

Report on U.S. Experimental Activities

WPEC 2014

Yaron Danon

Rensselaer Polytechnic Institute, Troy, NY 12180, USA

CSEWG measurements committee chair

WPEC May 15-16, 2014, NEA Paris, France

Introduction

- This presentation summarizes the activity that was presented in the November 2013 CSEWG meeting.
 - Full reports are available on the CSWEG web page.
- Reports from different laboratories:
 1. Nuclear Data Experiments at LANSCE: Highlights 2013, Robert Haight (LANL)
 2. Recent ORNL Measurements, Michael Dunn (ORNL)
 3. Recent Nuclear Data Research at RPI, Yaron Danon (RPI)
 4. NIST Measurements and Standards including Related Work at Other Facilities, Allan Carlson (NIST)
 5. Recent EGAF Thermal Neutron Cross Section Measurements, Richard Firestone (LBNL)
 6. Possibilities for nTOF at BNL, Steve Peggs (BNL)
- 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)**
 - Non Actinides
 - ^{152,154,156,158}Gd - Bayarbadrakh Baramsai, NCSU/LANL, Published
 - ⁹⁷Mo - Carrie Walker, NCSU PhD dissertation, completed
 - ^{117,119}Sn - Carrie Walker, NCSU PhD dissertation, in progress
 - ¹⁷³Lu – Capture, O. Roig (CEA), in progress
 - ^{184,186}W - Capture, Marian Jandel LANL, in progress
 - ^{191,193}Ir - Capture; Todd Bredeweg LANL,
 - ¹³⁶Xe - Capture, gas target; data taken
 - ¹⁶¹Dy - Capture, data taken
 - Actinides
 - ^{233,235}U, ^{239,241}Pu - Capture to fission: LANL, LLNL, in progress. ²³⁵U (n,γ) experiment was published in Phys. Rev. Let. ²³⁹Pu for E<1 keV was submitted for publication. ²⁴²Pu data was taken by LLNL.
 - ²³⁵U, ^{239,241}Pu - Fission gamma ray multiplicity and spectra: LANL/LLNL, (Prelim ²³⁹Pu, ²³⁵U was reported). ²³⁹Pu (n,γ) cross section was presented, it is generally in good agreement with ENDF.V-VII.1, disagreement in some resonances (~65 eV).
 - ²³⁹Pu - fission gamma spectrum was shown for different multiplicities.
 - ²³⁸Pu - Capture, capture/fission: LLNL, was published.
 - ²⁵²Cf - Fission gamma multiplicity and spectra: LLNL published in Phys. Rev. C.,
 - ^{242m, 243}Am - Capture, Marian Jandel LANL, preliminary report submitted
 - ²³⁸U - Capture cross section, gamma rays, John Ullmann LANL, near completion
 - **Cd** – gamma ray spectrum as a function of multiplicity was shown and compared with DICEBOX calculations.
- **GEANIE – (Germanium Array for Neutron Induced Excitations)**
 - ⁸⁶Kr (n, xn yp γ) - 10 new transitions (N. Fotiades ND2013). A plot with the new transitions was shown.
 - ¹⁰⁹Ag (n,xy) - over 100 transitions in 12 reaction channels leading to Ag and Pd – in progress (N. Fotiades)
 - ¹²⁴Xe, ¹⁷⁶Lu (n,xy) – in progress
 - Millisecond isomers: ^{71m}Ge, ^{114m2}I, ^{208m}Bi, ^{88m1}Y, ^{88m2}Y, and ^{75m}As - M. Devlin. An Example of the measured half-life of ^{75m}As was presented.
 - Various elements for a neutron-induced gamma-production reference cross sections (R. Nelson): ⁷Li (n,n')⁷Li*, **Ti, Cr, Fe**
 - x-ray yield from n-induced fission (R. Nelson and Thierry Granier - CEA) – published

LANL (continued)

- **Fission Cross Sections Fission Total Kinetic Energy Fission Fragment Yields**
 - $^{233,234,236,238}\text{U}$ (n,f) cross section measured from 0.2-200 MeV, completed, submitted to Nucl. Sci. Eng. Plots of results were shown comparing the data to ENDF/B-VII and JENDL 3.3 and 4.0
 - High precision cross sections with TPC
 - $^{238}\text{U}(n,f)$ relative to $^{235}\text{U}(n,f)$: Data collection and analysis in progress
 - $^{239}\text{Pu}(n,f)$ relative to $^{235}\text{U}(n,f)$: Production data collection in progress
 - $^{239}\text{Pu}(n,f)$ relative to $\text{H}(n,n)\text{H}$: not yet started
 - Total kinetic energy (TKE) release in fission
 - ^{238}U : Data collection completed, analysis in progress
 - ^{235}U : Data collection completed, analysis in progress
 - ^{239}Pu : Experiment was scheduled for Dec. 2013
 - Mass yields of fission fragments
 - SPIDER: $^{235}\text{U}(n,f)$ mass yields measured at thermal, analysis in progress
 - Gridded ionization chamber: same status as TKE
- **The Chi-Nu project**
 - Designed to measure prompt fission neutron spectrum using a fission chamber and neutron TOF to liquid scintillators and Li-Glass detectors. The system is now housed in a new building on a dedicated flight path, the new building has low mass floor. In addition to 54 liquid scintillation neutron detectors, it is now instrumented with 22 Li-Glass neutron detectors to allow measurement of fission neutrons with $E < 0.5$ MeV.

Nuclear Data Experiments at LANSCE: Highlights 2013

**Robert C. Haight for LANSCE-NS and colleagues
Los Alamos National Laboratory**

**Cross Section Evaluation Working Group Meeting
US Nuclear Data Program Meeting
Brookhaven National Laboratory
November 18-22, 2013**

LA-UR-13-28836

Collaborations

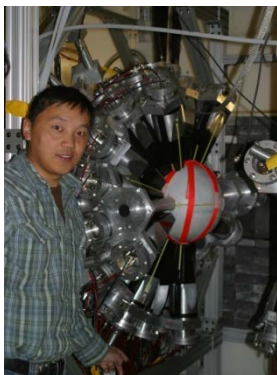
- LANL C-Division, P-Division, T-2
- LLNL
- INL
- ORNL
- NIST
- Universities
 - Rensselaer Polytechnic Institute
 - Rutgers University
 - North Carolina State University
 - Duke University
 - Notre Dame University
 - Ohio University
 - Abilene Christian University
 - Cal Poly San Luis Obispo
 - Colorado School of Mines
 - Georgia Institute of Technology
 - Ohio University
 - Oregon State University
 - Univ. Michigan
 - Univ. Kentucky
 - Brigham Young
 - Texas A&M
 - Washington University
 - Yale University

- Foreign

- CEA France
- IRMM – JRC Geel Belgium
- Charles University Prague, Czech Republic
- Univ. Frankfurt Germany

Nuclear data measurements at LANSCE are made with many different instruments

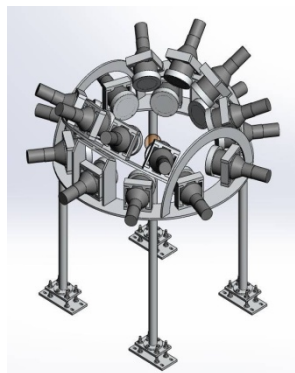
DANCE (n, γ)



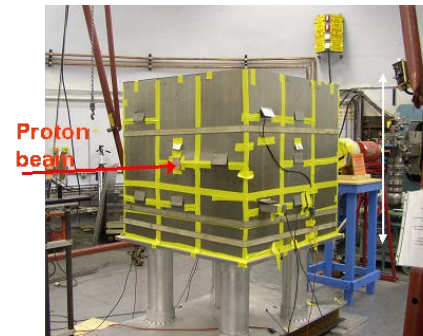
GEANIE ($n, x\gamma$)



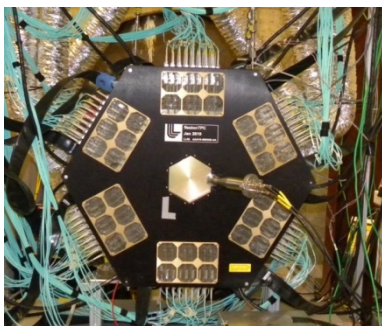
Chi-Nu (n, xn)



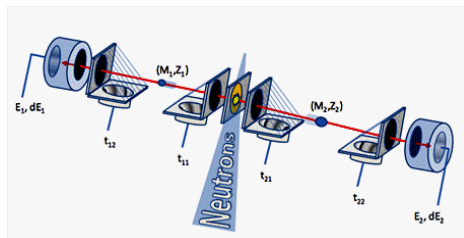
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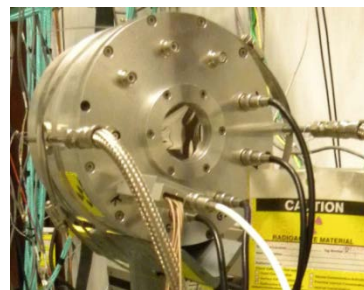
TPC



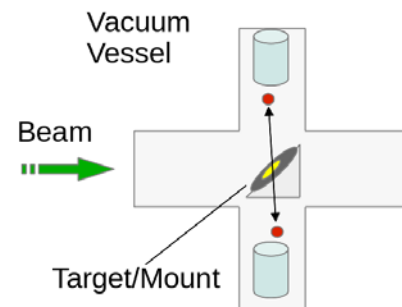
SPIDER



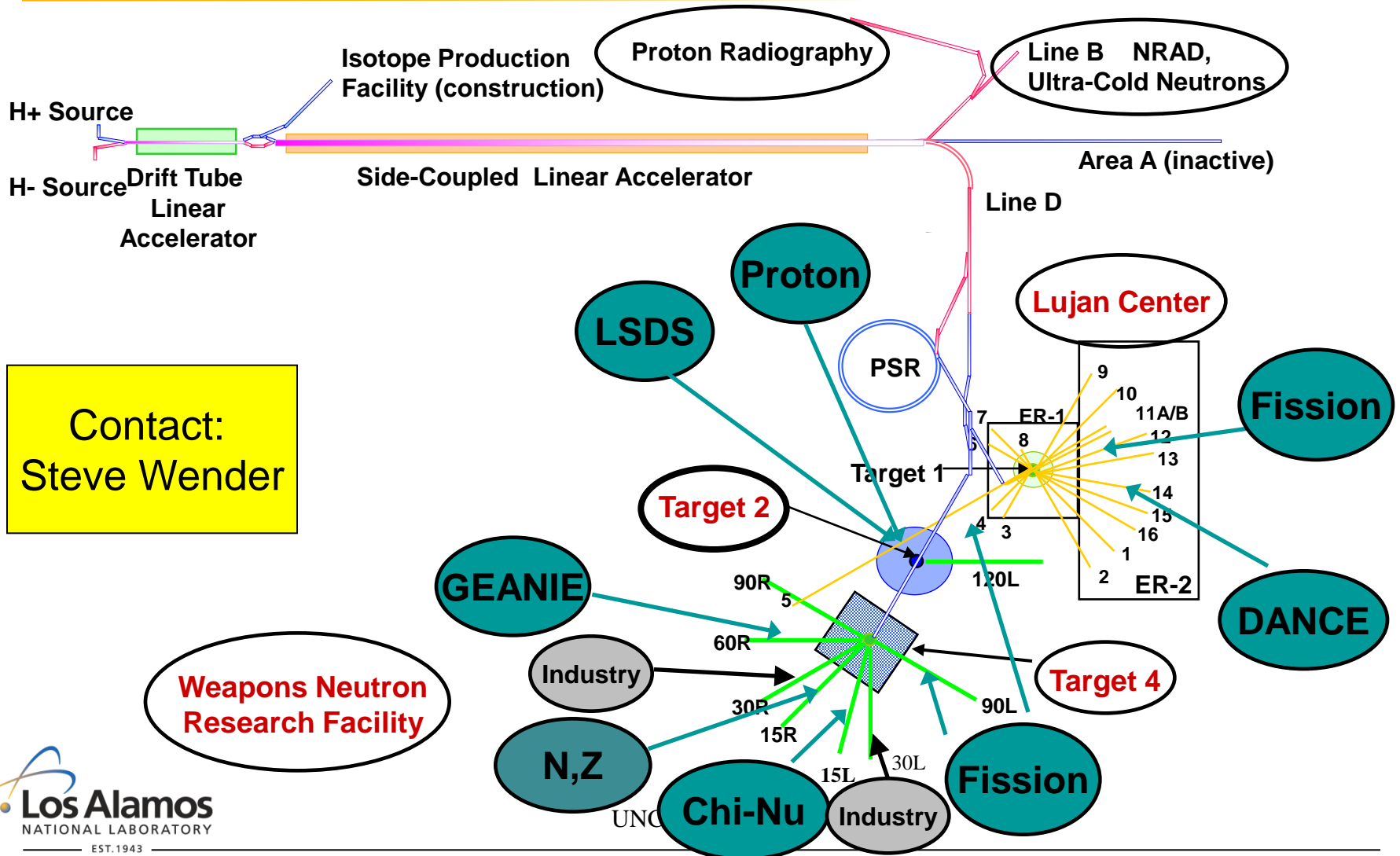
Double gridded ion chamber



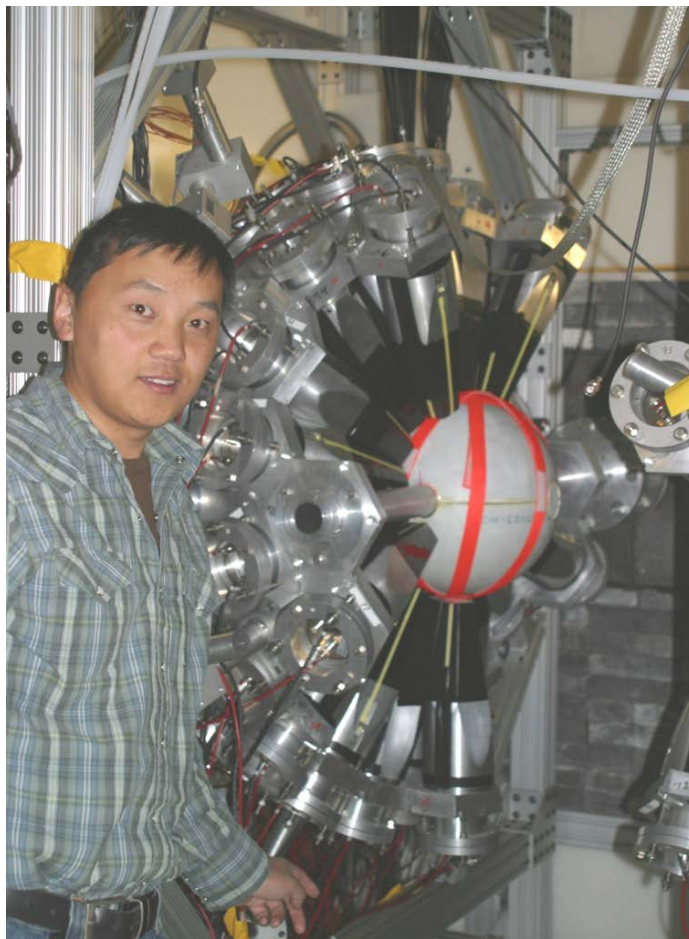
Surface barrier detectors



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



DANCE (n, γ)



Contacts:
John Ullmann
Aaron Couture
Marian Jandel

DANCE research in 2013 (1) – non actinides

$^{152,154,156,158}\text{Gd}(n,\gamma)$

^{97}Mo

$^{117,119}\text{Sn}$

^{173}Lu ($t_{1/2} = 1.37\text{y}$)

$^{184,186}\text{W}$

$^{191,193}\text{Ir}$

^{136}Xe

^{161}Dy

Bayarbadrakh Baramsai, NCSU/LANL; published
 Carrie Walker, NCSU PhD dissertation; completed
 Bayarbadrakh Baramsai, NCSU/LANL; in progress
 Capture. O. Roig (CEA); in progress
 Capture, Marian Jandel LANL; in progress
 Capture; Charles Arnold LANL; in progress
 Capture, gas target; data taken
 Capture, data taken

DANCE research in 2013 (2) - Actinides

$^{233,235}\text{U}$, $^{239,241,242}\text{Pu}$

Capture to fission: LANL, LLNL; in progress

^{235}U published in Phys. Rev. Lett.

^{239}Pu En < 1 keV; submitted for publication

^{242}Pu data taken (LLNL)

^{235}U , $^{239,241}\text{Pu}$

Fission gamma ray multiplicity and spectra: LANL/LLNL (Prelim ^{239}Pu , ^{235}U reported)

Comparison Paper: submitted to Phys Rev C.

Detailed analysis of each: In preparation

^{238}Pu

Capture, capture/fission; published (LLNL)

^{252}Cf

Fission gamma multiplicity and spectra; published (LLNL)

$^{242\text{m},243}\text{Am}$

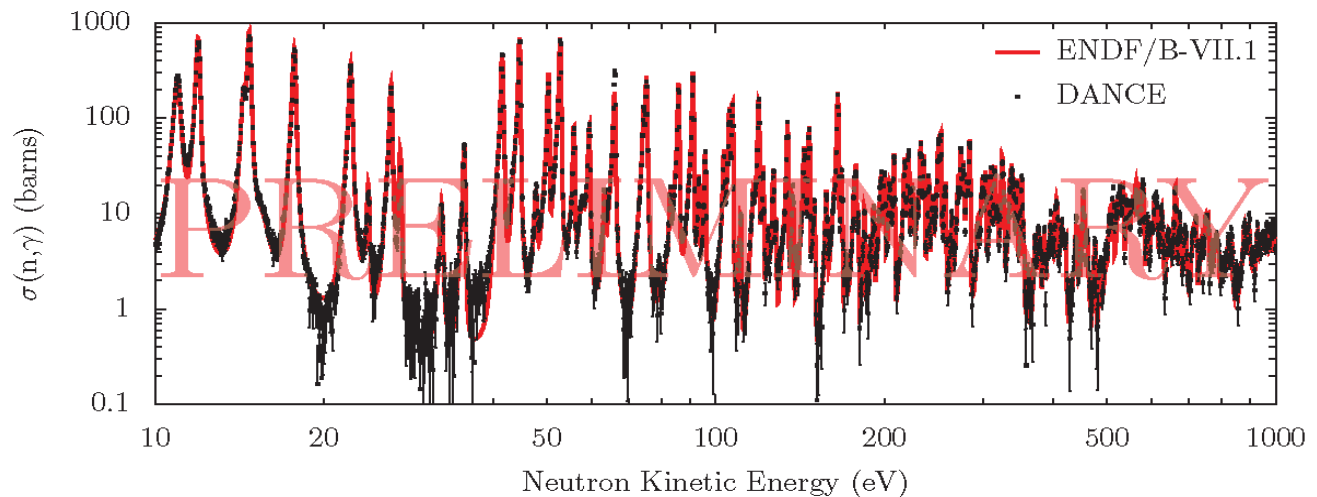
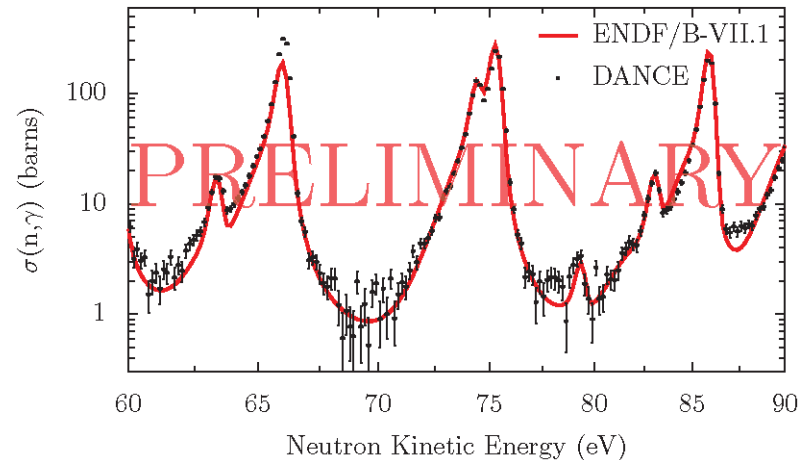
Capture, Marian Jandel LANL; prelim report

^{238}U

Capture xsec, gamma rays John Ullmann LANL; near completion

$^{239}\text{Pu}(n,\gamma)$ cross section from 10 – 1000eV

- Generally good agreement with ENDF/B-VII.1; disagreements at a few resonances
- Good separation between gammas from capture and those from fission through observed multiplicity
- Measurement at higher incident energy in progress



Fission gamma rays from $^{239}\text{Pu}(n,f)$

- **Gamma-ray spectra for several (cluster) multiplicities**
- **Previous works gave average energies and average multiplicities**
- **DANCE gives detailed energy-multiplicity data**

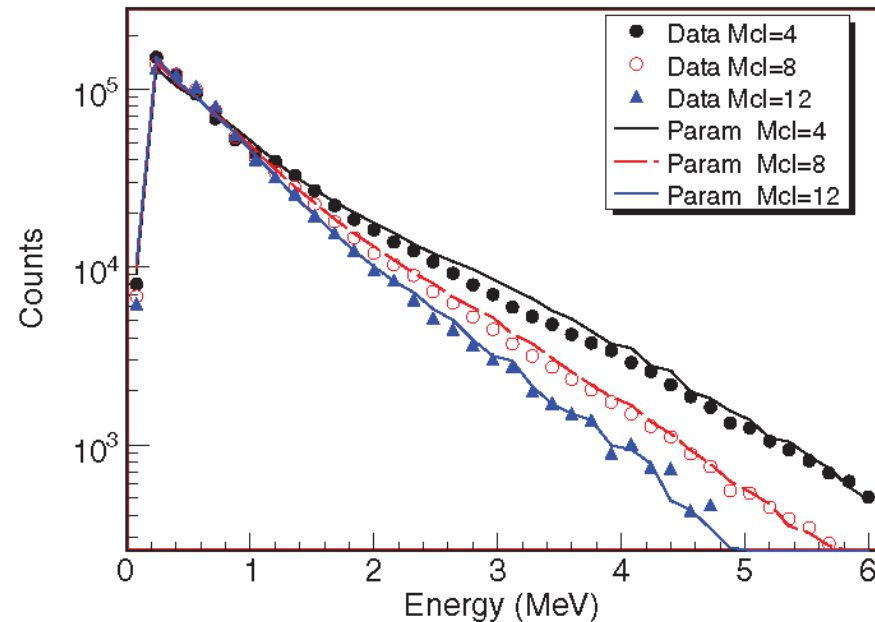
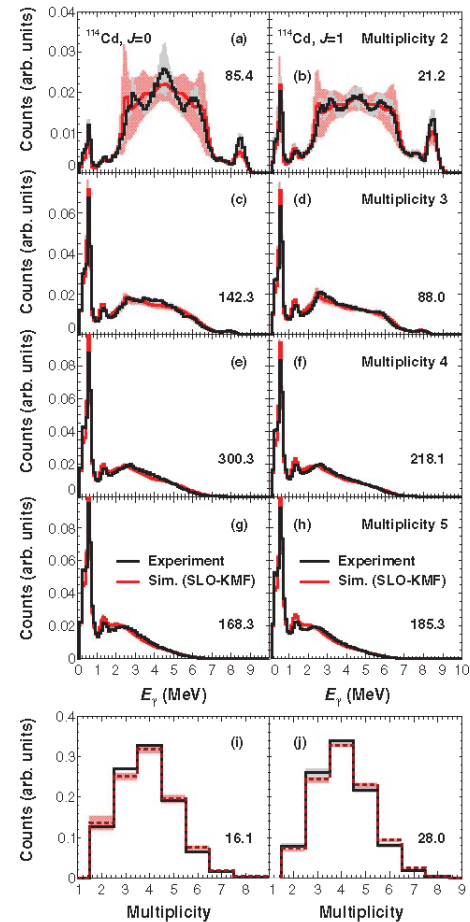


FIG. 2. (Color online) Measured gamma-ray cluster energy for cluster multiplicities (Mcl) 4, 8, and 12 compared with the spectra calculated with the best-fit parameters. For comparison, the spectra were all normalized to the Mcl = 4 data over the energy region 0.2–1.1 MeV.

Gamma rays from neutron capture by cadmium

- Practical importance for neutron absorber
- Test of gamma-ray strength functions (SLO, KMF, pygmy resonances, etc.)
- DANCE provides a wealth of data on multiplicities, spectra



DICEBOX, with chosen parameters, fits the gamma-ray data for $^{113}\text{Cd}(n,\gamma)$

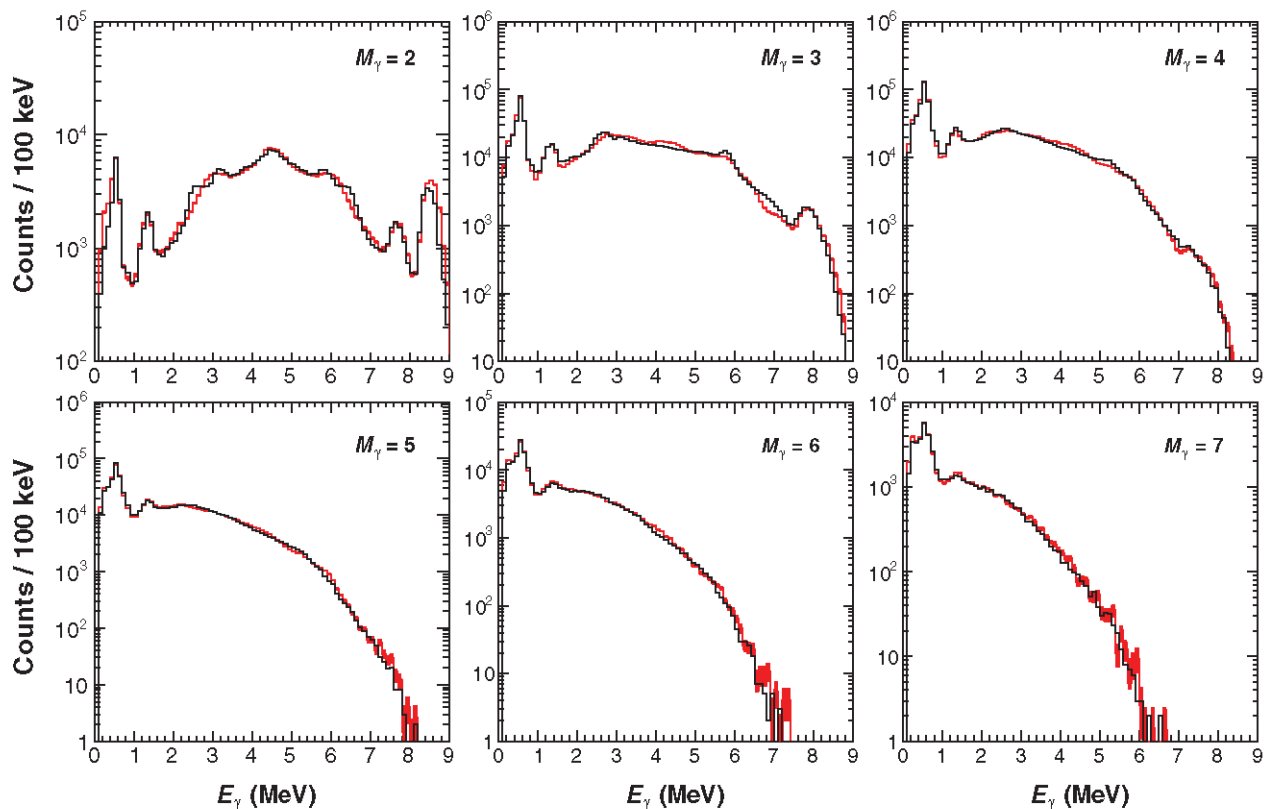


FIG. 1. (Color online) Measured γ -ray spectra with DANCE from the 0.178 eV resonance of the $^{113}\text{Cd}(n, \gamma)$ reaction for γ -ray multiplicities $M_\gamma = 2$ to 7. Predicted spectra corresponding to a DICEBOX realization which represents best the cascade transitions from the 0.178-eV resonance are shown in red.

Fission Cross Sections

Fission Total Kinetic Energy

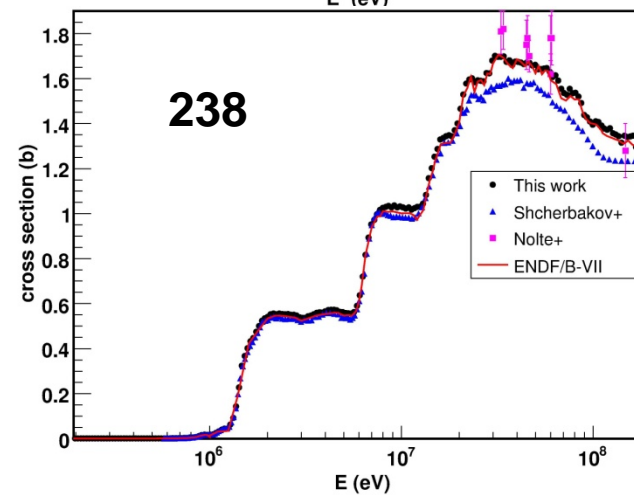
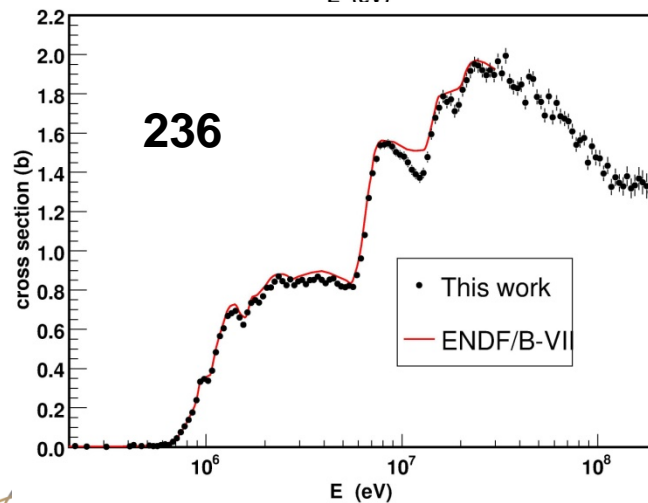
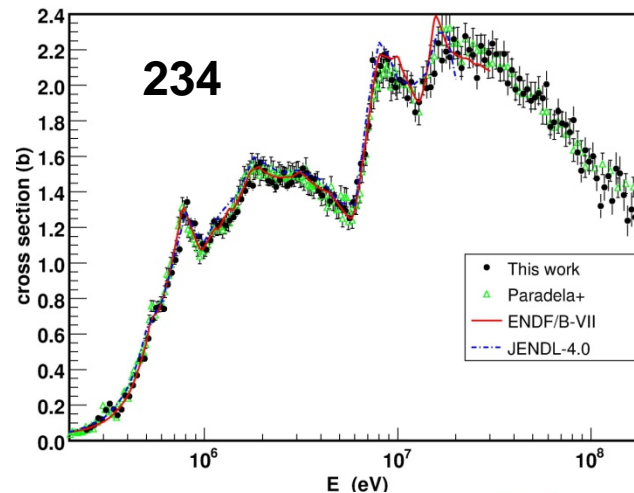
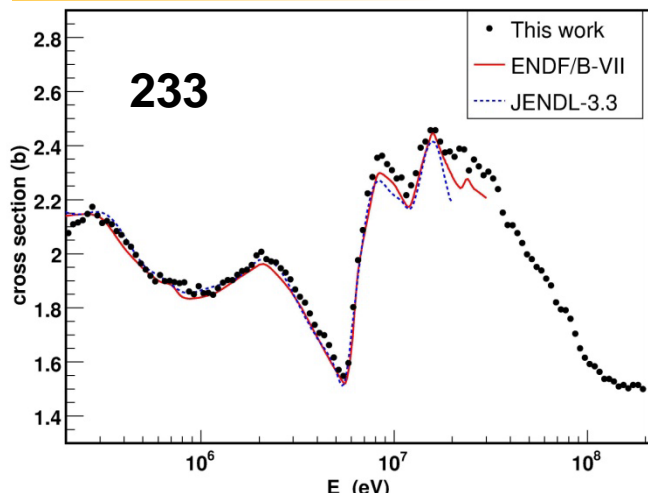
Fission Fragment Yields

Contact:
Fredrik Tovesson

Status: fission cross sections and fragment properties

- Completed: U-233,234,236,238 (n,f) measured from 0.2-200 MeV
 - completed, submitted to Nucl. Sci. Eng.
- High precision cross sections with TPC
 - U-238(n,f) relative to U-235(n,f): Data collection and analysis in progress
 - Pu-239(n,f) relative to U-235(n,f): Production data collection in progress
 - Pu-239(n,f) relative to H(n,n)H: not yet started
- Total kinetic energy (TKE) release in fission
 - U-238: Data collection completed, analysis in progress
 - U-235: Data collection completed, analysis in progress
 - Pu-239: Experiment scheduled for Dec. 2013
- Mass yields of fission fragments
 - SPIDER: U-235(n,f) mass yields measured at thermal, analysis in progress
 - Gridded ionization chamber: same status as TKE

Fission cross sections of U-233,234,236,238 with standard ionization chamber

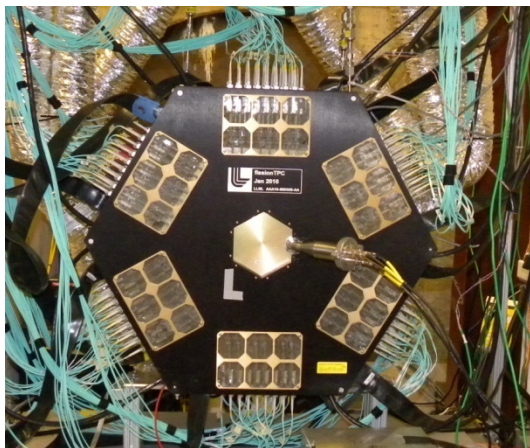


Studies of fission cross sections and fragment properties at LANSCE

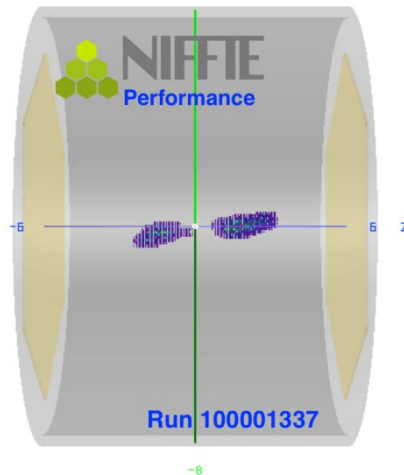
- Fission cross sections
 - Very High precision ($\sim 1\%$) with TPC
 - High precision with ionization chambers
- Total kinetic energy (TKE) release in fission
 - Frisch-gridded ionization chamber
 - SSBDs
- Mass yields of fission fragments
 - High mass resolution, low efficiency with SPIDER
 - Low mass resolution, high efficiency with Frisch-gridded ionization chamber

Time Projection Chamber (TPC)

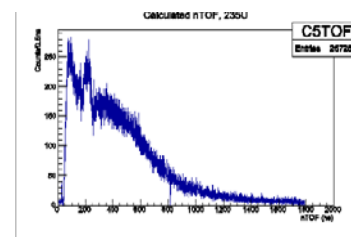
TPC on 90L



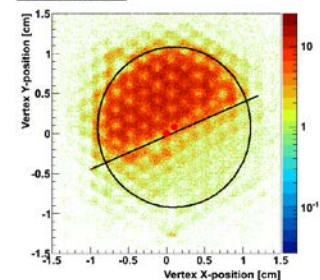
Fission fragment tracks



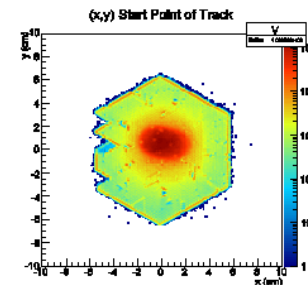
Neutron TOF



Target auto-radiograph

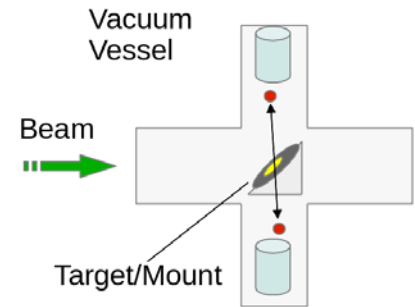
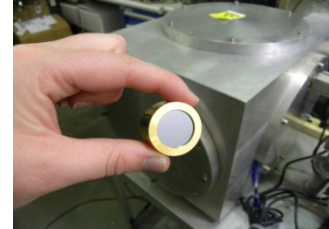
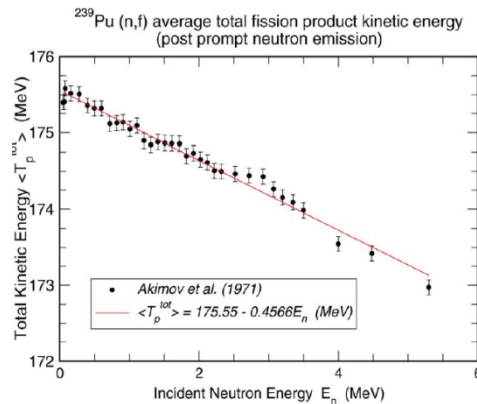
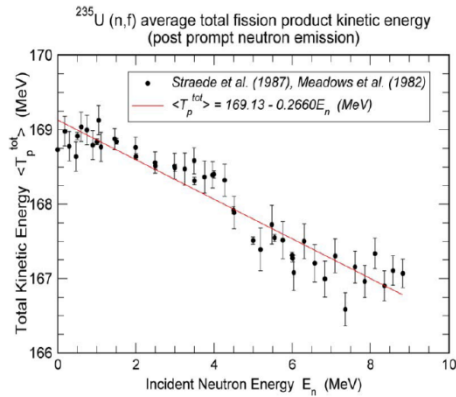


Beam profile imaging

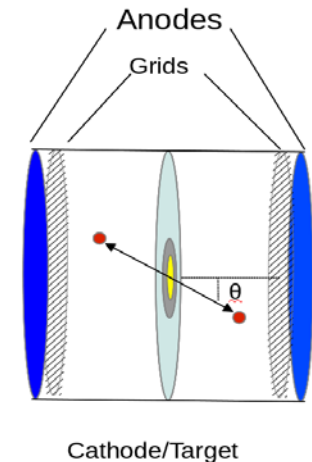
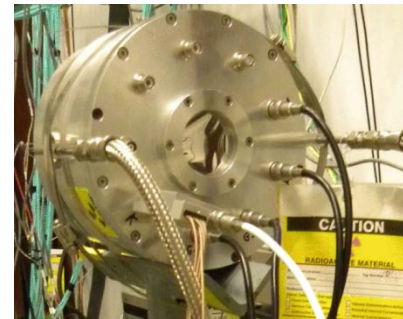


- Fully instrumented TPC was commissioned at LANSCE in August 2013
- Data on the U-238 (n,f) cross section were collected
- Currently taking production runs on Pu-239

Total Kinetic Energy (TKE) release in fission

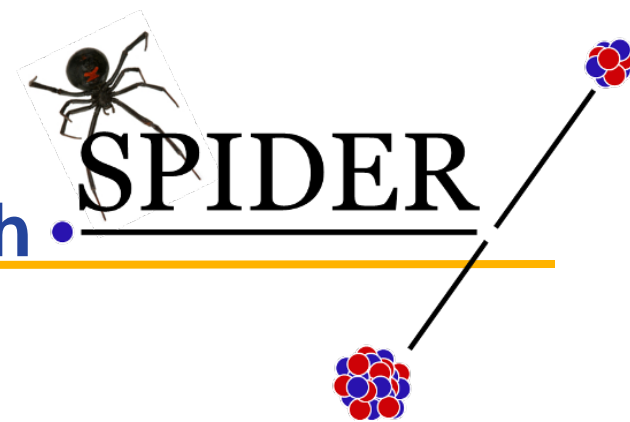


- **Madland has pointed out the need for new measurements of TKE in fission of U-235 and Pu-239 extending beyond 10 MeV**
- **Current measurements at LANSCE employ two detector types, Gridded IC and SSBD, to measure TKE at thermal and 0.2 – 100 MeV neutron energy**
- **Two detector types allow for better understanding of systematic effects**

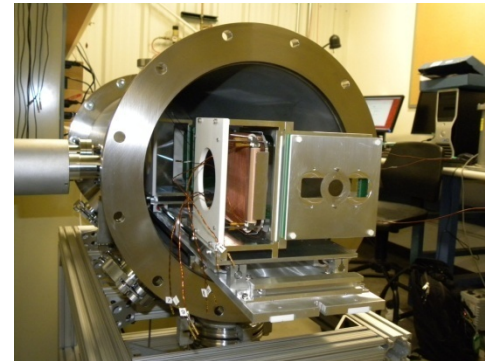


SPIDER

Spectrometer for Ion Determination in Fission Research

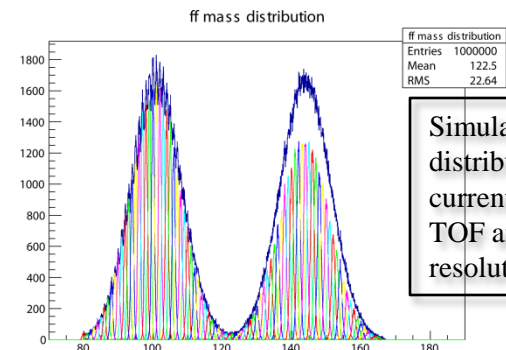


- New instrument for measuring independent fission yields
 - Fragment time-of-flight (TOF) spectrometer
 - Measures TOF and kinetic energy of both fragments in coincidence
 - Correlates fragment mass, charge and energy
 - Resolution
 - Mass: 1 amu for light fragments, 1.5 amu for heavy
 - Charge: 1 unit charge for light fragments (heavy fragment charge obtained from charge conservation)
 - Energy: 0.5-1.0%
 - Experiments at LANSCE
 - Incident neutrons ranges from thermal to several hundred MeV (moderated and un-moderated spallation targets)
 - Neutron time-of-flight to measure incident neutron energy



Timing detector assembly for the SPIDER spectrometer

- Timeline
 - Thermal fission yields for U-235 and Pu-239
 - Beam experiments Sept.-Dec. 2013
 - Preliminary results March 2014
 - Collect more data Fall 2014
 - Finalized mass yields Dec. 2014
 - Fast-neutron induced fission yields for U-235 and Pu-239
 - Beam experiments in 2014 and 2015
 - U-235 mass yields (E = 1 - 15 MeV) in 2015
 - Pu-239 mass yields (E = 1 - 15 MeV) in 2016



Simulated mass distribution based on currently achieved TOF and energy resolution

GEANIE (n, γ)



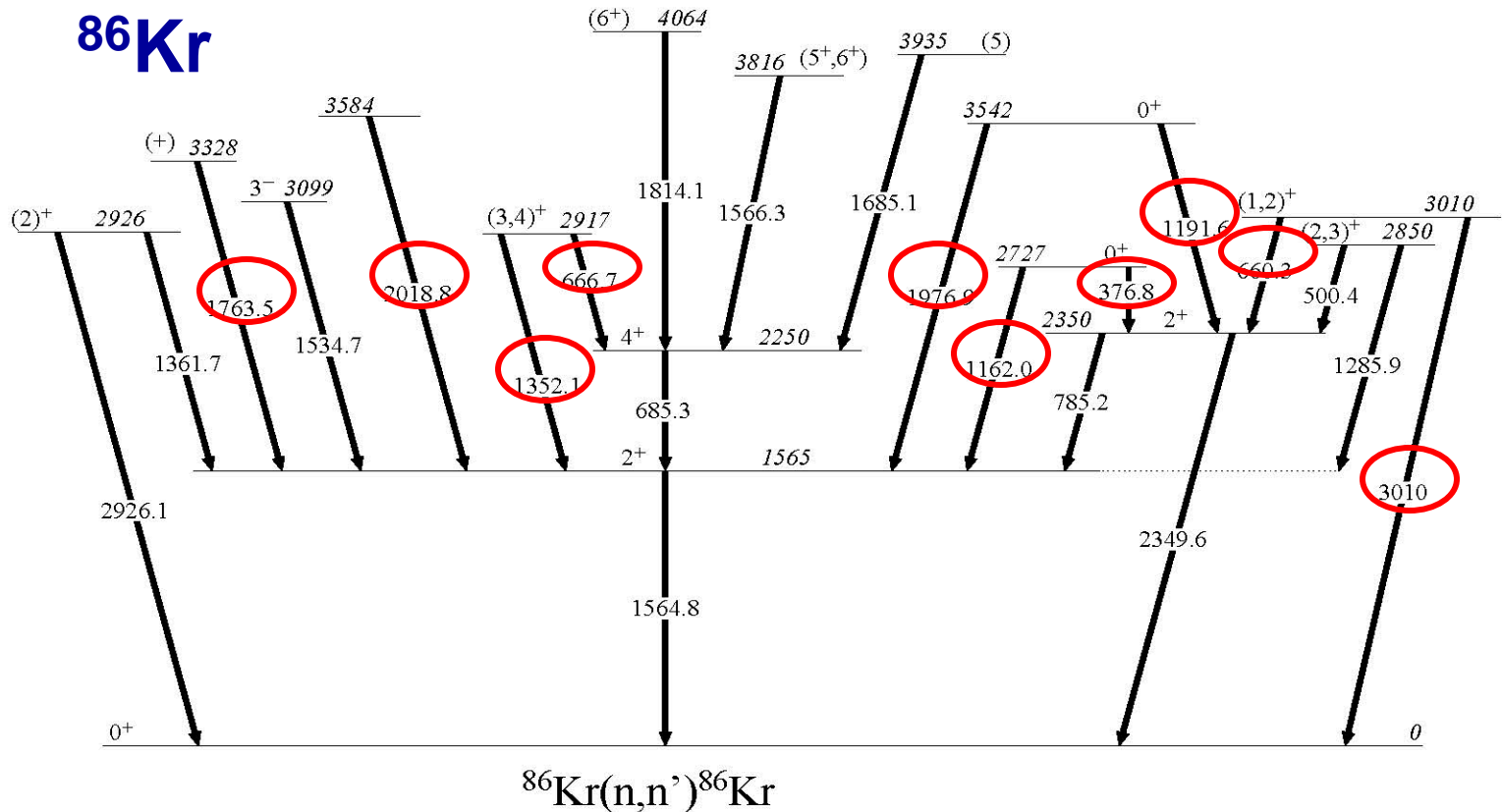
Contacts:
Ron Nelson
Nik Fotiades
Matt Devlin

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GEANIE measurements 2013

- ^{86}Kr (n, xn yp γ) - 10 new transitions (N. Fotiades ND2013)
- ^{109}Ag (n,xgamma) -- over 100 transitions in 12 reaction channels leading to Ag and Pd – in progress (N. Fotiades)
- ^{124}Xe , ^{176}Lu (n,xgamma) – in progress
- Millisecond isomers: $^{71\text{m}}\text{Ge}$, $^{114\text{m}2}\text{I}$, $^{208\text{m}}\text{Bi}$, $^{88\text{m}1}\text{Y}$, $^{88\text{m}2}\text{Y}$, and $^{75\text{m}}\text{As}$
M. Devlin
- Various elements for a neutron-induced gamma-production reference cross sections (R. Nelson): ^7Li (n,n') $^7\text{Li}^*$, Ti, Cr, Fe
- x-ray yield from n-induced fission (R. Nelson and Thierry Granier - CEA) - published

New transitions in ^{86}Kr were observed



Ten new transitions (red circles) were observed. All previously known levels (from Ref. [1]: B. Singh, Nucl. Data Sheets 94, 1 (2001)) up to 3.7MeV excitation identified.

Our ^{86}Kr results are published in Ref. [2]: N. Fotiades et al., PRC 87, 044336 (2013)

Example of a millisecond isomer, ^{75m}As

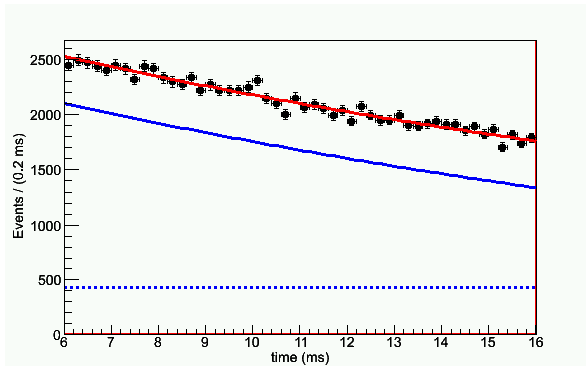


FIG. 7. Measured decay of the 280-keV transition from ^{75m}As as a function of time and a fit to the data (as in fig. 2).

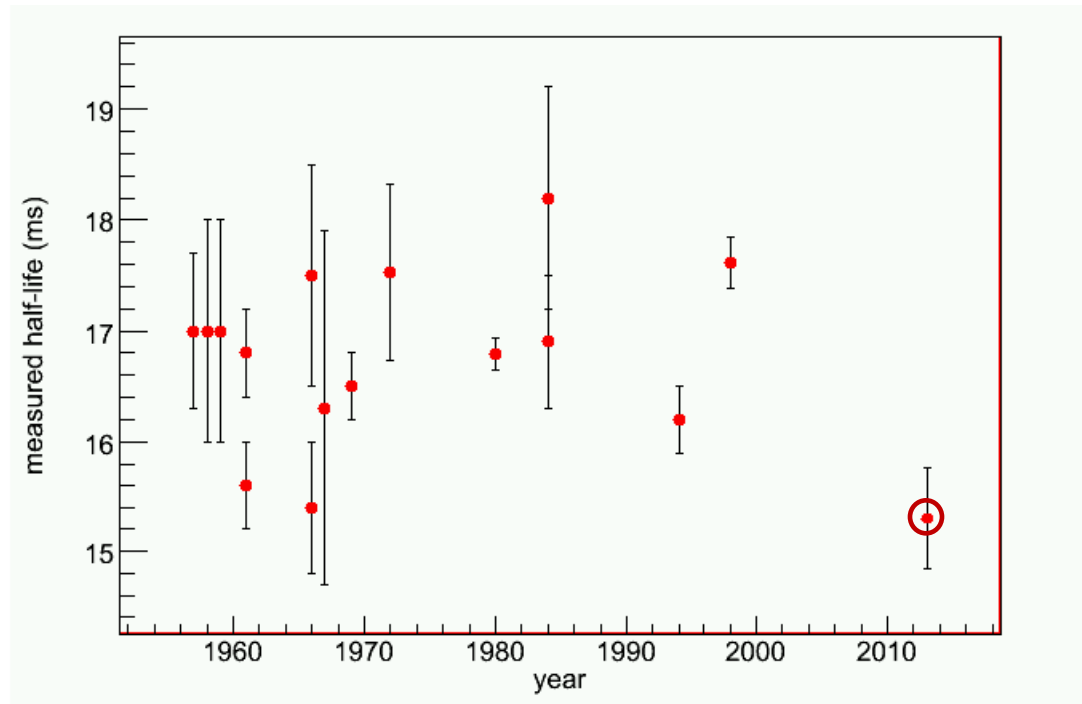
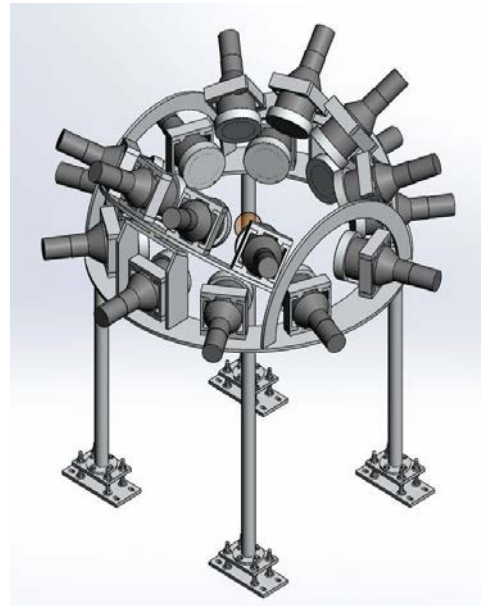
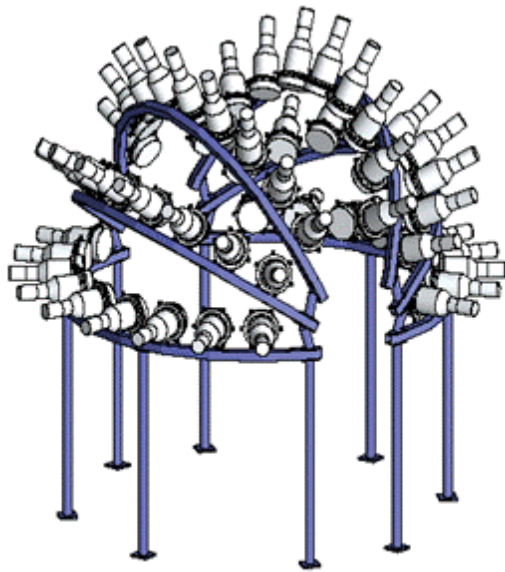


FIG. 8. Reported half-life measurements for ^{75m}As as a function of year, with the current measurement shown for 2012.

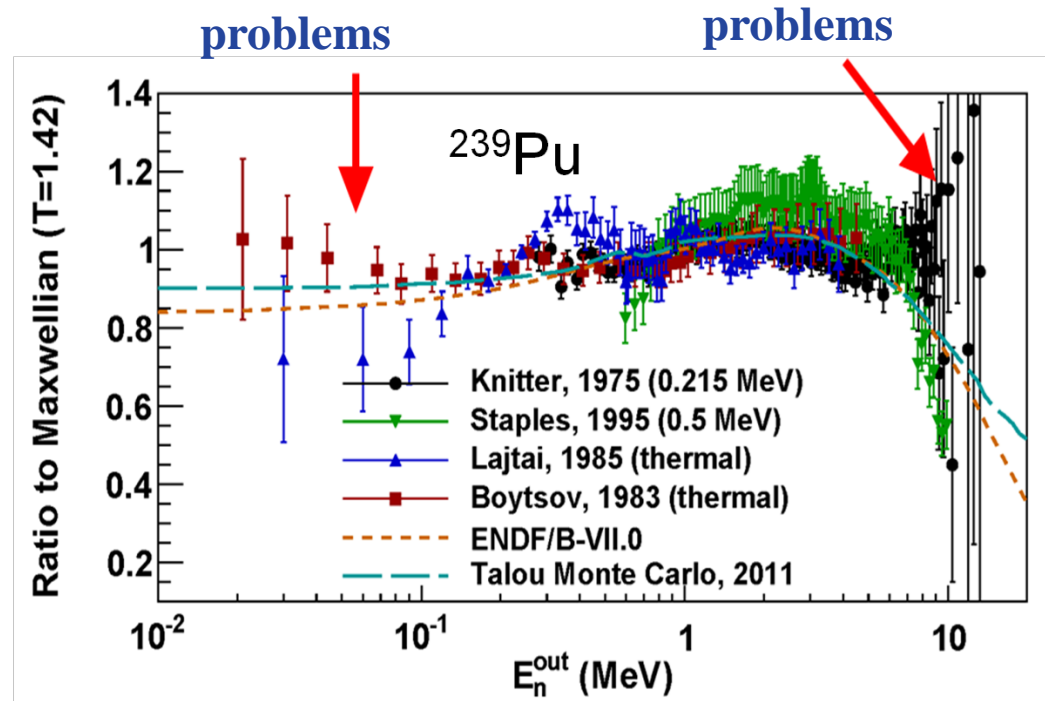
Chi-Nu - Prompt fission neutron spectra



Contacts:
LANL:
Bob Haight
Terry Taddeucci
Hye Young Lee
LLNL:
Ching-Yen Wu

Literature data for $^{239}\text{Pu}(n,f)$ PFNS

- Issues to be addressed
 - Discrepancies in literature data
 - Low energy
 - High energy
 - Lack of data for MeV incident neutron energies

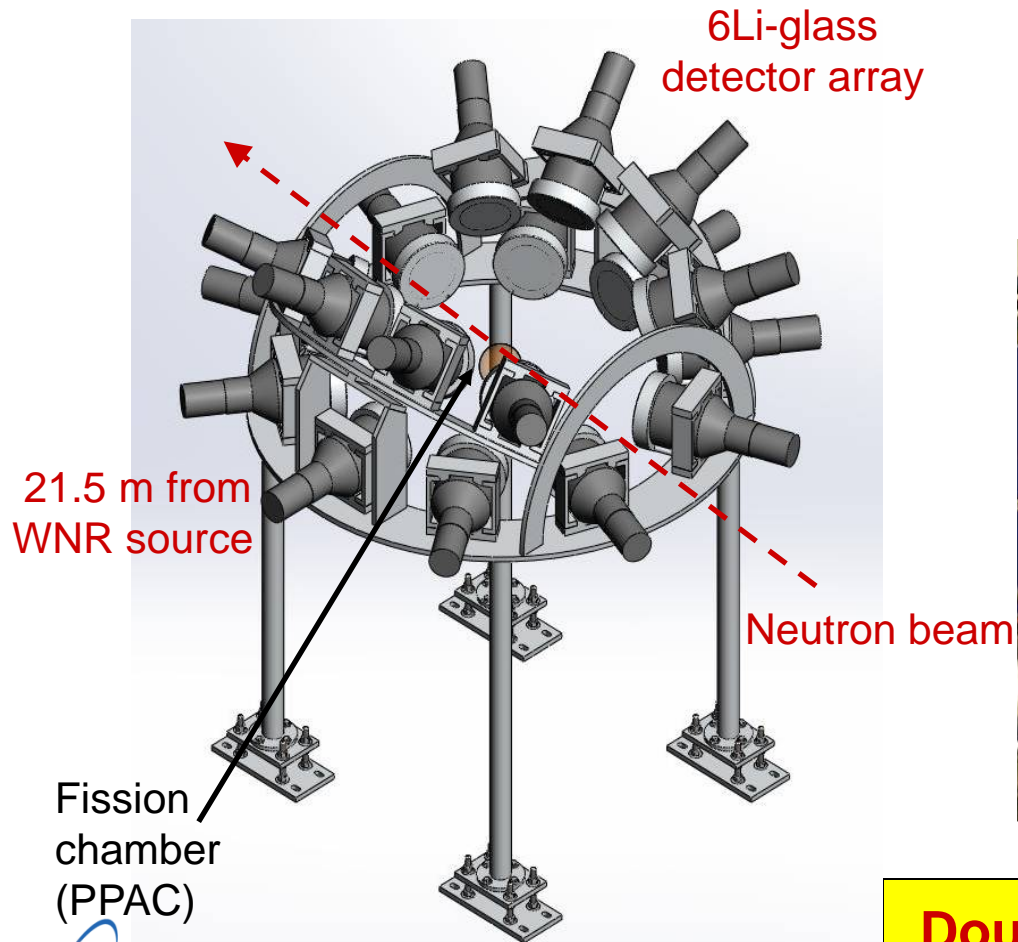


PHYSICAL REVIEW C 83, 064612 (2011)

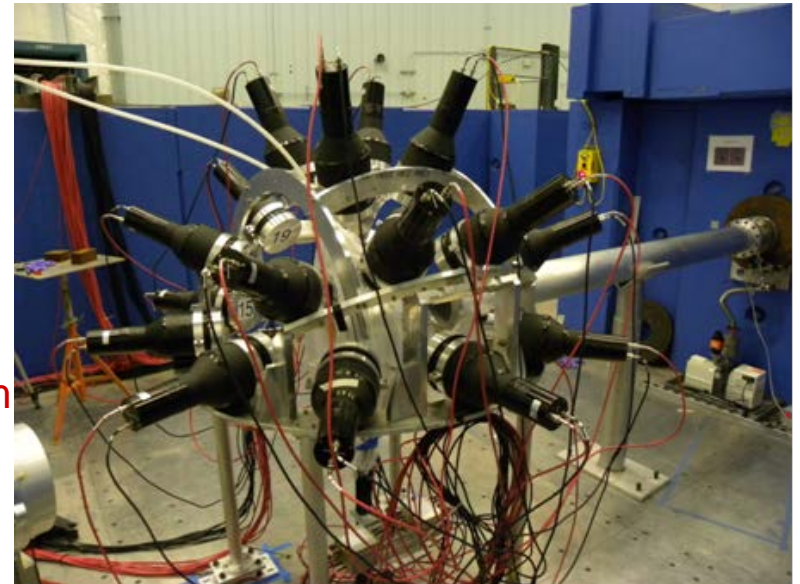
Advanced Monte Carlo modeling of prompt fission neutrons for thermal and fast neutron-induced fission reactions on ^{239}Pu

P. Talou,^{1,*} B. Becker,² T. Kawano,¹ M. B. Chadwick,³ and Y. Danon²

Chi-Nu array of fast neutron detectors measures prompt neutron spectra emitted in fission



- 22 ^6Li -glass scintillation detectors - - or
- 54 liquid scintillation neutron detectors



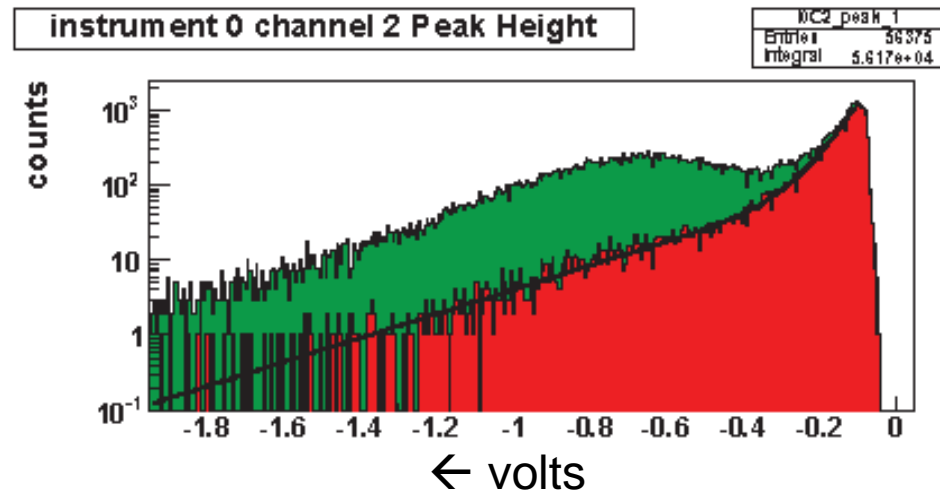
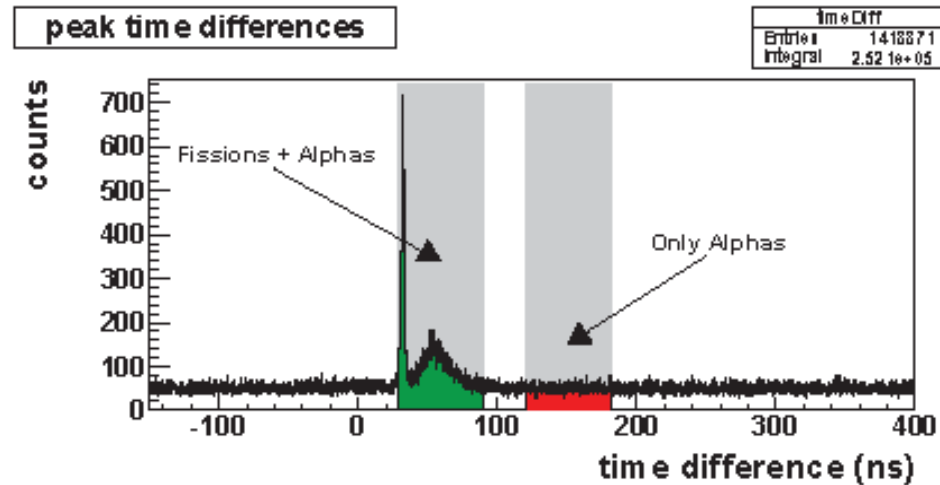
Double time-of-flight experiment

Progress in Chi-Nu

- Modeling
 - Previous measurements
 - Lack of neutron transport corrections
 - Problems at 30% level
 - Detector response
 - Multiple scattering
 - Scattering from photomultiplier tube
- Experiment
 - ^{239}Pu PPAC – 100 mg in 10 separate modules
 - 22 ^6Li -glass detectors
 - Digitizer Data Acquisition

Present challenge in PFNS of $^{239}\text{Pu}(n,f)$ is separating fissions from alphas in source

- ^{239}Pu fissions in PPAC
- EJ309 neutron detector
- Two cuts on TOF



UNCLASSIFIED

$n + {}^3\text{He}$

M. Drosg, R. Avalos Ortiz, and P. W. Lisowski, Neutron Interactions with ${}^3\text{He}$ Revisited—I: Elastic Scattering Around and Beyond 10 MeV Nuclear Science and Engineering 172, 87 (2012).

M. Drosg and P. W. Lisowski, “Neutron Interactions with ${}^3\text{He}$ Revisited- II: “Non-Elastic Cross Sections in the Mega-Electron Volt Range,” Nuclear Science and Engineering 175, 19-27 (2013).

LANL Contact:
Paul Lisowski

Acknowledgments for funding support

- **US DOE**
 - **NNSA**
 - **Nuclear Energy University Programs**
 - **Nuclear Physics**
- **LANL - LDRD**

Thank you!!!

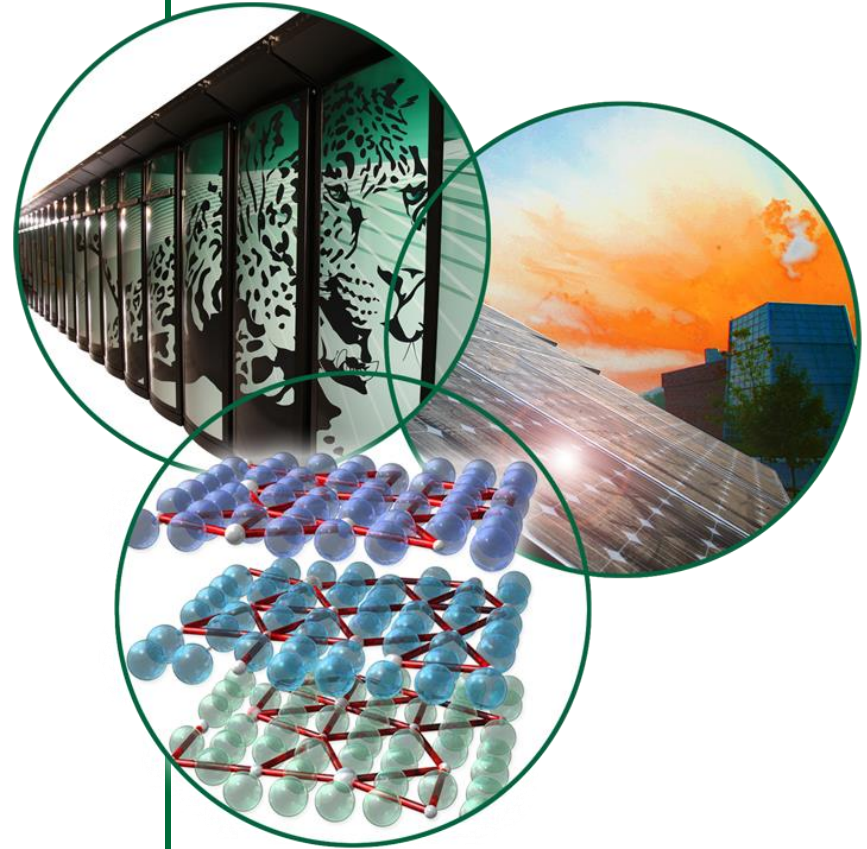
Oak Ridge National Laboratory

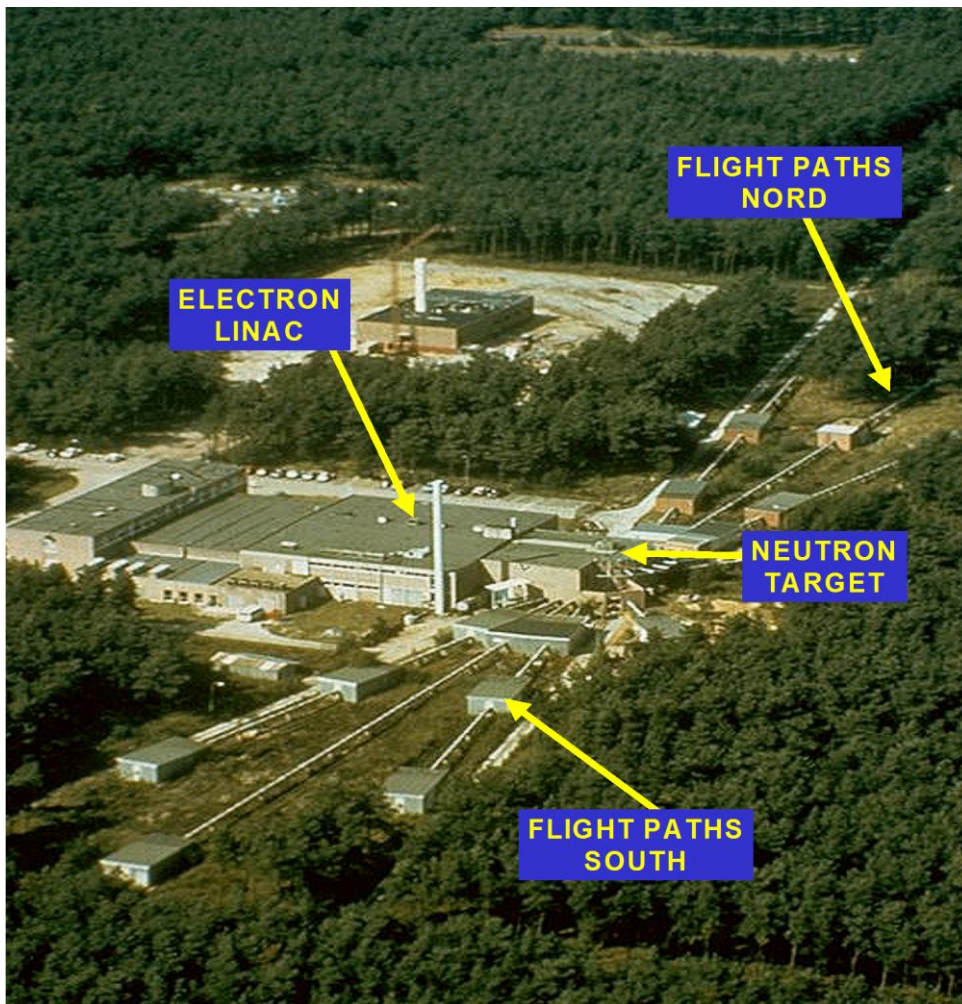
- Resonance Region Measurements
 - $^{183,184}\text{W}$ - New transmission data was taken at GEEL using 30m and 60m flight path without fixed notch filters and preliminary results were shown.
 - **Ca** - Preliminary capture yield was shown (60m flight path), several new resonances were observed. Transmission data was taken at a 50m flight path and preliminary SAMMY completed.
 - **Ce** - Capture data was taken (60m flight path).
 - $^{182,183,184,186}\text{W}$, $^{63,65}\text{Cu}$, $^{\text{nat}}\text{Ca}$ resonance analysis is in progress.

ORNL Neutron Cross-Section Measurements Activities

K. H. Guber
Oak Ridge National Laboratory
Oak Ridge, TN, USA

CSEWG meeting 2013





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:

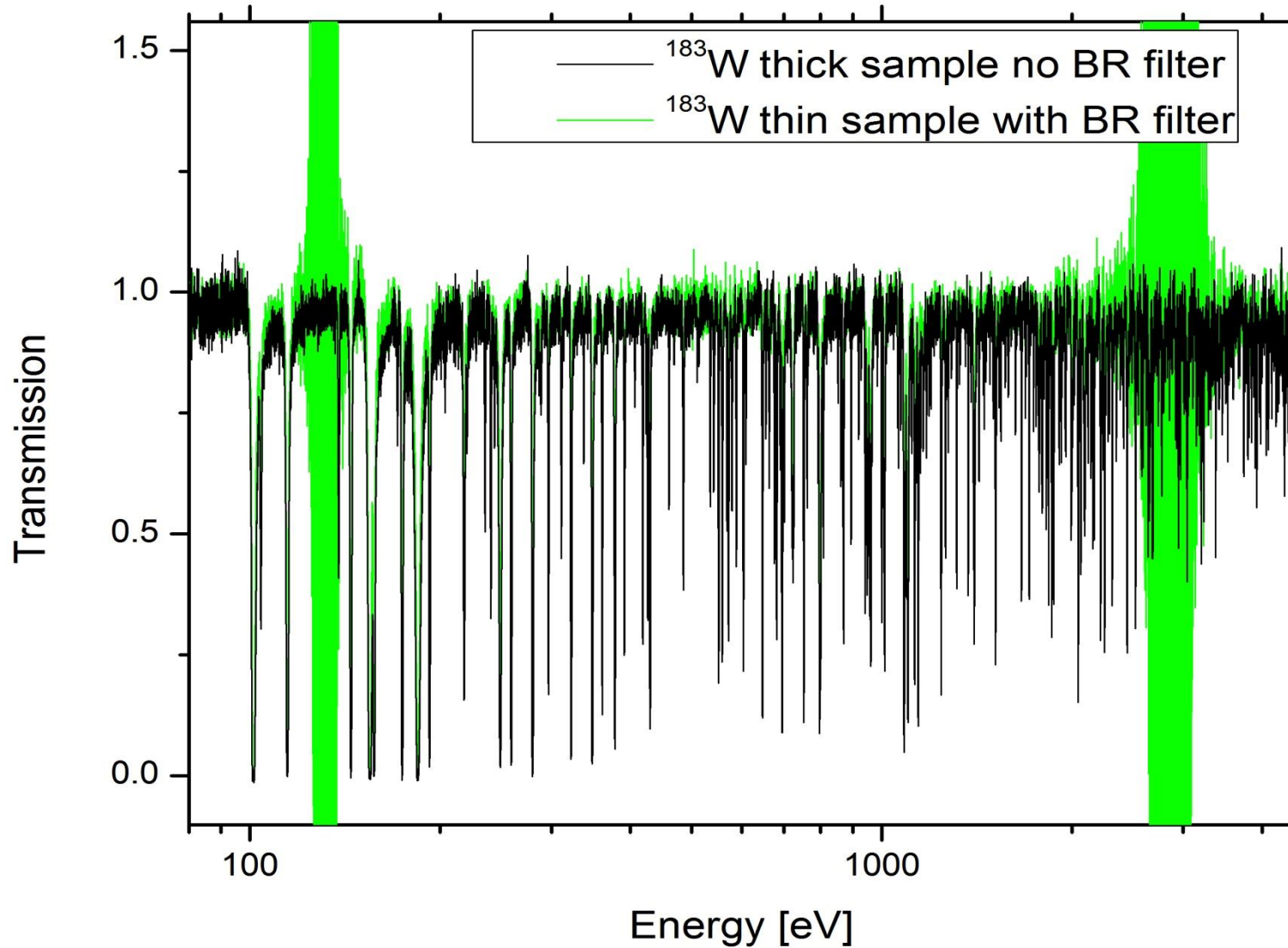
- Total cross section measurements
- Partial cross section measurements

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

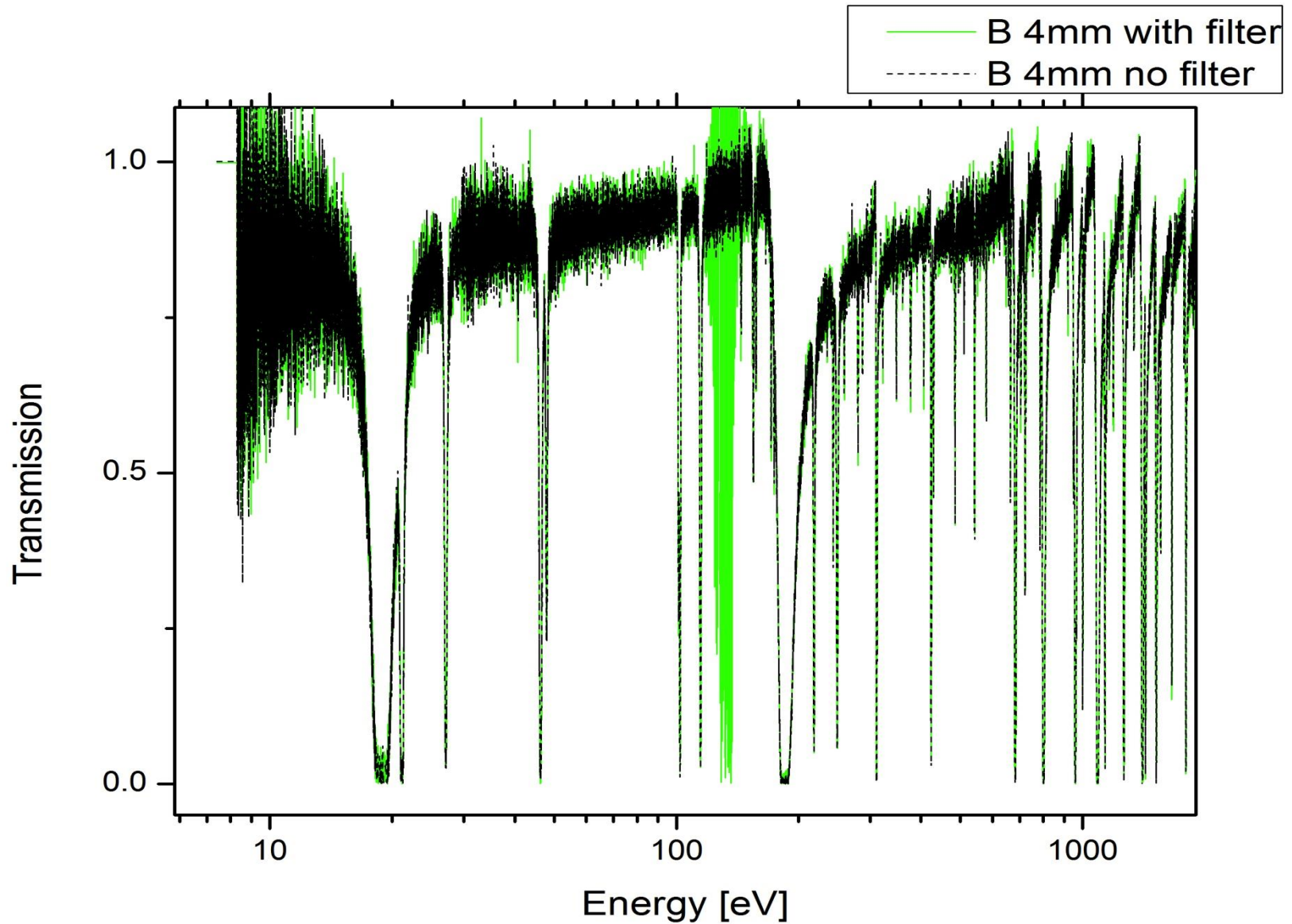
W Measurement Activities

- Transmission data for $^{182,183,184,186}\text{W}$ with different sample thickness available. But due to fixed filters there are gaps in the data. New experiments without filter and new set up were performed.
- In 2012 ^{183}W was re-measured without fixed background filters.
- In 2013 ^{184}W 1mm and 4mm samples were re-measured without fixed background filters.
- No differences compared to experiments with fixed filters were observed.

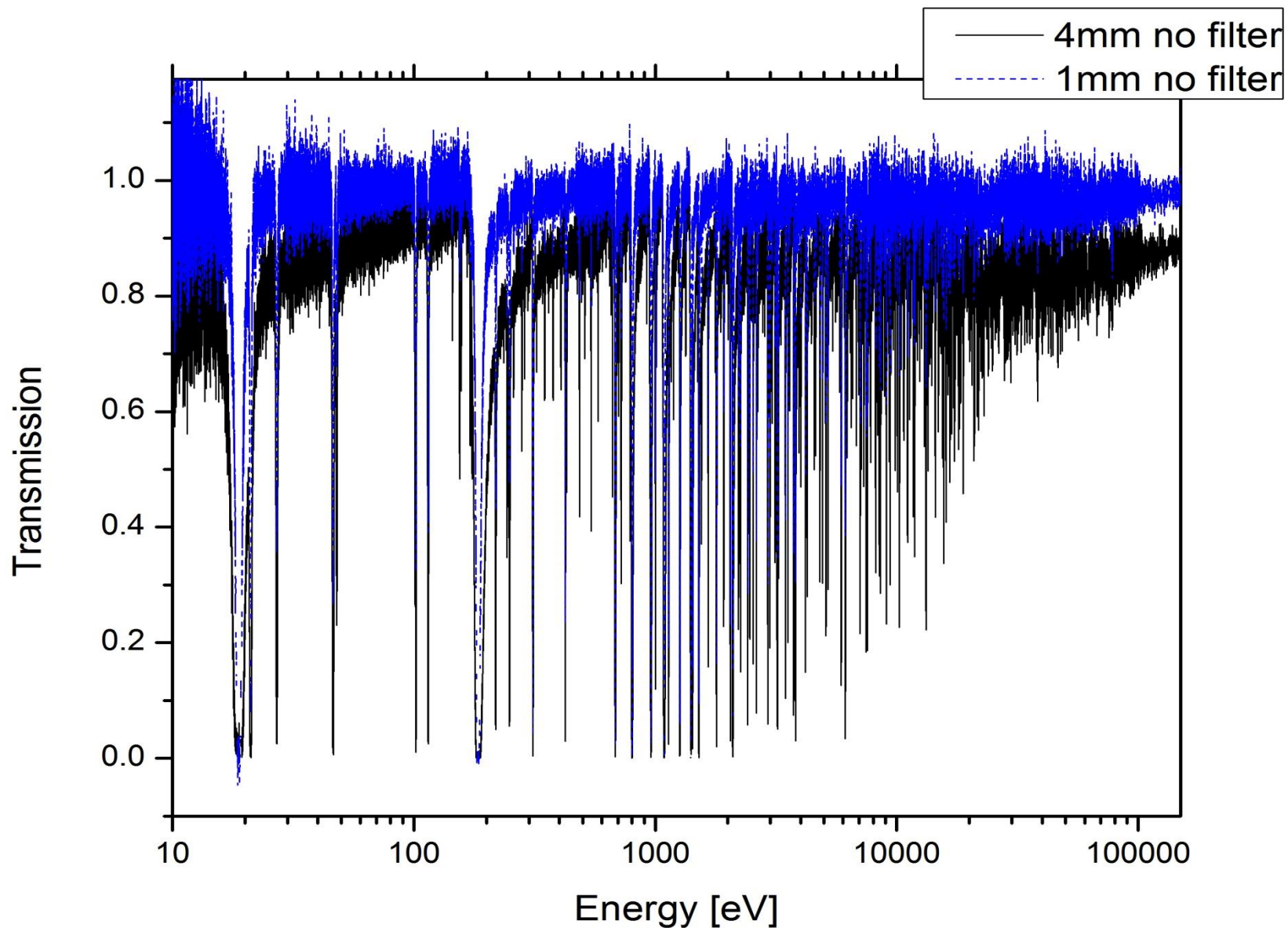
^{183}W Comparison thin thick sample



^{184}W with fixed and no filter



^{184}W Comparison 1mm 4mm sample



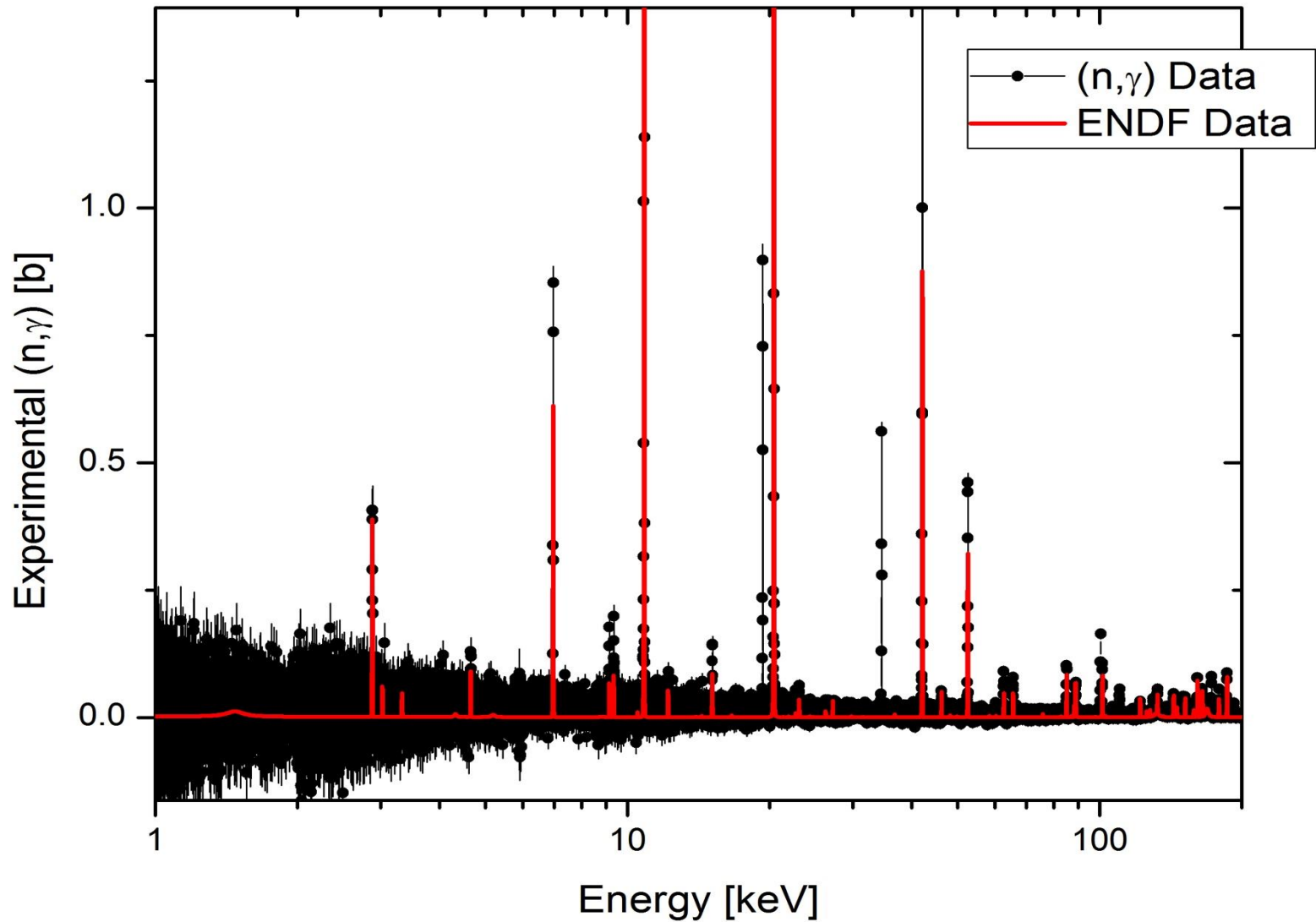
ORNL Measurement Activities for Calcium

- Measurements of Ca using metallic samples
- The samples are in Al canning due to reactivity with air
- Transmission experiments with different sample thickness available using FP4, 50 m
- Neutron capture using detector system at FP14, 60 m
- Capture Data reduced to cross section

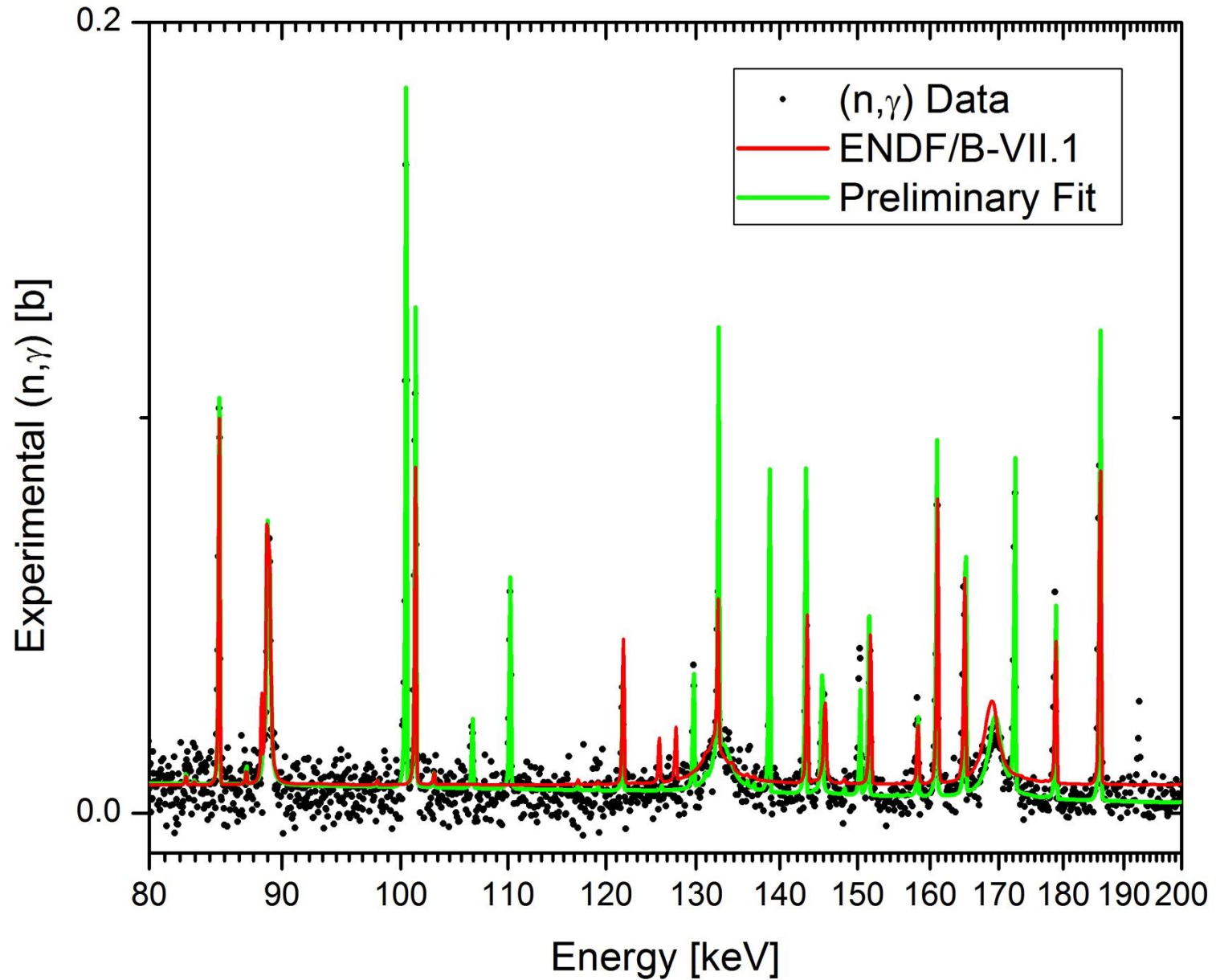
- Observation: Resonances are missing in ENDF file, even though reported in literature.

- Analysis of the data started and will include old cross section data.

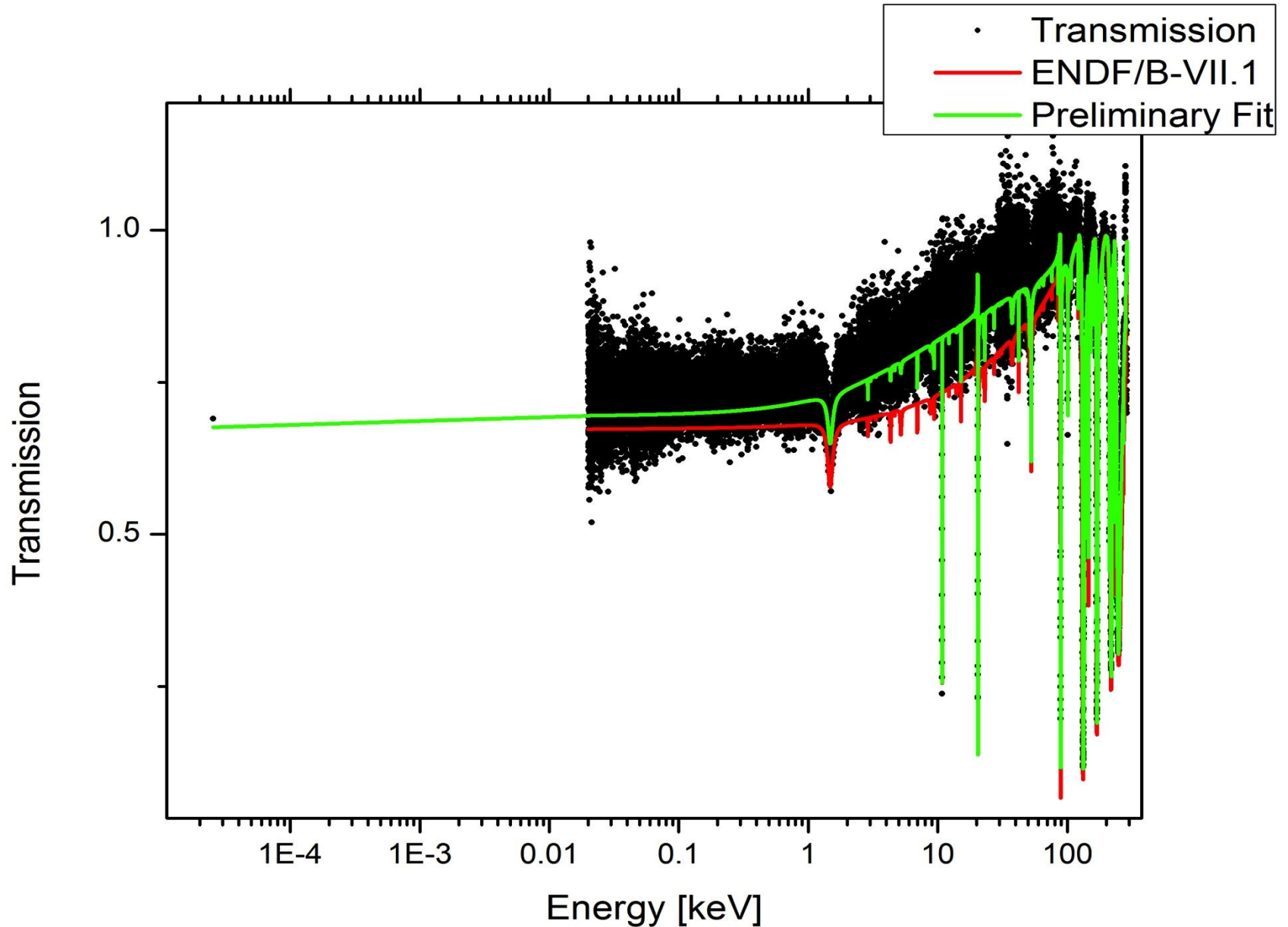
Natural Ca (n,γ) compared to ENDF



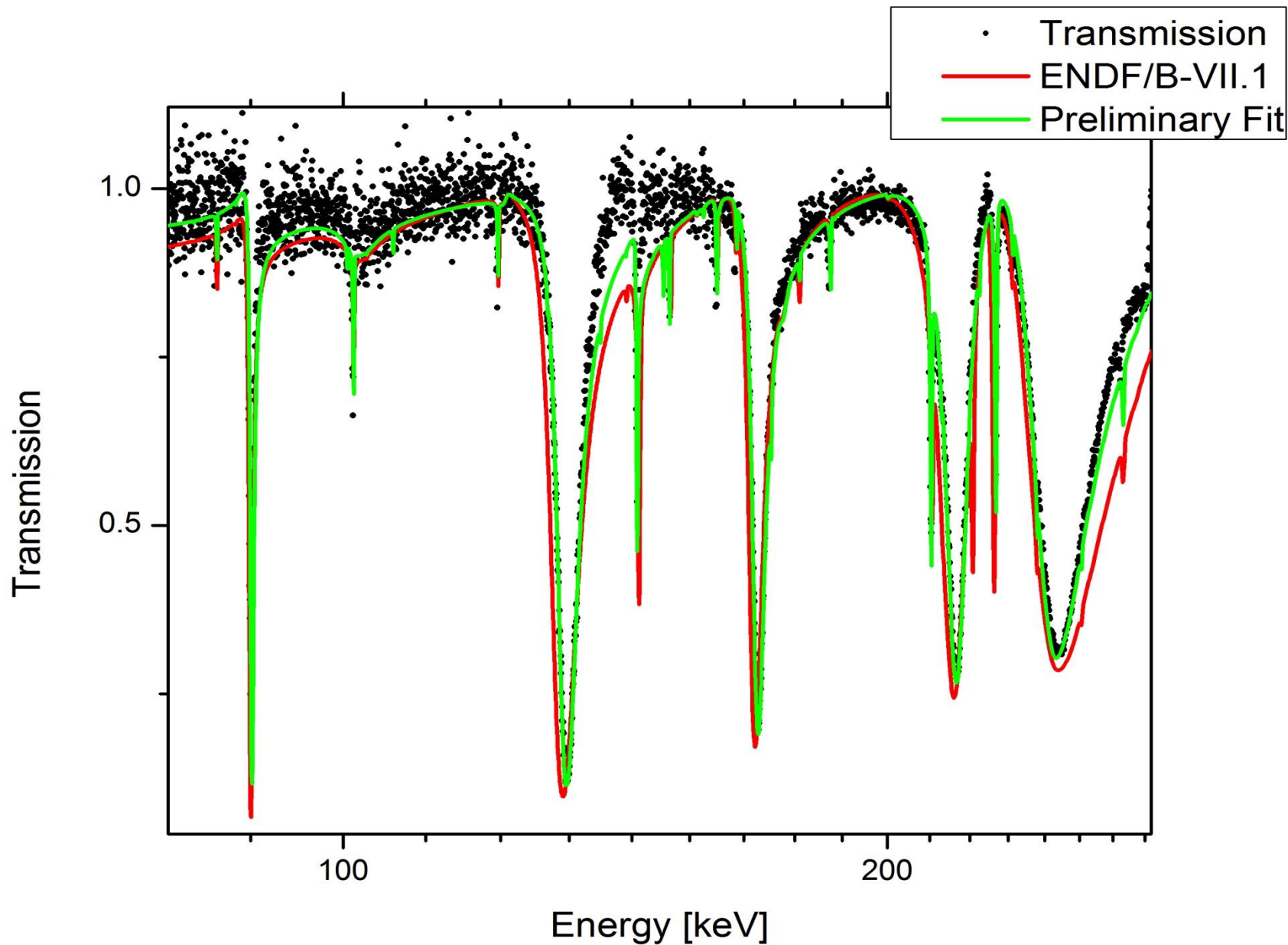
Natural Calcium (n,γ) compared to ENDF



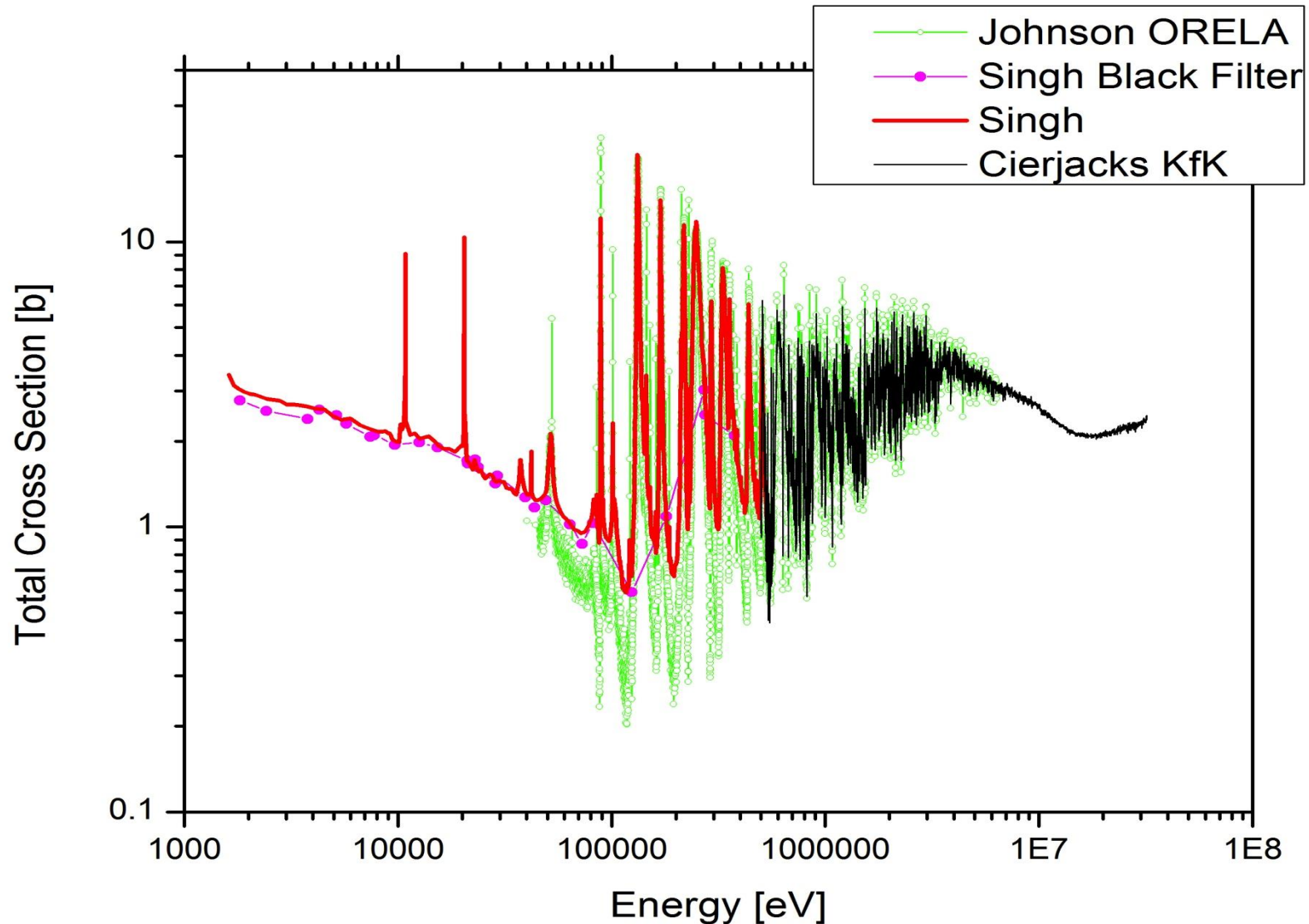
Ca Transmission preliminary fit



Ca Transmission Detailed View



Ca Total Cross Sections from CSISRS to be analyzed and included in Evaluation



ORNL Measurement Activities for Cerium

- **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**
- **Capture Data experiments started**
- **Experiments to be continued in FY14.**
- **Transmission and capture experiments using Ce142 oxide sample are planned for FY14.**

Status of Experiments at GELINA

	W	Cu	Ca	Ce
Sample	metallic disks 182,183,184,186	metallic disks 63 and 65	metallic disks nat Ca	Metallic disks Nat Ce, 142
Experiments GELINA	60m, 30m (n, γ) transmission	60m (n, γ)	60m (n, γ) transmission	60m (n, γ) started
Data Sorting	finished 60m + transmission	finished 60m high E need to be finalized	finished 60m Transmission under way	started
Reduced to Cross section	X-section transmission	X-section	X-section transmission	
Data Testing	Data ready for evaluation	Resonance data provided for evaluation	Data ready for evaluation	
Analysis and Evaluation	Started new transmission data available	Completed	Started	

Rensselaer Polytechnic Institute

- **Transmission**

- ^{92,94}Mo – data were measured at 30m and 100m flight path in the energy range from 5-600 keV, many new resonances were observed. Preliminary SAMMY fit of transmission data from 10-40 keV were presented.
- ¹⁸⁶W transmission at 45m flight path

- **Capture**

- Measured Fe in the energy range of 100 eV - 500 keV at 45m flight path. This measurement was a test for new capture gamma detection system.

- **Fission**

- Measurements using the gamma tag method were discussed. Prompt fission neutron spectra were measured for ²⁵²Cf and ²³⁸U. Experimental data for ²⁵²Cf from 50 keV to 7 MeV were presented and showed very good agreement with ENDF/B-VII.1. Preliminary data for ²³⁸U were shown from 0.5 MeV to 7 MeV for incident neutrons bin from 0.5 to 20 MeV.

- **Thermal neutron scattering**

- Measured double differential scattered neutron spectrum for incident energy of 55 meV was compared with ENDF/B-VII and MCNP scattering kernels (ACE files). The data is in better agreement with the RPI generated ACE files

- **Data Analysis**

- **Re** – Resonance analysis of transmission and capture measurements in the energy range of 0.01-500 eV was completed.
- ^{151,153}Eu - Resonance analysis of transmission and capture measurements in the energy range of 0.01-500 eV was completed, published ANE, **69**, Pages 74-89, 2014.
- ^{95,96,98,100}Mo – preliminary resolved and unresolved data analysis was completed and published in a PhD thesis.
- ⁵⁶Fe, ²³⁸U – analysis of neutron scattering and angular distribution in the incident energy range from 0.5-20 MeV was completed.

Recent Nuclear Data Research at RPI

Report to CSEWG November, 2013

Y. Danon, E. Liu, E. Blain, A. Daskalakis, B. McDermott, K. Ramic, C. Wendorff
Rensselaer Polytechnic Institute, Troy, NY, 12180

and

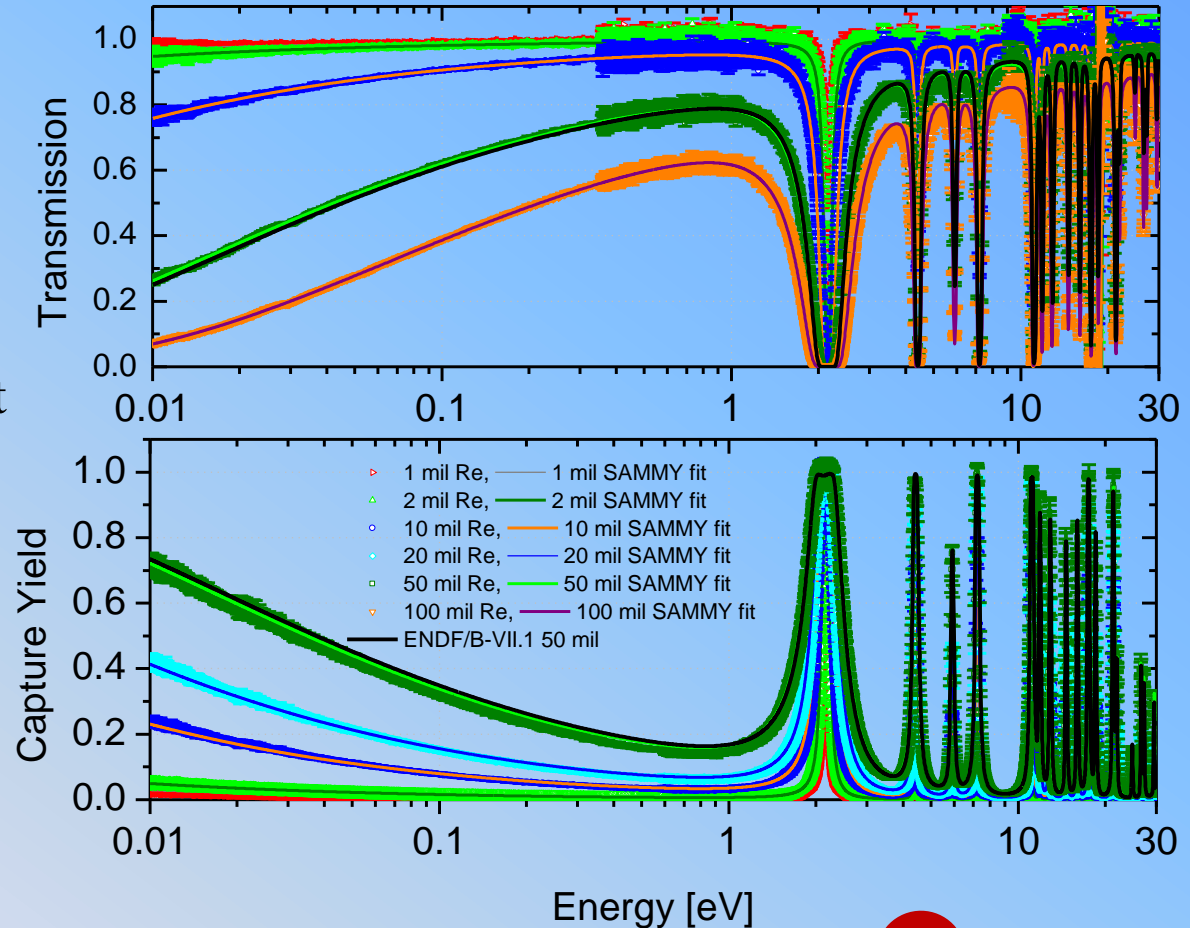
D. Barry, R. Block, J. Burke, T. Donovan, B. Epping, G. Leinweber, M. Rapp
KAPL, Bechtel Marine Propulsion Corporation, Schenectady, NY, 12301-1072



Rensselaer

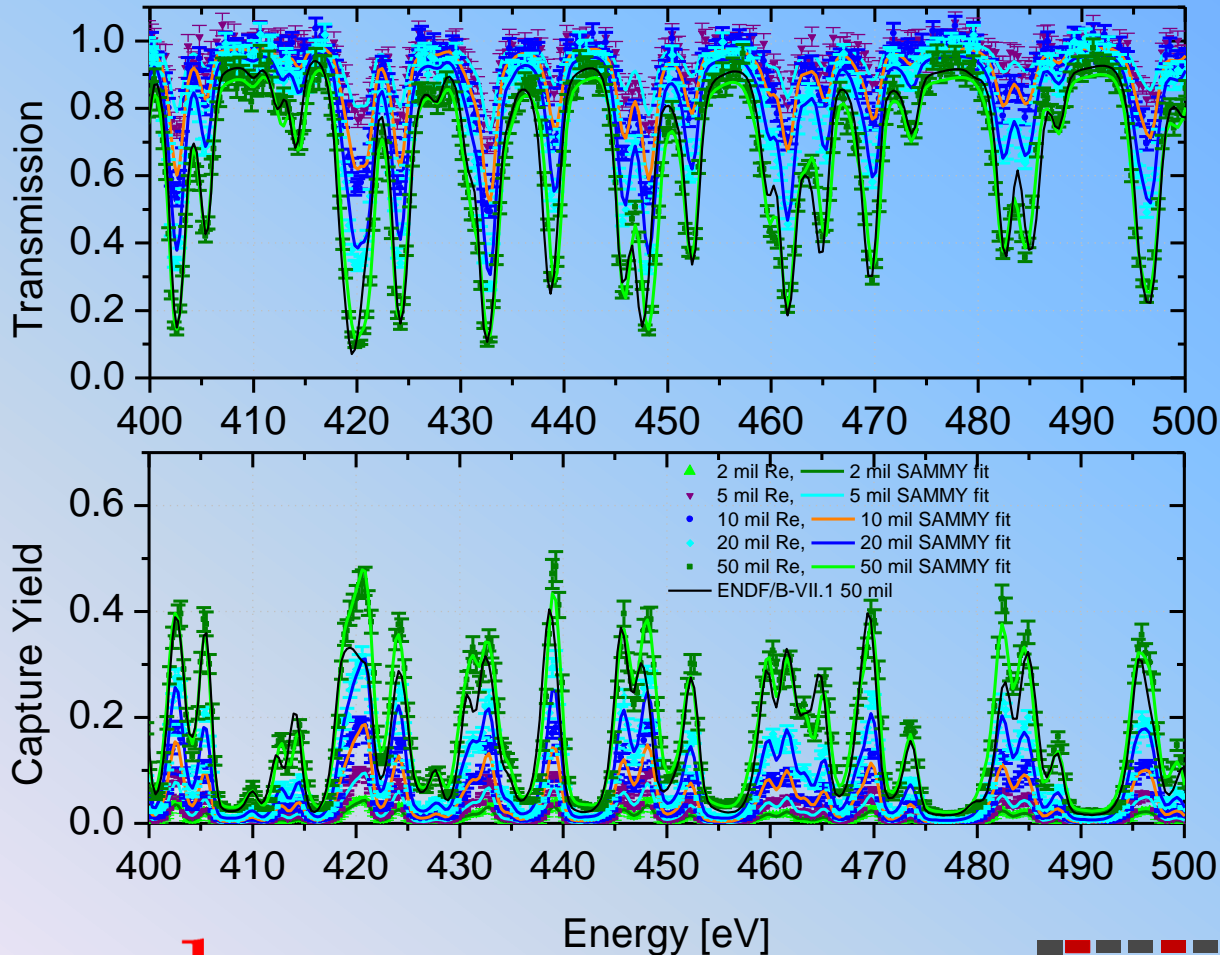
Re – Thermal Transmission and Capture Measurements

- Multiple sample thicknesses 1-100 mils
- Corrected for gamma attenuations (density=12.02 g/cm³)
- Simultaneous SAMMY fit to all data sets.
- Slightly lower thermal cross section compared to ENDF/B-VII.0
- MS Thesis nearly completed.



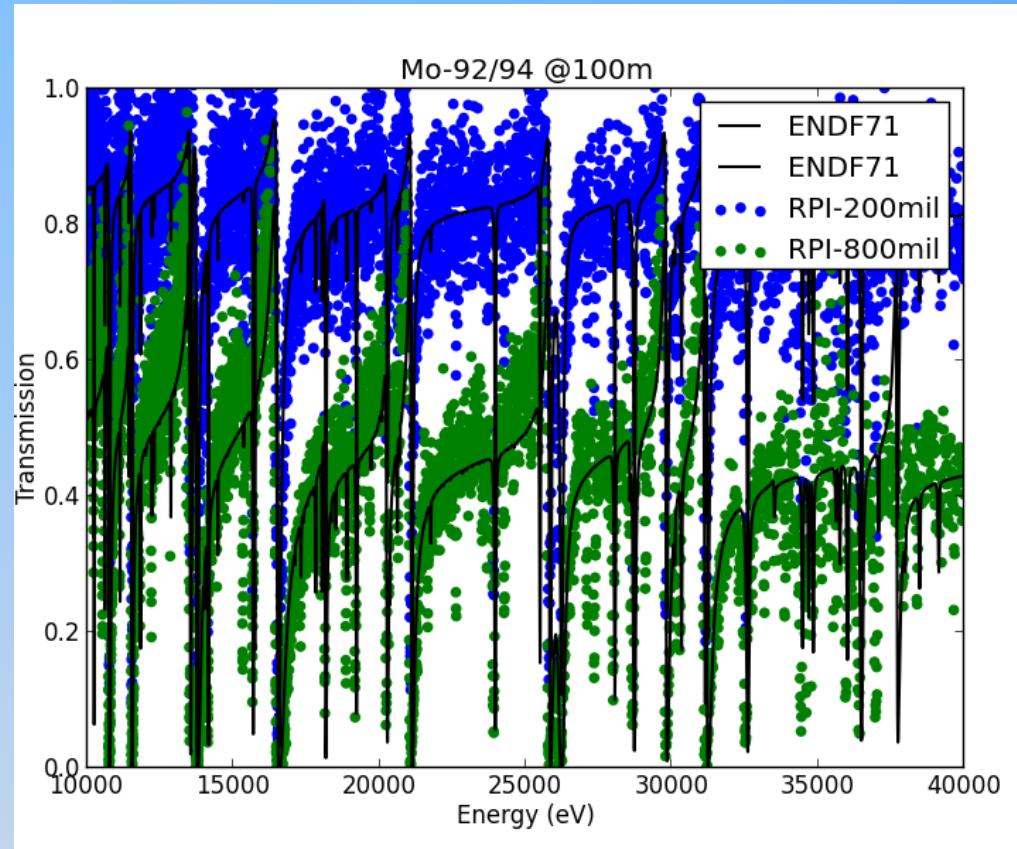
Re - Epithermal Measurements

- Capture corrected for gamma attenuation (2nd densest element)
- Transmission data analyzed to 1 keV, capture data to 600 eV.



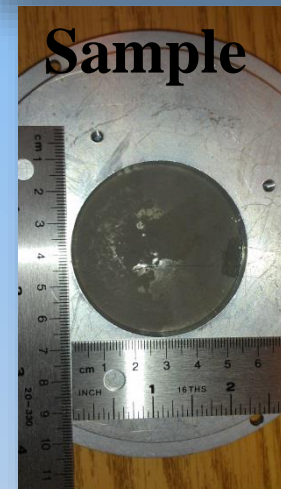
Measurements of $^{92/94}\text{Mo}$ Transmission at 100m Flight Path

- Enriched Mo samples were prepared by Bettis Atomic Power Lab (75.63% ^{92}Mo , 23.78% ^{94}Mo)
- High resolution (100m flight path) transmission was measured from 5 keV to 200 keV
- Resonance analysis currently being performed between 10 keV and 40 keV. New resonances have been identified.
- Transmission above 40 keV will be treated as URR.



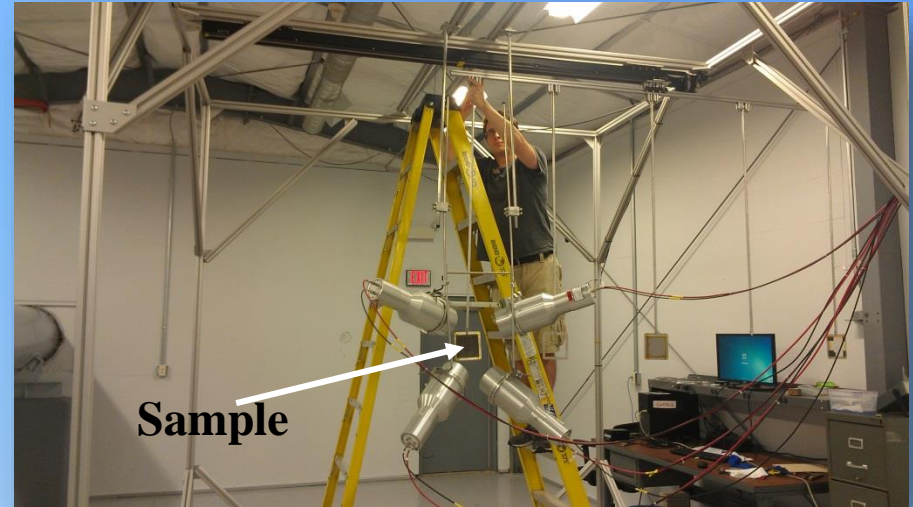
Transmission of ^{186}W

- Experiment was designed to provide data in the energy range from about 2-4 keV (Na fixed filter at Geel)
- Sample provided by ORNL
 - 3 discs, 0.01169 atoms/barn
 - ^{238}U sample for determination of the energy resolution
- Data was collected for 3.5 days.
 - 35 m flight path
 - Pulse width of 10 ns
- Co and Al fixed notches were used for background determination



Mid-Energy Capture Detector

- 4 deuterated benzene (C_6D_6) liquid scintillators with low neutron sensitivity
- Located at newly constructed 40m flight station
- 10-bit, 8 channel Struck Systems SIS3305 digital data acquisition system allows for low dead time operation
- Low mass design to minimize background contributions from neutrons captured in detector and surrounding structural materials



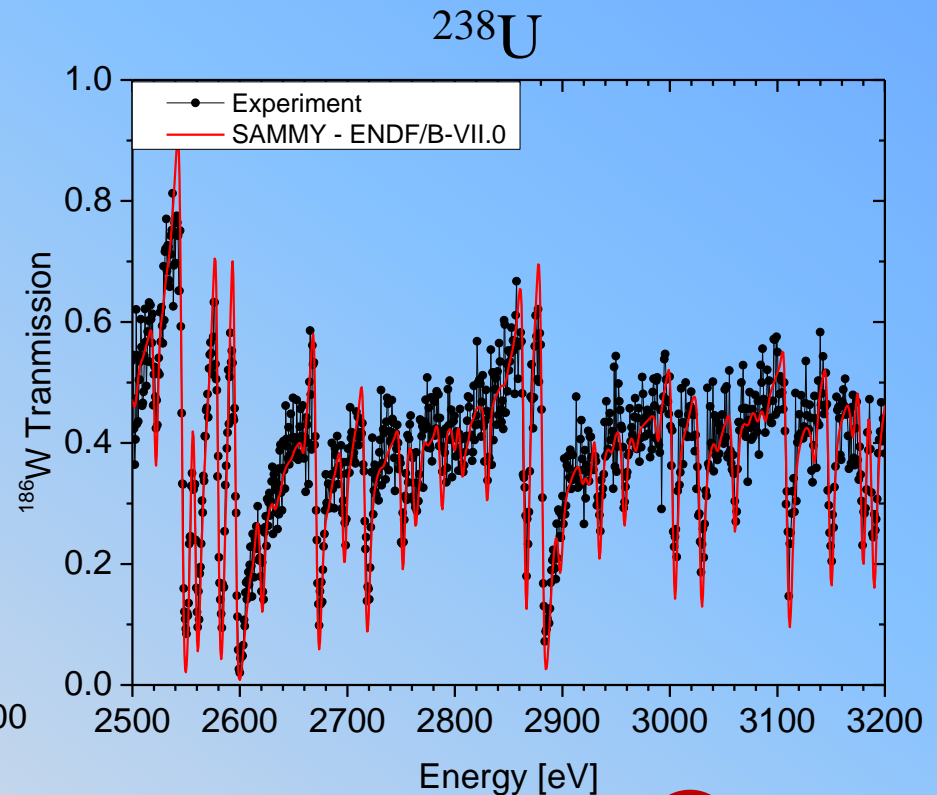
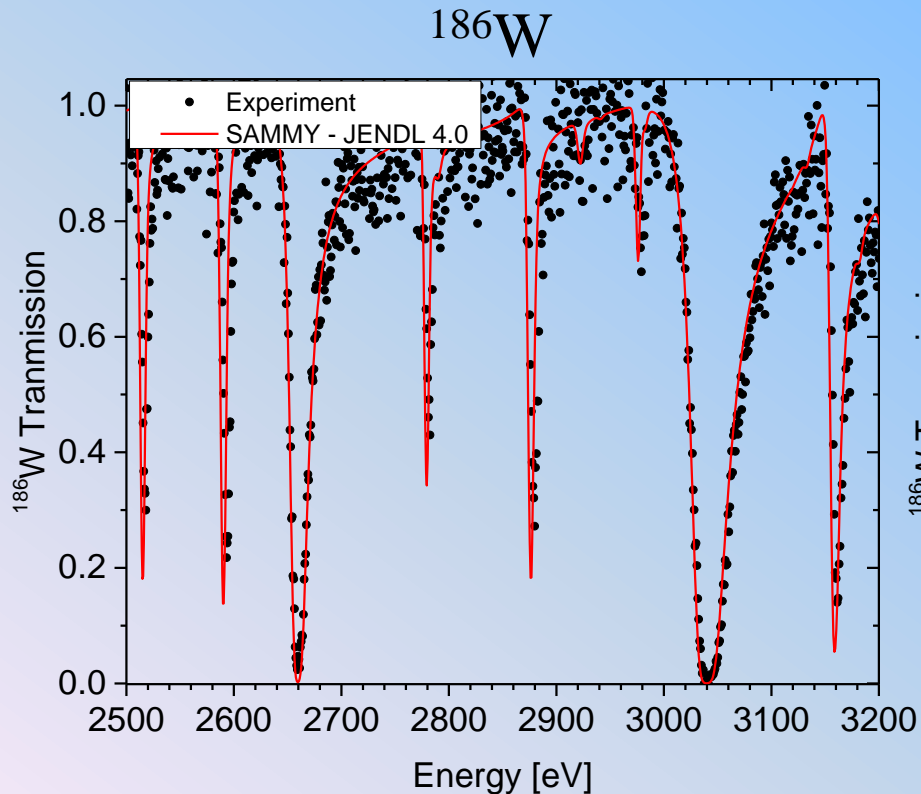
Brian is setting up the new detector system



A picture of flight path station

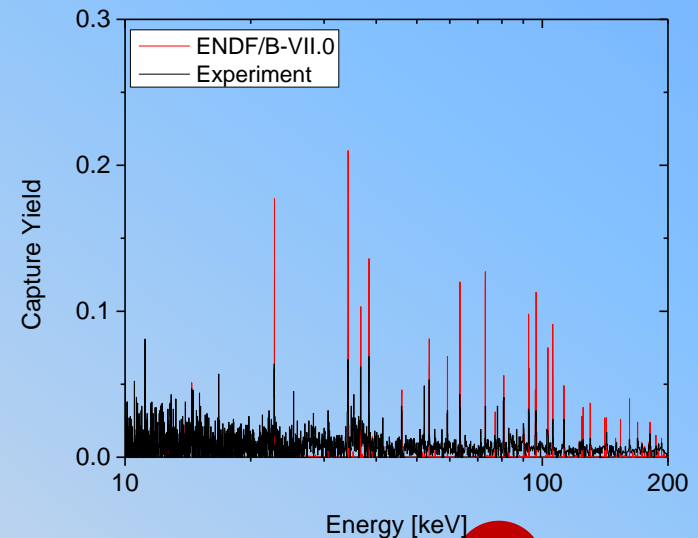
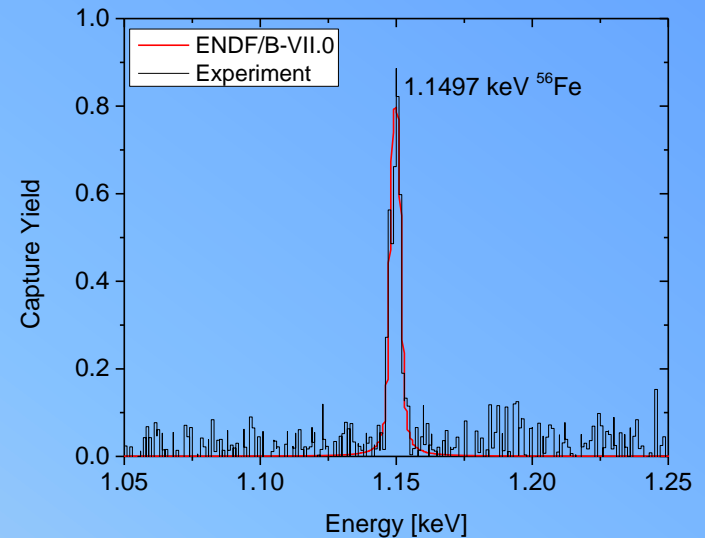
^{186}W Transmission results: 2.5 – 3.2 keV

- Energy resolution was fitted to the ^{238}U sample
- ^{186}W shows energy shift which are not visible in the ^{238}U
- Preliminary data was delivered to ORNL



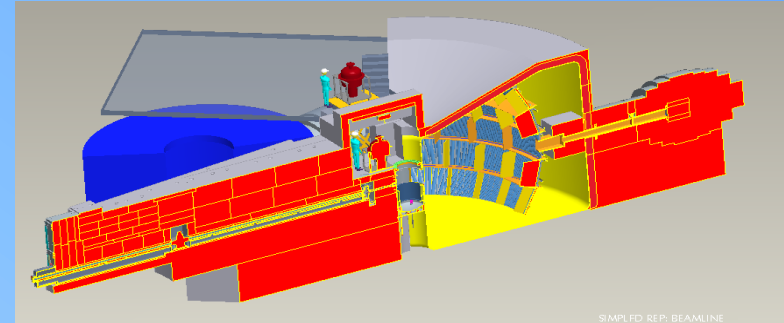
Test Measurement of Fe capture

- Capture measurements on a 1 cm thick Fe sample
- Three detectors were connected to digitizers
- One detector was connected to an analog system
- Data on Fe sample was taken for about 17 hours.
- Resonances in the keV region are resolved.
- A problem with the energy resolution of three detectors was identified, the detectors were returned to the vendor for repair



Thermal Scattering Experiment at SEQUOIA (SNS)

- SEQUOIA:
 - Fine-Resolution Fermi Chopper Spectrometer at SNS
 - $E_i = 10$ to 2000 meV
 - 900 ^3He detector tubes
 - Scattering angles: -30° to -3° horizontal and 3° to 60° vertical
 - Flux: $> 1 \times 10^5$ neutrons/cm 2 /s
 - Resolution: $\Delta E/E_i \sim 1\%$



- Double differential scattering cross section for inelastic scattering:

$$\frac{d^2\sigma}{d\Omega dE'}(E \rightarrow E', \Omega \rightarrow \Omega') = \frac{\sigma_b}{4\pi kT} \sqrt{\frac{E'}{E}} e^{-\frac{\beta}{2}} S(\alpha, \beta)$$

$$\alpha = \frac{E' + E - 2\sqrt{E'E \cos \theta}}{AkT} = \frac{\hbar^2 \kappa^2}{2MkT}$$

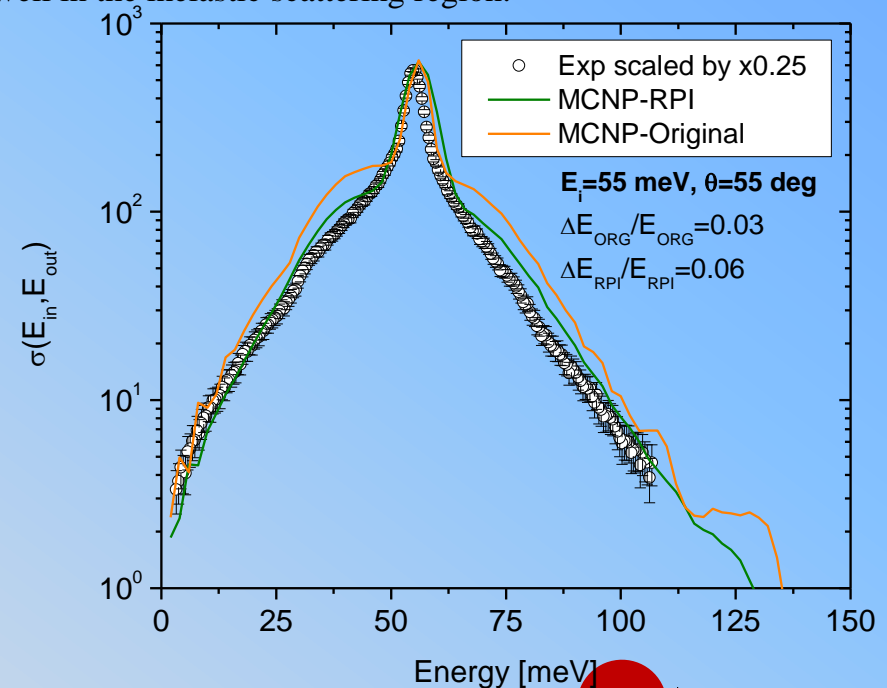
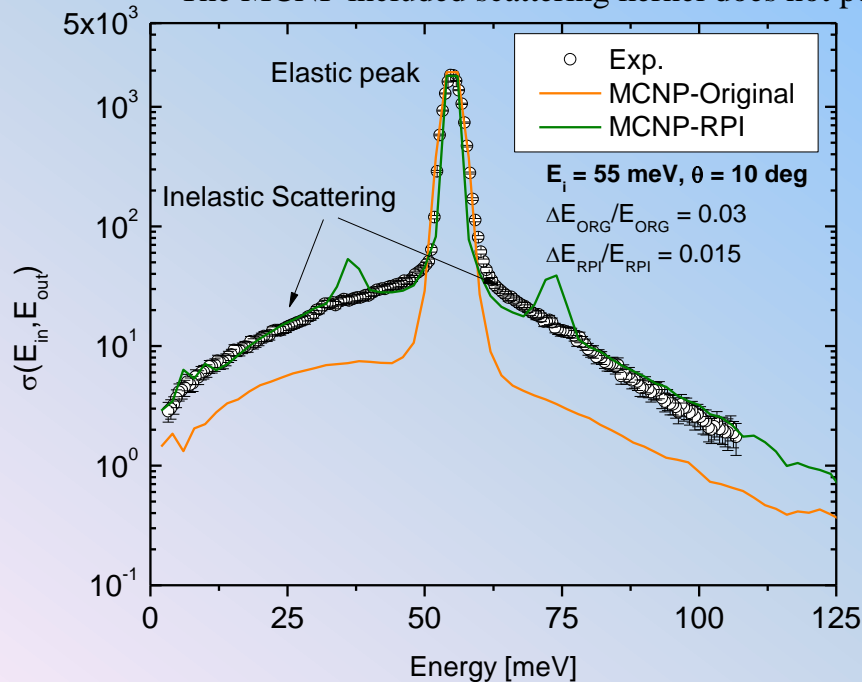
$$\beta = \frac{E' - E}{kT} = \frac{\varepsilon}{kT}$$



Thermal Scattering Measurements

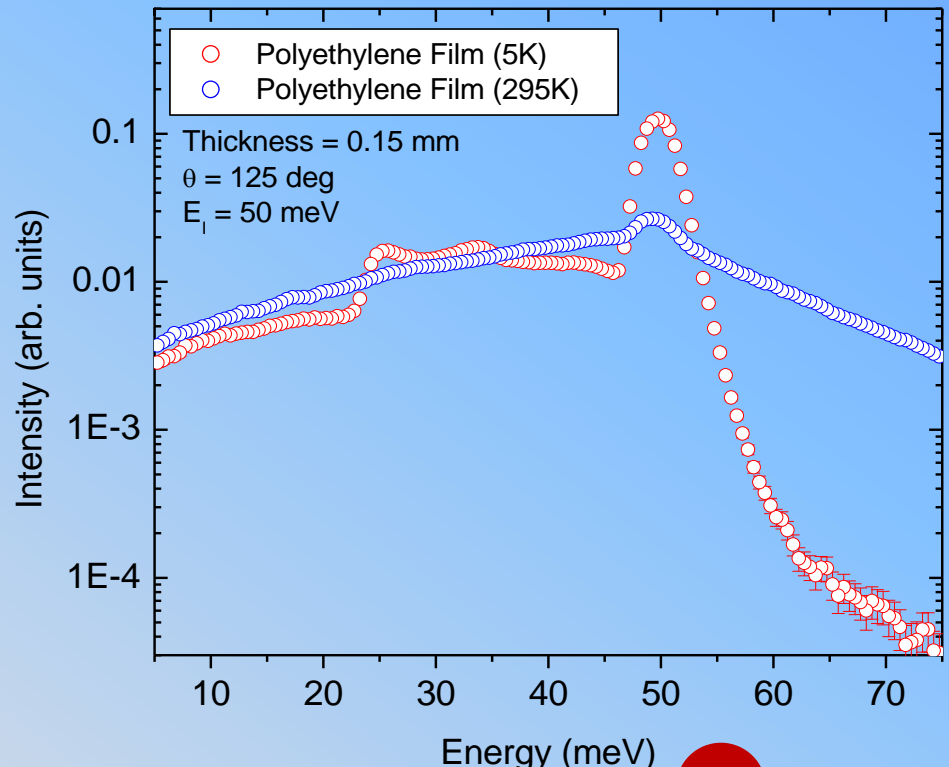
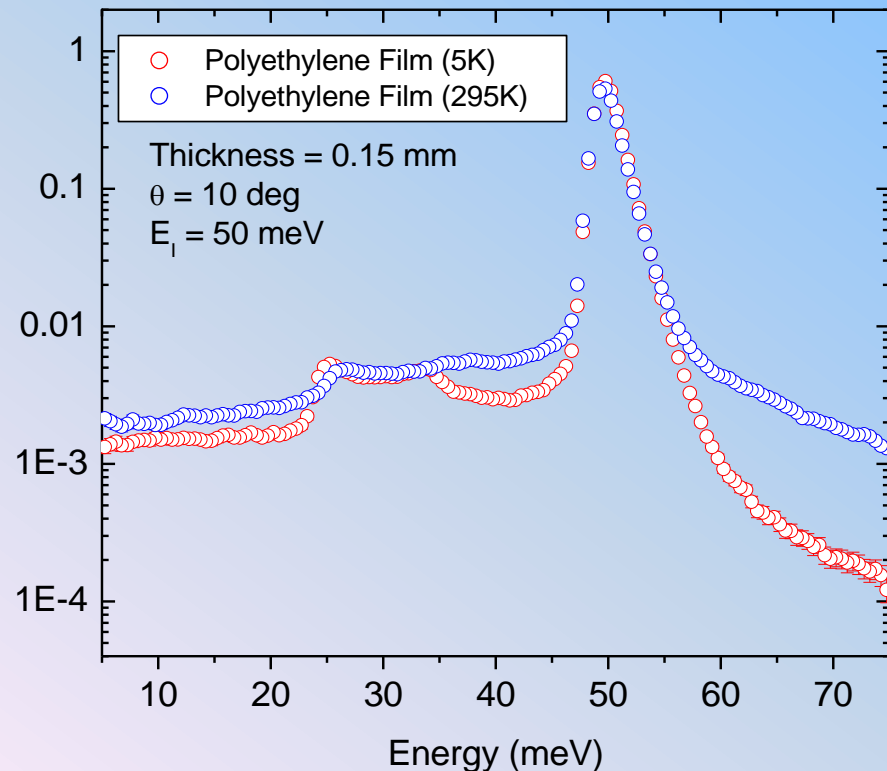
Mid Density Polyethylene

- Samples: H₂O, Polyethylene, Empty Can, Vanadium
- Data were measured for several incident energies, E_i (eV): 0.055, 0.16, 0.25, 0.6, 1, 3, 5
- Use the MCNP provided scattering kernel and our own generated kernel to simulate the experiment using MCNP
 - Included spectrometer incident energy resolution.
 - Data were normalized at the elastic scattering peak
 - The MCNP included scattering kernel does not perform well in the inelastic scattering region.



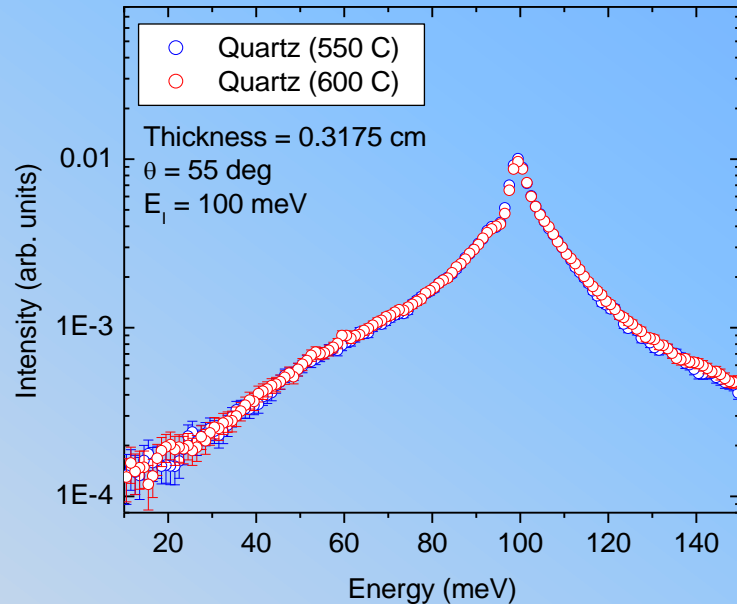
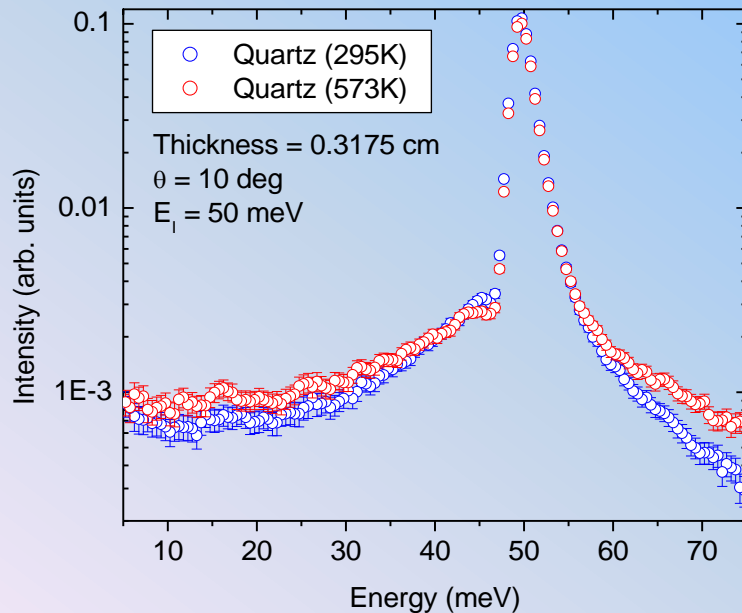
Poly New Raw Experimental Data

- Polyethylene using ARCS-Wide Angle Spectrometer at SNS

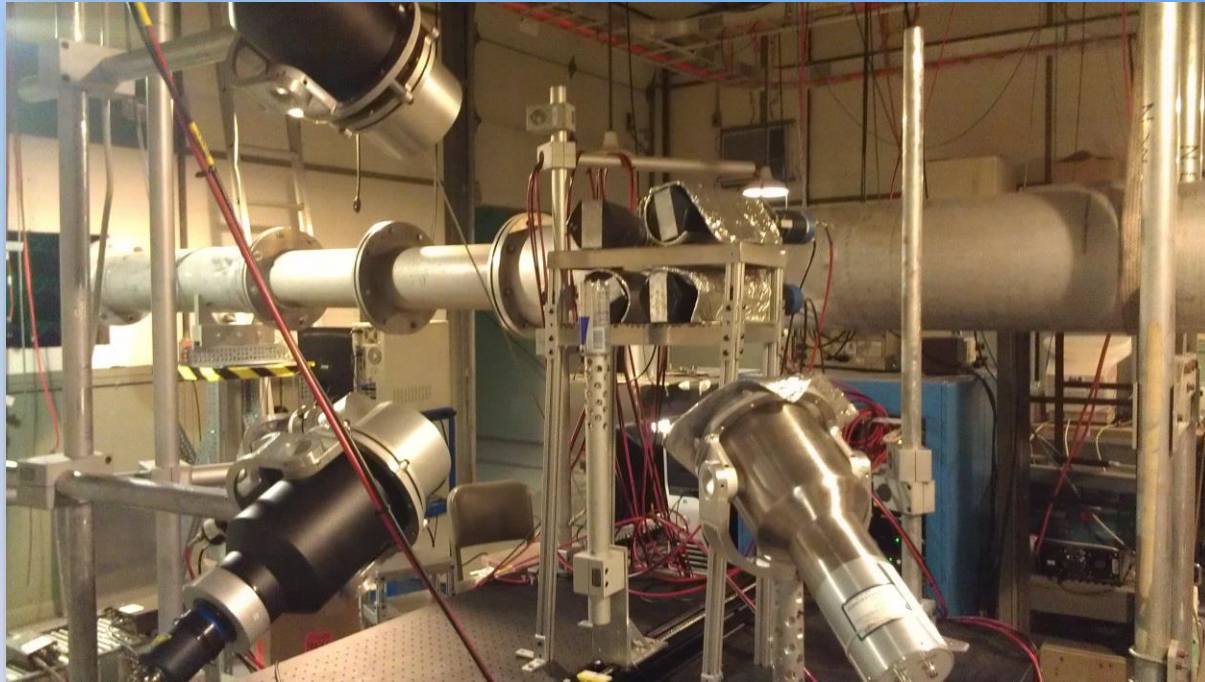


Quartz Crystal

- SiO_2 was measured at multiple thicknesses
 - 0.3175 cm and 0.635 cm ($1/8^{\text{th}}$ and $1/4^{\text{th}}$ inches)
 - Temperatures: 20 C, 300 C, 550 C, 600 C



Prompt Fission Neutron Spectra



Gamma Tagging

- Advantages
 - Eliminated the need to construct a complicated multiplate fission chamber
 - Simpler sample preparation
 - Can use relatively large samples
 - Can increase the detected fission rate
- Disadvantages
 - False fission detection due to:
 - Random coincidence for radioactive decay
 - Neutron interactions with the gamma detector
 - Beam related:
 - Gamma capture
 - Inelastic Scattering
 - Increased background



Fast neutrons scattering detector array

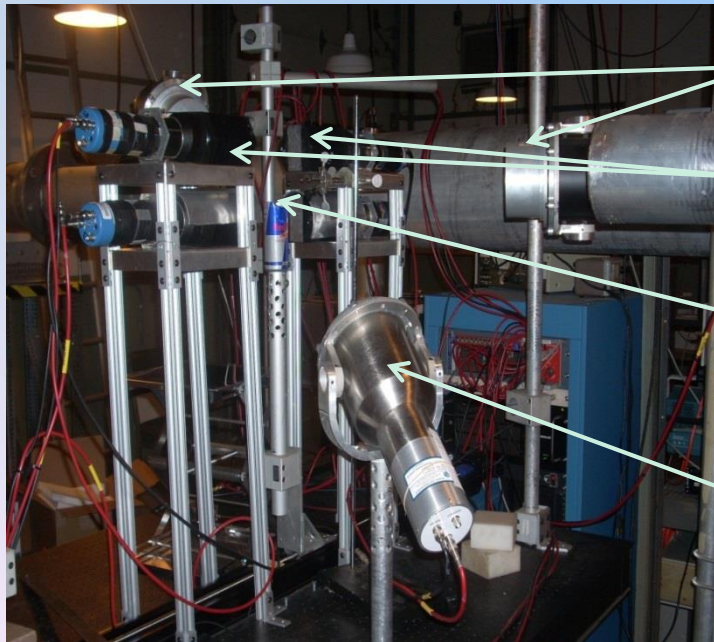
Experimental Setup

- Neutron Detectors

- EJ-204 Plastic Scintillator
 - 0.5" x 5"
 - 47 cm away from center of sample
- 2 EJ-301 Liquid Scintillators
 - 3" x 5"
 - 50 cm away from center of sample

- Gamma Detectors

- 4 BaF₂ detectors on loan from ORNL
- Hexagonal detectors 2" x 5"
- 10 cm from center of sample
- 1/4" lead shield between detectors
 - Reducing scattering between detectors



EJ-301 Detectors
 Gamma Detectors
 Sample Position
 EJ-204 Detector

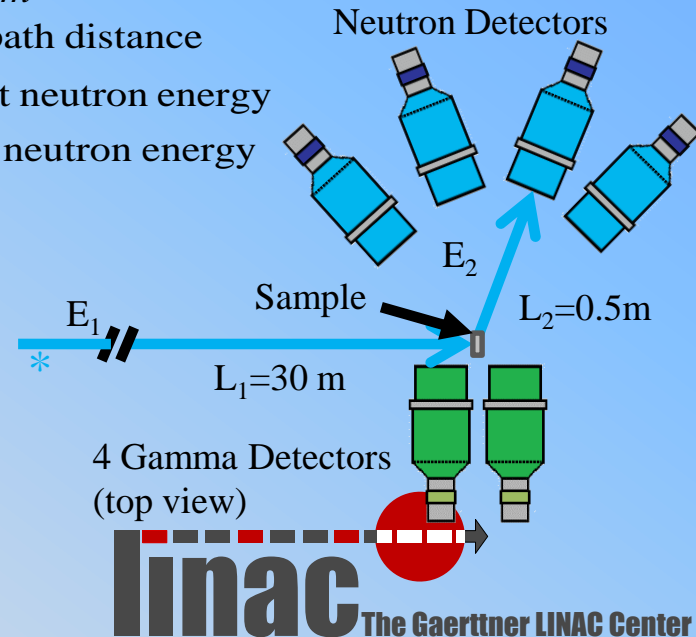
$$ToF = \frac{kL_1}{\sqrt{E_1}} + \frac{kL_2}{\sqrt{E_2}}$$

$$k \approx 72.3 \frac{\mu s eV^{1/2}}{m}$$

$L_{1,2}$ – flightpath distance

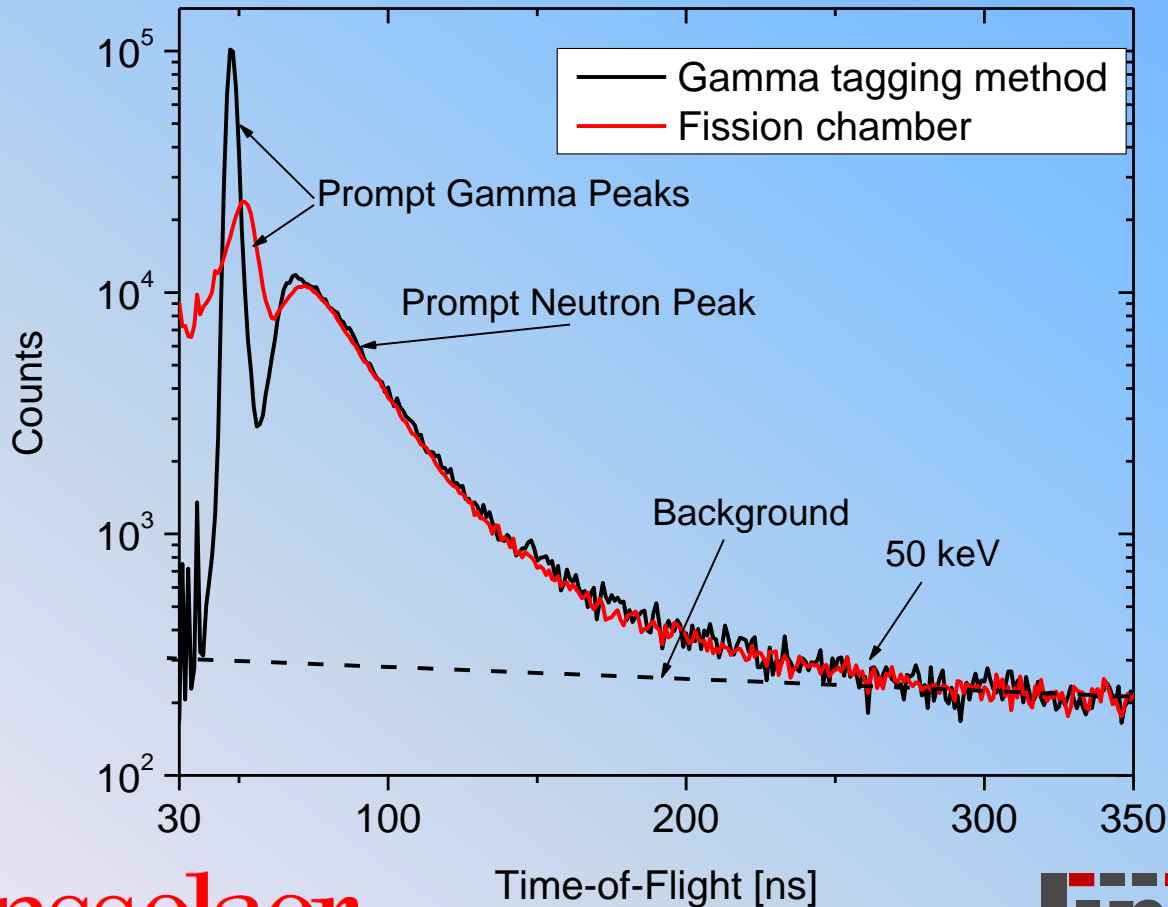
E_1 – incident neutron energy

E_2 – fission neutron energy

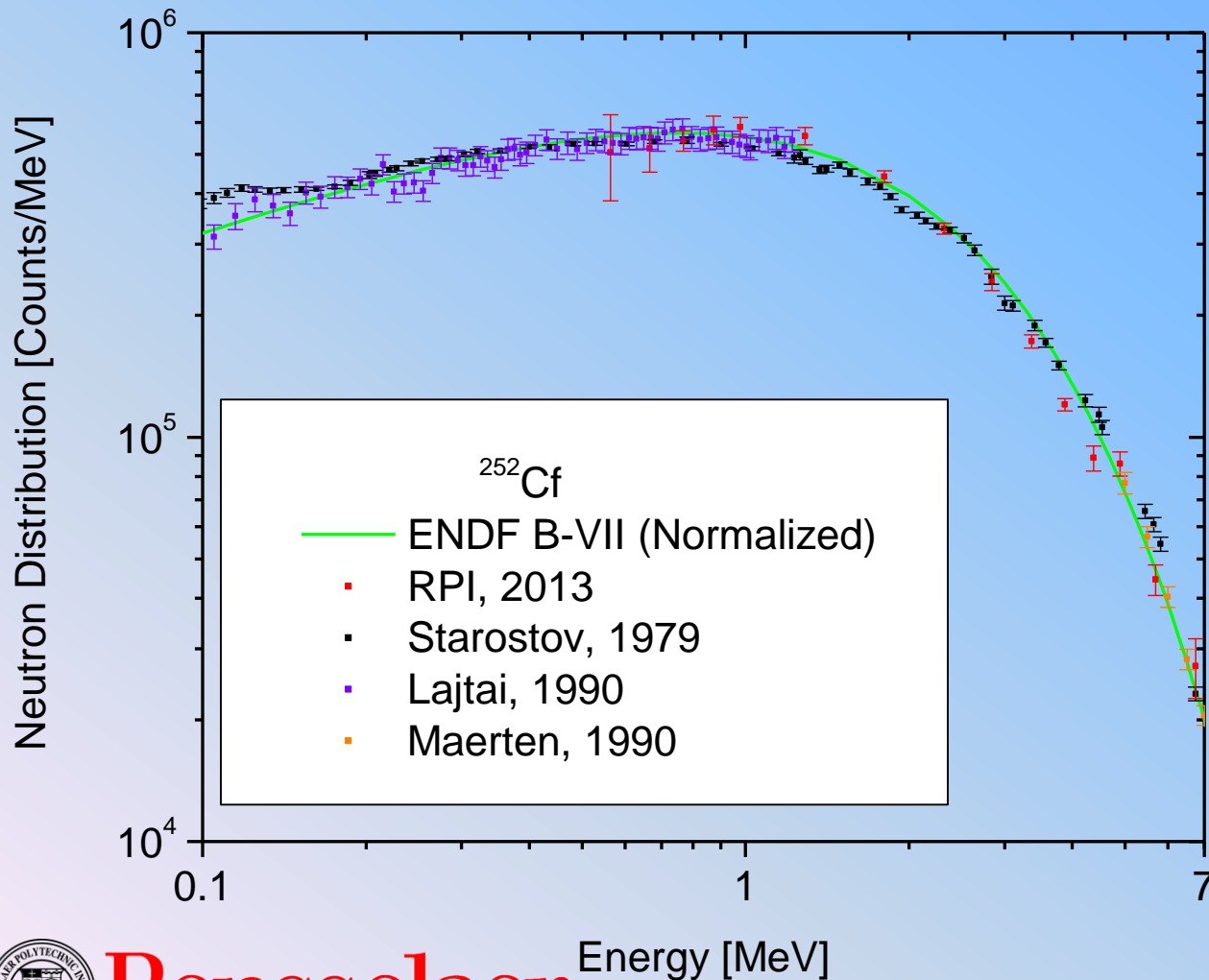


Gamma Tagging - EJ-204

- Gamma tagging method corrected for 30% detection efficiency compared to 83% detection efficiency with fission chamber



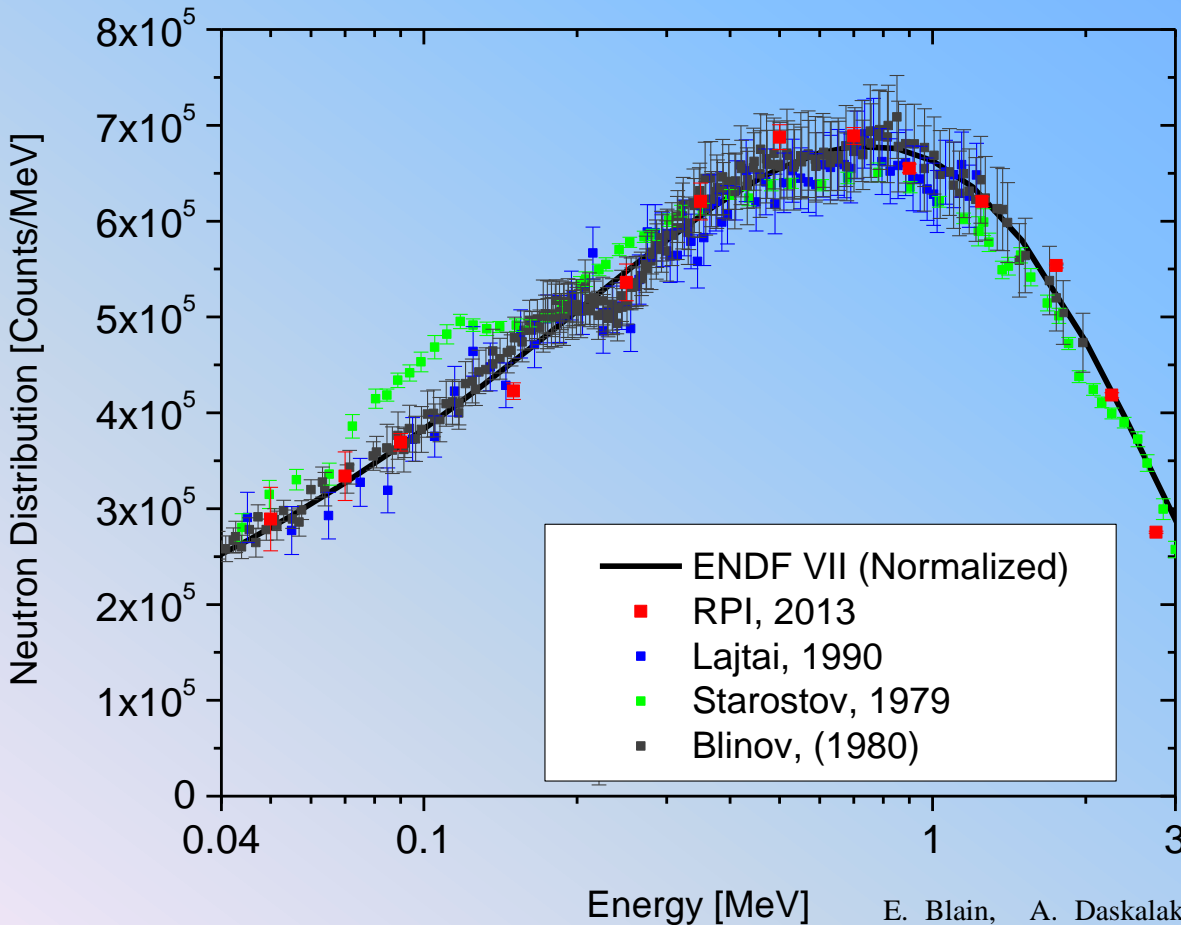
^{252}Cf Prompt Fission Neutron Spectrum High Energy



- High Energy spectrum taken with EJ-301 liquid scintillator
- The gamma tagging method shows good agreement to ENDF/B-VII in the energy range from 0.6 MeV to 7 MeV



^{252}Cf Prompt Fission Neutron Spectrum Low Energy



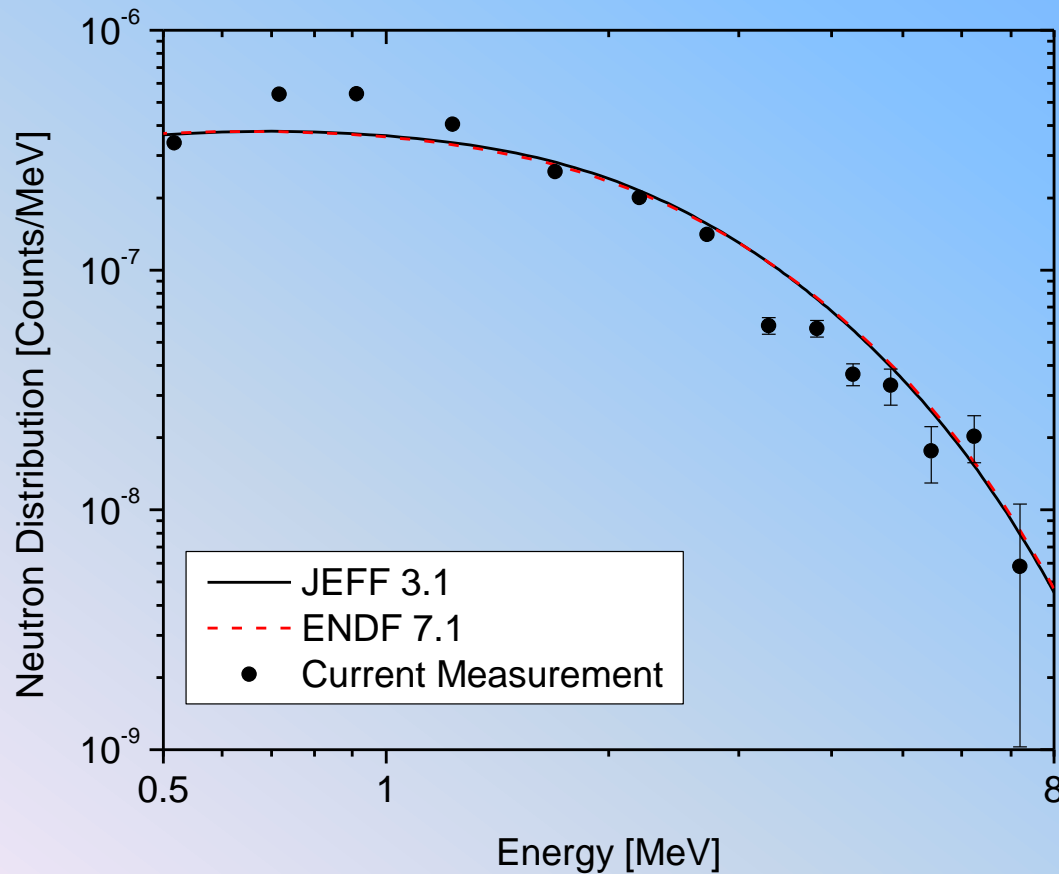
- Low energy data taken with 0.5" EJ-204 plastic scintillator
- RPI data show good agreement to Lajtai, Blinov data and ENDF evaluation
- Thin plastic detector allows for measurement down to 50 keV
- Gamma tagging method accurately reproduces PFNS for ^{252}Cf

E. Blain, A. Daskalakis, and Y. Danon, "Measurement of Fission Neutron Spectrum and Multiplicity using a Gamma Tag Double Time-of-Flight Setup", **invited talk**, International Conference on Nuclear Data for Science and Technology, New York, New York, March 4-8, 2013.



^{238}U Prompt Fission Neutron Spectrum

Preliminary Results



- Spectrum is normalized to ENDF at 2 MeV
- Spectrum is integrated over from 0.5 MeV to 20 MeV
- Only statistical uncertainty was plotted.
- Preliminary data show reasonable agreement with current evaluations

National Institute of Standards

- Review of standards:
- **H(n,n)**
 - Measurements of Daub et al. from 150 keV to 800 keV were 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. Now the Arndt evaluation is larger than ENDF/B-VII by about 0.1% at low energies and about 1% at about 12 MeV.
 - Angular distributions - work is being 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
- **³He(n,p)**
 - This measurement would constrain the fundamental nucleon-nucleon interaction models that underlie all of our cross section work. This work could help with Hale's R-matrix evaluation of the ³He(n,p) cross section.
- **⁶Li(n,t)**
 - Absolute measurement of the cross section at 4 meV was completed (NIST, LANL, the University of Tennessee and Tulane University). Flux accuracy is known to 0.05% and mass accuracy to 0.25%, total error of about 0.3% is expected.
- **C(n,n)**
 - Daub et al. 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 but generally within their uncertainties of 1.1 to 2%. These data have already been put into the carbon evaluations being done by Hale and Young.
- **²³⁸U(n,γ)**
 - Ullmann et al. made measurements of the ²³⁸U(n,γ) cross sections using the DANCE (160 BaF₂ crystals) detector at LANSCE and thin samples. The neutron beam was monitored with a ²³⁵U fission chamber, a BF₃ counter, a 6LiF detector and a ³He detector. Analysis is in progress.
- **²³⁵U(n,f), ²³⁸U(n,f) and ²³⁹Pu(n,f)**
 - additional work should be done in the high energy region of the cross sections to support of the needs for better standards in that energy region.
- **Au(n,γ)**
 - Wallner using AMS with a simulated Maxwellian neutron source spectrum of 25 keV mean energy obtained a ratio to the standards evaluation for gold capture of 1.04 ± 0.05 . The Au(n,γ) cross section measurements of Borella et al. support the standards evaluation. Schillebeeckx repeated that experiment of Borella et al. with considerable concern about corrections to the data. The new results support the standards results.
- Work on prompt gamma-ray production reference cross sections considering ^{nat}Ti with large yields of two gamma-lines, 984 keV from ⁴⁸Ti(n,n'γ) and 160 keV from ⁴⁸Ti(n,2nγ) and ⁴⁷Ti(n,n'γ)

**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 21, 2013**

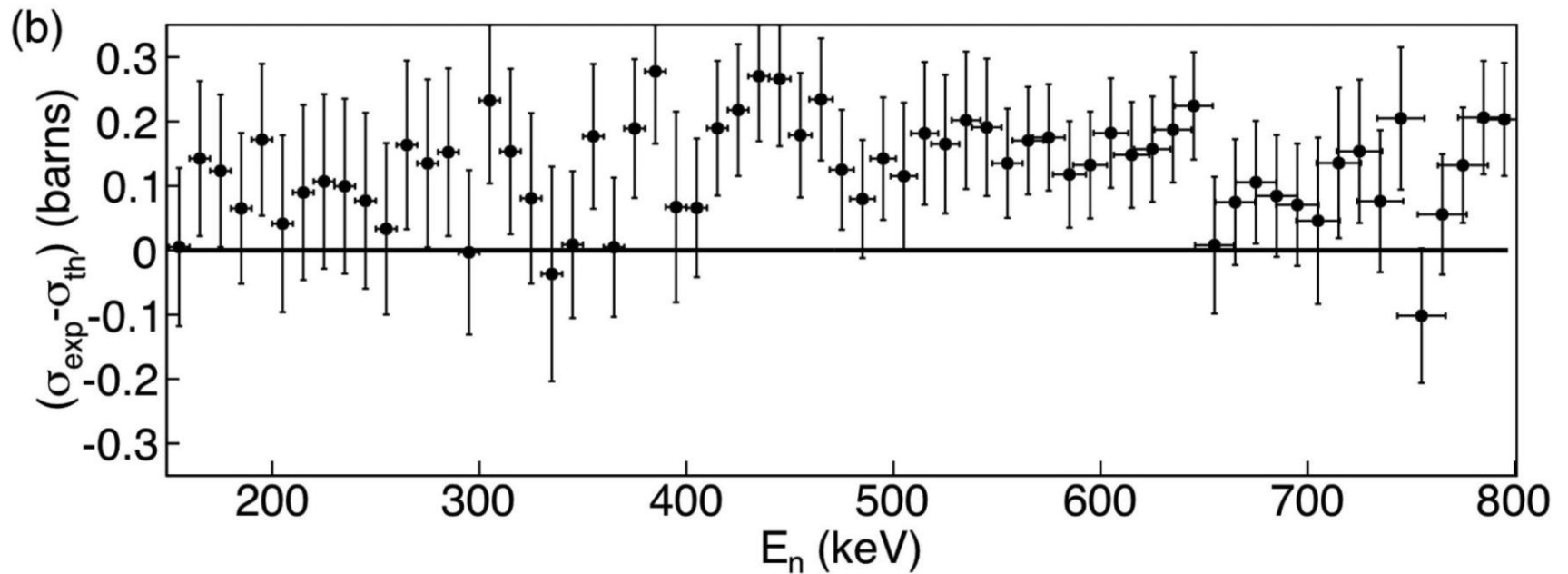
THE NEUTRON CROSS SECTION STANDARDS

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

H(n,n)H Standard Measurements .

- Concerns about the hydrogen total scattering cross section at low neutron energies led to Van de Graaff work by Daub *et al.* from 150 keV to 800 keV. The results were 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. Now the Arndt evaluation is larger than ENDF/B-VII by about 0.1% at low energies and about 1% at about 12 MeV.

Daub *et al.* 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 is being 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.
- To obtain the accuracy needed for this work, the neutron detector efficiency must be determined accurately.

H(n,n)H Angular Distribution Measurements (cont.)

➤ 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 $180 - \Theta$ 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.

➤ Our study of possible reactions indicated that the ${}^6\text{Li}({}^6\text{Li},n){}^{11}\text{C}$ reaction would be the best for our use, however for the only suitable targets we successfully made, ${}^6\text{LiF}$ and ${}^6\text{LiCl}$, the backgrounds were very large. Measurements with $\text{C}(\text{C},n)$ were successful however the Q value of -2.6 MeV is a limitation. Targets are being made for a $\text{D}(\text{d},n)$ source. The Q value of 3.3 MeV will allow data to be taken at small angles for 10 MeV neutrons. Going to 14.9 MeV will require further study.

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

$^3\text{He}(n,p)$ Measurements

➤ Progress continues on an experiment to measure the n - ^3He coherent scattering length. This measurement is complementary to the n - ^3He work. This measurement would constrain the fundamental nucleon-nucleon interaction models that underlie all of our cross section work. This work could help with Hale's R-matrix evaluation of the $^3\text{He}(n,p)$ cross section.

(collaboration of NIST with Indiana University and the University of North Carolina)

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

- A measurement has been completed of the ${}^6\text{Li}(n,t)$ cross section standard at ~ 4 meV neutron energy. This is the first direct and absolute measurement of this cross sections in this neutron energy range using monoenergetic neutrons. A primary effort was very accurate measurements of the fluence. The fluence (efficiency) has now been determined with an uncertainty of 0.05%.
- The limitation on the accuracy of the ${}^6\text{Li}(n,t)$ cross section measurement is the mass uncertainty of the ${}^6\text{Li}$ target. The present mass uncertainty is about 0.25%. The deposits were made at IRMM. Studies have been made to compare the mass with the value obtained when it was characterized a number of years ago. Comparisons have also been made with a number of other deposits made at the same time at IRMM. It is expected that an ultimate total uncertainty less than 0.3% for the cross section can be obtained from this experiment.

(collaboration of NIST, LANL, the University of Tennessee and Tulane University)

$^{10}\text{B}+\text{n}$ Measurements

➤ Measurements have been made of the $^{10}\text{B}(\text{n},\alpha_1)$, $^{10}\text{B}(\text{n},\alpha_0)$, $^{10}\text{B}(\text{n},\text{p})$ and $^{10}\text{B}(\text{n},\text{t})$ cross sections using four E- Δ E telescopes at WNR-LANL in a LANL-Ohio University collaboration. The neutron fluence was determined using a ^{238}U fission chamber.

➤ Due to the thickness of target, there was a problem separating the alpha groups. Also it may not be possible to separate the proton and triton groups. Analysis is being done now to see if the separation can be improved.

It is possible that only the $^{10}\text{B}(\text{n},\alpha)$ cross section and the $^{10}\text{B}(\text{n}, \text{p}+\text{t})$ cross section will be obtained from the new analysis. The data extend to 5 MeV.

➤ It is not clear what impact this work may have on an R-matrix evaluation of the standards.

➤ A paper on this work, by Massey et al., shown as preliminary, was given at the ND2013 conference.

C(n,n) Data

➤ Gritzay *et al.* measured the carbon total cross section 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. They suggest that the resonance in ^{13}C at 152.9 keV may cause this increase. Further work is being done on this using modified filters.

However

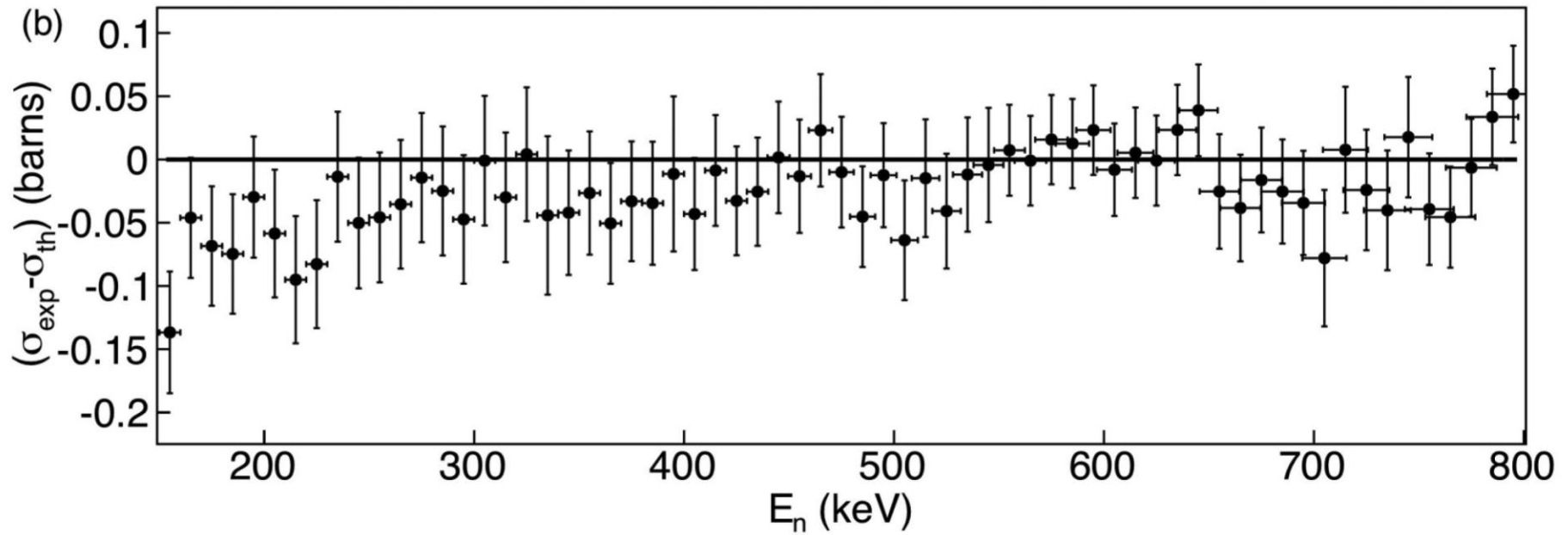
➤ Danon *et al.* made very accurate measurements of the carbon total cross section using an iron filtered linac neutron beam. The data were obtained for 19 peaks from 24.3 to 945 keV. This method provided very low backgrounds. The results obtained with an accuracy of better than 1% were in excellent agreement with the ENDF/B-VII evaluation.

➤ Anh *et al.* made total cross section measurements with reactor filtered beams at 54 and 148 keV that agree with the ENDF/B-VII.0 evaluation. The results were given at the ND2013 Conference.

Daub *et al.* Carbon Total Cross Section

➤ 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 but generally within their uncertainties of 1.1 to 2%. These data have already been put into the carbon evaluations being done by Hale and Young.

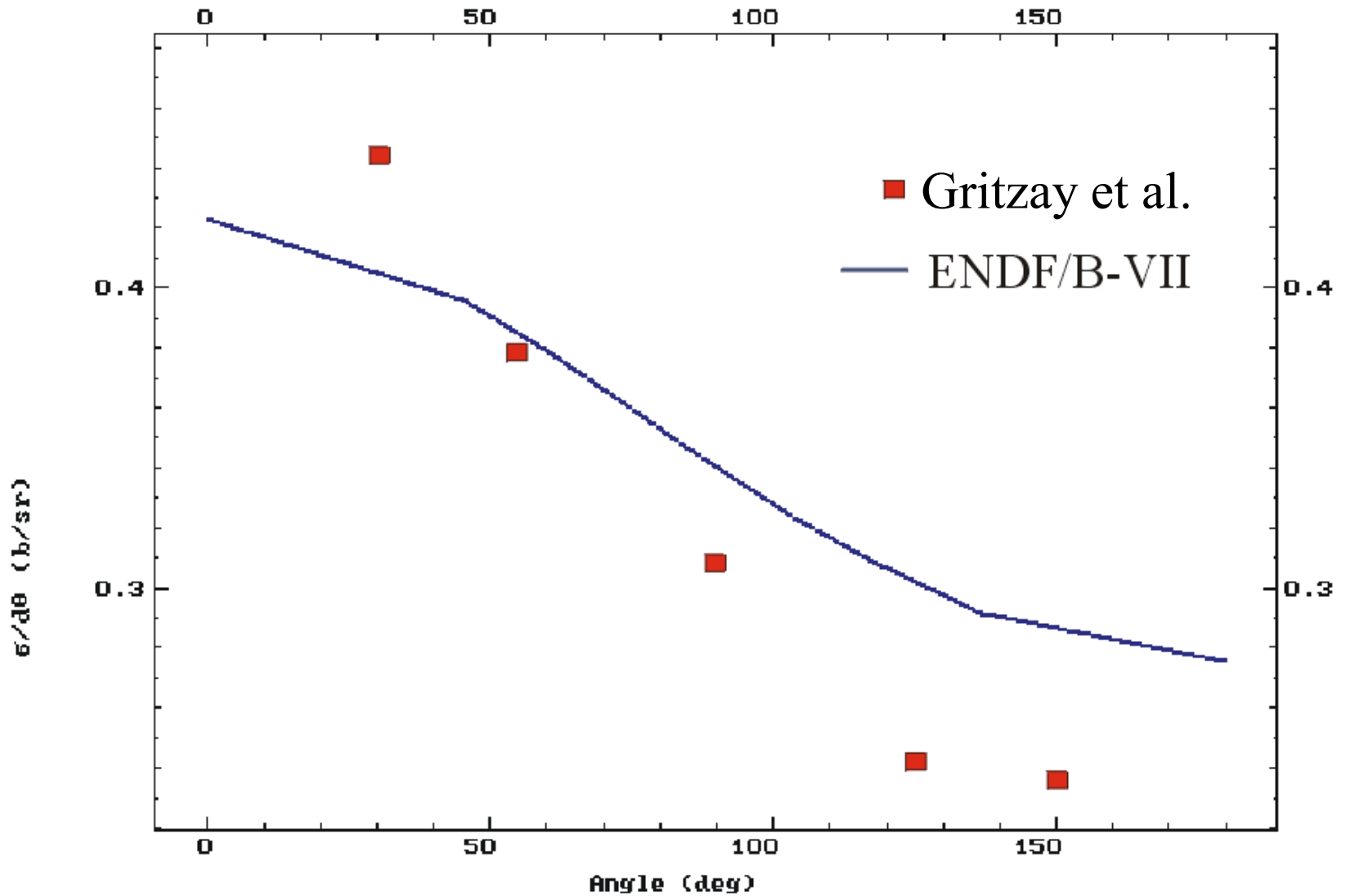
Daub *et al.* Carbon Total Cross Section – ENDF/B-VII Evaluation



C(n,n) Angular Distribution Data

- Gritzay et al. data were shown at the last CSEWG Meeting. they have angular distribution data for 2, 59 and 133 keV. The data were taken at the Kyiv reactor using filtered beams. The measurements were made at 30, 55, 90, 125 and 150°. They were measured relative to lead scattering but the shape should still be relatively good anyway.
- In her last correspondence she indicated she was planning on continuing this work. But her immediate effort is developing a new method for measuring the carbon total cross section in the 90 – 160 keV energy region that encompasses the 152.9 keV carbon resonance. Her previous work indicated that the resonance has a much larger neutron width than previously thought. The method she is using is called modified filtered beams. It involves making measurements with many different types of filters and analyzing the results. A paper on this work was given at the NPAE-2012 conference in Kiev.
- The measurements at 133 keV are shown in the next figure. The results differ from the carbon standard.
- Hale will be checking to see what effects the 152.9 resonance due to ^{13}C would have on this angular distribution measurement.

C(n,n) $E_n = 133$ keV



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

- Ullmann et al. made measurements of the $^{238}\text{U}(n,\gamma)$ 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 $^6\text{Li F}$ detector and a ^3He 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 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.
- He had hoped to have the data finalized by now but he has had some setbacks. He plans to have the data available soon for use in the standards evaluation.

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

- Collaborative measurements have been made recently at GELINA and n_TOF using the same sample.
- At GELINA, Lampoudis And Günsing made measurements using a C_6D_6 detector. Data were obtained from 10 keV to 1 MeV. The data are being analyzed.
- At n_TOF, measurements were made with a C_6D_6 detector by Mingrone et al. from thermal to about 500 keV. Data were also obtained with 40 BaF_2 detectors, (the Total Absorption Calorimeter, TAC), by Wright from about 0.3 eV to 100 keV. They anticipate that average values will be available from 20 keV to 1 MeV for that detector.
- Initial work by this collaboration was reported at the ND2013 conference. At the CIELO meeting this November, they reported TAC results up to 10 keV and C_6D_6 results up to 3 keV.

Additional Standards Work

- In order to improve the standards on a continuing basis, an IAEA Nuclear Data Development Project “Maintenance of the Neutron Cross Section Standards” was initiated.
 - This project has pursued improvements in the experimental database, considered additional standards, maintained evaluation codes and will periodically update the standards so they are available for new versions of data libraries. In addition to the conventional standards:
 - Work has been done on the gold cross section at energies below where it is considered a standard.
 - Reference cross sections for prompt gamma-ray production in fast neutron-induced reactions have been studied and the best candidates have been suggested.
 - An effort was directed at improvements in the evaluations of the ^{252}Cf spontaneous fission neutron spectrum and the ^{235}U thermal neutron fission spectrum

Au(n, γ) Data at Low Neutron Energies

➤ Au(n, γ) reference cross section for capture cross section measurements for astrophysics (below the standards energy region)

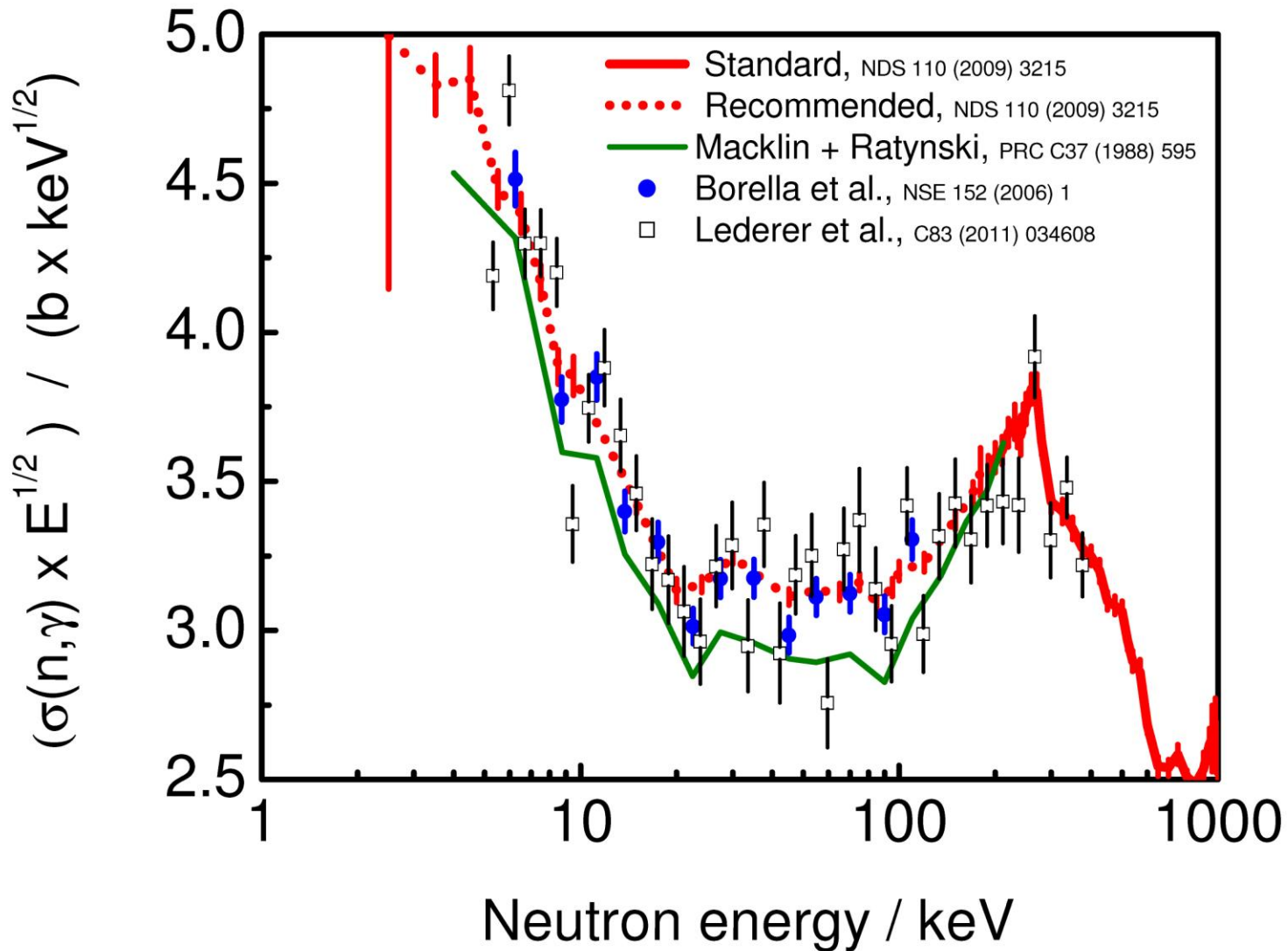
➤ The measurements cited below all support the results of the standards evaluation. They indicate the Ratynski and Käppeler results are low by about 5-7% from 15 to 25 keV.

➤ Wallner using AMS with a simulated Maxwellian neutron source spectrum of 25 keV mean energy obtained a ratio to the standards evaluation for gold capture of 1.04 ± 0.05

➤ Lederer reanalyzed n_TOF gold capture data of Massimi and folded a simulated Maxwellian neutron source spectrum of 25 keV mean energy into that data. The result was 564 ± 23 mb compared with the standards evaluation of 575 mb. That is a 2% difference with an uncertainty of 4%.

➤ The Au(n, γ) cross section measurements of Borella et al. support the standards evaluation. Schillebeeckx repeated that experiment of Borella et al. with considerable concern about corrections to the data. The new results support the standards results.

Low Energy Au(n, γ) Cross Section Measurements and Evaluations



Prompt Gamma-Ray Production Reference Cross Sections

- Reference cross sections for measurements of prompt gamma-ray production cross sections.
 - Many nuclides and reactions were considered
 - ^{nat}Ti with large yields of two gamma-lines, 984 keV from $^{48}\text{Ti}(n,n'\gamma)$ and 160 keV from $^{48}\text{Ti}(n,2n\gamma)$ and $^{47}\text{Ti}(n,n'\gamma)$ reactions appears to be one of the most suitable for use as a reference cross section. More work needs to be done to improve the experimental database.
 - New measurements by Nelson using GEANIE have been made and are being analyzed.
 - An improved evaluation by Simakov has been done.
 - $\text{Li}(n,n'\gamma)$ also appears to be a reasonable candidate
 - New measurements have been made by Nelson with GEANIE
 - There is little high quality data at higher neutron energies except the Nelson work

Lawrence Berkeley National Laboratory

- Measurements of prompt gammas at the Budapest reactor using HPGe detectors. Samples includes standards such as B, H, N, Cl, S, Na, Ti, Au.
- Uses DICBOX to calculate the contribution from the continuum level states.
- New Data for ^{23}Na , $^{39,40,41}\text{K}(n,\gamma)$ was recently published:
 - ^{23}Na : $\sigma_0(\text{Atlas})=0.541(3)$, $\sigma_0(\text{this work})=0.517(4)$,
 - ^{39}K : $\sigma_0(\text{Atlas})=2.1(2)$, $\sigma_0(\text{this work})=2.28(4)$
 - ^{40}K : $\sigma_0(\text{Atlas})=30(8)$, $\sigma_0(\text{this work})=90(7)$
 - ^{41}K : $\sigma_0(\text{Atlas})=1.46(3)$, $\sigma_0(\text{this work})= 1.62(3)$
- New Data for $^{182,183,184,186}\text{W}(n,\gamma)$ publish in Phys. Rev. C 89, 014606, 9 January 2014.
- Data for $^{152,154}\text{Eu}$, $^{155,157}\text{Gd}(n,\gamma)$ were submitted for publication.

Recent EGAF Thermal Neutron Cross Section Measurements

R.B. Firestone

Lawrence Berkeley National Laboratory

Database of Prompt Gamma Rays
from Slow Neutron Capture for
Elemental Analysis

$$\begin{aligned}\kappa^0(E\gamma) &= \kappa\zeta(E\gamma) / \kappa\text{H}(2223) \\ &= [\sigma\gamma\zeta(E\gamma) / A\rho(Z)] / [\sigma\gamma\text{H}(2223) / A\rho(\text{H})] \\ &= 3.03 \xi [\sigma\gamma\zeta(E\gamma) / A\rho(Z)]\end{aligned}$$



IAEA

International Atomic Energy Agency



IAEA

International Atomic Energy Agency



Evaluated Gamma-ray Activation File (EGAF)

1999-2004: IAEA CRP on "Development of a Database for Prompt Gamma-ray Neutron Activation Analysis"

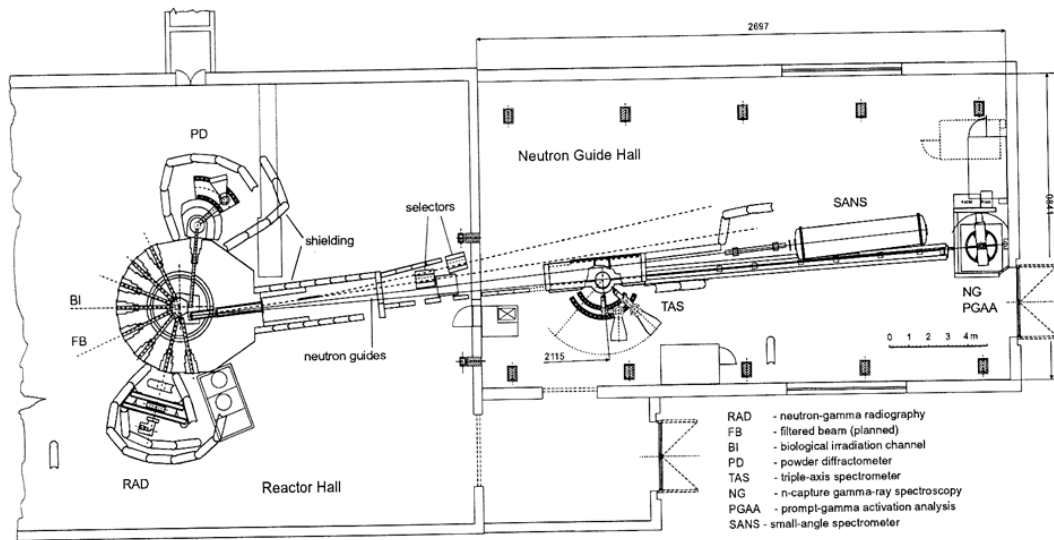
- Evaluation of thermal neutron capture prompt γ -ray cross sections for all elements with $Z=1-83,90,92$ except He and Pm.
- Measurements performed at the Budapest Reactor
- Determined prompt and delayed E_γ , σ_γ , σ_0 , level schemes and S_n

2004: Published *Handbook of Prompt Gamma Activation Analysis*, Kluwer Publishers.

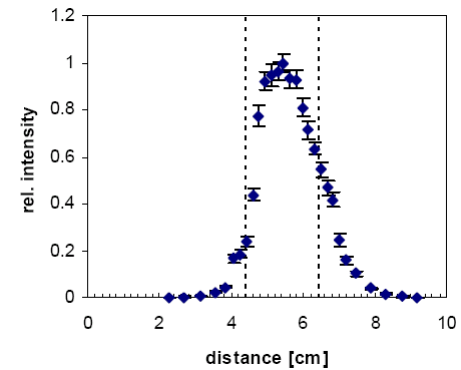
2007: Published *Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis*, IAEA STI/PUB/1263.

>2007: Continued (n,γ) measurements on enriched isotopic targets at the Budapest and FRM-II (Garching) reactors.

Measurements



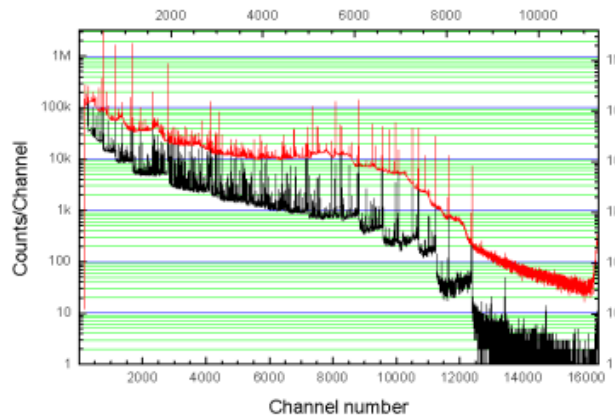
Guided, curved neutron beam
 Prompt γ -rays were measured ≈ 30 m from the reactor wall in a low background counting area.



Measured beam profile

Thermal flux: $2 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$.

Cold flux: $5 \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$



HPGe: Compton suppressed γ -ray spectrum for CCl_4
 Efficiency: $<1\%$ for $E=0.5-6 \text{ MeV}$, $<3\%$ for $6-10 \text{ MeV}$

The Budapest neutron beam is a pure cold/thermal beam with no fast component!

Standardization

Thermal γ -ray cross sections were determined using internal standards of known composition. For $1/v$ isotopes this measurement is independent of neutron energy. For non- $1/v$ isotopes g-factor corrections were made.

1. **Stoichiometric compounds** containing elements with well-known cross sections: **B, H, N, Cl, S, Na, Ti, Au**

e.g. KCl , $(\text{CH}_2)_n$, $\text{Pb}(\text{NO}_3)_2$, GdB_6 , Ti_2SO_4

2. **Homogenous mixtures**

Aqueous (H_2O) or acid (20% HCl) solutions, mixed powders (TiO_2)

3. **Activation products** with well-known decay P_γ

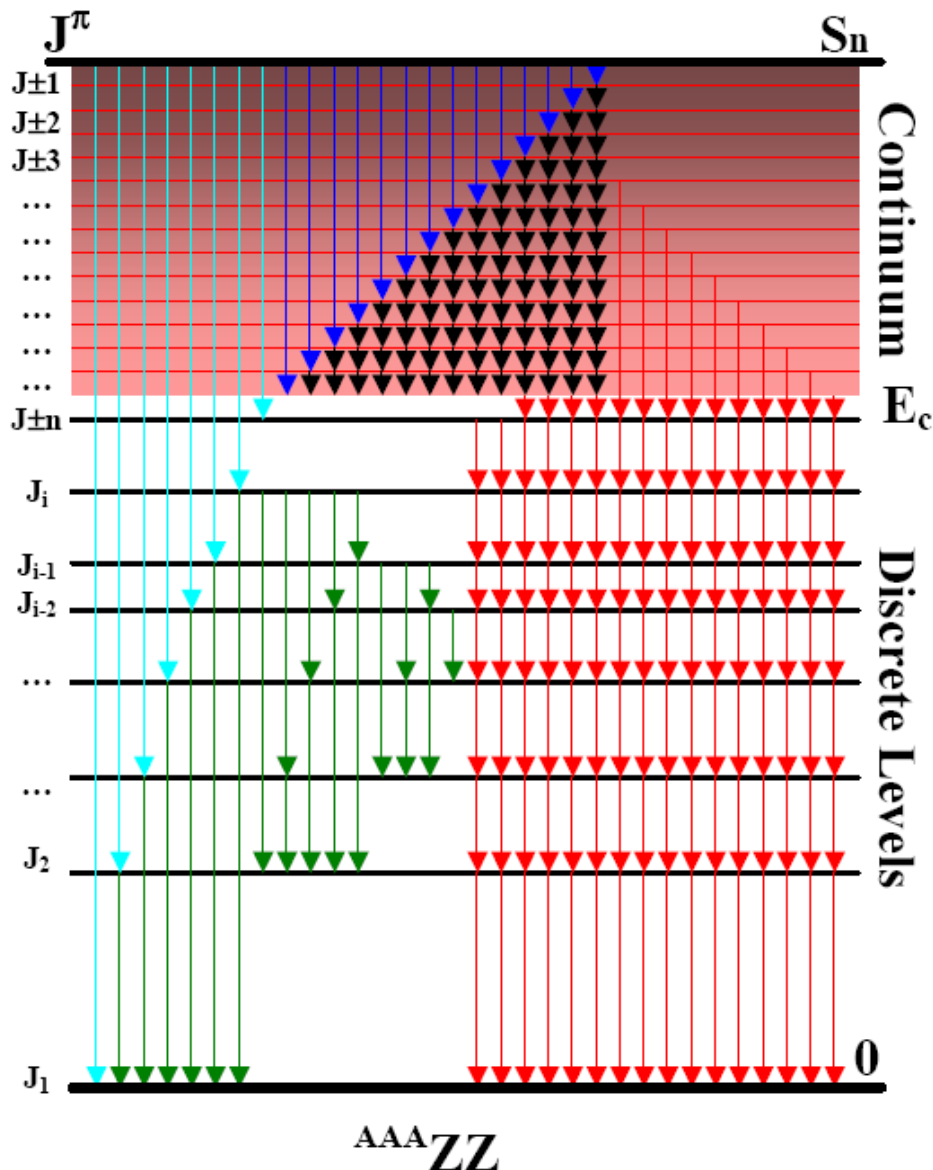
^{19}F , ^{28}Al , ^{100}Tc , ^{235}U

Measurements were performed on all elemental targets with

$Z=1-83, 92$ except for He and Pm

and on the selected radioactive targets ^{99}Tc , and ^{129}I .

Determination of σ_0



For **low-Z** complete (n,γ) decay schemes are measured in EGAF and

$$\sigma_0 = \Sigma \sigma_\gamma(GS) = \Sigma \sigma_\gamma(CS)$$

For **high-Z**, when the (n,γ) continuum feeding is significant,

$$\sigma_0 = \Sigma \sigma_\gamma(GS)_{E < E_{crit}}^{EGAF} + \Sigma \sigma_\gamma(GS)_{E > E_{crit}}^{cont}$$

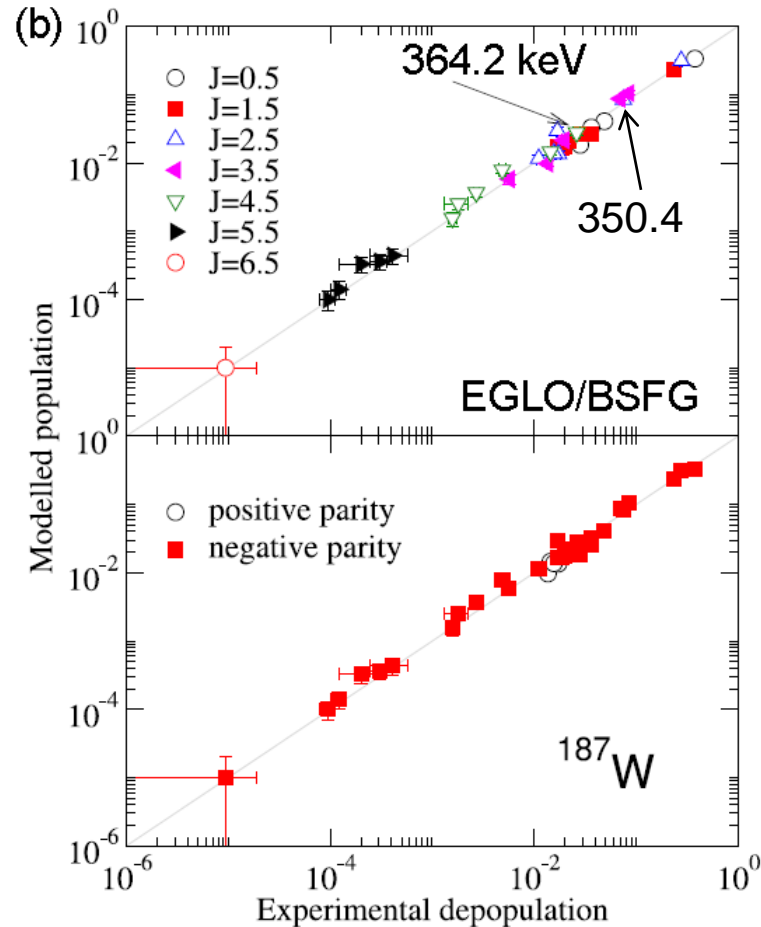
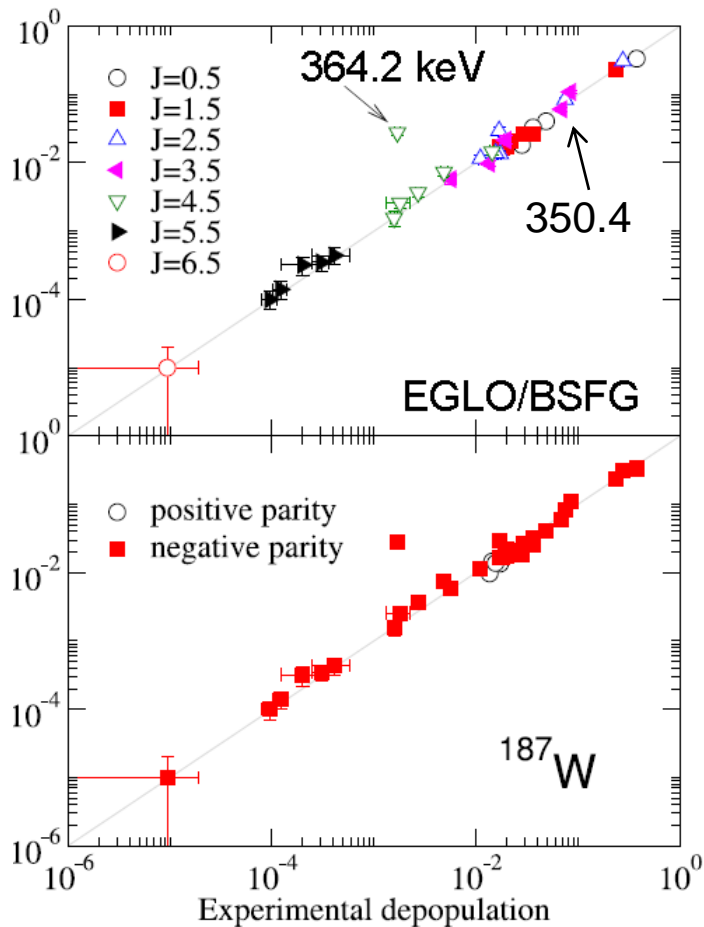
E_{crit} is the excitation energy up to which the level scheme is complete.

We use the **DICEBOX*** statistical model code to calculate continuum feeding to the GS.

- **DICEBOX** calculates multiple decay scheme “realizations” to estimate inherent statistical variations.
- Numerous photon strength and level density models are available.
- Calculated feeding to excited states below E_{crit} is normalized to EGAF cross section deexciting these levels.

*F. Becvar and M. Krlicka, Charles University, Prague.

Population/Depopulation Plot



- Calculated population of levels below E_{crit} for ^{187}W agrees well with EGAF cross section deexciting these levels over 5 orders of magnitude in intensity.
- Disagreement for 364.2-keV $9/2^-$ level resolved by addition of 13.8 keV γ -ray to 350.4-keV $7/2^-$ level improving the fit to both levels.
- Population/depopulation plots are only weakly model dependent.

EGAF Evaluation Status

Publications (47 isotopes)

Z=1-17 (25 isotopes) – Proceedings of ND2013

$^{23}\text{Na}(n,\gamma)$ – submitted to Phys. Rev. C.

$^{39,40,41}\text{K}(n,\gamma)$ – Phys. Rev. C 87, 024605 (2013).

$^{102,104,105,106,108,110}\text{Pd}(n,\gamma)$ – Phys. Rev. C 77, 054615 (2008).

$^{152,154}\text{Eu}(n,\gamma)$ – Proceedings of ND2013

$^{155,157}\text{Gd}(n,\gamma)$ – Nucl. Sci. Eng. In press.

$^{182,183,184,186}\text{W}(n,\gamma)$ – submitted to Phys. Rev. C.

Evaluations in progress (13 isotopes)

$^{54,56,57,58}\text{Fe}(n,\gamma)$ – Firestone, Krticka

$^{89}\text{Y}(n,\gamma)$ – Abusaleem, Hurst

$^{93}\text{Nb}, ^{103}\text{Rh}(n,\gamma)$ – Turkoghu*, Basunia

$^{139}\text{La}(n,\gamma)$ – Ureche[†], Hurst

$^{180}\text{W}(n,\gamma)$ – Hurst

$^{185}\text{Re}(n,\gamma)$ – Lerch*, Hurst, Carroll

$^{237}\text{Np}, ^{241}\text{Am}, ^{242}\text{Pu}(n,\gamma)$ – Genreith*, Hurst

$^{238}\text{U}(n,\gamma)$ – Basunia, Genreith*, Sleaford

Recent Measurements (Garching FRM-II)

$^{70,72,74,76}\text{Ge}, ^{90,91,92,94}\text{Zr}, ^{192,196,198}\text{Pt}(n,\gamma)$ – Firestone, Oslo Group

* Graduate student, [†] Undergraduate student

$^{23}\text{Na}, ^{39,40,41}\text{K}(n,\gamma)$

^{23}Na : R.B. Firestone et al, submitted to Phys. Rev. C.(2103)

$^{39,40,41}\text{K}$: R.B. Firestone et al, Phys. Rev. C 87, 024605 (2013)

Isotope	σ_0 (b) Atlas*	σ_0 (b) This work
^{23}Na	0.541(3)	0.517(4)
^{39}K	2.1(2)	2.28(4)
^{40}K	30(8)	90(7)
^{41}K	1.46(3)	1.62(3)

E_γ (^{41}K)	P_γ ENSDF	P_γ This work
1524.7	0.1808(9)	0.164(4)

*Atlas of Neutron Resonances, S.F. Mughabghab, Elsevier (2006).

New Potassium Nuclear Structure Data				
Isotope	^{23}Na	^{40}K	^{41}K	^{42}K
# levels below E_{crit} (RIPL) [†]	4	15	11	4
# levels below E_{crit} (This work) [†]	13	21	16	17
New J^π assignments	21	3	2	8
New levels placed	0	18	0	0
Previous levels removed	0	1	0	0
New γ -rays placed	27	2	0	0

[†] E_{crit} is the excitation energy where the level scheme is complete.

182,183,184,186W(n,γ)

A.M. Hurst, et al, submitted to Phys. Rev. C.

Tungsten Thermal (n,γ) Cross Sections		
Isotope	Cross section (b)	
	This work	Atlas
$^{182}\text{W}(n,\gamma)^{183}\text{W}$	20.5(14)	19.9(3)
$^{182}\text{W}(n,\gamma)^{183}\text{W}^m$	0.177(18)	---
$^{183}\text{W}(n,\gamma)^{184}\text{W}$	9.4(4)	10.4(2)
$^{183}\text{W}(n,\gamma)^{184}\text{W}^m$	0.025(6)	---
$^{184}\text{W}(n,\gamma)^{185}\text{W}$	1.43(10)	1.7(1)
$^{184}\text{W}(n,\gamma)^{185}\text{W}^m$	0.0062(16)	---
$^{186}\text{W}(n,\gamma)^{187}\text{W}$	33.3(6)	38.1(5)
$^{186}\text{W}(n,\gamma)^{187}\text{W}^m$	0.400(16)	---

^{187}W β– decay P_γ(686 keV)	
This work	0.352(9)
ENSDF	0.332(5)

Tungsten Neutron Separation Energy		
Isotope	S_n (keV)	
	This Work	AME
^{183}W	6190.88(6)	6190.81(5)
^{184}W	7411.11(13)	7411.66(25)
^{185}W	5753.74(5)	5753.71(30)
^{187}W	5466.62(7)	5466.79(5)

152,154Eu, 155,157Gd(n,γ)

^{152,154}Eu: Proceedings of ND2013

^{155,157}Gd: Nucl. Sci. Eng. In press.

Tungsten Thermal (n,γ) Cross Sections		
Isotope	Cross section (b)	
	This work	Atlas
¹⁵² Eu(n,γ) ¹⁵³ Eu ^g	7060(400)	5900(200)
¹⁵² Eu(n,γ) ¹⁵³ Eu ^{m1}	2345(220)	3300(200)
¹⁵² Eu(n,γ) ¹⁸⁴ Eu ^{g+m1}	9405(460)	9200(100)
¹⁵⁴ Eu(n,γ) ¹⁵⁵ Eu ^m	335(10)	310(7)
¹⁵⁵ Gd(n,γ) ¹⁵⁶ Gd	56,700(2100)	60,900(500)
¹⁵⁷ Gd(n,γ) ¹⁵⁸ Gd	239,000(6000)	254,000(815)

Discrepancy in ¹⁵³Eu^{m1} cross section due to decay scheme normalization

Z≤17 (n,γ)

Target	σ_0 (EGAF)	σ_0 (Atlas*)
⁶ Li	52.6(22) mb	44.8(3) mb
⁷ Li	46.3(13) mb	45.2(14) mb
⁹ Be	8.8(6) mb	8.5(3) mb
¹⁰ B	3.90(11) mb	3.05(16) mb
¹¹ B	9.06(20) mb	5.5(33) mb
¹² C	3.89(6) mb	3.53(7) mb
¹³ C	1.51(3) mb	1.37(4) mb
¹⁴ N	78.5(7) mb	80.1(6) mb
¹⁵ N	39(3) mb	24(8) mb
¹⁶ O	197(7) mb	190(20) mb
¹⁹ F	9.63(16) mb	9.51(9) mb
²³ Na	541(3) mb	517(4) mb
²⁴ Mg	535(20) mb	538(13) mb
²⁵ Mg	196(8) mb	199(3) mb
²⁶ Mg	38.8(14) mb	38.4(6) mb
²⁷ Al	232.2(17) mb	231(3) mb
²⁸ Si	186(2) mb	171(3) mb
²⁹ Si	128(4) mb	119(3) mb
³⁰ Si	112(6) mb	107(2) mb
³¹ P	169(5) mb	165(3) mb
³² S	542(7) mb	518(14) mb
³³ S	449(7) mb	454(20) mb
³⁴ S	285(8) mb	256(9) mb
³⁵ Cl	44.00(20) b	43.6(4) b
³⁷ Cl	50.0(8) mb	43.3(6) mb

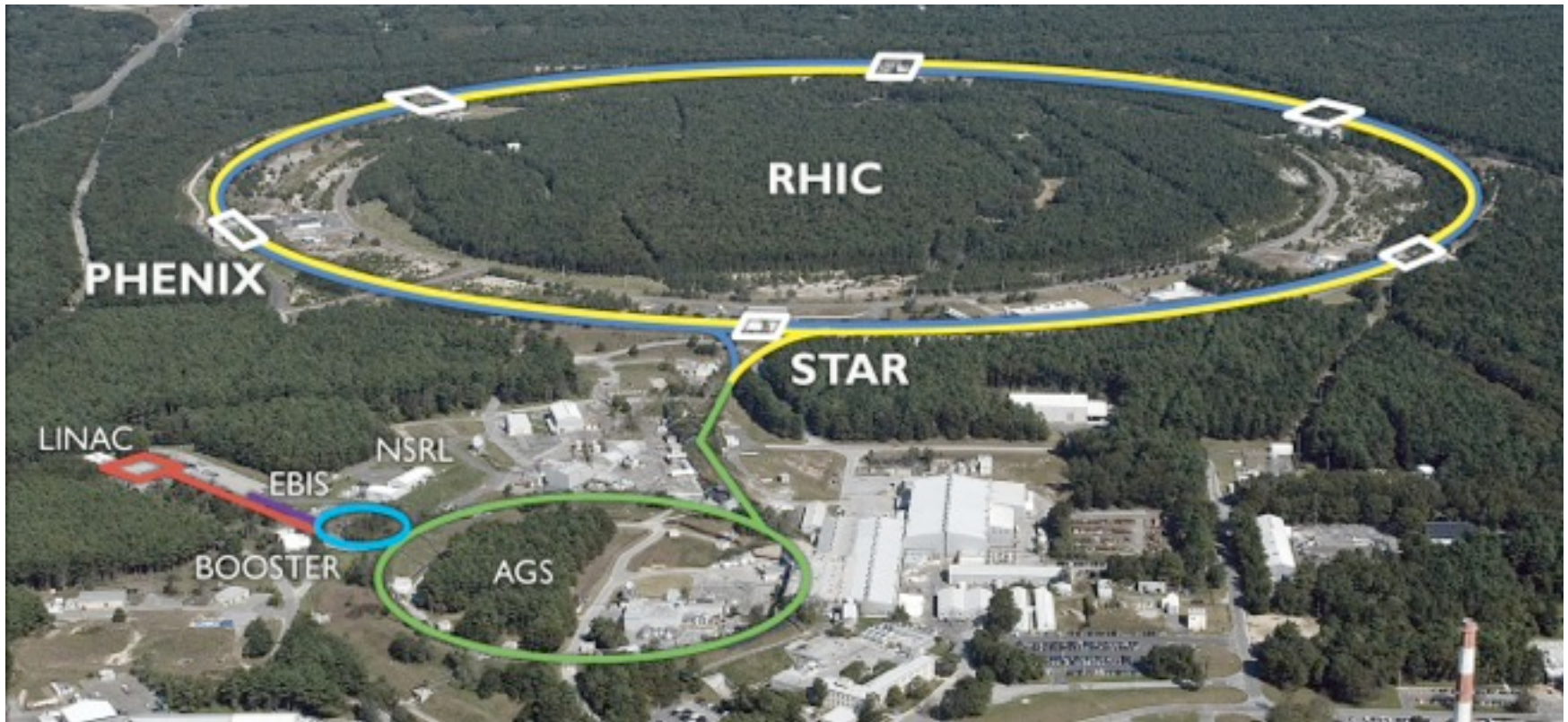
Measurements published in the proceedings of ND2013.

Complete decay schemes available for all isotopes.

Possibilities for nTOF @ BNL

Steve Peggs, Mei Bai, Phil Pile

BNL accelerators, big & small



From 0.75 MeV to 250 GeV.

From biology to isotope production, radiobiology, chemistry, basic energy sciences, & nuclear physics.

From electrons to Uranium.

Accelerator inventory

Nuclear Physics, Radiobiology, Isotope Production

Relativistic Heavy Ion Collider (2 rings)	250	GeV (2nd only to LHC)
Alternating Gradient Synchrotron	28	GeV
Booster	5	GeV/c
Proton linac	200	MeV
Accelerator Test Facility electron linac	70	MeV
Tandem Van de Graaff (2 accelerators)	15	MeV
RFQ linac	0.75	MeV

Chemistry, Isotope Production

Electron linac	10	MeV
Cyclotron	35	MeV
Cyclotron	19	MeV
Cyclotron	17.5	MeV
Van de Graaff	2	MeV

Basic Energy Sciences

National Synchrotron Light Source II	3.0	GeV (in construction)
Electron storage ring (X-ray)	2.5	GeV
Electron storage ring (UV)	750	MeV
Electron booster synchrotron	750	MeV
Electron linac (DUV-FEL)	230	MeV
Electron linac	200	MeV
Electron linac	80	MeV

Biology

Scanning Transmission Electron Microscopes (3)

Compare CERN & BNL

Parameter	Unit	CERN	BNL
Length	m	200, 20	200, 20
Proton energy	GeV	20	24 (max ~28)
Bunches per pulse		1	1 to 12
Protons per bunch	E12	7	5 to 10
Repetition period	s	1.2	2.8
Target power	kW	19	14 to 84

CERN & BNL capabilities are very similar at first glance

- with significant enhancements possible at BNL