Neutron-Capture Elements in Metal-Poor Stars

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Neutron-capture processes in the early Galaxy

- **r-process**
  - supernovae (?) \(\Rightarrow\) early Galactic enrichment

- **s-process**
  - *main* component: intermediate-mass stars
    The effect appears more slowly than r-process
  - *weak* component: massive stars. Efficient at high metallicity?

- very metal-poor stars with excesses of light neutron-capture elements \(\Rightarrow 2^{\text{nd}}\) component of r-process?
- *r/s* stars: stars showing double enhancements of r- and s-process elements
Observational studies for the process that produces light neutron-capture elements in the early Galaxy

I. Abundance distributions of light and heavy neutron-capture elements in very metal-poor stars

II. Abundance patterns of metal-poor stars having excesses of light neutron-capture elements: -- a constraint on nucleosynthesis models

III. Neutron-capture elements in the most Fe-deficient star: -- a clue for the site of the light neutron-capture element production
   Frebel et al. (2005, Nature, 434, 871)
Abundance pattern of r-process stars

- Universality of the abundance pattern of heavy n-capture elements
- Variation of the pattern of light n-capture elements

The “r-process star” CS22892-052 (Sneden et al. 2003)
Multi-components of “r-process” elements in the solar system

The light neutron-capture elements of the Solar-System r-process component are not completely explained by the abundance pattern of r-process stars.

↓

2\textsuperscript{nd} component of r-process (“weak r-process”)

n.b. Uncertainties in the estimate of s- and r-process components of light n-capture elements in solar-system material are relatively large.

⇒ Observational constraints from metal-poor stars are important!
I. Abundance distributions of light and heavy neutron-capture elements
(1) Sr and Ba in very metal-poor field stars

Field halo stars with [Fe/H]<-2.5 (s-process-enhanced stars are excluded)

Aoki et al. 2005

Weak r-process? Sr/Ba >> 1

'Sr/Ba >> 1'

Field halo stars with [Fe/H]<-2.5 (s-process-enhanced stars are excluded)

Aoki et al. 2005
I. Abundance distributions of *light* and *heavy* neutron-capture elements (2) metallicity dependence

- Ba enrichment is found in stars with $[\text{Fe/H}] \geq -3$.
- Sr excess is found in some objects with $[\text{Fe/H}] < -3$. 

[Graphs showing abundance distributions for different metallicity ranges.]
I. Abundance distributions of \textit{light} and \textit{heavy} neutron-capture elements

(3) Y and Eu in very metal-poor field stars

Y and Eu are measured only for neutron-capture enhanced stars, but the measurement accuracy is higher.

Field halo stars with $[\text{Fe/H}] < -2.5$

(s-process-enhanced stars are excluded)

\textit{Aoki et al. 2005}
n-capture elements in M15 giants

- Abundance scatter in n-capture elements (Sneden et al. 1997)

- Scatter is small in light n-capture elements?

Otsuki et al. 2006
I. Abundance distributions of light and heavy neutron-capture elements.

(4) metal-poor ([Fe/H]=-2.3) globular clusters

Contribution of the weak r-process is also found in metal-poor globular clusters.

Otsuki et al. 2006
Contribution of the weak r-process at low metallicity

- The effect of weak r-process is generally found in metal-poor stars, including globular cluster objects (though the contribution is not homogeneous).

- The weak r-process occurs even in the progenitors of extremely metal-poor stars ([Fe/H]<-3), while the effect of the main r-process appears in [Fe/H]≥-3. → the astrophysical sites are quite different
II. Abundance patterns of metal-poor stars having excesses of light neutron-capture elements

- Objects representing the weak r-process
- 'r-process stars'
- CS22892-052
- 'main r-process'
Abundance pattern of HD122563, a bright metal-poor red giant star representing the weak r-process

$\text{Eu}$

[Fe/H]=-2.7

Honda et al. 2006
Abundance pattern of HD122563

Logarithmic abundance differences from the solar-system r-process pattern

The abundance continuously (gradually) decreases with increasing atomic number.
Abundance patterns of HD88609 ([Fe/H]=-3.0) and HD122563

Honda et al. (in prep)
Which process is responsible for the abundance patterns of HD122563 and HD88609?

- main r-process? No, because of the excess of light n-capture elements
- main s-process? No, because of relatively high abundances of Pd etc.
- weak s-process? No, because of relatively high abundances of Pd etc.

HD122563 and HD88609 show the abundance pattern produced by the weak r-process
Observational constraints on the abundance pattern produced by the weak r-process

- Large excesses of light neutron-capture elements ([Sr/Ba]~+1)
- Continuously (gradually) decreasing abundances between the elements at 1\textsuperscript{st} and 2\textsuperscript{nd} abundance peaks.

_Honda et al. (in prep)_
III. Neutron-capture elements in the most iron-deficient star HE1327-2326 - A clue for the site of the weak r-process

[Fe/H] = -5.4
Frebel et al. (2005)
Aoki et al. (2006)
Chemical abundance pattern of HE1327-2326

Fe-peak elements are deficient, while C (and N, Na etc) show large excesses.

Average of extremely metal-poor stars
Proposed models to explain the abundance pattern of HE1327-2326

• Population III (=1st generation star) scenario:
  HE1327 (as well as HE0107) formed from primordial (metal-free) clouds, but polluted by interstellar medium (Fe etc.) and AGB stars (C etc.).

• Population II (>2nd generation star) scenario:
  HE1327 (as well as HE0107) formed from clouds polluted by 1st generation massive stars, that have provided C-rich material.
  → SNe with mixing & fallback
    (Umeda & Nomoto 2003, Iwamoto et al. 2005)
  → Wind from rotating massive stars
    (Meynet et al. 2006)
Sr overabundance in HE1327-2326

- Excess of Sr: $[\text{Sr/Fe}] \approx +1$
- Ba is not detected.

Lower-limit of Sr/Ba ...

$[\text{Sr/Ba}] > -0.4$

The main r-process is not excluded as a source of n-capture elements, but weak r-process would be preferable.

Progenitor of HE1327 is the weak r-process site?
Summary of the observational studies on “weak r-process”

I. The contribution of weak r-process is generally found in metal-poor stars (even with \([\text{Fe/H}]<-3\)), though that is inhomogeneous.

II. Observational constraints on the abundance pattern produced by the weak r-process is provided: abundances continuously (gradually) decrease with increasing atomic number.

III. The progenitor of the most Fe-deficient star known might be a site of the weak r-process.
Stars with double enhancements of r- and s-proces elements (r/s stars)

r/s stars: s-process (and carbon) enhanced stars that also show excesses of Eu.

observational facts:
• r/s stars are extremely s-process enhanced stars
• number fraction of r/s stars among s-process enhanced stars is high

Jonsell et al. 2006
Abundance pattern of the r/s star CS31062-050

• For CS31062-050, 24 neutron-capture elements including Os and Ir, the 3rd peak r-process elements, are measured (Johnson et al. 2004, Aoki et al. 2006).

• Comparison with production by s-process model shows large excesses of the r-process elements Eu, Os, and Ir.
Detection of Os and Ir in the r/s star CS31062-050

Aoki et al., submitted to ApJL
Abundance pattern of the r/s star CS31062-050

M ~ 1.3 M\(_\odot\) case: ST/10
dil = 0.0
T\(_{\text{eff}}\) = 5500 K; log g = 2.7

Thick line: \([\text{Eu/Fe}]^{\text{ini}} = 1.5\)
Thin line: \([\text{Eu/Fe}]^n = 0.0\)

CS31062-050
Johnson and Bolte 2004
Ba, Os, Ir this work
[Fe/H] = -2.42

Os Ir
r+s-process

Aoki, Bisterzo, Gallino et al., submitted to ApJL
Possible scenarios to interpret r/s stars

• Modified s-process models? ⇒ No(?), because of high Os and Ir

• s-process in an (intermediate mass) AGB star that has formed from r-process enhanced material?

• A high mass (8-10Msun) AGB star produced s-process elements, and then exploded as a supernova that provided r-process elements. *Wanajo et al. 2006*

r/s stars may have a key to understanding the r-process and its astrophysical site.
Variation of neutron-capture processes in the early Galaxy

r-process
main component
weak component?

s-process
main component
(weak component)

“r/s stars”

Further variation found by future observations?