Neutron capture cross section measurements for nuclear astrophysics by the activation method at the n_TOF NEAR Station

A. Manna & M.E. Stamati on behalf of the n_TOF Collaboration

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Neutron Capture @ NEAR

Neutron capture cross section measurements by the activation method at the n TOF NEAR Station

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Outline

1) Motivation and introduction

2) The activation technique and instrumentation

3) The filtering method

4) Conclusions and proton request
Motivation

Why are we interested in MACS measurements

- Measurements of Maxwellian Averaged Cross-Sections (MACS) are fundamental in nuclear astrophysics\(^1\)

- Half the atomic nuclei heavier than iron are created through the s-process, a series of neutron capture reactions and β-decays\(^1\)

- Accurate measurements of cross-sections are an essential input to calculate element abundances\(^2\),\(^3\)

- Typical temperatures for nucleosynthesis studies are in the range \(kT = 5-100\) keV (60 – 1100 M Kelvin)

\(^1\) Burbidge, E. M. et al (1957), Reviews of Modern Physics. 29 (4), 547–650
Q: Can we perform MACS measurements at NEAR?

- At n_TOF, we usually measure the energy dependent cross-section so we can calculate MACS for various temperatures.

- However, not all physics cases are suitable to measure via the time-of-flight technique (e.g. low-mass samples).

- At NEAR we can perform integral measurements for those challenging cases that could not be measured via ToF.
The NEAR Station is the n_TOF facility’s new high-flux irradiation station.

It is located just outside the target bunker shielding, at only 3m distance from the target.
The Facility

NEAR: parasitic measurements without compromising other experiments @ EAR1 and EAR2
The Activation Technique

The activation technique is a well-established method of determining cross-sections, thanks to the sensitivity and the selectivity that it provides. It consists of two steps:

1) The irradiation of the sample
2) The measurement of the induced activity

It can only be applied to isotopes with suitable decay parameters\(^1\)
(decay mode, intensity, half-life, etc)

The formula\(^2\) to calculate the cross-section is:

\[ \sigma = \frac{\text{counts}}{\Phi \epsilon I N_T e^{-\lambda t_{\text{wait}}} (1 - e^{-\lambda t_{\text{meas}}}) f_B} \]

\(^1\) Measurement and Detection Radiation, Nicholas Tsoulfanidis, Taylor & Francis (1798)
Instrumentation

The measurement of the induced activity of the samples will be measured in the new Gamma-ray Spectroscopy Experimental Area (GEAR) of n_TOF with the use of a HPGe.

This HPGe

- Is of high relative efficiency (60%),
- Is shielded
- and has a window of Carbon epoxy,

allowing for high-accuracy measurements in a wide energy range
MACS is needed in nuclear astrophysics for modeling neutron capture processes.

Typical temperatures for nucleosynthesis studies are in the range

\[ kT = 5 \text{ to } 100 \text{ keV} \]

(Temperatures of 60 - 1100 MKelvin)

**HOWEVER**

the neutron spectrum at the NEAR Station is not at all Maxwellian
Feasibility of MACS measurements at n_TOF/NEAR

With suitable filters:

- the neutron flux can be shaped so that the Spectral Averaged Cross Section (SACS) is close (or as close as possible) to the MACS.

To investigate this possibility, we propose to measure the SACS.
Filtered neutron flux

SACS measurements at n_TOF/NEAR

Filter: B4C

Sample

Counts/pulse/energy-bin

10^5

10^4

10^3

10^2

10

10^{-8}  10^{-7}  10^{-6}  10^{-5}  10^{-4}  10^{-3}  10^{-2}  10^{-1}  1  10  10^2  10^3

Neutron energy (MeV)

Incident flux

Filtered flux
Filtered neutron flux

SACS measurements at n_TOF/NEAR

Counts/pulse/energy-bin

- $kT = 0.15$ keV

Neutron energy (MeV)

B4C cylinder

5 mm thick
Filtered neutron flux

SACS measurements at n_TOF/NEAR

- B4C cylinder 5 mm thick
- B4C cylinder 20 mm thick

Counts/pulse/energy-bin vs. Neutron energy (MeV) for kT = 0.15 keV and kT = 27.7 keV.
Filtered neutron flux

SACS measurements at n_TOF/NEAR

B-enriched filter + AlF3 Moderator (30 cm th)
Reactions chosen

These reactions are the neutron capture of

- $^{197}\text{Au}$
  
  \text{“}{^{197}\text{Au}}(n,\gamma)\text{ cross section in the unresolved resonance region}{\text{” C. Lederer et al., Physical Review C 83, 034608 (2011)}}$
  
  \text{“}{^{197}\text{Au}}(n,\gamma)\text{ cross section in the resonance region}{\text{” C. Massimi et al., Physical Review C 81, 044616 (2010)}}$

- $^{76}\text{Ge}$
  
  \text{“Measurement of the 76 Ge(n,\gamma) cross section at the n_TOF facility at CERN”, A. Gawlik-Ramiega et al., Physical Review C 104, 7 (2021)}}$

- $^{94}\text{Zr}$
  
  \text{“Neutron capture on 94 Zr: Resonance parameters and Maxwellian-averaged cross sections”, G. Tagliente et al., Physical Review C 84, 015801 (2011)}}$

- $^{140}\text{Ce}$
  
  \text{“First Results of the 140 Ce(n,\gamma) 141 Ce Cross-Section Measurement at n_TOF”, S. Amaducci et al., Universe 7, 200 (2021); S. Amaducci et al., in preparation (2021)}}$

- $^{89}\text{Y}$
  
  \text{G. Tagliente, P.M. Milazzo al., in preparation (2021)}}$
## Reactions chosen

<table>
<thead>
<tr>
<th>Reaction</th>
<th>γ-ray energy [keV]</th>
<th>Product half-life</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{197}$Au(n,γ)</td>
<td>411.8</td>
<td>2.69 d</td>
<td>0.015</td>
</tr>
<tr>
<td>$^{76}$Ge(n,γ)</td>
<td>264.4</td>
<td>11.2 h</td>
<td>0.09</td>
</tr>
<tr>
<td>$^{94}$Zr(n,γ)</td>
<td>756.7</td>
<td>64 d</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{140}$Ce(n,γ)</td>
<td>145.4</td>
<td>32.5 d</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{89}$Y(n,γ)</td>
<td>(2186)</td>
<td>64 h</td>
<td>0.14</td>
</tr>
</tbody>
</table>

With: irradiation time of 14 days  
(1.4x10^18 protons in parallel with EAR1 and EAR2 runs)  
For: uncertainty of the measurement below 3%
### Reactions chosen

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Average $\beta$ energy [keV]</th>
<th>$\gamma$-ray energy [keV]</th>
<th>Product half-life</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{89}\text{Y}(n,\gamma)$</td>
<td>932.4</td>
<td>(2186)</td>
<td>64 h</td>
<td>0.14</td>
</tr>
</tbody>
</table>

One of the samples that will be irradiated is the $\beta$-emitter $^{90}\text{Y}$.

In this case, the HPGe will still be used, but in comparison with a plastic scintillator, in order to explore the feasibility of such an application.
Conclusions

The realisation of the proposed set of irradiations will be a fundamental benchmark for the future measurements at n_TOF’s NEAR Station.

A successful shaping of the neutron beam is going to pave the way for many MACS measurements that were too challenging to be performed with the ToF method.

The number of requested protons is: 0

as the irradiations will take place parasitically during normal operation, in parallel with measurements in the two experimental areas.
Thank you for your attention
Extra Slides
Neutron flux at different positions

SACS measurements at n_TOF/NEAR

Variation of the neutron energy distribution as a function of the distance of the irradiated sample from the center of the B4C cylinder.
More details on the reactions: $^{76}\text{Ge}(n,\gamma)$
More details on the reactions: 94Zr(n,y)
More details on the reactions: $^{94}\text{Zr}(n,\gamma)$

Small correction of the order of $\sim 2\%$ needed
More details on the reactions: $^{140}$Ce(n,y)
More details on the reactions: $^{140}\text{Ce}(n,y)$

Expected correction of the order of ~20 - 30%
More details on the reactions: $^{89}\text{Y}(n,y)$

\[
\begin{align*}
\text{Q}^- &= 2278.5 \pm 16 \\
\%\beta^- &= 100 \\
\text{Log } ft &= 1.4 \times 10^{-6}, 11.04 \\
0.0115 &= 9.64^{1+} \\
99.9885 &= 9.2240^{1+} \\
2^{-} &= 0 \\
\text{stable} &
\end{align*}
\]

Experimental $^{90}\text{Sr}$ spectrum with HPGe

Energy (keV)
Possible Contamination of The Spectra

Reactions on other isotopes

<table>
<thead>
<tr>
<th>Reaction of interest</th>
<th>Peak of interest (keV)</th>
<th>Interfering peak (keV)</th>
<th>Caused by reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge(n,$\gamma$)</td>
<td>264.5</td>
<td>264.6</td>
<td>$^{74}$Ge(n,$\gamma$)$^{75}$Ge $^{76}$Ge(n,2n)$^{75}$Ge</td>
</tr>
</tbody>
</table>

Background

<table>
<thead>
<tr>
<th>Reaction of interest</th>
<th>Peak of interest (keV)</th>
<th>Interfering peak (keV)</th>
<th>Caused by</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{89}$Y(n,$\gamma$)</td>
<td>1760</td>
<td>1764</td>
<td>$^{214}$Bi</td>
</tr>
</tbody>
</table>

Furthermore:
Peaks originating from $^{228}$Ac
→ Suppressed by the HPGe’s lead shielding

![Background Spectrum](image-url)
Ratio between MACS and SACS

![Graph showing the ratio between MACS and SACS against mass number A. The graph includes data points for different categories: All std: 15.7%, even-A std: 17.0%, odd-A std: 8.6%. The data spread is indicated by a shaded area around the line ratio = 1.](image-url)