Gd(n, γ) cross sections measured at n_TOF

M. Mastromarco on behalf of the n_TOF Collaboration
Main motivation

✓ **FAs** of current **Light Water Reactor** make extensive use of the so-called “**burnable neutron poisons**” characterized by a neutron capture cross section comparable or higher than $^{235}$U(n, f);

✓ Among these isotopes **the most common is Gadolinium**, taking advantage of the very large capture cross section at neutron energies below 1 eV of the two odd isotopes: $^{155}$Gd and $^{157}$Gd;

✓ Accurate predictions about their burning rate are fundamental for **safety reasons** and predicting the **appearance of FAs reactivity peak** and its intensity;
State of the Art: $^{155}$Gd

Baramsai et al. and Leinweber et al.

$155$Gd neutron capture cross-section

Cross-section (b)

Incident energy (keV)
State of the Art: $^{157}$Gd

157Gd neutron capture cross-section

Leinweber et al.
At the n_TOF facility neutrons are produced by spallation, on a Lead target, of 20 GeV protons coming from the PS.
At the n_TOF facility, neutrons are produced by spallation, on a Lead target, of 20 GeV protons coming from the PS.
At the n_TOF facility, neutrons are produced by spallation, on a Lead target, of 20 GeV protons coming from the PS.
At the n_TOF facility, neutrons are produced by spallation, on a Lead target, of 20 GeV protons coming from the PS.
n_TOF facility @ CERN: neutron flux characteristics

- $10^6$ neutrons/pulse
- white energy spectrum from 25.3 meV to some GeV
- $\Delta E/E \approx 10^{-4}$ for $E_n < 1$ keV
- Low repetition rate (no wrap-around)
Neutron flux during the Gd campaign

$^6\text{Li}(n, t)^4\text{He}$
Neutron flux during the Gd campaign

$^6\text{Li}(n, t)^4\text{He}$

SiMon – EAR1

$^6\text{Li}$

$n$ $\alpha, t$

---

Graph showing neutron flux per pulse as a function of neutron energy (eV). Two lines are plotted:
- Red: 2014 – Evaluated flux
- Blue: 2016 – SiMON

---

06/09/2018
Mario Mastromarco @ EuNPC 2018, Bologna, Italy
Neutron flux during the Gd campaign

${^6}\text{Li}(n, t)^4\text{He}$

2014 - Evaluated flux
2016 - SiMON

Neutrons per pulse, $\frac{dN}{d\ln E}$

Neutron energy (eV)
Neutron flux during the Gd campaign

$^6\text{Li}(n, t)^4\text{He}$

$^6\text{Li}$

$\alpha, t$

$^6\text{Li}(n, t)^4\text{He}$

Neutrons per pulse, $\frac{dN}{dE}$

2014 - Evaluated flux
2016 - SiMON

9% @ 25.3 meV
Experimental setup

4 deuterated benzene C$_6$D$_6$ liquid scintillator detectors placed at 90° with respect to each other and in front of the sample.

The total energy detection principle was used by combining the detection system described above with the so-called Pulse Height Weighting Technique (PHWT) (see Ref. [1] and [2])

- Two sample of $^{157}$Gd:
  - thin sample of 4.7 mg
  - thick sample of 191.6 mg

- Two sample of $^{155}$Gd:
  - thin sample of 10 mg
  - thick sample of 100.6 mg

- Empty and natPb: background
- Gold: normalization

Yield calculation

\[ Y(E_n) = \frac{N}{S_n + E_n \frac{A}{A+1}} \times \frac{C_w(E_n) - B_w(E_n)}{\varphi_n(E_n) f_{BIF}(E_n)} \]

- **Normalization factor**
- **Sample counts background subtracted**
- **Energy of the compound nucleus**
- **Flux fraction intercepted by the sample**
Background
Quality check: Calibrations + WF

- **Calibrations:**
  1. Linear
  2. Quadratic

- **Weighting Functions:**
  1. Exponential emission (7 cases) and omogeneous, threshold 150, 175 and 200 keV

Yields in agreement within 1.5 %
Yield: Gold Normalization
@ 4.9 eV
Yield: thermal region
Yield: thermal region, the expected yield

\[ Y(E_n) = (1 - e^{-n\sigma_{tot}(E_n)}) \frac{\sigma_\gamma(E_n)}{\sigma_{tot}(E_n)} \]

\[ n\sigma_{tot}(E_n) \gg 1 \]

\[ Y(E_n) \approx \frac{\sigma_\gamma(E_n)}{\sigma_{tot}(E_n)} \approx 1 \]
Yield: thermal region, the expected yield

\[ Y(E_n) = (1 - e^{-n\sigma_{tot}(E_n)}) \frac{\sigma_\gamma(E_n)}{\sigma_{tot}(E_n)} \]
Yield: BIF correction

GOLD
Yield: BIF correction

Capture yield vs. Neutron energy, eV

06/09/2018
Yield: BIF correction

In agreement within 1.5%
Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$^{155}\text{Gd}(n,\gamma)$ near thermal</th>
<th>$^{155}\text{Gd}(n,\gamma)$ resonance region</th>
<th>$^{157}\text{Gd}(n,\gamma)$ near thermal</th>
<th>$^{157}\text{Gd}(n,\gamma)$ resonance region</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHWT</td>
<td>1.5%</td>
<td>1.5%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Normalization</td>
<td>1.5%</td>
<td>1.5%</td>
<td>1.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Background</td>
<td>1.4%</td>
<td>$\approx$ 1%</td>
<td>1.0%</td>
<td>$\approx$ 1%</td>
</tr>
<tr>
<td>Sample mass</td>
<td>1.0%</td>
<td>$&lt;$ 0.1%</td>
<td>2.1%</td>
<td>$&lt;$ 0.1%</td>
</tr>
<tr>
<td>BIF</td>
<td>2.0%</td>
<td></td>
<td>2.0%</td>
<td></td>
</tr>
<tr>
<td>Flux</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td><strong>3.5%</strong></td>
<td><strong>2.5%</strong></td>
<td><strong>3.9%</strong></td>
<td><strong>2.5%</strong></td>
</tr>
</tbody>
</table>
$^{155, 157}\text{Gd thick: resolved region (ENDF Upper Limit)}$
Resonance structures are present up to keV region; the RRR stops at 200 eV for $^{155}\text{Gd}$ and at 300 eV for $^{157}\text{Gd}$ in ENDF.
$^{155}$Gd: RSA by SAMMY code

Capture yield vs Neutron energy (eV)

- n$^{155}$Gd
- ENDF/B-VIII.0
- JEFF3.3
- JENDL4.0
$^{155}\text{Gd: RSA by SAMMY code}$

Capture yield vs Neutron energy (eV) for $n^{155}\text{Gd}$ and other models.

- Blue: ENDF/B-VIII.0
- Green: JEFF3.3
- Black: JENDL4.0
155\text{Gd}: RSA by SAMMY code

Capture yield

Capture yield

Capture yield

Capture yield

Neutron energy (eV)

06/09/2018

Mario Mastromarco @ EuNPC 2018, Bologna, Italy
155Gd: Resonance kernels
$^{157}\text{Gd}$: thermal region

![Graph showing the neutron energy (eV) versus capture yield $x E_n^{1/2}$ for $n^{157}\text{Gd}$ and different nuclear data libraries: ENDF/B-VIII.0, JEFF3.3, JENDL4.0, and Leinweber.](image-url)
$^{157}$Gd: RSA by SAMMY code
\[ ^{157}\text{Gd}: \text{RSA by SAMMY code} \]
$^{157}$Gd: RSA by SAMMY code
$^{157}$Gd: Resonance kernels
RSA: Above the upper limit

Resonance spacing $D_0 \approx 1.6$ eV

Capture yield

Neutron energy (eV)
RSA: Above the upper limit

Resonance spacing $D_0 \approx 1.6 \text{ eV}$

- $n^{+155}\text{Gd}$
- this RSA

Resonance spacing $D_0 \approx 5.0 \text{ eV}$

- $n^{+157}\text{Gd}$
- this RSA

Capture yield vs. Neutron energy (eV)
Conclusions

- The $^{155,157}\text{Gd}(n,\gamma)$ reaction has been analyzed up to 1 keV; from RSA by R-matrix code the cross-section has been extracted from thermal to about 1 keV;
- These data sets can be used for future evaluations combining with the results of a new transmission measurement;
- In the RRR the comparisons with ENDF/B-VIII.0 and JEFF-3.3 data libraries show a fair agreement whereas sizable differences are present with Leinweber et al. data and with JENDL-4.0 evaluation;
- The thermal cross-sections in this work are about 2% higher for $^{155}\text{Gd}$ and 6% smaller for $^{157}\text{Gd}$ than those reported in nuclear data libraries;