Introduction

- This presentation summarizes the activity that was presented in the 2007 CSEWG meeting.
  - The full reports are available on the CSWEG web page.
- Additional information from Rutgers University and TUNL is included.
- The reports includes: LANL, ORNL, NIST, LBNL, LLNL Rutgers, TUNL and RPI.
- The report mostly emphasize nuclear reaction data.
- This represents only part of the U.S. nuclear data activity.
Utilizes 800 MeV protons to produce intense neutron beams

Large variety of detector and capabilities

- DANCE – Capture
  - \((n, \gamma)\) cross section on isotopes of Mo, Nd, Sm, Gd, Eu, Sm, Tl, Pu, and Am

- GEANIE – \((n,x\gamma)\)
  - Isomer lifetimes for \(^{203}\)Ti, \(^{205}\)Ti
  - \(^{48}\)Ti \((n,x\gamma)\) cross section
  - Levels and isomers studies on \(^{103}\)Rh, \(^{169}\)Tm, nat-Lu \((n,x\gamma)\)
  - Spin studies on \(^{135}\)Xe and \(^{202}\)Tl

- FIGARO
  - Fission neutron and gamma emission \(^{239}\)Pu, \(^{235}\)U and \(^{237}\)Np.
  - Scattered neutron distribution for \(^{56}\)Fe and natural Mo.

- LSDS – Fission measurements

- Fission cross section – new TPC is under construction
  - \((n,f)\) cross section of \(^{237}\)Np were published. Fission measurements of on \(^{240,242,241,239}\)Pu and \(^{233}\)U are in progress

- Charge particles
  - \(^{6}\)Li\((n,t)\alpha\) cross section
  - He production cross section from neutrons on Fe, Cr, Ta ,5 MeV to 100 MeV
Nuclear Data Experiments at LANSCE: Highlights 2007

Robert C. Haight
Los Alamos National Laboratory

Cross Section Evaluation Working Group Meeting
US Nuclear Data Program Meeting
Brookhaven National Laboratory
November 6-9, 2007
Nuclear data measurements at LANSCE are made with several instruments:

- **GEANIE** \((n,x_\gamma)\)
- **FIGARO** \((n,x_{n+\gamma})\)
- **DANCE** \((n,\gamma)\)
- **N,Z** \((n,\text{charged particle})\)

**LSDS** Double Frisch-grid fission chamber; also standard fission ion chamber; new detector station for fission and \((n,\alpha)\)
Nuclear data experiments at LANSCE use neutrons at the Lujan Center, Target 2 and Target 4.
GEANIE (n,xγ)
Recent Neutron-Induced Gamma-Ray Measurements with GEANIE at LANSCE/WNR

\[ \sim 1 \text{ MeV} < E_n < 200 \text{ MeV} \]

- \(^{203,205}\text{Tl}(n,2n\gamma) – N. Fotiades, levels, isomer lifetimes - Phys. Rev. C 76, 0143092 (2007) and submitted to Phys. Rev. C.


- \(^{103}\text{Rh}, \, ^{169}\text{Tm}, \, ^{\text{nat}}\text{Lu}(n,x\gamma), – levels, isomers – under analysis.

- \(^{150}\text{Sm}(n,n'\gamma) – pre-equilibrium analysis continuing.

- \(^{186}\text{W}(n,x\gamma) – analysis in progress.

- \(^{70,72,74}\text{Ge}, \, ^{100}\text{Mo}, \, ^{124}\text{Sn}, \, ^{130}\text{Te}, \, ^{136}\text{Xe}, \, ^{138}\text{Ba}, \, ^{\text{nat}}\text{Lu}(n,x\gamma) \) data acquired.

- \(^{\text{nat}}\text{Cu}, \, ^{\text{nat}}\text{Pb}, \, ^{\text{nat}}\text{Te}, \, \text{and} \, ^{76}\text{Ge}(n,x\gamma) \) for 0\(\nu\beta\beta \) decay experiment backgrounds – analysis in progress
Excitation functions of many gamma rays can be described by model calculations.

Branching ratios must be known correctly for calculations to match experiment.

Some reactions are more difficult to fit with model calculations

FIGARO \( (n,xn+\gamma) \)
Present and future experiments at FIGARO/WNR: neutron-and-gamma emission spectra and \( \nu \)-bar (fission)

1 MeV < \( E_n \) < 200 MeV

**Fission**

- \( ^{239}\text{Pu}(n,f): \ E_{fn}, E_{fgamma}, \nu\text{-bar} \)  
  In progress
- \( ^{235}\text{U}(n,f): \ E_{fgamma} \)  
  R. Nelson, in progress
- \( ^{237}\text{Np}(n,f): \ E_{fn}, \nu\text{-bar} \)  
  ND2007 (CEA)

**Non-fission**  
\[ \text{[Gamma-ray trigger -- HPGe, BaF}_2, \text{ NaI(Tl) and LaCl}_3\text{(Ce)}] \]

- \( ^{56}\text{Fe}, \text{ all-A}\text{Mo, others: } E_n \)  
  In progress

Contact: Bob Haight
FIGARO at WNR consists of an array of 20 neutron detectors and several gamma-ray detectors

- **Detectors**
  - Fission ion chambers from CEA
  - 20 EJ301 liquid scintillation neutron detectors
  - BaF₂, BGO and LaCl₃ gamma-ray scintillators
- **Double time of flight:**
  - Source-fission chamber → Incident $E_n$
    - Flight path = 22.7 meters
  - Fission chamber – neutron detector → $E_{fn}$
    - Flight path ~ 1.0 meters
- **Test of Los Alamos Model of fission**
- In collaboration with CEA-Bruyères-le-Châtel (BRC, France)
- Completed: $^{235,238}$U, $^{237}$Np neutron output
- In progress: $^{239}$Pu neutron output and all gamma
N,Z = (n,charged particle) cross sections
-- studied in two ways
Angular distribution measurements at LANSCE/WNR: charged-particle detector array for (n,z) reaction studies

Angular distributions are needed to constrain the theoretical model for this reaction in the few MeV region.

Data were taken in 2006; angular distributions were given to Gerry Hale in Feb-Mar 2007.

Result to be published in Nuclear Data 2007 Proceedings

**FIGURE 4.** Partial-wave decomposition of the $^6\text{Li}(n,\alpha)$ cross section from the EDA fit.
$^6\text{Li}(n,t)\alpha$ angular distribution measurements: results from 2006 data

- Triton data from 2006 at eight laboratory angles: 20, 30, 45, 60, 75, 90, 120, and 135 degrees.
- Covers the incident neutron energy for tritons from 0.18 to >10 MeV; alpha particle data at 5 angles from 1.5 to 20 MeV.
- More data taken recently.
$^6\text{Li}(n,t)\alpha$ angular distribution measurements: more results
$^6$Li(n,t)$^\alpha$ -- Current status, summary, and plans

• The $^6$Li(n,t)$^\alpha$ reaction cross section
  – data taken in 2006 with good statistics for $E_n = 0.1$ to 8 MeV; data analysis is in progress
  – need attention to systematic errors, target characterization, etc.
  – beamtime in Sep-Dec 2007 to address systematic errors, increase statistics (for $E_n > 5$ MeV)
  – want to measure the $^6$Li(n,$\alpha$)dn reaction channel as well

• Angular distributions
  – need to characterize the target foils
  – want more data to constrain the R-matrix fit in the 2-4 MeV range

We expect to be done taking data in December; analysis to be completed in early 2008.
We measure hydrogen and helium production cross sections for the Advanced Fuel Cycle Initiative

These data differentiate among evaluations

Contact: Bob Haight
ENDF/B-VII has problems for helium production by neutrons on iron in the 7-13 MeV range

Previous data
Helium production data is being measured for several materials for neutron energies up to 100 MeV

New data

Helium production
LANSCE data

Cross section (mb)

En (MeV)

- Chromium
- Iron
- Molybdenum
- Tantalum
Hydrogen production also is being measured

New data

Hydrogen production
LANSCE data

Chromium

Iron

Tantalum

Cross Section (mb)

En (MeV)
Plans for hydrogen and helium production cross sections for Global Nuclear Energy Partnership (GNEP)

1 MeV < En < 100 MeV

- Mo(n,xp) and (n,xα) -- completed
- Zr(n,xp) and (n,xα) -- nearly completed
- “Minor” elements in alloys – planned for this year

Goal is to determine, e.g. helium production / dpa for GNEP application and for accelerated radiation damage testing with a spallation neutron source
DANCE (n,γ)
Detector for Advanced Neutron Capture Experiments - DANCE

**Gamma Detector:**
- 160 BaF$_2$ crystals
- 4 different shapes
- $R_i=17$ cm, $R_a=32$ cm
- 7 cm $^6$LiH inside
- $\varepsilon_\gamma \approx 90\%$
- $\varepsilon_{\text{casc}} \approx 98\%$

**Neutrons:**
- Spallation source
- Thermal .. 500 keV
- 20 m flight path
- $3 \times 10^5$ n/s/cm$^2$/decade

**Sample:**
- $t_{1/2} > 100$ d
- m ~ 1 mg

**Collimated Neutrons Beam:**
- 34 cm

**Contacts:**
- John Ullmann
- Aaron Couture
- Bob Rundberg
Analysis of DANCE Data is in Progress

\[ ^{94,95}\text{Mo} \text{ (S. Sheets, NC State Univ.)} \]
\[ ^{143}\text{Nd}, ^{149}\text{Sm} \text{ (P. Koehler, ORNL)} \]
\[ ^{152,154,157,160}\text{Gd} \text{ (W. Parker, Livermore)} \]
\[ ^{151,153}\text{Eu} \text{ (U. Agvanluvsan, Livermore)} \]
\[ ^{151}\text{Sm} \text{ (R. Reifarth, Los Alamos and GSI)} \]
\[ ^{203,205}\text{TI} \text{ (A. Couture, Los Alamos)} \]
\[ ^{235}\text{U} \text{ PPAC (T. Bredeweg, M. Jandel, Los Alamos)} \]
\[ ^{240,242}\text{Pu} \text{ (A Couture, Los Alamos)} \]
\[ ^{241,243}\text{Am} \text{ (T. Bredeweg, M. Jandel, Los Alamos)} \]
\[ ^{242m}\text{Am} \text{ PPAC (C.Y. Wu, Livermore, M. Jandel, Los Alamos)} \]
$^{240}$Pu Cross Section

Contact:
Aaron Couture
$^{242}$Pu Cross-Section

Preliminary

$\log_{10} \sigma$ (barns) vs. Neutron Energy (eV)

- ENDF/B-VI.8, SAMMY Broadened
- DANCE Data, Scaled to Thermal

Preliminary

$\log_{10} \sigma$ (barns) vs. Neutron Energy (eV)

- ENDF/B-VI.8, SAMMY Broadened
- DANCE Data, Scaled to Thermal

Preliminary

$\log_{10} \sigma$ (barns) vs. Neutron Energy (eV)

- ENDF/B-VI.8
- DANCE Data, Scaled to Thermal
$^{241}$Am (n,γ) -- Cross section 0.02-36 eV

- At first two resonances our data are closer to JEFF and JENDL evaluations than ENDF
- Self shielding correction was not applied yet on the data, and is planned at the last stage when precise SAMMY fit will be performed
- Resonance at 10.4 eV is underestimated in ENDF evaluation (our analysis excludes fission contribution to a high degree)
- Statistical uncertainties are decided mainly with dE/E choice
- At thermal (0.02-0.1eV) 4% systematic uncertainty should be considered, stemming from the inconsistency between our beam monitors

Contact: Marian Jandel
**241Am Resonance Parameters**

- Comparison to ENDF/B-VII
- SAMMY7 was used to fit resonances below 20 eV
- Self shielding + multiple scattering effects included in the fitting procedure
- Neutron widths as a fitting parameter
- Gamma width kept from ENDF
- $2g\Gamma_n$ are compared in the upper panel
- lower panel shows the ratio of $\Gamma_n$ : ENDF/DANCE
Capture/fission ratios are measured with DANCE

$^{235}\text{U}$ fission gammas
Fission-tagging detector

- Best Correction: Fission Tagging
- For many threshold fissioners, can make correction
- Events with cluster mult > 7 and Summed Gamma Energy >6 MeV are almost purely fission

Background from fission gammas can be determined by normalizing $^{235}\text{U}$ spectrum
PPAC Detector for Capture and $\sigma_\gamma/\sigma_f$ Measurements

Parallel-Plate Avalanche Counter

Close-up of PPAC showing removable cathode/target assembly

PPAC Assembly with gas lines and signal cables ready for insertion into DANCE center
Fission Cross Sections
Recent and Future Fission Cross Section Measurements at LANSCE

- **Np-237** fission cross section from threshold to 200 MeV

- **Np-237** fission cross section from sub-thermal energies to 200 keV

- **Pu-240 and Pu-242** from 1 keV to 200 MeV
  Measurements completed and results delivered to evaluators at the T-16 group at LANL.

- **Pu-239 and Pu-241**
  Preliminary results obtained, more data will be collected this year.

- **U-233**
  In progress, to be completed Sept. 2008

Contacts:
Tony Hill
Fredrik Tovesson
Pu-240 $\sigma(n,f)$ results

The evaluations agree well with the measurement in the unresolved resonance region and for first chance fission. At higher energies there are significant discrepancies.
Pu-242 $\sigma(n,f)$ results

The JENDL evaluation is in good agreement with the data below reaction data. Both JENDL and ENDF seem to underestimate the first-chance fission cross section.
Measurements on Pu-241 $\sigma(n,f)$

Preliminary results have been obtained over the full energy range.
Additional measurements are being analyzed.
Fission cross sections of $^{239-242}$Pu compared

\[ \sigma(n,f) \]
Parallel-plate fission ionization chamber is used for fission cross section measurements at present

Parallel plate ionization chamber (PPIC)
- Commonly used for flux monitoring
- Detects on fission fragment per even
- Holds up to 4 samples

Next – Time-projection chamber
- Records
  - Angle $\Theta$
  - Fragment energy $E_f$
  - Track length $\rightarrow Z,A$
Fission Cross Sections
On Very Small Samples
A Lead Slowing-Down Spectrometer is under development, driven by 800 MeV protons from the PSR

Neutron trajectories following the interaction of 1 proton with the tungsten target in the lead cube

Contact: Bob Haight
First excited (isomeric) state of $^{235}$U is produced in decay of $^{239}$Pu

- $^{235m}$U
  - 26 min half-life
  - 73eV
  - Decays by internal conversion
  - 99% of $^{239}$Pu decays populate $^{235m}$U
  - 5 gm of Pu produces 10ng of $^{235m}$U

- Fast extraction of $^{235m}$U from $^{239}$Pu is required
We address the needs of LANSCE sponsors

- **National Nuclear Security Administration**
  - Program in radchem cross section measurements
    - Neutron capture cross sections on radioactive targets (DANCE)
    - Cross section measurements on high-order \((n,2n)\), \((n,xn)\) reactions (GEANIE)
  - Program in neutron-induced fission measurements
    - Fission product distributions (GEANIE)
    - Energy output in fission: neutron and \(\gamma\)-ray spectra (FIGARO)
    - Nuclear properties of fission products and isomers (GEANIE and FIGARO)
    - Cross sections on ultra-small samples (LSDS)

- **Office of Nuclear Energy**
  - Measurements in support of the GNEP program include:
    - Capture and fission cross section on actinides
    - Gas production: \((n,p)\), \((n,\alpha)\) reactions in structural materials

- **Office of Science**
  - Support of SNS in studies of pulsed radiation effects on liquid mercury targets
  - Fundamental physics experiments and nuclear data

- **National Resource**
  - Nuclear science User Facility for defense, basic and applied research
  - Industrial testing of semiconductor devices in neutron beams
  - University research in nuclear science
The LANSCE program in nuclear data involves many laboratories

- **GEANIE** – LANL, LLNL, INL, ORNL, Bruyères-le-Châtel, NC State
- **FIGARO** – LANL, BNL, Bruyères-le-Châtel
- **N,Z** – LANL, Ohio U
- **DANCE** – LANL, LLNL, ORNL, INL, Colorado School of Mines, FZK Karlsruhe
- **LSDS** – LANL, LLNL, BNL, Bruyères-le-Châtel, RPI
- **Fission** – LANL, IRMM, LLNL, INL
- **Others** – MIT, Kentucky, Kyushu, Harvard,…
ORELA is back in operation

- Capture
  - $^{53}\text{Cr}$, $^{58}\text{Ni}$, $^{60}\text{Ni}$, $^{63}\text{Cu}$, $^{65}\text{Cu}$, $^{86,87}\text{Sr}$, in progress

- Transmission - $^{53}\text{Cr}$, $^{58}\text{Ni}$

- $(n,\alpha)$ - $^{149}\text{Sm}$, $^{64}\text{Zn}$

- Analysis - $^{41}\text{K}$
New Neutron Cross-Section Measurements from ORELA


Oak Ridge National Laboratory, Oak Ridge, TN, USA
ORELA

Applications

Basic Science

Cross-Section Evaluations

ORNL Data Support for Nuclear Applications

AMPX

Nuclear Astrophysics

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

COMPUTATIONAL MODELING

EVALUATED NUCLEAR DATA FILES (ENDF/B)

SAMMY: MULTILEVEL R-MATRIX FITS TO NEUTRON DATA USING BAYES' EQUATIONS
Existing Experiments at ORELA

• 11 Flight paths
• Flight Stations: 8-18, 20, 35, 40, 85, 150, and 200 m
New NCSP Measurements

- Completed $^{41}$KCl capture and transmission.
- Measured Mn capture using thick sample (0.018at/b).
- Started natural Cr transmission (energy range 100eV to 50 keV), good high energy data available. Completed capture on natural Cr.
- Started capture on $^{58}$Ni, good transmission data available.
New ORNL Evaluation for Cl helps to extract $^{41}$K parameters

- $^{41}$KCl sample used with 99.17% enrichment. (0.00797at/b)
- Including the new resonance parameter set from the ORNL Cl evaluation it will be possible to extract reliable parameter for $^{41}$K.
ORELA capture data for $^{41}\text{KCl}$ compared to JENDL3.3 and Preliminary SAMMY fits.

Several resonance areas too large (neutron sensitivity) in evaluation.
ORELA capture data for $^{41}\text{KCl}$ compared to JENDL3.3 and Preliminary SAMMY fits.

Several resonance areas too large (neutron sensitivity) in evaluation.
Preliminary fit to the Transmission data of metallic K and $^{41,39}\text{KCl}$

- Preliminary SAMMY fits to the transmission data of the $^{39,41}\text{KCl}$ samples and natural metallic K.
- With the use of the resonance parameter from the most recent Cl evaluation (Sayer et. al. Phys. Rev. C) it is possible to extract reliable K parameters.
New ORELA Mn Neutron Capture compared to ENDF/B VI Evaluation

Very thick sample used, multiple scattering effect enormous
New ORELA $^{\text{Nat.}}\text{Cr}$ Capture TOF data; using a metallic sample
New ORELA $^{58}\text{Ni}$ Capture TOF data; using a metallic sample; 8 hours running time
New $^{95}\text{Mo}(n,\gamma)$ experiments

- AGB stellar models overpredict the abundance of $^{95}\text{Mo}$ compared to observation in SiC grain which origin from an AGB star where the s-process takes place.

- M. Lugaro et al. 2003: calculations show a 30% enhancement in the $(n,\gamma)$ cross section for $^{95}\text{Mo}$ would solve the problem.
New $C_6D_6$ Apparatus on FP6 in 40-m Station

- New system for $(n,\gamma)$ experiments built in collaboration with JNC.
- Improved set up compared to last year. Less structural material. Two new $C_6D_6$-detectors.
- $L = 38.5$ m, 2.5-cm diameter beam at sample.
- $^6\text{Li}$-glass flux monitor.
- First test measurement: $^{95}\text{Mo}(n,\gamma)$. Finished!
- Completed transmission measurements.
Outlook

• Perform or finish new total and capture cross section measurements for the NCSP, i.e. nat. Cr, $^{53}$Cr, $^{58}$Ni, $^{60}$Ni, $^{63}$Cu, $^{65}$Cu

• Continue nuclear astrophysics experiments
  Finish $^{64}$Zn$(n,\alpha)$
  Future experiments include $(n,\gamma)$ and $\sigma_t$ for $^{86,87}$Sr and $^{149}$Sm$(n,\alpha)$
National Institute of Standards

- $H(n,n)$ at 14.9 MeV (Ohio U. + LANL + U. Guelma)
- $^3\text{He}(n,p)$ – Separate the 2 spin channels (Indiana U + U North Carolina)
- $^6\text{Li}(n,t)$, $^{10}\text{B}(n,\alpha)$ – at 4 meV
National Institute of Standards

Slide Show
NIST Nuclear Data Standards Measurements
Including other Standards Activity

Allan D. Carlson
Ionizing Radiation Division
National Institute of Standards & Technology

Presented at
The CSEWG meeting
Brookhaven National Laboratory
November 7, 2007
H(n,n)H Angular Distribution Work

•Measurements were made at laboratory angles of 0 degrees, ± 12 degrees (one on each side of the beam direction), ± 24 degrees, ± 36 degrees, ± 48 and ± 60 degrees at the Ohio University accelerator facility. A paper on this work was given at the ND2007 conference. The data are obtained at 14.9 MeV neutron energy.

•Plans are being made to continue this type of work using a Time Projection Chamber which will provide higher counting rates than are possible with the scattering chamber now being used.

(collaboration with Ohio University, LANL and the University of Guelma)
H(n,n)H Differential Scattering Cross Section at 14.9 MeV

- Data
- ENDF/B–VII
- Arndt
- Nijmegen
- Legendre fit

Differential Cross Section (mb/sr) vs. Center-of-Mass Angle (degrees)
H(n,n)H Angular Distribution Work at ~200 MeV

There is a discrepancy between the results of the Uppsala University and Indiana University measurements (shown here as Present exp’t).

- Present exp’t, 194 MeV.
- Uppsala, 162 MeV.
- PWA93 (T_{LAB}= 194 MeV)
- PWA93 (T_{LAB}= 162 MeV)
H(n,n)H Angular Distribution Work at ~200 MeV (cont.)

- The Indiana experiment used tagging so the neutron’s incidence angle is determined. If that angle is not known, the yield at small outgoing proton angles can be dominated by incident neutrons in the divergence of the beam. The incident neutron angle is not known for the Uppsala work. An analysis of the Indiana University data ignoring the neutron’s incidence angle was done to determine this effect.

![Graph](image.png)
The Uppsala group wrote an analysis code with the objective of correcting their data for this effect. Using the details of their experimental setup, they found the effect was very small (0.2%-0.6%). They also calculated the effect for the Indiana experiment and obtained results consistent with those obtained by the Indiana group.
\(^{3}\text{He}(n,p)\) Work

• An NIST collaborative experiment employing polarized neutrons and a polarized \(^{3}\text{He}\) beam has been designed. This measurement will allow separation of the real part of the two spin channels of this interaction. These data can be used in R-matrix evaluations to improve the \(^{3}\text{He}(n,p)\) standard cross section. (collaboration with Indiana University and the University of North Carolina)
6Li(n,t) Work

• NIST collaborative measurements are being made of the 6Li(n,t) cross section standard at ~ 4 meV. These are the first direct and absolute measurements of this cross sections in this neutron energy range using monoenergetic neutrons.

• The neutron fluence measurements are based on counting prompt gamma-rays that originate from neutron capture in a totally absorbing boron target. The gamma-ray efficiency is known accurately from alpha-gamma coincidence measurements using a thin 10B target and also indirectly from measurements using a standard alpha source. A thin 6Li target whose geometry and target mass are both well known was used for the 6Li(n,t) cross section measurement. This procedure is capable of achieving an accuracy of ± 0.25%.

(collaboration with the University of Tennessee and Tulane University)
Experimental setup for the $^7$Li(n,t) reaction rate measurement to obtain the 6Li(n,t) cross section
6Li(n,t) Work (cont.)

• The Frisch gridded ionization chamber work of Zhang et al. has been published. Angular distribution measurements were made at 1.05, 1.54, 1.85, 2.25, 2.67, 3.67 and 4.42 MeV. Integrated cross sections were obtained at 1.05 MeV and 1.54 MeV relative to the $^{10}$B(n,α) standard; and at 1.85, 2.25, 2.67, 3.67 and 4.42 MeV relative to the $^{238}$U(n,f) standard. Corrections are not made for the “particle leaking effect”; but the range of angles where the effect is present was calculated.

• New measurements are now being made by Devlin et al. at LANL. Angular distribution data are being obtained from 0.2 to 10 MeV at eight laboratory angles using four E-ΔE telescopes. Also cross sections are being obtained with a detector system composed of two closely spaced silicon solid state detectors for the energy range from 0.1 to 8 MeV. Preliminary results from these experiments were reported at the ND2007 conference.
**$^{10}\text{B}(n,\alpha)$ Work**

• The same basic experimental setup being used for the NIST collaborative measurements of the $^6\text{Li}(n,t)$ cross section at ~ 4 meV will be used to measure the $^{10}\text{B}(n,\alpha)$ cross section also.

• The angular distribution measurements of Hambsch were recently published. Data accumulation continues for the branching ratio experiment which is being extended to about 3 MeV. Plans have been made to make measurements of the $^{10}\text{B}(n,\alpha)$ and $^{10}\text{B}(n,\alpha_1\gamma)$ cross sections relative to the $^{235}\text{U}(n,f)$ standard up to about 3 MeV.
Additional Work Supporting the Standards

- Measurements are expected on the $^{239}$Pu(n,f) cross section in the MeV energy region with NERI funding. This work will use Time Projection Chambers for fission detection. Very accurate measurements should be possible with these detectors. It may be possible to also make measurements on the $^{235}$U(n,f) and $^{238}$U(n,f) standards.

- Cross section measurements have been made using NBS-I as a standard neutron source. An independent determination of the neutron intensity of this source has been made to compare with the established value obtained from manganese sulfate bath measurements and calculations. The new determination is in principle only limited in accuracy by the uncertainty in nu-bar of $^{252}$Cf. The determination was made by measuring the neutron source intensity of a bare $^{252}$Cf source (from the fission fragment rate into a well defined solid angle measured with a solid state detector and nu-bar), comparing this source to a sealed $^{252}$Cf source (by relative counting with $^3$He neutron detectors) to determine the sealed source intensity, and comparing this result with that obtained from a calibration of the sealed source relative to NBS-I in a large manganese sulfate bath.
Data Development Project Activities

• Pronyaev has worked on a new method for smoothing the Au(n,γ) cross section by using statistical model calculations. The objective is to remove non-physical fluctuations (structure) and maintain real structure such as the cusps that occur from competition with inelastic scattering. The model fit will be used in the standards database as shape input.

• Updating of the standards database.

• Investigating the possibility of developing an inelastic scattering cross section standard.

• Considering adding additional standards energy ranges for the Au(n,γ) cross section.

• Proposing updates for the evaluations of the $^{252}$Cf spontaneous fission neutron spectrum and the $^{235}$U thermal neutron-induced fission neutron spectrum.
237(n,f) cross section using the surrogate reaction 238U(3He,t)238Np + models (0.5-20 MeV).

236U(n,f) using the surrogate reaction 238U(3He,α)/235U(3He,α) and (n,γ) for 153,155,157Gd

Thermal (n,γ) cross section measurements
Determining \((n, f)\) and \((n, \gamma)\) cross sections: Study of the surrogate method

Collaboration:
Lawrence Livermore National Laboratory
Lawrence Berkeley National Laboratory and
University of Richmond

Shamsu Basunia
*Nuclear Science Division*
*Lawrence Berkeley National Laboratory*
Contents

• The surrogate method provides alternative way to determine nuclear cross section for difficult cases

• Recent experiments provide important cross sections using the surrogate method
  
  – $^{237}\text{Np}(n, f)$ in the 10 to 20 MeV energy range using $^{238}\text{U}(^{3}\text{He}, t)^{238}\text{Np}$: pre-equilibrium effect
  
  – $^{236}\text{U}(n, f)$ using $^{238}\text{U}(^{3}\text{He}, \alpha)^{237}\text{U}$: angular momentum effect
  
  – $^{153}\text{Gd}(n, \gamma)^{154}\text{Gd}$ cross section using $^{154}\text{Gd}(p, p')^{154}\text{Gd}$: s-process branch-point
The Surrogate Method

Hard to measure “Desired” reaction (rad target, n-beam etc.)

Easier to measure “Surrogate” reaction

Central assumption: Both reactions form a compound nucleus

\[ \sigma_{A(a,x)C} = \sum_{J,\pi} P_c (J,\pi,E_x) \sigma_{a+A}^{\text{comp reac}} (J,\pi,E_x) \]

Weisskopf – Ewing: \[ \sigma_{A(a,x)C} = P_c \sigma_{a+A}^{\text{comp reac}} \]

If \( P_c \neq P_c(J,\pi) \)
LIBERACE and STARS detectors at the 88-Inch Cyclotron, LBNL
$^{237}\text{Np}(n, f)$ from $^{238}\text{U}(^{3}\text{He}, t)^{238}\text{Np}$ surrogate reaction: pre-equilibrium effect

M. S. Basunia et al., submitted to PRC

$^{236}\text{U}(n, f)$ from $^{238}\text{U}(^{3}\text{He}, \alpha)/^{235}\text{U}(^{3}\text{He}, \alpha)$ ratio and absolute: angular momentum effect

Ph.D. thesis project

Courtesy of B. F. Lyles, LLNL, UCB

B. F. Lyles et al., PRC 76, 014606, 2007
s-process branch-point nucleus $^{153}$Gd

...for $(n, \gamma)$ on these isotopes

Targets used ...

- $^{152,154}$Gd cannot be produced by the $r$-process and therefore these abundances can be used to investigate the s-process

- $(n, \gamma)$ cross sections at energies 0-200 keV in branch-point nuclei such as $^{153}$Gd (for which the time scales for $n$ capture and $\beta$-decay are comparable) are needed

- $^{153}$Gd is radioactive ($t_{1/2}$=240 days), making direct measurements very difficult

- Well-suited for surrogate measurement because of neighboring stable Gd isotopes that can be used as targets for measurement and benchmarks.
\((n, \gamma)\) cross section for \(^{153,155,157}\text{Gd}\) isotopes from \((p, p')\)

Excite Gd nuclei \((S_n \approx 8-9\) MeV) through inelastic \((p, p')\) scattering

Detect scattered \(p\) in segmented silicon detector array in coincidence with characteristic \(\gamma\)-rays from lowest excited states of Gd

\[\begin{align*}
\Delta E \text{ detector} \\
(500 \text{ } \mu\text{m})
\end{align*}\]

\[\begin{align*}
\text{E1 detector} \\
(1000 \text{ } \mu\text{m})
\end{align*}\]

\[\begin{align*}
\text{E2 detector} \\
(1000 \text{ } \mu\text{m})
\end{align*}\]

\[\begin{align*}
\text{Gd target}
\end{align*}\]

\[\begin{align*}
p \text{ beam} \\
(22 \text{ MeV})
\end{align*}\]

\[\begin{align*}
\delta\text{-electron} \\
\text{shield}
\end{align*}\]

Compton-suppressed "clover" HPGe detector

\[\begin{align*}
\gamma
\end{align*}\]

\[\begin{align*}
p-\gamma \text{ coincidence vs. } ^{158}\text{Gd}^* \text{ excitation energy shows drop as } S_n \text{ is crossed}
\end{align*}\]

\[\begin{align*}
154,156,158\text{Gd}(p,p'\gamma) \text{ experiment finished 6/4/07}
\end{align*}\]
Neutron Cross Section Measurements at LBNL

Richard B. Firestone
Lawrence Berkeley National Laboratory

Collaborators
Zs. Revay and T. Belgya (Budapest Reactor)
M. Krticka, F. Becvar (Charles University, Prague)
D. McNabb, B. Sleaford, U. Agvaanluvsan (LLNL)
Measurements

At the Budapest Reactor we have measured thermal neutron $\gamma$-ray cross sections for all elements with $Z=1-83, 92$ except He and Pm.

- Pure thermal guided neutron beam
- Internal standard calibrations
- Precision of $<3\%$ for strong transitions
- IAEA sponsored evaluation of $\sigma_\gamma$
Budapest Prompt Gamma-ray Facility

N-type coaxial HPGE detector  
(25%, 1.8 keV@1332)
BGO Compton shield
Thermal beam – $2 \times 10^6$ n·s$^{-1}$cm$^{-2}$
Cold beam – $5 \times 10^7$ n·s$^{-1}$cm$^{-2}$

Beam profile at the target position

Compton suppression lowered background by a factor of ~5@1332 to ~40 at 7 MeV.
Internal Cross Section Calibration

Calibration Methods

– Stoichiometric compounds of well-known composition containing elements with well-known cross sections e.g. H,N,Cl,S,Na,Ti,Au, → KCl,(CH₂)n,Pb(NO₃)₂,Tl₂SO₄

– Homogenous mixtures
  • Aqueous solutions (H₂O) or acid solutions (20% HCl)
  • Mixed powders (TiO₂)

– Activation product cross section e.g. ²⁸Al, ¹⁰⁰Tc, ²³⁵U
IAEA/EGAF $\sigma_\gamma$ Database

The Evaluated Gamma-ray Activation File (EGAF) is the result of an IAEA CRP established in 1999 to evaluate $k_0/\sigma_\gamma$ measurements at the Budapest Reactor and compare them with literature data. EGAF contains over 13,000 $\gamma$-rays from 81 elements. These results are published in


LBNL Capture Gamma-ray Data: [http://ie.lbl.gov/ng.html](http://ie.lbl.gov/ng.html)
Total Thermal Neutron Radiative Cross Sections $\sigma_0$ – Low Z

For *complete decay schemes* the total thermal radiative neutron cross section $\sigma_0 = \Sigma \sigma_{\gamma e}(\text{GS}) = \Sigma \sigma_{\gamma e}(\text{CS})$
Example – $^{24}\text{Mg}(n,\gamma)^{25}\text{Mg}$

Cross section balance for the $^{25}\text{Mg}$ neutron capture decay scheme

<table>
<thead>
<tr>
<th>E (Level)</th>
<th>$\sigma$(in)</th>
<th>$\sigma$(out)</th>
<th>$\Delta\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0536(14)</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>585.01(3)</td>
<td>0.0406(11)</td>
<td>0.0398(14)</td>
<td>0.0008(18)</td>
</tr>
<tr>
<td>974.68(3)</td>
<td>0.0157(4)</td>
<td>0.0158(4)</td>
<td>0.0001(6)</td>
</tr>
<tr>
<td>1964.69(10)</td>
<td>0.00022(2)</td>
<td>0.00026(3)</td>
<td>0.00004(4)</td>
</tr>
<tr>
<td>2563.35(4)</td>
<td>0.00202(10)</td>
<td>0.00179(7)</td>
<td>0.00023(12)</td>
</tr>
<tr>
<td>2801.54(9)</td>
<td>0.00047(4)</td>
<td>0.00061(5)</td>
<td>0.00013(6)</td>
</tr>
<tr>
<td>3413.35(3)</td>
<td>0.0411(14)</td>
<td>0.0416(11)</td>
<td>0.0005(18)</td>
</tr>
<tr>
<td>4276.33(4)</td>
<td>0.0105(4)</td>
<td>0.0107(3)</td>
<td>0.0002(5)</td>
</tr>
<tr>
<td>4358.2(5)</td>
<td>0.00009(2)</td>
<td>0.0</td>
<td>0.00009(2)</td>
</tr>
<tr>
<td>5116.37(15)</td>
<td>0.00038(4)</td>
<td>0.00027(3)</td>
<td>0.00011(5)</td>
</tr>
<tr>
<td>7330.53(4)</td>
<td>0.0</td>
<td>0.0539(14)</td>
<td>0.0539(14)</td>
</tr>
</tbody>
</table>

$\sigma$(Mughabghab[23]) 0.0536(15) b
$\sigma$(Measured, average) 0.0538(14) b
$^{12}\text{C}(n,\gamma)^{13}\text{C}$ Discrepancy

$^{12}\text{C}(n,\gamma)\sigma_0$ Measurements

<table>
<thead>
<tr>
<th>Reference</th>
<th>$\sigma_0$(mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestwich(1981)</td>
<td>3.50(16)</td>
</tr>
<tr>
<td>Jurney(1963)</td>
<td>3.53(7)</td>
</tr>
<tr>
<td>Nichols (1960)</td>
<td>3.57(3)</td>
</tr>
<tr>
<td>Mughabghab(2006)</td>
<td>3.53(7) mb</td>
</tr>
<tr>
<td>Sagot (1963)</td>
<td>3.72(15)</td>
</tr>
<tr>
<td>Starr (1962)</td>
<td>3.83(6)</td>
</tr>
<tr>
<td>Koechlin (1957)</td>
<td>3.85(15)</td>
</tr>
<tr>
<td>Yonezawa (2003)</td>
<td>4.01(15)</td>
</tr>
<tr>
<td>This work*</td>
<td>3.86(6) mb</td>
</tr>
</tbody>
</table>

* Average of measurements with various stoichiometric carbon compounds.
(\textsuperscript{15}NH\textsubscript{2})\textsubscript{2}\textsuperscript{13}CO(Urea) Analysis

- Urea sample enriched to >99% in \textsuperscript{13}C, \textsuperscript{15}N
- Hydrogen internal standard \((\sigma_0=0.3326(7) \text{ b})\)

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
Isotope & Total radiative cross section \(\sigma_0\) & This work \\
\hline
\textsuperscript{13}C & \(1.37\pm0.04 \text{ mb}\) & \(1.50\pm0.03 \text{ mb}\) \\
\hline
\textsuperscript{15}N & \(24\pm8 \mu\text{b}\) & \(39\pm3 \mu\text{b}\) \\
\hline
\end{tabular}
\end{center}
Summary of $\sigma_0$ results for low-Z isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\sigma$ (Atlas)*</th>
<th>$\sigma$ (EGAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>332.6(7) mb</td>
<td>$\approx$332.6(7) mb</td>
</tr>
<tr>
<td>$^2$H</td>
<td>0.508(15) mb</td>
<td>0.492(25) mb</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>38.5(30) mb</td>
<td>52.6(22) mb</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>45.4(27) mb</td>
<td>45.7(9) mb</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>8.49(34) mb</td>
<td>8.8(6) mb</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>305(16) mb</td>
<td>384 mb 8</td>
</tr>
<tr>
<td>$^{10}$B(n,α)</td>
<td>3837(9) b</td>
<td>3820(135) b</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>5.5(33) mb</td>
<td>11.4(10) mb</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>3.53(7) mb</td>
<td>3.89(6) mb</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>1.37(4) mb</td>
<td>1.50(3) mb</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>80.1(6) mb</td>
<td>79.0(9) mb</td>
</tr>
<tr>
<td>$^{15}$N</td>
<td>24 μb 8</td>
<td>39 μb 3</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>0.190(19) mb</td>
<td>0.189(8) mb</td>
</tr>
<tr>
<td>$^{19}$F</td>
<td>9.51(9) mb</td>
<td>9.50(11) mb</td>
</tr>
<tr>
<td>$^{23}$Na</td>
<td>517(4) mb</td>
<td>527(7) mb</td>
</tr>
<tr>
<td>$^{23}$Na($^m$472)</td>
<td>400(30) mb</td>
<td>478(4) mb</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>53.8(13) mb</td>
<td>53.7(14) mb</td>
</tr>
<tr>
<td>$^{25}$Mg</td>
<td>199(3) mb</td>
<td>197(5) mb</td>
</tr>
<tr>
<td>$^{26}$Mg</td>
<td>38.4(6) mb</td>
<td>37.7(13) mb</td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>231(3) mb</td>
<td>232(3) mb</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>177(4) mb</td>
<td>186(3) mb</td>
</tr>
<tr>
<td>$^{29}$Si</td>
<td>119(3) mb</td>
<td>118(3) mb</td>
</tr>
<tr>
<td>$^{30}$Si</td>
<td>107(2) mb</td>
<td>116(3) mb</td>
</tr>
<tr>
<td>$^{31}$P</td>
<td>165(3) mb</td>
<td>167(5) mb</td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>518(14) mb</td>
<td>536(8) mb</td>
</tr>
<tr>
<td>$^{33}$S</td>
<td>454(25) mb</td>
<td>461(15) mb</td>
</tr>
<tr>
<td>$^{34}$S</td>
<td>256(9) mb</td>
<td>277(8) mb</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>43.6(4) b</td>
<td>43.84(17) b</td>
</tr>
<tr>
<td>$^{37}$Cl</td>
<td>433(6) mb</td>
<td>553(23) mb</td>
</tr>
<tr>
<td>$^{39}$K</td>
<td>2.1(2) b</td>
<td>2.19(3) b</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>30(8) b</td>
<td>92(8) b</td>
</tr>
<tr>
<td>$^{41}$K</td>
<td>1.46(3) b</td>
<td>1.73(2) b</td>
</tr>
</tbody>
</table>

Analysis of $\sigma_0$ for heavier isotopes

For most isotopes with $Z \geq 20$ the neutron capture decay schemes are incomplete

- High level density below the capture state
- Numerous unresolved continuum gamma rays

What to do?
The cross section deexciting low-lying states in higher-Z nuclei, $\Sigma\sigma_\gamma$(out), is complete.

The observed cross section populating these states $\Sigma\sigma_\gamma$(in) is incomplete due to unresolved continuum $\gamma$-rays.

$$\sigma_0(tot) = 21.0 \pm 1.5 \text{ b}$$

Mughabghab (2006)

<table>
<thead>
<tr>
<th>E(level)</th>
<th>J^z</th>
<th>$\Sigma\sigma_\gamma$(in)</th>
<th>$\Sigma\sigma_\gamma$(out)</th>
<th>$\Delta\Sigma\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0+</td>
<td>20.26</td>
<td>17.91</td>
<td>4.03</td>
</tr>
<tr>
<td>511.844</td>
<td>2+</td>
<td>13.88</td>
<td>4.263</td>
<td>8.92</td>
</tr>
<tr>
<td>1128.04</td>
<td>2+</td>
<td>2.371</td>
<td>0.565</td>
<td>1.383</td>
</tr>
<tr>
<td>1133.79</td>
<td>0+</td>
<td>0.227</td>
<td>0.565</td>
<td>0.338</td>
</tr>
<tr>
<td>1229.2</td>
<td>4+</td>
<td>1.630</td>
<td>3.479</td>
<td>1.849</td>
</tr>
<tr>
<td>1557.67</td>
<td>3+</td>
<td>1.183</td>
<td>2.142</td>
<td>0.959</td>
</tr>
<tr>
<td>1562.16</td>
<td>2+</td>
<td>0.312</td>
<td>1.869</td>
<td>1.557</td>
</tr>
<tr>
<td>1706.44</td>
<td>0+</td>
<td>0.012</td>
<td>0.193</td>
<td>0.181</td>
</tr>
<tr>
<td>1909.39</td>
<td>2+</td>
<td>0.063</td>
<td>0.724</td>
<td>0.661</td>
</tr>
<tr>
<td>1932.37</td>
<td>4+</td>
<td>0.217</td>
<td>0.590</td>
<td>0.373</td>
</tr>
<tr>
<td>2001.56</td>
<td>0+</td>
<td>0.029</td>
<td>0.118</td>
<td>0.089</td>
</tr>
<tr>
<td>2077.1</td>
<td>6+</td>
<td>0.001</td>
<td>0.103</td>
<td>0.102</td>
</tr>
<tr>
<td>2077.37</td>
<td>(4)+</td>
<td>0.057</td>
<td>0.440</td>
<td>0.383</td>
</tr>
<tr>
<td>2084.39</td>
<td>-3</td>
<td>0.123</td>
<td>1.033</td>
<td>0.910</td>
</tr>
<tr>
<td>2242.4</td>
<td>2+</td>
<td>0.026</td>
<td>0.499</td>
<td>0.473</td>
</tr>
<tr>
<td>2278.47</td>
<td>0+</td>
<td>0</td>
<td>0.056</td>
<td>0.056</td>
</tr>
<tr>
<td>2282.89</td>
<td>4+</td>
<td>0.0007</td>
<td>0.275</td>
<td>0.274</td>
</tr>
<tr>
<td>2306.01</td>
<td>-3</td>
<td>0.053</td>
<td>0.542</td>
<td>0.489</td>
</tr>
<tr>
<td>2308.73</td>
<td>2+</td>
<td>0.000</td>
<td>0.283</td>
<td>0.283</td>
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<tr>
<td>2350.96</td>
<td>4+</td>
<td>0.018</td>
<td>0.304</td>
<td>0.286</td>
</tr>
<tr>
<td>2366.09</td>
<td>5+</td>
<td>0.003</td>
<td>0.116</td>
<td>0.114</td>
</tr>
<tr>
<td>2397.37</td>
<td>(5)-</td>
<td>0.055</td>
<td>0.263</td>
<td>0.209</td>
</tr>
<tr>
<td>2401</td>
<td>(2,-,3-)</td>
<td>0.037</td>
<td>0.300</td>
<td>0.263</td>
</tr>
<tr>
<td>2439.11</td>
<td>2+</td>
<td>0.055</td>
<td>0.293</td>
<td>0.227</td>
</tr>
<tr>
<td>2472.09</td>
<td>0+</td>
<td>0.000</td>
<td>0.055</td>
<td>0.055</td>
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<tr>
<td>2484.76</td>
<td>(1-)</td>
<td>0.043</td>
<td>0.253</td>
<td>0.211</td>
</tr>
<tr>
<td>2500.01</td>
<td>-2</td>
<td>0.028</td>
<td>0.296</td>
<td>0.267</td>
</tr>
<tr>
<td>2578.64</td>
<td>(4-)</td>
<td>0.00004</td>
<td>0.221</td>
<td>0.221</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>9561.4</td>
<td>2+,3+</td>
<td>0.554</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The continuum contribution can be calculated assuming level density and γ-ray transition probability varies statistically leading to a random distribution of partial level widths \( \langle \Gamma_{ij} \rangle = f^{XL}(E_\gamma, \xi)E_\gamma^3/\rho(E_i, J^{\pi_i}) \) where

1. Level density \( \rho(E_i, J^{\pi_i}) \) can be described by
   a) Constant temperature formula
      \[
      \rho(E, J) = \frac{f(J)}{T} \exp\left(\frac{E - E_0}{T}\right)
      \]
   b) Back-shifted Fermi Gas formula
      \[
      \rho(E, J) = f(J) \frac{\exp\left(2\sqrt{a(E - E_1)}\right)}{12\sqrt{2}\sigma_a a^{1/4}(E - E_1)^{5/4}}
      \]

2. Photon strength \( f^{XL}(E_\gamma, \xi)E_\gamma^3 \) for multipolarity XL=E1, M1
   a) E1: Brink-Axel
      \[
      f^{(E1)}_{BA}(E_\gamma) = \frac{1}{3(\pi \hbar c)^2} \frac{\sigma_G E_\gamma \Gamma_G^2}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_G^2}
      \]
      also, Kadmenskii et al (KMF), Generalized Laurentzian (GLO).
      GDER parameters: Dietrich, Berman(ATNDT) or Herman (Empire)
   b) M1: Single particle, \( f^{E2}(SP) = 5 \times 10^4 E_\gamma^3 \), spin flip (SF), or \( f^{E1}/f^{M1} = 5-7 \)
   c) E2: Single particle, \( f^{E2}(SP) = 1 \times 10^{-7} E_\gamma^5/A^{4/3} \)
DICEBOX Monte Carlo Code

DICEBOX generates \((n, \gamma)\) level scheme simulations (nuclear realizations) based on statistical model level densities \(\rho(E_i, J^{\pi}_i)\) and \(\gamma\)-ray transition probabilities \(\Gamma_{if}\) where

a) All levels and \(\gamma\)-rays below \(E_{\text{crit}}\) are taken from experiment.

b) All levels and \(\gamma\)-rays above \(E_{\text{crit}}\) are generated randomly from level density and PSF models.

c) Primary \(\gamma\)-ray cross sections are taken from experiment when known.

Typically 30,000 capture state \(\gamma\)-ray decay cascades are randomly generated for each nuclear realization.

50 separate realizations are usually averaged to get the statistical variation in the simulated level feedings.
Statistical Model Selection Example

Model dependence of the total capture state width $\Gamma_{\gamma}^{\text{tot}}$

<table>
<thead>
<tr>
<th>$^{105}\text{Pd}(n,\gamma)$</th>
<th>E1-PSF*</th>
<th>M1-PSF</th>
<th>$\rho(E,J)$</th>
<th>$\Gamma_{\gamma}^{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brink-Axel</td>
<td>SP</td>
<td>CTF</td>
<td></td>
<td>410±47</td>
</tr>
<tr>
<td>Brink-Axel</td>
<td>SF</td>
<td>CTF</td>
<td></td>
<td>352±42</td>
</tr>
<tr>
<td>KMF</td>
<td>SP</td>
<td>BSFG</td>
<td></td>
<td>201±14</td>
</tr>
<tr>
<td>KMF</td>
<td>SF</td>
<td>BSFG</td>
<td></td>
<td>172±12</td>
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<tr>
<td>GLO</td>
<td>SP</td>
<td>BSFG</td>
<td></td>
<td>156±8</td>
</tr>
<tr>
<td>GLO</td>
<td>SF</td>
<td>BSFG</td>
<td></td>
<td>126±8</td>
</tr>
<tr>
<td>Experiment (Mughabghab, 2006)</td>
<td></td>
<td></td>
<td></td>
<td>148±10</td>
</tr>
</tbody>
</table>

*GDER parameters from Dietrich and Berman, ADNDT 38, 199 (1988).
Comparison of $^{105}$Pd(n,γ) simulated $\Sigma\sigma_\gamma$(in) with experimental $\Sigma\sigma_\gamma$(out)

$\sigma_0 = \sigma_\gamma^{(GS)}_{\text{expt}} + \sigma_\gamma^{(GS)}_{\text{calc}} = 20.3 \pm 0.3 \text{ b} + 1.4 \pm 0.3 \text{ b} = 21.7 \pm 0.5 \text{ b}$

$\sigma_0$ (Mughabghab, 2006) = 21.0 ± 1.5 b
## Determination of $\sigma_0$ for $^{104}\text{Pd}(n,\gamma)^{105}\text{Pd}$

If minimal experimental data is available $\sigma_0$ can be calculated with DICEBOX independently for each observed level feeding.

<table>
<thead>
<tr>
<th>PSF</th>
<th>LD</th>
<th>$\rho(E,J)$</th>
<th>GDER</th>
<th>$E_{\text{crit}}$(keV)</th>
<th>280</th>
<th>306</th>
<th>344</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLO</td>
<td>SP</td>
<td>BSFG</td>
<td>Dietrich</td>
<td>350</td>
<td>23(9)</td>
<td>4.3(13)</td>
<td>10(3)</td>
</tr>
<tr>
<td>KMF</td>
<td>SP</td>
<td>BSFG</td>
<td>Herman</td>
<td>350</td>
<td>26(9)</td>
<td>4.1(12)</td>
<td>10(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Average</strong></td>
<td>24(9)</td>
<td>4.2(12)</td>
<td>10(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma^\text{expt}_\gamma$(b)</td>
<td>0.145(13)</td>
<td>0.040(8)</td>
<td>0.099(18)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_0$(b)</td>
<td>0.60(23)</td>
<td>0.95(35)</td>
<td>0.99(35)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Average</strong></td>
<td>0.77(17) b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mughabghab, 2006 0.65(30) b
### Pd $\sigma_0$ results*

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\sigma_0$(literature) (barns)</th>
<th>$\sigma_0$(this work) (barns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{102}\text{Pd}(n,\gamma)^{103}\text{Pd}$</td>
<td>1.6±0.2</td>
<td>1.1±0.4</td>
</tr>
<tr>
<td>$^{104}\text{Pd}(n,\gamma)^{105}\text{Pd}$</td>
<td>0.65±0.30</td>
<td>0.77±0.17</td>
</tr>
<tr>
<td>$^{105}\text{Pd}(n,\gamma)^{106}\text{Pd}$</td>
<td>21.0±1.5</td>
<td>21.7±0.5</td>
</tr>
<tr>
<td>$^{106}\text{Pd}(n,\gamma)^{107}\text{Pd}$</td>
<td>0.30±0.03</td>
<td>0.36±0.10</td>
</tr>
<tr>
<td>$^{108}\text{Pd}(n,\gamma)^{109}\text{Pd}$</td>
<td>7.6±0.5</td>
<td>7.2±0.5</td>
</tr>
<tr>
<td>$^{108}\text{Pd}(n,\gamma)^{109}\text{Pd}^m$</td>
<td>0.185±0.010</td>
<td>0.185±0.011</td>
</tr>
<tr>
<td>$^{110}\text{Pd}(n,\gamma)^{111}\text{Pd}$</td>
<td>0.70±0.17</td>
<td>0.34±0.10</td>
</tr>
</tbody>
</table>

* Submitted to Physical Review C.
Future Directions

- The EGAF database will be expanded to include activation data in collaboration with the IAEA CRP Reference Database for Neutron Activation Analysis.
- Total thermal radiative neutron cross sections $\sigma_0$ will be derived from EGAF data for all isotopes.
- The EGAF $\sigma_0$ values will be compared with literature values and new evaluated $\sigma_0$ values will be included in EGAF.
- Capture $\gamma$-ray spectra will be compared with DICEBOX calculations to find input parameters that best reproduce the continuum shape.
- EGAF will be extended to include continuum $\gamma$-rays.
- DICEBOX calculations will be extended to use the thermal parameters for calculations at higher neutron energies.
- ENDF format $\gamma$-ray libraries will be generated in collaboration with LLNL.
241Am(n,2n) at TUNL, 11 points, 7-15 MeV
- Measure partial (n,γn) cross section and use model to back the (n,2n).

Plan a measurement of 239Pu(n,2n)

237U(n,f) by using surrogate 238U(α,α’), 0.5-20 MeV, 10-30% accuracy

241mAm capture at DANCE (LANL), 1 eV – 105 eV

ALEXIS intense neutron source (10^{10} n/sec) under construction, tunable 0.01-15 MeV
Experimental program at LLNL

Ching-Yen Wu
Lawrence Livermore National Laboratory
Nov 7, 2007
Outline

1. Tailored to the need of Stockpile Stewardship Program
2. Direct cross section measurement
   • \((n,2n)\) cross section measurement using \(A\). the activation method or \(B\). the prompt \(\gamma\)-ray technique
   • \((n,\gamma)\) cross section measurement using DANCE
3. Indirect cross section measurement using the surrogate technique
4. Direct and indirect \((n,f)\) cross section measurement
5. New capabilities under development:
   • Time Projection Chamber
   • ALEXIS
6. Summary
\[^{241}\text{Am}(n,2n)\] cross section; activation method

1. Activation technique – counting the $\gamma$ activity after irradiation of $^{241}\text{Am}$
2. Fielded at Triangle Universities Nuclear Lab (TUNL) in FY06
3. Monoenergetic neutrons with $7.6 \leq E_n \leq 14.5$ MeV and flux $\sim 10^7 - 10^8$/(cm$^2$ sec)
4. $^{241}\text{Am}$ targets with a total mass about 1 mg each
5. The neutron fluence measured by multiple witness foils:
   - $^{27}\text{Al}(n,\alpha)$ ($T_{1/2} = 15$ hr),
   - $^{58}\text{Ni}(n,p)$ ($T_{1/2} = 71$ d),
   - $^{197}\text{Au}(n,2n)$ ($T_{1/2} = 6.2$ d)

LANL/TUNL/LLNL collaboration
$^{241}\text{Am}(n,2n)$: experimental setup at TUNL

Irradiation for ~24 h

Target assembly; $^{241}\text{Am}$ together with Al-Ni-Au monitor foils

$^2\text{H}(d,n)^3\text{He}$

25 mm
$^{241}\text{Am}(n,2n)$: results

Eleven data points from 7.6 to 14.5 MeV with excellent statistical accuracy
$^{241}$Am(n,2n): comparison of cross section

Good agreement with the early measurements except for the data near 11 MeV
$^{239}\text{Pu}(n,2n)$ cross section; prompt $\gamma$-ray technique

1. $^{239}\text{Pu}(n,2n)$ cross section deduced from the reaction modeling of measured $(n,2n\gamma)$ partial cross section

2. Cross section was deduced for $E_n$ from threshold to $<20$ MeV from the $6^+\rightarrow 4^+$ transition of $^{238}\text{Pu}$ in an earlier work (PRC 65, 02160(R), 2002)

3. The new effort aims to deduce the cross section from the $4^+\rightarrow 2^+$ transition to reduce the uncertainty introduced by modeling

4. Accomplished by enhancing the sensitivity of $\gamma$-ray spectroscopy by excluding the $\gamma$ rays of fission fragments that tagged by a fission counter

5. Experiments scheduled at TUNL in FY08 and FY09

LLNL/TUNL/LANL collaboration

Hauser-Feshbach Model

Deduce $\sigma_{n,2n}$ with models
$^{239}$Pu(n,2n): fission counter

1. Multi-anode structure
2. Four targets with a total mass $\sim$10 – 14 mg
3. Two LEPS for the $\gamma$-ray detection in a close geometry
Surrogate technique: introduction

A useful technique for the neutron-induced reaction cross sections that are difficult to measure directly

\[ \sigma_{\alpha\chi}(E) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E, J, \pi)G_{\chi}^{CN}(E, J, \pi). \]

\[ P_{\chi}(E) = \sum_{J,\pi} F_{\delta}^{CN}(E, J, \pi)G_{\chi}^{CN}(E, J, \pi), \]

\(^{237}\text{U}(n,\text{destruction})\) cross section; surrogate technique

**Surrogate reaction:** \(^{238}\text{U}(\alpha,\alpha')\) at \(E_\alpha = 55\) MeV (PRC 73, 054605, 2006)

1. Direct cross section measurement for \(^{237}\text{U}\) is difficult because of the short half-life, 6.75 d
2. Using the surrogate technique, reaction cross sections for the \((n,\gamma)\), \((n,2n)\), and \((n,f)\) channels can be determined with an accuracy of 10 – 30%
Surrogate technique: experimental setup at LBNL

1. Forward $\Delta E-E$ silicon array for the light charged-particle identification
2. Backward $E$ silicon detector for the fission-fragment detection
3. Six clover detectors for the $\gamma$-ray detection

LIBERACE collaboration (LLNL/LBNL/U Cal at Berkeley/U Richmond/Yale)
Direct and indirect \((n,f)\) cross section measurement

1. **Direct measurement**
   - Fission-fragment detection using the gas avalanche counter
     - Together with DANCE at LANL for \(E_n\) from thermal to about 100 keV
     - Together with two LEPS at TUNL for \(E_n\) from 4 to 14 MeV
   - Trajectory tracking by the Time Projection Chamber

2. **Indirect measurement using the surrogate technique; example:** \(^{237}\text{U}(n,f)\) via \(^{238}\text{U}(\alpha,\alpha' f)\)
242m Am(n,f) cross section: results from DANCE

1. ~47 µg material
2. Six-day beam time
3. $\sigma_f$ for $E_n$ up to ~100 keV was determined
4. Agreement with early results is reasonable
5. Early results were obtained in 12 – 18 months

LLNL/LANL/TUNL collaboration
Time Projection Chamber: introduction

Improve the precision of measured $^{239}$Pu(n,f) cross section to ~1%

Capability:
1. Trajectory reconstruction
2. High background-event rejection
3. Charged-particle identification
4. Standalone or in conjunction with other detectors

LLNL/LANL/INL/Georgia Inst Tech/Ohio U/Oregon St U/Cal Poly St U/Col Sch Mines/Abilene Chris U
**ALEXIS: an intense, tunable neutron source at LLNL**

Pelletron accelerates *light ions* (p, d, He) which impinge on various isotopic targets to produce neutron beams with specified intensities and energy spectrum.

**Neutron Production:**

<table>
<thead>
<tr>
<th>Production Reaction</th>
<th>Neutron Energy Range (MeV)</th>
<th>Neutron Energy Spread (FWHM)</th>
<th>Total Neutron Yield (n/s)</th>
<th>Neutron Flux at 10 cm from target (n/cm²/s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^7\text{Li}(p,n)^7\text{Be})</td>
<td>0.01-0.4</td>
<td>~30 keV</td>
<td>(10^9)</td>
<td>(10^7)</td>
<td>4</td>
</tr>
<tr>
<td>(t(p,n)^3\text{He})</td>
<td>0.5-5.0</td>
<td>~400 keV</td>
<td>(&gt;10^9)</td>
<td>(&gt;10^7)</td>
<td>1,2</td>
</tr>
<tr>
<td>(d(d,n)^3\text{He})</td>
<td>5.0-9.0</td>
<td>~400 keV</td>
<td>(&gt;10^{10})</td>
<td>(&gt;10^8)</td>
<td>3</td>
</tr>
<tr>
<td>(t(d,n)^4\text{He})</td>
<td>13.0-15.0</td>
<td>~100 keV</td>
<td>(10^{10})</td>
<td>(10^7)</td>
<td>1,2</td>
</tr>
</tbody>
</table>

1. 5 mg/cm² titanium assumed for tritium target.
2. Same tritium target can be use for both (p,n) and (d,n) reactions.
3. ~0.5 MeV is assumed energy loss in deuteron target.
4. \(^7\text{Li}(p,n)\) produces roughly 30 keV thermal spectra with beam energy of 1.918 MeV.
ALEXIS: 3-D view

Accelerator at Livermore for Experiments in Isotopic Science: ALEXIS

Charged Particle Beamline

Neutron Production Target

Pelletron
Summary

1. Experimental program at LLNL is developed to support the Stockpile Stewardship Program
   • Provide the data in uncharted territory
   • Improve the precision for the measured cross section
   • Improve the predictive capabilities of nuclear modeling
2. Also relevant to GNEP
3. Team with the university personnel funded under NNSA/SSAA, LANL, and LBNL in both experimental and theoretical areas
4. TPC begins the prototyping in FY08
5. ALEXIS begins the beam delivery in FY09
6. Continue to develop new direction and capability as needed
Acknowledgement


5. U. Richmond – C.W. Beausang

6. Yale U – A. Ai

7. TPC – M. Heffner (LLNL)

8. ALEXIS – L. Ahle (LLNL)
Iron filtered beam measurements of Mo and Be
Transmission measurements on C and Be and Mo, 0.4-20 MeV
Neutron Scattering from C, 0.5-20 MeV
Transmission and Capture measurements on Cd
LSDS
  - Simultaneous measurements of the fission cross section and fission fragment mass and energy distributions for $^{235}\text{U}$ and $^{239}\text{Pu}$.  
  - Developing capabilities (n,α) cross sections on small samples or low cross sections
Cross Section Measurements and Analysis at Rensselaer

Report to CSEWG November, 2007

Y. Danon, R. C. Block, N. Francis, M. Lubert, M. Rapp, F. Saglime, R. Bahran, C. Romano, J. Thompson

Rensselaer Polytechnic Institute, Troy, NY, 12180

and

D.P. Barry, N.J. Drindak, J.G Hoole, G. Leinweber

KAPL Inc., Lockheed Martin Corporation, Schenectady, NY 12301-1072
Measurements Completed This Year

- **Mo**
  - High energy (0.4-20 MeV) transmission
  - High accuracy filtered beam transmission (0.024 - 0.9 MeV)
- **Be**
  - High energy (0.4-20 MeV) transmission
- **C**
  - High energy (0.4-20 MeV) neutron scattering
- **Cd**
  - Thermal (0.01-20 eV) transmission measurements on thin natural metallic samples
Planned Measurements

• Transmission and capture on $^{153}$Eu and natural Eu
• High energy (0.4-20 MeV) Transmission for Zr
• High energy (0.4-20 MeV) neutron scattering from Be and Mo
• Resonance region (1 eV- 400 keV) transmission for Mo
• Isotopic Mo – ORNL is developing methods for sample production
## Data Analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh</td>
<td>SAMMY analysis pending</td>
</tr>
<tr>
<td>Cd</td>
<td>SAMMY/REFIT analysis pending (Moxon has our data)</td>
</tr>
<tr>
<td>Re</td>
<td>Data analysis in progress</td>
</tr>
<tr>
<td>U-236</td>
<td>Sammy analysis in progress</td>
</tr>
<tr>
<td>Dy</td>
<td>Data reduction and SAMMY analysis in progress.</td>
</tr>
</tbody>
</table>
New Capabilities

- Transmission Measurements at 100m flight path
  - High energy transmission and spectra measurements in the energy range 0.2-20 MeV. The system is installed and running, results will be shown
  - New resonance region detector is under construction

- Scattering detector array at ~30m flight path for the energy range 0.2-20 MeV
  - A digital data acquisition system allows pulse shape analysis with dead time on the order of the detector response time (~100ns)
  - Testing with graphite completed, flux measurements completed

- High precision filtered beam transmission measurements.
  - Discrete points in the energy range from 0.2 - 0.9 MeV
  - Cross section accuracy of ≤1% was demonstrated with graphite, Be and Mo
Iron Filter Experimental Setup

Water Cooled Ta Target

30 cm Fe

Sample

Li-Glass Neutron Detector

Collimation

Collimation

Collimation

25.55 m.
Mo Total Cross Section (filtered beam)

- Data shows evidence of structure
- Data points overlap within 2*error.
- Between 0.2 MeV to 0.8 MeV the data closer to ENDF/VI.8
- In general in this energy region ENDF/B-VII.0 tends to have smoother cross sections than previous versions
- More on structure later
High Energy Transmission Experimental Setup

Graphite Samples

Nominal thickness in cm
33 13 7 5

99.93 m

EJ-301 Liquid Scintillator Modular Detector
Results – Carbon Total Cross Section
Beryllium Transmission

Beryllium samples
Sample thickness is given in cm

Reconfigured the detector with two units to reduce background
Beryllium Total Cross Section (Low Energy)
Beryllium Total Cross Section (High Energy)
Mo transmission initial analysis

Natural Mo
• RPI-3 cm sample
• RPI-8 cm sample
• RPI-Filtered beam
- ENDF/B-VII.0
- ENDF/BVI.8
Mo Data 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
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 EJ301 Liquid Scintillation Detectors
  – Detector Stands
• Sample Holder / Changer
• The RPI developed software can process the TOF data and distinguish neutrons from gammas by pulse shape analysis
Preliminary Carbon Scattering Results

New data emphasizes the low energy (0.5-5 MeV) region

7cm thick Graphite Target

Pulsed Neutron Beam

26°

120°

90°
High Resolution Transmission Detector

• Modular Li-Glass detector will be positioned at 100m flight path
  – Extends our capabilities up to the unresolved resonance region
Thermal Total Cross Section of Natural Cd - I

- 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

\[ \sigma_t \text{ (barns)} \]

\[ \text{Energy (eV)} \]

~5% difference in 0.0253 eV !!!
Lead Slowing Down Spectrometer

- **Fission** cross section and fission fragment spectroscopy
  - Measure a $^{235}\text{U}$ sample to get more data with improved setup.
  - Run a $^{239}\text{Pu}$ sample

- **Detectors for** ($\text{n},\alpha$) **measurements** are being developed
  - Compensated Solar Cells
  - Compensated PIPS detectors
  - Compensated GEM amplified detectors (shown on the right)
Results – Fission Fragment Mass distribution $E_n < 0.1$ eV

252Cf

235U

239Pu

252Cf Pre-neutron Emission Masses

252Cf Post-neutron Emission Masses

235U Pre-neutron Emission Fission Fragment Masses

235U Post-neutron Emission Masses

239Pu Pre-neutron Emission Masses

239Pu Post-neutron Emission Masses
Results – Fission Fragment Energy Distribution

\[ ^{235}\text{U Preneutron Emission Energy} \]

\[ ^{252}\text{Cf Preneutron Emission Energy} \]

\[ ^{239}\text{Pu Preneutron Emission Energy} \]

Yield vs. Energy [MeV]

Current Data and Hambsh Data comparison for preneutron emission energy distributions.
Results – Measured Fission Cross Section

$^{235}$U Cross Section Measured in LSDS

- This Experiment
- OLD RPI Measurement

$\sigma_f \text{ [barn]}$

Neutron Energy [eV]

Current Data
Broadened ENDF/B-VII.0

$^{239}$Pu Cross Fission Cross Section

- Current Data
- Broadened ENDF/B-VII.0

$\sigma_f \text{ [barns]}$

Neutron Energy [eV]

ENDF/B-VI broadened
LSDS Compensated Fission Chamber 9.87 ng
LSDS Compensated Solar Cell 27 ng

$^{239}$Pu(n,f)

RPI 2007
LANL 2006

Sigma (Barns)
Energy (keV)
Summary

- Re, Rh, Cd, $^{236}\text{U}$, Dy and Mo measurements are currently being analyzed.
- New detector systems for transmission and scattering are now operational.
  - High energy transmission measurements on C, Be and Mo were completed.
  - Scattering data on graphite is being analyzed.
- An Iron filtered beam is used for high precision transmission measurements in the energy range from 0.24 keV to 0.9 MeV.
  - Measurements on C, Be and Mo were completed.
- New transmission detector for high resolution resonance measurements is under construction.
- A Lead slowing down spectrometer is used for fission and (n,α) cross section measurements.
Problem with Data Sets??
Cd-113 Thermal cross section

<table>
<thead>
<tr>
<th>ENDF/B-VII</th>
<th>NNDC Sigma [barn]</th>
<th>NNDC (Old) [barn]</th>
<th>JANIS 3 [barn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Header</td>
<td>20641</td>
<td>20641</td>
<td>20641</td>
</tr>
<tr>
<td></td>
<td>20672.8</td>
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<td>20672.8</td>
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<tr>
<td>Plot</td>
<td>20802.3</td>
<td>20826.89</td>
<td>20748.35</td>
</tr>
<tr>
<td>Integral Table</td>
<td></td>
<td></td>
<td>20748.3</td>
</tr>
</tbody>
</table>
Use surrogate (d,p) to measure (n,\(\gamma\))
Test on known Develop for \(^{73,74,75}\text{As}(n,\gamma)\) and \(^{92,94}\text{Sr}(n,\gamma)\)
Test on known \(^{171,173}\text{Yb}\)
New Results from Radioactive Ion Beam Studies for Stewardship Science

Stewardship Science Academic Alliance Program

Jolie A. Cizewski
Rutgers University
Challenge: Understanding neutron capture reactions on unstable nuclei

- Important for understanding origin of elements heavier than Fe
  - Slow (s) and rapid (r) neutron capture nucleosynthesis processes
- Important for understanding performance of next generation reactors
  - Reactions on long-lived fission products and materials in reactors
- Common challenge: Intense source of neutrons
  - Multiple neutron-induced reactions on unstable nuclei
  - Direct \((n,\gamma)\) measurements limited to \(t_{1/2}>100 \text{ days}\)
Addressing the Challenge:
Surrogate reactions

- Measure surrogate of \((n, \gamma)\) reaction, the \((d,p)\) reaction, with beams of unstable rare isotopes

\[
A(n,\gamma)(A+1) \leftrightarrow A(d,p)(A+1)
\]

- First step: Demonstrate that \((d,p\gamma)\) IS surrogate for \((n, \gamma)\)
  - Measure \((d,p\gamma)\) cross sections for systems with \((n,\gamma)\) cross sections known
- Future: Measuring \((d,p\gamma)\) reactions with rare isotope beams
  - \(^{75}\text{As}(d,p\gamma)\) approved as development for future \(^{73,74}\text{As}(d,p\gamma)\) surrogate measurements
  - \(^{92,94}\text{Sr}(d,p\gamma)\) approved
  - Future: other rare isotope beams basic and applied nuclear science and astrophysics
Experimental Setup: (d,pγ) surrogate for (n,γ)

- Targets: $^{171,173}$Yb
  - (n,γ) known
- Beam: 18.5 MeV deuterons of the 88” Cyclotron at LBNL
- 3 Si detectors for particle detection (STARS)
- 6 Ge clover detectors to detect coincident γ-rays (LIBERACE)
Preliminary Analysis $^{171,173}$Yb(d,p$\gamma$)

- Particle identification
- Clearly distinguish protons
- Gate on protons
- Interest $E_x > S_n$ in $^{172}$Yb

Gamma-ray spectrum gated above $S_n$ in $^{172}$Yb

R. Hatarik et al.,
CNR 2007 Proceedings
Preliminary Analysis $^{171,173}$Yb(d,p$\gamma$)

Ratios of intensities of $4\rightarrow2$ transitions in $^{172}$Yb and $^{174}$Yb gated above $S_n$ can be $(n,\gamma)$ surrogate cross sections for $^{171,173}$Yb.

Analysis: gate on (d,p$\gamma$) spectra that most accurately reflect the spin distribution from (n,$\gamma$).

R. Hatarik et al., CNR 2007 Proceedings
Triangle Universities Nuclear Laboratory

- Precision measurements of $(n,2n\gamma)$ cross section
- Results on $^{241}$Am$(n,2n)^{240}$Am from 7-15 MeV
- Work on $^{235}$U$(n,2n)^{234}$U is in progress
Neutron Induced Reactions on Actinides Using Pulsed and Monoenergetic Beams at Triangle Universities Nuclear Laboratory

Anton P. Tonchev

Duke University and Triangle Universities Nuclear Laboratory

Los Alamos National Laboratory

TUNL
Precision Measurements of the $(n,2n\gamma)$ Reaction Cross Sections on Actinides

**Goal:** Improve partial cross section data of actinide nuclei for the Stockpile Stewardship Program

**Emphasis:** The $^{239}\text{Pu}(n,2n\gamma)$ cross section

**Technique:** High-resolution $\gamma$-ray spectroscopy measurements:
- in beam with pulsed and monoenergetic neutron beam
- off-line with DC neutron beam

**Modeling:** Hauser-Feshbach theory (GNASH, EMPIRE, TALYS)

SSAA 2008 Symposium
Motivation for the $^{241}\text{Am}(n,2n)$ Reaction Cross Section Measurements

Improved $^{241}\text{Am}(n,2n)$ cross sections are needed for:

- Nuclear forensics $\Delta A(^{240}\text{Am}/^{241}\text{Am})$
- Analogous to $\Delta P (^{238}\text{Pu}/^{239}\text{Pu})$
- Sensitive to high-energy neutrons
- Advance Fuel Cycle / new fast reactors
- Important in transmutation studies

**Goal:** To measure the $^{241}\text{Am}(n,2n)$ cross section within 5-10% from $E_n = 6.7$ MeV to 14.5 MeV
Status of the (n,2n) Measurements on $^{241}\text{Am}$

- (n,2n) data for $^{241}\text{Am}$ around 14 MeV
- Energy dependence near 14 MeV
- No data below $\sim$13 MeV
- Different evaluations
- The recent data shows very high (n,2n) cross section at $E_n \approx 11\text{MeV}


Need to extend and verify the $^{241}\text{Am}(n,2n)^{240}\text{Am}$ cross section to lower energies
**Activation Measurements at TUNL**

- **DENIS**
- **Neutron production**
  - D(d,n) neutron source
  - $I_d = 2 \mu A$
  - $E_n = 7.6 - 14.5 \text{ MeV}$
  - Pulsed at 2.5 MHz

- **Activation parameters**
  - $\phi_n = (1-5) \times 10^7 \text{ n/(cm}^2 \text{ sec)}$
  - Fluence = $(1-5) \times 10^{12} \text{ n}$
  - $\sim 1\text{mg } ^{241}\text{Am targets (} \phi = 1\text{cm)}$

- **Neutron TOF area**
  - 3 monitor foils (Al, Ni, Au)
  - n-flux monitoring: 3 neutron detectors ($0^\circ, \pm 10^\circ$)

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SSAA 2008 Symposium
$^{240}$Am $\gamma$-Ray Signature

- Measured 2000-3000 $\gamma$-events after a 1-2 day irradiation and 1 day counting time
- Measured 11 energies in March, Nov., Dec. 2006 runs
Experimental Results: $^{241}\text{Am}(n,2n)^{240}\text{Am}$

- Good agreement between Al, Ni and Au foils up to 9 MeV
- Strong deviation of the Ni foils at $E_n > 9$ MeV
- CS saturation at $E_n = 13$ MeV
- $\sigma_{\text{max}} = 264$ mb
- Rule out the CS data at $E_n = 11$ MeV
- ENDF-B/VII agrees well with the TUNL data

A. Tonchev et al. Submitted to PRC.
SSAA 2008 Symposium
TUNL and In-beam Measurements

DENIS

Shielded Neutron Source Area

Neutron production
- D(d,n) neutron source
- $\phi_n = 2 \times 10^4$ n/(cm$^2$ sec)
- Tunable from 4 – 20 MeV
- Pulsed at 2.5 MHz

A. Hutcheson et al. NIMB 261 (2007) 369
SSAA 2008 Symposium
NNSA Setup at TUNL

- 4 Clovers + BGO
- 2 Planars + BGO
- $10 \text{ keV} < E_{\gamma} < 10 \text{ MeV}$
- $20^0 < \theta_{\text{lab}} < 160^0$
- $\epsilon_{\text{array}} = 1.4\%@E_{\gamma} = 1.33 \text{ MeV}$

**Capabilities**

- $\gamma$-$\gamma$ coincidence measurements
- Angular distribution measurements
- Lifetimes (by Doppler method)

⇒ Excellent tool for precision neutron induced cross section measurements in the fast energy region ($4 \leq E_n \leq 20 \text{ MeV}$)
Neutron Induced Cross Section on $^{235}\text{U}$

$^{235}\text{U}(n,2n)^{234}\text{U}$

Gamma-ray spectrum

$E_n = 10\text{MeV}$

$^{234}\text{U}$

SSAA 2008 Symposium
Educational Importance and Broader Impact Activities of the NNSA at TUNL

NNSA (n,xnγ) activity: low-energy introduction to nuclear experimental techniques for the Research Experience for Undergraduates (REU) program at TUNL

- Average 8-10 REU students every summer
- For the past four years one or two has been involved in the TUNL NNSA project
- Diversification of the NNSA setup for basic research:
  - nuclear structure
  - nuclear astrophysics
  - neutrino and dark matter
- NNSA electronics and DAQ system:
  (poster presented by John Kelley)
Conclusion

- Complete cross section measurements of the $^{241}\text{Am}(n,2n)^{240}\text{Am}$ reaction.

- $\gamma$-ray partial cross sections from $(n,n'\gamma)$ and $(n,2n'\gamma)$ reactions were measured in $^{238}\text{U}$ and $^{235}\text{U}$ from 6 to 14.5 MeV.

- This program plays important role in attracting young nuclear scientist.

⇒ Strong TUNL-LANL-LLNL Collaboration Effort
### Participants*

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<tr>
<th>TUNL</th>
<th>Livermore</th>
<th>Los Alamos</th>
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<td><strong>Duke:</strong></td>
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*(n,2n) measurements supported by the NNSA Stewardship Science Academic Alliance and by DOE/NNSA LANL & LLNL