Neutron-induced cross sections measurements via surrogate reactions: a way to determine new transmutation nuclear data for minor actinides

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Outlook

1. Nuclear data and transmutation

2. Neutron-induced cross sections measurements for short-lived nuclei
   
   This part exposes the surrogate reaction method and its validity.

3. Surrogate measurements in CENBG and recent studies applied to capture reactions

4. Perspectives
Energetic context and nuclear waste issues

→ Few words about nuclear energy...

Evolution of fuel in PWR 900MW

- 33 kg de $^{235}$U
- 967 kg de $^{238}$U

After 3 years

- 8 kg de $^{235}$U
- 943 kg de $^{238}$U
- 35 kg de PF
- 9 kg de Pu
- 4.6 kg de $^{236}$U
- 0.5 kg de $^{237}$Np
- 0.5 kg de $^{243}$Am
- 0.04 kg de $^{244}$Cm

Valorized waste
Ultimate waste
Minor Actinides

Volume: 0.1% but radiotoxicity after 100 years: 96%

→ Geological waste disposal

→ Transmutation: decrease the radiotoxicity of waste before disposal
From nuclear issues to neutron data needs

Fission products transmutation

Neutron capture

\[ \text{Neutron capture} \]

\[ \text{T}_{1/2} = 2.11 \times 10^5 \text{ ans} \]

\[ \text{T}_{1/2} = 15 \text{ s} \]

Incineration via ADS

Incineration via RNR

Minor actinides incineration

Fission

\[ \text{T}_{1/2} = 7380 \text{ ans} \]

\[ \text{~A/2Y} \]

\[ \text{~A/2Z} \]

Incineration power...

\[ \alpha = \frac{\sigma_{\text{capture}}}{\sigma_{\text{fission}}} \]

... best with FAST NEUTRONS

- Incineration via RNR
- Incineration via ADS
Current context for neutron data

Simulation tools

Neutron Nuclear Database

Fundamental models

Evaluation

EXFOR

Contribution of CENBG

- Uncompleted database
- Difficulties for experimentalists

$T_{1/2} = 162.8 \text{d}$

No data, only predictions...

$\sigma_\gamma [\text{b}]$ vs $E_n [\text{MeV}]$

$^{242}\text{Cm} \sigma(n,\gamma)$

Short half life = Highly radiotoxic targets
How to measure cross sections for short-lived nuclei?

Neutron-induced reaction

\[ n + (A-1) \rightarrow (A)^* \]

Highly radiotoxic targets! = Strong background +

\[ P_{\text{neutron,decay}}(E^*) = P_{\text{transfer,decay}}(E^*) \]

The surrogate method

\[ \sigma_{\text{decay}}^{A-1}(En) \cong \sigma_{\text{CN}}^A(En).P_{\text{transfer}}^{A,\text{decay}}(E^*) \]

Calculated (optical model) in CEA-DAM-BIII

Measured

J.D. Cramer et H.C. Britt, Nucl. Sci. And Eng. 41 (1970) 177
**Neutron-induced decay probability**

\[ P_{\text{neutron,decay}}(E^*) = \sum_{J^\pi} P_{\text{neutron}}(E^*, J^\pi) \cdot G_{\text{decay}}(E^*, J^\pi) \]

**Transfer-induced decay probability**

\[ P_{\text{transfer,decay}}(E^*) = \sum_{J^\pi} P_{\text{transfer}}(E^*, J^\pi) \cdot G_{\text{decay}}(E^*, J^\pi) \]

**J^\pi-independent decay probability for the exit channel**

\[ G_\gamma(E^*, J^\pi) = G_\gamma(E^*) \]

*Weisskopf-Ewing limit:*

Valid at high \( E^* \) in which the decay is dominated by statistical level densities!!

*Low J^\pi population mismatch*

**Spin distribution of the compound nucleus in the**

\[ ^{175}\text{Lu}(n,\text{g})^{176}\text{Lu} \text{ (solid line) for } E_n=100 \text{ keV} \text{ (red), } 1 \text{ MeV} \text{ (green) and } 2 \text{ MeV} \text{ (blue) and in the } ^{174}\text{Yb}(3\text{He},p\gamma)^{176}\text{Lu} \text{ (dotted line), for } E^*=6\text{MeV} \text{ (red), } 7 \text{ MeV} \text{ (green) and } 8 \text{ MeV} \text{ (blue).} \]
Some works about surrogate method validation

**Fission cross sections** for Am/Cm isotopes → Good agreement the surrogate data for fission.

**Capture cross section** for $^{233}\text{Pa}$, but unfortunately no direct neutron-induced measurement for comparison.

Capture cross sections for minor actinides and validation of the surrogate method for minor actinides is the aim of my PhD thesis.

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

$^{232}\text{Th}(^3\text{He},p\gamma)^{234}\text{Pa}^*$
Validation of the surrogate method for neutron capture cross sections

- Undisponibility of targets in the region of actinides
- Continuity of a preliminary experiment with stable rare-earth target:
  \[ {^{174}Yb}(3\text{He},p\gamma){^{176}Lu} \]
- Region of interest for astrophysics
- Well known cross section (for comparison with neutron-induced reaction measurements)
Methodology for $^{175}$Lu capture cross sections

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

γ detection via 6x C6D6

2x ejectile (proton) identification

Faisceau $^3$He

Sensitive Position Si Detector

Si(Li) Detector

Proton Identification = $^{176}$Lu* formation

Cinematic parameters:
From E and $\theta$, we can determine $E^*$
(excitation energy of the nucleus $A^*$)

Probability of $^{176}$Lu gamma emission
$P_\gamma(E^*) = N_{\gamma^p} / \varepsilon_{\gamma}.N_p$

Coincidence $p\gamma$ detection

Identification des particules (Cs11 vs PSD)
Preliminary experiment (TANDEM IPN Orsay - February 2009)

Our goal: test of the charged particle detector (CPD) and its coupling to the γ-ray detectors (Ge and C6D6)

Ge (ORGAM in the future)

γ Transition intensities

Identification of decaying nucleus

ΔE-E telescopes

174Yb target

C6D6 scintillators

γ decay probability

Definitive experiment planned for February 2010
Check the validity of surrogate method for minor actinides.

- $^{236}\text{U}(3\text{He},p)^{238}\text{Np} \rightarrow ^{237}\text{Np}(n,\gamma)$
- $^{238}\text{U}(3\text{He},t)^{238}\text{Np} \rightarrow ^{237}\text{Np}(n,\gamma)$
- $^{236}\text{U}(3\text{He},4\text{He})^{235}\text{U} \rightarrow ^{234}\text{U}(n,\gamma)$
- $^{238}\text{U}(3\text{He},4\text{He})^{237}\text{U} \rightarrow ^{236}\text{U}(n,\gamma)$
- $^{238}\text{U}(d,p)^{239}\text{U} \rightarrow ^{238}\text{U}(n,\gamma)$
- $^{232}\text{Th}(d,p)^{233}\text{Th} \rightarrow ^{232}\text{Th}(n,\gamma)$

Complete or reactualize nuclear data for minor actinides transmutation, but also thorium cycle, fission products, fusion applications and astrophysics.
Difficulty to measure neutron capture cross sections because of fission background.

- No E-W approximation in the range 1-700 keV
- Necessity to have similar $J\pi$ distribution
Les états $J^\pi$ peuplés par les deux réactions sont-ils les mêmes ??

\[
J = J(J_{\text{cible}}, J_{\text{part}}, \ell)
\]

Distributions du moment angulaire transféré pour des neutrons

(J.P. Delaroche et al. (2002))

Réactions de transfert

(B.B. Back et al. (1974))
Semimicroscopic optical model calculation Bruyeres le Chatel, E. Bauge

Based on →
• HFB calculations with Gogny D1S interaction to predict deformed proton and neutron densities
• The deformed densities are folded with the Jeukenne, Lejeune & Mahaux (JLM) effective interaction

![Graph showing Cm isotopes](image)

- 242Cm
- 243Cm
- 244Cm

Dashed: nonelastic cross section (Col. 3)
Solid: compound cross section (Col. 3 minus Cols. 5-8)