The rapid neutron capture process

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Open questions:
• where in nature does the r-process take place?
• is there more than one r-process in nature?
• what are the heaviest elements produced by the r-process?
• what is the exact reaction sequence?
  (does it include neutrino reactions, fission, …)
• Can the r-process tell us something about the physics of extreme astrophysical environments?
The r-process signature in the solar abundances

Solar abundance distribution of nuclei (summed by mass number)

Conclusion: r-process produces about half of heavy elements beyond Fe peak
each process contribution is a mix of many events!
Heavy elements in Metal Poor Halo Stars

recall:
$[X/Y] = \log(X/Y) - \log(X/Y)_{\text{solar}}$

CS22892-052
red (K) giant
located in halo
distance: 4.7 kpc
mass $\sim 0.8 \text{ M}_\odot$
$[\text{Fe/H}] = -3.0$
$[\text{Dy/Fe}] = +1.7$
A single (or a few) r-process event(s)

CS22892-052 (Sneden et al. 2003)

- solar r

CS31082-001 with U
(Cayrel et al. 2001)
Age: 16±3 Gyr
(Schatz et al. 2002 ApJ 579, 626)

other, second r-process to fill this up?
(weak r-process)

main r-process matches exactly solar r-pattern conclusions?
s- and r-process history revealed by metal poor stars


(note: r-process and s-process Ba disentangled by calculation using info from other s-only and r-only elements)
How does the r-process work?

Need:  
- mix of suitable heavy seed nuclei (A=56-90) and neutrons  
- sufficient large number density of neutrons (max at least $\sim 1 \times 10^{24}$ cm$^{-3}$)  
- sufficient large neutron/seed ratio (at least $\sim 100$)

Temperature: $\sim 1$-2 GK  
Density: 300 g/cm$^3$ ($\sim 60\%$ neutrons !)  
neutron capture timescale: $\sim 0.2$ $\mu$s

Rapid neutron capture  
\[(\gamma, n)\] photodisintegration  
Equilibrium favors "waiting point"  
$\beta$-decay
Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie: H. Schatz, National Superconducting Cyclotron Laboratory
Calculation: K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame
Model: B. Meyer, Clemson University
and R. Surman, North Carolina State

Pt
Xe
Ni

Temperature: 1.50 GK
Time: 2.7e-14 s

- r-process needed
  - produce abundance peaks at right “location”
  - produce nuclei beyond Bismuth

→ Need nuclear physics to disentangle nuclear and astro effects from observed abundances
• Site independent models:
  • $n_n$, $T$, $t$ parametrization (neutron density, temperature, irradiation time)
  • $S$, $Y_e$, $t$ parametrization (Entropy, electron fraction, expansion timescale)

• Core collapse supernovae
  • Neutrino wind
  • Jets
  • Explosive helium burning
  • Gamma-ray bursts

• Neutron star mergers
  • Hot models
  • Cold decompression
Neutron star forms (size ~ 10 km radius)

Matter evaporated off the hot neutron star r-process site?
How does the r-process work? Neutron capture!
Most favored scenario for high entropy:

Neutrino heated wind evaporating from proto neutron star in core collapse

**Weak interactions regulate n/p ratio:**

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]  \hspace{1cm} faster as \( \bar{\nu}_e \) come from deeper and are therefore hotter!

\[ \nu_e + n \rightarrow p + e^- \]

**Therefore matter is driven neutron rich**
How to make r-process seeds out of light particles?

\[ \alpha + \alpha + \alpha, \gamma \]

\[ \alpha + \alpha + n, \gamma \]

\[ \alpha, n \]

3a not important

Most important: \( \alpha + \alpha + n \)

Recently emphasized:
Maybe \( (t, \gamma)(n, \gamma)(\alpha, n) \)
also relevant
(Sasaqui et al. 2005)

For successful r-process one needs (choose one)
(A) slow, inefficient seed production
(B) fast, efficient seed production

\( \alpha \)-process to A~90 or r-process right away
Results for Supernova r-process

(for latest treatment of this scenario see Thompson, Burrows, Meyer ApJ 562 (2001) 887)

- Density artificially reduced by factor 5.5
- A~90 overproduction
- Can’t produce A~195 anymore
- Artificial parameter to get A~195 peak (need S increase)
- Other problem: the $\alpha$ effect
other problem: the $\alpha$ effect

Recall equilibrium of nucleons in neutrino wind:

\[ \begin{align*}
\bar{\nu}_e + p &\rightarrow n + e^+ \\
\nu_e + n &\rightarrow p + e^-
\end{align*} \]

\[ \left\{ \text{Maintains a slight neutron excess} \quad \frac{n_p}{n_p + n_n} \approx 0.4 \right\} \]

What happens when $\alpha$-particles form, leaving a mix of $\alpha$-particles and neutrons?
r-process in neutron star mergers?
Ejection of matter in NS-mergers


Destiny of Matter:
- red: ejected
- blue: tails
- green: disk
- black: black hole

(here, neutron stars are co-rotating – tidally locked)
r-process in NS-mergers

large neutron/seed ratios, fission cycling!

But: \( Y_e \) free parameter …
### Summary theoretical scenarios

<table>
<thead>
<tr>
<th></th>
<th>NS-mergers</th>
<th>Supernovae</th>
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<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>1e-5 - 1e-4</td>
<td>2.2e-2</td>
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<tr>
<td>(per yr and Galaxy)</td>
<td></td>
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<tr>
<td><strong>Ejected r-process mass</strong></td>
<td>4e-3 – 4e-2</td>
<td>1e-6 – 1e-5</td>
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<tr>
<td>(solar masses)</td>
<td></td>
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<tr>
<td><strong>Summary</strong></td>
<td>less frequent but</td>
<td>more frequent and</td>
</tr>
<tr>
<td></td>
<td>more ejection</td>
<td>less ejection</td>
</tr>
</tbody>
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What does galactic chemical evolution observations tell us?


Supernovae

Model star average with error
Average ISM

Dots: model stars

NS mergers

observations

→ Neutron Star Mergers ruled out as major contributor