Report on U.S. Experimental Activities
WPEC 2013

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CSEWG measurements committee chair

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Introduction

- This presentation summarizes the activity that was presented in the November 2012 CSEWG meeting.
  - Full reports are available on the CSWEG web page.
- Some updates were given during ND2013, March4-8, in NYC
- Reports from different laboratories:
  - LANL
  - LLNL
  - ORNL
  - RPI
  - LBNL
  - NIST
- This report represents only part of the U.S. nuclear data activity.

Los Alamos National Laboratory

- **GEANIE – (GErmanium Array for Neutron Induced Excitations)**
  - Summary of recent activity:
  - Cu(n,xnγ), x = 1,2,… for double-beta decay papers submitted to Phys Rev C.
  - Ar(n,xnγ), x=1,2,... Phys. Rev. C 85, 064614 (2012)
  - NaI(n,xnγ) for data libraries (N. Fotiades) – data taken
  - ^{86}Kr(n,xnγ), x= 1,2,... (Matt Devlin), ata taken; structure and transitions
  - NaI(n,xn) for data libraries (Nikolaos Fotiades),
  - Various elements for a neutron-induced gamma-production reference cross sections (R. Nelson) ^{7}Li (n,n')^{7}Li* (LiF target – "optical window"), Ti (n,xγ), Cr, Fe.
  - X-ray yield from n-induced fission (R. Nelson and Thierry Granier - CEA)
  - ^{114}In Isomer search continues.
  - Results for Ni(n,x γ) were shown for several gamma transitions
- **Capture measurement with DANCE (Detector for Advanced Neutron Capture Experiments)**
  - **Non Actinides**
    - **^{152,154,156,158}Gd** - Bayarbadrakh Baramsai, NCSU/LANL,
    - **^{97}Mo** - Carrie Walker, NCSU PhD dissertation, in progress,
    - **^{117,119}Sn** - Carrie Walker, NCSU PhD dissertation, in progress
    - **^{184,186}W** - Capture, Marian Jandel LANL (in progress),
    - **^{173}Lu** – Capture, O. Roig (CEA) (In progress)
    - **^{191,193}Ir** - Capture; Todd Bredeweg LANL,
  - **Actinides**
    - **^{233,235}U, ^{239,241}Pu -** Capture to fission: LANL, LLNL, **^{235}U (n, γ),published in Phys. Rev. Let. Results for**
    - **^{235}U** - capture cross section shown between 1-2.5 keV the new data is lower than ENDF/B-7.1 by about 20%. Above 3 keV the data is higher than ENDF/B-7.1 by 5-10%. Overall the new data is in better agreement with JENDL 4.0. Preliminary Capture cross section for **^{239}Pu** was shown; above 1 keV the data seems lower than previous experiments and lower than ENDF/B-7.1
    - **^{235}U, ^{239,241}Pu** - Fission gamma ray multiplicity and spectra: LANL/LLNL, (Prelim ^{239}Pu,^{235}U reported) ,. Comparison Paper: submitted to Phys. Rev C. Results on gamma multiplicity and energy spectrum for ^{239}Pu fission were shown.
    - **^{238}Pu** - Capture, capture/fission: LLNL,
    - **^{252}Cf** - Fission gamma multiplicity and spectra: LLNL submitted to Phys. Rev. C.,
    - **^{242}m, ^{243}Am** - Capture, Marian Jandel LANL (preliminary report submitted),
    - **^{238}U** - Capture cross section, gamma rays John Ullmann LANL (preliminary report submitted).
- **Fission cross section measurements (includes TPC and Chi nu)**
  - **^{233,238}U** - New measurement was completed.
  - **^{236}U, ^{243}Am** - Measurements of are in progress. Results for 236U were also shown and are in good agreement with the Lisowski data.
  - **^{234}U** - Results for fission cross section of where shown. Between 1-10 MeV the data seem slightly high than ENDF/B-70.01 and JENDL-4.0.
- **LSDS**
  - **^{237}U** (t1/2=6.75d) - Fission cross section was measured (2 eV- 2 keV) and follow up measurement of the decayed sample was shown.

Nuclear Data Experiments at LANSCE: Highlights 2012

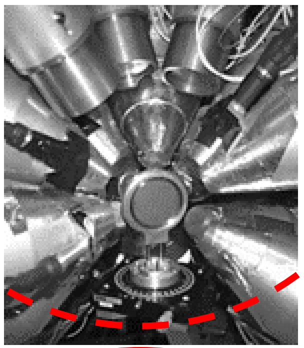
Robert C. Haight for LANSCE-NS and colleagues
Los Alamos National Laboratory

Cross Section Evaluation Working Group Meeting
US Nuclear Data Program Meeting
Brookhaven National Laboratory
November 5-9, 2012

LA-UR-12-25988

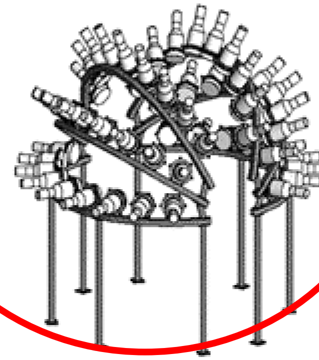
Experiments with actinides

GEANIE (n,xγ)

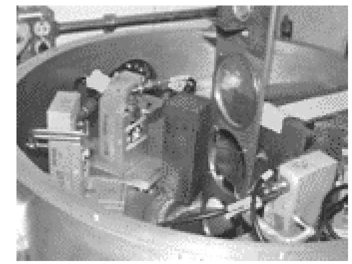


DANCE (n,γ)

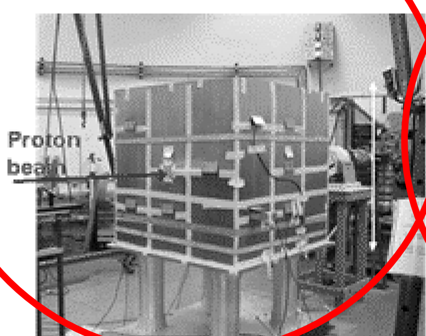
Chi-Nu (n,xn)



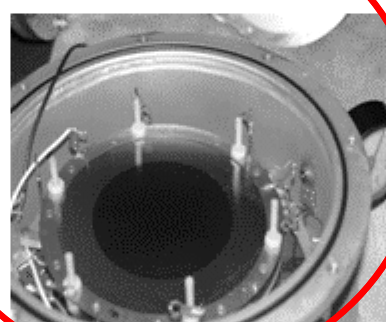
N,Z (Z= p, d, α)



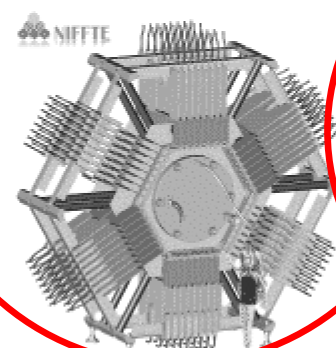
LSDS



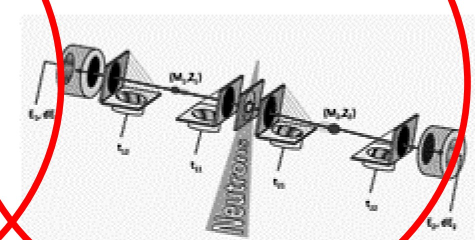
Ion Chambers



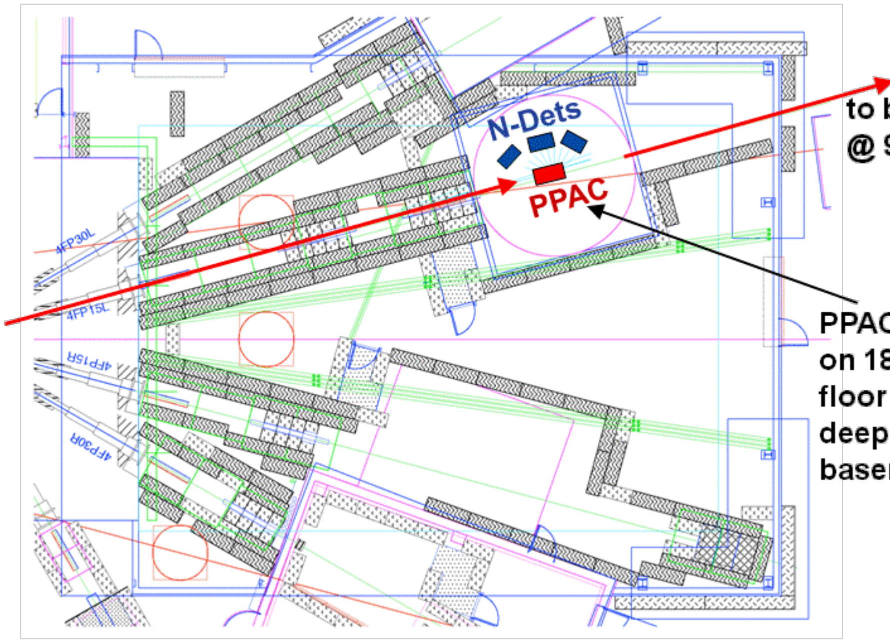
TPC



SPIDER

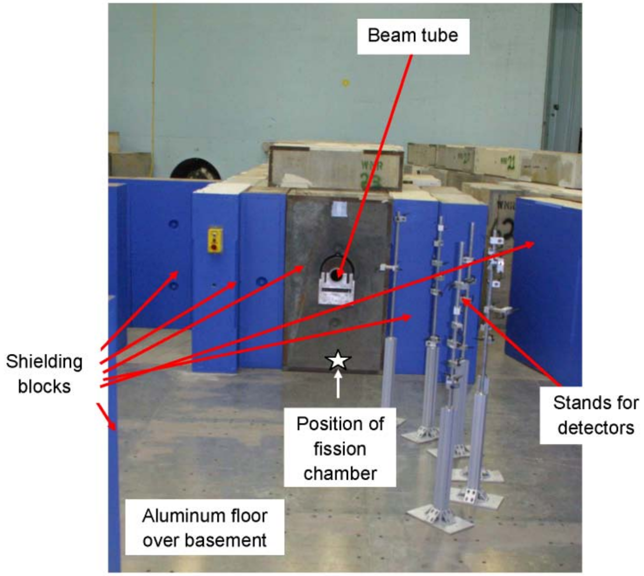


New building; new flight paths



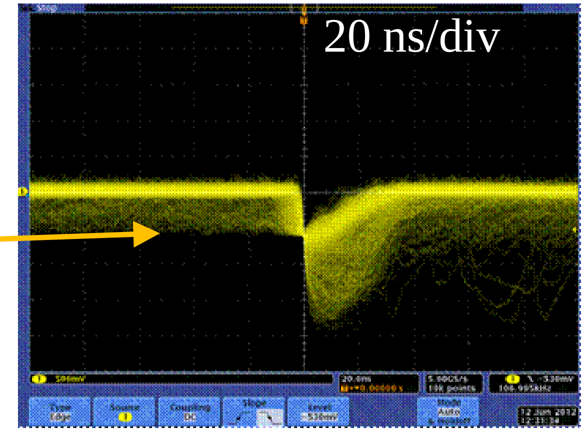
to beam dump @ 90 m

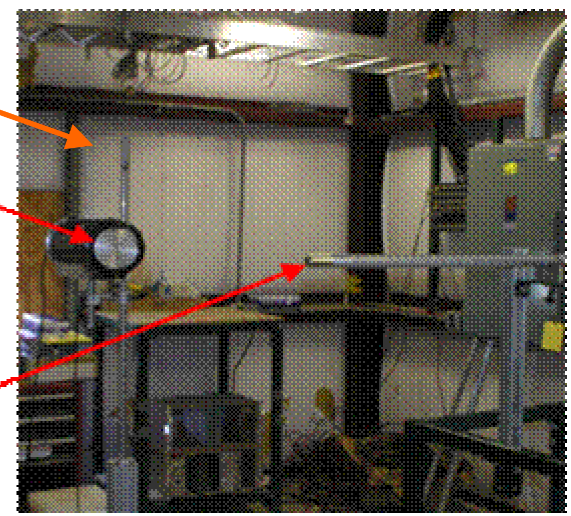
PPAC centered on 18' x 18' floor over 7' deep "get-lost" basement



Test facility – ^{252}Cf fission chamber

- ^{252}Cf fission chamber from ORNL
- About 6.2 E5 fissions per second
- Good timing ~ 1 ns
- Set up in MPF-34
  - 1.50 m above floor
  - Minimal scattering
- Signals sent to MPF17
  for radiation protection
- Used for:
  - Detector characterization
  - DAQ development





GEANIE (n,xγ)

Contacts:
Ron Nelson
Nik Fotiades
Matt Devlin

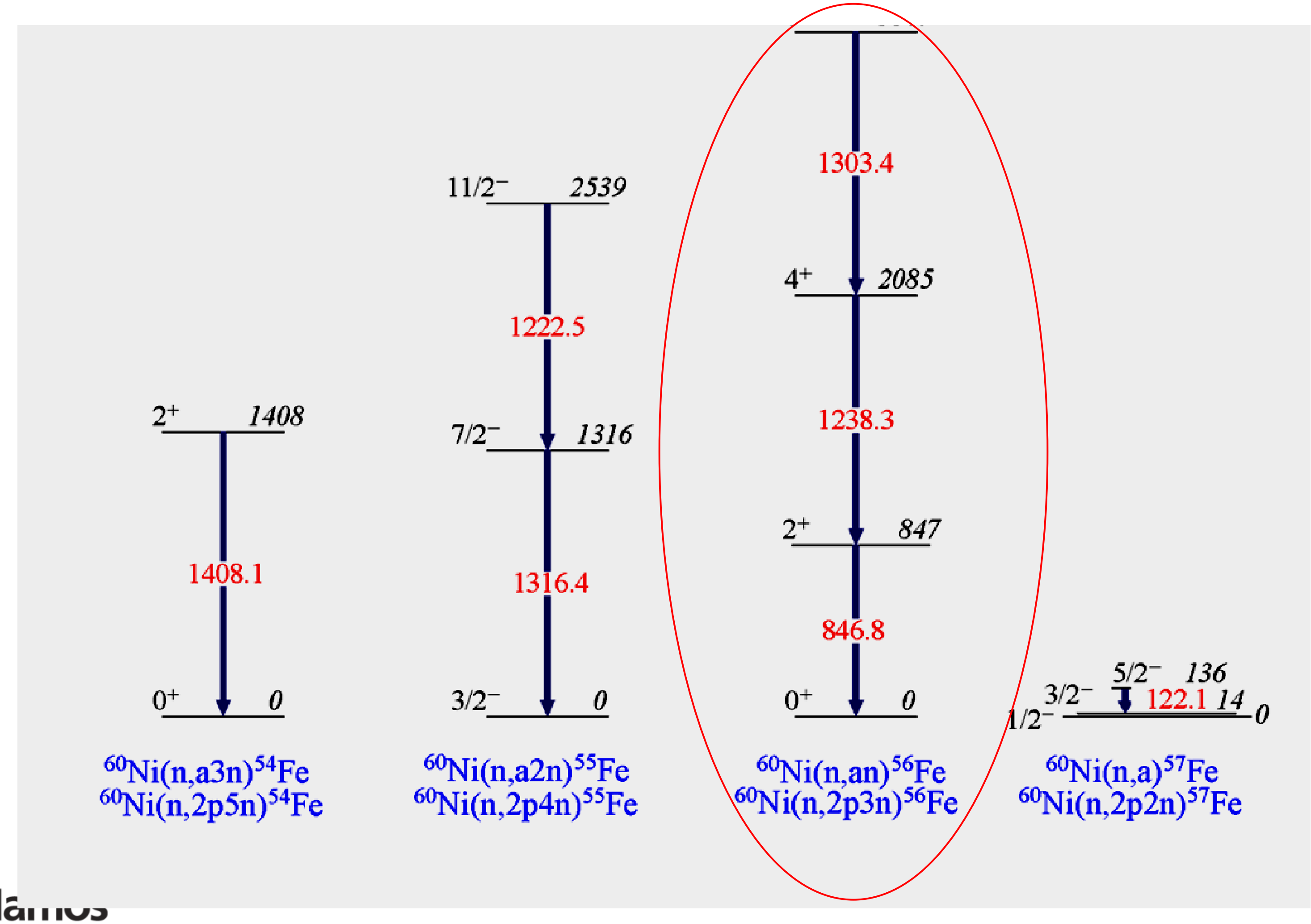
GEANIE measurements 2012 (1)

- Sn → structure of $^{118,120, 122, 124}$Sn -- N. Fotiades, et al.
  - combine GEANIE and GAMMASPHERE experiments
  - "States built on the 10+ isomers in 118,120,122,124Sn"
  - Phys. Rev. C 84, 054310 (2011).
- Measurements for double-beta decay experiments (Mitzi Boswell and Sean MacMullin (UNC))
  - Cu(n,xnγ), x = 1,2,.. – submitted to Phys. Rev. C
  - Ar(n,xnγ), x=1,2,... Phys. Rev. C 85, 064614 (2012)
  - Ne(n,xng), x=1,2,.. Submitted to Phys. Rev. C
- ^{86}Kr(n,xnγ), x= 1,2,... (M. Devlin) – data taken; structure and transitions
- NaI(n,xnγ) for data libraries (N. Fotiades) – data taken

GEANIE measurements 2012 (2)

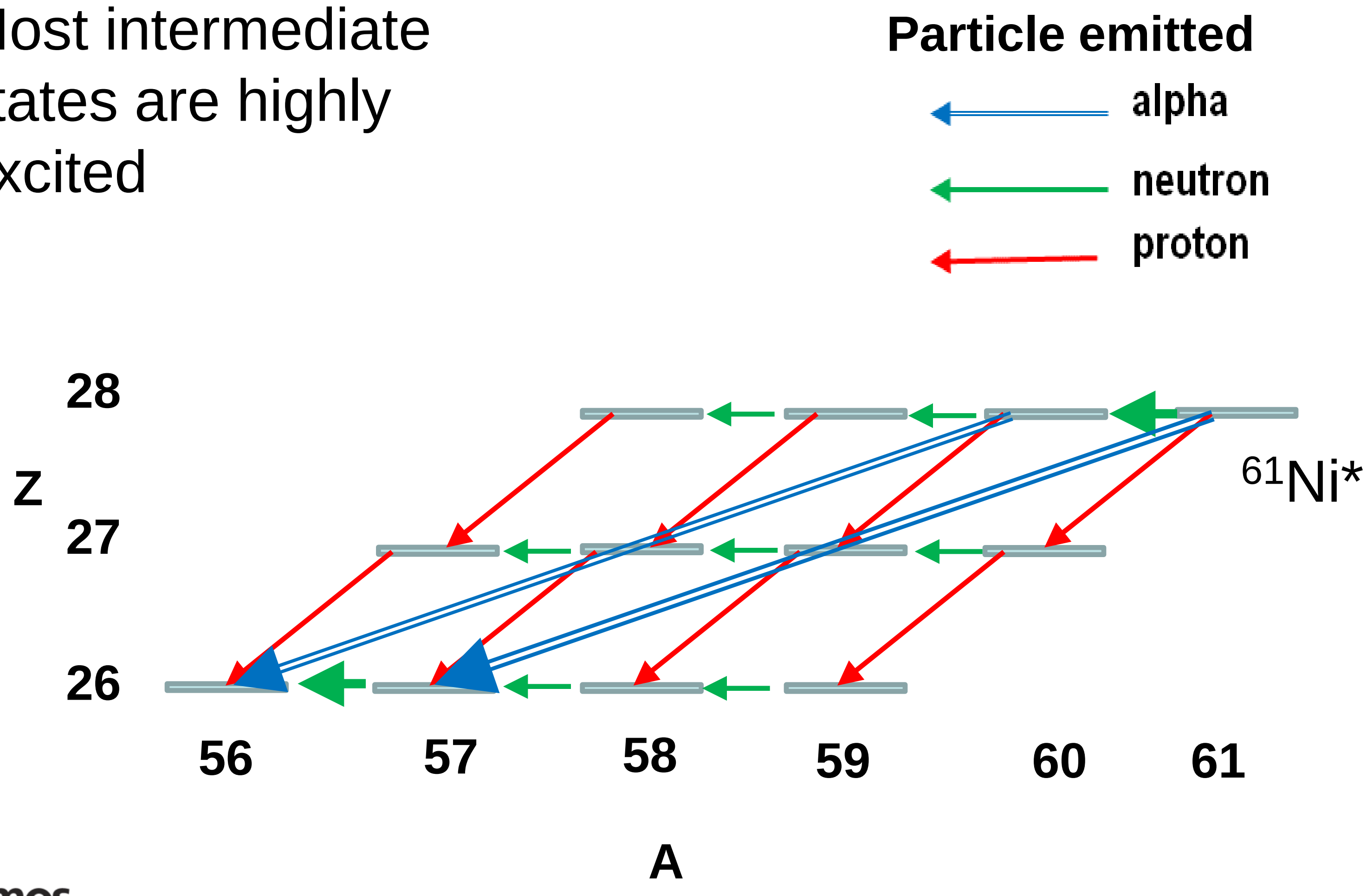
- **Isomer searches**
  - **$t_{1/2}$ ~ tens of μs to 100 ms – e.g. ^{114}In (M. Devlin)**
- **Various elements for a neutron-induced gamma-production reference cross sections (R. Nelson)**
  - **^{7}Li (n,n') ^{7}Li* (LiF target – "optical window")**
  - **Ti (n,xγ)**
  - **Cr**
  - **Fe**
- **x-ray yield from n-induced fission (R. Nelson and Thierry Granier - CEA)**
- **^{95}Mo (n, γ) – J. Cizewski et al. – extends neutron energy range of measurements made at Lujan Center last year into the 100's of keV range; test of surrogate reaction approach**

^{60}Ni(n,xγ) – c.f. (n,xα)



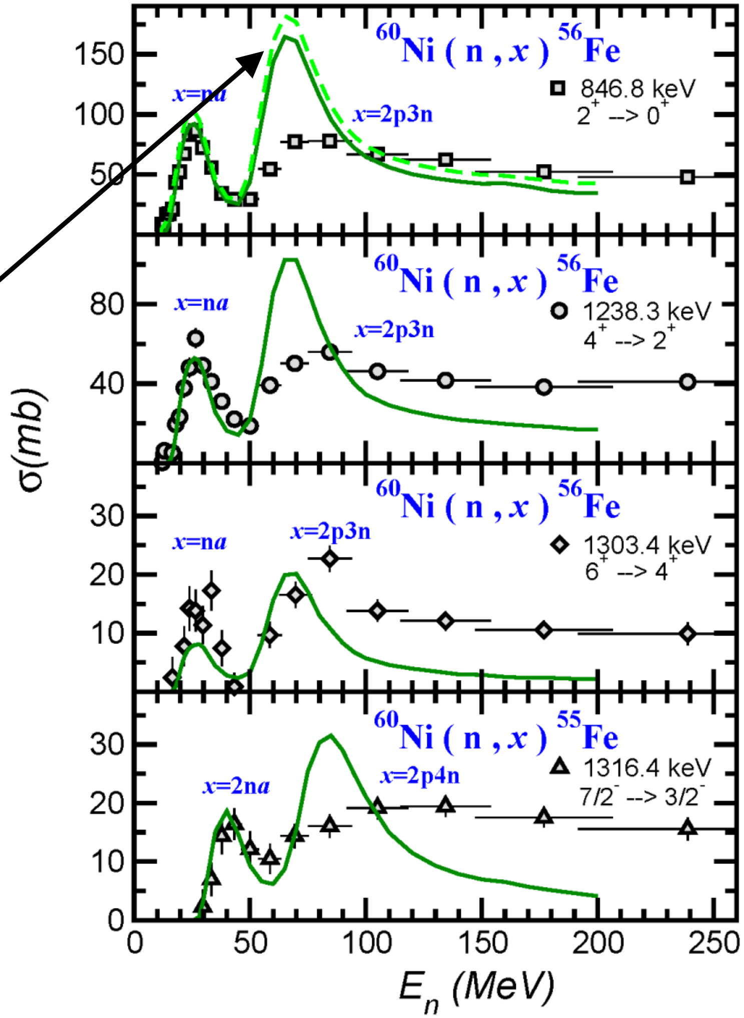
Many paths from ^{60}Ni+n to ^{56}Fe

- Most intermediate states are highly excited

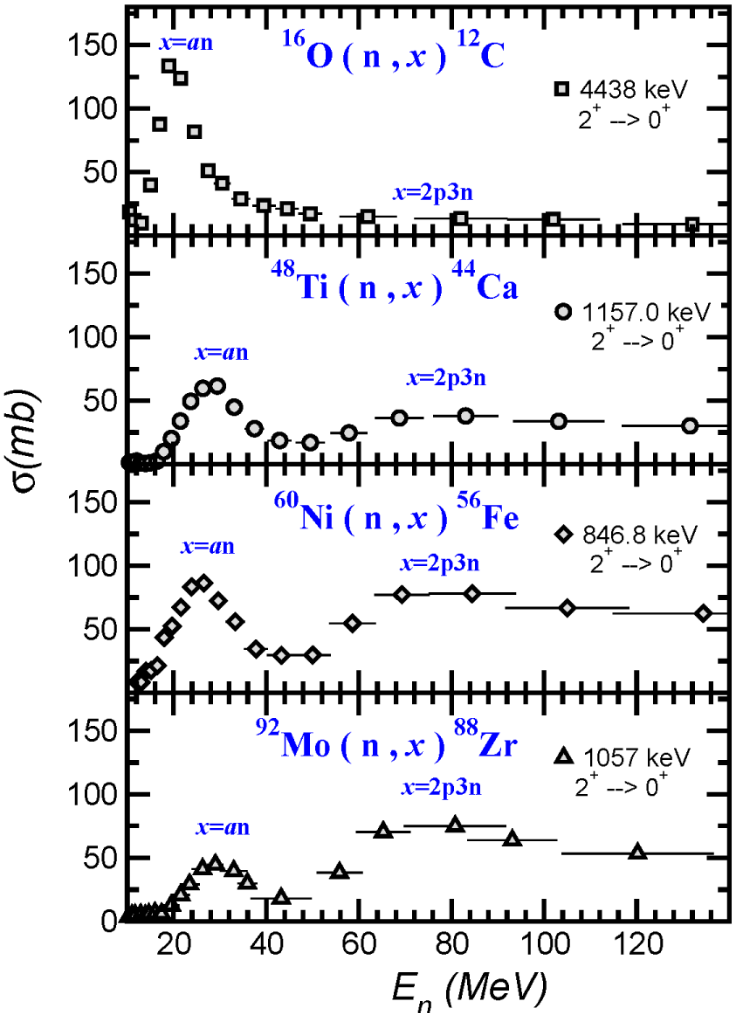


^{60}Ni(n,xγ) – c.f. (n,xα)

- Calculations
  - Hauser-Feshbach plus pre-equilibrium
  - Dashed curve is for total ^{56}Fe production

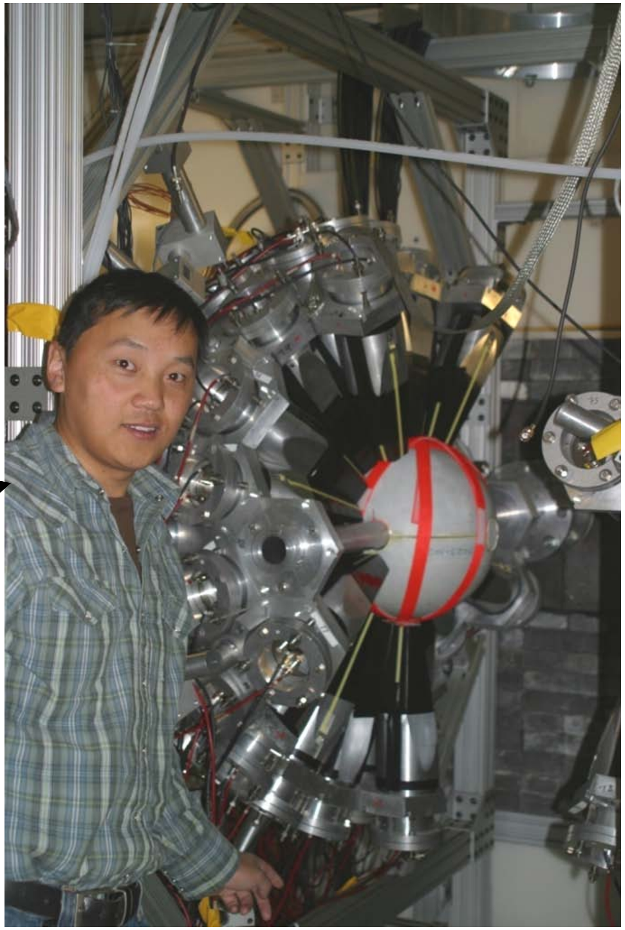


^{60}Ni(n,xγ) – c.f. other targets



DANCE (n,γ)

Bayarbadrakh Baramsai (NCSU)



Contacts:
John Ullmann
Aaron Couture
Marian Jandel

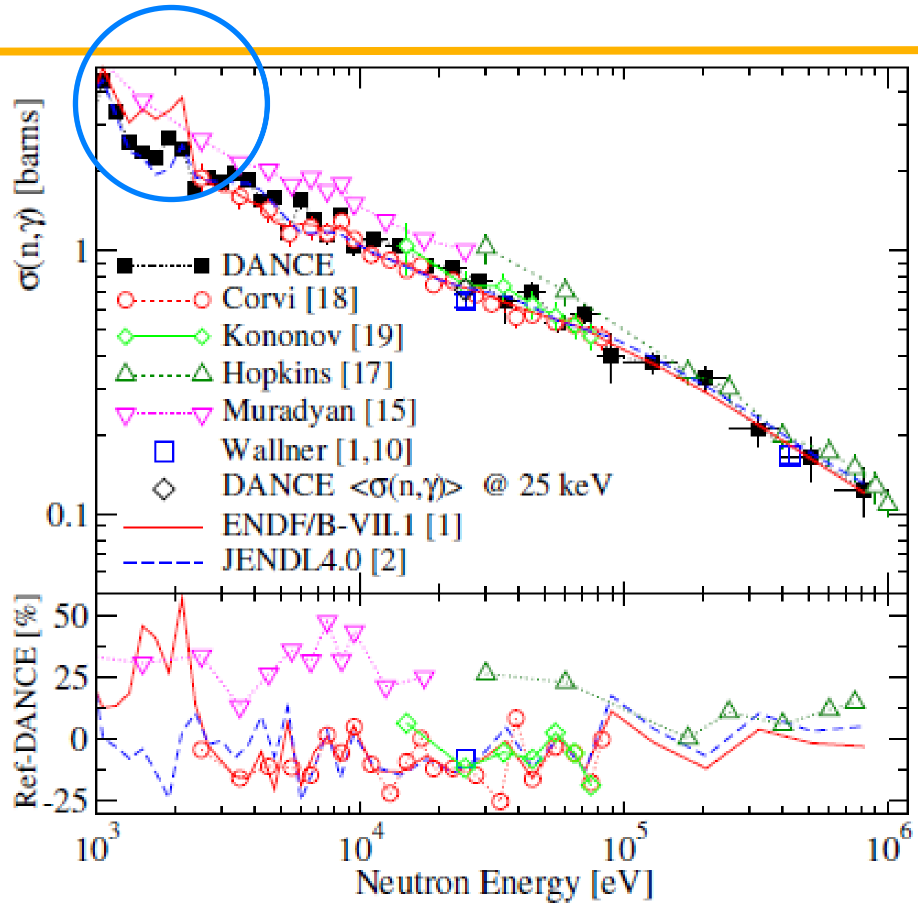
DANCE research in 2012 (1) – non actinides

$^{152,154,156,158}Gd(n,g)$	Bayarbadrakh Baramsai, NCSU/LANL In progress.
^{97}Mo	Carrie Walker, NCSU PhD dissertation, in progress
$^{117,119}Sn$	Bayarbadrakh Baramsai, NCSU/LANL (In progress)
^{173}Lu	Capture. O. Roig (CEA) (In progress)
$^{184,186}W$	Capture, Marian Jandel LANL (in progress)
$^{191,193}Ir$	Capture; Todd Bredeweg, Charles Arnold LANL

DANCE research in 2012 (2) - Actinides

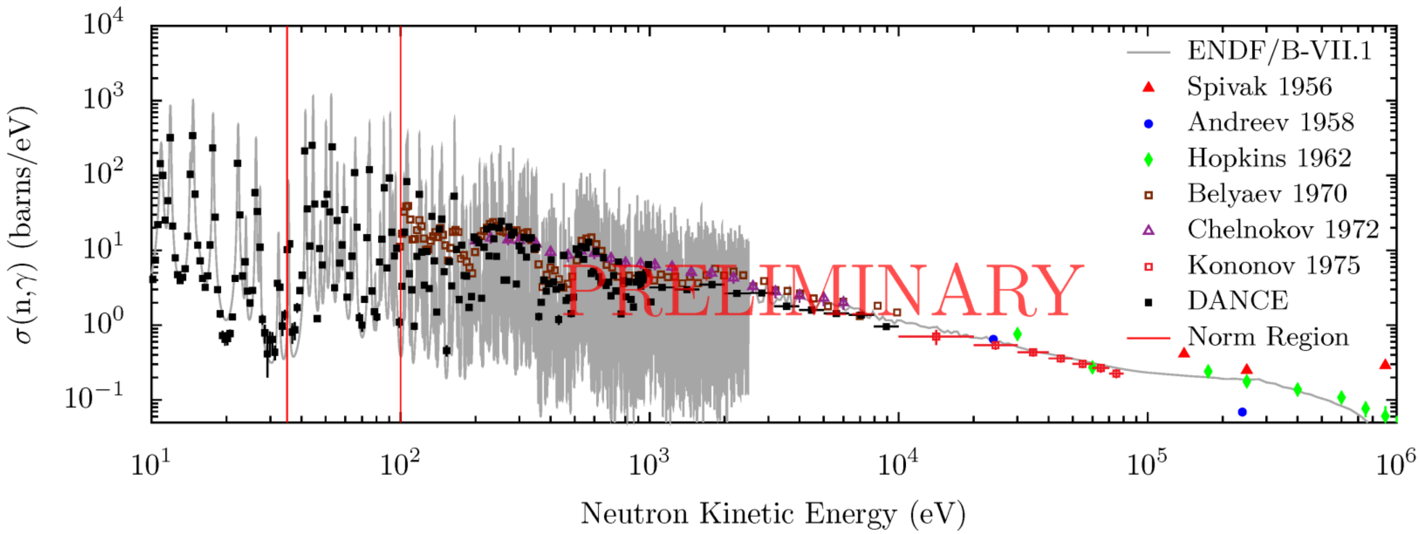
$^{233,235}U,^{239,241}Pu$	Capture to fission: LANL, LLNL In progress ^{235}U accepted by Phys. Rev. Lett.
$^{235}U,^{239,241}Pu$	Fission gamma ray multiplicity and spectra: LANL/LLNL (Prelim $^{239}Pu,^{235}U$ reported) Comparison Paper: submitted to Phys Rev C. Detailed analysis of each: In preparation
^{238}Pu	Capture, capture/fission: LLNL
^{252}Cf	Fission gamma multiplicity and spectra: Phys Rev C
$^{242m,243}Am$	Capture, Marian Jandel LANL (Prelim report)
^{238}U	Capture xsec, gamma rays John Ullmann LANL (prelim. report)

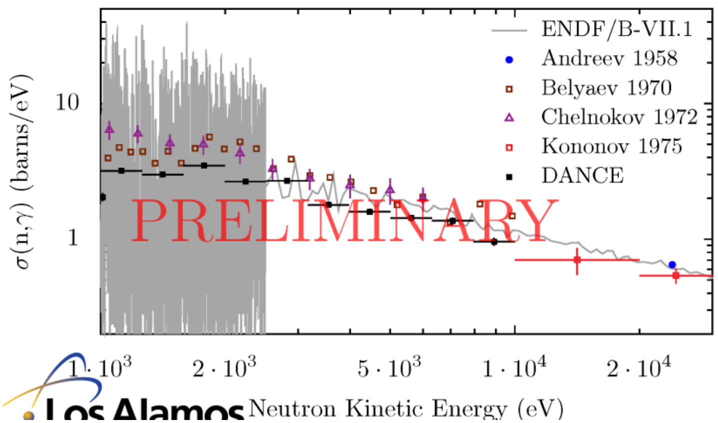
New DANCE measurement of $^{235}U(n,\gamma)$



"New Precision measurements of the $^{235}U(n,\gamma)$ Cross Section." M. Jandel, et al., accepted by Phys. Rev. Lett.

^{239}Pu (n,γ) preliminary results



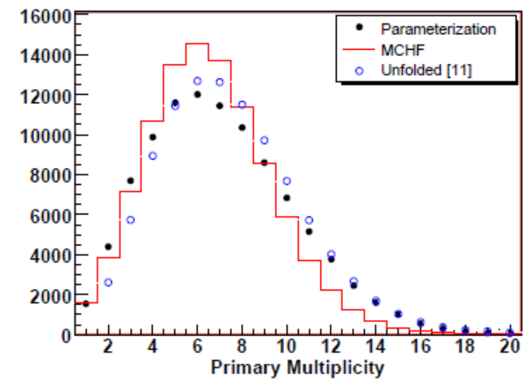


- Current Status: ^{239}Pu(n,γ) cross section measured from 10 eV to 10 keV
- 50 mg sample run pushed back - not run yet

Highly segmented DANCE array gives information on gamma multiplicity and spectra

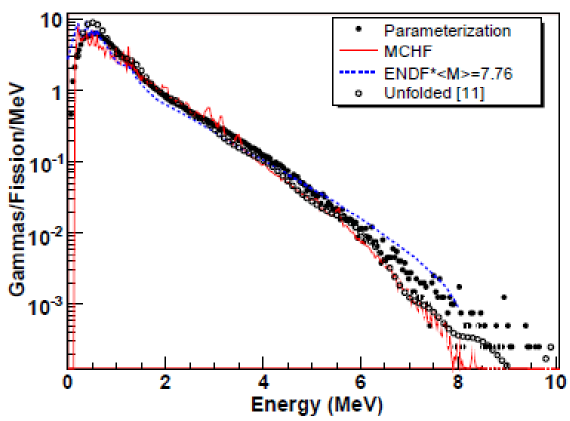
^{239}Pu(n,f) gamma emission spectra 1^{+} 10.93 eV resonance

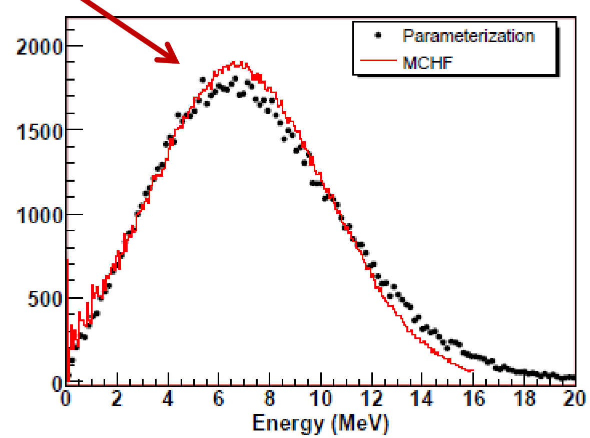
- Multiplicity distribution



- Energy distribution of individual gamma rays

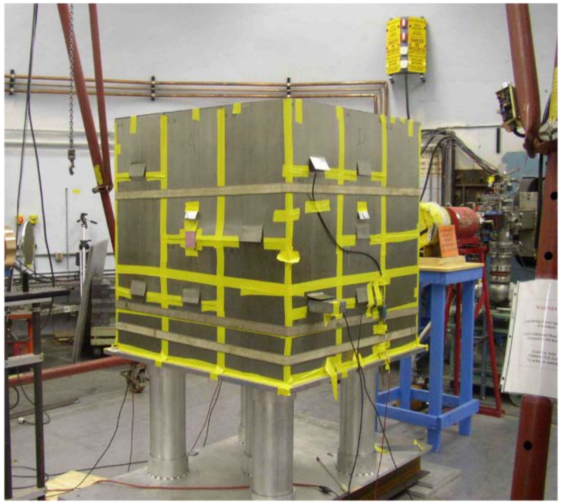
Total gamma energy distribution





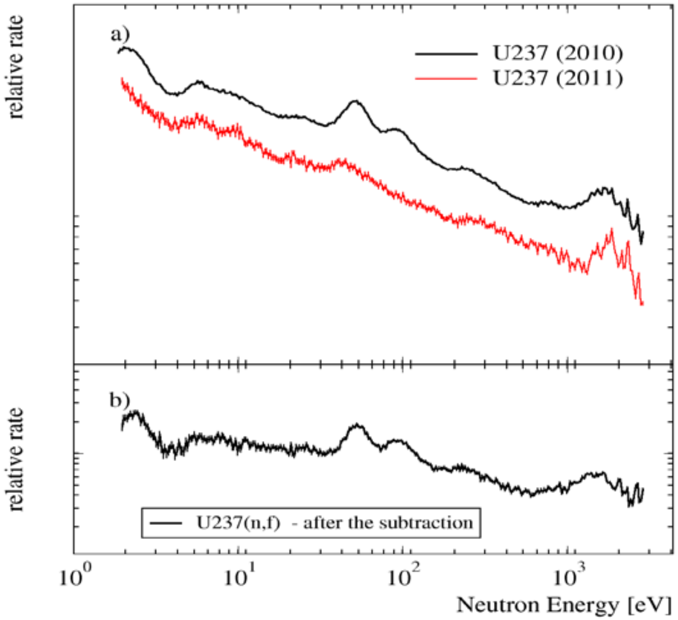
^{237}U(n,f) cross section measurement

- A cube 1.2 m on a side from high purity Pb
- 800 MeV p + W → neutrons + spallation products
- Allows for measurements with ~ng targets
- 20-40 Hz repetition rate



Two Measurements: Dec 2010 and June 2011

- U-237: M(t)=2μg(1-e$^{-\lambda t}$)
- U-236: 239 μg
- Preliminary results



Fission Cross Sections

Contacts:
Fredrik Tovesson
Alexander Laptev

LANSCE fission cross section program status

EXFOR			
#14130002	Np-237		Completed
#14271004	Pu-239		Completed
#14223002	Pu-240	($t_{1/2}$=6600 a)	Completed
#14271007	Pu-241	($t_{1/2}$=14 a)	Completed
#14223003	Pu-242		Completed

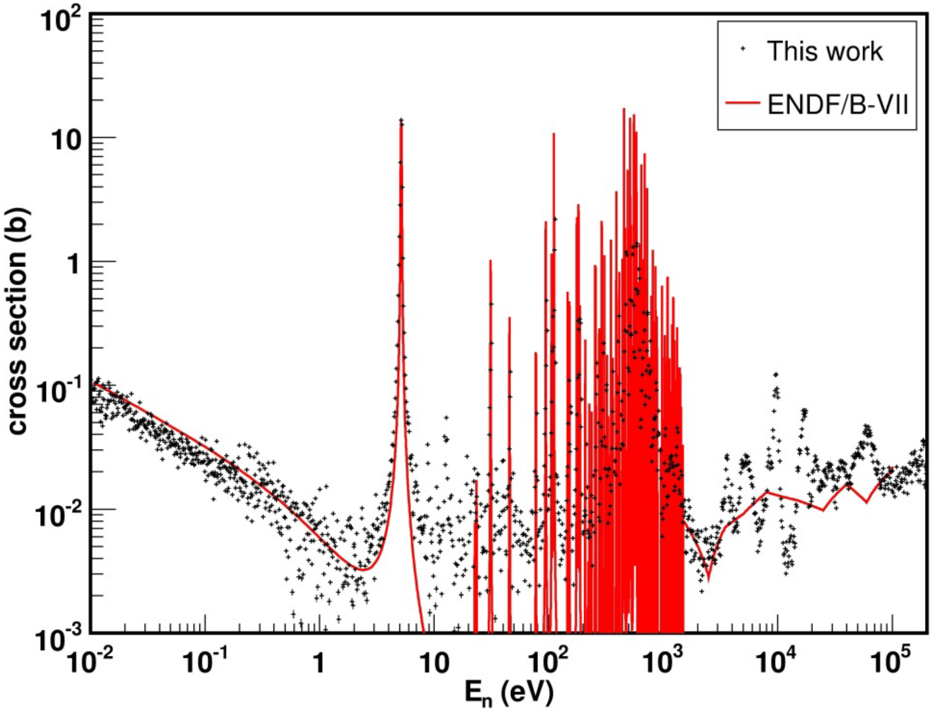
U-238, U-233 — Recently completed

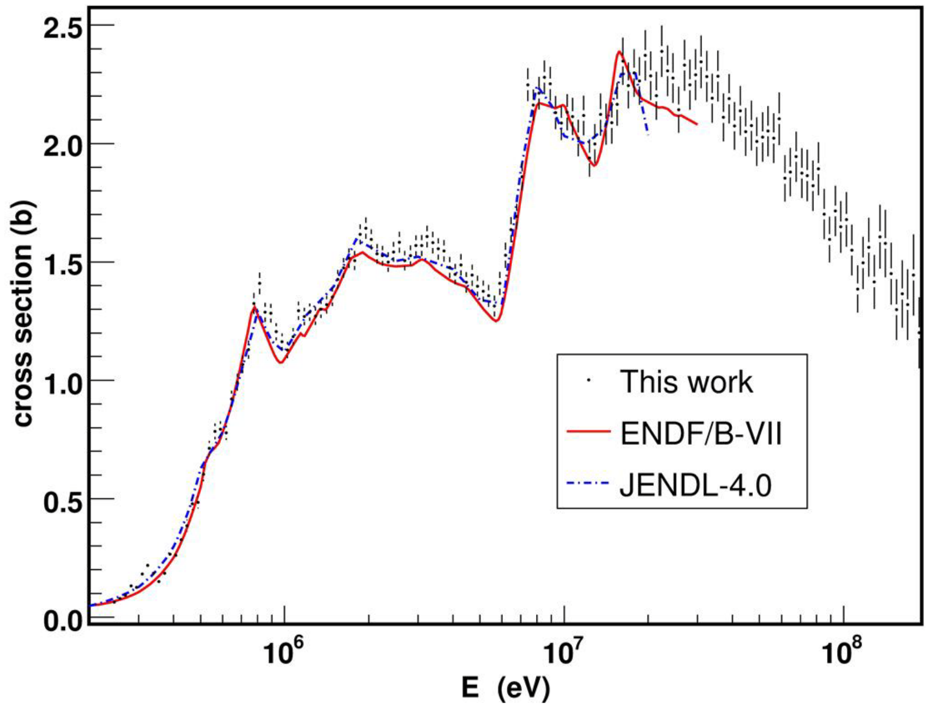
U-236, Am-243 — In progress

U-234 — Measured in 2011-2012 run cycle

F. Tovesson, A. Laptev, T.S. Hill, *J. Korean Phys. Soc.* **59**, 1400 (2011)
F. Tovesson, A. Laptev, T.S. Hill, *AIP Proc.* **1336**, 598 (2011)
F. Tovesson, A. Laptev, T.S. Hill, *Trans. of the Amer. Nucl. Soc.* **102**, 490 (2010)
F. Tovesson, T. S. Hill, *Nucl. Sci. Eng.* **165**, 224 (2010)
F. Tovesson, T. S. Hill, M. Mocko, J. D. Baker, C. A. McGrath, *Phys. Rev. C* **79**, 014613 (2009).
F. Tovesson, T. S. Hill, *Nucl. Sci. Eng.* **159**, 83 (2008).
M. Mocko, G. Muhrer, F. Tovesson, *Nucl. Instr. and Meth.* **A 589**, 455 (2008).
J. D. Baker, C. A. McGrath, T. S. Hill, R. Reifarth, F. Tovesson, *J. Radioanalytical Nucl. Chem.* **276**, 555 (2008).
F. Tovesson, T. S. Hill, *Phys. Rev. C* **75**, 034610 (2007).
F. Tovesson, T. S. Hill, K. M. Hanson, P. Talou, T. Kawano, R. C. Haight, L. Bonneau, *LANL report LA-UR-06-7318*, (2006).

The U-234 neutron-induced fission cross section

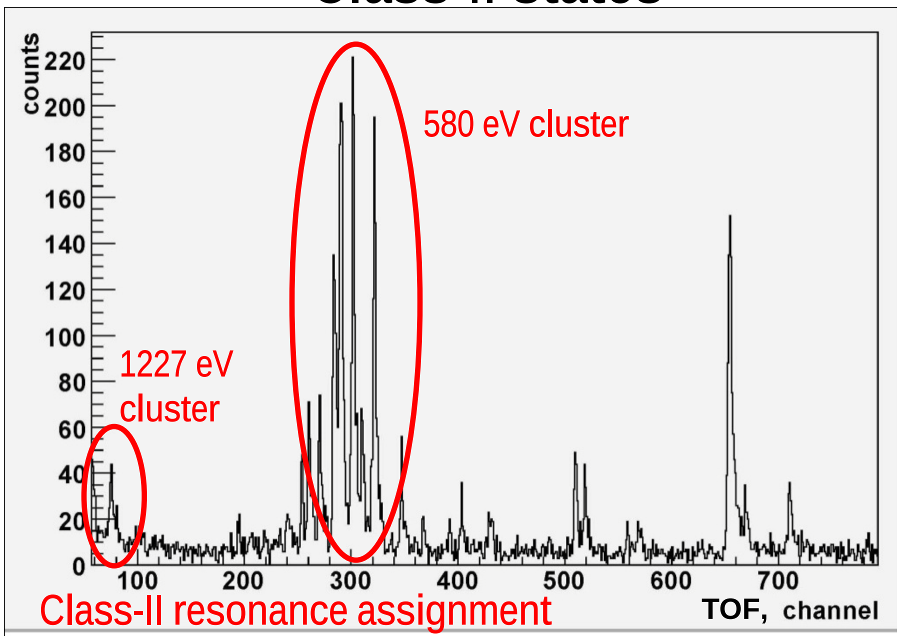




- **U-234 completes the Uranium measurements. Full suite of Uranium data is a valuable data set for evaluators**
- **High statistics data for subthreshold fission**

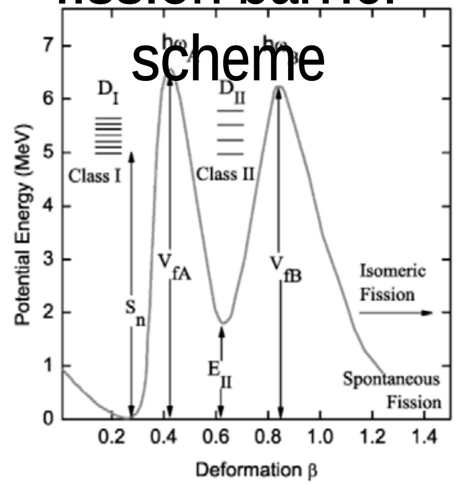
Subthreshold fission of U-234

Class-II states



Class-II resonance assignment based on G.James *et al.* data

The double-humped fission barrier scheme



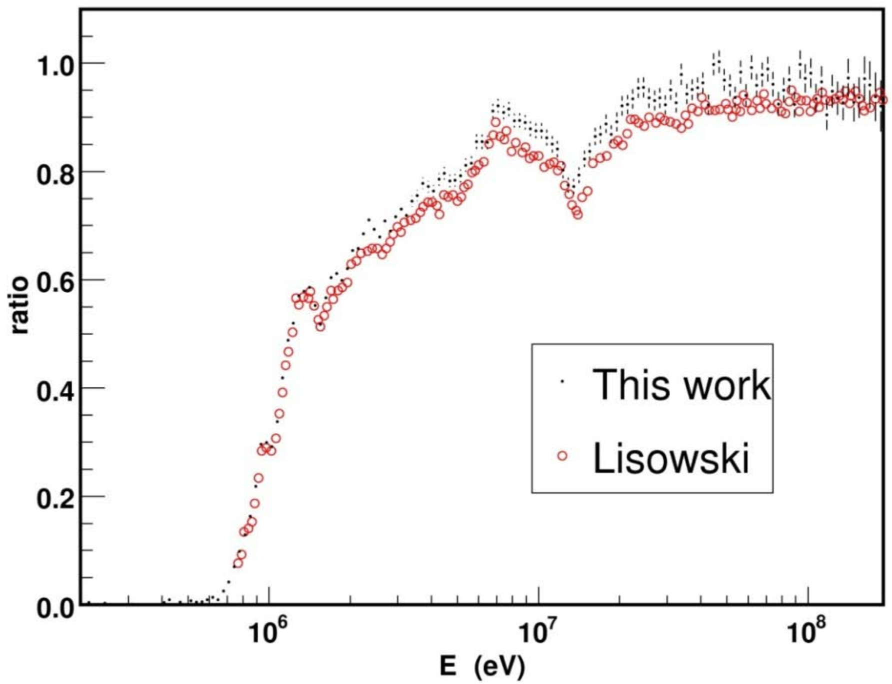
Mughabghab, Atlas of Neutron Resonances, 2006

- **Clear demonstration of the class-II resonances**
- **Clustering of subthreshold fission strengths is explained in terms of the double-humped fission theory**
- **First class-II resonance analysis was done by James *et al.*, PRC 15(1977)2083**

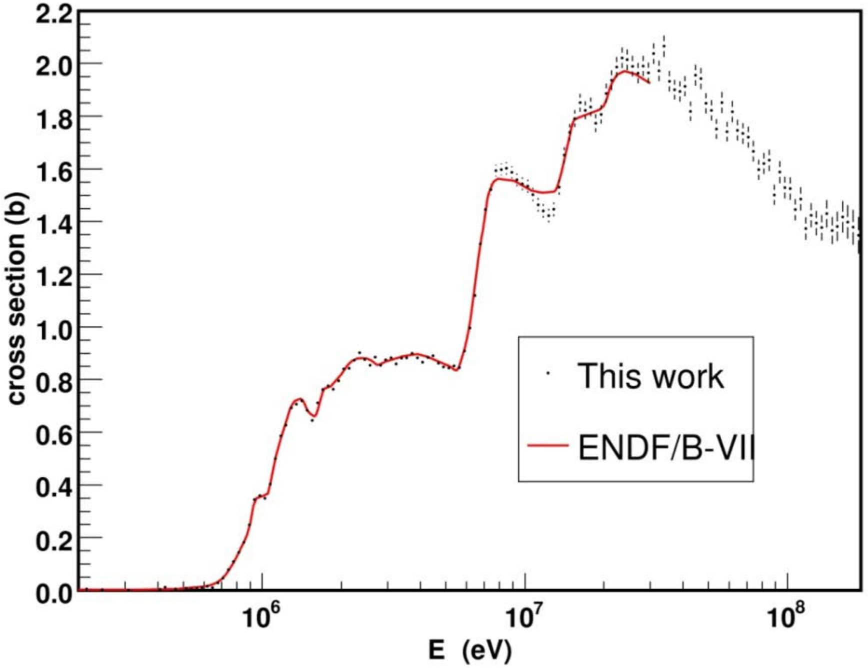
- **Gives unique information about fission barriers**
- **Average level spacing of class-II states can be estimated (in progress)**

The U-236 neutron-induced fission cross section and ratio to U-235

Ratio



Cross section



- **The current result for U-236 ratio fairly good agrees with Lisowski *et al.* data**
- **Current evaluations are representing the data well**

The TPC and SPIDER Projects

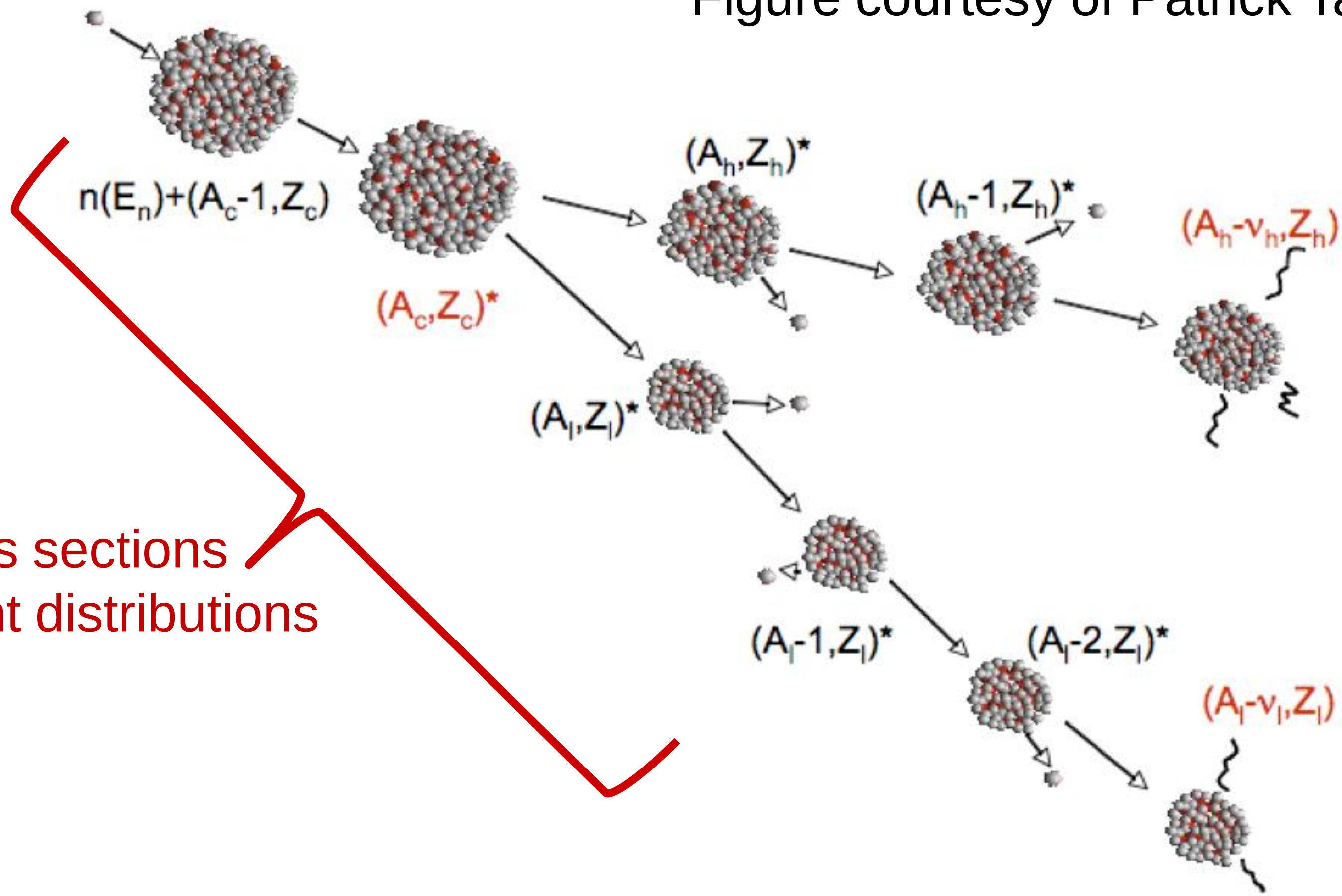
Rhiannon Meharchand

Los Alamos National Laboratory

On behalf of the NIFFTE and SPIDER collaborations

Our place in the bigger picture

Figure courtesy of Patrick Talou

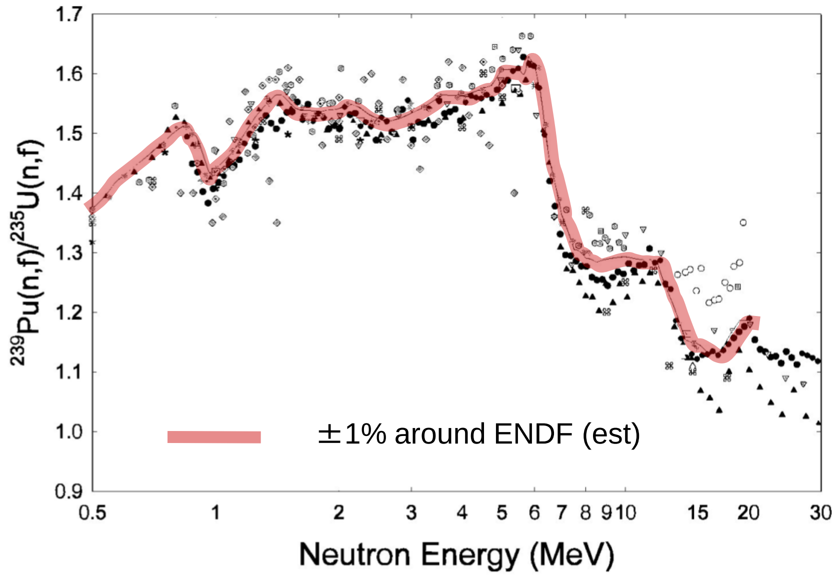


Fission cross sections
and fragment distributions

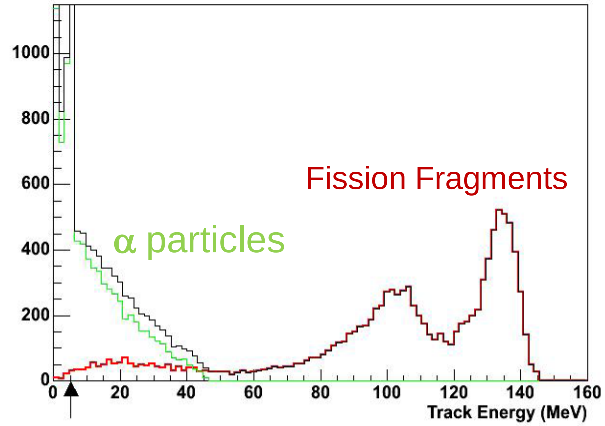
Goals

- **Implement a fission cross section measurement program with the goal of providing the most needed measurements with unprecedented precision and accuracy**

- **Address major sources of systematic uncertainties that have plagued previous measurements:**
  - Misidentification of fission products and alpha decays
  - Sample and beam non-uniformities
  - Uncertainties inherent to reference standards

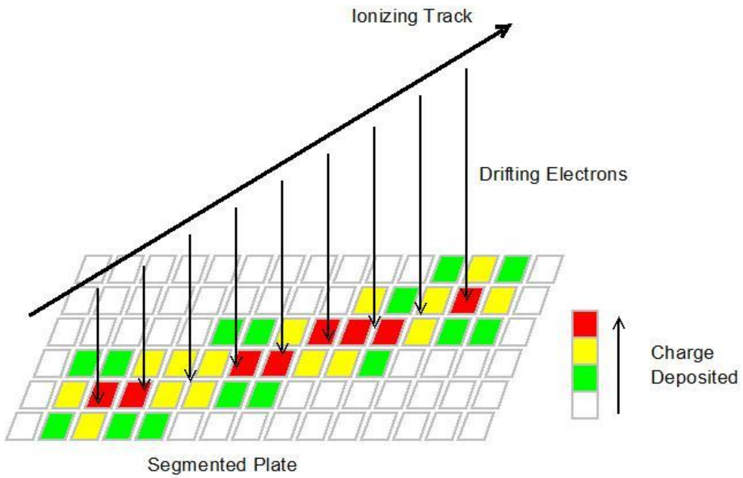


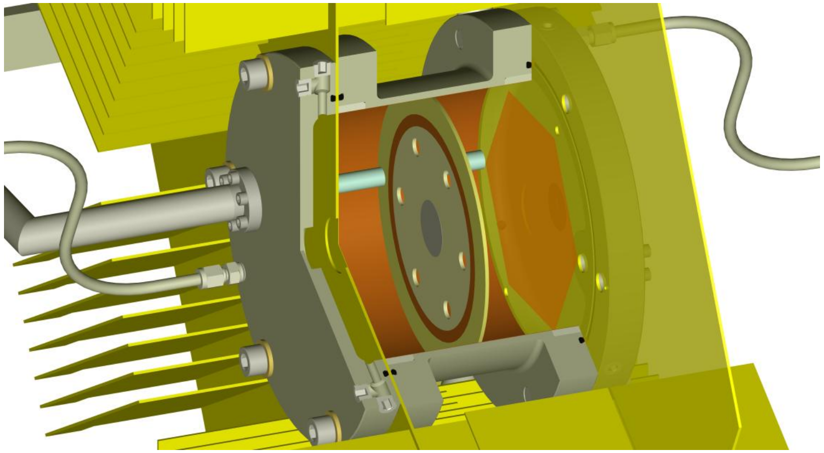
Staples & Morley; Nucl. Sci. and Eng. v.**129** (June 1998)



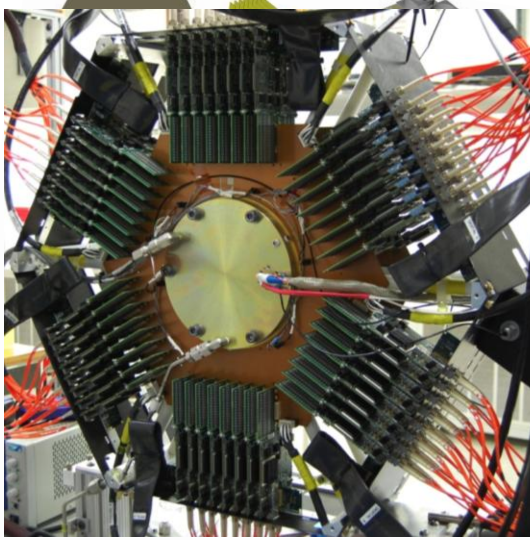
The NIFFTE Time Projection Chamber (TPC)

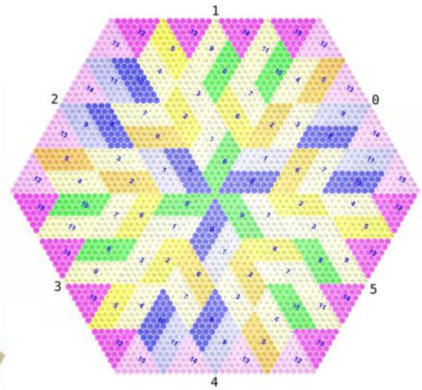
- **First application of TPC technology to fission research**
- **3-D particle tracking**
  - Enables autoradiograph of target material and neutron beam profile
  - Betters particle ID capabilities
- **Near-4π solid angle coverage**
  - Detection of both light and heavy fragments
- **Designed to use hydrogen gas in active volume**
  - Normalize data to H(n,n)H elastic scattering cross section

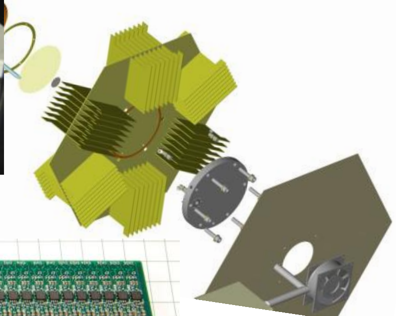




Highly advanced technology, software, and controls



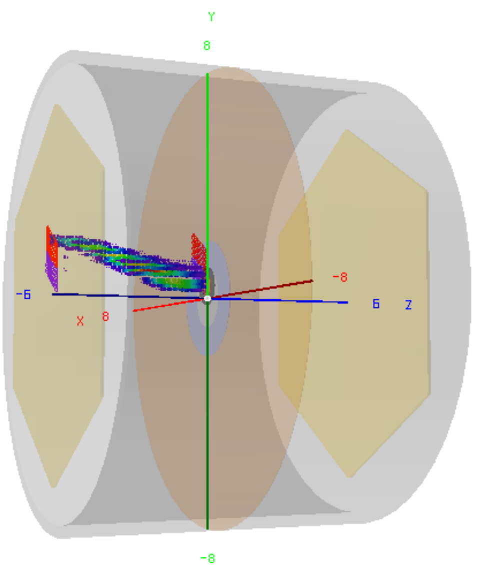


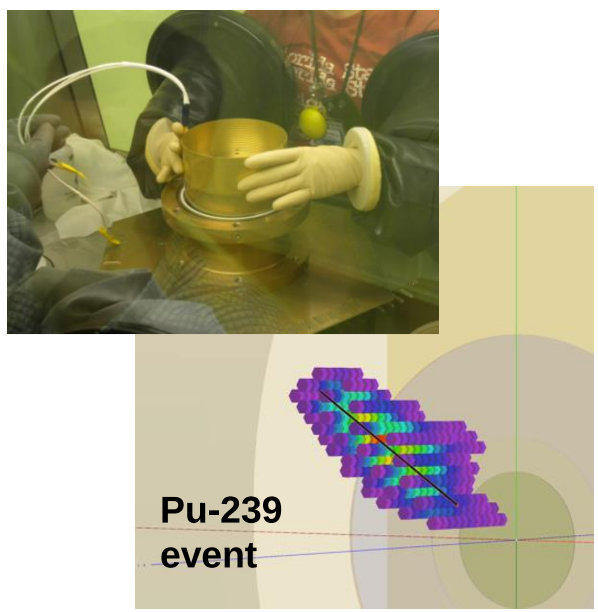


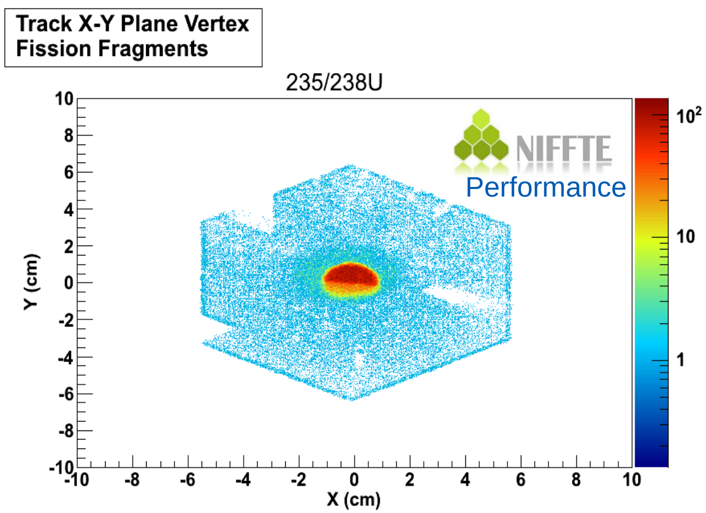
- Thin (~100 ug/cm2) actinide samples, variable size/shape deposits
- Field cage steps down uniformly from -1400V→-340V over 5.4 cm
- Pressure vessel holds up to 5 bar
- 2976 readout pads *per side*
- 192 preamp (analog) + EtherDAQ (digital) card pairs
- Remote monitoring and control of HV, LV, Gas Handling and Slow Control systems
- Complete software suite including online monitoring and detailed simulation

Beam measurements with the TPC

- **2010:**
  - C backing (64 channels)
  - U-238 (64 channels)
  - U-238 (192 channels)
- **2011(Nov) - 2012 (Feb):**
  - 496 channels (1/12 TPC)
  - U-238 (15 days, 48% production)
  - U-238/U-235 #1 (19 days, 72%)
  - U-238/U-235 #2 (16 days, 69%)
  - Pu-239 (21 days, 45%)
- **2012:**
  - 2976 channels (1/2 TPC)
  - Fast Timing (TOF)
  - U-238/U-235 (~24 days production)
  - Pu-239/U-235 (~24 days)
  - More U-238/U-235…







SPectrometer for Ion DEtermination in fission Research

SPIDER

The SPIDER instrument

- **Goal**
  - Develop an instrument for measuring fission fragment properties (mass, charge and kinetic energy) with high resolution
- **Applications**
  - Fission yields for nuclear applications
  - Improved understanding of the fission process
- **Target accuracies**
  - 1 unit resolution for mass and charge
  - 0.5% energy resolution for light fragments
  - >1 % detection efficiency
- **Collaboration**
  - **LANL** (F. Tovesson, C. Arnold, T. Bredeweg, T. Burr, E. Esch, M. Jandel, J. Jorgensen, A. Laptev, J. Lestone, P. Lisowski, R. Meharchand, K. Meierbachtol, P. Moller, R. Nelson, J. O'Donnell, B. Perdue, T. Renshaw, A. Sierk)
  - **UNM** (A. Hecht, R. Blakely, D. Mader, E. Dughie)
  - **CSM** (U. Greife, B. Moore. D. Shields, B. Moore)
  - **LBL:** J. Randrup
  - **LLNL** (L. Snyder)
  - **Slovak Academy of Sciences** (J. Kliman)

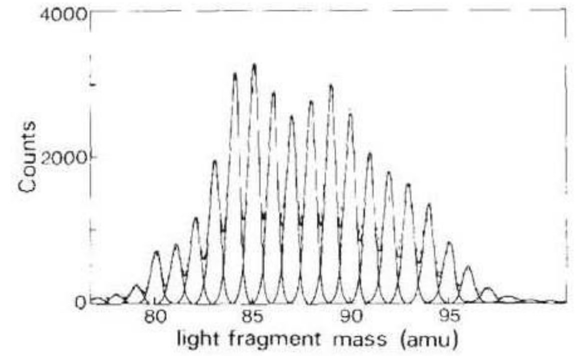
The 2E-2V method

- First demonstrated in mid 1980's
- <1 amu mass resolution of light fragments
- ~1 unit charge resolution for light fragments
- (A,Z,TKE) yields for both fragments
  - Significant information about the fission process

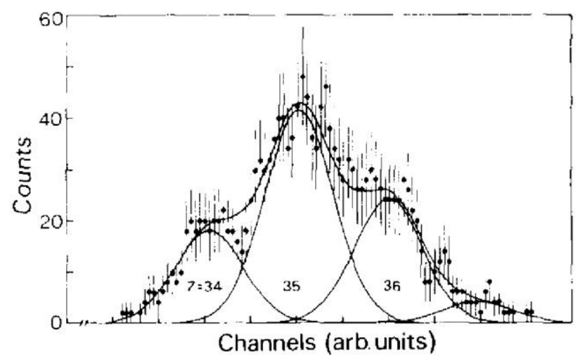
$$M = \frac{2Et^2}{l^2}$$

$$\frac{\delta M}{M} = \sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(2\frac{\delta t}{t}\right)^2 + \left(2\frac{\delta l}{l}\right)^2}$$

FPY measured with COSI-FAN-TUTTE

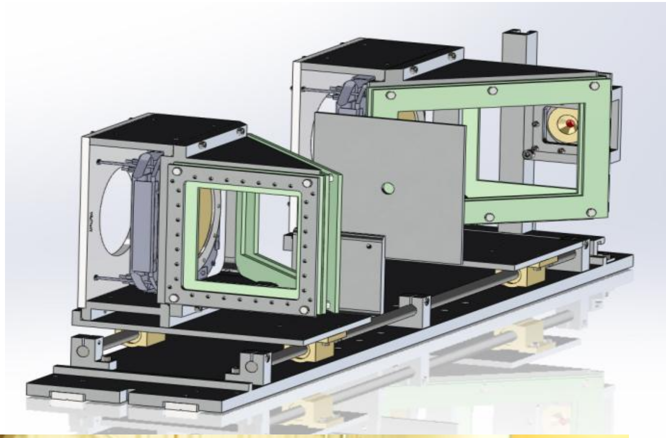


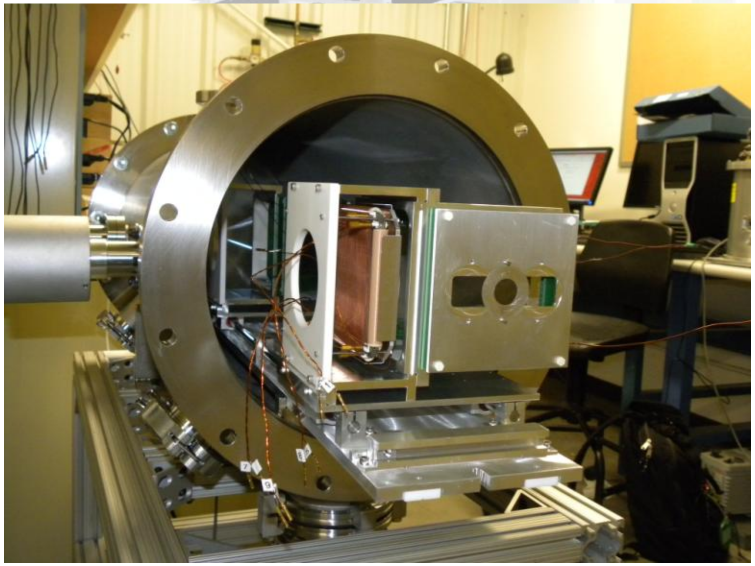
Nuclear charge distribution for A=87



Time-of-flight detectors

- **MCP plates used for fast time pick-off**
  - ~100 ps (FWHM) resolution possible
  - Large effective area: 75mm diameter with good timing
- **Electrostatic mirrors**
  - Fission fragment generate secondary electrons when passing through conversion foils
  - Electrostatic mirrors accelerate electrons and reflect them onto the MCPs
  - Geometric transmission trough the grids is 98%
- **Delay-line anodes**
  - High spatial resolution (µm)
  - Fast readout (<100 ns)
- **Analogue signal processing**
  - Fast preamps (>100 MHz bandwidth)
  - Fast constant fraction discriminators

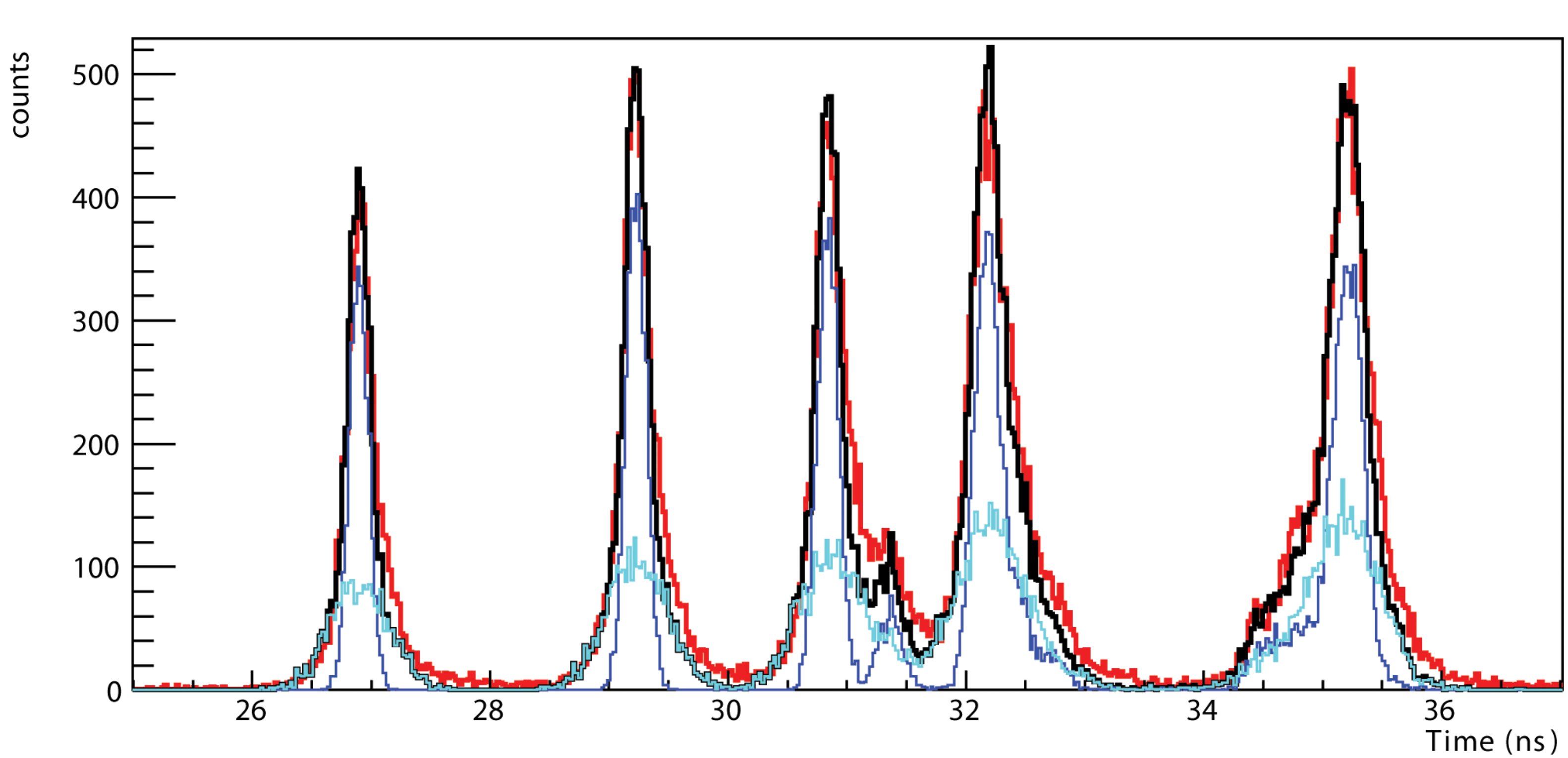




Time of flight spectra for ^{229}Th alpha-source

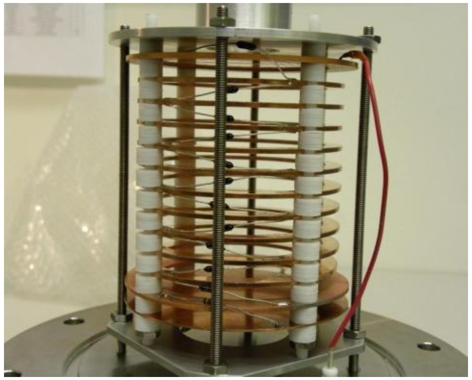
- **Data (Red)**
- **Overlaid Simulation (Black)**
- **Individual components of width (Blue and Blue)**

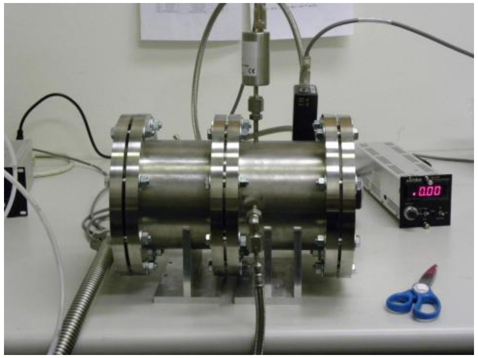
Figure courtesy of Charles Arnold



Energy and Bragg peak detectors

- **Axial ionization chambers**
  - Ion enters chamber perpendicular to anode
  - Single anode (as supposed to segmented readout)
- **Energy resolution**
  - Best achieved (literature) 0.4% for light fragments and 0.8% for heavy fragments
- **Bragg peak spectroscopy**
  - For a fixed mass and energy the track length can be used to separate ion species
  - Pulse shape analysis in another option
- **Analogue signal processing**
  - Low-noise charge sensitive preamps





Pictures courtesy of Krista Meierbachtol

Lawrence Livermore National Laboratory

- **Fission**
  - **^{239}Pu, ^{235}U, ^{252}Cf** - Results for the gamma energy spectrum and multiplicity spectrum from 0.5-9 MeV measured at DANCE were shown. The observed most probable multiplicity (6-8) is increasing with mass..
  - TPC project is in progress at LLNL and LANL
- **Capture**
  - **^{238}Pu** - preliminary results of the capture cross section of which looks almost 50% higher than ENDF/B-7.1.
- **surrogate reaction measurements**
  - **^{240,241,242}Am(n,f)** - Cross section measurements of have been completed. Evaluations are underway and expect to be complete by December 2012.
  - **^{88}Y(n,2n**) - Cross section measurement of is complete and final evaluation is underway. Evaluation to be complete December 2012.
  - **^{87,88}Y(n,γ**) - Data for has been taken and data analysis and reduction is underway, evaluation to be completed September 2013.
  - **^{239}Np(n,f)** - Final analysis being completed on cross section, results to be submitted to peer-reviewed journal.
  - **^{237}U** - Nuclear structure investigated: 2 new states and 10 new γ rays discovered
  - **^{235}U** - Nuclear structure investigated: 1 new state and 6-8 new γ rays discovered
  - **^{236,237}Pu(n,f)** - Data taken and analysis underway for cross sections over neutron energy range 0-6 MeV.
  - **^{232,233}U(n,f)** - Data taken and analysis underway for cross sections over neutron energy range 0-6 MeV.
  - **Yb** - Data taken on isotopes to validate (p,d) reaction channel in preparation for Lu measurements in FY13.
  - **^{95}Mo(d,p)** - Data taken on to benchmark surrogate technique in spherical region for (n,γ) reactions

Lawrence Livermore National Laboratory

Update of Experimental Activities in Low-Energy Nuclear Physics at LLNL

N.D. Scielzo

Cross Section Evaluation Working Group Annual Meeting

November 8, 2012

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

This work performed under the auspices of the U.S. Department of Energy by
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Direct measurements of neutron-induced rea[ctions] on actinides

slide from
C.Y. Wu

- Measurements of the prompt neutron and γ-ray emission in the neutron-induced fission using the $\chi\nu$ array
- Measurements of neutron capture and fission prompt γ-ray emission using the DANCE array

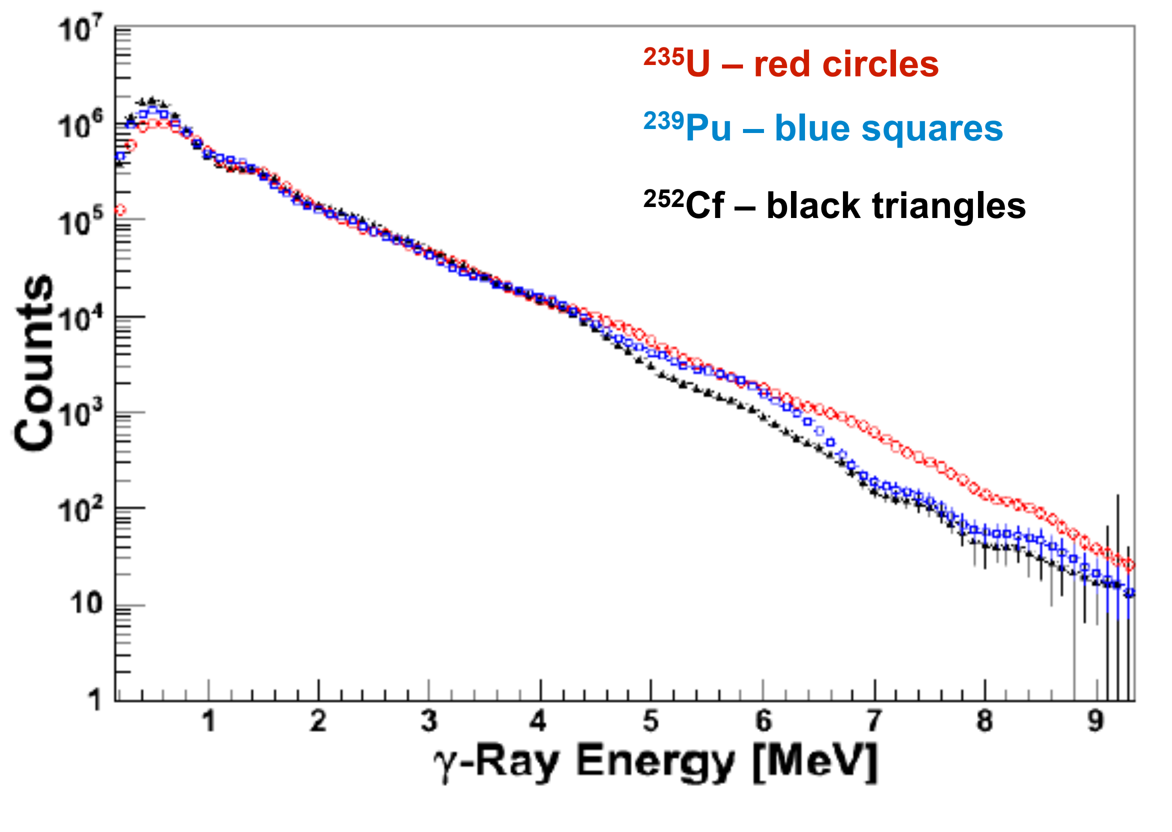
slide from
C.Y. Wu

Published results

- "*Evidence for the stochastic aspect of prompt gamma emission in spontaneous fission*" A. Chyzh *et al*., PRC 85, 021601(R) (2012)
- "*Prompt energy distribution of $^{235}U(n,f)\gamma$ at bombarding energies of 1 – 20 MeV*" E. Kwan et al., NIMA 688, 55 (2012)
- "*Systematics of the prompt gamma-ray emission in fission*", A Chyzh *et al*., submitted to PRC for publication Oct, 2012

Systematics of the prompt γ-ray energy distribution in fission

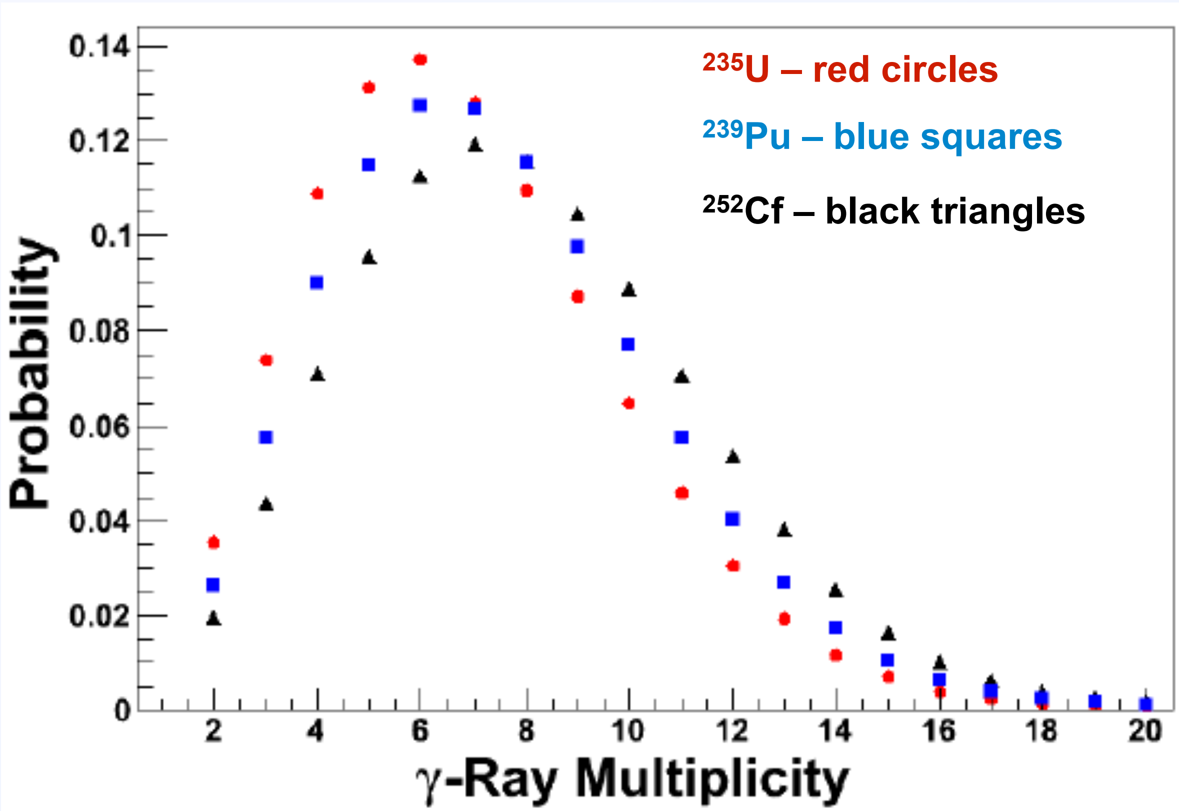
slide from
C.Y. Wu



- Data normalized according to the yields of γ-ray energy between 1 – 4 MeV
- The spectrum above 5 MeV shows a strong dependence on the species of fissile nuclei

Systematics of the prompt γ-ray multiplicity distribution in fission

slide from
C.Y. Wu

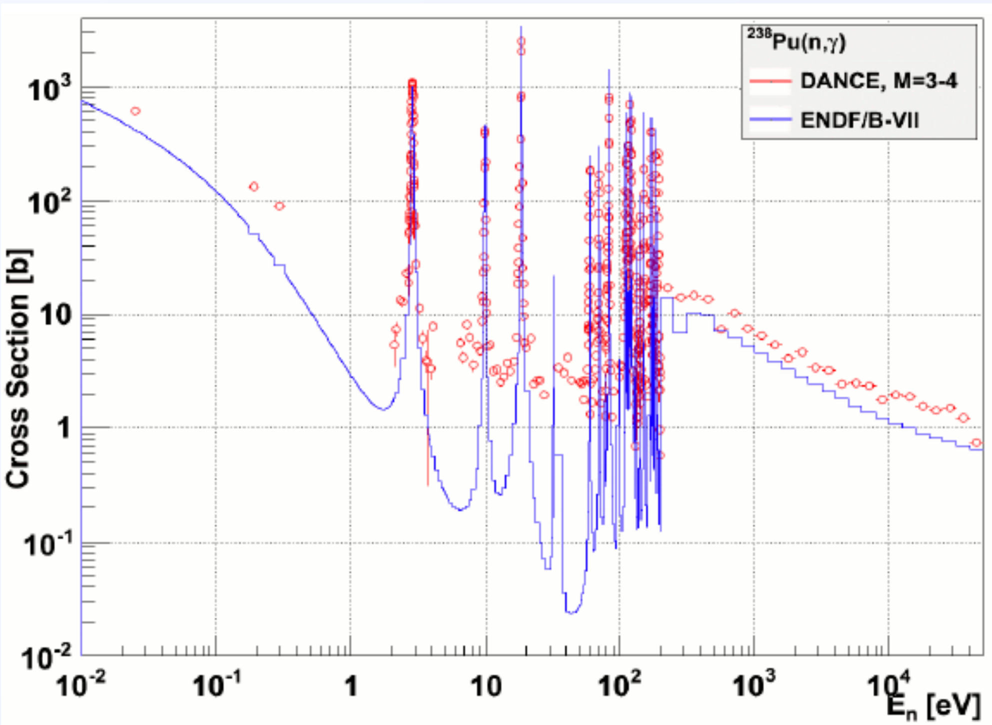


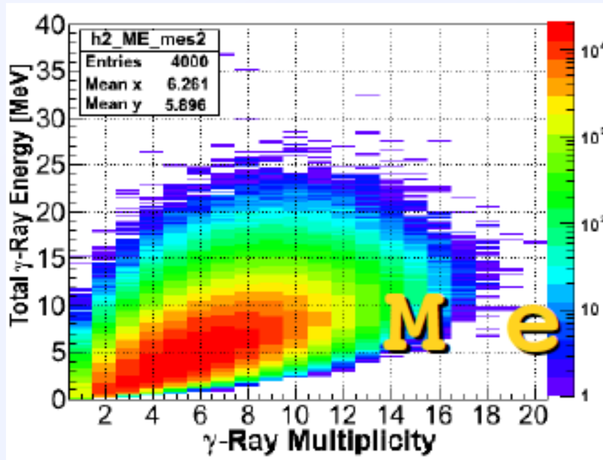
- Distributions have a similar Gaussian-like shape with the tail extending to the higher M_γ
- The mean M_γ is increasing with increasing mass of fissile nuclei, while the width shows the same trend and is nearly the same as the mean value

Coming soon…

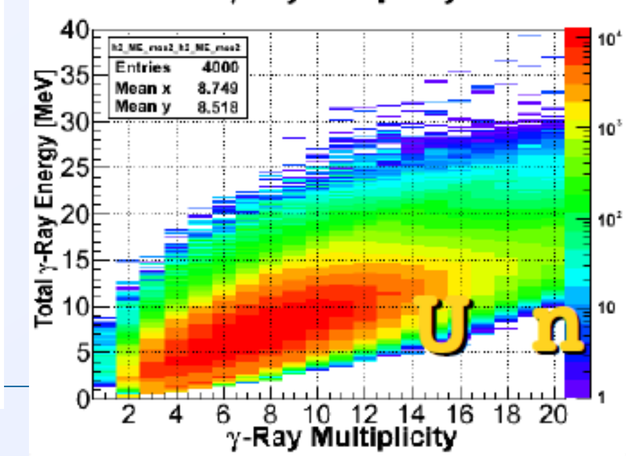
slide from C.Y. Wu

- Precision measurement of the neutron-capture cross section on ^{238}Pu
  - *The first ever measured at laboratory environment*
- The total γ-ray energy vs. multiplicity for the fission prompt γ-ray emission
  - *The unfolding story continues*





Measured

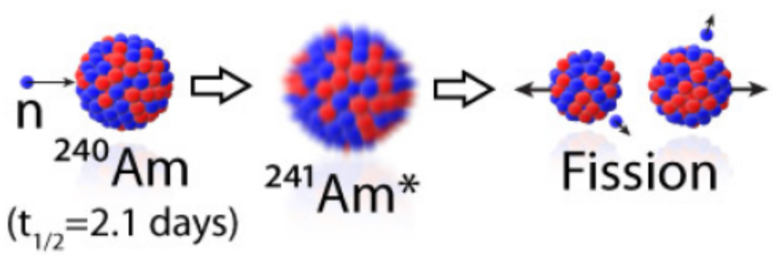


Unfolded

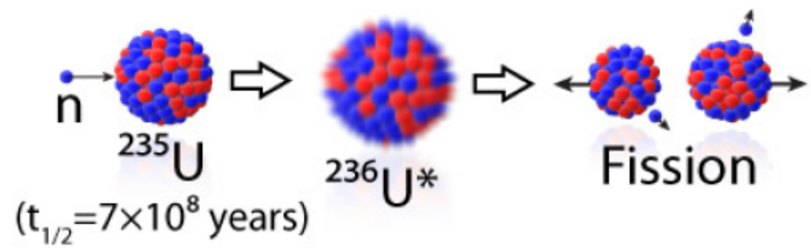
The Surrogate Reaction

slide from
R. Casperson

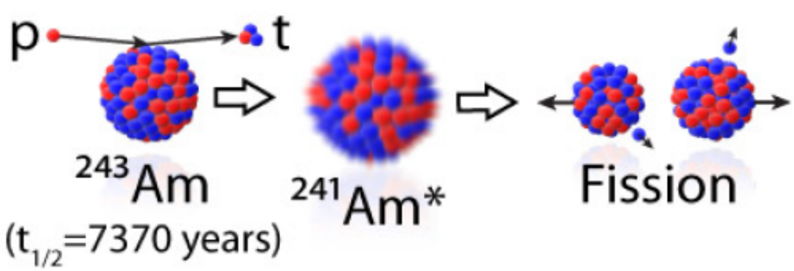
Desired Reaction: ^{240}Am(n,f)



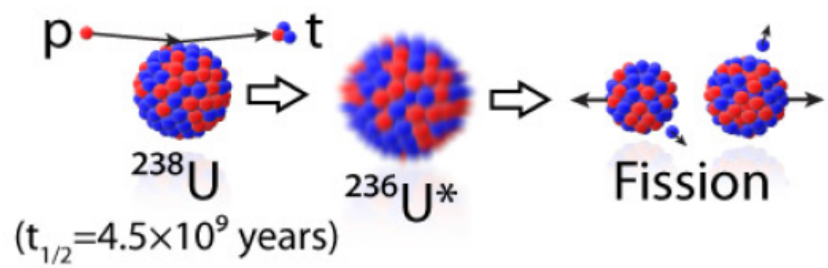
Reference Reaction: ^{235}U(n,f)



Surrogate Reaction: ^{243}Am(p,tf)



Ratio Reaction: ^{238}U(p,tf)



$$\sigma(^{240}\mathrm{Am}(n,f),E) = \frac{N(^{243}\mathrm{Am}(p,tf),E)}{N(^{238}\mathrm{U}(p,tf),E)} \times \frac{\sigma_{CN}(^{240}\mathrm{Am}(n,tot)^{241}\mathrm{Am}^*,E)}{\sigma_{CN}(^{235}\mathrm{U}(n,tot)^{236}\mathrm{U}^*,E)} \times \sigma(^{235}\mathrm{U}(n,f),E)$$

Status of Surrogate Cross Section Measurements

Cross section measurements of $^{240,241,242}Am(n,f)$ have been completed. Evaluations are underway and expect to be complete by December 2012.

Cross section measurement of $^{88}Y(n,2n)$ is complete and final evaluation is underway. Evaluation to be complete December 2012.

Data for $^{87,88}Y(n,\gamma)$ has been taken and data analysis and reduction is underway. Evaluation to be completed September 2013.

Final analysis being completed on $^{239}Np(n,f)$ cross section. Results to be submitted December 2012 to peer-reviewed journal.

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Data taken on Yb isotopes to validate (p,d) reaction channel in preparation for Lu measurements in FY13.

Data taken on $^{95}Mo(d,p)$ to benchmark surrogate technique in spherical region for (n,γ) reactions.

Surrogate Reactions Publications in FY12

Review of Modern Physics article on surrogate nuclear reactions method

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

Compound-nuclear reaction cross sections from surrogate measurements

Jutta E. Escher, Jason T. Burke, Frank S. Dietrich, Nicholas D. Scielzo,
Ian J. Thompson, and Walid Younes
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

(published 13 March 2012)

Nuclear reaction cross sections are important for a variety of applications in the areas of astrophysics, nuclear energy, and national security. When these cross sections cannot be measured directly or predicted reliably, it becomes necessary to develop indirect methods for determining the relevant reaction rates. The *surrogate nuclear reactions* approach is such an indirect method. First used in the 1970s for estimating (n, f) cross sections, the method has recently been recognized as a potentially powerful tool for a wide range of applications that involve compound-nuclear reactions. The method is expected to become an important focus of inverse-kinematics experiments at rare-isotope facilities. The present paper reviews the current status of the surrogate approach. Experimental techniques employed and theoretical descriptions of the reaction mechanisms involved are presented and representative cross section measurements are discussed.

DOI: 10.1103/RevModPhys.84.353 PACS numbers: 24.87.+y, 24.60.Dr, 25.85.Ec, 24.50.+g

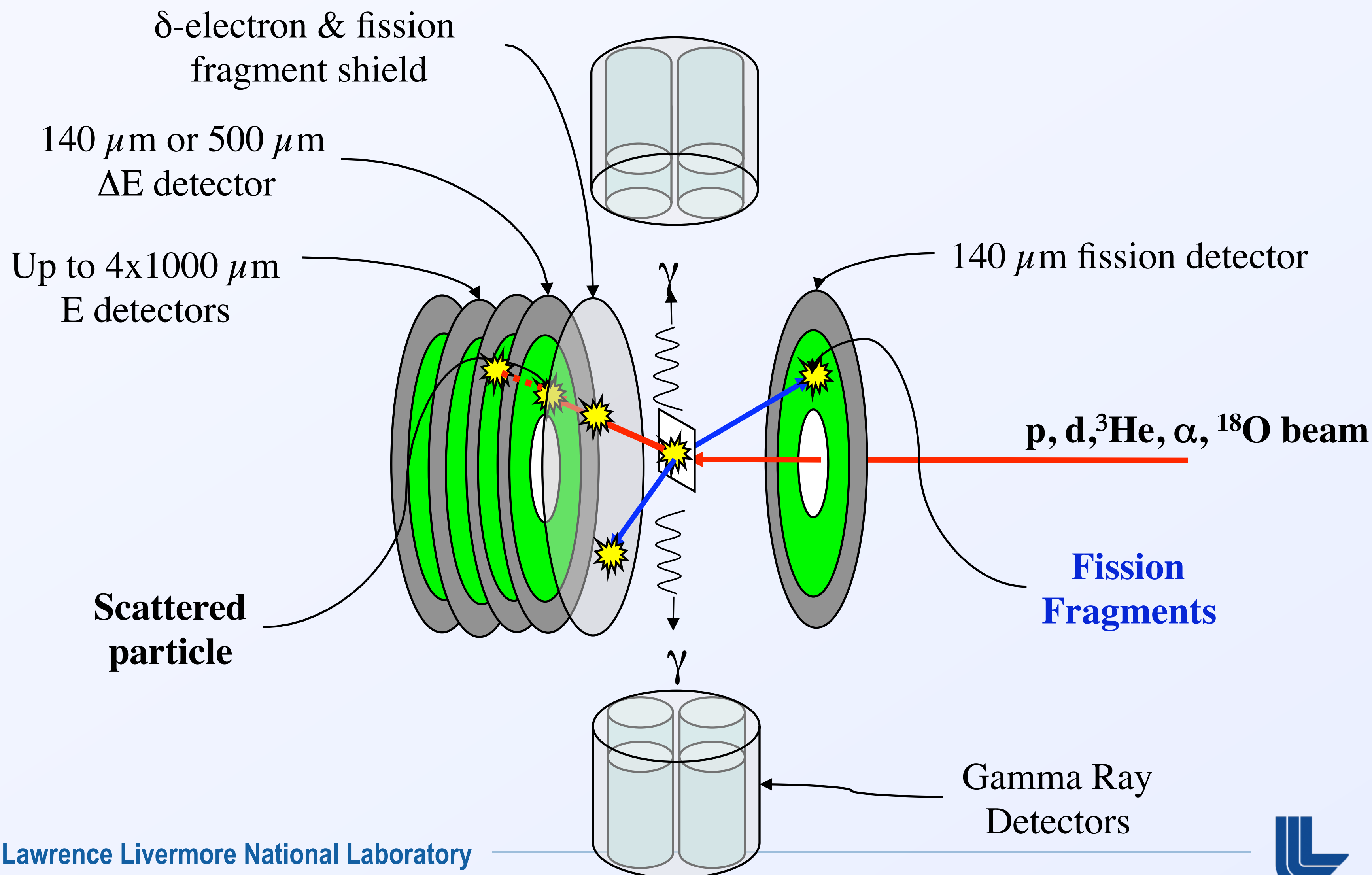
R.O. Hughes *et al*., "Utilizing (p,d) and (p,t) reactions to obtain (n,f) cross sections in uranium nuclei via the surrogate-ratio method," Physical Review C **85**, 024613 (2012)

N.D. Scielzo *et al*., "Statistical gamma rays in the analysis of surrogate nuclear reactions", Physical Review C **85**, 054619 (2012)

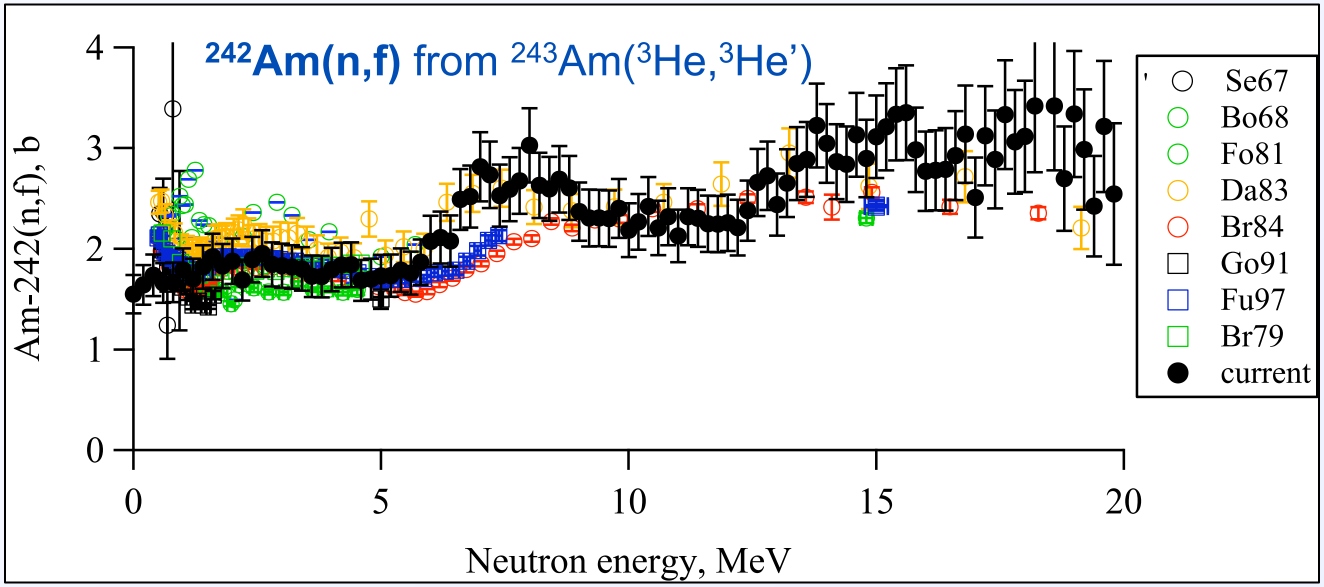
B.L. Goldblum *et al*., "Indirect determination of neutron capture cross sections on spherical and near-spherical nuclei using the surrogate method", Physical Review C **85**, 054616 (2012)

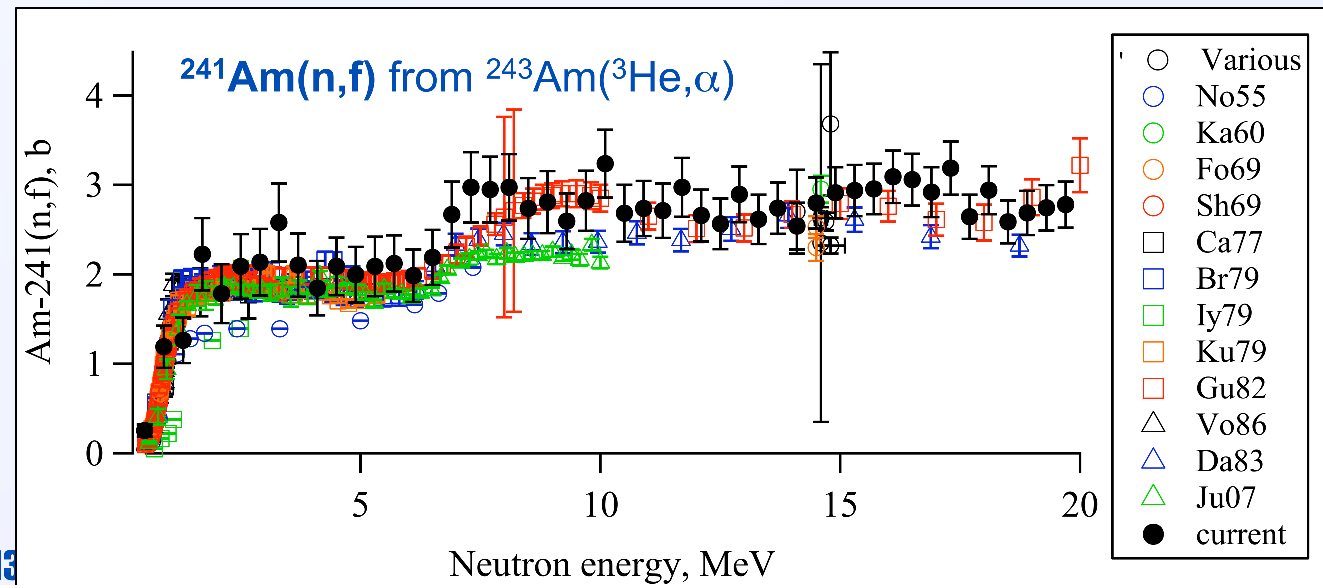
G. Boutoux *et al*., "Study of the surrogate-reaction method applied to neutron-induced capture cross sections," Physics Letters B **712**, 319 (2012)

Silicon Telescope Array for Reaction Studies (STARS)
Livermore Berkeley Array for Collaborative Experiments (LIBERACE)



^{241,242}Am(n,f) cross sections

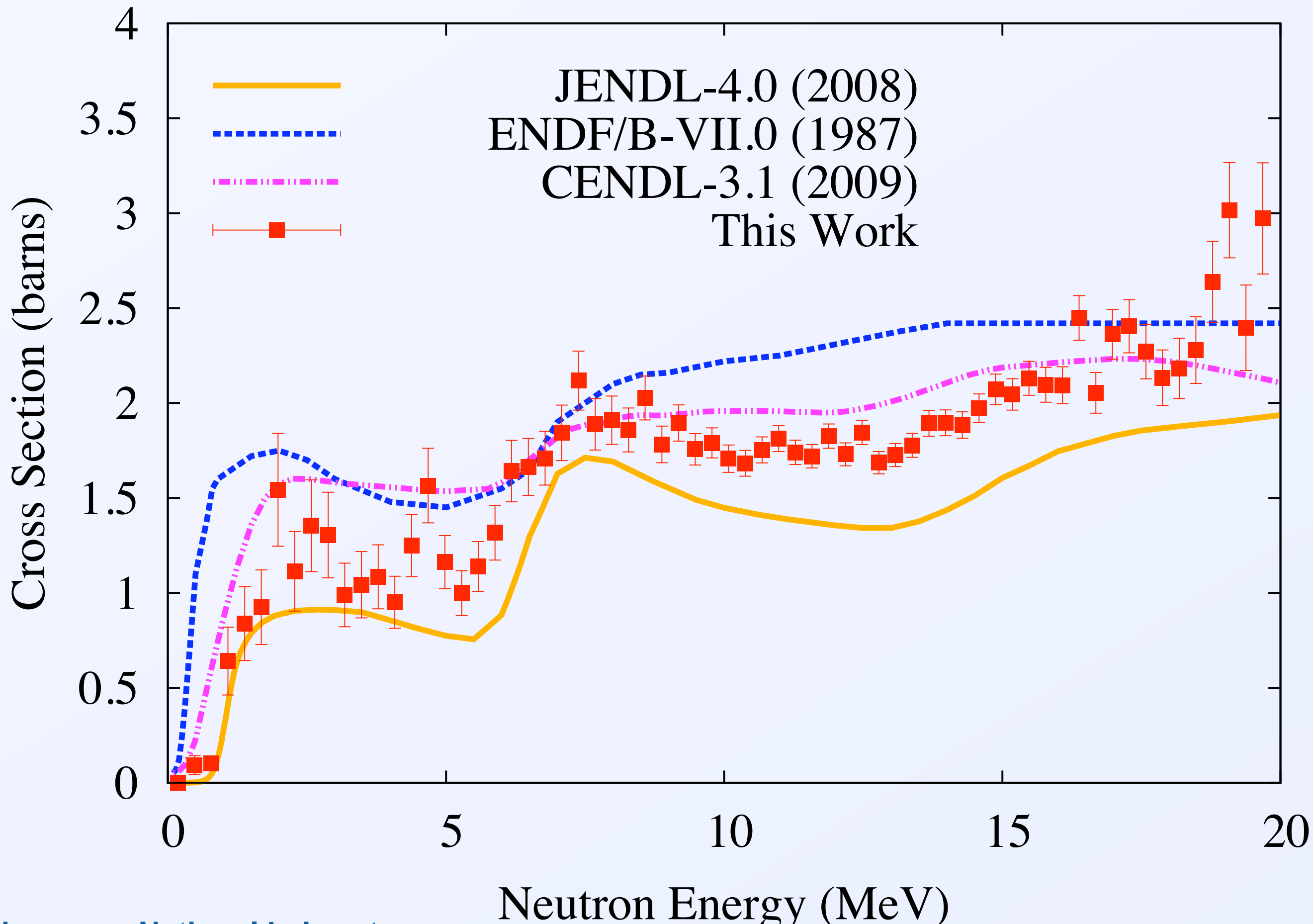




- ^{242}Am(n,f) and ^{241}Am(n,f) agree well with previous data
- Some differences at first-chance fission – may be due to spin effects
- New measurement provides consistent cross section value
- Measurements performed relative to ^{234,235}U(n,f) cross sections

$^{239}Np(n,f)$ SRM Cross Section Measurement

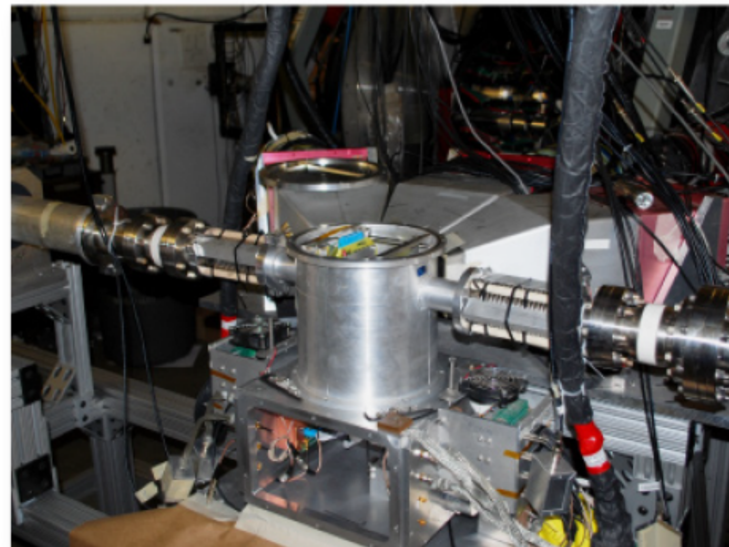
Using reactions $^{238}U(^{3}He,p)^{240}Np$ and $^{236}U(^{3}He,p)^{238}Np$, normalized to well-known $^{237}Np(n,f)$



The STARLiTe detector system

slide from
R. Casperson

Texas A&M Cyclotron Institute



STARLiTe

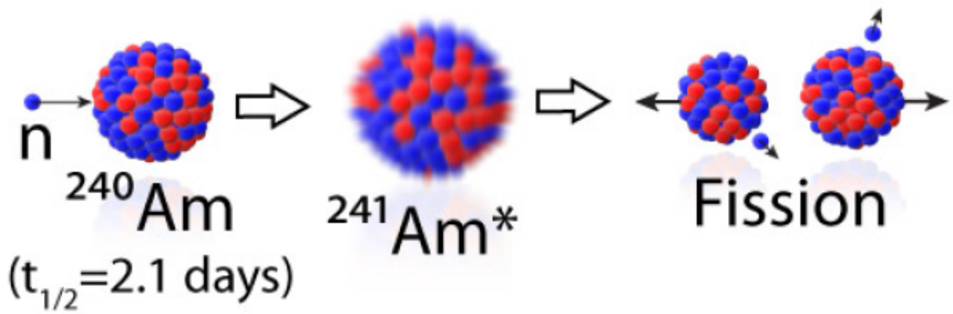
The silicon telescope and high purity germanium array have moved to the Texas A&M Cyclotron Institute on the K150 cyclotron beam line.

This was the first experiment fielded on the new setup.

The desired reaction: ^{240}Am(n,f)

slide from
R. Casperson

This reaction has never been measured. ^{240}Am has a half-life of 2.1 days, which makes it unreasonable to use as a target.

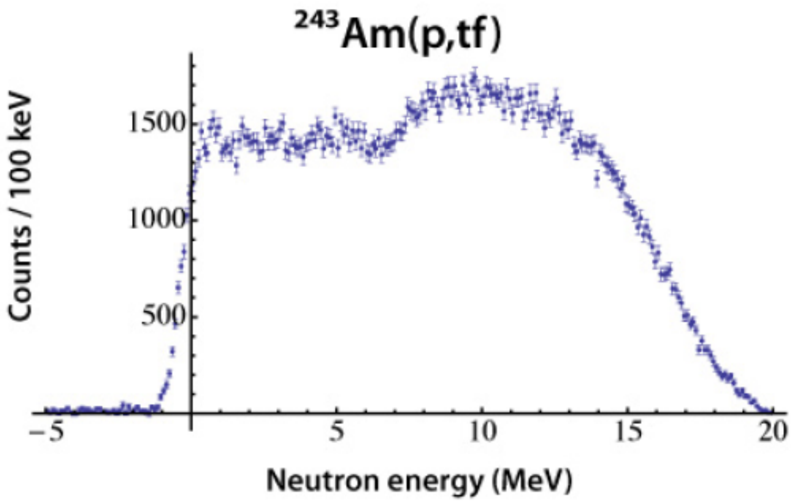


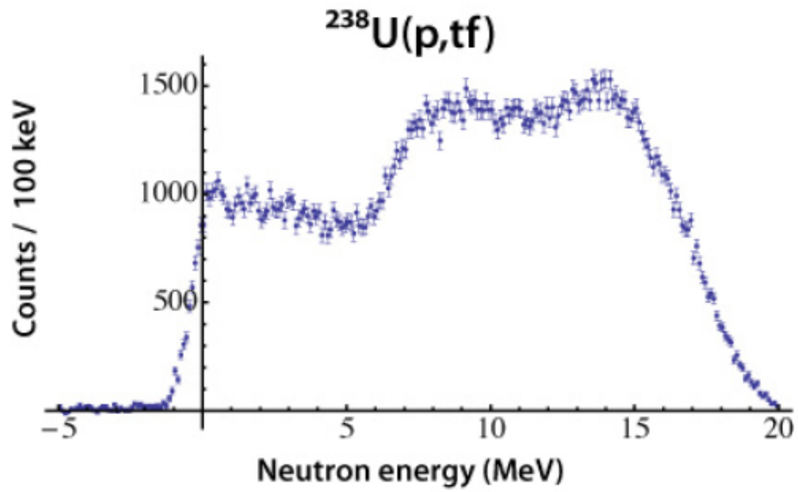
^{239}Am	^{240}Am	^{241}Am	^{242}Am	^{243}Am	^{244}Am
12 hours	2.1 days	433 years	16 hours	7370 years	10 hours

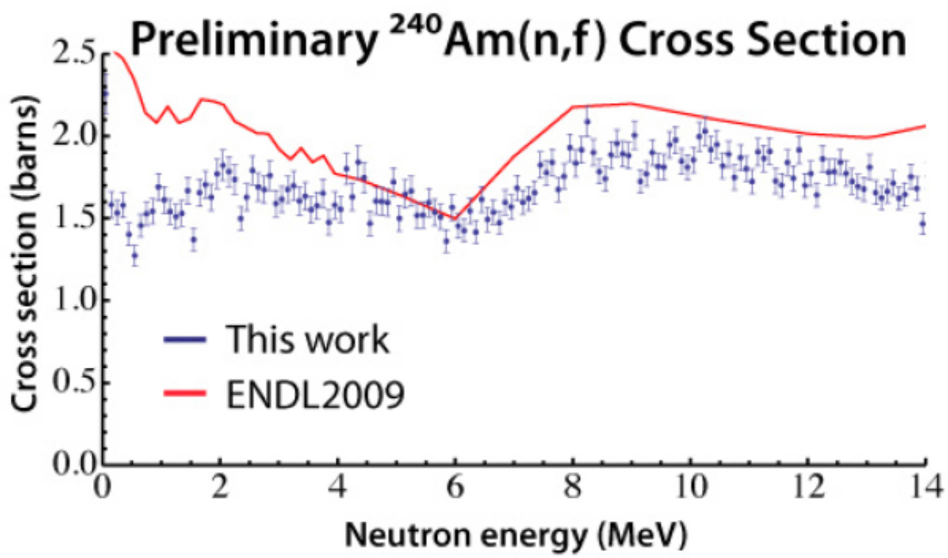
The surrogate ratio technique can be used, by populating the same compound nucleus using a longer-lived target.

Particle spectra and $^{240}Am(n,f)$

slide from
R. Casperson

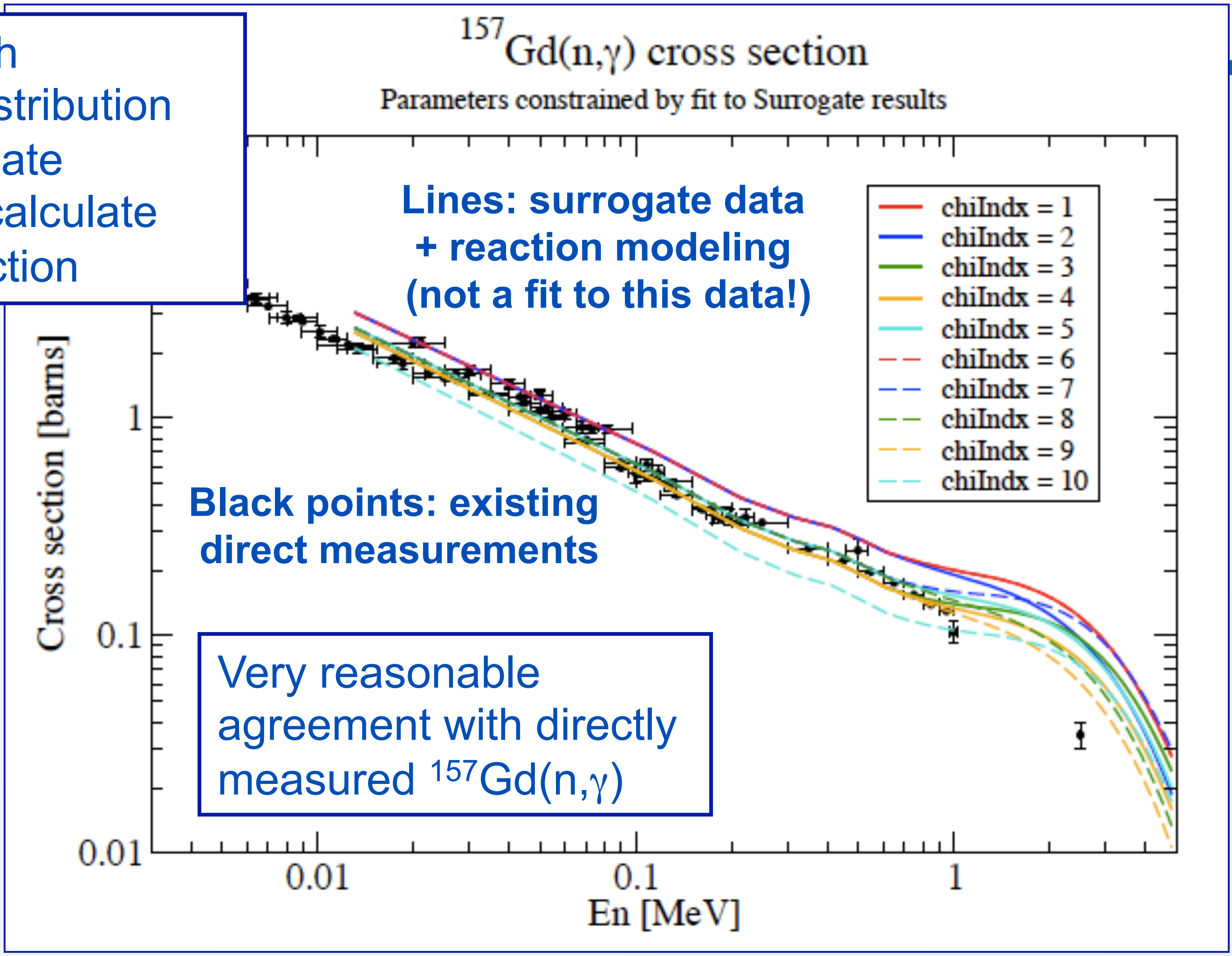






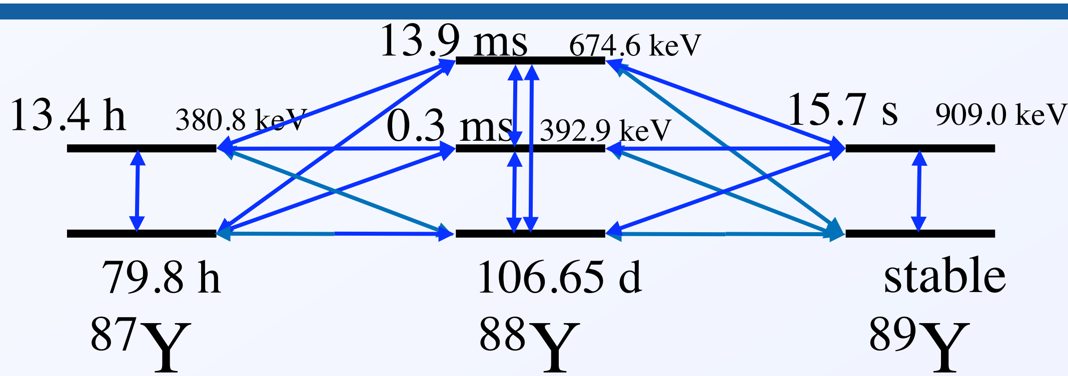
Obtaining an (n,γ) cross section using surrogate reactions

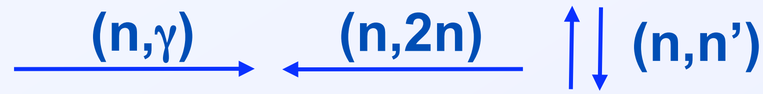
Using Hauser-Feshbach parameters and spin distribution determined from surrogate ^{158}Gd(p,p') reaction to calculate the ^{157}Gd(n,γ) cross section



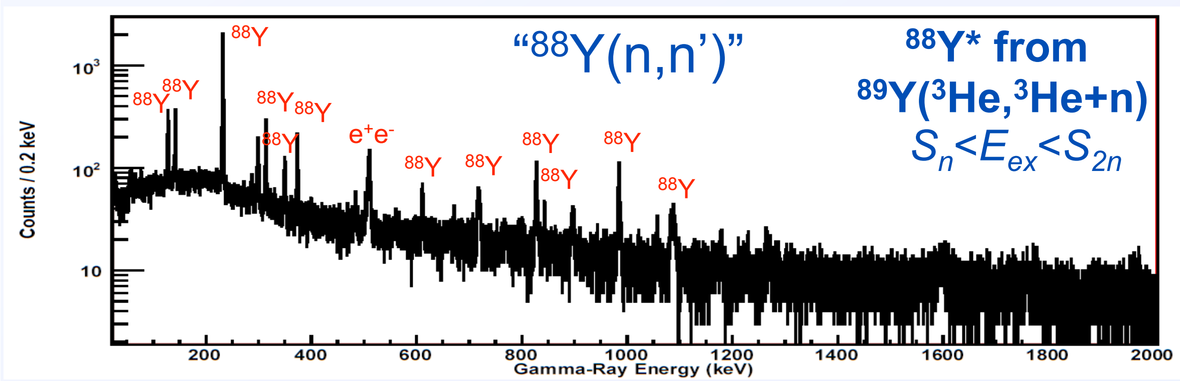
Next step: Improve precision and apply technique to determine unknown ^{153}Gd(n,γ), ^{87,88}Y(n,γ) and ^{87,88}Y(n,2n) cross sections

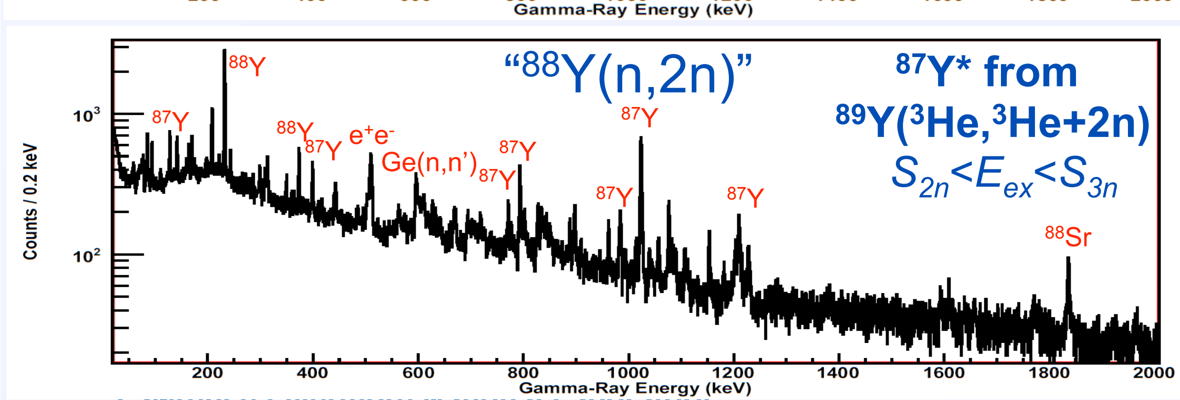
Surrogate data to determine ^{87}Y(n,γ) and ^{88}Y(n,2n) cross sections → bombard ^{89}Y, $^{90-92}$Zr with 50-MeV ^{3}He

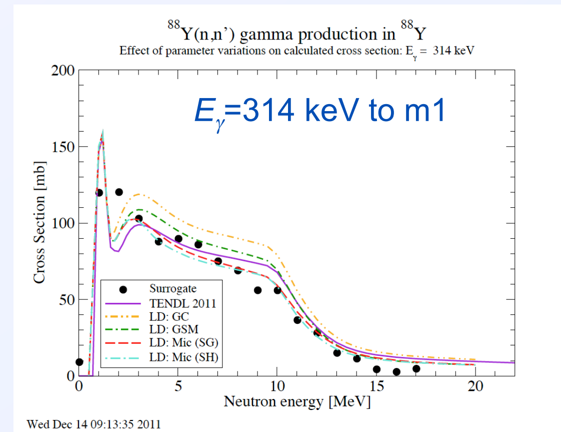


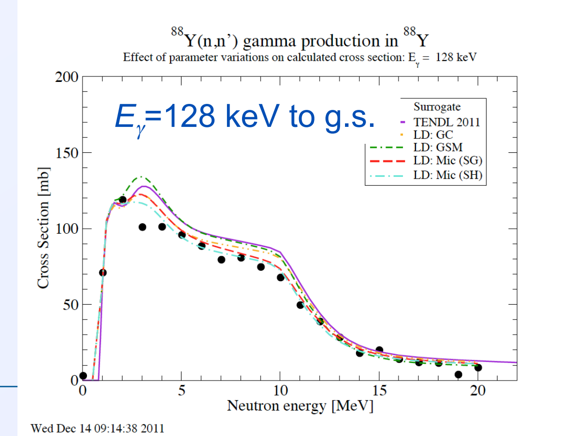


measured Y/Zr decay probabilities used to calculate J^{π} distribution and nuclear-structure parameters needed for Hauser-Feshbach cross section calculations









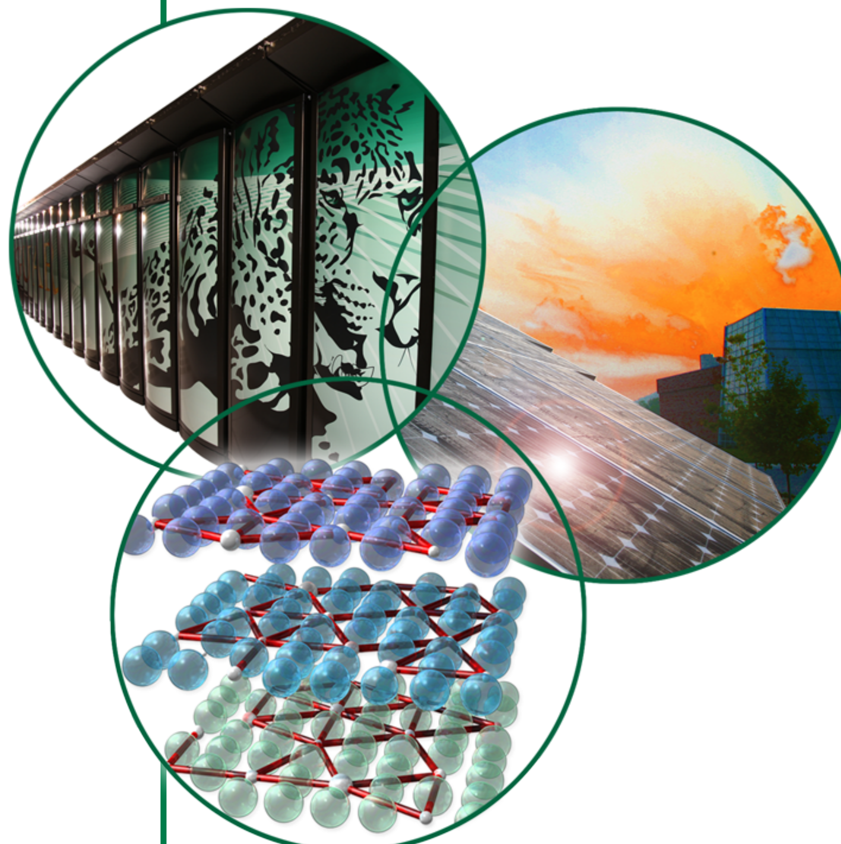
Oak Ridge National Laboratory

- Resonance Region Measurements
  - **^{183}W** - New transmission data was taken at GEEL using 30m and 60m flight path and preliminary results were shown.
  - **Ca** - Preliminary capture yield was shown (60m flight path), several new resonances were observed.
  - **Ce** - Preliminary capture data was shown (60m flight path).
  - **^{182,183,184,186}W, ^{63,65}Cu**, Ca-nat resonance analysis is in progress.

ORNL Neutron Cross-Section Measurements Activities

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

CSEWG meeting 2012

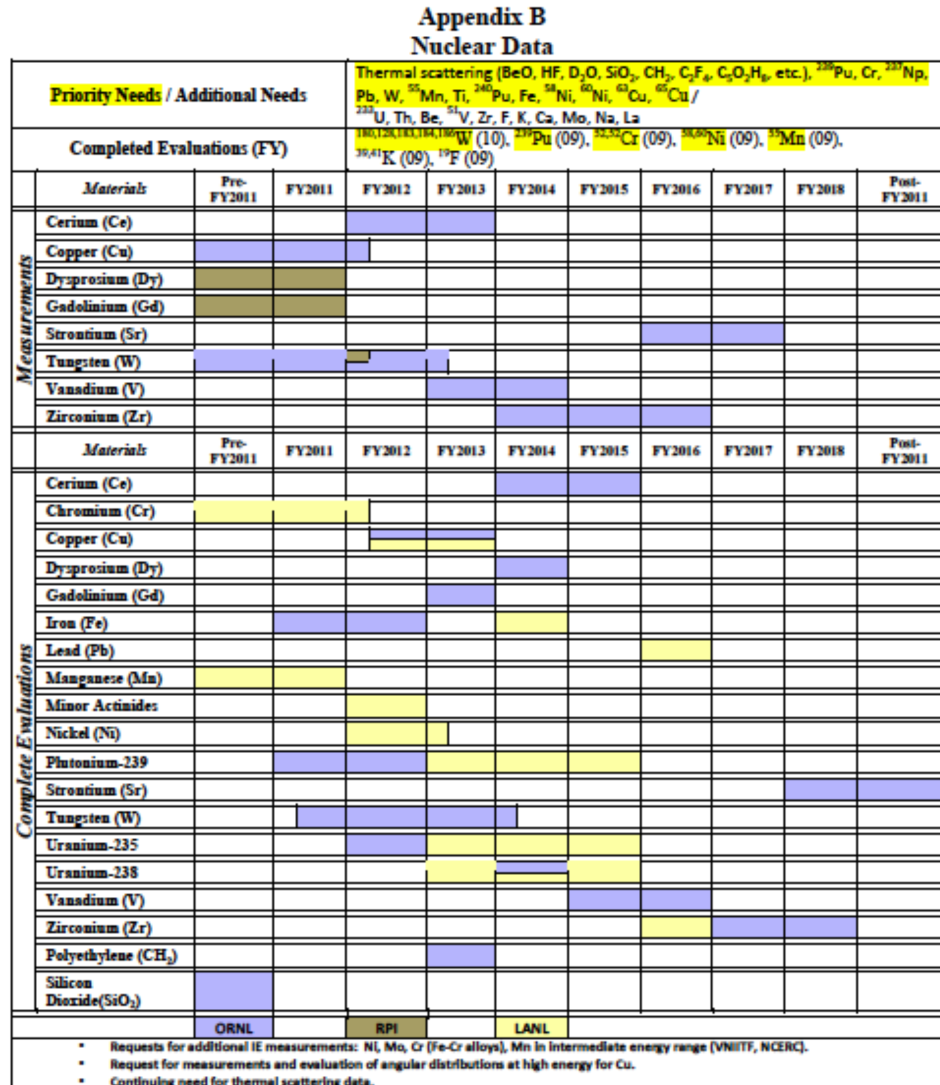


U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Resonance Region Nuclear Data Work for NCSP

- **Objective:** Provide measured and evaluated resonance-region cross-section data to address the priority NCSP nuclear data needs
- **Vision:** Addresses multiple Nuclear Data 5- and 10-year goals and attributes identified in the NCSP Vision
- **Final product:** rigorous ENDF/B resonance evaluations produced from cross-section measurements and analyses
- FY11 and 12 measurement work effort focused on tungsten, copper, calcium, and cerium—identified differential nuclear data needs by NCSP Nuclear Data Advisory Group (NDAG)

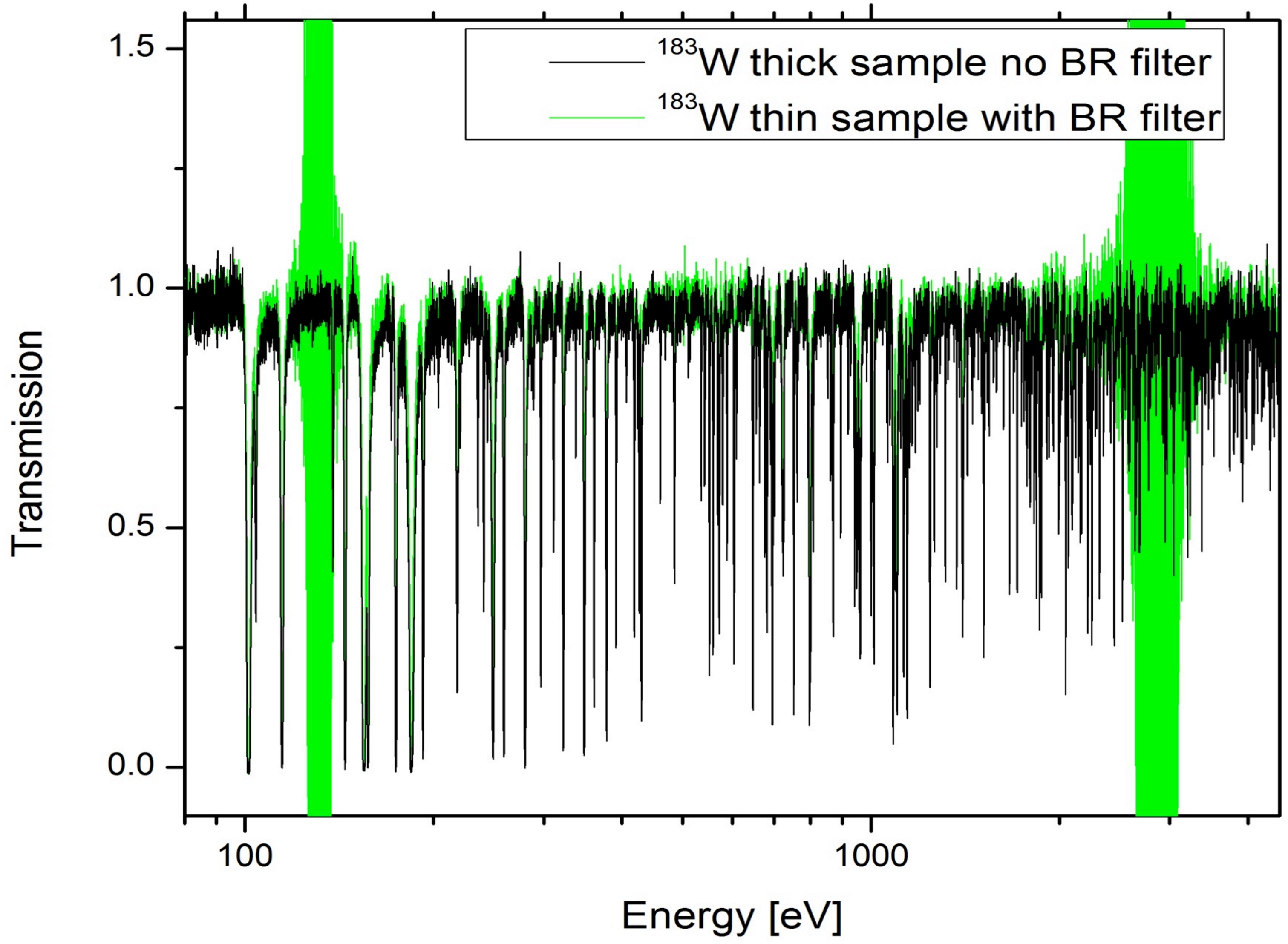


Oak Ridge National Laboratory

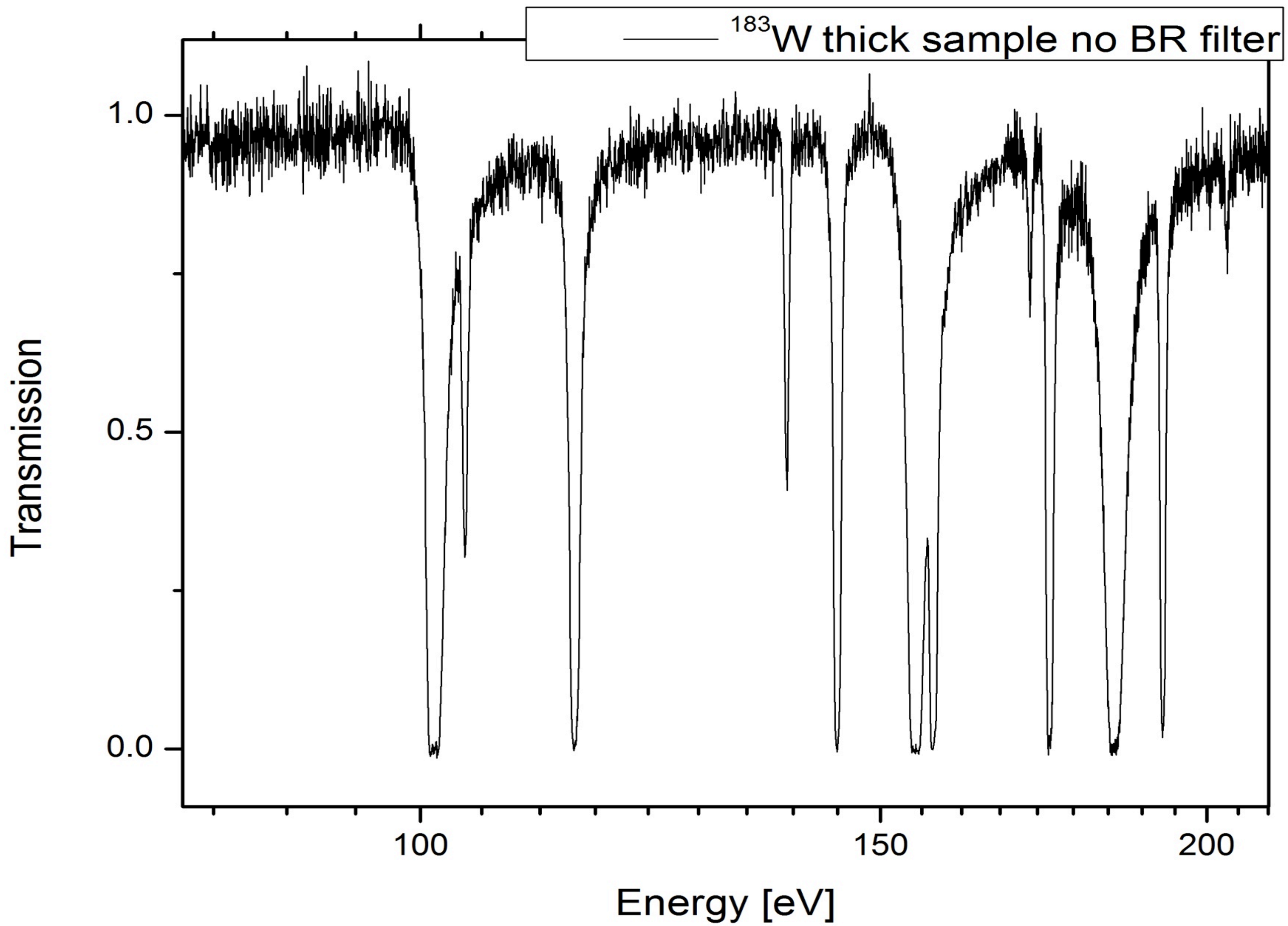
W Measurement Activities

- Measurements completion of the stable W isotopes. Experiments started in FY09 using enriched samples for 4 isotopes
  → 12 experiments.
- Data sets cover now the complete resolved resonance region, as well as part of the unresolved region.
- Normalization of the capture data finalized.
- Capture data for $^{182,183,184,186}W$ from the high repetition run available to analyze.
- Transmission data for $^{182,183,184,186}W$ with different sample thickness available. But due to filters there are gaps in the data. New experiments without filter and new set up performed.

^{183}W Comparison thin thick sample



^{183}W thick sample detail



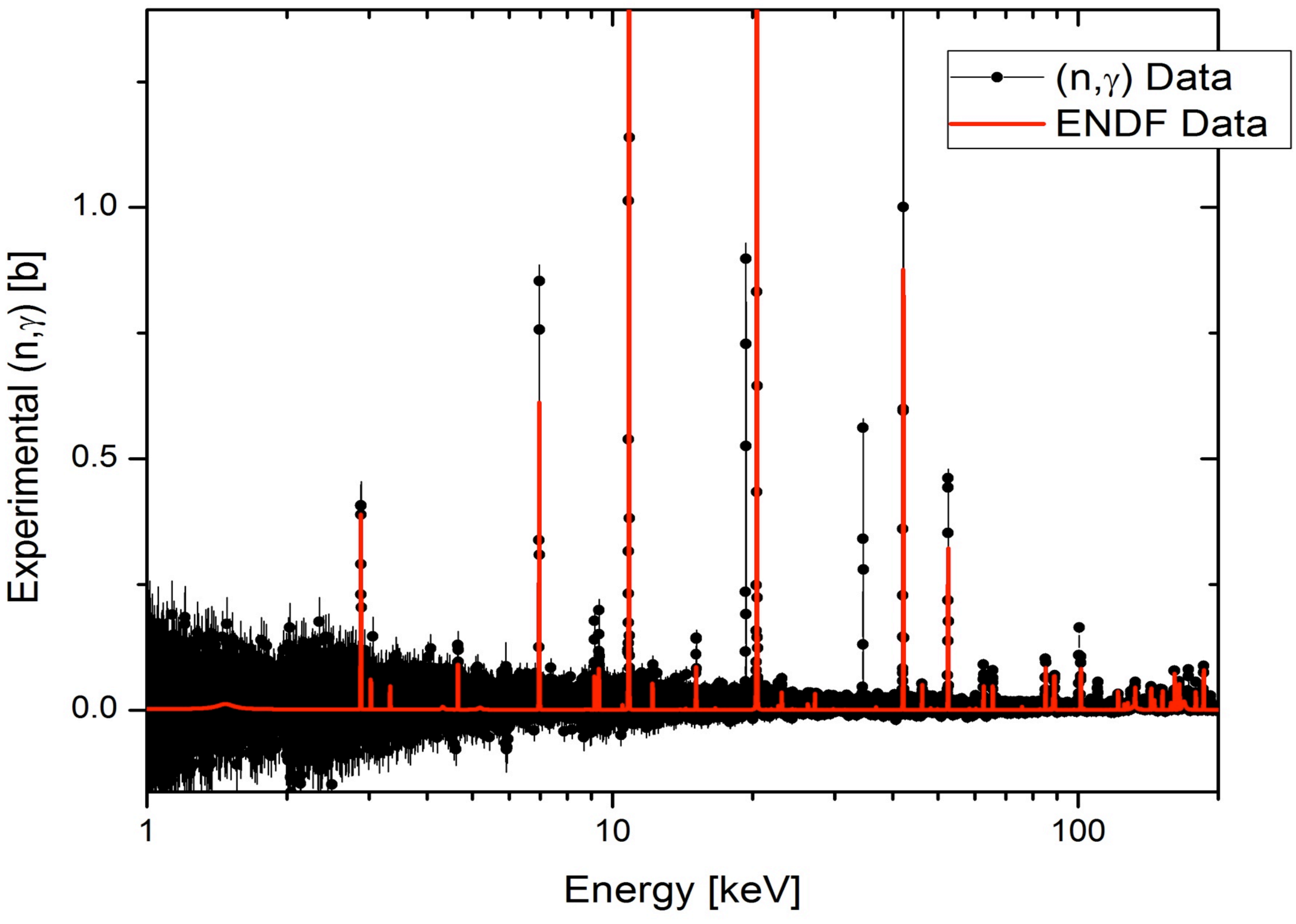
ORNL Measurement Activities for Calcium

- 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.

Ca Samples

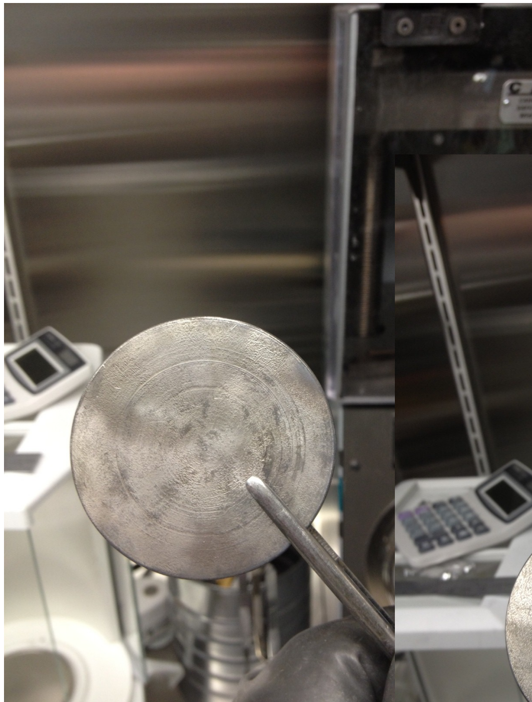
Natural Ca (n,γ) compared to ENDF



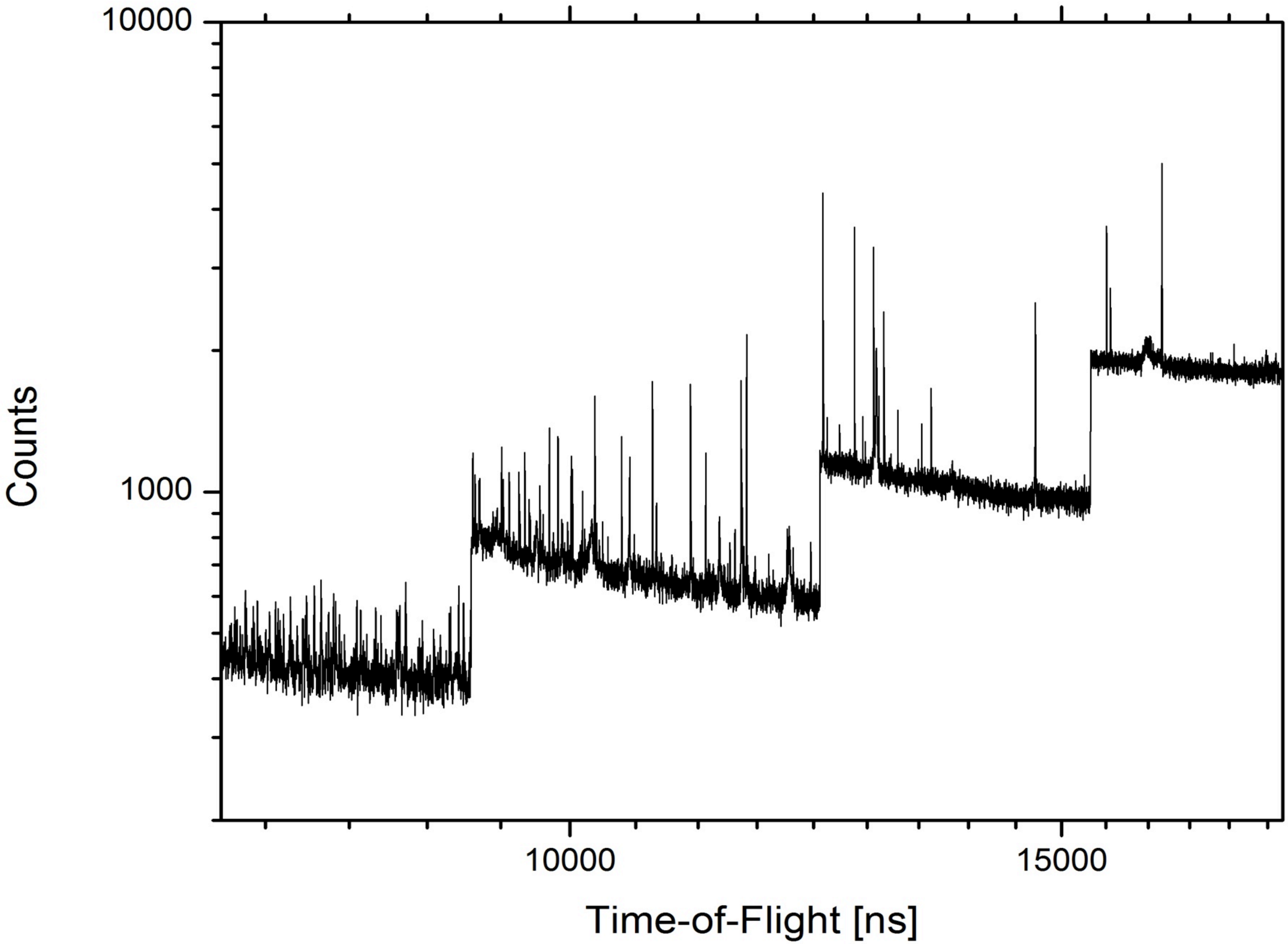
ORNL Measurement Activities for Cerium

- 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

Cerium Samples



Natural Ce (n,γ)



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	
Reduced to Cross section	X-section, transmission	X-section	X-section	
Data Testing	Data ready for evaluation	Data ready for evaluation	Under way	
Analysis and Evaluation	Started	Started		

Lawrence Berkeley National Laboratory

- Thermal capture cross sections (Firestone's group)
  - Measurements are done at the Budapest reactor. The measurements are done by summing all the observable levels and adding levels from a statistical model. Results were given for several samples:
  - **^{64,66}Cu** - Thermal neutron capture measurements were shown. Gamma levels are measured and combined with model simulation (DICEBOX) for the continuum ($E>E_{crit}$). For ^{66}Cu σ_0=2.27±0.08 b compared with 2.17±0.03 b from Mughabghab 2006
  - Measurements of tungsten capture cross section measurements at the Budapest reactor were discussed. The updated results:
  - **^{182}W**, σ_γ=20.9(26), (atlas, σ_γ=19.9(3))
  - **^{183}W** σ_γ=9.5(12), (atlas, σ_γ= 10.4(2))
  - **^{184}W** σ_γ= 1.45(28), (atlas, σ_γ= 1.7(1))
  - **^{186}W** σ_γ= 33.0(12), (atlas, σ_γ= 38.1(5))
  - **^{180}W** preliminary results: σ_γ=21.0(43) (current value $4b<\sigma_\gamma<150b$)

Thermal Neutron Capture of $^{64,66}Cu$

Andrew M. Rogers
Nuclear Science Division
Lawerence Berkeley National Laboratory

USNDP / CSEWG
11-08-2012

Outline

63Zn 38.47 M ϵ: 100.00%	64Zn ≥7.0E20 Y 49.17% 2ϵ	65Zn 243.93 D ϵ: 100.00%	66Zn STABLE 27.73%	67Zn STABLE 4.04%
62Cu 9.673 M ϵ: 100.00%	63Cu STABLE 69.15%	64Cu 12.701 H ϵ: 61.50% β-: 38.50%	65Cu STABLE 30.85%	66Cu 5.120 M β-: 100.00%
61Ni STABLE 1.1399%	62Ni STABLE 3.6346%	63Ni 101.2 Y β-: 100.00%	64Ni STABLE 0.9255%	65Ni 2.5175 H β-: 100.00%

- Introduction
  - Motivation and method
  - DICEBOX
- Experimental setup (Budapest research reactor)
- Preliminary analysis ^{65}Cu(n,γ)^{66}Cu
- Summary and outlook

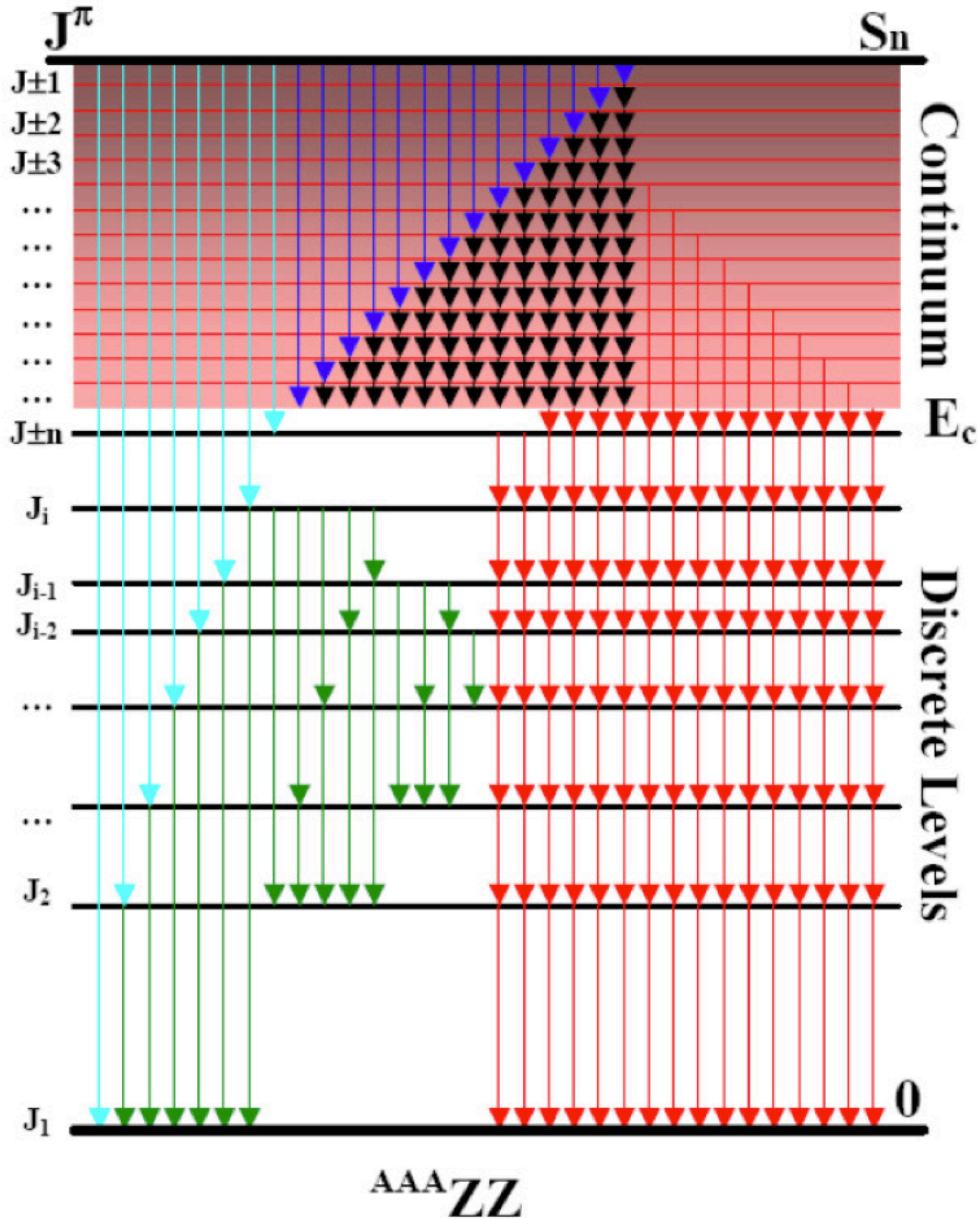
PRELIMINARY

Motivation and Method

- General improvements in the total radiative neutron-capture cross sections (σ_0).
- Constrain spins, search for new transitions, and etc..
- Method:
  - Experimental data of thermal (n,γ) cross sections on *elemental* Copper samples.
  - Generate simulated neutron capture decay schemes using the statistical decay code DICEBOX.
  - Compare measured *depopulation* from experiment to the *population* of levels generated by DICEBOX.

$$\sigma_0 = \Sigma\sigma_\gamma^{\mathrm{exp}}(\mathrm{g.s.}) + \Sigma\sigma_\gamma^{\mathrm{sim}}(\mathrm{g.s.})$$

DICEBOX

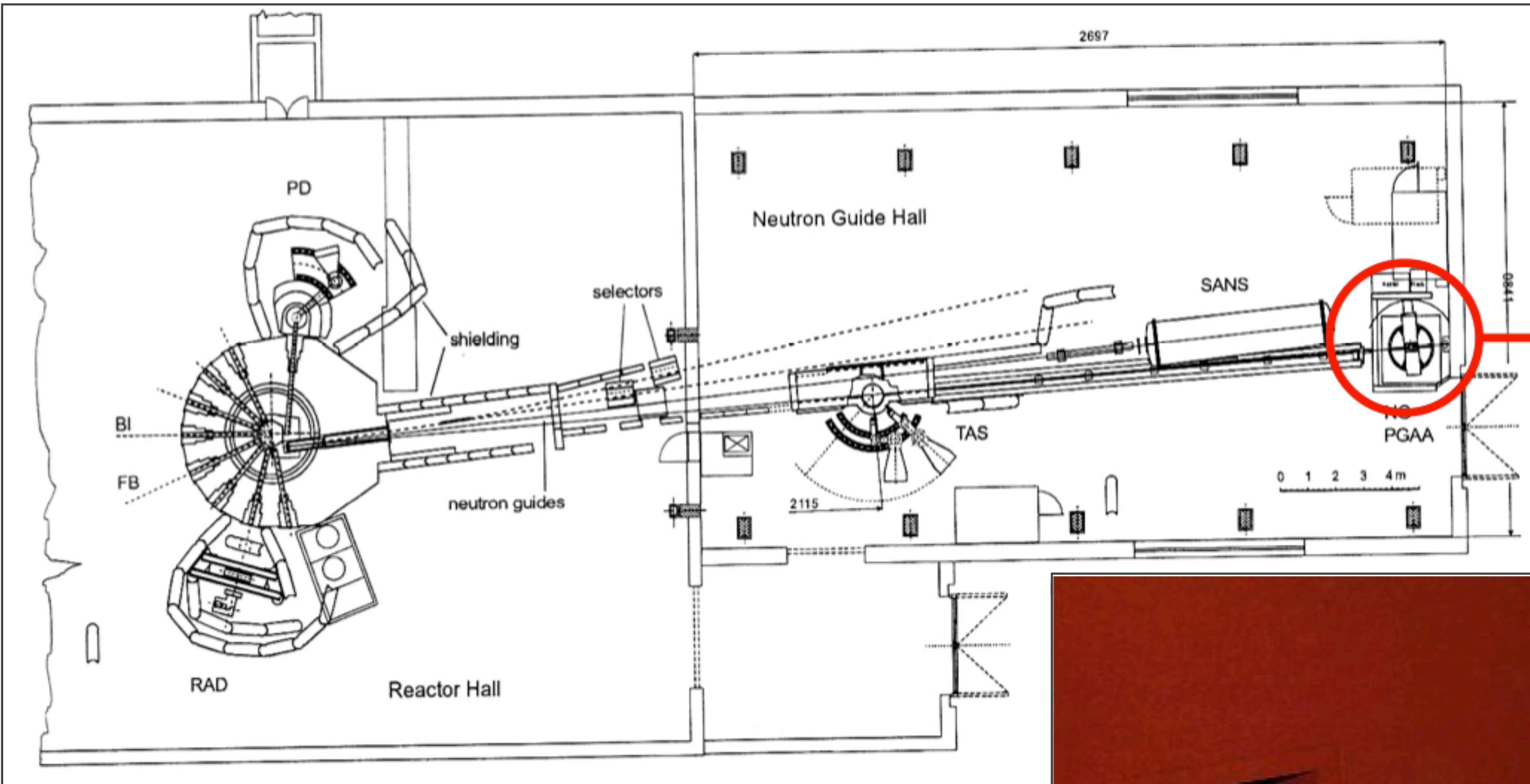


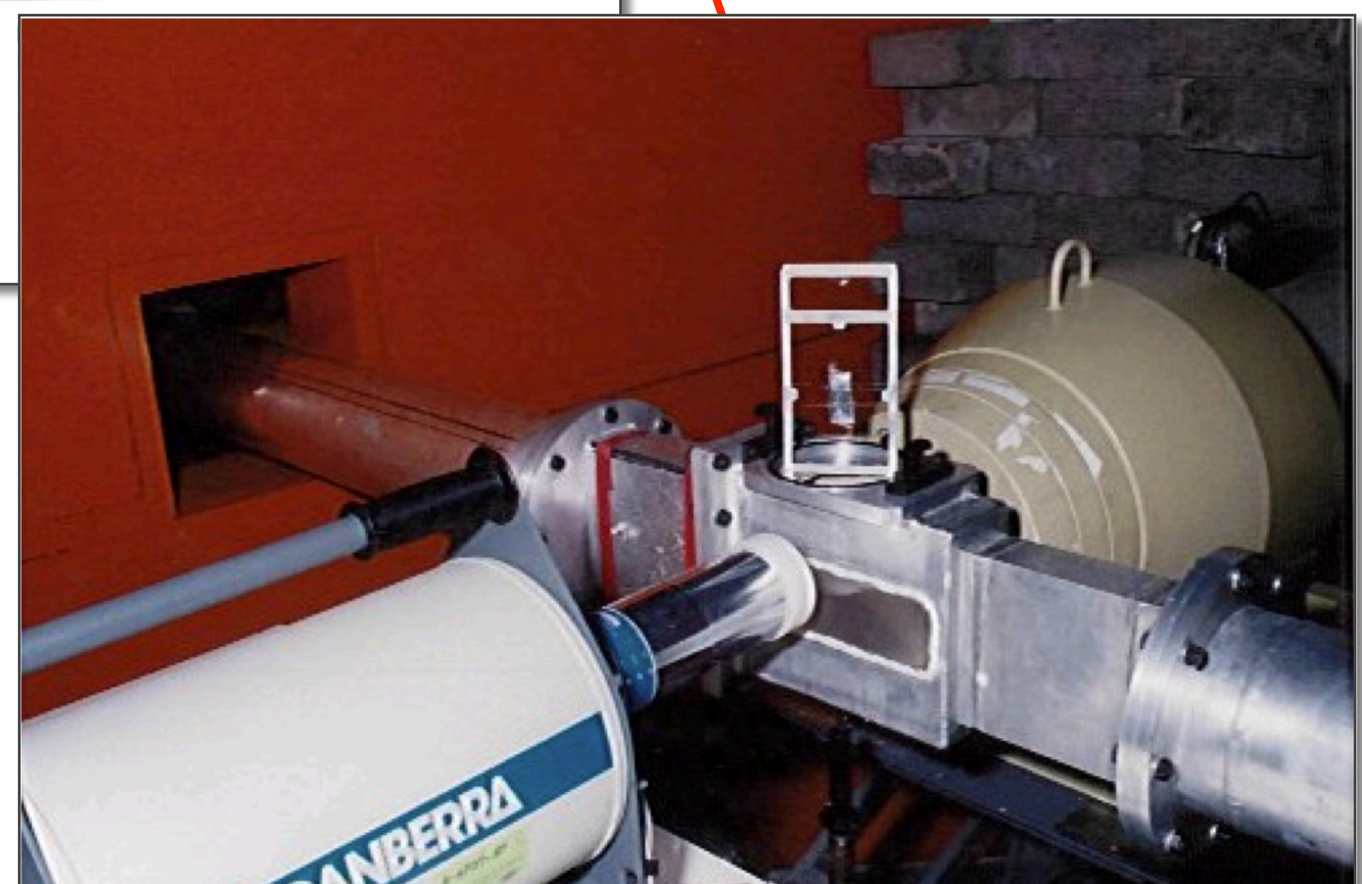
- Simulates spectra of nuclear γ cascades using Monte Carlo methods.
- Below a *critical energy*, E_{crit}, the spectrum is considered to be complete.
- Above E_{crit},
  - Sets of levels are generated from a known level-density formula ρ(E,J^{π})
  - Samples and incorporates uncertainties due to Porter-Thomas fluctuations.

Experimental setup - research reactor

- 10-MW Budapest research reactor
- Guided thermal-neutron beam
- Thermal flux: $\sim 10^6$ $cm^{-2}s^{-1}$
- Cold flux: $\sim 10^7$ $cm^{-2}s^{-1}$
- PGAA (Prompt Gamma Activation Analysis)
- Primary and secondary capture γ rays measured in low-background environment.
- No epithermal, fast, or high-energy neutrons!!!

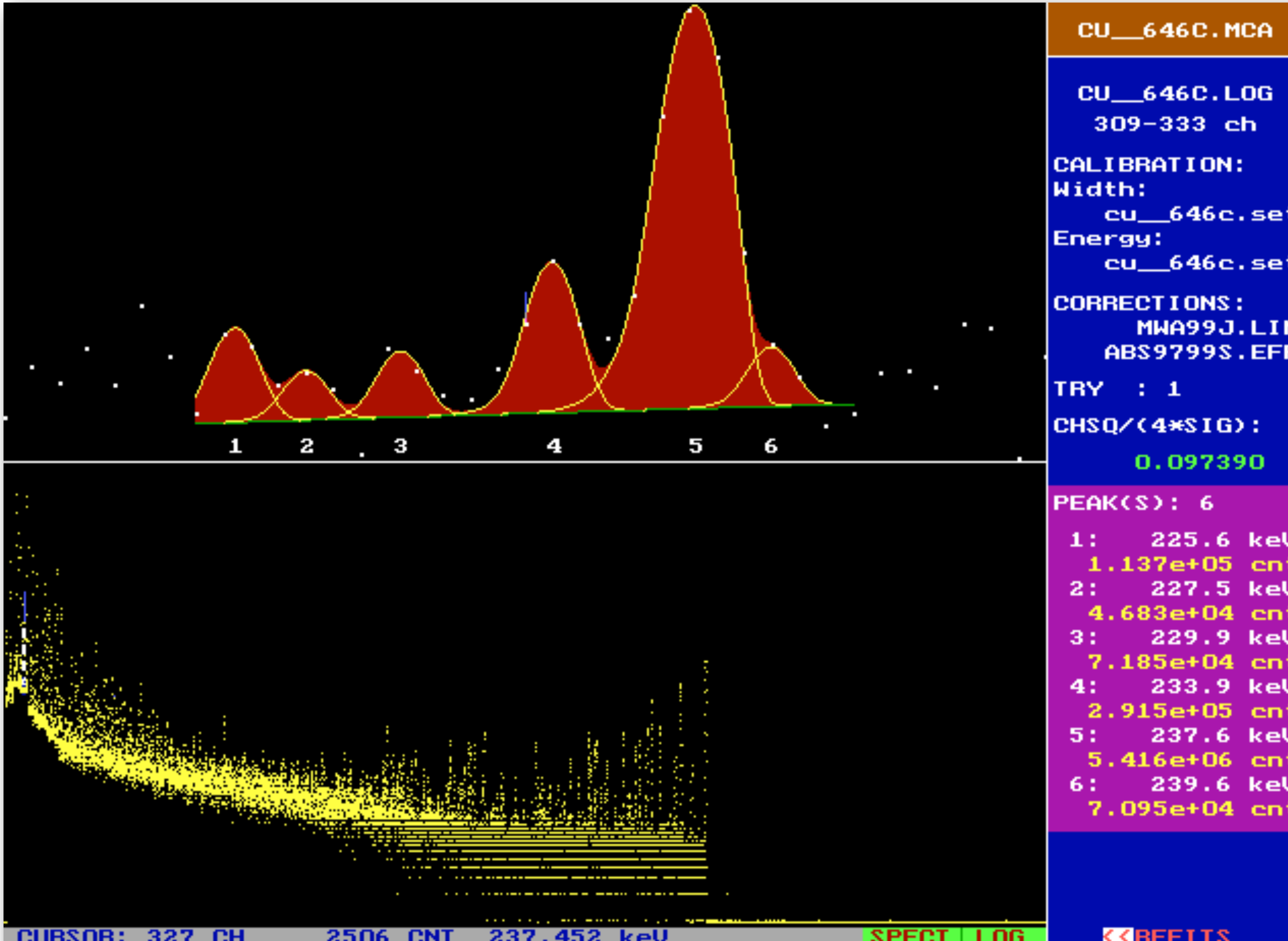
Experimental setup - beamline



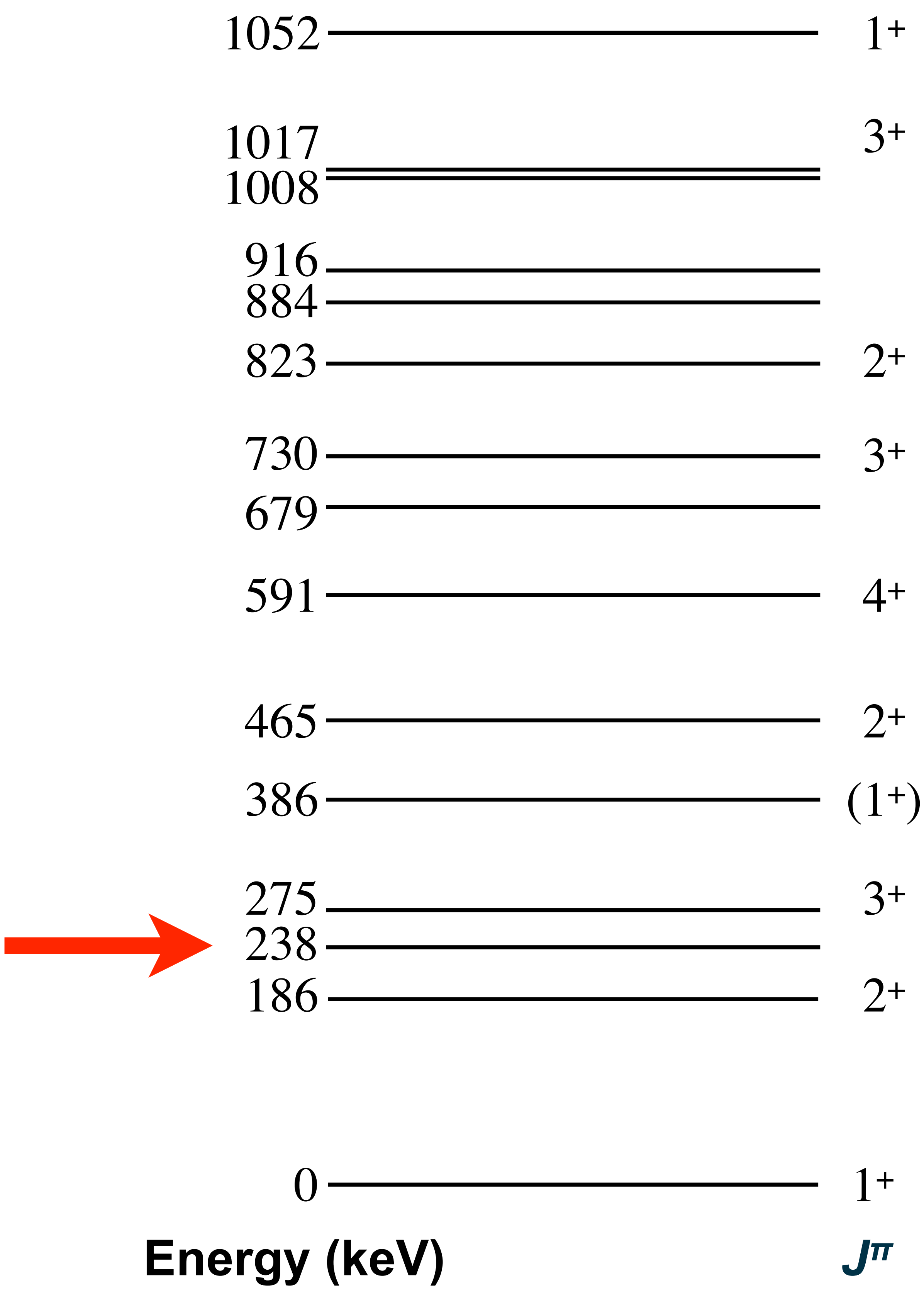


- Experimental setup is located ~35 m from the reactor wall.
- HpGe detector (closed-end coaxial) located ~23 cm from target.
- Compton-suppressed, shielded with BGO detectors.

Copper (n,γ) thermal-capture spectrum



^{66}Cu ENSDF level scheme



- Last evaluation done in 2009.
- Low-lying 2nd excited state at 238 keV has unknown J^{π}.
- Total thermal-neutron capture cross section (*S.F. Mughabghab 2006*)

  σ_0 = 2.17±0.03 b
  S_n = 7066.7±0.8 keV
- ^{65}Cu spin state $3/2^-$
- RIPL: E_{crit} = 186 keV
  $J^{\pi} = 2^-$

Summary and outlook

- Low-lying 2nd excited state is consistent with a spin assignment of J=0.
- 386-keV excited state tentative 1^+ assignment.
- Consistency between the experimental data and simulated cascades for E_{crit} = 823 keV and possibly raised to 1009 keV.
- Good agreement of total thermal capture cross section with previous measurements.

σ_0 = 2.27±0.08 b **(2.17±0.03 b)**

- Explore the effects of additional models and parameters.
- Continue analysis for $^{63}Cu(n,\gamma)^{64}Cu$

Lawrence Berkeley National Laboratory
Nuclear Science Division

New measurement of the radiative thermal-capture cross section for the rare isotope ^{180}W

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National Nuclear Data Week, November 5th – 9th, 2012
Cross Section Evaluation Working Group
Brookhaven National Laboratory
Upton, New York

Capture-state total radiative widths

Compound	PSF/LD	Γ_0 [eV]	$\langle\Gamma_0\rangle$ [eV] (adopted)
^{183}W	EGLO/BSFG	0.072(4)	**0.051(4)**
	EGLO/CTF	**0.040(3)**	
	BA/BSFG	0.137(8)	
	BA/CTF	0.075(6)	
^{184}W	EGLO/BSFG	0.140(3)	**0.073(6)**
	EGLO/CTF	**0.073(3)**	
	BA/BSFG	0.250(6)	
	BA/CTF	0.127(5)	
^{185}W	**EGLO/BSFG**	**0.051(2)**	**0.052(4)**
	EGLO/CTF	0.034(3)	
	BA/BSFG	0.106(5)	
	BA/CTF	0.070(7)	
^{187}W	**EGLO/BSFG**	**0.058(2)**	**0.051(5)**
	EGLO/CTF	0.038(2)	
	BA/BSFG	0.126(5)	
	BA/CTF	0.081(4)	

Total radiative capture cross sections for the W isotopes

$$\sigma_0 = \sum \sigma_\gamma^{\mathrm{exp}}(\mathrm{GS}) + \sum \sigma_\gamma^{\mathrm{sim}}(\mathrm{GS})$$

Isotope (compound)	E_{crit} [keV] RIPL-3	N RIPL-3	E_{crit} [keV] this work	N this work	σ_0 [b] adopted	σ_0 [b] this work
^{183}W: ^{182}W(n,γ)	475.4	11	**480.0**	**11**	19.9(3)	**20.9(26)**
^{184}W: ^{183}W(n,γ)	1252.2	12	**1370.0**	**18**	10.4(2)	**9.5(12)**
^{185}W: ^{184}W(n,γ)	243.4	8	**392.0**	**12**	1.7(1)	**1.45(28)**
^{187}W: ^{186}W(n,γ)	145.9	3	**900.0**	**40**	34.7(2)*	**33.0(26)**

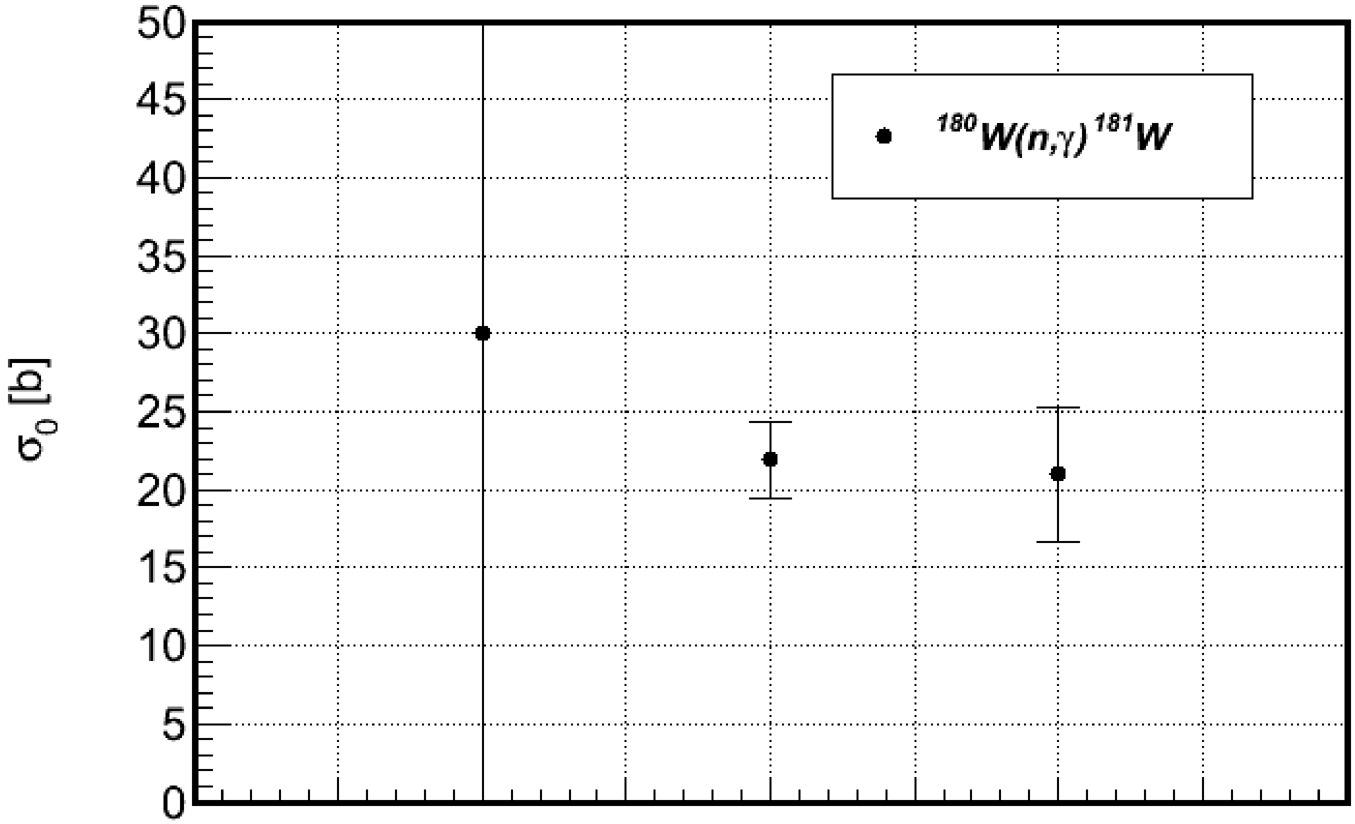
*N. Marnada et al., J. Nucl. Sci. Tech. **36**, 1119 (1999) [4πβ-γ]
cf.:V. Bondarenko et al., Nucl. Phys. A811, 28 (2008): **σ_0 = 35.9(11) b** [(n,γ)]
S. Muhghabghab, Atlas of Neutron Resonances (2006): **σ_0 = 38.1(5) b**

Summary: structural improvements for γ-ray libraries

Quantity	^{183}W	^{184}W	^{185}W	^{187}W
Primary γ rays	2	5	3	8
New γ rays	1	3	2	5
New levels	0	0	0	1
Confirmed J^{π}	3	4	3	19
Proposed J^{π}	0	0	0	5

New results to be communicated through RIPL/ENSDF

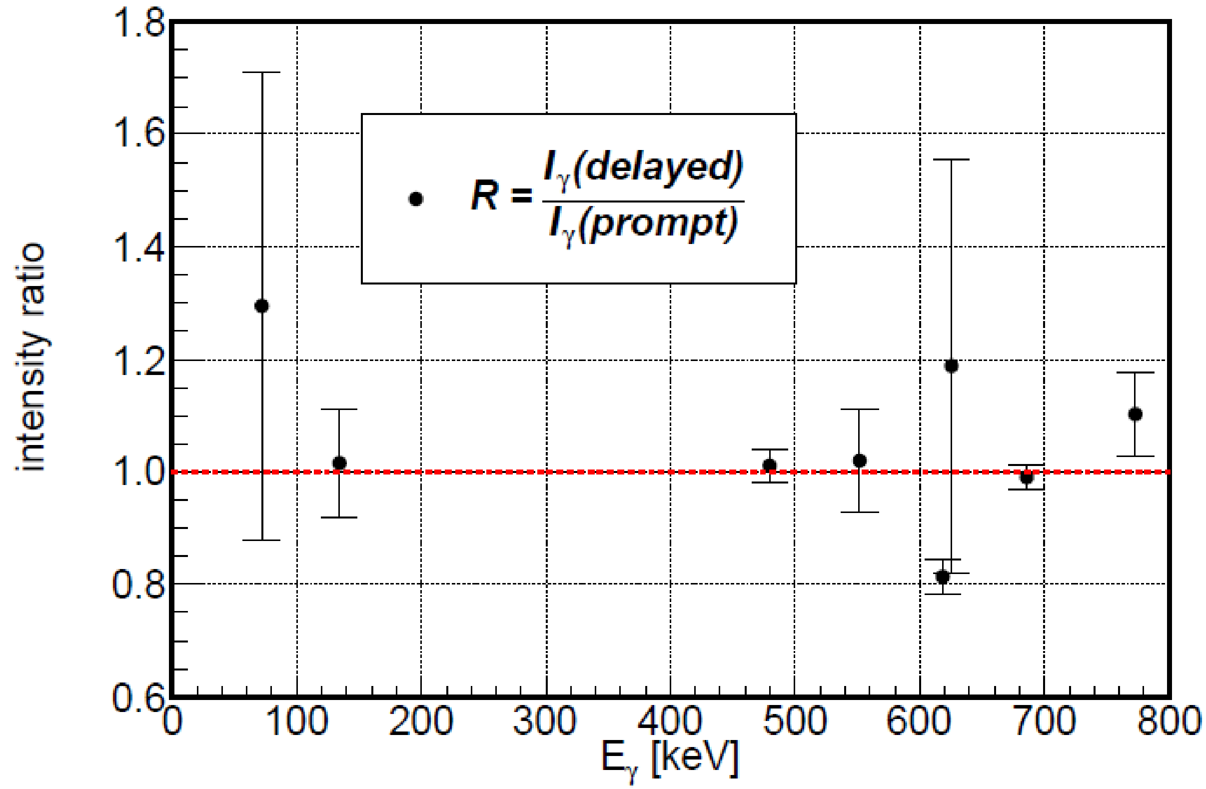
σ_0: $^{180}W(n,\gamma)$



1952 **2008** **2012**

?

P_γ measurements: $^{187}W \rightarrow {}^{187}Re + \beta^-$



E_γ [keV]	P_γ	P_γ
72.0	0.186(45)	-
134.3	0.110(11)	0.111(9)
479.5	0.288(24)	0.281(23)
551.2	0.066(5)	0.065(5)
618.0	0.076(6)	0.081(7)
625.0	0.012(1)	0.014(1)
685.7	0.350(28)	0.357(29)
773.0	0.053(5)	0.053(4)

Independent confirmation of $\sigma_0(^{186}W(n,\gamma))$ = 33.0(26) b

$$P_\gamma = \frac{\sigma_\gamma}{\theta \cdot \sigma_0}$$

P_γ: This work

P_γ: L. Szentmiklosi *et al.*, NIMA 564, 655 (2006)

Rensselaer Polytechnic Institute

- **Transmission measurements**
  - **Ti** - measured at 250m flight path, energy range 0.5-20 MeV, this improves the previous RPI data at 100m and based on EXFOR the best resolution available. JEFF 3.1 shows some energy shifts.
  - **Cu** - measured at 250m flight path, energy range 0.5-20 MeV, an energy shift was observed in some of the evaluations. Care was taken to make sure the RPI energy grid agrees with C and Fe-56.
  - ^{92,94}**Mo** – data measured at 100m flight path was presented many new resonances were observed.
- **Scattering Measurements**
  - ^{56}**Fe** – Data for neutron scattering in the energy range from 0.5-20 MeV was presented. The data has sufficient resolution to show individual resonance, the data seems to have shaper resonance structure compared to the evaluations.
  - ^{238}**U** - Neutron scattering data in the energy range from 0.5-20 MeV was presented differences between evaluations and experimental data are more evident in back angles.
- **Capture and Fission**
  - RPI is developing a system to measure fission neutron energy distributions using a gamma tag. Results for ^{252}Cf were shown for fission neutron in the energy range from 0.2-5 MeV.
- **Analysis**
  - ^{151,153}**Eu** - Thermal capture cross sections were extracted from capture and transmission measurements and show slightly higher values compared ENDF/B-7.0.
  - **Rh** - Resonance parameter analysis of capture and transmission measurements is ongoing data for the energy range of 10 eV to 100 eV was shown.
  - ^{95,96,98,100}**Mo** – preliminary resolved and unresolved data analysis was presented.
- **Thermal neutron scattering Measurements (S(α,β))**
  - Thermal scattering data measured at SNS were shown for water at room temperature for several scattering angles.
  - **H_2O** at room temp data analysis in progress
  - **CH_2** at room temp analysis in progress.

Nuclear Data Related Activity at RPI

Report to CSEWG November, 2012

Y. Danon, R. Bahran, E. Blain, A. Daskalakis, B. McDermott , S. Piela

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

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Measurements Completed This Year

- **Scattering**
  - ^{56}Fe, Neutron Scattering (7 angles), 0.5-20 MeV, 30m flight path.
- **Transmission**
  - $^{92/94}$Mo, 5-600 keV, 100m flight path
  - Ti, 0.5-20 MeV, 250m flight path
  - Cu, 0.5-20 MeV, 250m flight path

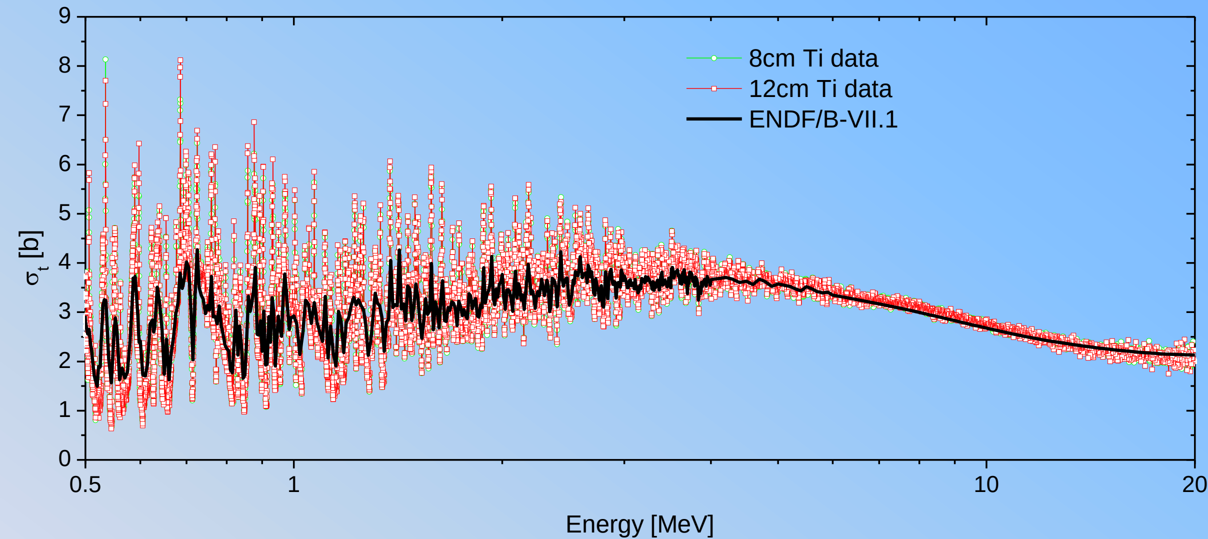
Planned Measurements

- **Scattering**
  - H_2O, Thermal Neutron scattering, develop capability
- **Transmission**
  - ^{92,94}Mo, 10 eV - 600 keV, 100m and 30m flight paths (improve statistical accuracy)
  - ^{236}U, 15m flight path, concentrate on the 5.45 eV resonance
  - Fission neutrons spectrum for ^{252}Cf and ^{235}U
- **Capture**
  - Develop capability for KeV measurments

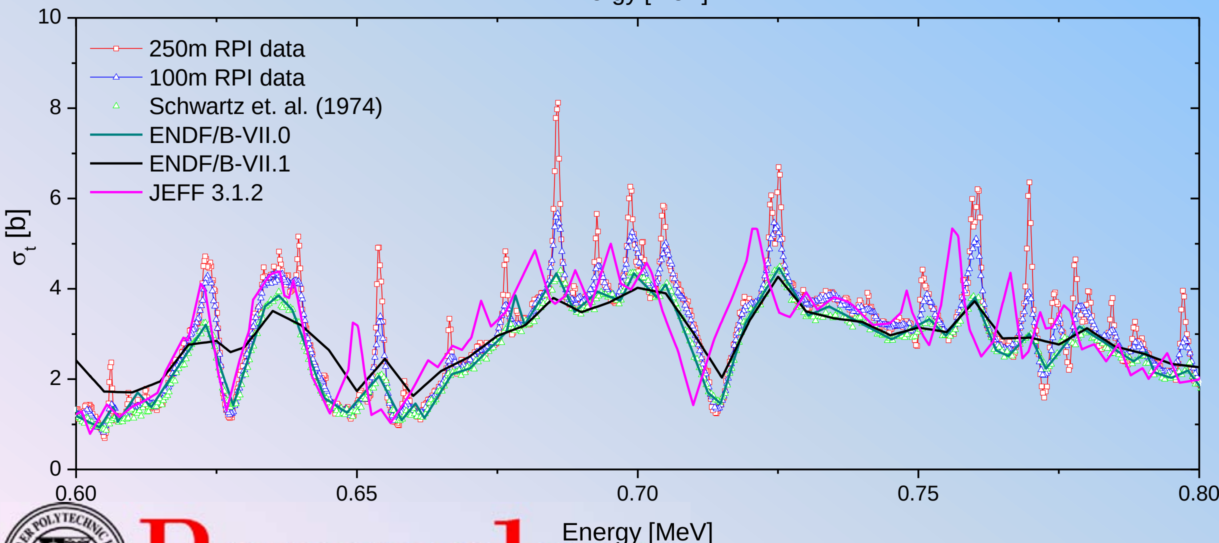
Data Analysis

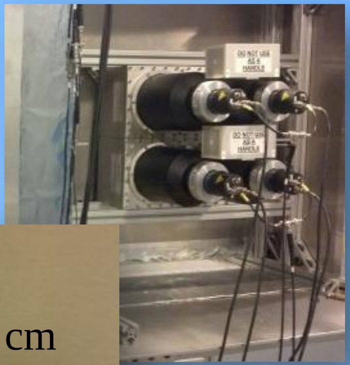
Sample	Status
Be, C	High energy (0.5-20MeV) transmission, Accepted for publication (NS&E)
Zr	High energy (0.5-20MeV) scattering, Accepted for publication (NS&E)
^{147,149}Sm (n,α)	Cross section measurements with the LSDS, Published *J.T. Thompson, T. Kelley, E. Blain, R.C. Haight, J.M. O'Donnell, Y. Danon, "Measurement of (n,α) reactions on ^{147}Sm and ^{149}Sm using a lead slowing-down spectrometer", Nuclear Instruments and Methods in Physics Research Section A, Volume 673, Pages 16-21, 1 May (2012)*
Ti, Ta, Zr, $^{92/94,95,96,98,100,nat}$Mo	High energy (0.5-20MeV) publication in preparation
^{235}U	Capture and fission in the energy range thermal to 5 keV (thesis in progress), keV data analyzed by ORNL
$^{92/94,95,96,98,100,nat}$Mo, ^{153,nat}Eu, ^{161,162,163,164}Dy ^{155,156,157,158,160}Gd,	Gd publication in preparation Resonance parameters analysis in progress (Dy, Eu)

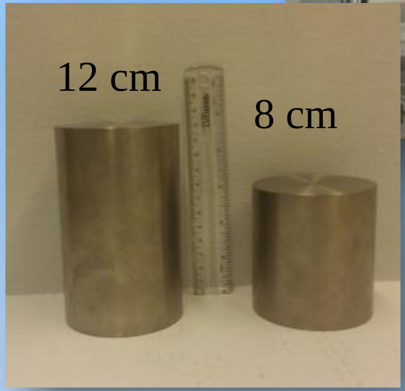
Ti Total Cross Section Measurements 0.5 – 20 MeV



- 250m flight path measurement shows structure that was not resolved in prior measurements
- JEFF 3.1.2 shows an energy shift
- ENDF/B-VII.1 lower resolution than JEFF 3.1.2 and ENDF/B-VII.0

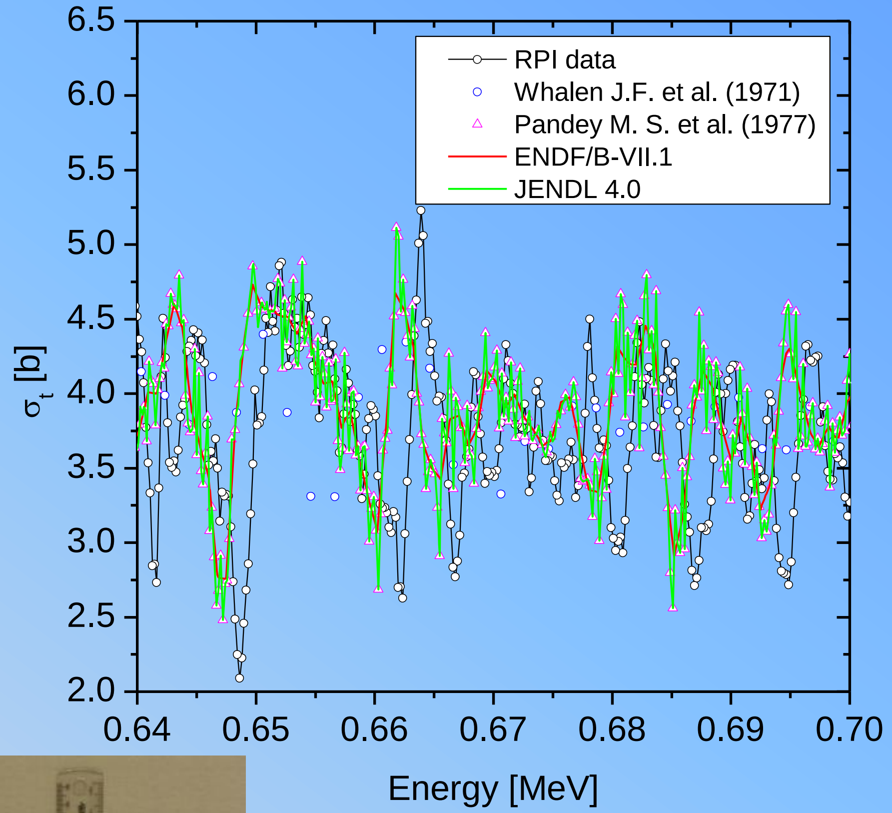


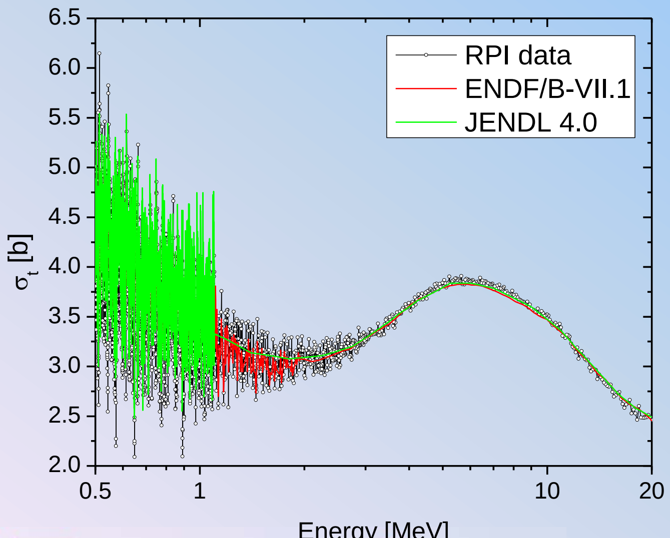


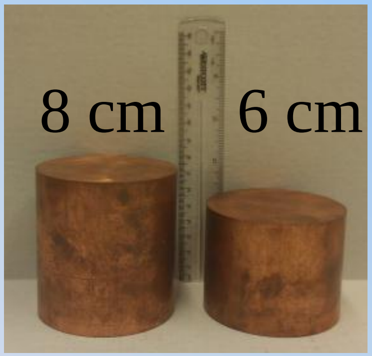


Cu Total Cross Section Measurements 0.5 – 20 MeV

- All Evaluations similar with the exception of JENDL 4.0
  - Follows the isotopic measurements by Pandey et al.
  - JENDL shows more structure below 1.1 MeV, but smoothes to average value prior to other libraries (1.1 MeV vs. 2.0 MeV)
- Shift in energy seen in evaluations







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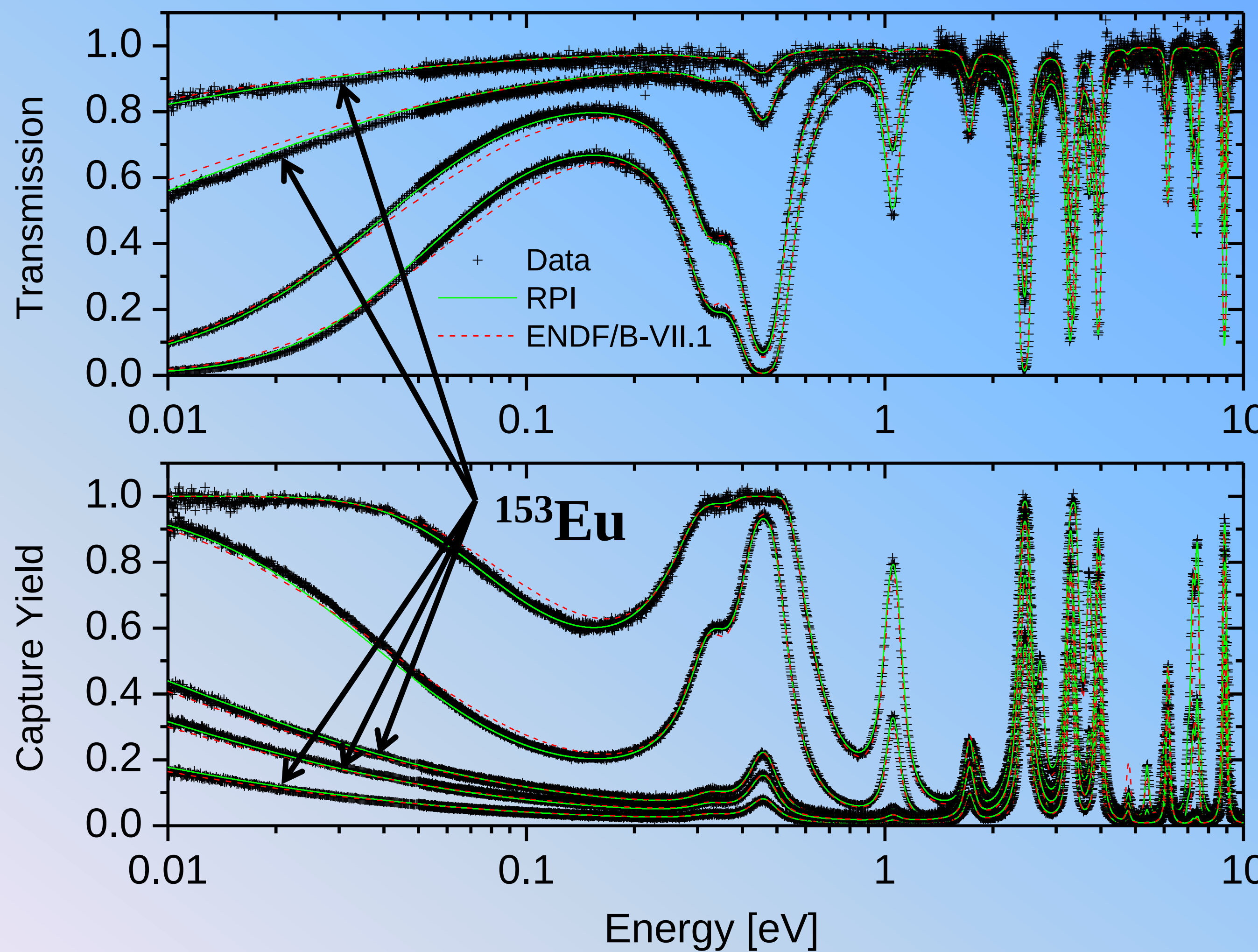
^{151,153}Eu Measurements - Samples

- Stable samples of volatile metals
- Natural and enriched metal samples
- Sample thickness details verified by X-ray imaging.*

	Natural Samples [at frac.]	Enriched [at frac.]
^{151}Eu	0.478	0.0123
^{153}Eu	0.522	0.9877

*Jeffrey A. Geuther, Robert C. Block, Brian Methe, Devin P. Barry, Gregory Leinweber, "X-ray Determination of the Thickness of Thin Metal Foils", submitted to Journal of X-Ray Science and Technology, 2012.

^{153,nat}Eu Thermal/Epithermal Region Fit



Eu Thermal Total Cross Sections (barns) from SAMMY fits

- Results in significant changes to negative energy resonances

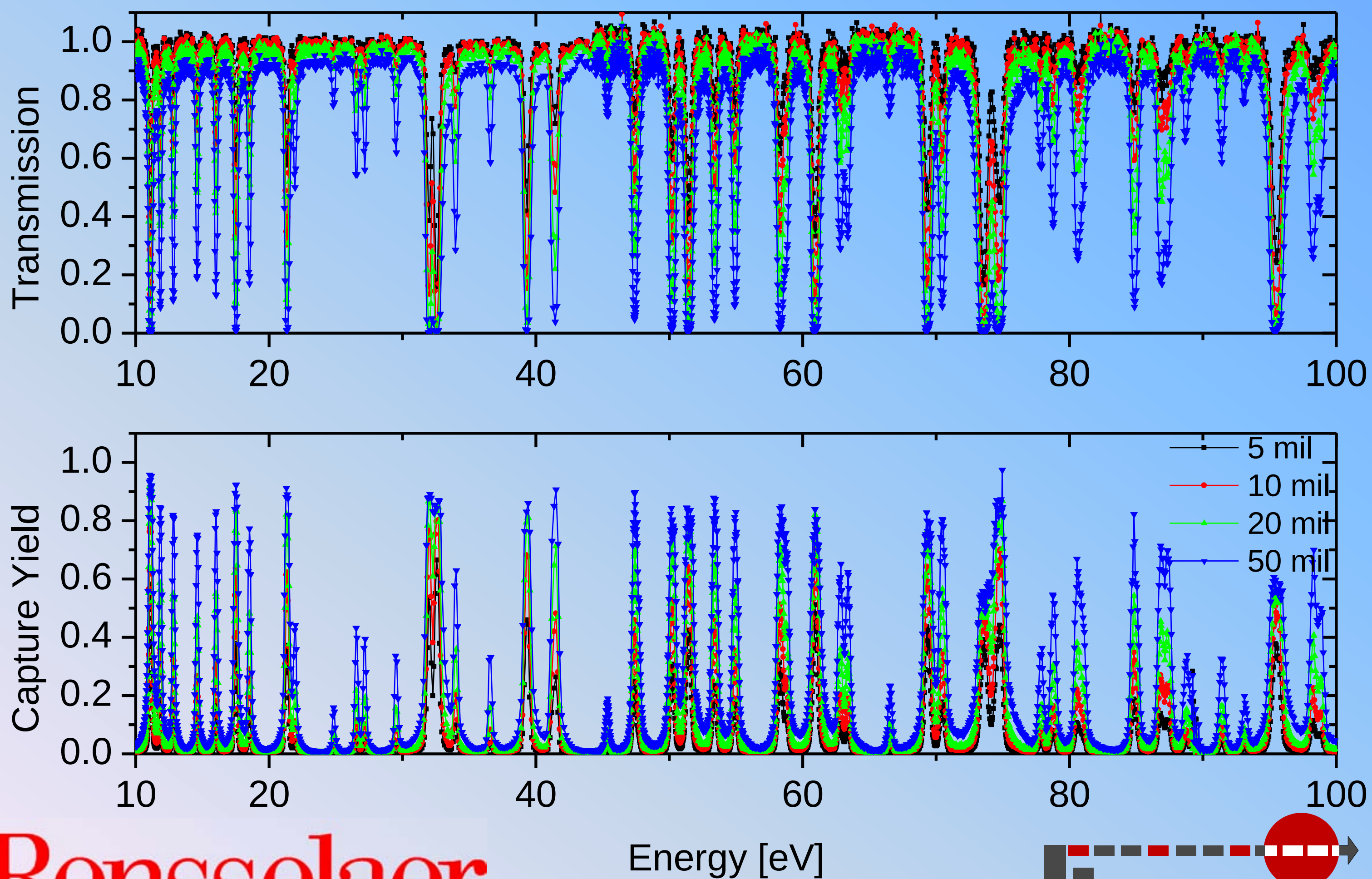
Isotope	ENDF error from atlas [b]	RPI [b]	Dean et al. Reactivity Worth [b]	Mughabghab [b]
^{151}Eu	9187±100	9700±200		
^{153}Eu	321±8	350±20	382*	358*

(Uncertainties provided at the one sigma level)

** Said Mughabghab, "Analysis of Measurements in the Unresolved Resonance Region for ENDF Evaluations", PI Nuclear Data (RND) 2011 Symposium for Criticality Safety and Reactor Applications.*

Re Epithermal Measurements

- Capture corrected for gamma attenuation (2nd densest element)
- Higher and lower energy transmission and capture data taken; analysis underway



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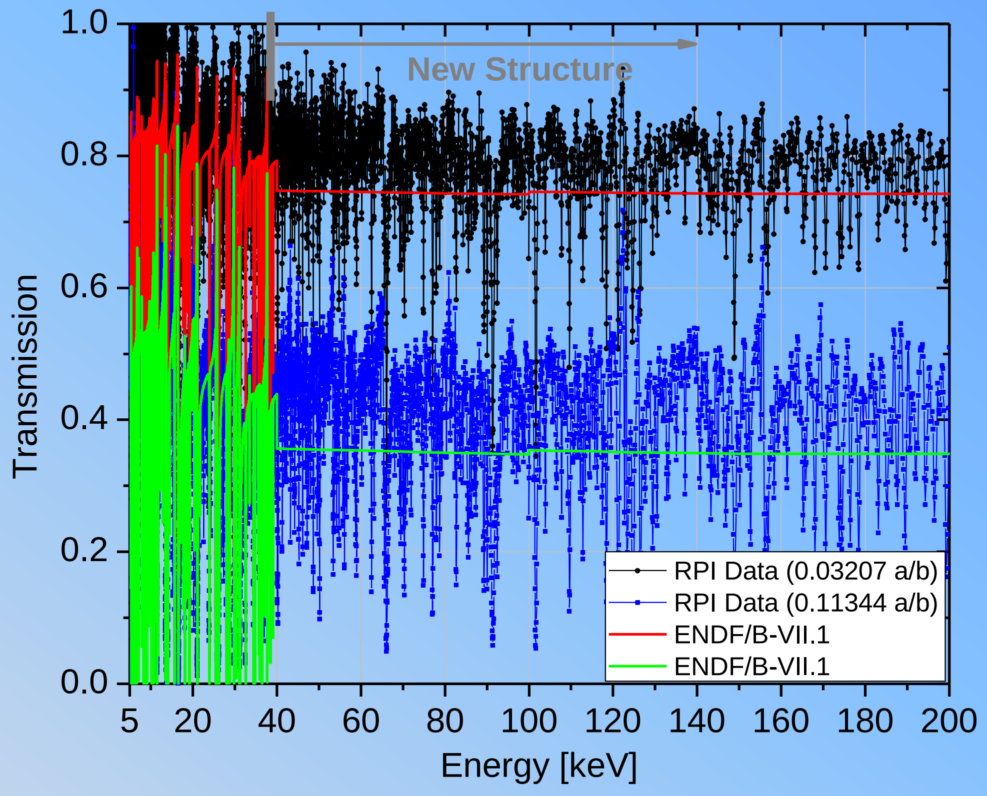
Measurements of $^{92/94}Mo$ Transmission at 100m Flight Path

- High resolution Mo transmission data was measured from 5 keV to 200 keV
- Enriched Mo samples were prepared by Bettis (75.57% ^{92}Mo, 23.77% ^{94}Mo)
- The data show (possibly resolved) structure within the current URR
- Additional experiments are planned for next year to improve statistics
- Data analysis started.



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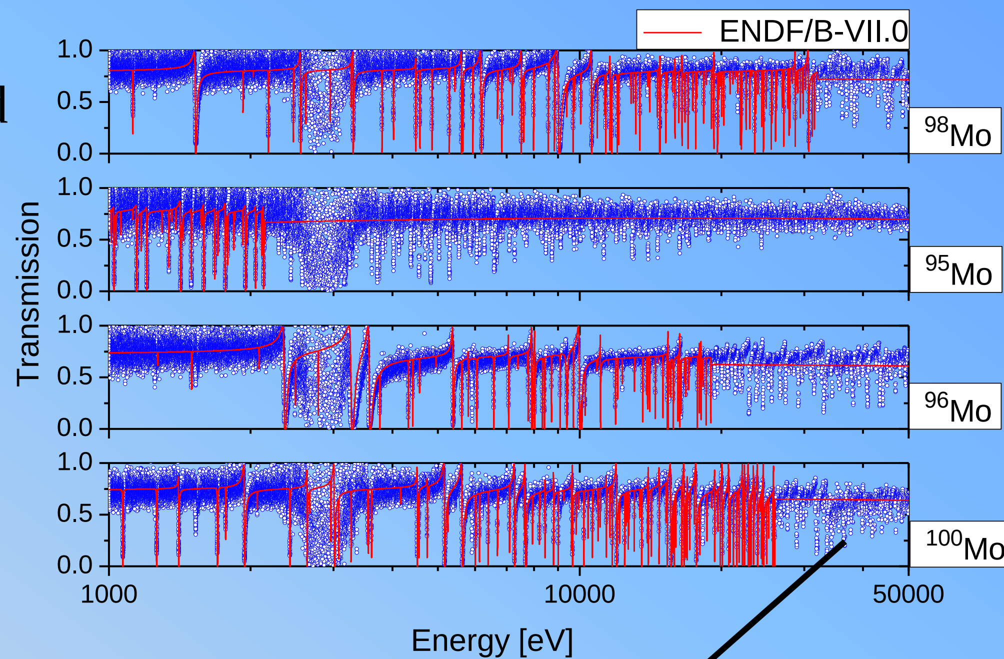
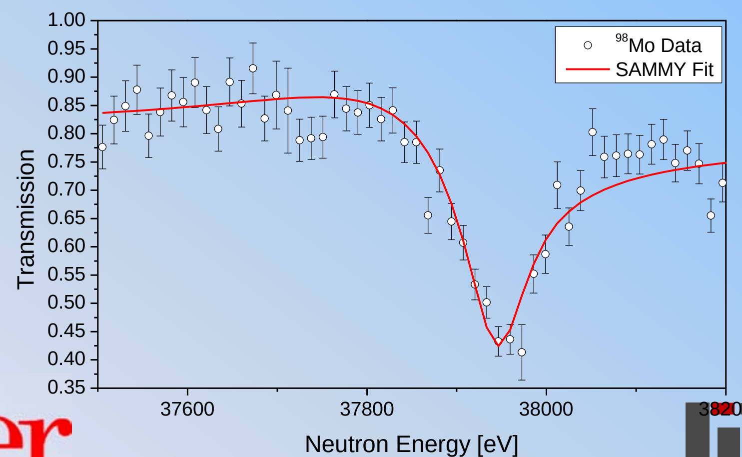
Isotopic Mo Measurements in the Energy Range 1 – 620 keV

- ^{95,96,98,100}Mo data in the resolved region shows good agreement with ENDF in the RRR.
- The new high resolution data include newly resolved resonances extending the RRR for each isotope.
- A treatment for data analysis in the URR is currently under development.





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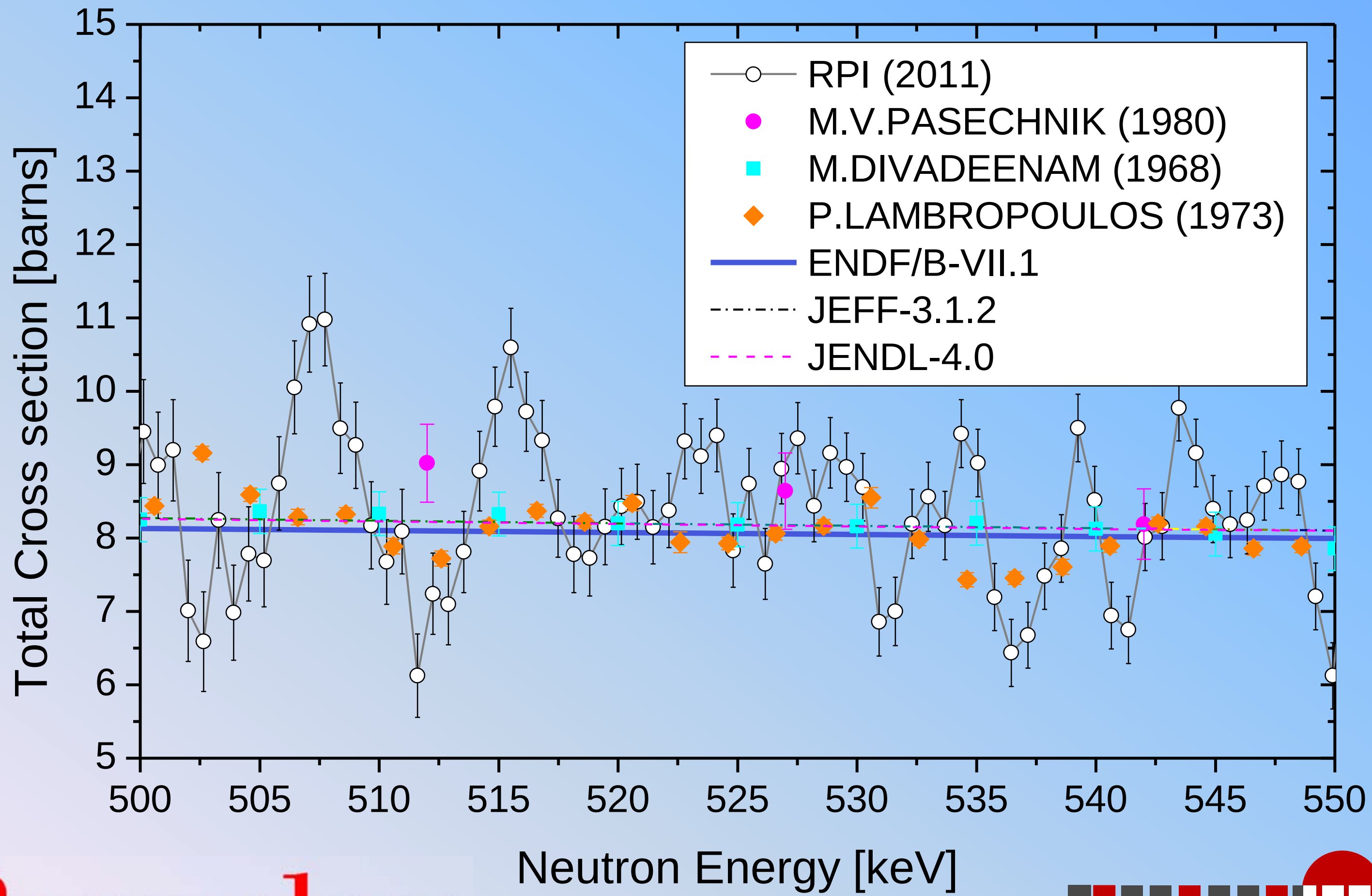
Isotopic Mo Experimental Data in the URR

- New ^{100}Mo experimental data is compared to previous data.
- Partially resolved structure can clearly be seen due in the higher resolution of the RPI experiment.



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Isotopic Mo Measurement and Evaluation in the URR

- Average resonance parameters / covariances extracted from SAMMY fit in URR.
- Comparisons were made to JENDL-4 (ENDF/B-VII.1 has average parameters only up to 100 keV and they were obtained from the JENDL-3.3).

^{100}Mo Varied Parameter	Atlas Value	SAMMY
R' (fm)	6.9 ± 0.2	6.81 ± 0.02
$S_{l=0}$	0.8 ± 0.22	←Kept
$S_{l=1}$	5.14 ± 0.71	4.66 ± 0.05
$S_{l=2}$	N/A	2.00 ± 0.01
$\Gamma_{\gamma\, l=0}$ (eV)	0.064 ± 0.004	0.064 ± 0.004
$\Gamma_{\gamma\, l=1}$ (eV)	0.093 ± 0.012	0.093 ± 0.012

^{100}Mo: $S_{l=0}$, $J^{\pi} = +^1/_2$

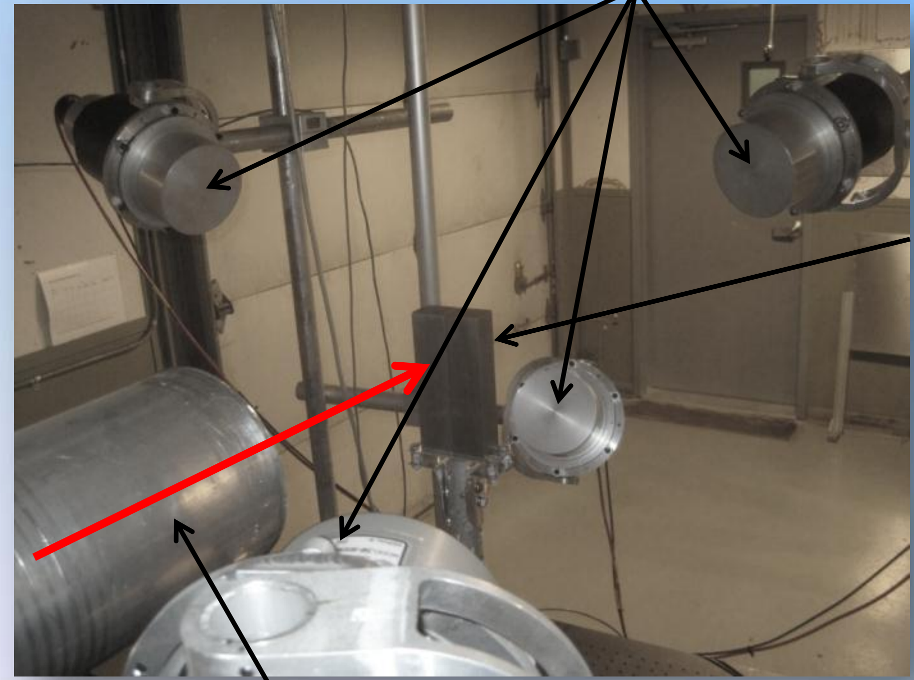
SAMMY			JENDL-4		
E (keV)	D (eV)	$g\Gamma_n^0$ (meV)	E (keV)	D (eV)	$g\Gamma_n^0$ (meV)
100	521.58	0.0417	100	617	0.039488
200	441.52	0.0353	200	435.63	0.02788
300	374.26	0.0299	300	322.16	0.020619
400	317.65	0.0254	400	247.08	0.015813
500	270	0.0216	500	195.52	0.012513

^{100}Mo: $S_{l=1}$, $J^{\pi} = +^1/_2$

SAMMY			JENDL-4		
E (keV)	D (eV)	$g\Gamma_n^0$ (meV)	E (keV)	D (eV)	$g\Gamma_n^0$ (meV)
100	521.58	0.244	100	617	0.31714
200	441.52	0.207	200	435.63	0.22391
300	374.26	0.175	300	322.16	0.16559
400	317.65	0.149	400	247.08	0.127
500	270	0.126	500	195.52	0.1005

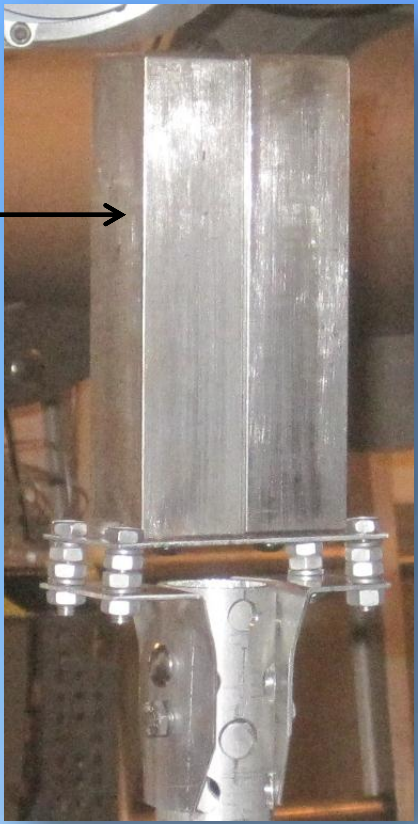
^{56}Fe Scattering Measurement - Setup

EJ-301 Liquid Scintillator Neutron Detectors



Evacuated Flight Tube

- ^{56}Fe Sample
- 99.87% metallic ^{56}Fe
- Dimensions 77.0 x 152.6 x 32.2 mm



The neutron beam size is smaller than the sample.

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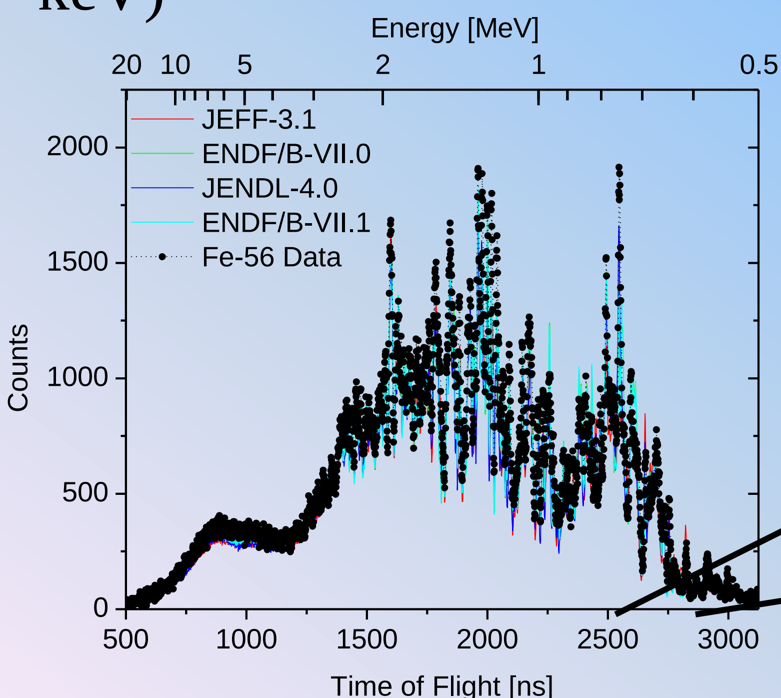
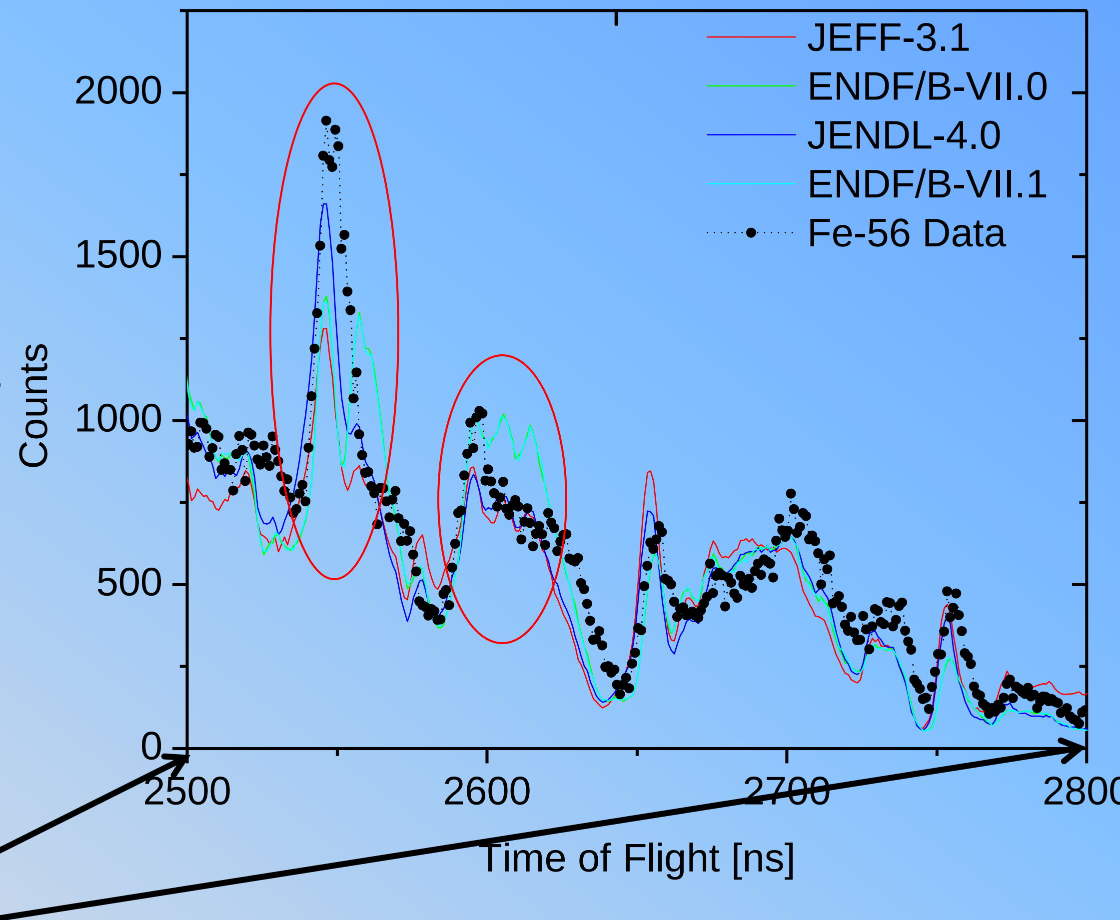
^{56}Fe Scattering Measurement – Results 155°

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





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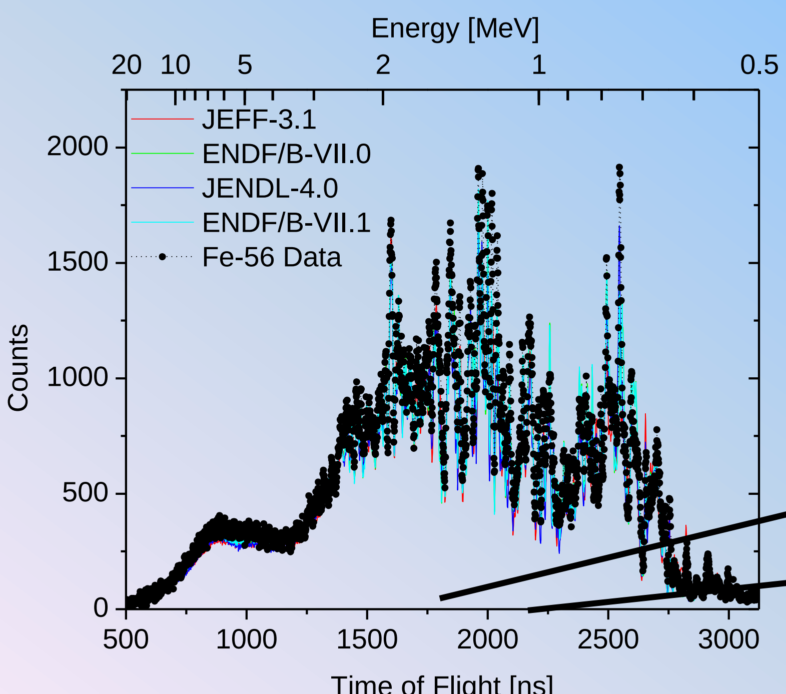
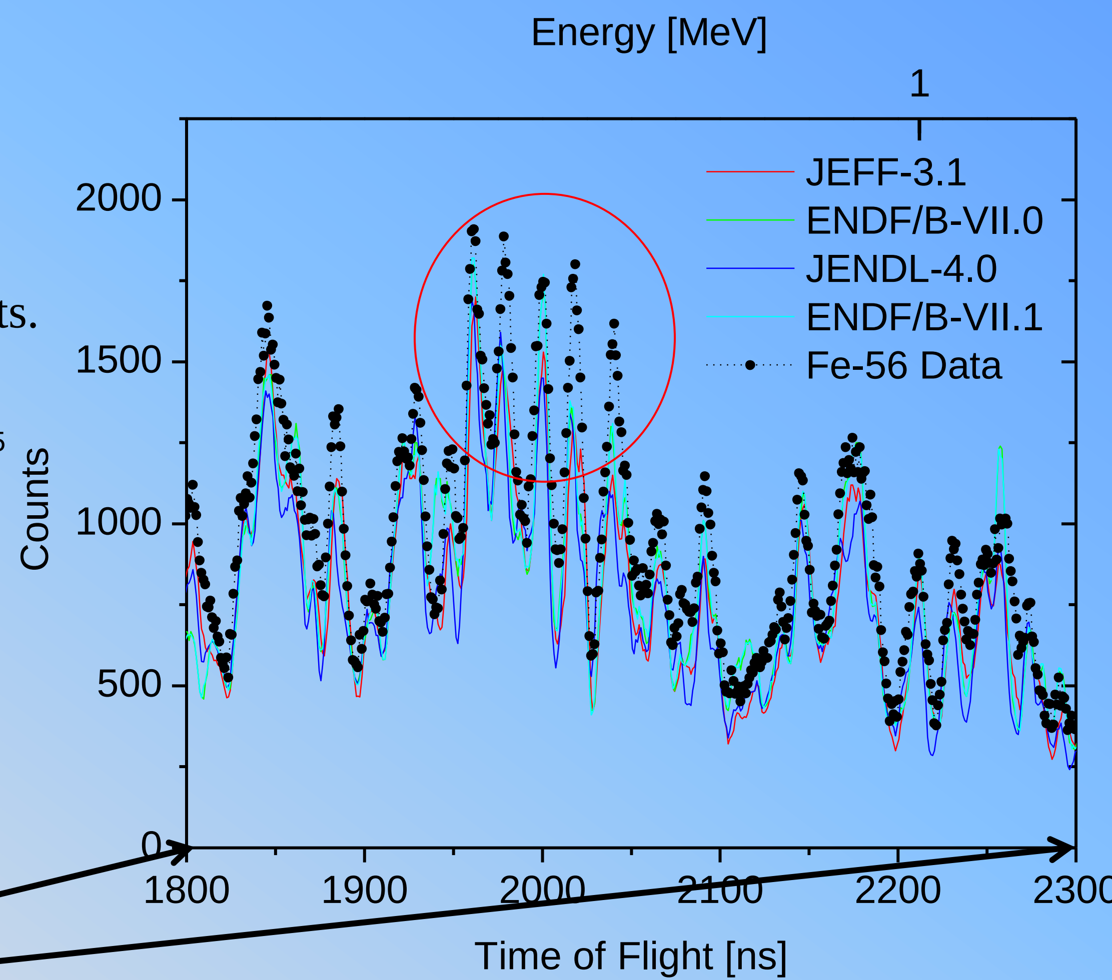
Fe-56 Scattering Measurement – Results 155°

- Above the first inelastic state (E>847 keV) there are some differences with the evaluations
- We are exploring the possibility to extract double differential cross section data from these experiments.





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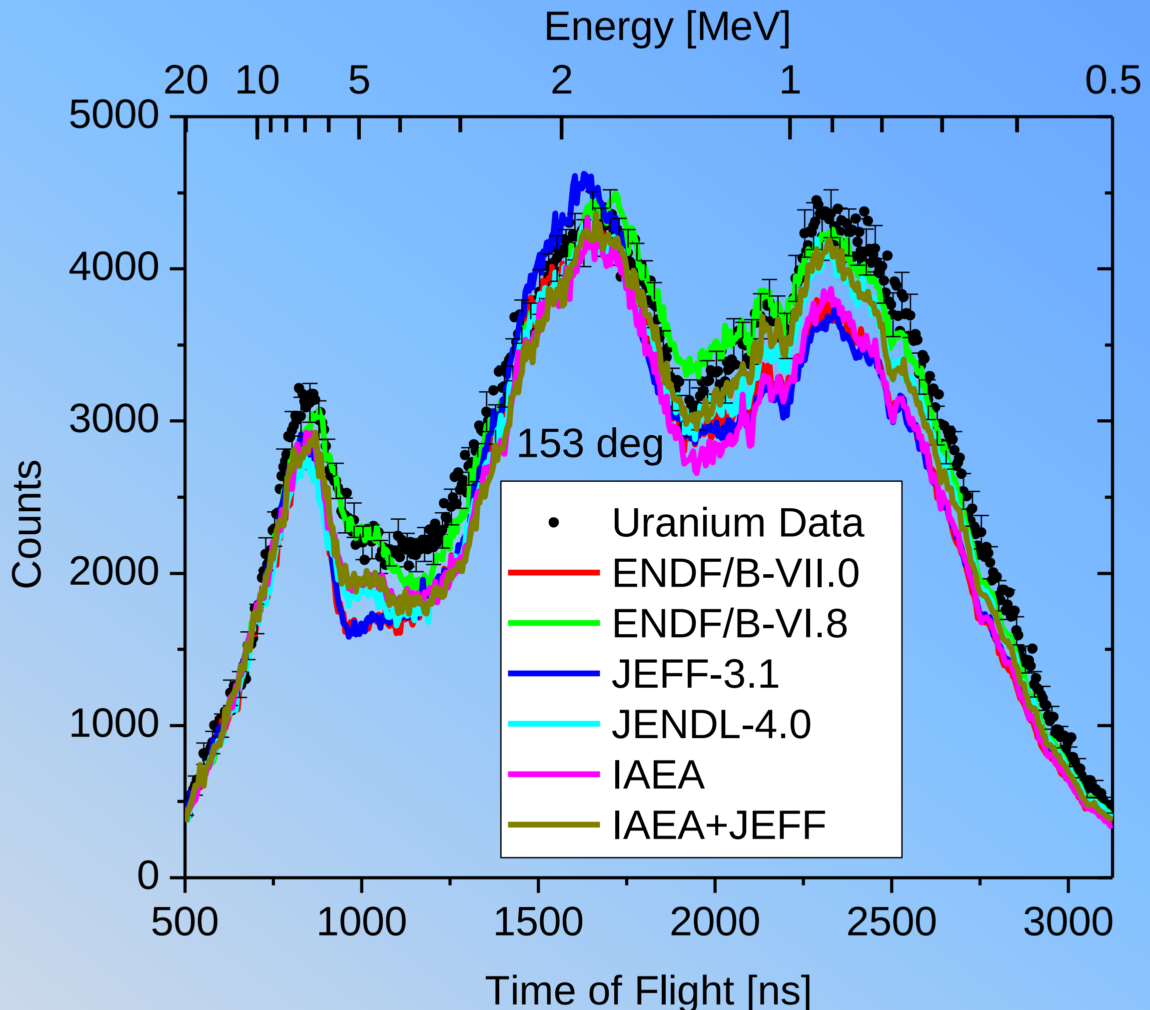
^{238}U Scattering Revisited

- Following the WINS meeting we interacted with Trkov Andrej and Roberto Capote from IAEA to help improve new ^{238}U evaluation
- The new evaluation performed well at forward angles
- At back angles the IAEA evaluations with JEFF angular distributions performed better than JEFF3.1 and ENDF/B-VII.1 but for E> 2 MeV still lower than the experimental data (ENDF/B-VI.8 performs better).



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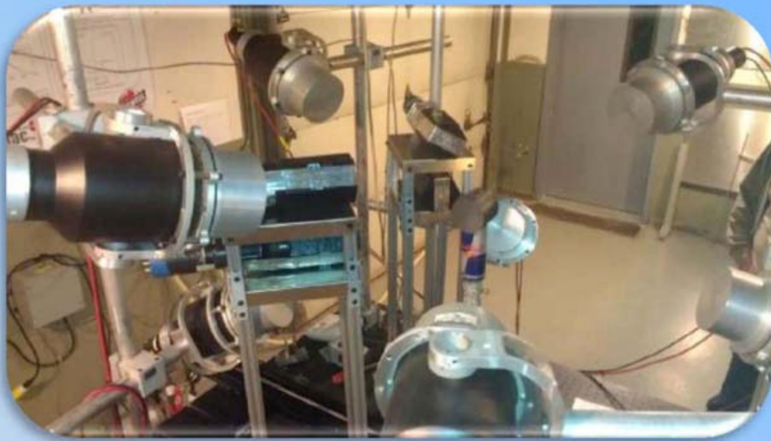

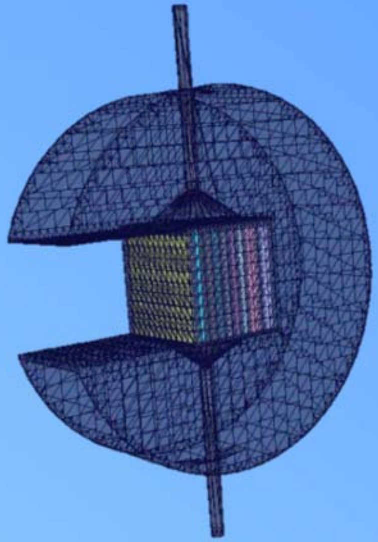

Development of New Capabilities

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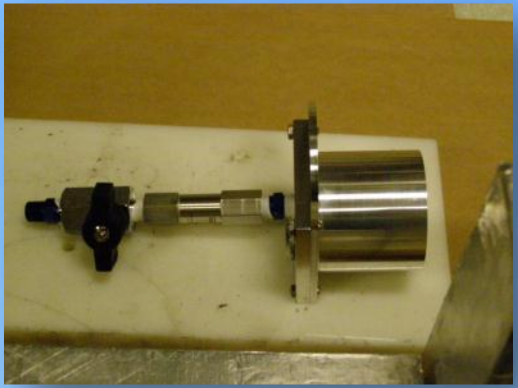
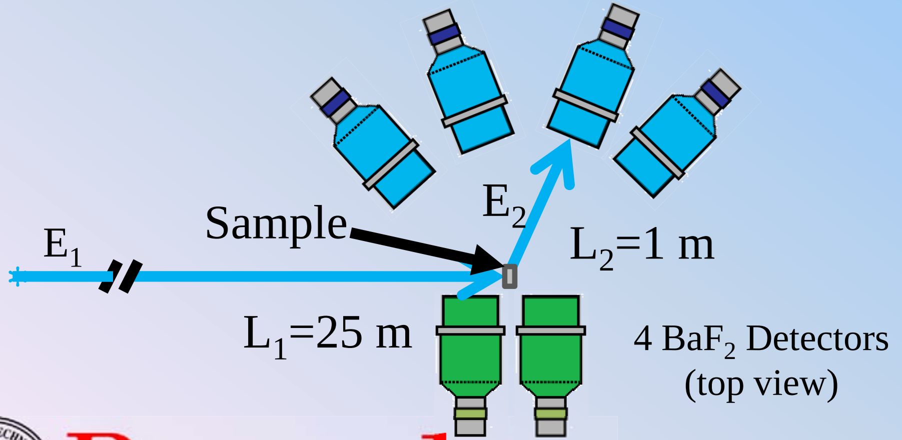
Nu-bar and Fission Spectrum Measurements (SSAA)

- A system under development for the simultaneous measurement of nu-bar and fission spectrum.
- This system utilizes a coincidence requirement on an array of gamma detectors to tag fission events.
- This allows for much larger samples to be used than with conventional fission chambers
- Initial tests with ^{252}Cf fission are ongoing

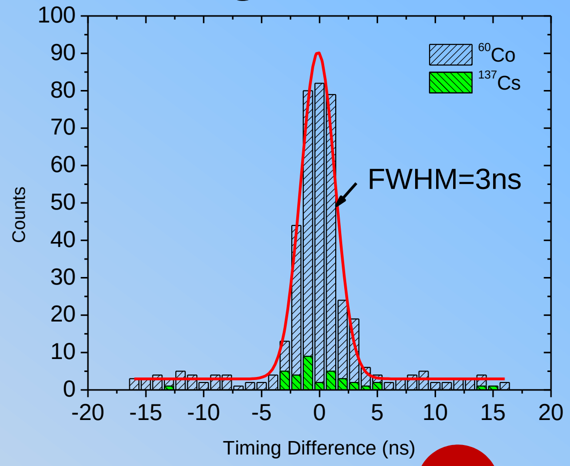
RPI designed and fabricated ^{252}Cf (~18ng) fission chamber



Experimental Setup



Timing Resolution



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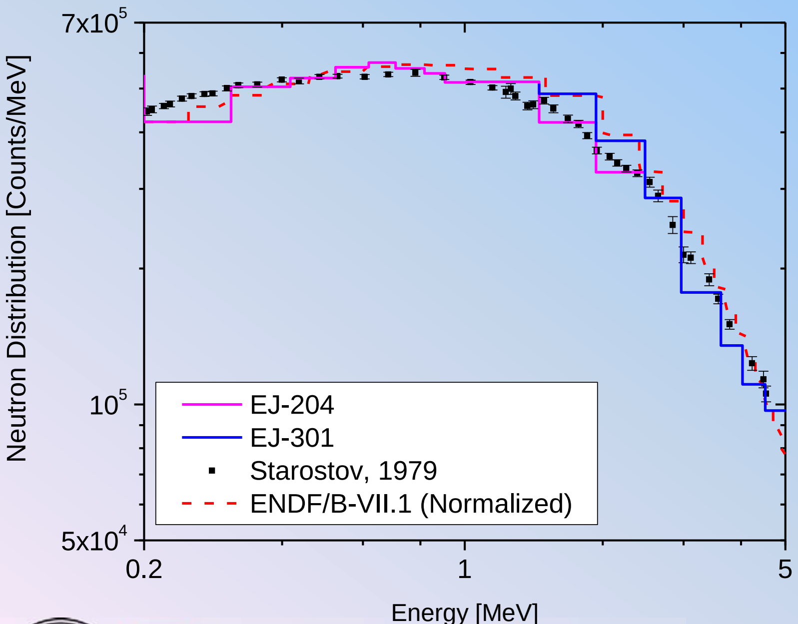
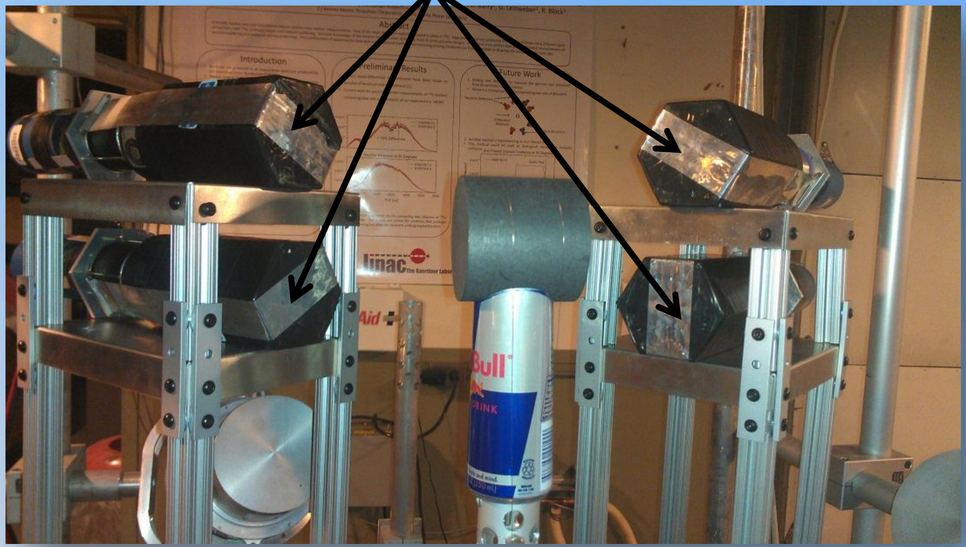
Measurement of ^{252}Cf Prompt Fission Neutron Spectrum

- A preliminary step ^{252}Cf was measured using the fission chamber as a fission tag.
- This kind of data will be compared with measurements using the gamma tag.
- EJ-301 measurements agree with ENDF/B-VII.1 from 5 MeV to 1 MeV while EJ-204 measurements extend the agreement down to 0.2 MeV

^{252}Cf Prompt fission neutron spectrum

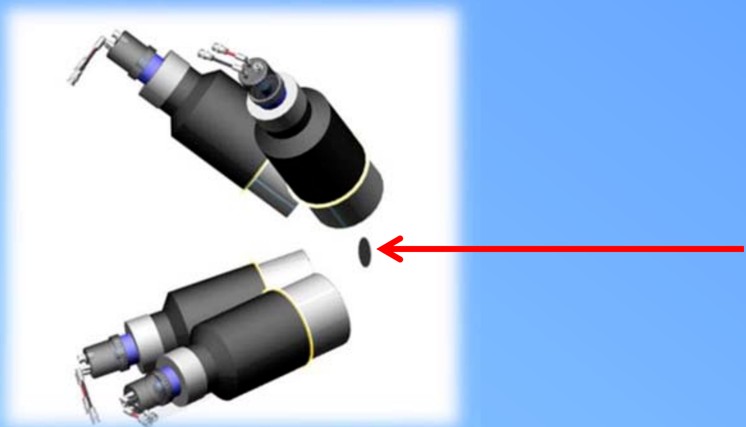


BaF_2 detector array



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

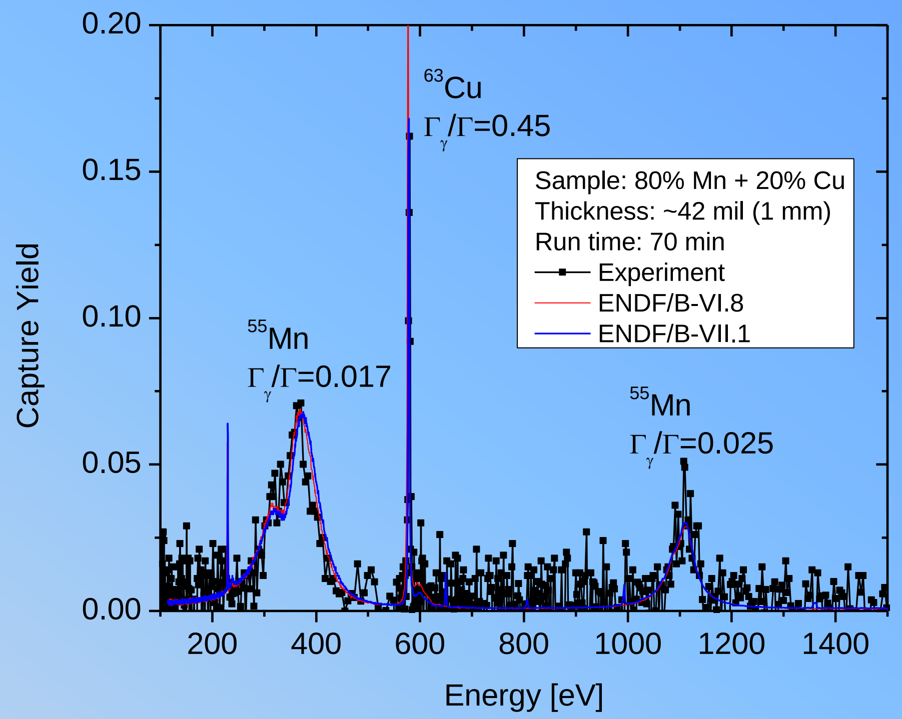


CAD model of the detector array and sample

A picture of the prototype detector

Mid-Energy Capture Detector
First Test

- Capture measurements performed on Mn/Cu sample using existing analog TOF setup
- Experimental results show consistency with ENDF/B-VI.8 and VII.1 data libraries
- Low contribution from scattered neutrons is apparent
- Future experiments will incorporate a digital DAQ system



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Summary

- **Publications in 2012**
  - ^{147,149}Sm (n,α) cross section measurements with the LSDS (Published, Nuc. Inst Meth. A)
  - Eu sample x-ray characterization (submitted to Journal of X-Ray Science and Technology)
  - High energy scattering from Zr (accepted to NS&E)
  - High energy transmission for Be and C (accepted to NS&E Nov. 2012)
- **Analysis in progress**
  - Ti, Ta, Zr and $^{92/94,95,96,98,100,nat}$Mo high energy (0.5-20 MeV) transmission
  - Eu, ^{153}Eu, ^{161,162,163,164}Dy, ^{155,156,157,158,160}Gd, ^{236}U– Resonance parameter analysis
  - $^{92/94,95,96,98,100}$Mo resonance region (10 eV - 600 keV) transmission measurements
  - ^{238}U, ^{56}Fe neutron scattering
- **Planned measurements**
  - $^{92/94}$Mo, Transmission, 10 eV - 600 keV, 100m and 30m flight paths
  - ^{236}U, Transmission, 15m flight path, concentrate on the 5.45 eV resonance
  - Fission neutron spectra and nubar from ^{252}Cf and ^{235}U
  - H_2O, Thermal neutron scattering
  - Continue development of mid energy capture detector

National Institute of Standards

- Review of standards:
- H(n,n)
  - Several regions that need more work (some is in progress) were highlighted:
    - small angles in the CMS near 15 MeV, at intermediate and high energies where data are sparse and typically not available for a large angular range
    - there is the lingering concern for back angles in the hundred + MeV region..
- ^{6}Li(n,t) ^{10}B(n,α)
  - The ^{10}B standards need additional work with emphasis on extending the energy range to higher energies
  - The NIST setup for the ^{6}Li(n,t) will be used for the ^{10}B(n,α) reaction.
- Fission
  - ^{235}U(n,f), ^{238}U(n,f) and ^{239}Pu(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.

NIST Measurements and Standards Related Work at Other Facilities

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

Presented at
The CSEWG Meeting
BNL
November 8, 2012

THE NEUTRON CROSS SECTION STANDARDS

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

H(n,n)H 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.

•To obtain the accuracy needed for this work, the neutron detector efficiency must be determined accurately. At neutron energies below about 9 MeV ^{252}Cf spectra are being used.

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

•Plans are being made to make hydrogen angular distribution measurements using a Time Projection Chamber which will provide higher counting rates than are possible with the other methods.

(collaboration of Ohio University and LANL)

Hydrogen Angular Distribution at High Neutron Energies

•The most recent measurements of the hydrogen angular distribution in the 100 MeV energy region are not consistent at back angles. Larger cross sections were measured at Uppsala (96 and 162 MeV) and PSI (many energies from about 280 MeV to 580 MeV), both using pseudo-monoenergetic sources. The work at Indiana University at 194 MeV, using neutrons tagged by detection of the associated protons from the D(p,n)2p reaction, indicate lower cross sections and they agree with PWA calculations.

•The Uppsala group suggest that the Indiana experiment may be preferred due to the smaller total uncertainties.

•Though there is an indication that the discrepancy may be resolved at about 160 MeV - 200 MeV, the PSI data which cover a very large energy range (200-580 MeV) still stand as measured. Further work should be done to understand this problem.

•Also more work should be done on angular distribution measurements in the intermediate energy region from about 30 MeV to 150 MeV. Little data are now available and the angular interval measured is very limited.

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

•Progress continues on an experiment to measure the n-^{3}H coherent scattering length. This measurement is complementary to the n-^{3}He 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 $^{3}He(n,p)$ cross section.

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

^{6}Li(n,t) Measurements

•A measurement has been completed of the ^{6}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}Li(n,t) cross section measurement is the mass uncertainty of the ^{6}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)

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

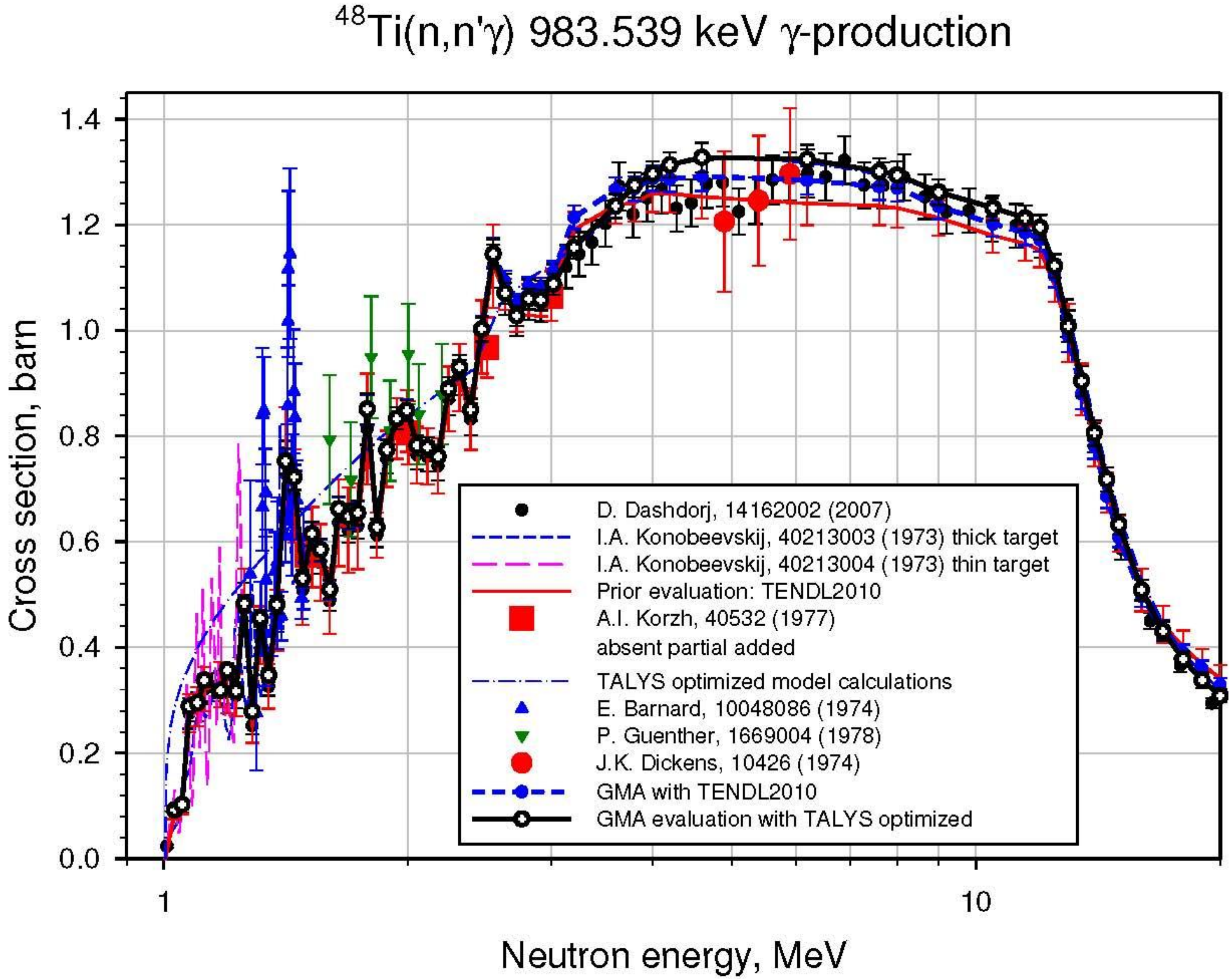
• Ullmann et al. made measurements of the $^{238}U(n,\gamma)$ cross sections using the DANCE (160 BaF_2 crystals) detector at LANSCE. The neutron beam was monitored with a ^{235}U fission chamber, a BF_3 counter, a ^{6}Li F detector and a ^{3}He detector. Small ^{238}U samples could be used due to the high neutron intensity at DANCE. This reduces the uncertainty due to multiple scattering. Though the data could be made absolute, they 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 is presently working on the normalization of that data and expects results by the end of the year.

Recent Activities Related to the Data Development Project (cont.)

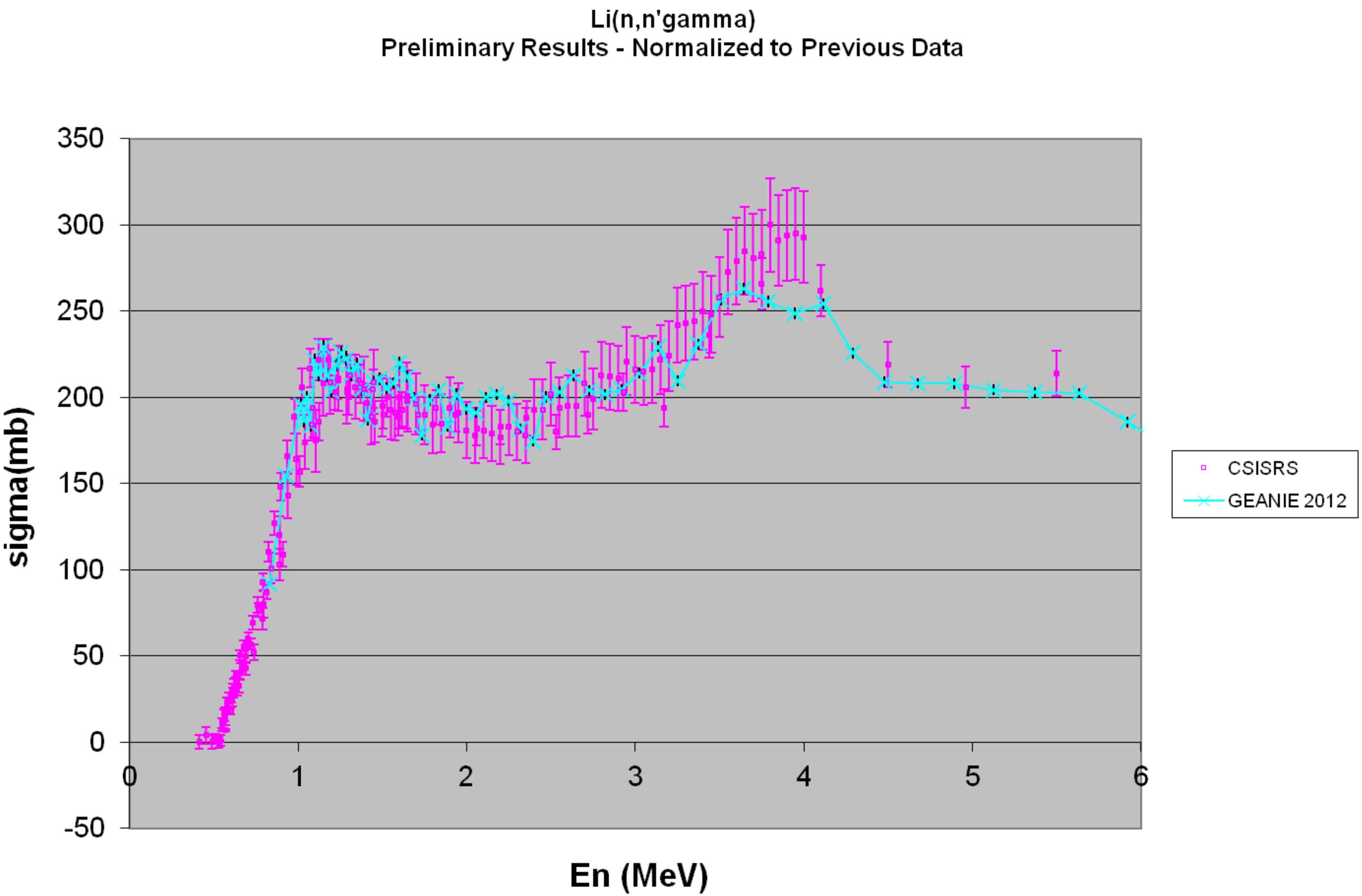
- Neutron spectra
    - No new measurements have been made of the ^{252}Cf spontaneous fission neutron spectrum. There are new measurements of the $^{235}U(n_{th},f)$ neutron spectrum made by Kornilov (Hambsch) et al. and Vorobyev et al.

Recent Activities Related to the Data Development Project (cont.)

- Reference cross sections for measurements of prompt gamma-ray production cross sections. (cont.)
  - Many nuclides and reactions were considered
    - ^{nat}Ti with large yields of two gamma-lines, 984 keV from ^{48}Ti(n,n'γ) and 160 keV from ^{48}Ti(n,2nγ) and ^{47}Ti(n,n'γ) 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.
  - Li(n,n'γ) 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



$^{48}Ti(n,n'\gamma)$ 983.539 keV γ-production
Cross section, barn
Neutron energy, MeV
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
10
D. Dashdorj, 14162002 (2007)
I.A. Konobeevskij, 40213003 (1973) thick target
I.A. Konobeevskij, 40213004 (1973) thin target
Prior evaluation: TENDL2010
A.I. Korzh, 40532 (1977)
absent partial added
TALYS optimized model calculations
E. Barnard, 10048086 (1974)
P. Guenther, 1669004 (1978)
J.K. Dickens, 10426 (1974)
GMA with TENDL2010
GMA evaluation with TALYS optimized



National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

Conclusions

•Recent experimental activity has improved the quality of the standards database. In most cases the data are in reasonable agreement with the evaluation. Areas of concern are:

- •H(n,n) at small angles in the CMS near 15 MeV
- •H(n,n) at intermediate and high energies where data are sparse and typically not available for a large angular range.
- •Both ^{6}Li(n,t) and the ^{10}B standards need additional work as the emphasis is on extending the energy range to higher energies
- •Additional work should be done in the high energy region on the ^{235}U(n,f), ^{238}U(n,f) and ^{239}Pu(n,f) cross sections to support of the needs for better standards in that energy region .
- •More work should be done on prompt gamma-ray reference cross sections and the gold capture cross section at low energies.

• The standards should be at the forefront, producing high accuracy cross sections including energy regions that may shortly require improved standards. It is short sighted to not have quality standards whenever they may be needed.