The $^{140}\text{Ce}(n,\gamma)^{141}\text{Ce}$ reaction at n_TOF-EAR1: a litmus test for theoretical stellar models.
The solar distribution and the s-process peaks

Magic nuclei are bottlenecks for the s-process nucleosynthesis

N=50: $^{88}\text{Sr}, ^{89}\text{Y}, ^{90}\text{Zr}$

N=82: $^{138}\text{Ba}, ^{139}\text{La}, ^{140}\text{Ce}, ^{141}\text{Pr}, ^{142}\text{Nd}$

N=126: $^{208}\text{Pb}$
The s-process in Asymptotic Giant Branch (AGB) stars

Busso et al. 1999
The s-process in Asymptotic Giant Branch (AGB) stars

$^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction ($\sim 8 \text{ keV}$)

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ reaction ($\sim 23 \text{ keV}$)
The pollution of AGB stars with a mass ranging between 3 to 6 $M_{\text{SUN}}$ may account for most of the features of the s-process enrichment of M4 and M22.
The s-process in Globular Clusters

Roederer+ 2011 (6 stars)

Young+ 2008 (14 stars)

Straniero, Cristallo & Piersanti 2014

The pollution of AGB stars with a mass ranging between 3 to 6 $M_{\text{SUN}}$ may account for most of the features of the s-process enrichment of M4 and M22.
The s-process in Globular Clusters

Roederer+ 2011 (6 stars)

Young+ 2008 (14 stars)
The s-process in Globular Clusters

Roederer+ 2011 (6 stars)

Young+ 2008 (14 stars)

M22(s+r) - M22(r only)
\[ \Delta t = 149 \text{ Myr} \quad \text{IMF } \alpha = 2.35 \]

s-process dominated

50%

Figure 11. Best fit of the s-process in stars in M22.

Figure 13. Best fit of the s-process in stars in M4.

M4 - M5
solid - \( \Delta t = 149 \text{ Myr} \) \ IMF \( \alpha = 2.35 \)
dashed - \( \Delta t = 265 \text{ Myr} \) \ IMF \( \alpha = -5 \)
The s-process in Globular Clusters

1. From the observational point of view, data relative to Ce are very robust.
2. Stellar models uncertainties affect the average absolute values of the three peaks and their relative ratios.
3. Within a single peak the relative distribution is determined by nuclear inputs.
Cerium

$^{140}\text{Ce}$ is the most abundant cerium isotope (88%)

- $(n,\gamma)$
- $\beta^-$ decay

Its production channel has already been explored by the n_TOF collaboration (Terlizzi+ 2007)
Cerium

$^{140}$Ce is the most abundant cerium isotope (88%)

$\text{(n,}\gamma\text{)}$

$\beta^-$ decay

Its production channel has already been explored by the n_TOF collaboration (Terlizzi+ 2007)
Expected variations on a theoretical AGB model (M=4 M_{\odot})

\begin{align*}
\sigma^{(140\text{Ce})}/1.5 \\
\sigma^{(140\text{Ce})}*1.5
\end{align*}
$^{140}$Ce neutron capture cross section (I)

![Graph showing the neutron capture cross section for $^{140}$Ce as a function of kinetic energy (KT) in keV. The graph includes data from KADONIS 1p0 and MACS.]
$^{140}\text{Ce}$ neutron capture cross section (I)

\begin{align*}
140\text{Ce} &\text{ neutron capture cross section} \\
\text{Stellar cross section} \quad [\text{mb}] \\
\text{MACS} \\
\text{KADONIS 1p0} \\
\end{align*}
$^{140}\text{Ce}$ neutron capture cross section (I)
$^{140}$Ce neutron capture cross section (II)

SSR (1973)
K. Siddappa+, Nuovo Cim. 18A, 48

MAM (1979)
A.de L. Musgrove+, Aust. J. Phys. 32, 213

XWY (1990)
Y. Xia+, Chin. J. Nucl. Phys. 12, 261

F. Käppeler+, Phys. Rev. C 53, 1397
H. Beer +, Phys. Rev. C 21, 534

HIM (2000)
S. Harnood+, J. Nucl. Sci. Techn.37 740

KADONIS 1p0
$^{140}$Ce neutron capture cross section (II)

SSR (1973)
K. Siddappa+, Nuovo Cim. 18A, 48

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HIM (2000)
S. Harnood+, J. Nucl. Sci. Techn. 37 740

Experimental

Library

Theoretical

Stellar cross section [mb]

Date

KADONIS 1p0

Activation @24-30 keV
$^{140}$Ce neutron capture cross section (II)

SSR (1973)
K. Siddappa+, Nuovo Cim. 18A, 48

MAM (1979)
A.de L. Musgrove+, Aust. J. Phys. 32, 213

XWY (1990)
Y. Xia+, Chin. J. Nucl. Phys. 12, 261

F. Käppeler+, Phys. Rev. C 53, 1397
H. Beer +, Phys. Rev. C 21, 534

HIM (2000)
S. Harnood+, J. Nucl. Sci. Techn.37 740

**Experimental Library**

**Theoretical**
EVALUATIONS:

Capture ORELA 40 m, \( C_6 F_6 \), 5 < \( E_n \) < 100 keV  
A.de L. Musgrove+, Aust. J. Phys. 32, 213

Transmission RPI 250 m  
20 < \( E_n \) < 60 keV  
H. S. Camarda. PRC 18, 1254

Transmission JAERI \( \text{nat} Ce \)  
\( E_n < 60 \) keV  
Ohkubo, jaeri report 1993

Capture (preliminary) 1974  
\( E_n < 65 \) keV  
by Hacken (Columbia)
140Ce neutron capture cross section (III)

**EVALUATIONS:**

Capture ORELA 40 m, C₆F₆
5 < Eₙ < 100 keV
A.de L. Musgrove+, Aust. J. Phys. 32, 213

Transmission RPI 250 m
20 < Eₙ < 60 keV
H. S. Camarda. PRC 18, 1254

Transmission JAERI natCe
Eₙ < 60 keV
Ohkubo, jaeri report 1993

Capture (preliminary) 1974
En<65 keV
by Hacken (Columbia)

**40% discrepancy at kT=8 keV**

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>MACS @ 8 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENDF/B-VIII.b</td>
<td>13.8 mb</td>
</tr>
<tr>
<td>(ENDF/B-VI)</td>
<td>(40.3 mb)</td>
</tr>
<tr>
<td>JEFF-3.1</td>
<td>16.7 mb</td>
</tr>
<tr>
<td>JENDL-4.0</td>
<td>17.3 mb</td>
</tr>
</tbody>
</table>
$^{140}\text{Ce}$ neutron capture cross section (III)

**EVALUATIONS:**

Capture ORELA 40 m, $C_6F_6$

$3 < E_n < 100 \text{ keV}$

A. de L. Musgrove+, Aust. J. Phys. 32, 213

Transmission RPI 250 m

$20 < E_n < 60 \text{ keV}$

H. S. Camarda. PRC 18, 1254

Transmission JAERI $^{\text{nat}}\text{Ce}$

$E_n < 60 \text{ keV}$

Ohkubo, jaeri report 1993

Capture (preliminary) 1974

$E_n < 65 \text{ keV}$

by Hacken (Columbia)
Room for improvement with $C_6D_6$
$^{140}$Ce neutron capture cross section (III)

EVALUATIONS:

Capture ORELA 40 m, $C_6F_6$
$3 < E_n < 100$ keV
A.de L. Musgrove+, Aust. J. Phys. 32, 213

Transmission RPI 250 m
$20 < E_n < 60$ keV
H. S. Camarda. PRC 18, 1254

Transmission JAERI $^{nat}$Ce
$E_n < 60$ keV
Ohkubo, jaeri report 1993

Capture (preliminary) 1974
$E_n < 65$ keV
by Hacken (Columbia)

$E \sim 2.5$ keV

not published
\(^{140}\)Ce neutron capture cross section (III)
$^{140}\text{Ce}$ neutron capture cross section (III)

1\textsuperscript{st} resonance ~ 15% of MACS @ $kT=8$ keV
Count rate @ EAR1 – 4 g $^{140}\text{Ce}$
Conclusions

- $^{140}\text{Ce}$ is a magic nucleus (88% os solar cerium), mostly synthesized by the s-process (81% of Galactic cerium).
- Heavy-element abundances in s-rich galactic Globular Clusters show good agreement with theoretical AGB models for elements belonging to the 2nd s-process peak...apart from cerium!
- MACS at AGB energies are highly uncertain due to lack of experimental data:
  - 2 transmission experiments in literature ($^{\text{nat}}\text{Ce}$ was used, energy region does not cover the whole region of interest, $E_n>$20 keV)
  - 1 capture experiment in literature ($C_6F_6$ as capture detector, not well suited for this measurement: $\Gamma_n \gg \Gamma_\gamma$)
  - No capture data below 5 keV reported in literature (just one unpublished report)!
- **Clear need of accurate capture data on $^{140}\text{Ce}$**

- n_TOF can provide capture data in the energy region of interest:
  - Low cross section $\rightarrow$ $2.9 \times 10^{18}$ protons
  - Resonances in the keV region $\rightarrow$ EAR1
  - $\Gamma_n \gg \Gamma_\gamma$ $\rightarrow$ $C_6D_6$