Weak sr(p)-process in Massive Stars

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- Marco Pignatari

In collaboration with Alexander Heger & Stan Woosley

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Objectives

✓ S-process nucleosynthesis in Massive Stars
✓ Neutron source $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
  (most neutrons are captured by light poisons,
  a few available for the s-process)

$\text{CNO} \rightarrow ^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$

✓ Metallicity dependence
✓ Convective core He-burning (classical weak s-process)
Previous calculations of the weak s-process in massive stars (core He-burning):

The production of the s-nuclei from Fe to Sr has long been ascribed to massive stars \((M > 10 \, M_\odot)\) during the hydrostatic phases of their evolution (Couch, Schmiedekamp, & Arnett 1974; Lamb et al. 1977; Arnett & Thielemann 1985; Busso & Gallino 1985; Prantzos, Arnould, & Arcoragi 1987; Langer, Arcoragi, & Arnould 1989; Prantzos, Hashimoto, & Nomoto 1990a; Raiteri et al. 1991a, b, hereafter Paper I and Paper II; Baraffe, El Eid, & Prantzos 1992). Most studies concentrated on the convective core He-burning stage, where \(\alpha\) captures on \(^{22}\text{Ne}\) at temperatures greater than \(T_8 = 2.5\) \((T_8\) being temperature in \(10^8\) K) give rise to a single neutron irradiation with low mean neutron densities not exceeding \(10^6\) cm\(^{-3}\).

(Raiteri et al. 1993)
✓ Convective shell carbon burning (s or ?) 
Neutron density ~ few $10^{12}$ n/cm$^3$

Example: neutron captures

<table>
<thead>
<tr>
<th>Ge</th>
<th>70</th>
<th>11.2m</th>
<th>72</th>
<th>73</th>
<th>74</th>
<th>83m</th>
<th>76</th>
<th>11.3h</th>
<th>88m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga</td>
<td>69</td>
<td>21.15m</td>
<td>71</td>
<td>14.1h</td>
<td>4.86h</td>
<td>8.1m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

...and p-process on s-seeds

<table>
<thead>
<tr>
<th>Ge</th>
<th>70</th>
<th>2.3h</th>
<th>18.7m</th>
<th>288d</th>
<th>39.0h</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga</td>
<td>69</td>
<td>15m</td>
<td>9.4h</td>
<td>78.3h</td>
<td>68.3m</td>
<td>69</td>
</tr>
</tbody>
</table>
P-process (Explosive nucleosynthesis). Example: $^{74}\text{Se}$, $^{78}\text{Kr}$, $^{84}\text{Sr}$

$M=25 \text{ Msun, } Z=Z_{\text{sun}}$ (Nucl. Data Page, A. Heger)
Kippenhan’s Diagram for a star with $M = 25 \, M_{\text{sun}}$ and solar metallicity (Woosley, Heger & Weaver 2002)
Post-Supernova production factors

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

$M=25 \text{ Msun, } Z=Z_{\odot}$ (Nucl. Data Page, A. Heger)
Theoretical prediction for evolution of $[\text{Cu/Fe}]$ vs $[\text{Fe/H}]$ in the galaxy
Timmes Woosley & Weaver 1995
Bisterzo et al. 2004 (NIC8)
70Zn overproduced*2

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

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M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

\[ \text{Br} \]

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

\[ M = 25 \text{ M}_\odot, \ Z = \text{Z}_\odot \] (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

Solar $^{36}\text{S}$ lower by a factor 1.6.
Solar $^{35,37}\text{Cl}$ higher by a factor 1.4

M=25 M\text{sun}, Z=Z\text{sun} (Nucl. Data Page, A. Heger)
Post-Supernova composition (yields)

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova production factors

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
Post-Supernova production factors

M=25 Msun, Z=Zsun (Nucl. Data Page, A. Heger)
GCE
AGB contribution to solar abundances
(Travaglio et al. 1999, 2004)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$^{63}$Cu</td>
<td>5.4 %</td>
<td>$^{65}$Cu</td>
<td>4.9 %</td>
<td></td>
</tr>
<tr>
<td>$^{66}$Zn</td>
<td>3.1 %</td>
<td>$^{67}$Zn</td>
<td>4.7 %</td>
<td></td>
</tr>
<tr>
<td>$^{68}$Zn</td>
<td>7.1 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{69}$Ga</td>
<td>9.2 %</td>
<td>$^{71}$Ga</td>
<td>11.7 %</td>
<td></td>
</tr>
<tr>
<td>$^{70}$Ge</td>
<td>14.7 %</td>
<td>$^{72}$Ge</td>
<td>14.7 %</td>
<td></td>
</tr>
<tr>
<td>$^{73}$Ge</td>
<td>9.7 %</td>
<td>$^{74}$Ge</td>
<td>11.0 %</td>
<td></td>
</tr>
<tr>
<td>$^{75}$As</td>
<td>8.4 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{76}$Se</td>
<td>27.4 %</td>
<td>$^{77}$Se</td>
<td>11.9 %</td>
<td></td>
</tr>
<tr>
<td>$^{78}$Se</td>
<td>18.1 %</td>
<td>$^{80}$Se</td>
<td>14.0 %</td>
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</tbody>
</table>
GCE
AGB contribution to solar abundances
(Travaglio et al. 1999, 2004)

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</thead>
<tbody>
<tr>
<td></td>
<td>79Br</td>
<td>14.9 %</td>
<td>81Br</td>
<td>14.5 %</td>
</tr>
<tr>
<td></td>
<td>80Kr</td>
<td>17.8 %</td>
<td>82Kr</td>
<td>52.6 %</td>
</tr>
<tr>
<td></td>
<td>83Kr</td>
<td>17.3 %</td>
<td>84Kr</td>
<td>17.7 %</td>
</tr>
<tr>
<td></td>
<td>86Kr</td>
<td>56.0 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85Rb</td>
<td>22.4 %</td>
<td>87Rb</td>
<td>77.6 %</td>
</tr>
<tr>
<td></td>
<td>86Sr</td>
<td>52.1 %</td>
<td>87Sr</td>
<td>53.8 %</td>
</tr>
<tr>
<td></td>
<td>88Sr</td>
<td>74.6 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>89Y</td>
<td>69.0 %</td>
<td></td>
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</tr>
</tbody>
</table>
# GCE

AGB contribution to solar abundances
(Travaglio et al. 1999, 2004)

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Element</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{90}\text{Zr})</td>
<td>53.5 %</td>
<td>(^{91}\text{Zr})</td>
<td>79.9 %</td>
</tr>
<tr>
<td>(^{92}\text{Zr})</td>
<td>75.7 %</td>
<td>(^{94}\text{Zr})</td>
<td>79.7 %</td>
</tr>
<tr>
<td>(^{93}\text{Nb})</td>
<td>67.0 %</td>
<td>(^{150}\text{Sm})</td>
<td>101 %</td>
</tr>
<tr>
<td>(^{36}\text{S})</td>
<td>4.0 %</td>
<td>(^{40}\text{Ar})</td>
<td>19.4 %</td>
</tr>
<tr>
<td>(^{40}\text{K})</td>
<td>18.7 %</td>
<td>(^{46}\text{Ca})</td>
<td>18.8 %</td>
</tr>
<tr>
<td>(^{58}\text{Fe})</td>
<td>6.9 %</td>
<td>(^{204}\text{Pb})</td>
<td>96.4 %</td>
</tr>
</tbody>
</table>
Conclusions

✓ All isotopes in the Cu-Sr region are produced by massive stars within a factor of two by the weak sr(p)-process
✓ no need of classical r-process
✓ Weak sr(p)-process is metallicity dependent
✓ $^{36}\text{S}$, $^{40}\text{Ar}$, $^{40}\text{K}$, $^{46}\text{Ca}$, $^{50}\text{V}$, ($^{58}\text{Fe}$) are also produced by the weak sr(p)-process