Recent developments in neutron capture on actinides using the DANCE detector

J.L. Ullmann

Los Alamos National Laboratory

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Other DANCER’s


Los Alamos National Laboratory

C.-Y. Wu, J.A. Becker

Lawrence Livermore National Laboratory

A. Chyzh, G.E. Mitchell

North Carolina State University

M. Krticka

Charles University, Prague
Capture cross-sections and spectra important

- Neutron capture cross sections and gamma-emission spectra of importance to basic science and many applied fields

- Capture cross sections difficult to calculate, rely on measurements

- Careful measurements have been made on most common stable nuclides

- Must rely on calculations for rare or unstable nuclides

- Benchmark calculations against measurements
  - Cross sections
  - Gamma-ray spectrum

Stellar capture cross sections calculated with the statistical model code NON-SMOKER compared with available experimental data.

(From Rauscher and Thielemann, *Atomic and Nuclear Astrophysics*, IOP, 1998)
Detector for Advanced Neutron Capture Experiments

- Nearly 4\(\pi\) coverage (\(\approx 3.5\pi\))
- 160 BaF\(_2\) crystals - 4 different shapes
- High efficiency - milligram samples
- Highly segmented - radioactive targets
- \(^6\text{LiH}\) inner sphere to absorb scattered neutrons
- 20.25 m from water moderator
- LANSCE spallation source - 800 MeV p @ 100 \(\mu\)A

\[
\Phi = 550E^{-1.04} \text{ n/cm}^2/\text{eV}/\text{To at 22.6 m}
\]
DANCE Calorimeter

- Calorimetric => Summed Gamma Energy ≈ Q value (S_n)
- Permits ID of target!
- \( E_x = T_n (1 + M_n / M_A) + Q \)

\[
\begin{align*}
\text{\(^{138}\text{Ba}(n,\gamma)\)} & \quad Q = 4.72 \text{ MeV} \\
\text{\(^{134,136}\text{Ba}(n,\gamma)\)} & \quad Q = 6.9 \text{ MeV} \\
\text{\(^{135,137}\text{Ba}(n,\gamma)\)} & \quad Q = 9.11, 8.62 \text{ MeV} \\
\text{\(\text{Au}(n,\gamma)\)} & \quad Q = 6.51 \text{ MeV}
\end{align*}
\]
Calculations – some formula’s

Hauser-Feshbach

\[ \sigma_{\text{capt}}(E_n) = \frac{\pi}{k_n^2} \sum_{j\pi} g_e \frac{T_n T_\gamma}{T_n + T_\gamma} W_{n\gamma}, \]

Gamma transmission coefficient

\[ T_\gamma = \sum_{j^\pi X_L} \int_0^{E'} 2\pi E_\gamma^{(2L+1)} f_{X_L}(E_\gamma) \rho(E_x, j^\pi) dE_x \]

Normalized γ transmission (s-wave)

\[ T_\gamma = 2\pi \frac{\langle \Gamma_\gamma \rangle}{D_0}. \]

DICEBOX

\[ \Gamma_{ab} = \sum_{X_L} y_{X_L}^2 [E_a - E_b]^{2L+1} \frac{f_{X_L}(E_a - E_b)}{\rho(E_a, j_{a}^\pi)} \]
\( ^{238}\text{U}(n,\gamma) \) Spectrum Simulations

Kopecky and Uhl
(Phys. Rev. C 41, 1941 (1990) )

\[ f = \text{GLO} + \text{SLO(SF)} + \text{SLO(E2)} \]

**SLO (Standard Lorentzian)**

\[ f^{\text{SLO}}(\varepsilon_\gamma) = \frac{1}{3\pi^2(\hbar c)^2} \frac{\sigma_R \varepsilon_\gamma \Gamma_R^2}{(\varepsilon_\gamma^2 - E_R^2)^2 + \varepsilon_\gamma^2 \Gamma_R^2} \]

**GLO (Generalized Lorentzian)**

\[ f^{\text{GLO}}(\varepsilon_\gamma) = \frac{\sigma_R \Gamma_R}{3\pi^2(\hbar c)^2} \left[ \frac{\varepsilon_\gamma \Gamma_K(\varepsilon_\gamma, T)}{(\varepsilon_\gamma^2 - E_R^2)^2 + \varepsilon_\gamma^2 \Gamma_K(\varepsilon_\gamma, T)} + 0.7 \frac{\Gamma_K(0, T)}{E_R^3} \right] \]

\[ \Gamma_K(\varepsilon_\gamma, T) = (\varepsilon_\gamma^2 + 4\pi^2 T^2) \frac{\Gamma_R}{E_R^2} \quad T = \sqrt{\frac{S_n - \varepsilon_\gamma}{\alpha}} \]

\[ S_n = 4.8 \text{ MeV} \]
$^{238}\text{U}(n,\gamma) \text{ M}=2 \text{ Gamma-ray spectrum}$

Kopecky and Uhl
(Phys. Rev. C 41, 1941 (1990))

\[ f_{XL} = GLO(E1) + SLO(SF) + SLO(E2) \]
(SF and E2 Parameters from RIPL)

DICEBOX calculation

\[ \Gamma_{ab} = \sum_{XL} y_{XL}^2 [E_a - E_b]^{2L+1} \frac{f_{XL}(E_a - E_b)}{\rho(E_a, J_a^\pi)} \]

MC cascades -> GEANT model
("forward modeling")

"Realizations" band
Oslo-method strength function

Fit to GDR (photoneutron yield)

Oslo method $f_{\text{xl}}$

2 component M1

$^{234,236,238}$U$(n,\gamma)$ Gamma Ray Spectra
Cross-section calculation with CoH$_3$

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

- PRC 89
- Full calculation
- Full calc, default $\rho$
- Kopecky-Uhl (GLO + GT)
- K-U, Norm to $\Gamma_1$ / $D_0$

**GDR:** Herman/EMPIRE (CoH$_3$)

$\rho$: Gilbert-Cameron (Kawano, J. Nucl. Sci. Tech. 43, 1 (2006))

Scissors: $E$ and $\Gamma$ from Guttormsen, Phys. Rev. C 89, 014302 (2014); Strengths adjusted

M1(SF), E2: RIPL-3
# Sensitivity of $<\Gamma_\gamma>$ to parameters

Calculate $<\Gamma_\gamma>$ with different $\rho$, strength function parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Gamma_{\gamma}$ (meV)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$^{235}$U</td>
</tr>
<tr>
<td>PSF</td>
<td>NLD</td>
</tr>
<tr>
<td>Von Egidy CT PRC 72</td>
<td>CoH$_3$ [17]</td>
</tr>
<tr>
<td>Von Egidy CT PRC 80</td>
<td>CoH$_3$ [18]</td>
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<tr>
<td>Kawano GC JNST 43</td>
<td>CoH$_3^*$ [19]</td>
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<td>Oslo*</td>
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<td>Oslo Renorm*</td>
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<td>MGLO* [17]</td>
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<tr>
<td>Evaluation [38]</td>
<td></td>
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</tbody>
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CoH$_3$ parameters from M. Herman, EMPIRE INDC-0603 (2013)

## Vary E1 GDR parameters (NLD, M1, E2 fixed)

- **CoH$_3$**
  - Veyssiere (Nucl.Phys. **A227**, 513 (1974) ) \( E1 = 6 \text{–} 10 \text{ meV} \)
  - Gurevich (Nucl. Phys. **A273**, 326 (1976) ) \( M1 + E2 = 16 \text{ meV} \)
Generalization to all nuclei

$$E_{sm} = 80 \beta_2/A^{1/3} \text{ MeV} \quad \sigma_{sm} \Gamma_{sm} = K \beta_2^2 \text{ mb-MeV} \quad (\Gamma = 1.5 \text{ MeV})$$

$$K = 42.4 \pm 5.0 \quad (\text{Fit to 106 FP's } A < 200)$$

FIG. 1. Ratios of the calculated capture cross sections at 200 keV to the selected evaluated cross sections in ENDF/B-VII.1 and JENDL-4. The triangles show the case when the Hauser-Feshbach calculations do not include the M1 scissors mode. The circles are with the scissors mode.

FIG. 2. Additional M1 strength $\sigma_{M1} \Gamma_{M1}$ GDR required to reproduce the evaluated capture cross section at 200 keV for selected nuclei in the fission product region. The quadratic curve is the least-squares fitting to the symbols, and the dashed curves are the 1-\sigma band. The filled points are for the Gd isotopes.

Kawano, APS DNP 2015
Mumpower, Kawano, et al., submitted to Phys. Rev. C
Compare measured $\langle \Gamma \gamma \rangle$ to Calculated

$\langle \Gamma \gamma \rangle$ calculated with parameters on previous slide
Actinide region was not used in determining K

Kawano, APS DNP 2015
Mumpower, Kawano, et al., submitted to Phys. Rev. C
\( ^{239}\text{Pu} \) capture – gamma-ray spectra

- \( ^{239}\text{Pu}(n,\gamma) S_n = 6.53 \text{ MeV} \)
- Fission tagging with PPAC
- Analysis underway
  - 11.90 eV \( 1^+ \) resonance
Results

- Shape of capture cross section vs neutron energy is not sensitive to exact form of strength function (although magnitude is)
- Kopecky-Uhl prescription ($GLO (E1) + SLO (M1SF) + SLO (E2)$ ) is not sufficient to describe shape of observed gamma-ray spectra
- Additional strength at low energies (2 ~ 3 MeV) - likely M1 Scissors Mode- is required
- Accurate calculations of capture cross section for $^{234,236,238}U$ can be made when including SM - with proper choice of $\rho$ and PSF
- Extending study to odd-mass actinides ($^{235}U$, $^{239}Pu$) and additional nuclei
Extra slides
Los Alamos Neutron Science Center (LANSCE)
Neutron Research facilities at LANSCE

Weapons Neutron Research Facility

Target-4
High-energy neutron research

Target-2
- Proton-induced reactions
- Single-pulse experiments

Lujan Center
Low-energy neutrons
- Material science
- Nuclear science

Proton Radiography
Linear Accelerator

NRAD
Line B
UCN

Area A (inactive)

Line D

PSR
Lujan Center

Target 1

Target 2

Target 4
Uranium resonances

\[ ^{234}\text{U}(n,\gamma) \]

\[ ^{236}\text{U}(n,\gamma) \]

\[ ^{238}\text{U}(n,\gamma) \]

\( \ell = 0 \ \frac{1}{2}^+ \)

Counts

Neutron Energy (eV)