\((\alpha,n)\) reaction cross section measurement on Mo isotopes for \(\gamma\)-process

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γ-process

- There are ~35* – mainly even-even – stable proton-rich nuclei between $^{74}$Se and $^{196}$Hg – so called p-nuclei – which cannot be produced via neutron capture
- The p-nuclei has typically two orders of magnitude lower abundance – except $^{92,94}$Mo and $^{96,98}$Ru – than the r- and s-nuclei
- These isotopes mainly synthetized by photodisintegration reactions [1-2], however, the rp- [3] and vp-process [4] can give a contribution to their abundance
- In a high temperature environment – $T=2-3 \text{ GK}$ – a sufficient amount of high energy photons are available to induce $(\gamma,n)$, $(\gamma,p)$ and $(\gamma,\alpha)$ reactions

* Such conditions can occurs in core collapse supernovae (SN) or type Ia supernovae and can last for not longer than 1-2 seconds

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* The $^{164}$Er, $^{152}$Gd and $^{180}$Ta nuclei has a large s process contribution to their observed abundances
Reaction network calculations

- To model the γ-process extended reaction network calculations are required, involving several thousand reactions on thousand(s) – mostly radioactive – nuclei.
- These reaction networks have astrophysical inputs – temperature, timescale, s- and r-nuclei abundance etc. – and nuclear physics inputs like reaction rate.
- Reaction rates are computed from cross sections, which are taken from the Hauser-Feshbach (HF) statistical model.
- The HF model involves input parameters, such as level densities, γ-strength functions and global optical model potentials (OMPs).
- Using different global OMPs as orders of magnitude difference in the predicted cross section can be found and this can affect the outcome of the reaction network calculation.
- The α-nucleus OMPs provides the most uncertainties [6] → by measuring (α,n) cross-sections the reliability of the different OMPs can be checked.

![Graph](image)

Ratio of p-abundances calculated with modified rates and the currently accepted HF rates for α-induced reactions. Figure taken from: [7]

Measurement concept

- \((\alpha, n)\) cross sections to evaluate \(\alpha\)-nucleus OMPs

  Thick target yield measurement

  Activation technique

  I. Irradiation
  II. \(\gamma\)-counting
Thick target technique

• The target is thick enough – based on SRIM calculation – to completely stop the beam even at the highest $\alpha$-beam energy $E_\alpha = 13$ MeV

• Reactions takes place with all the energies between the initial beam energy ($E$) and the threshold energy ($E_{th}$)

• The thick target yield ($Y_{TT}$) is in integral relation with the cross section ($\sigma$) and the effective stopping power ($\varepsilon$):

$$Y_{TT}(E) = \int_{E_{th}}^{E} \frac{\sigma(E')}{\varepsilon_{eff}(E')} dE'$$ (1)

• The cross section between two nearby energy can be determined by subtracting the adjacent yields:

$$\sigma(E_{eff}) = \frac{[Y_{TT}(E_2) - Y_{TT}(E_1)] \cdot \varepsilon_{eff}(E_1;E_2)}{E_2 - E_1}$$ (2)

<table>
<thead>
<tr>
<th>Target</th>
<th>92Mo</th>
<th>94Mo</th>
<th>100Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>14.5±0.3%</td>
<td>9.2±0.9%</td>
<td>9.8±0.3%</td>
</tr>
<tr>
<td>Product</td>
<td>95Ru</td>
<td>95Tc</td>
<td>97Ru</td>
</tr>
<tr>
<td>$T_{1/2}$</td>
<td>1.611±0.006 h</td>
<td>19.285±0.007 h</td>
<td>2.84±0.01 d</td>
</tr>
<tr>
<td>Gammas</td>
<td>$E_\gamma$[keV] ($I_\gamma$[%])</td>
<td></td>
<td></td>
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<td>--------</td>
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</tr>
<tr>
<td>336.4 (69.9±0.5)</td>
<td>765.8 (93.8±0.3)</td>
<td>215.7 (85.6±1.3)</td>
<td>497.1 (91±1.2)</td>
</tr>
<tr>
<td>626.8 (17.8±0.5)</td>
<td>947.7 (1.95±0.02)</td>
<td>324.5 (10.79±0.17)</td>
<td>610.3 (5.76±0.06)</td>
</tr>
<tr>
<td>1096.8 (20.9±1)</td>
<td>1073.7 (3.74±0.4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental setup

Target

- 0.5 mm thick molybdenum plate
- natural \(^{92}\text{Mo}: 14.5 \%, \quad \text{^{94}Mo: 9.2 \%,} \quad \text{^{100}Mo: 9.8 \%}) isotopic composition

Irradiation

- The beam is produced by the Atomki cyclotron in the 7.6 - 13 MeV energy range, covered by 0.5 MeV steps
- Current measurement
  - Current integration using a multichannel analyzer, stored in every minute
  - Collimator current has been monitored during the irradiation
  - -300 V voltage was used to suppress the secondary electrons
  - Typical beam current 0.3 - 2 μA
- The duration of the irradiations varied between 3 and 21 hours
- Water cooling was applied on the back of the target

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Investigated energy range</th>
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<tbody>
<tr>
<td>(^{92}\text{Mo(α,n)}^{95}\text{Ru})</td>
<td>10 – 13 MeV</td>
</tr>
<tr>
<td>(^{92}\text{Mo(α,p)}^{95}\text{Tc})</td>
<td>In progress</td>
</tr>
<tr>
<td>(^{94}\text{Mo(α,n)}^{97}\text{Ru})</td>
<td>8.7 – 13 MeV</td>
</tr>
<tr>
<td>(^{100}\text{Mo(α,n)}^{103}\text{Ru})</td>
<td>7.6 - 13 MeV</td>
</tr>
</tbody>
</table>

Current measurement during the irradiation

\(E_\text{α} = 12\) MeV
• Activity measurement: two geometries
  • At and above $E_\alpha = 10.5$ MeV far geometry
  • Below $E_\alpha = 10.5$ MeV close geometry (5cm detector endcap-source distance)
  • Efficiency correction factor was derived by measuring strong Ru sources in both geometries
• Spectra saved regularly to follow the decay
  • 10 min for $^{95}$Ru (first 8 hours)
  • 1 h for $^{97}$Ru and $^{103}$Ru (for 1-2 weeks after the end of the irradiation)

* 50% relative efficiency HPGe with 5cm thick lead shielding and 100% relative efficiency HPGe with 10cm thick lead shielding
Precise half-life measurement

- $\sigma(E) \sim N_{prod}(T_{1/2}) \rightarrow \Delta\sigma \sim \Delta T_{1/2}$
- The half-lives of the $^{95}$Ru and $^{95}$Tc isotopes are known with large uncertainties [8-9]
- The use of the literature values caused a trend in the number of produced $^{95}$Ru atoms
- Strong sources were produced by $E_\alpha = 13; 12; 11$ and $10.5$ MeV irradiations to determine the half-lives
- The literature value overestimates the real half-life value

<table>
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<tr>
<th>Properties of the half-life measurement</th>
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<tbody>
<tr>
<td>Isotope</td>
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<tr>
<td>Cooling time</td>
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<tr>
<td>Counting duration</td>
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<tr>
<td>Spectra were saved</td>
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<table>
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<tr>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotope</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
</tr>
<tr>
<td>difference between $T_{1/2}$ based on different $\gamma$-transitions</td>
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<tr>
<td>Peak integration (Gaussian/numerical integration)</td>
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<tr>
<td>Study on the reference isotopes ($^{97}$Ru)</td>
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</tbody>
</table>

Half-life comparison

- $^{95}$Ru: $1.643 \pm 0.013$ h
- $^{95}$Tc: $20.0 \pm 0.1$ h

- $^{95}$Ru: $1.613 \pm 0.004$ h
- $^{95}$Tc: $19.281 \pm 0.054$ h

Preliminary results

- Results were compared to previous data sets and theoretical predictions calculated using different OMPs.

\[ ^{94}\text{Mo}(\alpha,n)^{97}\text{Ru} \]

\[ ^{100}\text{Mo}(\alpha,n)^{103}\text{Ru} \]

\[ ^{92}\text{Mo}(\alpha,n)^{95}\text{Ru} \]

\[ ^{92}\text{Mo}(\alpha,p)^{95}\text{Tc} \]
Summary

• $(\alpha,n)$ cross sections can be used to evaluate $\alpha$-nucleus OMPs
• Lack of experimental data
• $^{92,94,100}$Mo$(\alpha,n)$ activation measurement using thick target
• Half-life measurement of the $^{95}$Ru and $^{95}$Tc
• Further investigation of the resulted cross sections are in progress

THANK YOU FOR YOUR ATTENTION!

G.G. Kiss, P. Mohr, Zs. Fülöp, Gy. Gyürky, T. Szücs
Data analysis

• The number of detected counts in a peak $N_{det}$

$$N_{det} = N_{trg} \sigma(E) \Phi \epsilon I_{\gamma} \left( \frac{1-e^{-\lambda \cdot t_{irrad}}}{\lambda} \right) \cdot e^{-\lambda \cdot t_{cool} \cdot (1 - e^{-\lambda \cdot t_{count}})} \quad (3)$$

• The cross section at the effective energy – derived from the excitation function – is calculated by applying the (2) equation

• Systematic uncertainties
  
  - Statistical: $< 10\%$
  - Detector efficiency: 5 % (far to close geometry correction factor: additional 1 %)
  - Current integration: 3%
  - Stopping power: 5 % based on SRIM code
  - Beam energy: 0.3 % (~30 keV)

• Several irradiations ($E_\alpha = 11.5, 10.5, 7.6$ MeV) were repeated, the resulted cross sections were calculated by weighting the values by their statistical uncertainties

\begin{itemize}
  \item $^{100}$Mo($\alpha$,n)$^{103}$Ru reaction cross section
  \item $^{100}$Mo($\alpha$,n)$^{103}$Ru reaction S-factor
\end{itemize}
**Optical potential**

- In optics, complex refractive index is used to describe the simultaneous reflection (real part) and absorption (imaginary part) of a light beam on a body.

- To this analogy, nuclear physics use global optical model potentials (OMPs) to describe the interaction of the projectile and the target nuclei:

  \[ U(r) = V_{Coul}(r) + V_{nucl}(r) + iW(r) \]

- In general, we distinguish between „nuclear“ and „astrophysical“ potentials.

- „Nuclear“ potentials → McFadden [15]
  - Developed in the 50’s and 60’s
  - Simple calculations with few parameters
  - Energy and mass independent
  - Reproduce the order of magnitude of the reaction cross sections

- „Astrophysical“ potentials → Avrigeanu [16], Demetriou [17], Atomki [18]
  - Continuously developing
  - More complicated calculations involving more parameters
  - Energy and mass dependence
  - More precise, but highly specific

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