The Nuclear Data Program at Rensselaer

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Collaboration

- **Rensselaer Polytechnic Institute, Troy, NY, USA**
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  - PhD. Students:
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- **Bechtel Marine Propulsion Corporation, Knolls Atomic Power Laboratory**
  - Dr. G. Leinweber
  - Dr. D.P Barry
  - Dr. R.C Block
  - J. Hoole
Outline

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

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

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

- $\sim 4 \times 10^{13}$ neutrons/sec
- 1-500 Hz
- 6-5000 ns pulse width
Neutron Producing Targets

“Bare Bounce Epithermal Target”

“Enhanced Thermal Target”
Detectors

Capture/multiplicity
25m

Transmission
25m - 30m

Scattering
30m

250m

100m

linac
The Gaerttner Laboratory
Current Activity

- **Time of flight measurements**
  - Resonance Region
    - Capture (0.01 eV – 2 keV)
    - Transmission (0.001 eV – 100 KeV)
    - Capture to fission ratio (alpha)
  - High energy (0.4-20 MeV)
    - Scattering (30 m flight path)
    - Transmission (100 m and 250 m flight path)
    - Fission spectra and nubar
  - High accuracy total cross section measurements using filtered beams
  - Resonance scattering

- **Lead Slowdown Spectrometer**
  - Simultaneous measurement of fission cross sections and fission fragment mass and energy distributions using the RPI lead slowing down spectrometer
  - Measurements of energy dependent \((n,p)\) and \((n,\alpha)\) cross sections of nanogram quantities of short-lived isotopes. (collaboration with LANL).
Resonance Region Detectors

Li-Glass Detector at 25m

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

Sample

$\sim$ 20 liter of NaI(Tl)
Transmission Experiment

Two Experiments:

1. Sample Out
   Neutron Beam → Sample → Li-Glass Neutron Detector

2. Sample In
   Neutron Beam → Sample → Li-Glass Neutron Detector

\[ T = \frac{C_{\text{Sample In}}}{C_{\text{Sample Out}}} = \exp(-N\sigma_t) \]

- \( N \) – Number density [atoms/barn]
- \( \sigma_t \) – Total cross section
Capture Experiments

The capture Yield:

\[ \text{Counts} = \phi Y \eta \]

\[ Y = \left(1 - \exp(-N\sigma_t)\right) \frac{\sigma_y}{\sigma_t} + Y_{ms} \]

\( \phi \) – neutron flux
\( \eta \) – detection efficiency
Resonance Cross Section Measurements and Data Analysis

Experiment

Data Reduction

Data Analysis

\[ T_i = \frac{R_i^{\text{sample}} - k_i^{\text{sample}} B(t_i)}{R_i^{\text{open}} - k_i^{\text{open}} B(t_i)} \]

\[ Y_i = \frac{R_i^{\text{sample}} - R_i^{\text{bkg}}}{\phi_i} \eta \]
Elemental Molybdenum

Elemental Molybdenum 120 eV - 145 eV

Transmission

- 200-mil Mo
- 100-mil Mo
- 50-mil Mo
- 25-mil Mo
- 10-mil Mo
- 5-mil

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Capture Yield

- 20-mil Mo
- 10-mil Mo
- 5-mil Mo
- 2-mil Mo

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Energy [eV]

- SAMMY Fit
- ENDF/B-VII.0 200-mil

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- SAMMY calc
- ENDF/B-VII.0 20-mil
New Gd Resonances

**Graphs:**

- **Capture Yield**
  - Data points for different thicknesses: 0.051-mm, 0.127-mm, 2.54-mm, 0.508-mm, 0.889-mm, 1.27-mm, 2.54-mm, 5.08-mm, and 1.02-cm.
  - Fits: SAMMY fit and ENDF.

- **Transmission**
  - Data points for different thicknesses: 0.051-mm, 0.127-mm, 2.54-mm, 0.508-mm, 0.889-mm, 1.27-mm, 2.54-mm, 5.08-mm, and 1.02-cm.
  - Fits: SAMMY fit and ENDF.

**Axes:**

- **X-axis:** Energy [eV]
- **Y-axis:**
  - **Capture Yield**
  - **Transmission**
$^{155,157}$Gd Thermal Region - Separated Isotopes

- **Capture Yield**
  - LX-4 $^{155}$Gd
  - LX-9 $^{155}$Gd
  - LX-10 $^{157}$Gd
  - LX-11 $^{157}$Gd
  - SAMMY fit

- **Transmission**
  - LX-2 $^{155}$Gd
  - LX-4b $^{155}$Gd
  - LX-5 $^{157}$Gd
  - LX-7 $^{157}$Gd
  - 0.025-mm metal
  - 0.051-mm metal
  - SAMMY fit

- **Energy [eV]**
  - 0.002 to 0.1
  - 0.0 to 1

- **Transmission**
  - 0.02 to 0.05

- **Capture Yield**
  - 0.02 to 1.0

- **Energy [eV]**
  - 0.02 to 0.05

**Legend**
- RPI
- ENDF
Many new resonances observed

Yeong-Rok Kang, Tae-TK Ro, Taofeng Wang, Sung-shul Yang, Manwoo Lee, Guinyun Kim, Jong-Hwan Lee, Robert Block, Devin Barry and Yaron Danon, “Neutron Capture Measurements and Parameters of Gadolinium”, International Conference on Nuclear Data for Science and Technology (ND2010), Korea, 26-30 April, 2010
The transmission and capture data are in very good agreement.

The data is in good agreement with ENDF/B-VI.8 elemental but not with the isotopic ENDF/B-VI.8 and ENDF/B-VII.0.

Surprisingly there are not many measurements of the thermal value.
Thermal Total Cross Section of Natural Cd - II

- RPI-Transmission 2 mil sample
- RPI-Transmission 4 mil sample
- RPI-Transmission 20 mil
- RPI-Capture 2 mil sample
- RPI-Capture 4 mil sample
- ENDF/B-6.8 from isotopes
- ENDF/B-7.0 from isotopes
- ENDF/B-6.8 Elemental

~5% difference in 0.0253 eV !!!
Eu Transmission compared to ENDF/B-7.0

$^{153}$Eu

Elemental Eu
High Resolution Transmission Detector

- Modular Li-Glass detector at 100 m flight path
  - Extends our capabilities to the unresolved resonance region
  - Qualification measurements in progress.
\( ^{235}\text{U} \) Alpha Measurements

- Place a \(^{235}\text{U}\) sample in the multiplicity detector

- Measurements with \(^{235}\text{U}\) samples
  - Use the multiplicity information
  - Use data above and below neutron binding energy
Simultaneous Measurement of the Fission And Capture Cross Section of $^{235}\text{U}$
Resonance Scattering Experiment

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

- Blank
- Sample
- Moderator
- Ta Target
- e⁻ beam line
Measured Data

- Thick Sample time-of-flight spectrum forwards scattering

![Graph showing measured data with energy levels and time-of-flight (TOF) values.](image)
Results - $^{238}$U Scattering

**Thick Sample**

**BACK**

- Experiment
- MCNP (Unchanged)
- MCNP (Modified)
- MCNP+S ($\alpha, \beta$)
- Geant 4

Sample thickness = 1/8"

$E_0 = 36.68$ eV

Counts vs. Scattered Neutron Energy [eV]

**FRONT**

- RPI Experiment
- MCNP (unchanged)
- MCNP (modified)
- MCNP+S ($\alpha, \beta$)

Sample thickness = 1/8"

$E_0 = 36.68$ eV

Counts vs. Scattered Neutron Energy [eV]

**Thin Sample**

**BACK**

- Experiment
- MCNP (Modified)
- MCNP+S ($\alpha, \beta$)

Sample thickness ~ 1/16"

$E_0 = 36.68$ eV

Counts vs. Scattered Neutron Energy [eV]

**FRONT**

- Experiment
- MCNP (Modified)
- MCNP+S ($\alpha, \beta$)

Sample thickness = 1/16"

$E_0 = 36.68$ eV

Counts vs. Scattered Neutron Energy [eV]
Other Resonances (Back Scattering)

\[ \frac{\Gamma_n}{\Gamma} = 0.31 \]

Sample thickness = 1/8"

20.872 eV Resonance

High Energy Transmission Experimental Setup

Graphite Samples

Nominal thickness in cm

33
13
7
5
Background Determination

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

Transmission vs. Neutron Energy [MeV]

- Data - 7 cm
- Data - 13 cm
- Data - 33 cm
- ENDF/B-7.0 - 7 cm
- ENDF/B-7.0 - 13 cm
- ENDF/B-7.0 - 33 cm
Results – Carbon Total Cross Section

Cross Section (b)

Energy (MeV)

7 cm
13 cm
ENDF/B-7.0
Beryllium Transmission

Energy [eV]

Transmission

Be 2 cm
Be 4 cm
Be 8 cm
ENDF/B-VII.0
JENDL3.3

Beryllium samples
Sample thickness is given in cm

Reconfigured the detector with two units to reduce background

Beryllium Total Cross Section (Low Energy)

Cross Section [barn] vs. Energy [MeV]

- 2 cm sample
- 4 cm sample
- Filtered Beam experiment
- ENDF/B-VI.8
- ENDF/B-VII.0
- JEND EL 3.2

Low energy region highlighted with a red circle.
Mo Total Cross Section

Cross Section (b) vs. Energy (MeV)

Natural Mo
- RPI-3 cm sample
- RPI-8 cm sample
- RPI-Filtered beam
- ENDF/B-VII.0
- ENDF/BVI.8

M. Rapp, Y. Danon, F. Saglime, Rian Bahran, Robert Block, Greg Leinweber, Devin Barry, Jeff Hoole, “Molybdenum and Zirconium Neutron Total Cross Section Measurements in the Energy Range of 0.5 to 20 MeV”, International Conference on Nuclear Data for Science and Technology (ND2010), Korea, 26-30 April, 2010
Mo Total Cross Section Below 1 MeV

- Notice the visible structure in the cross section
- Better agreement with ENDF/B-VII.0 below 0.8 MeV
- Should ENDF evaluations include some of this structure?
- The filtered beam transmission data is in good agreement with the transmission data
Zr Total Cross Section Measurements (0.5-20 MeV)

- Used low Hf (less than 100 ppm) Zr metal
- ENDF/B 6.8 seems like a better fit for E < 16 MeV
- New partially resolved structure below 2.0 MeV
- Data can be used to improve the unresolved resonance region evaluation
Ti Total Cross Section Measurements (0.5-20 MeV)

- The evaluations are generally in good agreement with the data.
- Below 2 MeV, the data has better energy resolution than the evaluation.
The Gaerttner Laboratory

Ti Total Cross Section Measurements
0.5-1 MeV energy region

The ENDF/B 6.8 and JEFF 3.1 evaluations seem to have an energy shift.

ENDF/B-7.0 and JENDL 3.3 are similar and seem to be based on low resolution measurements.
• Deviations from ENDF/B-7.0 and JENDL-3.3 below 3 MeV
• RPI measurement agrees with other experimental data
TALYS vs EMPIRE

- TALYS and EMPIRE calculations with default parameters for Zr and Mo are in agreement with the data.
- For Ta and E < 3 MeV the codes disagree.
  - Shades some light on the disagreements of the data with the evaluations.
Fast Neutron Scattering Detector Array
Scattering Detection System: Experimental Setup

- **Data Acquisition System**
  - Main DAQ Computer (HAL) - 25m Station
  - PCI Extension Chassis
    - Acqiris AP240 DAQ Boards
      (2 Channels per Board)
- **Data Processing System**
  - Data Processing Computer (SAL) - Control Room
- **Computer Controlled Power Supply**
  - Chassis - SY 3527 Board - A1733N
- **Detector Array**
  - 8 EJ 301 Liquid Scintillation Detectors
  - Detector Stands
- **Sample Holder / Changer**
Gamma Background Reduction by Pulse Shape Analysis

Gamma Ray Background

Neutron Time of Flight
Scattering Setup Illustration

7 cm thick Graphite Target

Pulsed Neutron Beam

Experimental Data

Simulation with ENDF7
Carbon Experimental Results (Validation)

7cm

Energy (MeV) at 30.1m

26deg

52deg

72deg

90deg

107deg

119deg

140deg

154deg

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Beryllium Experimental Results

4cm

Energy (MeV) at 30.1m

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

8cm

Energy (MeV) at 30.1m

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel
Molybdenum Experimental Results

5cm

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

8cm

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

Counts/Channel

Energy (MeV) at 30.1m

Time of Flight (nsec)

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

Iron Filter Experimental Setup

Water Cooled Ta Target

30 cm Fe

Sample

Li-Glass Neutron Detector

Collimation

Collimation

Collimation

25.55m.
Natural Iron Filter

Transmission

$\sigma_t$ [barn]

Energy [keV]

30 cm Natural Iron
Experimental Data

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

Graphite total cross section
- RPI (7cm sample)
- ENDF/B-VII.0

Statistical Error <1%
Sample thickness and time split was selected according to:

Lead Slowing Down Spectrometer
Lead Slowing-down Spectrometer at RPI

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

67 tons of Pb

Crossed I beam + Li$_2$Co$_3$

Neutron Source (He cooled Ta Target)
He Filled Drift Section
Vacuum
Electron Beam
Fission Chamber

Ti Window
Flux Monitor
Flux Monitor
Flux Monitor

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Fission Fragment Kinematics

- Objectives
  - Simultaneous measurement of the fission cross section and fission fragment mass and energy distributions of small samples (~nanograms).
  - Use the RPI lead slowing down spectrometer and a double gridded fission chamber.
  - Samples are deposited on very thin backing (120 nm thick polyimide with 15 nm gold coating)
In collaboration with LANL and BRC
• $^{237}$U Fission cross sections.
• (n,$\alpha$), (n,p) measurements on small samples.
Results - Fission Fragment Mass distribution $E_n < 0.1$ eV

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

Graphs showing the mass distribution of fission fragments for $^{252}$Cf, $^{235}$U, and $^{239}$Pu for pre-neutron and post-neutron emissions. The graphs compare current data with ENDF/B-VII.0 and Hambsch data.
Results – Fission Fragment Energy Distribution

\[ E_n < 0.1 \text{eV} \]

\[ \text{Yield} \]

\[ \text{Energy [MeV]} \]

\[ ^{252}\text{Cf, RPI-2008} \]
\[ ^{235}\text{U, RPI-2008} \]
\[ ^{239}\text{Pu, RPI-2008} \]

Hambsch Data
\(^{235}\text{U} \text{ Fission symmetry in resonance clusters}\)

\[
\frac{V}{P}_{\text{ratio}} = \frac{\left(\frac{V}{P}\right)_{\text{resonance}}}{\left(\frac{V}{P}\right)_{\text{thermal}}} \Rightarrow \frac{V_{\text{resonance}}}{V_{\text{thermal}}}
\]


V- Valley at mass range 115-121
\(P_{\text{resonance}}, P_{\text{thermal}}\) – average of the normalized yield=constant
Results – Measured Fission Cross Section

\( \sigma_f \) [barn] vs. Energy [eV]

- \( ^{235}\text{U} \)
  - This Experiment
  - RPI 1993

- \( ^{239}\text{Pu} \)
  - This Experiment
  - Broadened ENDF-7.0
(n,\(\alpha\)) and (n,p) Cross section Measurements

- **Relevant to astrophysics**
  - Can use very small samples (nanograms) or small cross section
  - The energy range and resolution in the LSDS provides data that can be used to produce Maxwellian averaged cross sections.

- **Develop a detector**
  - **Compensated**, to suppress the effect of the gamma flash
  - **Sensitive** to alpha but can also work in noisy RF environment.
  - **Not sensitive to gamma** background (from inelastic scattering in Pb)
Compensated PIPS Detector

- Gamma discrimination by recording the gamma spectra on two face to face detectors
- Digital DAQ collects a bipolar signal
- Correct for background by subtracting the bare detector signal from the sample detector on an event by event basis
Measurement of \((n,\alpha)\) cross section of \(^{147}\text{Sm}\)

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

Measurement of \((n,\alpha)\) cross section for \(^{149}\text{Sm}\)

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

- **Fission**

- **Mo Analysis in Progress**

- **C & Be**
  - Y. Danon, R.C. Block, M. Rapp, F. Saglime, D.P. Barry, N.J. Drindak, J. Hool, G. Leinweber, “High-Accuracy Filtered Neutron Beam and High-Energy Transmission Measurements at the Gaerttner Laboratory”, submitted to the International Conference on Nuclear Data for Science and Technology, April 22-27 2007, Nice, France

- **Sm**

- **Gd using diluted samples enriched with 155 and 157.**

- **Nb**

- **Nd**

- **Hf**

- **Cs** – Including CsF crystals and Cs$_2$Co$_3$ diluted sample
- **Cd** – Analysis in progress
- **$^{238}$U** – Analysis in progress
- **Thermal and epithermal Transmission with 89.2% enriched samples and capture with a ~50 mg sample of 99.8% enrichment were completed.
- **Rh** – Analysis in progress
- **Re** – Analysis in progress
- **Gd** – $^{155,156,157,158,160}$ Capture analysis in progress
- **Dy** – $^{151,152,153,154}$ Capture analysis in progress
- **Eu** – $^{153,155}$ Capture and Transmission analysis in progress