Status of \((n,xn \gamma)\) reaction cross section measurements on actinides with the GRAPhEME set-up at GELINA

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M. Nyman, A. J. M. Plompen - JRC/IRMM
C. Borcea, A. Negret, A. Olacel - IFIN-HH
General context

Fuel cycle

Systems, scenario

Gen IV reactor systems

EXFOR

ENDF

JENDL

NUCLEAR DATA

Reprocessing

Safety

Dismantling

Nuclear reaction codes

ACCURACY
General context: \((n,xn)\) reactions

\((n,xn)\) reaction in reactor core
- Energy loss mechanism
- Neutron multiplication
- \(\gamma\) production
- Production of radioactive isotopes

\(^{238}\text{U}(n,n')\) XS uncertainty
- from 5% to 20%

\(^{238}\text{U}(n,n')\) problematic

GEN-3 reactors:
- large sizes \(\Rightarrow\) radial power sensitive to ND

GEN-4 reactors:
- fast neutron spectrum \(\Rightarrow\) \(k_{\text{eff}}\) sensitive to ND

Target accuracy on \(^{238}\text{U}(n,n')\):
- PWR: \(\pm 10\%\)
- SFR: \(\pm 5\%\)
General context: experimental method

Prompt γ-ray spectroscopy method

Theoretical model

Spectroscopic parameters

Measured \((n,xn \, \gamma)\) cross sections

Level production and total \((n,xn)\) cross sections

Powerful method which provides a lot of cross sections:
- \((n,xn \, \gamma)\)
- Level production
- Total

Project:
- Experimental study of the neutron inelastic and \((n,xn)\) scattering by the prompt \(\gamma\)-ray spectroscopy method,
- 10 years collaboration IPHC/CNRS – IRMM/JRC – IFIN-HH,

See contributions: M.Nyman, IRMM
A.Olacel, IFIN-HH
A.Negret, IFIN-HH
G.henning, IPHC
Inelastic scattering and (n,xn) experimental studies

4 HPGe Planar (110°,150°) Actinides samples
ΔEn = 10 keV @ En = 1 MeV

GELINA@IRMM(Geel)

GELINA

GRAPhEME @ FP16/30 m

12 HPGe Ø 80 mm x L 80 mm (110°,150°)
ΔEn = 1 keV @ En = 1 MeV

Dresden, December 3th, 2014

Maëlle Kerveno
From \((n,xn \, \gamma)\) XS to total XS: step by step

Level production and total \((n,xn)\) cross sections

Prompt g-ray spectroscopy method

Theoretical model

Spectroscopic parameters

Measured \((n,xn \, \gamma)\) cross sections

Gamma efficiency
- detect. eff. determination
- sample characterization

Number of counts
- stability
- identification
- fitting procedure
- low energy gamma
(n,xn γ) challenges: $^{238}$U example

$^{238}$U level scheme

<table>
<thead>
<tr>
<th>E. (keV)</th>
<th>Reaction</th>
<th>E₁ (E₂)</th>
<th>E₂ (E₃)</th>
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<tbody>
<tr>
<td>44.915</td>
<td>(n,n')</td>
<td>44.915</td>
<td>0 (0+)</td>
</tr>
<tr>
<td>103.5</td>
<td>(n,n')</td>
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<td>44.915  (2+)</td>
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<td>104.2</td>
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<td>45.2 (2+)</td>
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<td>106.3$^a$</td>
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... and 1014.5 in $^{27}$Al

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<td>1278.54 (2-)</td>
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</table>

$^a$ Observed, but not referenced in NNDC website.

**Target** natU: 10.6 g, 0.18 mm

**Beam time**: 1200 h

36 (n,n' γ) XS
- Large set of data
- 5 in the main band
- 6 to the ground state

3 (n,2n γ) XS

4 (n,3n γ) XS

Analysis work: A. Bacquias (IPHC)
(n,xn $\gamma$) challenges: $^{238}$U example

**$\gamma$ efficiency:**
- MCNP, GEANT4 simulations, punctual and extended source meas.
- Precise sample characterization (number of atoms, oxidation)

Sample before polishing

Sample after polishing

**JRC/IRMM**
Precise $\gamma$-ray spectroscopy meas. ($^{234}$U $\gamma$-transition)
Atom number $^{238}$U (~1 %)

**IRMM target laboratory**
precise sample mass and thickness $\text{nat}^\text{U} \sim 10^{-3}$
determination before and after polishing

**JRC/ITU**
Surface oxidation type: mixed U$_3$O$_8$ + C
Image with secondary electron microscopy technique
(n,xn \( \gamma \)) challenges: \(^{238}\text{U}\) example

**Low \( \gamma \) energy:**
- Very low statistic (IC)
- High and complex background
- Electronic effect

---

Careful Fitting procedure
(less than 300 counts per energy windows and for one detector)
Correction procedure
(n,xn γ) challenges : $^{238}\text{U}$ example

**Low γ energy:**
- Very low statistic (IC)
- High and complex background
- Electronic effect

(n,n’) window for one detector
45 keV : ~ 2000 counts
103 keV : ~ 180000 counts

**L2 (4+) -> L1 (2+)**
$E_{\gamma} = 103$ keV

**L1 (2+) -> L0 (0+)**
$E_{\gamma} = 45$ keV

PRELIMINARY
From \((n,xn \gamma)\) XS to total XS: step by step

**Prompt g-ray spectroscopy method**

**Theoretical model**

**Spectroscopic parameters**

**Level production and total \((n,xn)\) cross sections**

**Measured \((n,xn \gamma)\) cross sections**

**Reconstruction method**

- \(\rightarrow\) level scheme
- \(\rightarrow\) branching ratio
(n,xn)\_L challenges: \(^{238}\text{U}\) example

**Determination of (n,xn) level production XS**
- Two possible methods without or with BR knowledge

Need the measurement of all the feeding and decaying transitions

Need the measurement of only one decaying transition of all involved levels

**Impossibility to deduced level XS without BR knowledge**
But checks are possible for some \(\gamma\) transitions
Known transitions:
- Trans. to GS
- Trans. With BR=0
- Even split trans.

- **Impact of low lying states**
  (even split redistribute flux to first and second level of GSB)
- **Sensitivity test, MC simul.** with several BR scheme possibilities
  (TALYS db, Weisskopf trans. Proba., all even splits)

⇒ **Effect of 10%** for the decay paths connected to first levels in the GSB
⇒ Need to **improve bibliography** study, **more simulations** of the effects, exp. determination on BR

(n,xn)_L challenges: \(^{238}\text{U}\) example
From \((n,xn \, \gamma)\) XS to total XS : step by step

**Reconstruction method**
- level scheme
- branching ratio
- need theoretical predictions
Dresden, December 3rd, 2014

Maëlle Kerveno

**Total (n,xn) challenges : $^{238}$U example**

**Determination of (n,xn) XS**

Total inelastic scattering cross section is the sum of the cross section carried by all transitions that directly decay to the ground-state.

**Several but not enough...!**

![Graph showing cross section vs energy](image1)

**Contribution of (n,n’ γ+EC) to the total XS**

![Graph showing contribution of (n,n’ γ+EC) to the total XS](image2)

**Need of theoretical predictions to provide missing XS**

$\Rightarrow$ With the preliminary test of predictive power on all measured $\gamma$-transitions.
$^{238}\text{U}(n,n'\gamma)$ XS versus model predictions

**No general trend**

- Disagreement between Exp. data

- TALYS, EMPIRE calculations:
  - No general agreement
  - Different inputs (structure models for low lying excitations, OMP, discrete levels embedded in the continuum ...)

### GS Band
- $45$ keV $2^+ \rightarrow 0^+$
- $103$ keV $4^+ \rightarrow 2^+$
- $159$ keV $6^+ \rightarrow 4^+$
- $211$ keV $8^+ \rightarrow 6^+$

### Band 2
- $635$ keV $1^- \rightarrow 2^+_{bgs}$
- $584$ keV $3^- \rightarrow 4^+_{bgs}$
- $519$ keV $5^- \rightarrow 6^+_{bgs}$

### Band 6
- $687$ keV $3^- \rightarrow 2^+_{bgs}$
- $678$ keV $5^- \rightarrow 4^+_{bgs}$
- $885$ keV $7^+ \rightarrow 8^+_{bgs}$
- $1060$ keV $3^+ \rightarrow 2^+_{bgs}$
- $1084$ keV $5^+ \rightarrow 4^+_{bgs}$
(n,xn γ) XS versus model predictions

Improvements are foreseen
For pre equilibrium emission

Total (n,xn) XS determination with the help of theoretical predictions
⇒ Improvements are necessary, lower limit XS otherwise

... See Marc Dupuis (CEA) contribution
The $^{233}$U($n$,xn $\gamma$) cross section measurements
(an already long story...)

$^{233}$U sample (7 years to obtain)
Made by IRMM target lab.
M = 8.3 g, $\varnothing$ = 3 cm,
thickness = 0.64 mm,
Activity $\sim$ 3 GBq

Segmented Ge detector
(54x54 mm, t=20 mm),
36 pixels (6.66 by 6.66)

⇒ Upgrade of the GRAPhEME set-up
(fall 2014)
(n,xn $\gamma$) XS : next challenge

The $^{233}$U(n,2n $\gamma$) cross section measurements
(an already long story...) upgrade of the set-up
(n,xn γ) XS : next challenge

The $^{233}$U(n,xn γ) cross section measurements
(an already long story...) First spectra!

Pile up rate
in monocristal : 32%
In pixel : ~ 2 %
Data rate
100MB/15 min

Measurement campaign:
Fall-winter 2014 : tuning and first in beam test
GELINA Shutdown South FP: 1/03 – 31/10/2015
Winter 2015 : data acquisition
**GRAPhEME** provides **comprehensive data sets**:

- $^{232}$Th, $^{233,235,238}$U(n,x$_{1,2,3}$n γ), level production and (n,n’) cross sections for 0<En<20 MeV
- Uncertainty target of few % -> difficult to reach (range 3%-20%).

- Long measurement for **low energy gamma transitions** in actinides or electron conversion measurements (CHANDA)?
- $^{238}$U **structure data** measurements (coupling GAINS-GRAPhEME).
- $^{233}$U measurements... but also data on $^{nat,182,183,184,186}$W and Zr

... See Greg Henning (IPHC) contribution

- Exclusive (n,xn γ) cross sections are a **real challenge** for the theoretical codes as many processes are involved and thus could be tested,
- Improvements are possible with **QRPA modelisation** of the pre equilibrium, more investigations on mechanisms are needed.

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**Necessity to keep strong links between experimentalists, theoreticians and evaluators.**

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Thank you for your attention...