$^{205}$Tl(n,γ) cross section measurement at n_TOF EAR1

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Outline of the presentation

• Introduction and motivations
  – s-process nucleosynthesis at the heaviest isotopes
  – The astrophysical importance of the $^{205}$Tl(n,$\gamma$) reaction rate
  – Current status of the $^{205}$Tl(n,$\gamma$) data
  – Nucleosynthesis calculations

• Experimental setup, counting rate estimation and beam time request
Overview of the s-process at 203<A<210

- Thallium, and especially, lead isotopes, are mainly produced by the s-process.
- The third s-process peak: abundance peak around double magic $^{208}$Pb.
- Accurate model of the s-process should describe faithfully the third peak requires best nuclear data (beta decay rates & capture rates) available.
The $^{205}\text{Pb}-^{205}\text{Tl}$ decay system

- $^{205}\text{Tl}$ is the most abundant (71%) stable (at earth) thallium isotope ($Z=81$)
  Already measured at n_TOF (C. Domingo-Pardo et al., Phys. Rev. C 75, 015806 (2007))

- The $^{205}\text{Pb}/^{204}\text{Pb}$ ratio could be used as a “chronometer” of the s-process$^{1,2,3}$
  - Time elapsed since the last injection of main s-process products into the pre-solar nebula
  - Stellar effects on $^{205}\text{Pb}$: at s-process sites temperature, EC decay is so strongly enhanced that its survival is compromised
  - Activation of the bound state $\beta$ decay of $^{205}\text{Tl}$

1. K. Yokoi et al., The production and survival of Pb-205 in stars, and the $^{205}\text{Pb}/^{205}\text{Tl}$ s-process chronometry, Astronomy and Astrophysics 145, 339-346 (1985)

After s-process

- C-13 pocket s-process
  $T \sim 10^8$ K ($kT \sim 8$ keV)

TP s-process
  $T \geq 3 \cdot 10^8$ K ($kT \sim 25$ keV)

AGB (red giant) time evolution
Main ideas

• $^{205}$Tl is the most abundant (71%) stable (at earth) thallium isotope ($Z=81$)

![Diagram showing the s-process flow]

The $^{205}$Pb/$^{204}$Pb ratio has the potential to be used as a “chronometer” of the s-process

![Diagram showing the s-process temperature]

The $^{205}$Tl(n,$\gamma$) capture reaction, by affecting the abundance of $^{205}$Tl, could play a relevant role in the final abundance (and survival) of $^{205}$Pb

Status of the data for $^{205}$Tl(n,γ) : cross section

  - Experimental capture cross section or resonance parameters never published
  - Related EXFOR data: only resonance kernels, no uncertainties
  - Explicit correction factor for systematic error at ORNL: not known (0.95 for $^{203}$Tl)

- Most recent evaluations show **important discrepancies**:
Status of the data for $^{205}$Tl(n,γ): MACS

- MACS at 30 keV comparison:
  - Kadonis reference value: 52.6 ± 3.9 mb (ENDF evaluation)
  - Examination of ENDF data suggests it is based on 1976 ORNL measurement
  - No direct uncertainty assessment in the whole energy range (8 keV to 50 keV)

![Graph showing MACS values over time with activation measurements and reference values.]

**Estimation of the uncertainty in the accuracy of the MACS**

±33%
205\( \text{Tl}(n,\gamma) \) impact: Nucleosynthesis calculations

- Post-processing calculation employing MSun = 3, Z=0.006 (half solar) star model from NuGrid set 1 ext. (C. Ritter et al. 2017\(^1\))

- Reference Kadonis 205\( \text{Tl}(n,\gamma) \) MACS has been varied ±33% in this simulations

\( \frac{205\text{Pb}}{204\text{Pb}} \) abundance ratio in the stellar envelope (normalized to the ref. rate)

\[ \sim 18\% \]

uncertainty in the 205\( \text{Pb} \)/204\( \text{Pb} \) ratio

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Main points

• From the current status of the data a ±33% uncertainty in the value of the 205Tl(n,γ) is assumed

• This leads to an approx. 18% global uncertainty in the $^{205}$Pb/$^{204}$Pb ratio only due to this reaction

• Goal: increase precision and accuracy of $^{205}$Tl(n,γ) to reduce the uncertainty in the $^{205}$Pb/$^{204}$Pb ratio
Experimental set-up and counting rate estimation

- 4 C₆D₆ detectors in n_TOF EAR1
  - Best energy resolution at the astrophysical energy range (1-100 keV range)
- Sample: 4 g of 99% pure ²⁰⁵Tl oxide (to be acquired). Size: 30 mm D., 1 mm thick.
- $2 \times 10^{18}$ protons to achieve a 2.5% statistical uncertainty at the 30 keV ²⁰⁵Tl predicted resonances

²⁰⁵Tl(n,γ) targeted total uncertainty: $\approx 5\%$
### Summary of requested beam time

<table>
<thead>
<tr>
<th>Sample</th>
<th>Purpose</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{205}$TI</td>
<td>$^{205}$TI(n,$\gamma$) with C6D6</td>
<td>$2 \times 10^{18}$</td>
</tr>
<tr>
<td>Dummy</td>
<td>$^{205}$TI sample background</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>Au, Pb, C</td>
<td>Normalization, beam induced background estimation</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>$3 \times 10^{18}$</strong></td>
</tr>
</tbody>
</table>
Final remarks

• The examination of the literature and databases shows that the cross section for the $^{205}\text{Tl}(n,\gamma)^{206}\text{Tl}$ reaction in the regions of astrophysical interest remains still uncertain (33% assumed uncertainty in the MACS value).

• The measurement proposed for EAR1 would improve the accuracy and precision of the $^{205}\text{Tl}(n,\gamma)$ cross section in the astrophysical energy range (1-100 keV, 5% goal of total uncertainty).

• The new CS will lead to an improvement of the $^{205}\text{Pb}/^{204}\text{Pb}$ ratio estimation (with the targeted CS uncertainty, down to 2.5%)

• It will, as well, contribute to a complete and reliable interpretation of the branching pattern around $^{204}\text{Tl}$ (whose capture cross-section results we expect to publish this year), important for the study of the third s-process lead isotopes peak
Thank you for your attention.
$^{205}\text{Tl}$ decay vs $^{205}\text{Pb}$ decay
\(^{205}\text{Tl}(n,\gamma)\) MACS: -40% to +5%
\( ^{205}\text{Tl} (n,\gamma) \text{ MACS: -40\% to +5\%} \)

\( ^{205}\text{Pb}/^{204}\text{Pb} \text{ abundance ratio in the stellar envelope (normalized to the ref. rate)} \)
Sensibility study from A. Koloczek et al. (2016)

- Atomic Data and Nuclear Data Tables 108 (2016) 1–14
- Sensitivity:
  \[ s_{ij} = \frac{\Delta N_j / N_j}{\Delta r_i / r_i} \]

**Table K**
Reactions with strongest local sensitivities in the $^{13}$C-pocket for each isotope.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Most important reactions with respective sensitivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{205}$Tl</td>
<td>$^{205}$Tl(n, $\gamma$) $^{142}$Nd(n, $\gamma$) $^{202}$Hg(n, $\gamma$)</td>
</tr>
<tr>
<td></td>
<td>$-0.849$ $0.174$ $0.127$</td>
</tr>
</tbody>
</table>

**Table L**
Reactions with strongest local sensitivities in the TP for each isotope.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Most important reactions with respective sensitivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{205}$Tl</td>
<td>$^{205}$Tl(n, $\gamma$) $^{205}$Pb(n, $\gamma$) $^{205}$Pb($\beta^+$)</td>
</tr>
<tr>
<td></td>
<td>$-0.520$ $-0.446$ $0.413$</td>
</tr>
</tbody>
</table>