Nuclear Astrophysics - Nucleosynthesis of the heavy elements

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One of the main goals of Nuclear Astrophysics is to explain how and where the chemical elements were produced.

- Evolution of stars
- Chemical evolution of Galaxy
- Age of the Universe

Outline

- Nucleosynthesis processes of heavy elements – overview
- Recent observations of metal-poor halo stars and consequences for the nucleosynthesis
- Results of \((n,\gamma)\) cross section measurements (activation method)
- Conclusions
Nucleosynthesis of the heavy elements

Production of the elements:
• s process (50%)
• r process (50%)
• p process (<1 %)

p-Process Region

N = 50

terminates at $^{209}\text{Bi}$

p-only
s-only
r-only

Seed for s-Process
s-Process Reaction Path
s-Branchings ($^{63}\text{Ni}, ^{79}\text{Se}, ^{85}\text{Kr}, \ldots$)
Nucleosynthesis - s-process

- **main s-process**
  - $90 < A < 210$
  - He-rich intershell of evolved red giants (AGB)
  - $1 < M \odot < 6$
  - Neutron sources: $^{13}\text{C}(\alpha,n)$, $^{22}\text{Ne}(\alpha,n)$
  - Temp.: $\sim 1 \cdot 10^8$ K
  - Neutron density: $4 \cdot 10^8$ cm$^{-3}$

- **weak s-process**
  - $A < 90$
  - Core helium burning
  - Temp.: $\sim 2-3 \cdot 10^8$ K
  - Neutron density: $\sim 1 \cdot 10^6$ cm$^{-3}$

- **strong s-process**
  - $A = 208$
  - Shell carbon burning
  - Temp.: $\sim 1 \cdot 10^9$ K
  - Neutron density: $\sim 1 \cdot 10^{11}$ cm$^{-3}$

- s-process is secondary, not unique, models very advanced
- Data needs: neutron capture cross sections, stellar $\beta$-decay rates
- Reliable abundance calculations if $(n,\gamma)$ cross sections are accurate
Nucleosynthesis - r-process

one unique r-process

Supernovae (asymmetric)
Neutrino driven winds of neutron star
Neutron star merger

data needs:
neutron separation energies (masses)
Half-lives,
neutron capture cross sections during freeze-out

p-process: contributes only marginally to the synthesis of the elements
The main s-process in AGB stars

Stellar model calculations of AGB stars in comparison with the solar abundances

\[ N_r = N_{\text{solar}} - N_s \]

Abundances from r-process studies

• Since many of the input parameters (masses, $\beta$-decay rates, ...) are not known, reliable abundance calculations are not available.

• r-process cannot be described with one single parameter set.

Observation of metal-poor halo stars

Metal-poor halo stars should show pure r-abundances

Comparison of observed abundances and scaled $N_r$


$$\log \varepsilon(A) = \log \left( \frac{N_A}{N_H} \right) + 12$$
Sum rule: $s + p + r = 100\%$

Weak $s$:
Raiteri et al.

Main $s$:
Arlandini et al.

Galactic chemical evolution:
Travaglio et al.

$r$-abundances from halo stars:
Sneden et al.,

$p$-process:
Mo: 24 %
Ru: 7 %

Additional $r$-process?
Additional $s$-process?
Can the weak $s$-process account for the missing part?
There must be an “s-like” process since s-only isotopes are also underproduced.
Weak s-process – example $^{62}$Ni(n,γ)

Recommended cross section (Bao et al.) at kT=30 keV: 12.5 mb

Nuclear data needs for the weak s-process

s-process abundances are determined mainly by Maxwellian averaged neutron capture cross sections for thermal energies of kT=25 – 90 keV.

Problems:
• small cross sections
• resonance dominated
• contributions from direct capture

Methods:
• TOF: measure $\sigma(E_n)$ between 0.1 and 500 keV by time of flight, determine MACS for stellar spectrum

• Activation: produce stellar spectrum at kT=25 keV in laboratory, measure directly MACS
### Results - neutron capture cross sections

<table>
<thead>
<tr>
<th>Isotope</th>
<th>MACS @ kT=30 keV in mbarn</th>
<th>Bao et al. @ kT=30keV in mbarn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{45}$Sc</td>
<td>57 ± 2</td>
<td>69 ± 5</td>
</tr>
<tr>
<td>$^{59}$Co</td>
<td>41 ± 2</td>
<td>38 ± 4</td>
</tr>
<tr>
<td>$^{63}$Cu</td>
<td>53 ± 2</td>
<td>94 ± 10</td>
</tr>
<tr>
<td>$^{65}$Cu</td>
<td>29 ± 2</td>
<td>41 ± 5</td>
</tr>
<tr>
<td>$^{79}$Br</td>
<td>626 ± 19</td>
<td>627 ± 42</td>
</tr>
<tr>
<td>$^{81}$Br</td>
<td>241 ± 9</td>
<td>313 ± 16</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>16.1 ± 2.0</td>
<td>15.5 ± 1.5</td>
</tr>
</tbody>
</table>
Results – weak s-process abundances

Stellar model calculations performed by Marco Pignatari
• We have a good description of the main s-process

• Models of the weak s-process and especially the r-process have to be improved

• Observation of metal-poor halo stars suggest:
  - a robust and unique r-process
  - an additional s- and/or r-component

• Can the weak s-process account for the missing part?

   We don’t know before neutron capture cross sections of all involved isotopes are measured!