The s-process in massive stars: the shell C-burning contribution

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In the C shell:

C-burning:

$^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$, $\alpha$-source (($\alpha,n$) channels are activated!)

$^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$, p-source

$^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}^*$, negligible

$^{16}\text{O}$ is the most abundant isotope ($\sim 0.7$)
\[ \text{+ \( \alpha \)-captures} \]
\[ \text{+ \( p \)-captures} \]
Photodisintegrations to consider during shell C-burning:

- $^{13}\text{N}(\gamma,p)^{12}\text{C}^*$
- $^{17}\text{F}(\gamma,p)^{16}\text{O}^*$
- $^{17}\text{O}(\gamma,n)^{16}\text{O}$
- $^{21}\text{Na}(\gamma,p)^{20}\text{Ne}$
- $^{25}\text{Al}(\gamma,p)^{24}\text{Mg}^*$

For $T9 > 1.2$

$^{29}\text{P}(\gamma,p)^{28}\text{Si}$, …

* = photodisintegrations dominant on the direct reaction at 1 GK
In the C Shell:

Possible neutron sources:

\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]
\[ ^{17}\text{O}(\alpha,n)^{20}\text{Ne} \]
\[ ^{18}\text{O}(\alpha,n)^{21}\text{Ne} \]
\[ ^{21}\text{Ne}(\alpha,n)^{24}\text{Mg} \]
\[ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]
\[ ^{25}\text{Mg}(\alpha,n)^{28}\text{Si} \]
\[ ^{26}\text{Mg}(\alpha,n)^{29}\text{Si} \]
The weak s-component: summary

<table>
<thead>
<tr>
<th>Convective Core He-burning</th>
<th>Convective Shell C-burning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low neutron density (~$10^6\ n/cm^3$)</td>
<td>Peak neutron density ($10^{11}- 10^{12}\ n/cm^3$)</td>
</tr>
<tr>
<td>$T \sim 3-3.5\ 10^8\ K$</td>
<td>$T \sim 1\ 10^9\ K$</td>
</tr>
<tr>
<td>Classical s-process</td>
<td>The convective shell works over the ashes of the core He-burning (Raiteri et al. 1991)</td>
</tr>
</tbody>
</table>


The final weak s component is an overposition of two different s(s+) components
Models:
Hydrostatic nucleosynthesis in massive stars

• Post-processing models follow:
  Convective core He-burning and
  Convective shell C-burning
  (Raiteri et al. 1991, 1993)

• Updated network
  Bao et al. 2000 for \((n,\gamma)\) + more recent
  measures (KADoNiS, I. Dillmann poster),
  \(\beta\) decay rates from various sources,
  \((n,p)\) and \((n,\alpha)\) channels....
$25 \, M_{\text{sun}} \, [\text{Fe/H}] = 0$
$25 \, M_{\text{sun}} \, [\text{Fe/H}] = 0$
The image shows a chart with elements arranged vertically with their atomic numbers (Z) on the left side. The elements include Ga, Zn, Cu, Ni, Co, and Fe. Each element has a box with additional numbers and letters inside. The numbers and letters inside the boxes represent specific data, possibly related to chemical or physical properties. The chart is labeled with 'Z' on the left and 'A' on the right, indicating a possible relationship between atomic number and some other property.
This is not a classic s-process!
Metallicity dependence of the Weak s-process

He core:

$^{22}\text{Ne}$ (secondary-like) is the neutron source
$^{25}\text{Mg}$ (secondary-like) is the main neutron poison

$\rightarrow$ constant neutron exposure at different metallicities
constant number of neutrons captured per iron seed

$n_c = \Sigma_{56}^{209}(A-56)[N_{\text{fin}}(A)-N_{\text{in}}(A)]/^{56}\text{Fe}_{\text{ini}}$

$\rightarrow$ S-PROCESS YIELDS BEYOND IRON SCALES WITH THE METALLICITY
C shell:

$^{22}\text{Ne}$ (secondary-like) is the main neutron source
$^{25}\text{Mg}$ (secondary-like) and $^{16}\text{O}, ^{23}\text{Na}, ^{24}\text{Mg}, ^{28}\text{Si}$.... (primary-like) are the main neutron poisons!

→ constant neutron exposure at different metallicities
constant neutrons captured per Iron seed

→ S-PROCESS YIELDS BEYOND IRON SCALES
WITH THE METALLICITY
$25 \, M_{\odot} \, [\text{Fe/H}] = 0, -1 \, (\text{He core})$
25 $M_{\text{sun}}$ $[\text{Fe/H}] = 0, -1$ (C shell)
$25 \, M_{\text{Sun}} \, [\text{Fe/H}] = 0$
$25 \, M_{\text{Sun}} [\text{Fe/H}] = -1$
Any confirmation from spectroscopic observations?

YES....copper!

-Bisterzo et al. 2004, NPhA
Reddy et al. 2003 - Thin disk dwarfs
Mishenina et al. 2002 - I (Intermediate), D (Thick disk), O (Halo)
Sneden et al. 1991
Cowan et al. 2002 - BD173248
Westin et al. 2000 - HD 115444, HD 122563 - Giants
Sneden et al. 2003 - CS 22892-052 - Giant
Yushchenko et al. 2004 - HD202109
Mishenina et al. 2002 - D (likely Thin disk)

Secondary-like contribution

SNIa Fe contribution
Ge Abundances in Halo Stars
(slide courtesy of John Cowan)

\[
[A/B] = \log_{10}(A/B)_{\text{star}} - \log_{10}(A/B)_{\text{sun}}
\]

What happens at higher \([\text{Fe/H}]\) with the s-process?

Ge \(\propto\) Fe

Challenge to theorists.

JC et al. (2005)
Summary

• The Weak s-process is not ... weak
• Convective C shell contribution is important for the Weak s-process
• The s-process in the He core is secondary-like. This is not true any more in the C shell.
• There are spectroscopic observations confirming that the Weak s-process is secondary-like at metallicities lower than solar
and

- R. Gallino and C. Baldovin (Università’ di Torino)
- M. Wiescher (University of Notre Dame)
- F. Herwig and A. Heger (LANL)
- M. Heil and F. Käppeler (FZK Karlsruhe)