Surrogate Reactions for Neutron Capture

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• Nucleosynthesis: the s- and r-processes are primarily responsible for the creation of elements heavier than iron.

• Applications:
  – National Security
  – Nuclear Energy

• Critical to a robust understanding of nuclear data, but hard to measure!
  – No pure neutron targets exist:
    • target lifetimes limited to $t_{1/2} \geq \sim 100$ days
    • can’t directly measure neutron capture for exotic systems.

• A surrogate measurement is necessary
  – NC reaction proceeds through a compound nucleus rather than directly (except in weakly-bound systems)
  – Neutron capture at energies of interest for astrophysics is dominated by s-waves
**Surrogate Technique**

\[ \sigma_{a\chi} (E_a) = \sum_{J,\pi} \sigma_{a\chi}^{CN} (E_{ex}, J, \pi) G_{\chi}^{CN} (E_{ex}, J, \pi) \]

**Ex. Ch. B.R.**

**Prob. B*:**

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

- **“Absolute” [1]:**  
  \[ P_{\delta\chi}^{exp} (E_{ex}) = \frac{N_{\delta\chi}}{N_{\delta}\epsilon_{\chi}} \]

- **“Ratio” [2]:** determine ratio of branching ratios

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**Figures from J. Escher et al. Rev. Mod. Phys. 84, 353 (2012).**


$^{155}\text{Gd}(n,\gamma)$ vs $^{156}\text{Gd}(p,p'\gamma)$

Black: measured and calculated $\sigma(n,\gamma)$

Blue, yellow data
Surrogate-deduced $\sigma(n,\gamma)$ from $2\rightarrow 0$ & $4\rightarrow 2$ transitions

Curves:
- Purple = (d) distribution; peak=1.5
- Red = (e) distribution; peak=4.5
- Green = (f) distribution; peak=7.5

N. Scielzo et al. PRC 81 034608 (2010)
## TABLE I. Summary of the cross sections examined in the last decade (ordered by isotope) using the surrogate reactions method. The neutron energy ($E_n$) range covered, surrogate-reaction used, type of measurement (absolute vs ratio), and publication reference are listed.

<table>
<thead>
<tr>
<th>Desired reaction</th>
<th>$E_n$ range (MeV)</th>
<th>Surrogate reaction</th>
<th>Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{230}$Th($n$, $f$)</td>
<td>0.5–10</td>
<td>$^{232}$Th($^3$He, $\alpha$))</td>
<td>absolute</td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{230}$Th($n$, $f$)</td>
<td>0.22–25</td>
<td>$^{232}$Th($^3$He, $\alpha$))</td>
<td>ratio</td>
<td>Goldblum et al. (2009)</td>
</tr>
<tr>
<td>$^{231}$Th($n$, $f$)</td>
<td>0.36–25</td>
<td>$^{232}$Th($^3$He, $^3$He')</td>
<td>ratio</td>
<td>Goldblum et al. (2009)</td>
</tr>
<tr>
<td>$^{231}$Pa($n$, $f$)</td>
<td>0.5–10</td>
<td>$^{232}$Th($^3$He, $t$)</td>
<td>absolute</td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{233}$Pa($n$, $f$)</td>
<td>0.5–10</td>
<td>$^{232}$Th($^3$He, $p$)</td>
<td>absolute</td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{233}$Pa($n$, $f$)</td>
<td>11.5–16.5</td>
<td>$^{232}$Th($^6$Li, $\alpha$)</td>
<td>ratio</td>
<td>Nayak et al. (2008)</td>
</tr>
<tr>
<td>$^{233}$U($n$, $f$)</td>
<td>0.4–18</td>
<td>$^{234}$U($\alpha$, $\alpha'$)</td>
<td>ratio</td>
<td>Lesher et al. (2009)</td>
</tr>
<tr>
<td>$^{236}$U($n$, $f$)</td>
<td>0–20</td>
<td>$^{238}$U($^3$He, $\alpha$)</td>
<td>absolute, ratio</td>
<td>Lyles et al. (2007a)</td>
</tr>
<tr>
<td>$^{237}$U($n$, $f$)</td>
<td>0–13</td>
<td>$^{238}$U($d$, $d'$)</td>
<td>ratio</td>
<td>Plettner et al. (2005)</td>
</tr>
<tr>
<td>$^{237}$U($n$, $f$)</td>
<td>0–20</td>
<td>$^{238}$U($\alpha$, $\alpha'$)</td>
<td>ratio</td>
<td>Burke et al. (2006)</td>
</tr>
<tr>
<td>$^{239}$U($n$, $f$)</td>
<td>0–20</td>
<td>$^{238}$U($^{18}$O, $^{16}$O)</td>
<td>ratio</td>
<td>Burke et al. (2011)</td>
</tr>
<tr>
<td>$^{237}$Np($n$, $f$)</td>
<td>10–20</td>
<td>$^{238}$U($^3$He, $t$)</td>
<td>absolute, ratio</td>
<td>Basunia et al. (2009)</td>
</tr>
<tr>
<td>$^{238}$Pu($n$, $f$)</td>
<td>0–20</td>
<td>$^{239}$Pu($\alpha$, $\alpha'$)</td>
<td>ratio</td>
<td>Ressler et al. (2011)</td>
</tr>
<tr>
<td>$^{241}$Am($n$, $f$)</td>
<td>0–10</td>
<td>$^{243}$Am($^3$He, $\alpha$)</td>
<td>absolute</td>
<td>Kessedjian et al. (2010)</td>
</tr>
<tr>
<td>$^{242}$Cm($n$, $f$)</td>
<td>0–10</td>
<td>$^{243}$Am($^3$He, $t$)</td>
<td>absolute</td>
<td>Kessedjian et al. (2010)</td>
</tr>
<tr>
<td>$^{243}$Cm($n$, $f$)</td>
<td>0–3</td>
<td>$^{243}$Am($^3$He, $d$)</td>
<td>absolute</td>
<td>Kessedjian et al. (2010)</td>
</tr>
</tbody>
</table>

| $^{155}$Gd($n$, $\gamma$) | 0.05–3.0 | $^{156}$Gd($p$, $p'$) | absolute, ratio | Scielzo et al. (2010) |
| $^{157}$Gd($n$, $\gamma$) | 0.05–3.0 | $^{158}$Gd($p$, $p'$) | absolute, ratio | Scielzo et al. (2010) |
| $^{161}$Dy($n$, $\gamma$) | 0.13–0.56 | $^{162}$Dy($^3$He, $^3$He') | ratio | Goldblum et al. (2010) |
| $^{170}$Yb($n$, $\gamma$) | 0.165–0.405 | $^{171}$Yb($^3$He, $^3$He') | ratio | Goldblum et al. (2008) |
| $^{170}$Yb($n$, $\gamma$) | 0.225–0.465 | $^{172}$Yb($^3$He, $\alpha$) | ratio | Goldblum et al. (2008) |
| $^{171}$Yb($n$, $\gamma$) | 0.12–0.24 | $^{171}$Yb($d$, $p$) | ratio | Hatarik et al. (2010) |
| $^{233}$Pa($n$, $\gamma$) | 0–1 | $^{232}$Th($^3$He, $p$) | absolute | Boyer et al. (2006) |
| $^{235}$U($n$, $\gamma$) | 0.9–3.3 | $^{235}$U($d$, $p$) | ratio | Allmon et al. (2009) |
| $^{237}$U($n$, $\gamma$) | 0.2–1.0 | $^{238}$U($\alpha$, $\alpha'$) | absolute, ratio | Bernstein et al. (2006); Young et al. (2007) |
\[ {^{95}\text{Mo}}(n,\gamma){^{96}\text{Mo}} \leftrightarrow {^{95}\text{Mo}}(d,p\gamma){^{96}\text{Mo}} \]

Validating Surrogate for (n,\(\gamma\))

\[ {^{95}\text{Mo}}(n}\gamma) \]

\[
\begin{array}{c}
\text{Sigma (mb)} \\
\hline
\text{Neutron energy (keV)} \\
\text{2441 keV} \\
\text{1870 keV} \\
\text{1628 keV} \\
\text{1626 keV} \\
\text{778 keV} \\
\end{array}
\]

Measure
Yrast I(\(\gamma\)) vs \(E_n\)
(n,\(\gamma\)) (d,p\(\gamma\)) normal (d,p\(\gamma\)) inverse

\[ {^{96}\text{Mo}}, J^{\pi} = 0^+ \]

Mugrove, et al., NPA \textbf{270}, 109 (1976)

Slide Courtesy of J. A. Cizewski
With $^{95}$Mo target

- Measure yrast $I(\gamma)$ vs $E_n$ in ($n,\gamma$)
- At LANSCE on FP12 with HPGe detectors

Musgrove, et al., NPA 270, 109 (1976)
• 0.960 mg/cm² thick $^{95}$Mo target
• Beam energy of 13 MeV
• 140 µm +1000 µm segmented telescopes at forward, backward angles.
• Four HPGe Compton-suppressed clovers.
• One hour of data shown.
Program to Validate \( (d,p\gamma) \): IK \( (d,p\gamma) \) at ANL

- Inverse Kinematics measurement of \( ^{95}\text{Mo}(d,p\gamma) \) at ANL with ORRUBA-Gammasphere

- Develop \( (d,p\gamma) \) in inverse kinematics with RIBS:
  - Confirm that \( (d,p\gamma) \) yields same results in normal and inverse kinematics.
  - Measure multiplicity of photons, for which Gammasphere is ideally suited.

- Details at ICFN5 (me) and at DNP (Shand).
Facilities:
- Beam rates on order of a nA
- Pure beams
- Energies near Coulomb barrier

Detector Systems:
- For particles: high energy, position (angular) resolution, large solid angle coverage (maximize detection efficiency without compromising angular resolution). Focus on good PID!
- For gammas: high $\gamma$-ray detection efficiency, high $\gamma$-ray energy resolution (becomes crucial as we begin to study more exotic systems)
Collaboration
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Amy Anderson and Charles Reed (ORAU)
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With Special Thanks to:

Mike Carpenter (ANL)
Shaofei Zhu (ANL)

Amy Anderson (ORAU)
Ken Carter (ORAU)
Charles Reed (ORAU)

Thank you for your attention!
TIARA Performance

Only core signals from EXOGAM clovers, limiting Doppler correction to 65 keV broadening.

$2 \times 10^5$ pps $^{24}$Ne

1 mg/cm$^2$ CD$_2$ target

2 mm beam spot

Slide courtesy of Steven Pain
## GS Efficiency

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Geo Efficiency</th>
<th>Boosted Efficiency</th>
<th>Total Boosted Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full, 0 cm/ns</td>
<td>45%</td>
<td>45%</td>
<td>10.6%</td>
</tr>
<tr>
<td>-1 ring, 0 cm/ns</td>
<td>43%</td>
<td>43%</td>
<td>10.2%</td>
</tr>
<tr>
<td>-2 rings, 0 cm/ns</td>
<td>41%</td>
<td>41%</td>
<td>9.7%</td>
</tr>
<tr>
<td>Full, 4.13 cm/ns</td>
<td>41%</td>
<td>41%</td>
<td>9.7%</td>
</tr>
<tr>
<td>-1 ring, 4.13 cm/ns</td>
<td>40%</td>
<td>40%</td>
<td>9.4%</td>
</tr>
<tr>
<td>-2 rings, 4.13 cm/ns</td>
<td>40%</td>
<td>40%</td>
<td>9.4%</td>
</tr>
</tbody>
</table>
Microball in Gammasphere

http://www.chemistry.wustl.edu/~dgs/mball/pics/mball-a.jpg