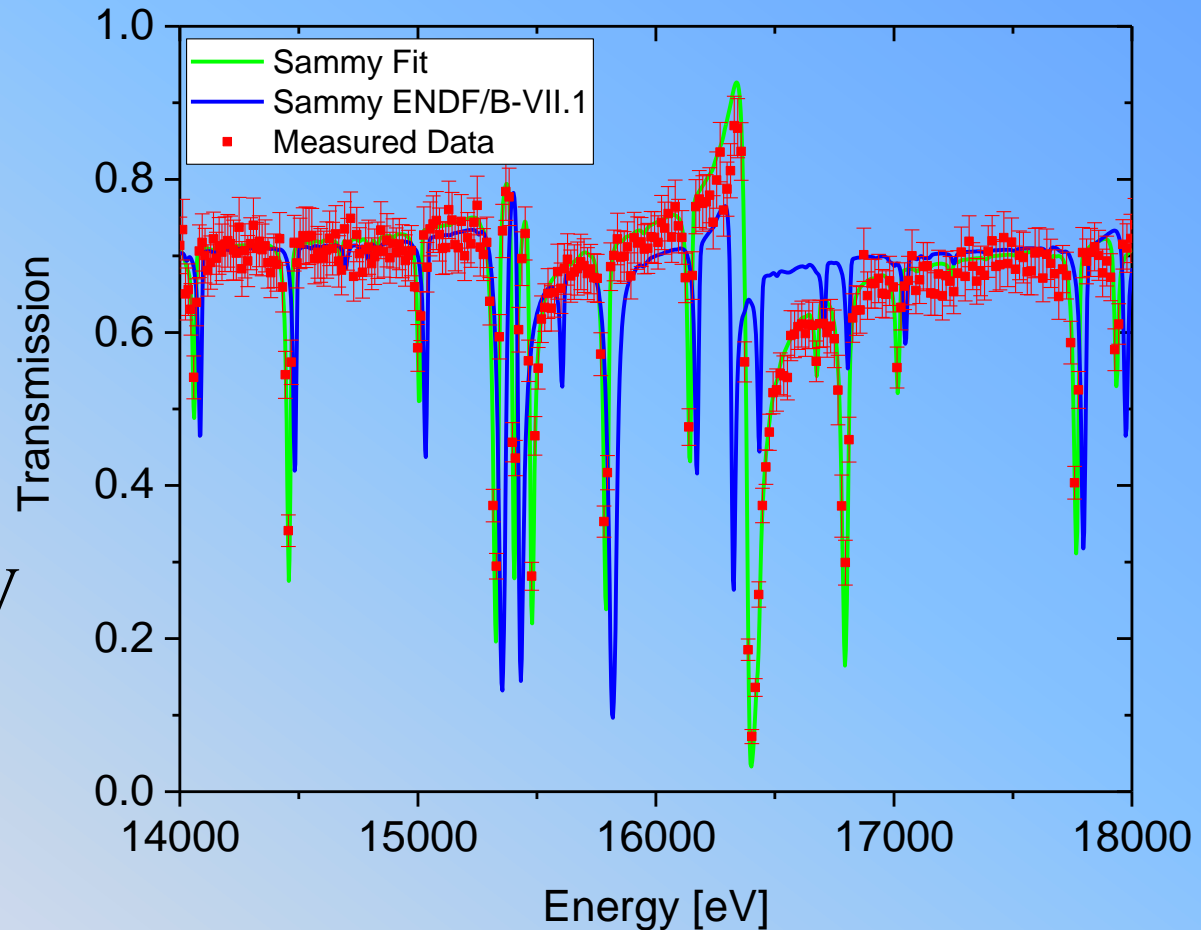
Mo-96 Transmission

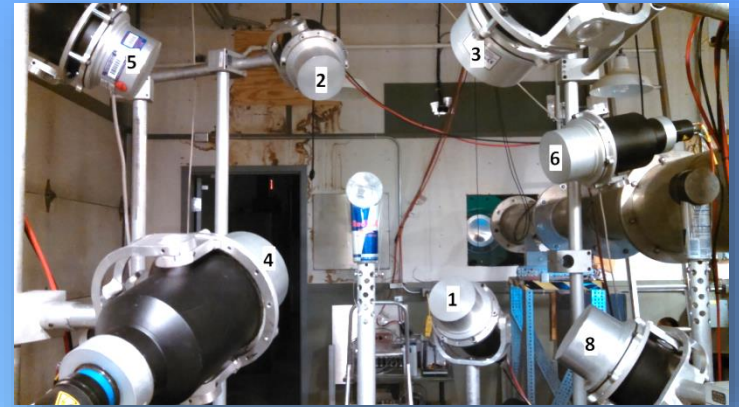
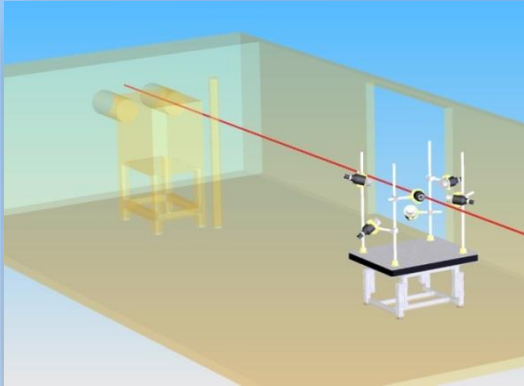
- Measurements included $^{95,96,98,100}\text{Mo}$
 - 100.141 m flight path
- Analysis of ^{96}Mo
 - 96.76% enriched
 - Areal density 0.05653 atoms/barn
- Use ^{238}U for energy alignment
 - Accurate determination of flight path and time zero.
 - Also used to verify the energy resolution used in SAMMY
- Observed
 - Energy shift in ^{96}Mo
 - Spin assignment problems (p-wave instead of s-wave)



Mo-96 Resonance Analysis up to 20 keV

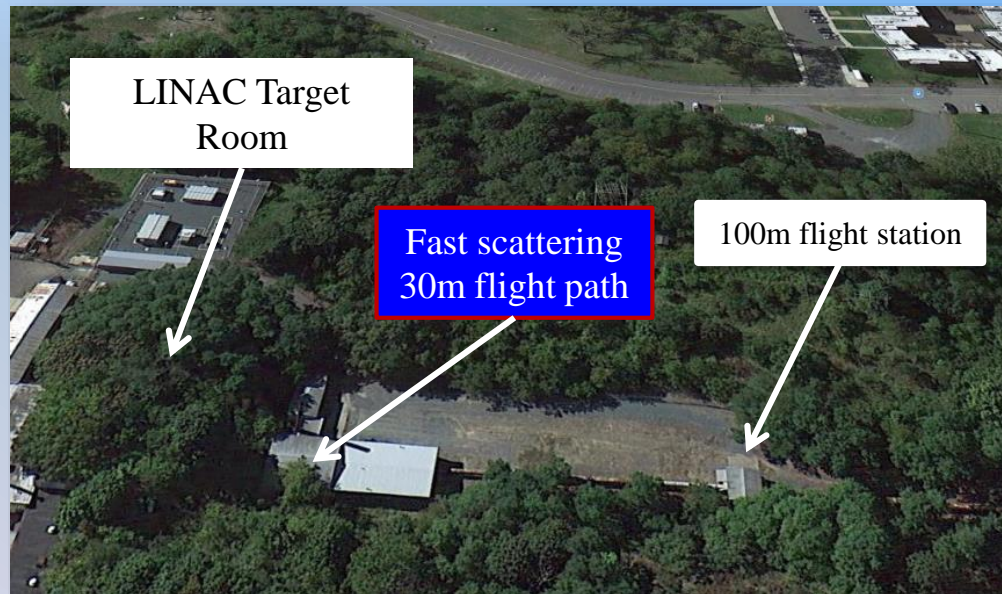
- Above 14 keV ENDF/B-VII.1 resonance parameters still shows
 - An energy shift
 - Issues with resonance parameters
- New resonance parameters from 5 keV to 30 keV were derived using the fitting code SAMMY





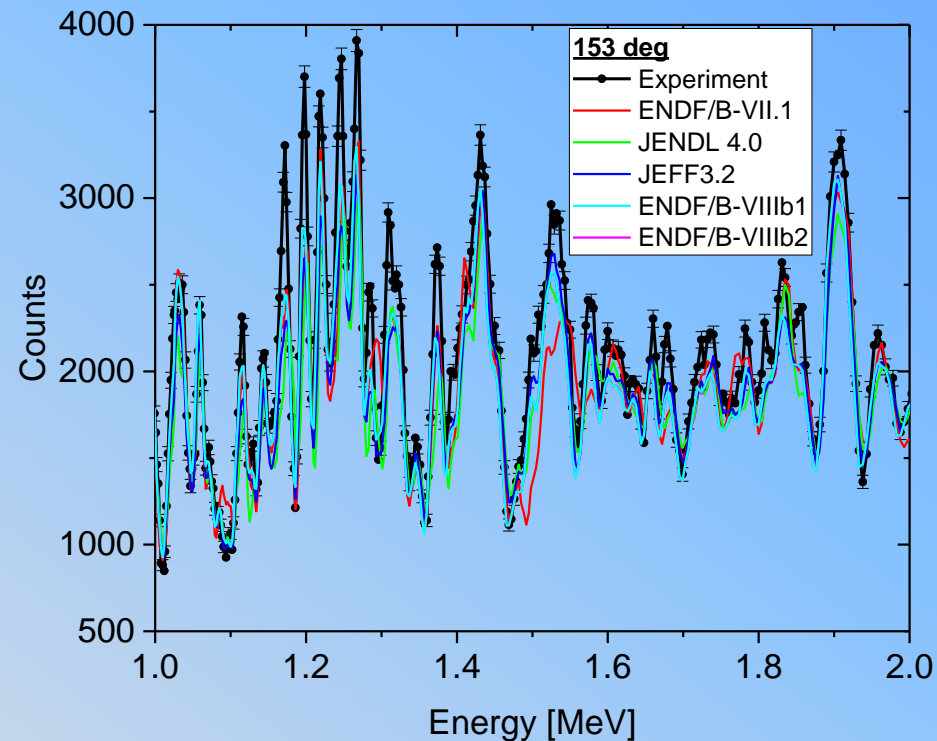
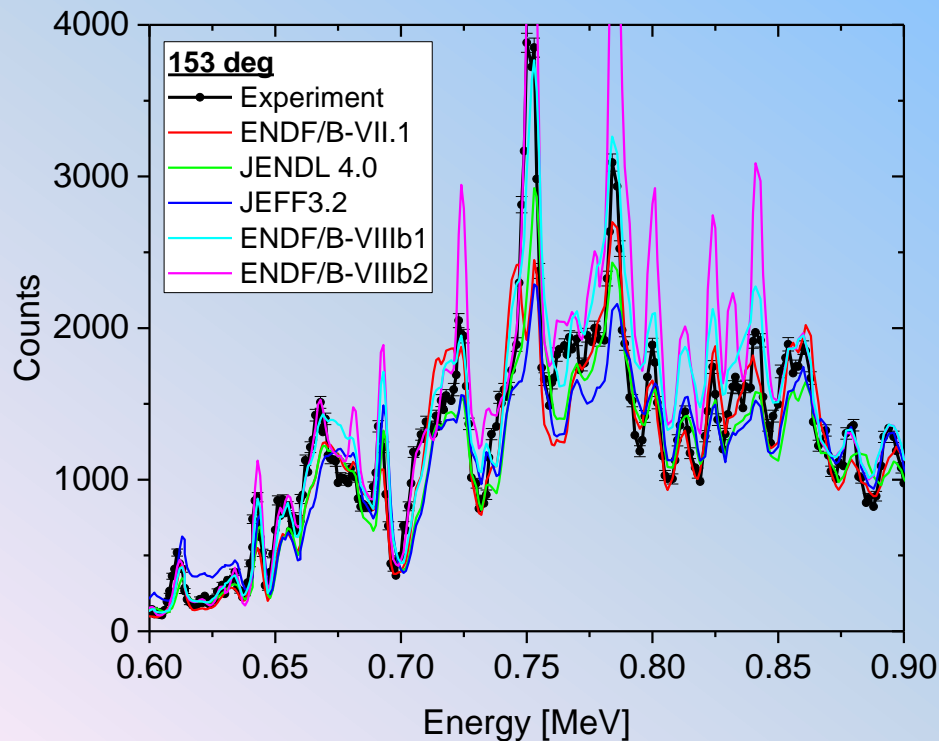
Neutron scattering benchmark of Fe-56 evaluations

Quasi-differential neutron scattering and angular distributions.



^{nat}Fe Scattering to 153 deg

- Left plot – energies below the 1st inelastic state (RRR region)
 - ENDF/B-VIIIb2 performs **very poorly** compared to other evaluations.
- Right Plot – above the first inelastic state (fast region)
 - ENDF/B-VIIIb2 and ENDF/B-VIIIb1 are same (b1 was plotted over b2)
- In order to quantify the differences FOM and C/E metrics were developed (next slides).



^{56}Fe FOM

- For this comparison we define for a given angle FOM as

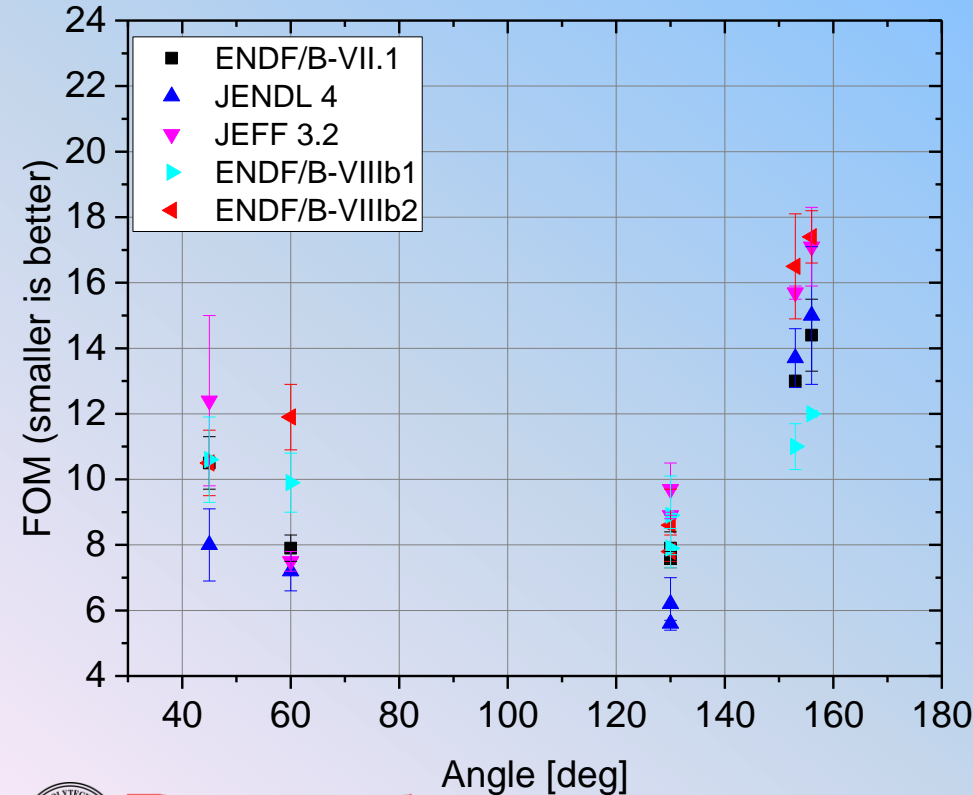
$$FOM = \frac{1}{n} \sum_{i=1}^n \frac{(Ex_i - Sim_i(1 \pm \epsilon_N))^2}{\Delta Ex_i^2 - (\epsilon_N Ex_i)^2}$$

n – number of TOF channels

Ex_i, Sim_i – Experimental net counts, and normalize net simulation results

ϵ_N – fractional normalization uncertainty

ΔEx_i - uncertainty in the measured net number of counts



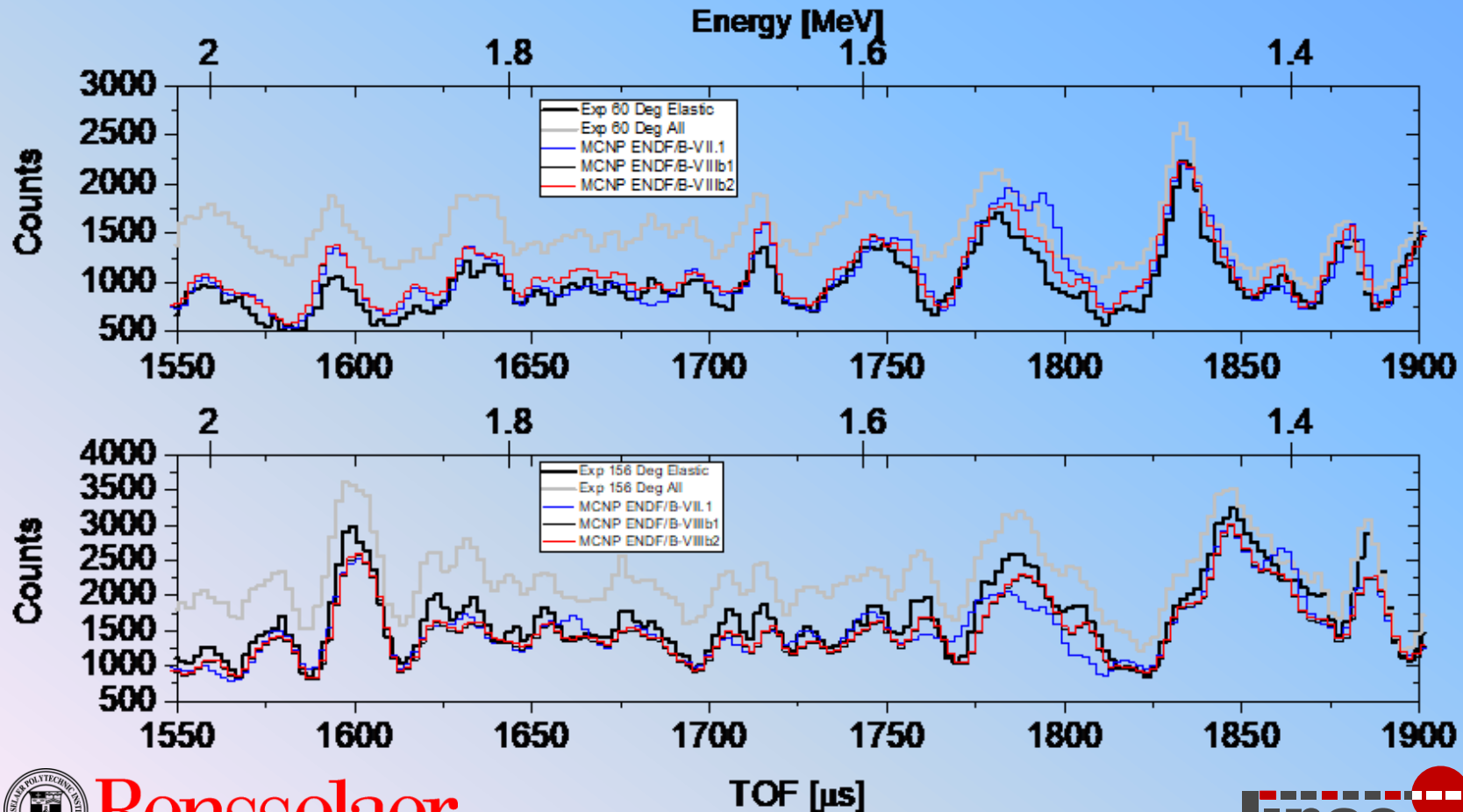
JENDL 4 is overall best (lowest FOM)

ENDF/B-VIIIb2 – performs poorly relative to other evaluations.

Table with numbers on next slide

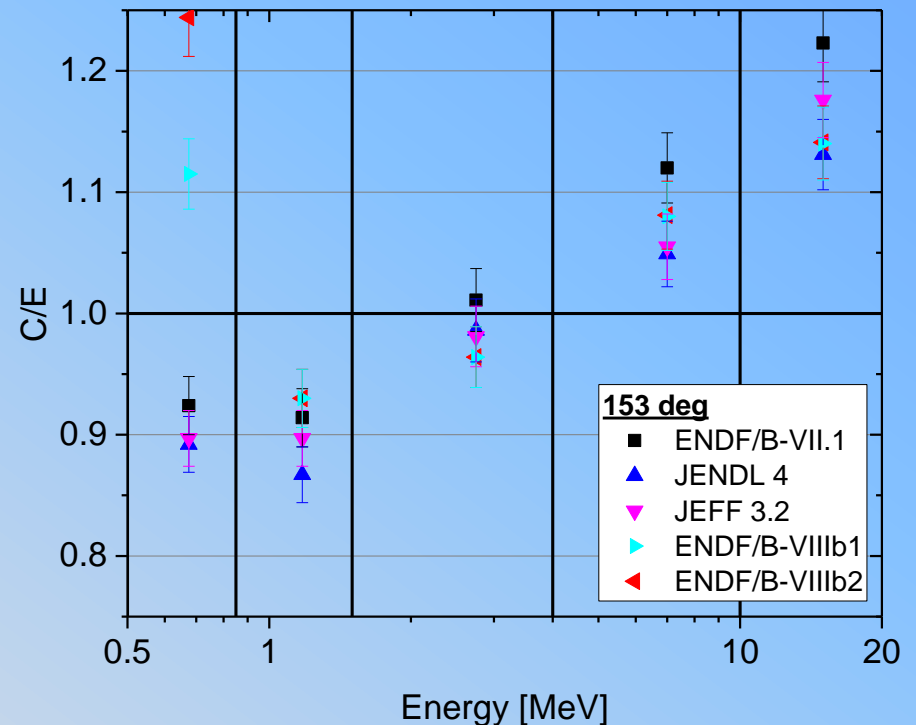
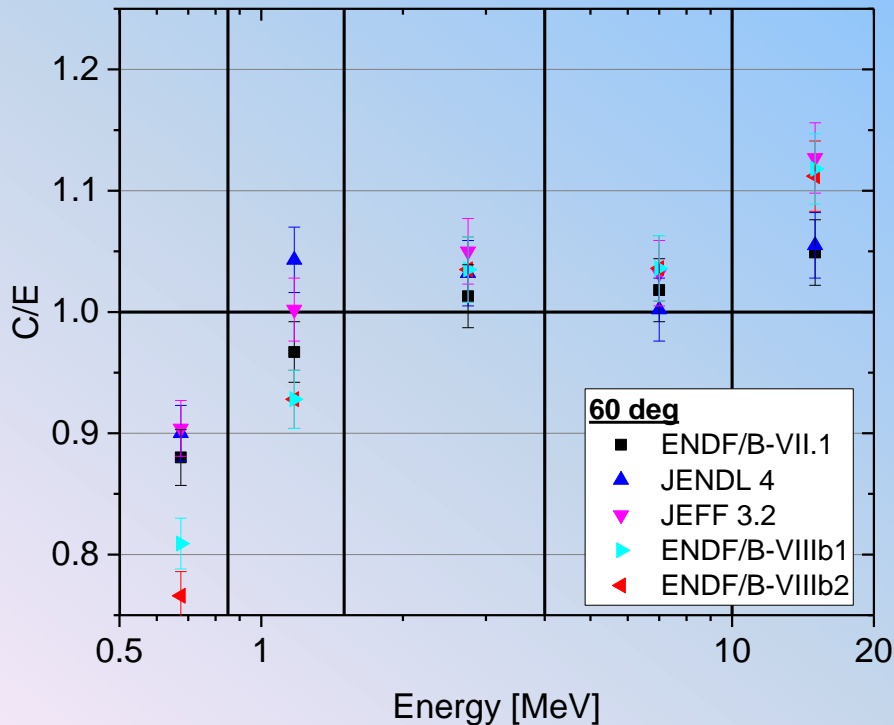
^{56}Fe elastic scattering

- Remove inelastic neutron by discriminating their low pulse height.
- ENDF/B-VIIIb1 and b2 are the same and seem to follow the experimental data closer than ENDF/B-VII.1



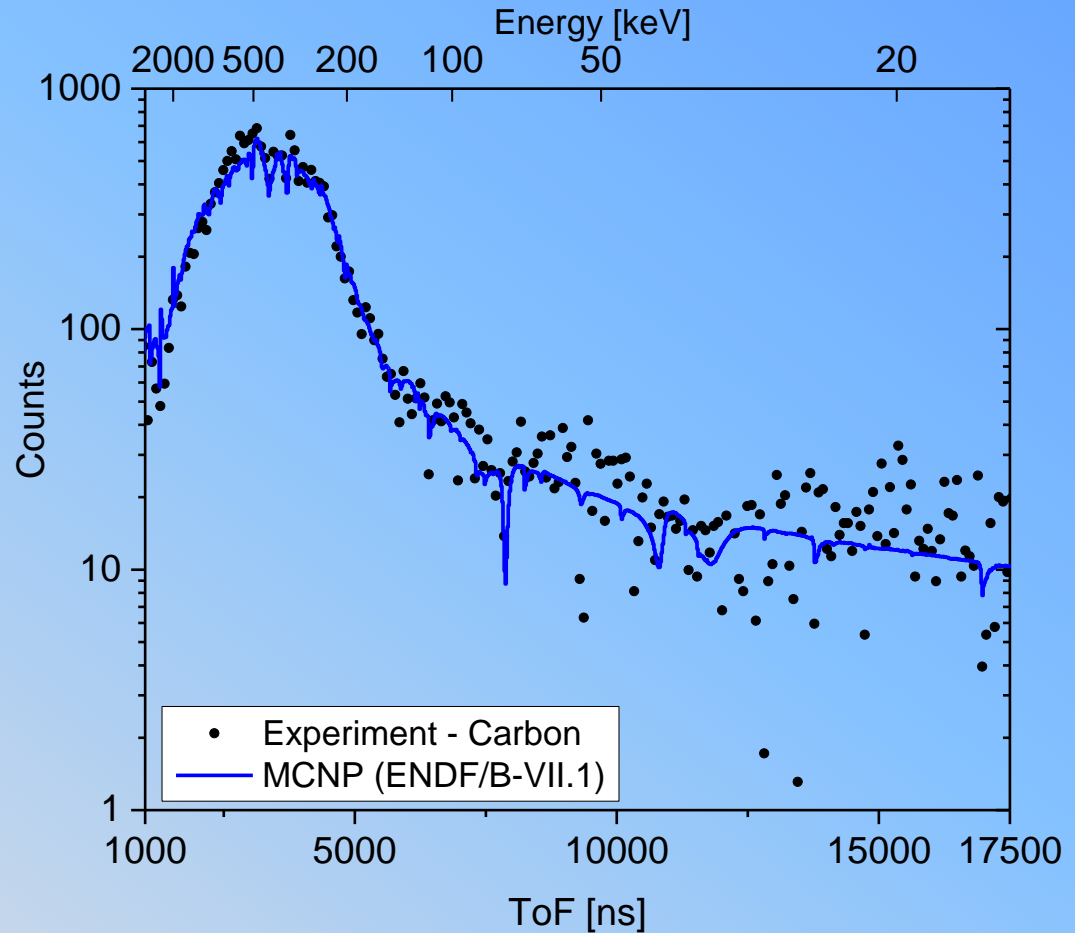
^{56}Fe C/E

- C/E was calculated by first grouping the data and calculating the group ratio
- The uncertainty includes only the simulation normalization uncertainty
- ENDF/B-VIIIb2 – performs poorly especially below 2 MeV.
- ENDF/B-VIIIb1 – shows slight improvement compared to ENDF/B-VII.1 for $E > 2$ MeV



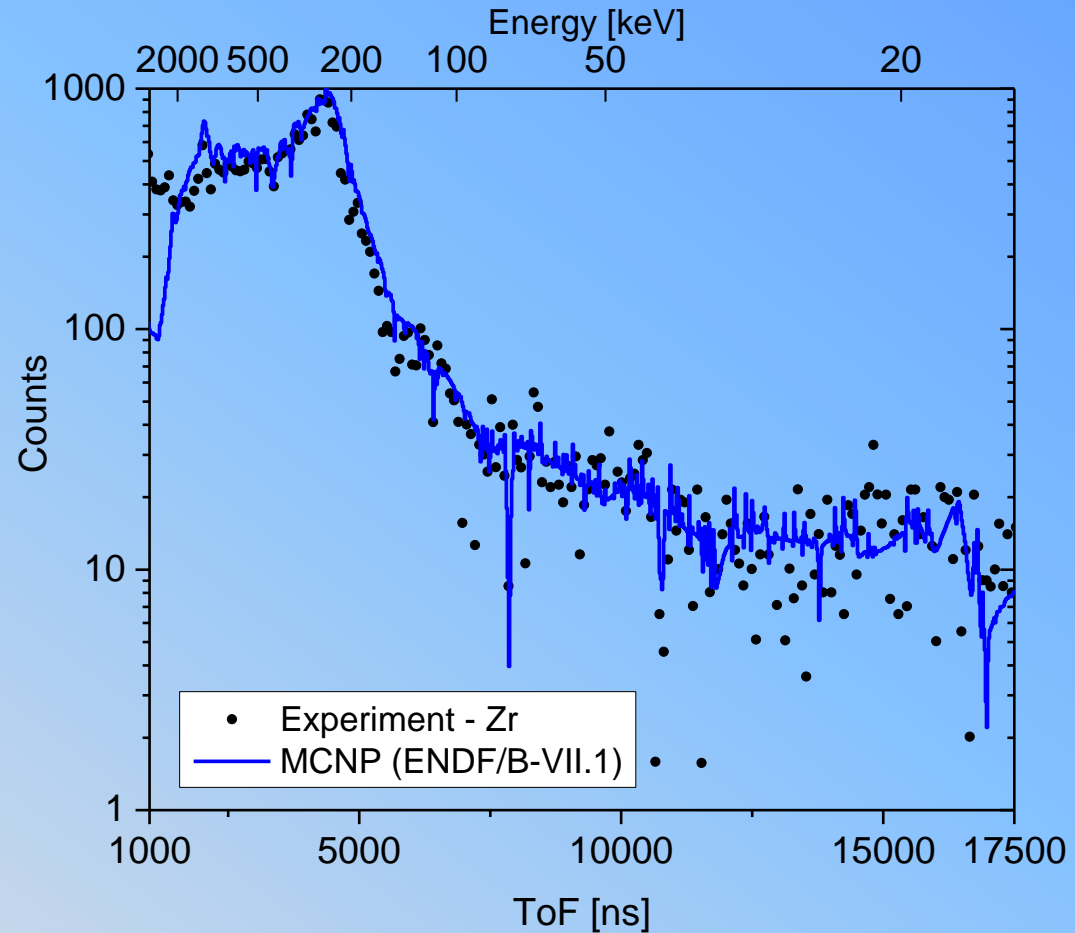
keV Region Scattering - Carbon

- **Objective:** supplement our fast (0.5-20 MeV) neutron scattering experiment with data below 0.5 MeV
 - Measure elastic/inelastic neutron scattering as several angles
- Carbon (graphite) was used for validation of the methodology
 - Structure in the data (dips) due to transmission through Al in the beam
- Neutron scattering from a 7 cm carbon sample was measured with a 1 inch diameter by 0.5 inch thick ^6Li detector at 45 degrees
 - Experiment and simulation show good agreement above 100 keV
 - Counting statistics need improvement



keV Region Scattering - Zr

- Neutron scattering from a 4 cm thick zirconium sample was measured with a 1 inch diameter by 0.5 inch thick ^6Li detector at 45 degrees
- Below 500 keV, good agreement was found between the measurement and simulation
- Improvements include:
 - Larger detector area (3" diam.)
 - Two detectors at the same angle
 - Improve counting statistics with a longer run time.
 - Used ~9 hours for the sample and ~3 hours for the open.



Measurements and Standards Work at NIST

- **Review of measurements on standard related cross sections**
 - H(n,n)H
 - ${}^6\text{Li}(n,p)$
 - ${}^3\text{He}(n,p)n,t)$
 - ${}^{10}\text{B}(n,a)$ and ${}^{10}\text{B}(n,a1g)$
 - C(n,n)
 - ${}^{238}\text{U}(n,g)$
 - Au(n, γ)
 - ${}^{239}\text{Pu}(n,f)$
 - ${}^{235,238}\text{U}(n,f)$
 - Thermal Constants

**Measurements and Standards Work at NIST
and
Standards Work at
Other Facilities**

**The Impact of the Standards Measurements on
the New Standards Evaluation**

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

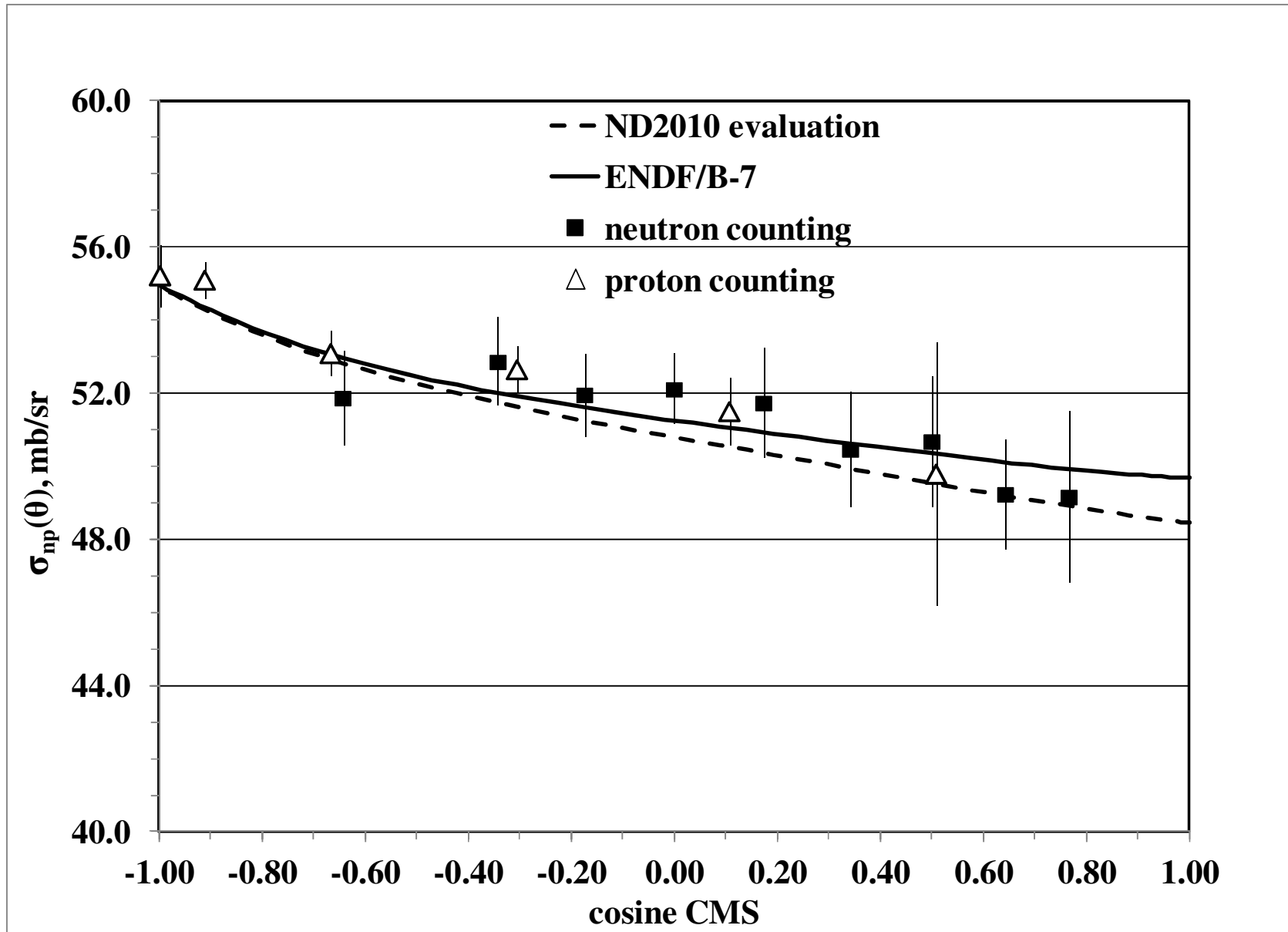
**Presented at
The CSEWG Meeting
BNL
November 14, 2016**

H(n,n)H Angular Distribution Measurements

- Previously, measurements were made at 14.9 MeV and 10 MeV to resolve problems with the hydrogen database. Measurements were made by detecting **recoil protons** at laboratory angles between 0 and 60 degrees at the Ohio University accelerator facility. An analysis of that data suggests differences near zero degrees in the CMS compared with evaluations.
- To obtain data at smaller CMS angles, new measurements have been made at 14.9 MeV by detecting recoil **neutrons**. Time-of-flight was used between the detection of the associated proton and the neutron with a flight path of about 4 m.
- The efficiency of the neutron detector was measured relative to the ^{252}Cf spontaneous fission neutron spectrum using the time-of-flight between a ^{252}Cf fission fragment and neutron. These measurements used the same flight path as was used for the angular distribution work.
- Also improvements were made to the earlier measurements at 10 MeV. This included providing the mean angles since the central angles were given in the publication and also the normalization was converted to the ENDF/B-VII total elastic cross section.

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

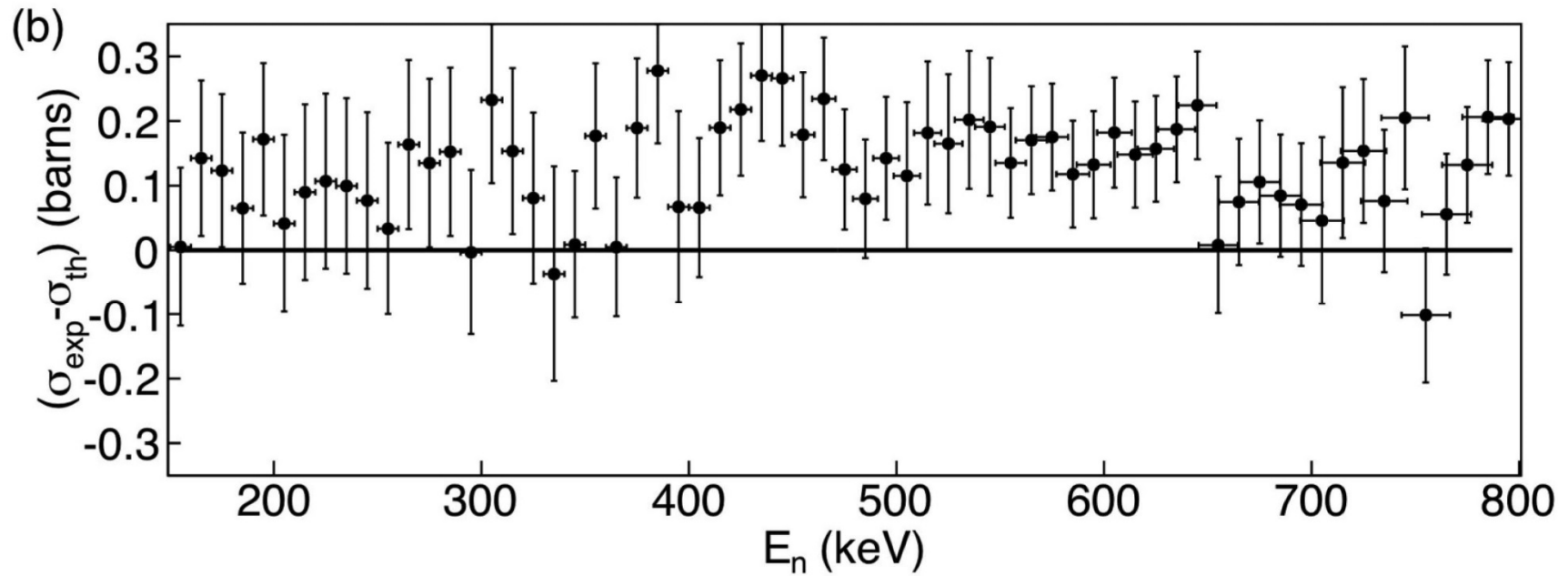
Ohio University Collaboration Results at 14.9 MeV compared with Evaluations



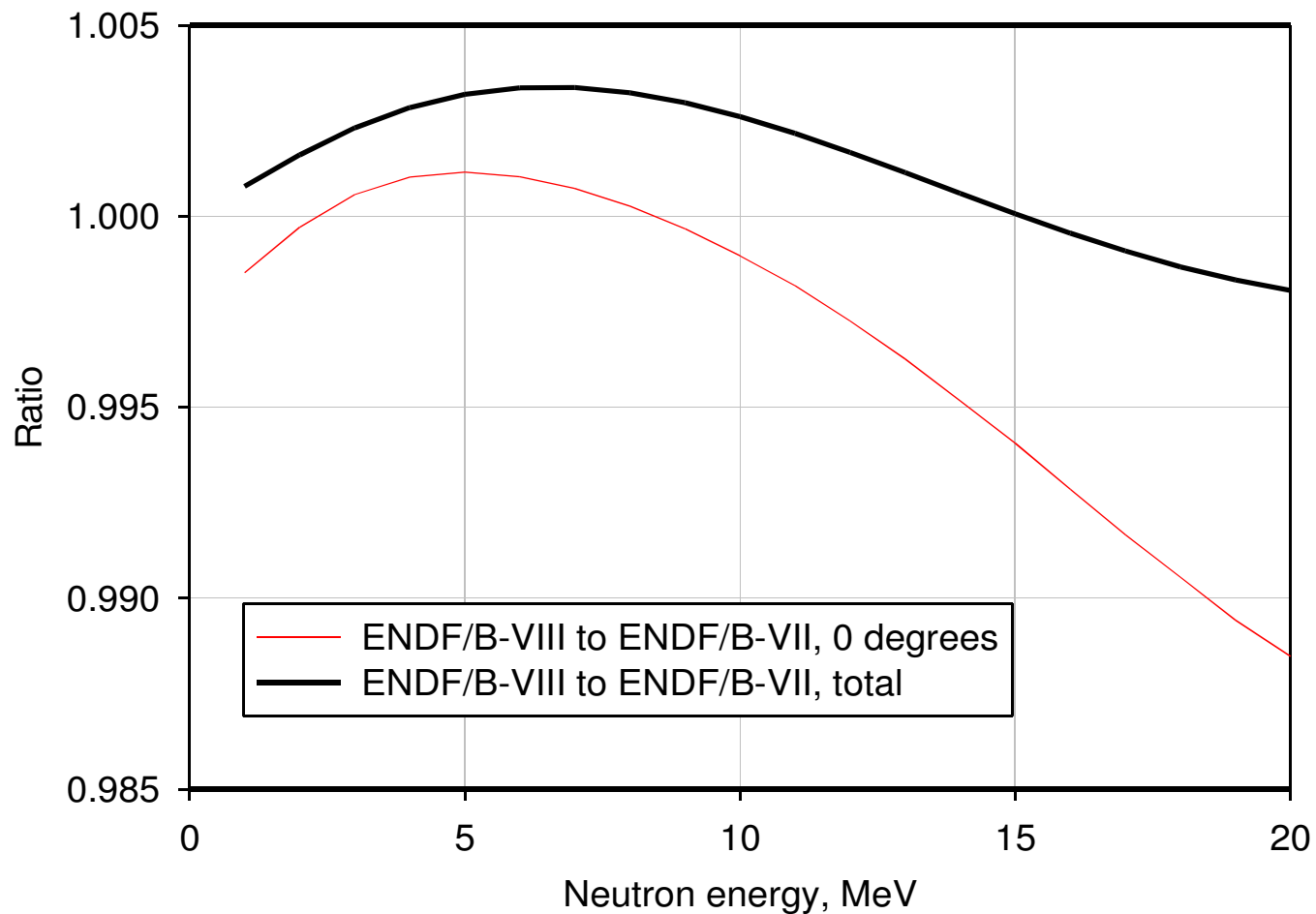
Recent H(n,n)H Standard Measurements

- Concerns about the hydrogen total scattering cross section at low neutron energies led to University of Kentucky Van de Graaff work 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%.
- Additional total cross section work at Kentucky has been done by Yang. The focus was on lower neutron energies than those obtained by Daub *et al.* Data were obtained from 90 keV to 1.8 MeV with uncertainties of 1-2%.

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



H(n,n) R-Matrix Evaluation by Hale and Paris (ENDF/B-VIII Standard) compared with the ENDF/B-VII Standards Evaluation



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

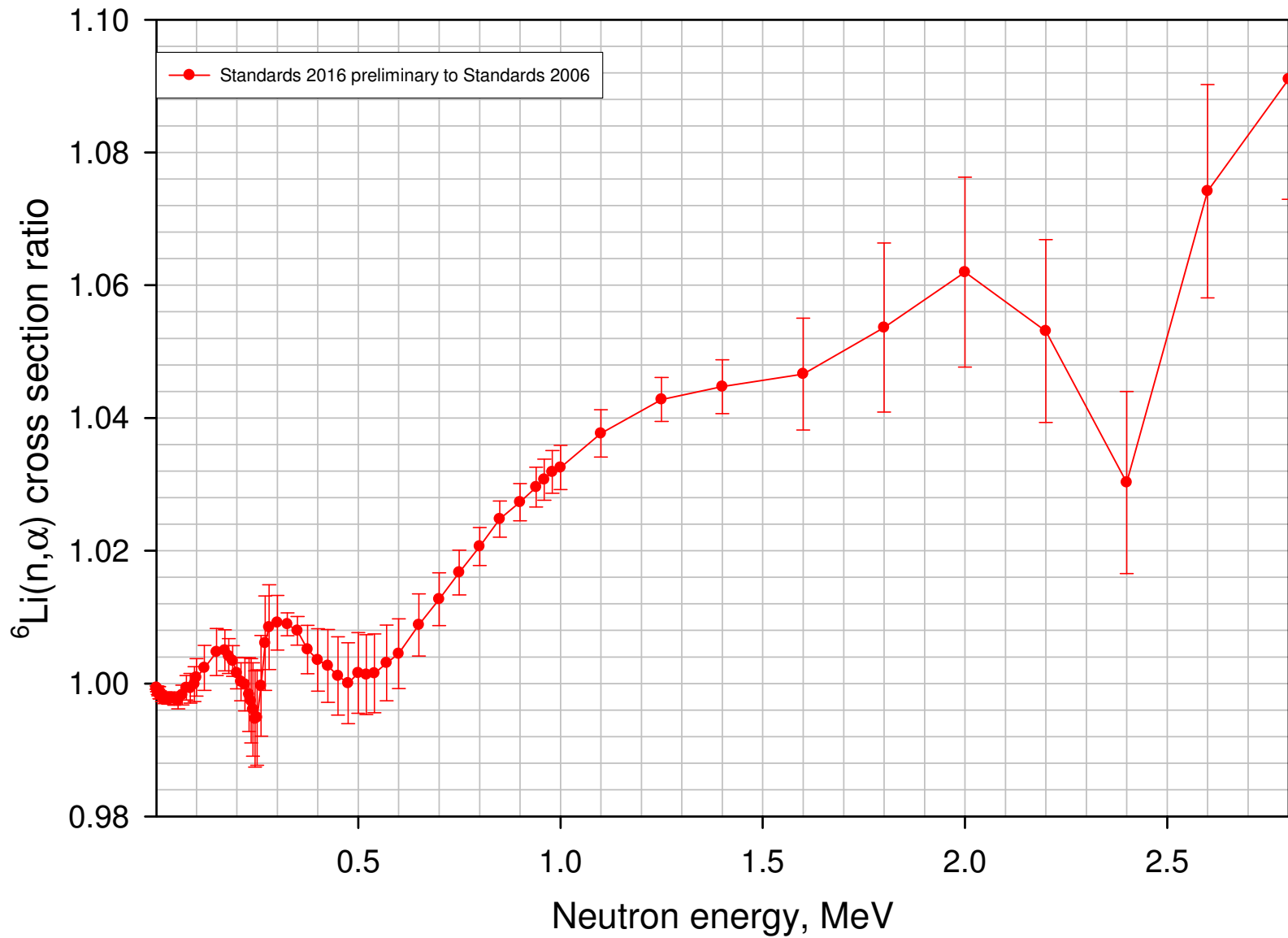
- At the NIST Neutron Center for Neutron Research a measurement was made of the ${}^6\text{Li}(n,t)$ cross section standard with a 0.3% uncertainty at 3.3255 meV.
- This is the first direct and absolute measurements of this cross section in this neutron energy range using monoenergetic neutrons.
- A primary effort was focused on measuring the neutron fluence accurately. It was determined with an uncertainty of 0.06%.
- Work continues on trying to determine the mass uncertainty of the ${}^6\text{Li}$ target. The original mass yielded a cross section in excellent agreement with the standards evaluation. The deposits were made at IRMM, however IRMM recently found an error so the mass changed by about 1%. This leads to a cross section lower than the standard by about 1%.
- To check the IRMM mass determination, a new measurement using Isotope Dilution Mass Spectrometry is planned at NIST if funding can be obtained.

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

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

- Measurements have been made of the ${}^6\text{Li}(n,t)$ cross section by Devlin et al. at LANL. This work includes angular distribution data obtained from 0.2 to 10 MeV at eight laboratory angles using four E- Δ E telescopes. These data are absolute ratios to the ${}^{235}\text{U}(n,f)$ cross section and also the hydrogen scattering cross section. An R-matrix analysis using these data led to larger cross sections particularly about 1 MeV and above.
- Measurements by Giorginis and Bencardino at IRMM were made in the 2 MeV energy region. The data agreed with the ENDF/B-VII standards evaluation at 1.9 MeV but was 2.6% higher at 2.0 MeV and 1.8% higher at 2.1 MeV
- Zhang at Peking University made angular distribution measurements at 1.05 MeV and 1.54 MeV relative to the ${}^{10}\text{B}(n,\alpha)$ standard; and at 1.85, 2.25, and 2.67 relative to the ${}^{238}\text{U}(n,f)$ standard.

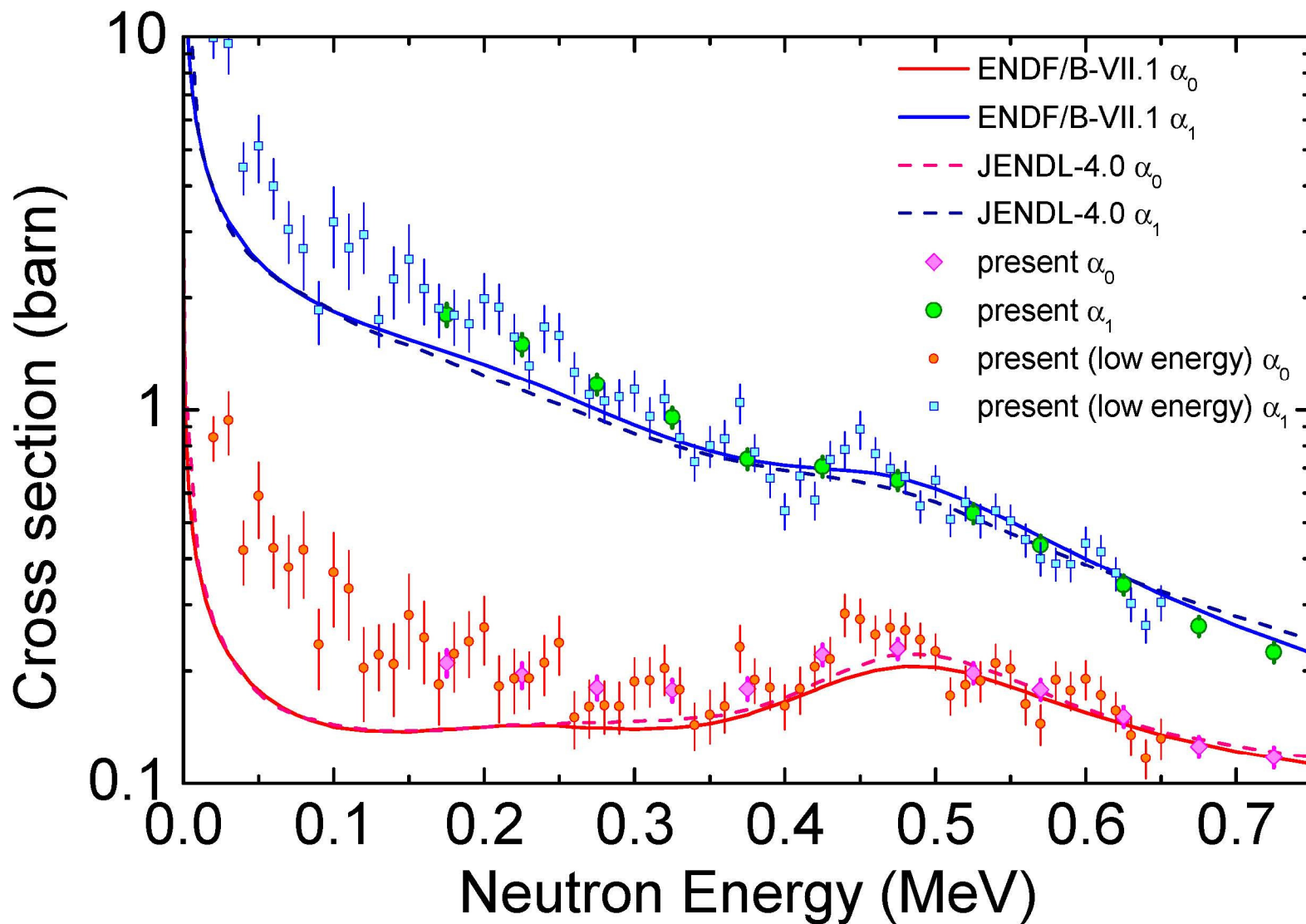
Comparison of the ${}^6\text{Li}(n,t)$ Standards Evaluations



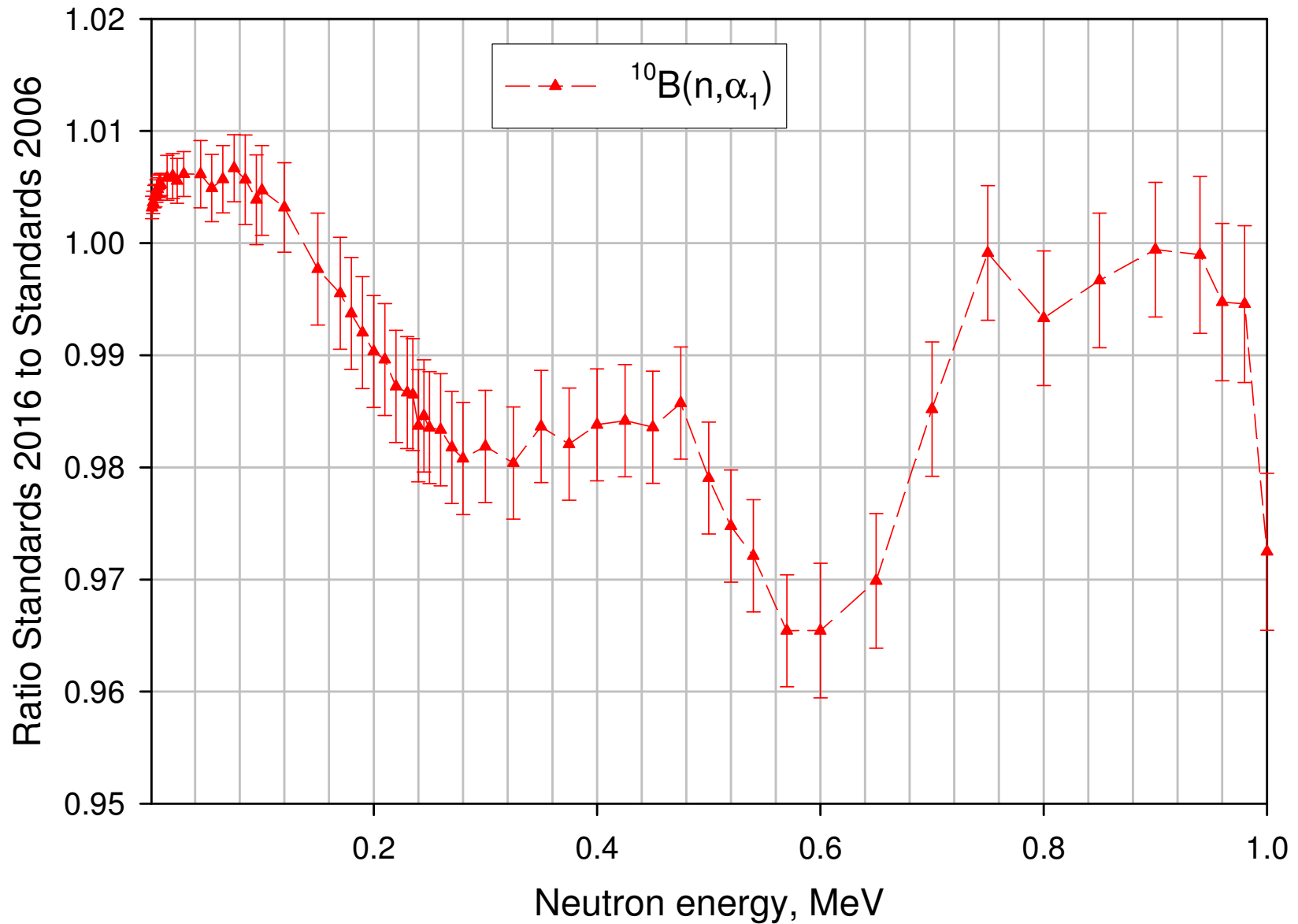
$^{10}\text{B}(n,\alpha)$ and $^{10}\text{B}(n,\alpha_1\gamma)$ Measurements

- Habsch has measurements of the branching ratio, the angular distribution and the $^{10}\text{B}(n,\alpha)$ and $^{10}\text{B}(n,\alpha_1\gamma)$ cross sections relative to the $^{235}\text{U}(n,f)$ standard up to 1 MeV. The data were obtained at the 60m station of GELINA at IRMM. They have good statistics but there appear to be some systematic problems. The branching ratio measurements look **high at the highest energies** and **the $^{10}\text{B}(n,\alpha)$ and $^{10}\text{B}(n,\alpha_1\gamma)$ cross sections used to make that ratio are high below about 0.5 MeV**. It could be something in common such as the fluence determination.
- Zhang et al. made measurements with a Frisch gridded ionization chamber of the $^{10}\text{B}(n,\alpha)$ angular distribution relative to the $^{238}\text{U}(n,f)$ standard at 4 and 5 MeV . These data are in very good agreement with the 2006 data of Giorganis and Khryachkov.

IRMM Preliminary Measurements of the $^{10}\text{B}(n,\alpha_0)$ & $^{10}\text{B}(n,\alpha_1)$ Cross Sections



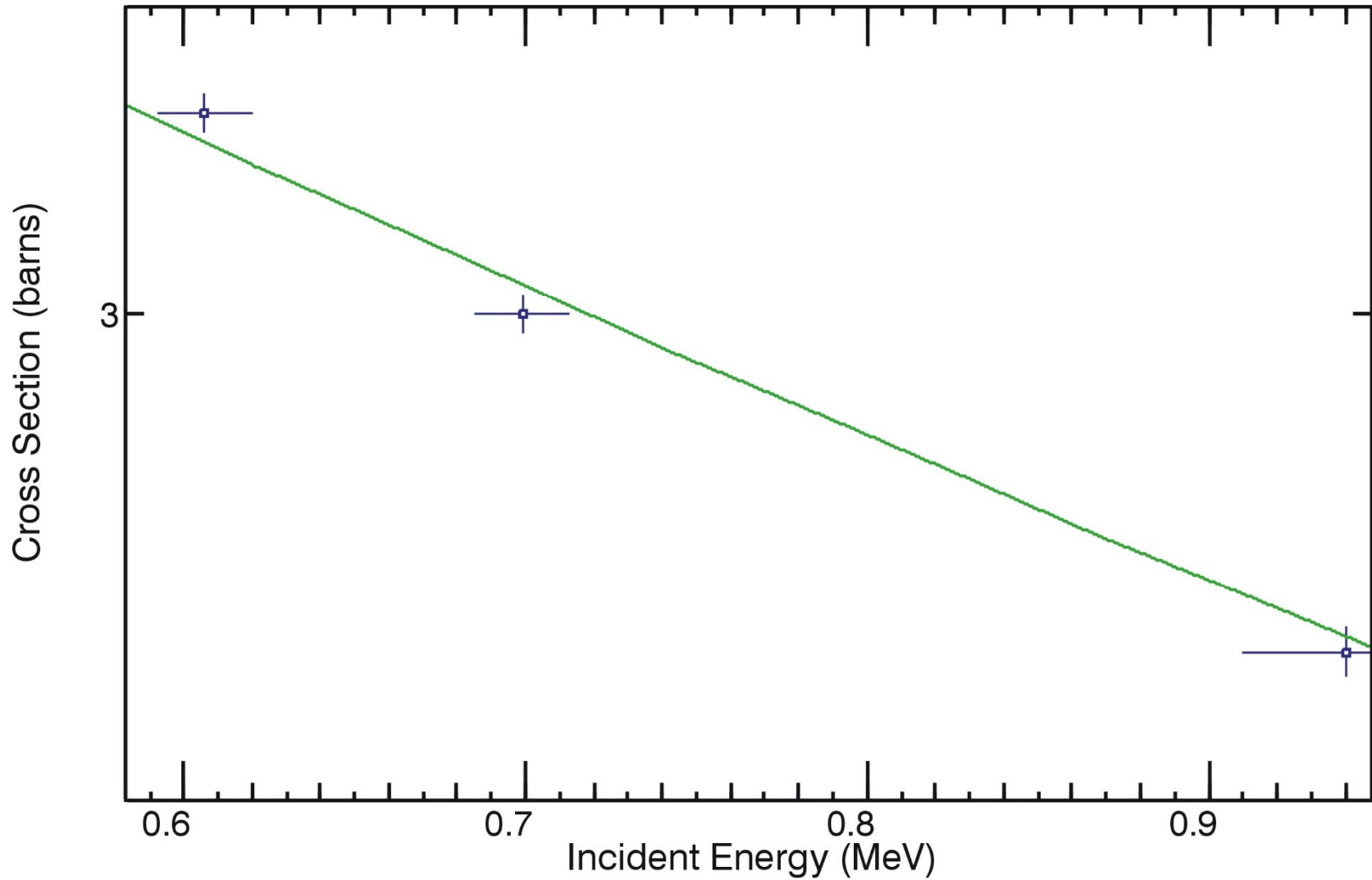
Comparison of $^{10}\text{B}(n,\alpha_1\gamma)$ Standards Evaluations



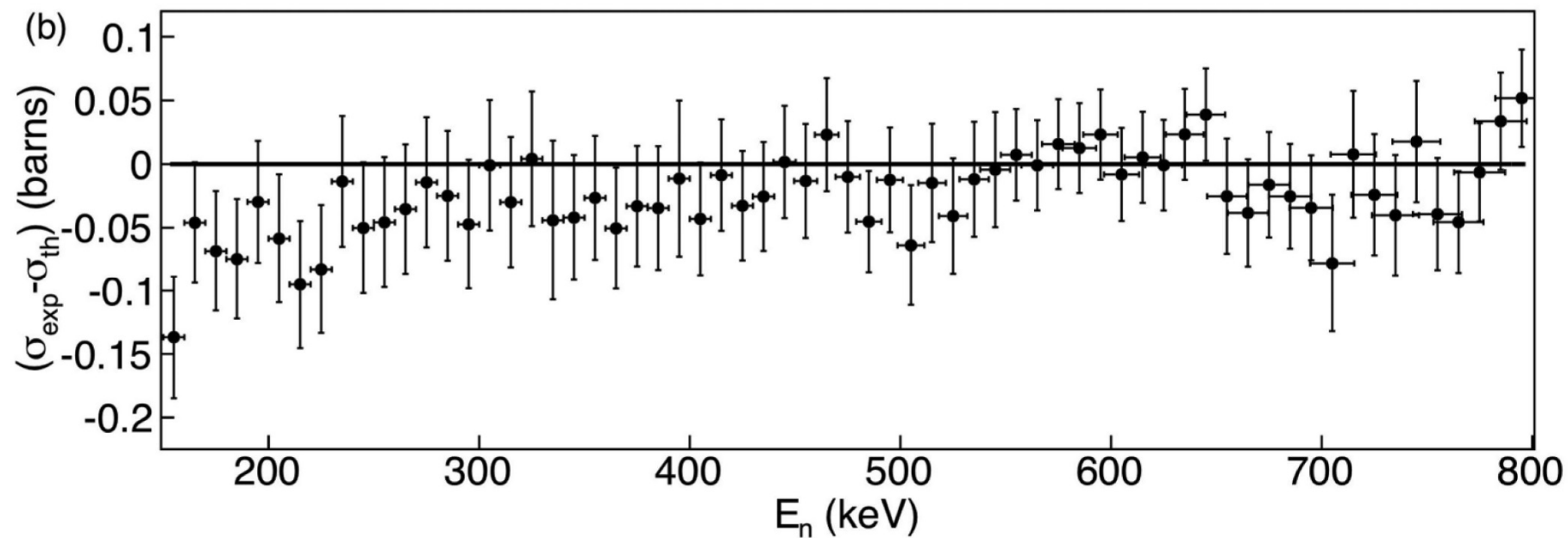
C(n,n) Data

- 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 evaluation values but generally within their uncertainties of 1.1 to 2%.
- In addition to the n-p total cross section work, Yang *et al.* also made carbon total cross section measurements since a polyethylene sample was used in the experiment. The focus was on lower neutron energies.
- Danon *et al.* made very accurate measurements of the carbon total cross section using an iron filtered linac neutron beam. The data were obtained for 19 peaks from 24.3 to 945 keV. This method provided very low backgrounds. The results obtained with an accuracy of better than 1% were in excellent agreement with the ENDF/B-VII evaluation.
- Gritzay *et al.* reported at the ND2007 conference carbon total cross section data taken at the Kyiv reactor using filtered beams with energies of 2, 3.5, 12, 24, 55, 59, 133 and 148 keV. They are generally in good agreement with the ENDF/B-VII evaluation. However, with 1-2% uncertainties, at the lower energies their results are somewhat low and at 148 keV their result is about 5 standard deviations higher. However these data are considered preliminary

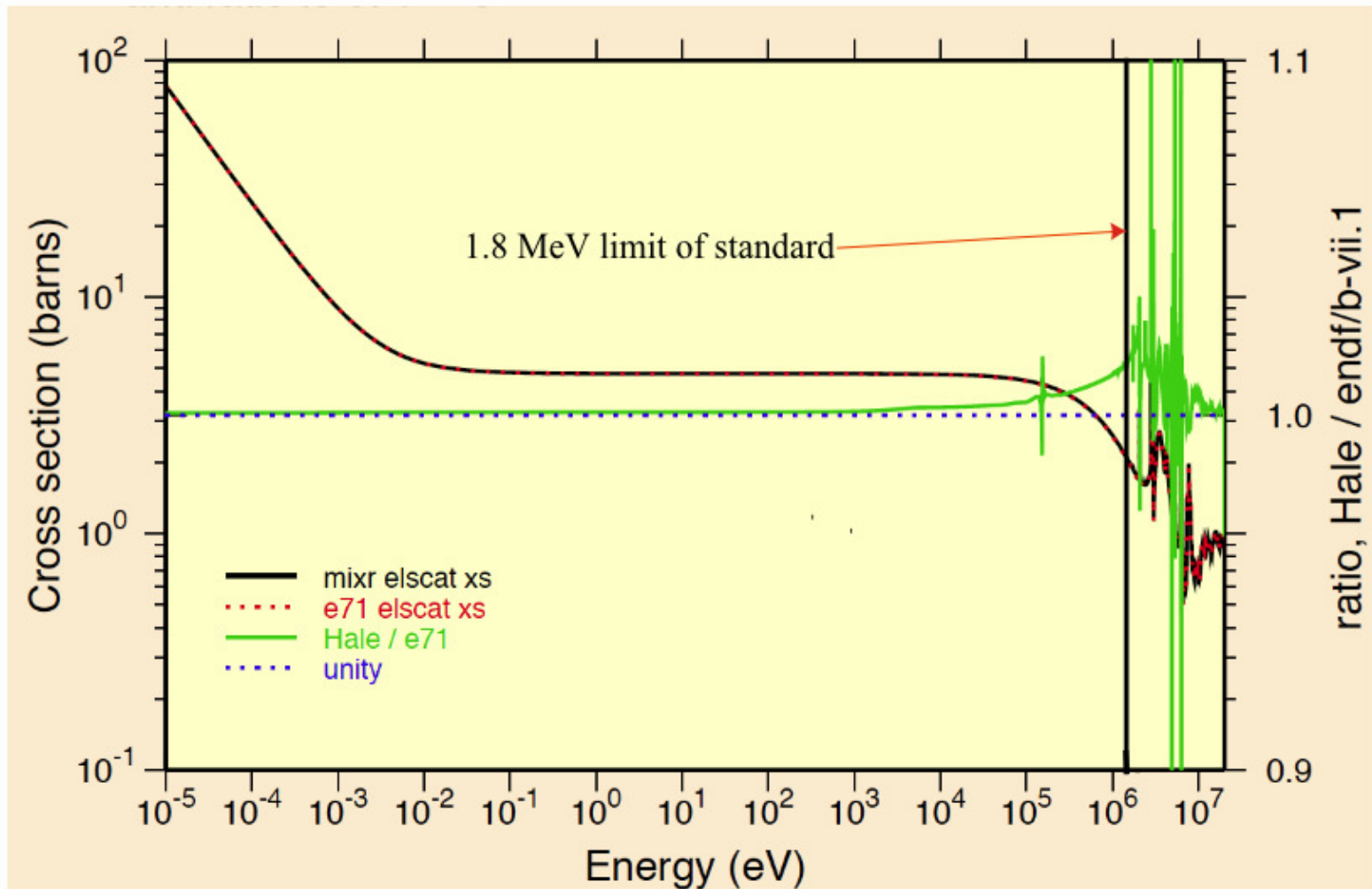
Danon *et al.* Carbon Total Cross Section Compared with ENDF/B-VII



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



Comparison of Natural Carbon Total Cross Section Standards Evaluations - Preliminary Results

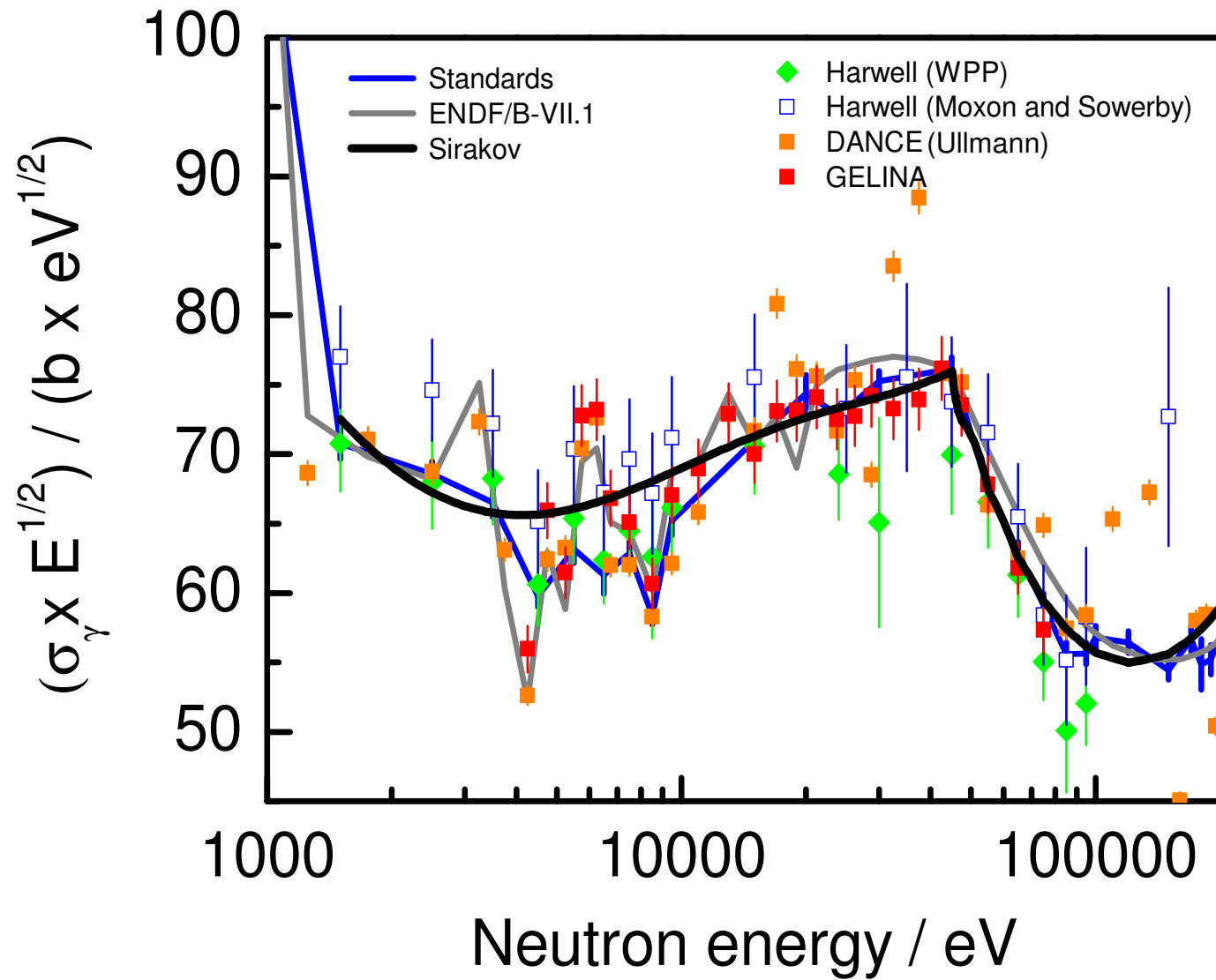


Au(n, γ) and $^{238}\text{U}(n,\gamma)$ Measurements

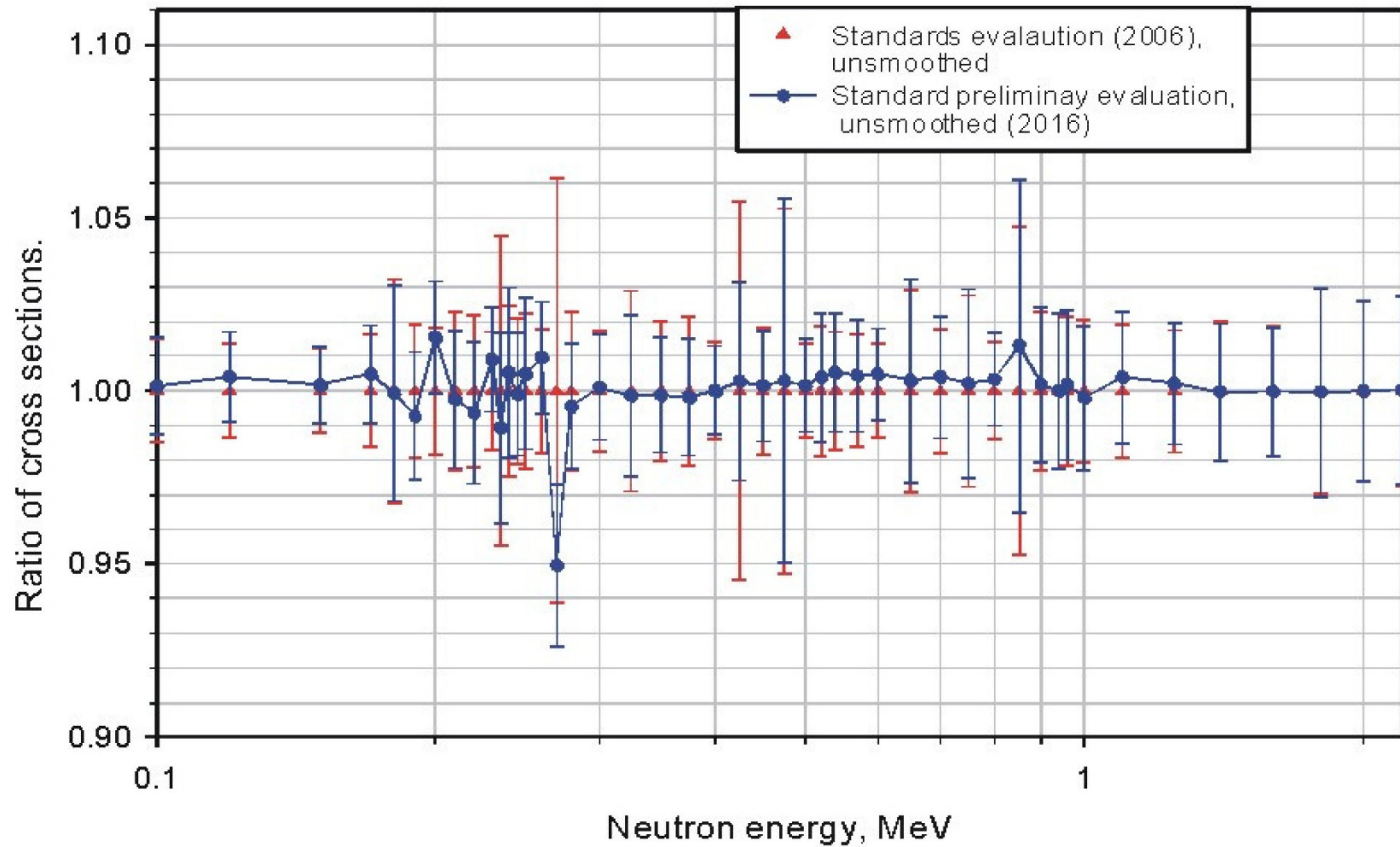
- Wallner (U. of Vienna) made measurements of the $^{238}\text{U}(n,\gamma)/^{197}\text{Au}(n,\gamma)$ cross section ratio at 426 keV. Accelerator mass spectrometry was used to measure the ^{239}Pu resulting from the ^{239}U . Activation was used for the gold measurements. The measurement has a large (150 - 200 keV FWHM) energy spread. That ratio, 0.99 ± 0.04 , compared with the standards evaluation is in excellent agreement.
- Ullmann *et al.* made measurements of the $^{238}\text{U}(n,\gamma)$ cross sections using the DANCE. Though the data could be made absolute, they are now normalized to capture in the 80 and 145 eV resonances. They associate a 2 percent uncertainty to this normalization. They state there is generally good agreement with the ENDF/B-VII evaluation. For the evaluation, it was decided that the data from 150 keV to 500 keV could be used in the evaluation, but the data from 10 keV to 150 keV could not be included due to structure in the data.

At GELINA $^{238}\text{U}(n,\gamma)$ cross sections measurements were made by Kim *et al.* using a C_6D_6 detector with very high accuracy. They agree very well with the ENDF/B-VII data

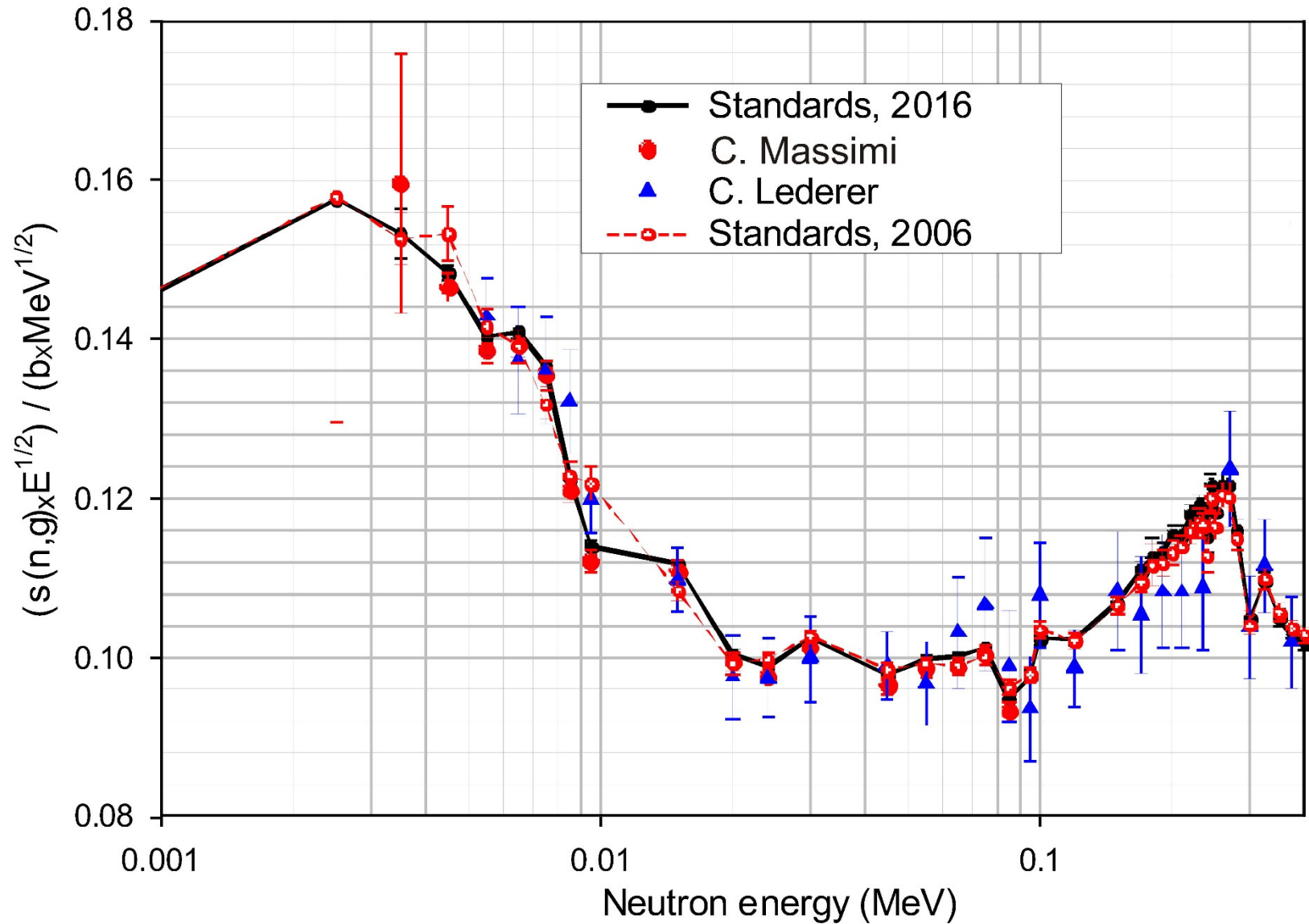
Measurements and Evaluations of the $^{238}\text{U}(n,\gamma)$ Cross Section



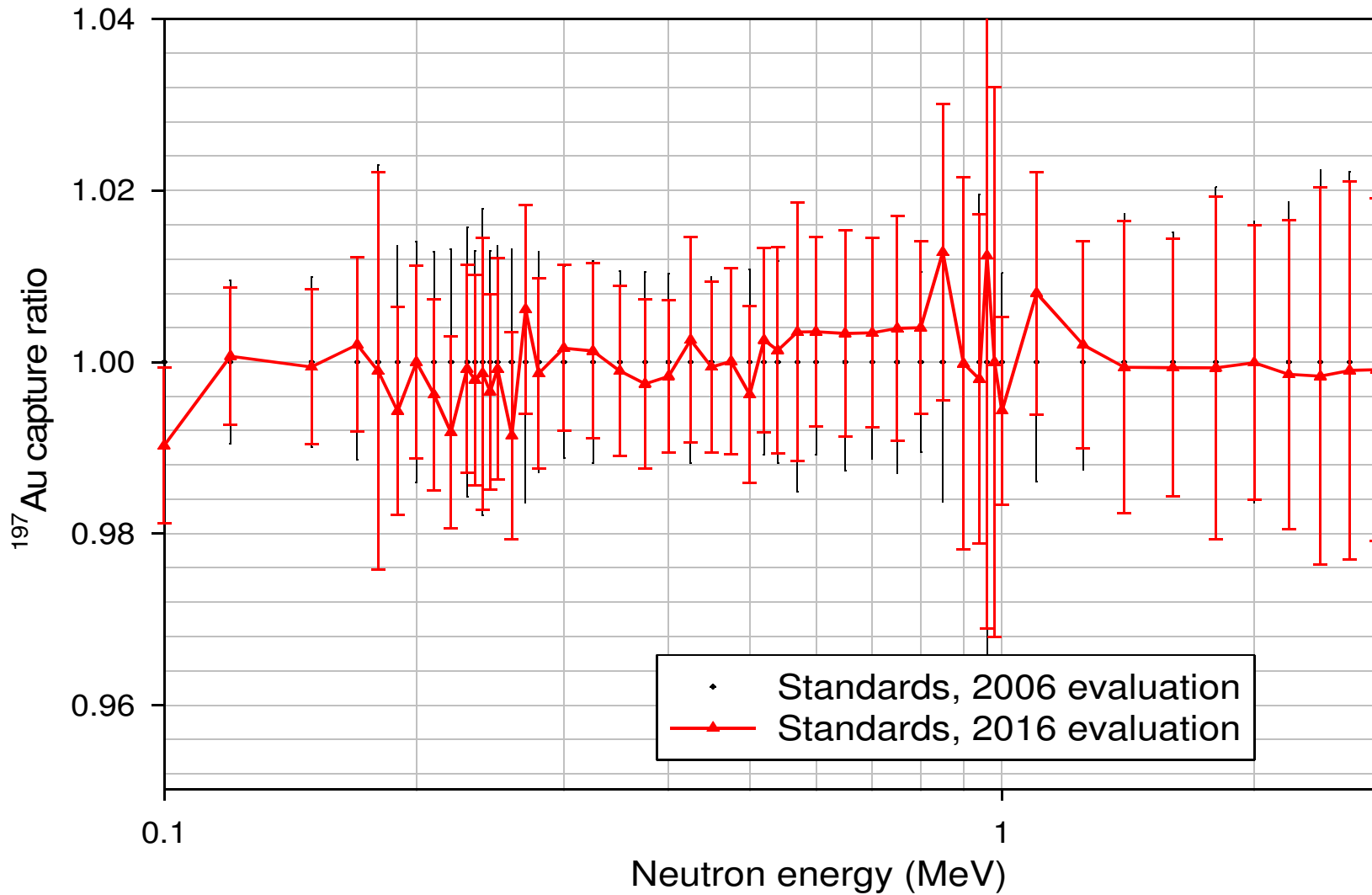
Comparison of $^{238}\text{U}(n,\gamma)$ Evaluations



Au(n, γ) Cross Section Measurements and Evaluations



Comparison of Au(n, γ) Standards Evaluations



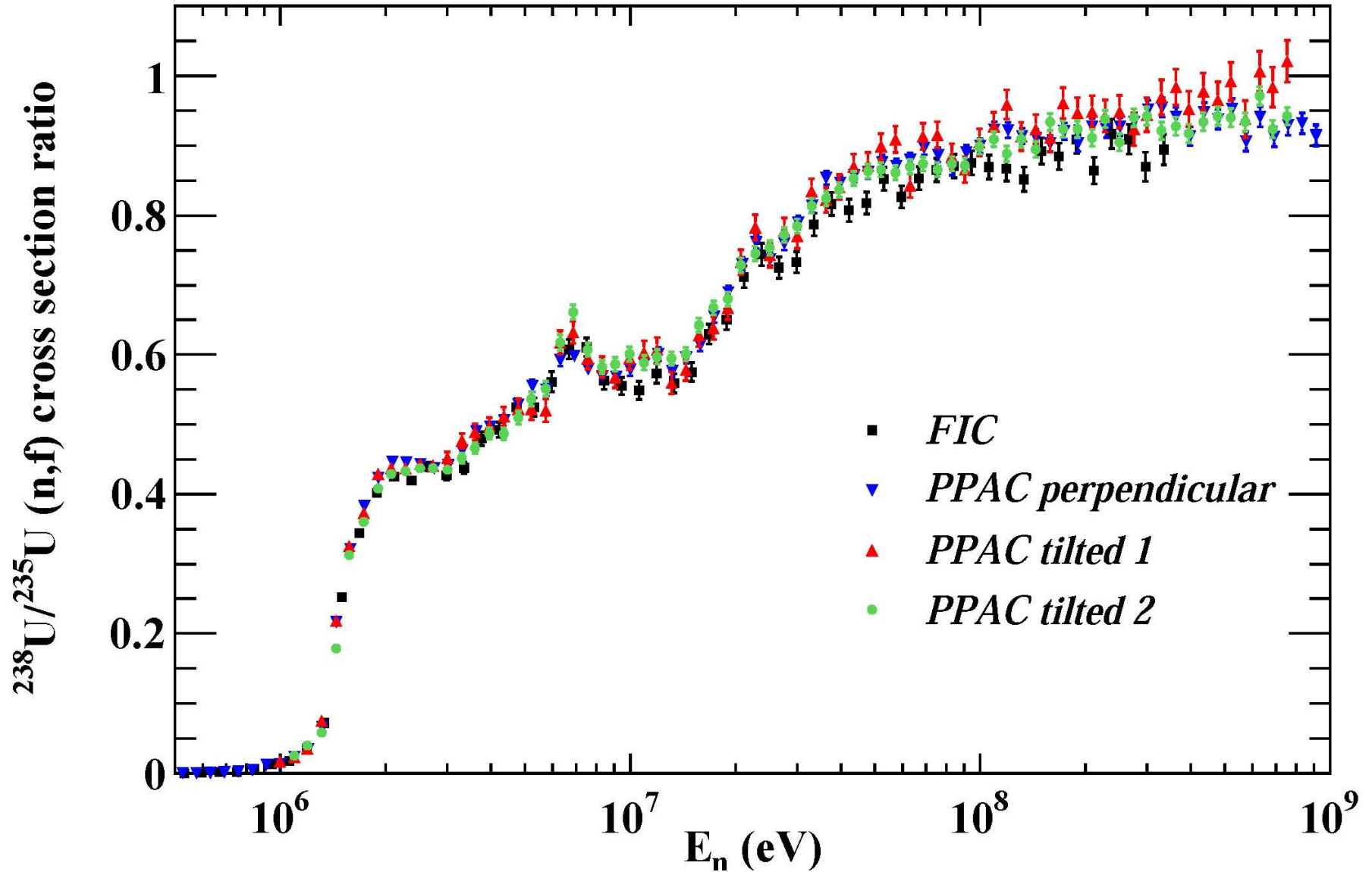
$^{239}\text{Pu}(n,f)$ Measurements

➤ The most recent $^{239}\text{Pu}(n,f)$ cross section measurements were made by Tovesson and Hill at WNR-LANL. They agree reasonably well with the ENDF/B-VII standards evaluation and the Lisowski *et al.* and Shcherbakov *et al.* measurements up to about 10 MeV. The new measurements have somewhat smaller uncertainties than these other two data Sets. Above 10 MeV these new measurements fall somewhat lower than the ENDF/B-VII evaluation and the Lisowski *et al.* and Shcherbakov *et al.* measurements except above about 100 MeV where they agree with the Lisowski *et al.* data.

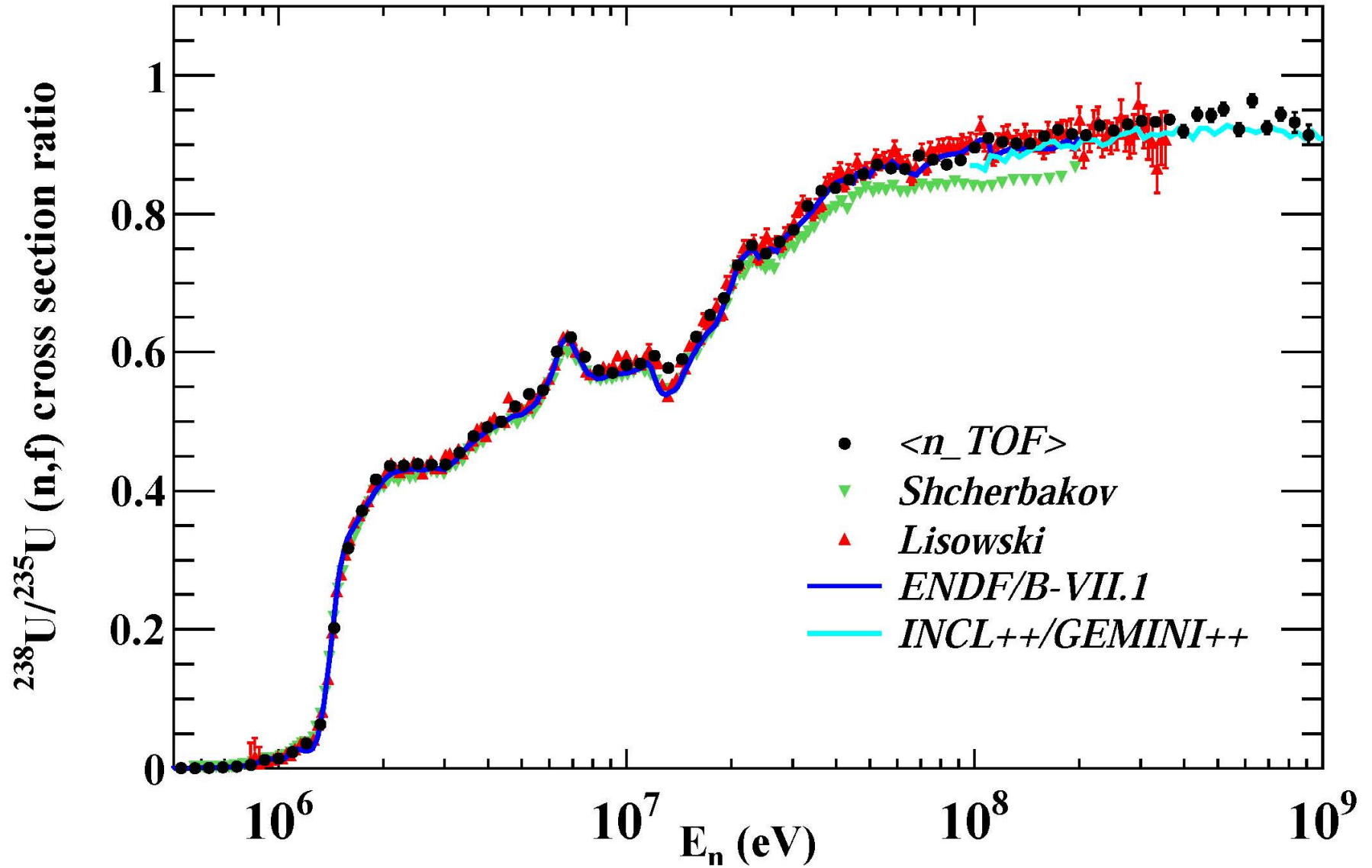
$^{235}, ^{238}\text{U}(\text{n},\text{f})$ Measurements

- Four measurements of the $^{238}\text{U}(\text{n},\text{f})/^{235}\text{U}(\text{n},\text{f})$ cross section ratio were made at the n_TOF facility.
 - Fission chamber measurements were made (by Calviani).
 - Parallel plate avalanche counters were used for 3 sets of measurements (all formerly associated with Audouin).
 - The same deposits were used for both the PPAC perpendicular (by Paradela) and the PPAC tilted 1 (by Tarrío) measurements. The difference was that the perpendicular measurements were made with the deposits perpendicular to the beam direction whereas the tilted 1 measurements were made with the deposits at 45° to the beam direction.
 - The third setup for the PPAC detectors, PPAC tilted 2 (by leal-chidoncha), again were made with the deposits at 45° to the beam direction, were not as well characterized as the other deposits so they were normalized to ENDF/B-VII.1 between 3 and 5 MeV.
- The PPAC sets are slightly higher than the fission chamber data but they agree within their uncertainties. They all agree reasonably well with the standards evaluation.

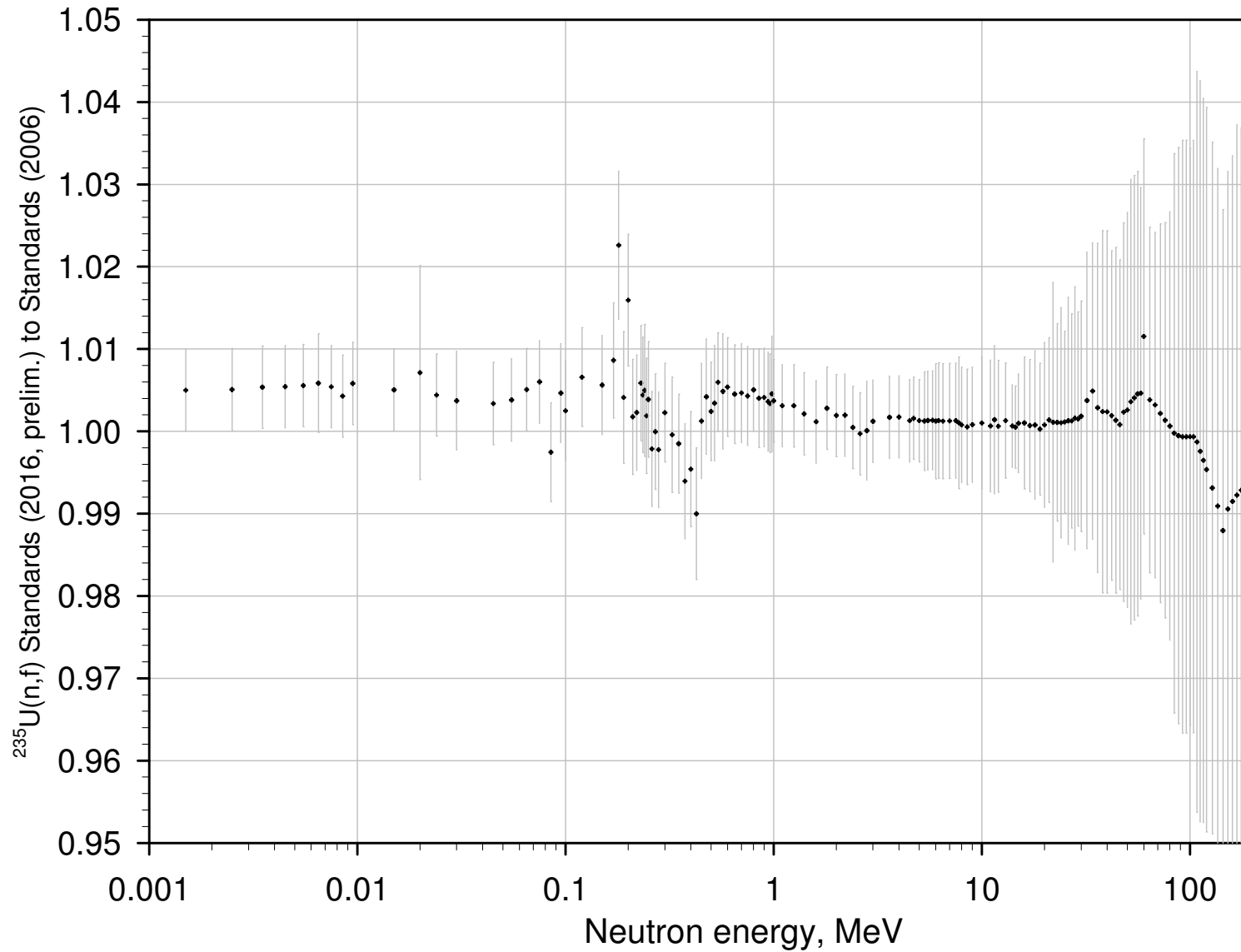
$^{235, 238}\text{U}(n,f)$ n_TOF Measurements



$^{235, 238}\text{U}(n,f)$ Measurements and Evaluations



Comparison of $^{235}\text{U}(n, f)$ Standards Evaluations

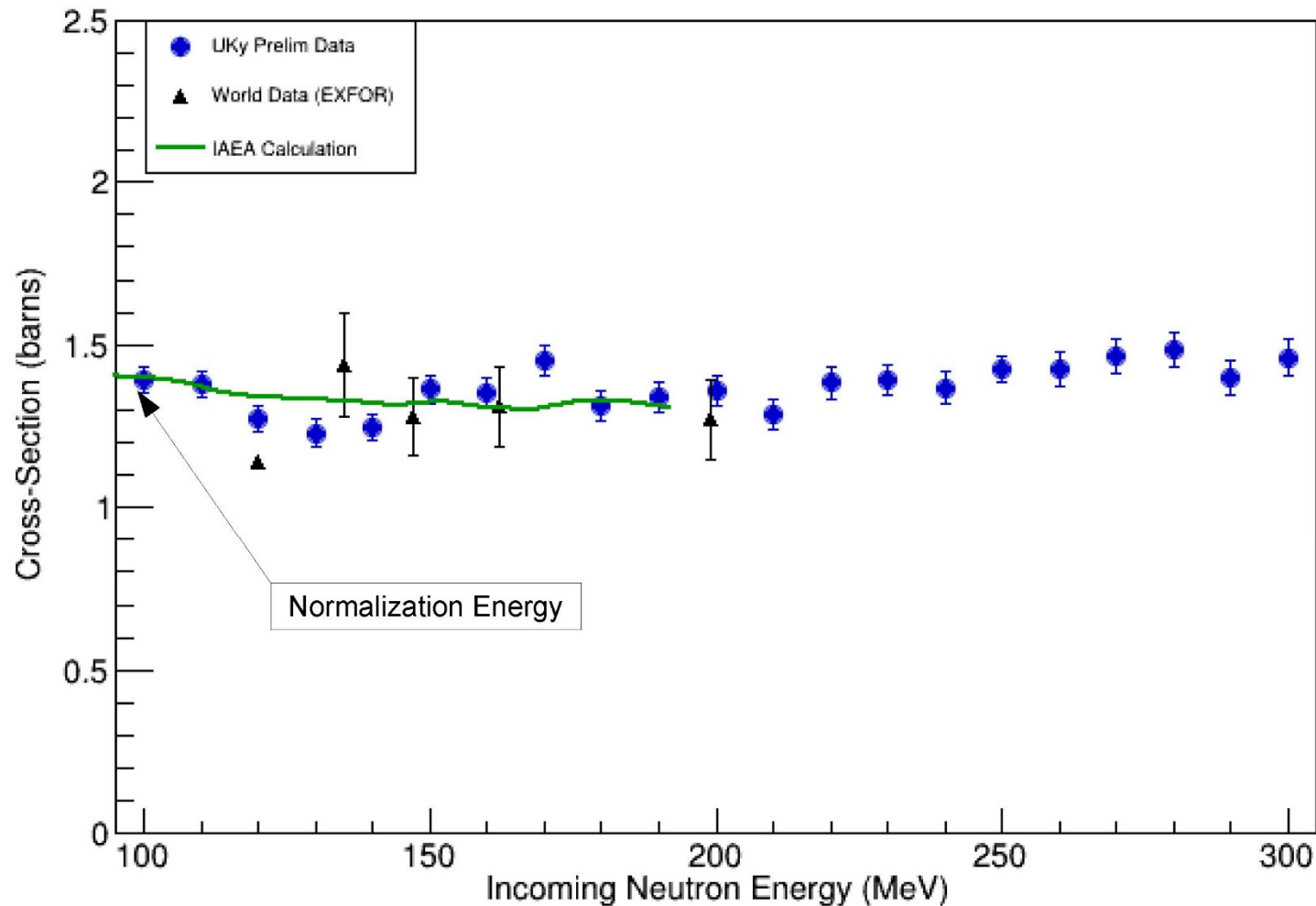


$^{238}\text{U}(\text{n},\text{f})$ Measurements

➤ Measurements were made by Miller from the University of Kentucky of the $^{238}\text{U}(\text{n},\text{f})$ cross section relative to hydrogen scattering. The data are shape measurements extending from 100 to 300 MeV. The data were obtained at the LANL WNR facility.

Very Preliminary Results

U-238 (n,f) Cross-Section



Comparison of $^{238}\text{U}(n, f)$ Standards Evaluations

