The neutron resonances of Gold, improved cross-section on $n^{+197}$Au from high resolution time-of-flight measurements at n_TOF and GELINA: the road to a new standard

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Improved cross-section on n$^{+197}$Au from high resolution time-of-flight measurements at n_TOF and GELINA: the road to a new standard

- Nuclear data for science and technology
- The importance of $^{197}$Au(n,$\gamma$)$^{198}$Au reaction cross section
- Time-of-flight measurements
- Measurements techniques and detectors
- Measurements at CERN – n_TOF
- Measurements at IRMM – GELINA
- Results and conclusions
Nuclear Data for science and technologies

To understand the origin of the chemical elements in the stars, new capture cross section data are needed on a variety of isotopes:

- Radioactive isotopes
- Isotopes with very low neutron cross-section

Generation-IV (fast) reactors & Accelerator Driven System (ADS)

- New Fuel Cycle
- Transmutation of long-lived actinides
- Transmutation of Fission fragments

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The importance of $^{197}$Au(n,γ)$^{198}$Au "Reference cross-section"

- The $^{197}$Au(n,γ) cross section is considered as a standard:
  - at thermal energy (0.025 eV) where the cross section is known with an uncertainty of 0.1%
  - between 0.2 and 2.5 MeV of 1%
- Thanks to its high cross section the resonance at 4.9 eV is used to apply the "saturated resonance technique"
- In both cases it allows to normalize capture data (used as reference in neutron facilities)
- Widely used in nuclear reactors and other applications for neutron flux determination

Aim: to propose an extension of the energy region of the Au(n,γ) standard
The importance of $^{197}$Au($n,\gamma$)$^{198}$Au
“Reference cross-section”

The normalization factor ($N$) is the link between the measured capture yield and the cross-section.

$N$ is a factor that groups together:
- the detector efficiency
  - for capture measurement
  - for flux measurement
- the fraction of neutron flux impinging on the sample
- (…other experimental effects, if present)

Ideally the normalization factor is a time-independent factor, which can be deduced from a known yield:

$$\Rightarrow N = \frac{Y_{\text{calculated}}}{Y_{\text{measured}}}$$

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The importance of $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ "Reference cross-section"

**Capture detector**

$$Y_{\text{exp}}(E_n) = \frac{C_c(E_n)}{\Omega_c A_c \phi_n(E_n)}$$

$$Y_{\text{exp}}(E_n) = N \frac{C_c(E_n)}{C_{\phi}(E_n)} Y_{\phi}(E_n)$$

**"Flux" detector**

$$Y_{\phi}(E_n) = \frac{C_{\phi}(E_n)}{\Omega_{\phi} A_{\phi} \phi_n(E_n)}$$

$$Y_{\phi}(E_n) \approx n\sigma_{st}$$

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n_TOF and GELINA neutron TOF facilities

The **Time-Of-Flight (TOF)** technique requires a pulsed neutron source:

- charged particles on a target (proton spallation or electron Bremsstrahlung isotropic emission: $\Phi_n(L) \propto 1/L^2$)

**Related Problems**

- Neutrons overlap
- Dead time [1]
- Resolution

$$\frac{\Delta E_n}{E_n} = 2 \times \sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}$$

GELINA and n_TOF neutron TOF facilities

n_TOF at CERN and GELINA at IRMM

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Measurement techniques and detectors

Transmission experiment

\[ T = \frac{C_{\text{in}}}{C_{\text{out}}} \approx e^{-n\sigma_{\text{tot}}} \]

- Incoming neutron flux cancels out
- Detection efficiency cancels out

Good Geometry (collimation)

1. All detected neutrons have traversed the sample
2. Neutron scattered in the sample do not reach the detector

\[ \Phi_{n} \rightarrow \sigma_{\text{tot}} \]

→ Direct relation between \( T \) and \( \sigma_{\text{tot}} \)
Measurement techniques and detectors

Capture experiment I

\[ C_r = \varepsilon_r Y_r A_r \varphi_r \]

- \( \varphi_r \) Neutron Fluence Rate
- \( \varepsilon_r \) Detection efficiency (for a reaction event)
- \( A_r \) effective area
- \( Y_r \) reaction yield (beam fraction undergoing the partial Reaction)

Complex relation between \( C_r \) and \( Y_r \)

\( Y_r \) related to \( \sigma_r \)

\[ Y_r = (1 - e^{-n_r \sigma_t}) \frac{\sigma_r}{\sigma_t} \]
Measurement at CERN – n_TOF

Measurement carried out with two different detector systems:

- $4\pi$ γ-ray calorimeter [2], 40 BaF$_2$ crystals (total γ-ray absorption detector)
  - High detection efficiency
  - Sizeable neutron sensitivity
- C$_6$D$_6$ array (total energy detection)
  - Use of “Pulse Height Weighting Function”
  - Very low neutron sensitivity


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Measurement at CERN – n_TOF

Total Absorption Calorimeter

Study of the:
• Analysis conditions
• Dead time correction
• Pile up minimization
• Background
Measurement at CERN – n_TOF

Comparison with libraries (in the RRR):
- Good agreement except few, small resonances.
- No systematic effects
Measurement at IRMM – GELINA

Au transmission measurements

<table>
<thead>
<tr>
<th>Flight path</th>
<th>Frequency</th>
<th>Sample</th>
<th>Overlap</th>
<th>filters</th>
<th>Background</th>
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<tbody>
<tr>
<td>49.34</td>
<td>50Hz</td>
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<td>Cd</td>
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Measurement at IRMM – GELINA

Au transmission measurements

\[ J^m = 1^+, s\text{-wave} \]
\[ J^m = 1^-, p\text{-wave} \]

Transmission factor

\( E_n = 60.3 \text{ eV} \)
\( g = 0.625 \)

\( n + \text{Au}_{3 \text{mm thick}} \)

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# Measurement at IRMM – GELINA

## Au capture measurements

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<th>Sample</th>
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</tr>
</thead>
<tbody>
<tr>
<td>T2 - 1.0 mm</td>
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<td></td>
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<tr>
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<td>W, Co, Bi, Na</td>
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<tr>
<td>C1 - 0.1 mm</td>
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<tr>
<td>S1 - 0.05 mm</td>
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<td>N2 - 0.01 mm</td>
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<tr>
<td>N3 - 0.005 mm</td>
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**FP5-12m 50 Hz 4 C₆D₆ “pyramid”**

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<td>C2-0.5mm</td>
<td>Co, Bi, Na</td>
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**FP15-30m 50 Hz 2 C₆D₆ “cylinder”**

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<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>C2 - 0.5 mm</td>
<td>Na,Pb</td>
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<td></td>
</tr>
<tr>
<td>C2 - 0.5 mm</td>
<td>W, Co, Na, Pb</td>
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</tr>
<tr>
<td>C1 - 0.1 mm</td>
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<tr>
<td>N17 - 0.1 mm</td>
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<td>S1 - 0.05 mm</td>
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</tr>
<tr>
<td>N2 - 0.01 mm</td>
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</tr>
<tr>
<td>N3 - 0.005 mm</td>
<td>Na,Pb</td>
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**FP15-30m 800 Hz 2 C₆D₆ “cylinder”**

<table>
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<th>Sample</th>
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</thead>
<tbody>
<tr>
<td>T2 - 1.0 mm</td>
<td>Pb, Al</td>
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<tr>
<td>C2 - 0.5 mm</td>
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<tr>
<td>T1 - 0.1 mm</td>
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<tr>
<td>T1 - 0.1 mm</td>
<td>Pb, Al, Na</td>
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**FP14-60m 800 Hz 4 C₆D₆ “cylinder”**

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<th>filters</th>
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</tr>
</thead>
<tbody>
<tr>
<td>C1 - 0.1 mm</td>
<td>Co, Na</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**C₆D₆ γ-ray detectors**

1 γ-ray for each cascade

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Measurement at IRMM – GELINA

Au capture measurements
Measurement at IRMM – GELINA

Au capture measurements

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Results

n_TOF Total Absorption Calorimeter:
- Determination of analysis condition
- Definition of a method to minimize pile up, to correct for the dead time and to subtract background, relying purely on experimental data

n_TOF Au data:
- R-Matrix analysis of 263 resonances up to 5 keV → good agreement with libraries and n_TOF C₆D₆ data
- 7 resonances, not included in libraries, have been clearly resolved

GELINA Au data (determination of resonance parameters up to 200 eV):
- Validation of the results with the measurement of the cross section at thermal energy
- Deterministic assignment of the total angular momentum of 9 resonances
- Determination of the parameter of 12 resonances, in particular for the 4.9 eV resonance with an accuracy better than 0.5%

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Results

Comparison:

\( n\text{-TOF TAC data Vs GELINA C}_6\text{D}_6 \text{ data} \)
Conclusions

The results obtained at different neutron time-of-flight facilities, with different neutron capture detectors, and using different R-matrix codes, is one of the most important aspect of this work.

The good agreement, within 3\%, for the 12 resonances up to 200 eV between n_TOF TAC data and GELINA C₆D₆ data is the starting point for a new evaluation of ¹⁹⁷Au(n,γ) reaction cross-section.

Thanks to these results, the extension of the standard in the resolved resonance region is now within reach.