Strengths and limitations of the surrogate reaction method to access neutron-induced cross sections of actinides

P. Marini, Q. Ducasse, B. Jurado, M. Aiche, L. Mathieu, G. Barreau, S. Czajkowski, I. Tsekhanovic
CENBG, Gradignan, France

University of Oslo, Oslo, Norway

J. Wilson, M. Lebois
IPNO, Orsay, France

M. Wiedeking
iThemba, Somerset West, South Africa

O. Serot, G. Boutoux, P. Chau, V. Mot, O. Roig
CEA Cadarache and CEA-DAM, France
**Fundamental nuclear properties:**

- Reaction mechanisms: from CN formation to direct processes
- CN decay modeling (fission barrier, transmission coefficients... nuclear potential, nuclear structure)

**Nuclear energy applications:**

Development of new advanced nuclear systems

(\(^{235}\text{U}\) only fissile nucleus naturally available)

**Interest for Astrophysics:**

Understanding the origins of elements heavier than Fe

- observed isotopic abundances
- nuclear data
- parameters of stellar interior (\(\rho_n, p, T\))

Mainly short-lived nuclei

Surrogate reaction method
Detection of:

- ejectile:
  - Identify the CN
  - Determine the CN $E^*$

- reaction products
  - exit channel

Strengths:

- access to short-living nuclei (different transfer channels)
- simultaneous access to several nuclei on a broad $E^*$ range
- n free environment
- high beam intensity ($\sim 10^{12}$pps)
Assumptions

- Formation of CN (Bohr hypothesis)
- The $J^\pi$ distribution of the CN is the same in the two reactions
  OR
  the decay of the CN is independent of its $J^\pi$ distribution
  (Weisskopf-Ewing limit)

\[
\sigma_{\text{decay}}^{A-1}(E_n) \equiv \sum_{J^\pi} \sigma_{\text{CN}}^{A}(E_n, J^\pi) \cdot P_{\text{decay}}^{A,\text{transfer}}(E^*, J^\pi)
\]

Calculated
  (Optical model calculations)

Measured

Test of the assumptions
  (fission and $\gamma$ emission)
TEST OF THE ASSUMPTIONS : TWO EXAMPLES

FISSION on actinides

$^{243}$Am($^3$He,$\alpha$)$^{242}$Am$^*$

G. Kessedjian et al., PLB 692, 297 (2010)
FISSION on actinides

$^{243}\text{Am}(^{3}\text{He},\alpha)^{242}\text{Am}^*$

$^{241}\text{Am}(n,f)$

G. Kessedjian et al., PLB 692, 297 (2010)

$\gamma$ EMISSION on rare earth

$^{174}\text{Yb}(^{3}\text{He},p\gamma)^{176}\text{Lu}^*$

Only $\gamma$ and n channels open

G. Boutoux, et al., PLB 712 (2012) 319
FISSION on actinides

\[ ^{243}\text{Am} (^{3}\text{He}, \alpha) ^{242}\text{Am}^{*} \]

\[ ^{241}\text{Am} (n, f) \]

G. Kessedjian et al., PLB 692, 297 (2010)

\[ ^{176}\text{Lu}^{-7} \rightarrow ^{175}\text{Lu}^{9/2^+} + ^{7/2^+} \]

\[ E^{*} \]

\[ S_n \]

\[ ^{175}\text{Lu} \]

\[ ^{176}\text{Lu} \]

\[ ^{3}\text{He}, \gamma ^{176}\text{Lu}^{*} \]

\[ 243\text{Am} (^{3}\text{He}, \alpha) ^{242}\text{Am}^{*} \]

\[ ^{174}\text{Yb} (^{3}\text{He}, \gamma) ^{176}\text{Lu}^{*} \]

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

Different Jπ distributions populated

At E*~S_n n emission hindered by spin/parity selectivity of n-emission channel

Optical model TALYS (CEA Bruyères-le-Châtel)

From exp. Pγ

\[ P_n + P_\gamma = 1 \]
INTERNET OF THE RESULTS ON $\gamma$ EMISSION

FISSION on actinides
$^{243}\text{Am}(^{3}\text{He},\alpha)^{242}\text{Am}^*$

$^{176}\text{Lu}^{7-}$
$^{174}\text{Yb}^{3\text{He},\gamma)^{176}\text{Lu}^*$

G. Kessedjian et al., PLB 692, 297 (2010)
G. Boutoux, et al., PLB 712 (2012) 319

Only $\gamma$ and n channels open:
$P_n + P_\gamma = 1$

$\gamma$ EMISSION on rare earth

Different $J^\pi$ distributions populated

At $E^* \sim S_n$ n emission hindered by spin/parity selectivity of n-emission channel

Simultaneous measurement of fission and $\gamma$ probabilities on actinides
Ph. D. thesis of Q. Ducasse

$$^{238}\text{U} + n \rightarrow ^{239}\text{U}^* \rightarrow ^{238}\text{U}(d,p)$$

Corrected for d break-up (A. Moro – Seville Univ.)
Ph. D. thesis of Q. Ducasse

$^{238}\text{U} + n \rightarrow ^{239}\text{U}^* \xrightarrow{\gamma} ^{238}\text{U}(d,p)$

Corrected for $d$ break-up

(A. Moro – Seville Univ.)

Good agreement: fission not modified by $n$-emission hindering
Independent of the populated CN spin $J$

Strong discrepancies: $\gamma$ emission enhanced by $n$-emission hindering
Strong dependence on the populated CN $J$

is it explained by statistical model?
Ph. D. thesis of Q. Ducasse

**Statistical Model Predictions**

\[ P_f (E^*) \approx \sum_{J^*} \left[ \frac{1}{2\sigma \sqrt{2\pi}} e^{-\frac{(J-J^*)^2}{2\sigma^2}} \right] P^\text{TALYS} (E^*, J^*) \]

- Statistical model (TALYS, run by CEA evaluator)
- Statistical model (TALYS)
E*(239U) MeV

\[ P_f \approx \sum_{J^*} \frac{1}{2J^* \sqrt{2\pi}} e^{-\frac{(J^*-J)^2}{2\sigma^2}} P_{\gamma}^{\text{TALYS}}(E^*,J^*) \]

\( P_{\gamma}(E^*) \approx \sum_{J^*} \left( \frac{1}{2\sigma J^* \sqrt{2\pi}} \right) e^{-\frac{(J^*-J)^2}{2\sigma^2}} P_{\gamma}^{\text{TALYS}}(E^*,J^*) \)

**SUMMARY**

- \( \gamma \) probability is enhanced by n-emission hindering, i.e. dependence on the populated CN J
- Fission probability not enhanced by n-emission hindering, i.e. independent of the populated CN J
- Statistical model predicts a higher fission threshold (dependence of fission on J)

**new experiment**
Ph. D. thesis of Q. Ducasse

\[ ^{236}\text{U} + \text{n} \rightarrow ^{237}\text{U}^* \rightarrow ^{238}\text{U}(^{3}\text{He},^{4}\text{He}) \]

- Setup not adapted for this reaction
- Low statistics
- No d break-up

Same effects!!

new dedicated experiment
NEW PRECISE SIMULTANEOUS MEASUREMENT OF FISSION AND GAMMA PROBABILITIES OF ACTINIDES

- Ejectile detector: xy segmented Si telescope
- $\gamma$ detectors: Ge and C$_6$D$_6$
- FF detectors: segmented photovoltaic cells

- Reduce the uncertainties on $P_f$ and $P_\gamma$ on $^{238}$U($^3$He,$\alpha$): measure on FF anisotropy
- Increase the statistics
- Well defined beam energy
- No break-up of $^3$He projectile
Ge detectors

\( \text{C}_6\text{D}_6 \)

Reaction chamber

Sas

- Ejectile detector: xy segmented Si telescope
- \( \gamma \) detectors: Ge and C6D6
- FF detectors: segmented photovoltaic cells

- Reduce the uncertainties on Pf and P\( \gamma \) on \(^{238}\text{U}(^3\text{He},\alpha)\)
- Measure on FF anisotropy
- Increase the statistics
- Well defined beam energy
- No break-up of \(^3\text{He}\) projectile
Surrogate reaction method: only way to access short-lived nuclei.

Surrogate reactions vs neutron induced reactions:
- Fission cross section measurements in good agreement
- Gamma emission cross sections in strong disagreement

- Strong dependence of gamma emission on the populated CN J distribution
- Independence of fission on the populated CN J distribution

These observations are not currently explained within statistical model.

Need to understand the formation and decay mechanisms of CN in surrogate reactions.

New experimental data with better resolution and statistics (April 2015)
- Theoretical support is welcome....
**STATISTICAL MODEL PREDICTIONS**

---

**Statistical Model**

(TALYS, run by CEA evaluator)

\[ P_j(E^*) \approx \sum_{J^\pi} \frac{1}{2\sigma J} e^{-\frac{(J-J_j)^2}{2\sigma^2}} P_J^{TALYS}(E^*, J^\pi) \]

---

**Data**

- \( ^{238}\text{U}(p,d)^{239}\text{U}^* \)
- \( 2n \) E\(^*(239\text{U}) \) MeV

---

**Graphs**

- Graphs showing probability distributions for different energies and reactions.
27 NaI inorganic scintillators (γ-ray detection)

4 PPACs Fission-fragments detection

8 telescopes of 8 strips ΔE/E

THE OSLO EXPERIMENT SETUP
### SURROGATE REACTION EXPERIMENTS SINCE 2004

<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>$^{232}$Th(n, f)</td>
<td>0.5–10</td>
<td>($n, f$) cross sections</td>
<td></td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{209}$Th(n, f)</td>
<td>0.22–25</td>
<td>$^{232}$Th($^3$He, α)$^1$</td>
<td>absolute</td>
<td>Goldblum et al. (2009)</td>
</tr>
<tr>
<td>$^{211}$Th(n, f)</td>
<td>0.36–25</td>
<td>$^{232}$Th($^3$He, $^3$He)$^1$</td>
<td>ratio</td>
<td>Goldblum et al. (2009)</td>
</tr>
<tr>
<td>$^{211}$Pa(n, f)</td>
<td>0.5–10</td>
<td>$^{232}$Th($^3$He, t)$^1$</td>
<td>absolute</td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{232}$Pa(n, f)</td>
<td>0.5–10</td>
<td>$^{232}$Th($^3$He, p)$^1$</td>
<td>absolute</td>
<td>Petit et al. (2004)</td>
</tr>
<tr>
<td>$^{232}$Pa(n, f)</td>
<td>11.5–16.5</td>
<td>$^{232}$Th($^3$Li, α)$^1$</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($^3$He, α)$^1$</td>
<td>absolute, ratio</td>
<td>Lesher et al. (2009)</td>
</tr>
<tr>
<td>$^{236}$U(n, f)</td>
<td>0–20</td>
<td>$^{236}$U($^3$He, α)$^1$</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($d, d'$)$^1$</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($^3$He, α)$^1$</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($^3$He, t)$^1$</td>
<td>absolute, ratio</td>
<td>Burke et al. (2011)</td>
</tr>
<tr>
<td>$^{238}$Pu(n, f)</td>
<td>0–20</td>
<td>$^{239}$Pu($^3$He, t)$^1$</td>
<td>absolute, ratio</td>
<td>Basunia et al. (2009)</td>
</tr>
<tr>
<td>$^{238}$Am(n, f)</td>
<td>0–10</td>
<td>$^{243}$Am($^3$He, α)$^1$</td>
<td>absolute</td>
<td>Ressler et al. (2011)</td>
</tr>
<tr>
<td>$^{246}$Cr(n, f)</td>
<td>0–10</td>
<td>$^{247}$Am($^3$He, t)$^1$</td>
<td>absolute</td>
<td>Kessedjian et al. (2010)</td>
</tr>
<tr>
<td>$^{248}$Cm(n, f)</td>
<td>0–3</td>
<td>$^{249}$Am($^3$He, d)$^1$</td>
<td>absolute</td>
<td>Kessedjian et al. (2010)</td>
</tr>
<tr>
<td>$^{155}$Gd(n, γ)</td>
<td>0.05–3.0</td>
<td>$^{155}$Gd(p, p)$^1$</td>
<td>absolute, ratio</td>
<td>Sciellz et al. (2010)</td>
</tr>
<tr>
<td>$^{157}$Gd(n, γ)</td>
<td>0.05–3.0</td>
<td>$^{155}$Gd(p, p)$^1$</td>
<td>absolute, ratio</td>
<td>Sciellz et al. (2010)</td>
</tr>
<tr>
<td>$^{161}$Dy(n, γ)</td>
<td>0.13–0.56</td>
<td>$^{161}$Dy($^3$He, $^4$He)$^1$</td>
<td>ratio</td>
<td>Goldblum et al. (2010)</td>
</tr>
<tr>
<td>$^{170}$Yb(n, γ)</td>
<td>0.165–0.405</td>
<td>$^{171}$Yb($^3$He, $^4$He)$^1$</td>
<td>ratio</td>
<td>Goldblum et al. (2008)</td>
</tr>
<tr>
<td>$^{171}$Yb(n, γ)</td>
<td>0.225–0.465</td>
<td>$^{171}$Yb($d, p$)$^1$</td>
<td>ratio</td>
<td>Hatarik et al. (2010)</td>
</tr>
<tr>
<td>$^{171}$Yb(n, γ)</td>
<td>0.12–0.24</td>
<td>$^{171}$Yb($d, t$)$^1$</td>
<td>ratio</td>
<td>Allmond et al. (2009)</td>
</tr>
<tr>
<td>$^{233}$Pa(n, γ)</td>
<td>0–1</td>
<td>$^{232}$Th($^3$He, p)$^1$</td>
<td>absolute</td>
<td>Boyer et al. (2006)</td>
</tr>
<tr>
<td>$^{235}$U(n, γ)</td>
<td>0.9–3.3</td>
<td>$^{235}$U($d, p$)$^1$</td>
<td>ratio</td>
<td>Allmond et al. (2009)</td>
</tr>
<tr>
<td>$^{237}$U(n, γ)</td>
<td>0.2–1.0</td>
<td>$^{238}$U($^3$He, α)$^1$</td>
<td>absolute, ratio</td>
<td>Bernstein et al. (2006);</td>
</tr>
</tbody>
</table>

**References**


---

$^{232}$Th(n,γ) 0–1.2  $^{232}$Th(d,p) absolute J. Wilson et al. (2012)

$^{175}$Lu(n,γ) 0–1  $^{174}$Yb($^3$He,p) absolute G. Boutoux et al. (2012)

$^{172}$Yb(n,γ) 0–1 $^{174}$Yb($^3$He,α) absolute G. Boutoux et al. (2012)
(d,p) reaction are interesting for inverse kinematics experiments (…RIBs…)

CDCC framework

Elastic breakup

Inelastic breakup

Breakup fusion

Difficult to be distinguished by theory!

CDCC (Continuum discretized coupled-channel calculation)

Antonio Moro and Jin Lei, Univ. of Sevilla, Spain