Understanding the r-process
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• r-process
• Nuclear physics
• CARIBU (Masses, half-lives and $\beta$-delayed neutron branching ratios)

Open questions:
• Where does the r-process occur?
• What are the actual reaction sequences?
• Are there multiple processes in the early Galaxy?
• What can the r-process tell us about physics of extreme environments?
Metal-poor stars

For individual stars all elemental abundances were first scaled to their Eu values, then averaged for all six stars, and finally zero offset is indicated by the dashed horizontal line. Symbols for the stars are the same as in panel a.

The abundance data of all stars except CS 22892-052 have been vertically displaced downward for display purposes. The solid light blue lines are the scaled r-process-only abundance distribution.

Table 1: [Fe/H] < -2.5

Metal poor (old stars)

Table 2: Individual stellar abundance offsets with respect to Simmerer et al. (2004)

Sneden et al., Annu. Rev. Astro. 2008, 46, 241


Eu: r-process element
Multiple r-processes?


Light Element Primary Process
LEPP

r-process:
Most of the elements heavier than Sr

LEPP:
Only Sr - Ag?

HD 122563 ([Fe/H] = -2.77, Honda et al. 2006)

translated solar r-pattern (Arlandini et al. 1999)

Weak r-process (Truran&Cowan 2000)
Charge-particle reaction process
(Woosley&Hoffman 1992; Freiburghaus et al. 1999)
Most of the heavy elements (Z>30) are formed in neutron capture processes, either the slow (s) or rapid (r) process.
Where does the r-process occur?

**Neutron star mergers** (Freiburghaus et al. 1999, Goriely et al. 2005)
- Mergers rate too low to explain [Eu/Fe] ratio
- Composition of ejected material unknown

**Gamma ray bursts**
(Surman et al. 2005)

**Supernovae**
- ONeMg core collapse (Wanajo et al. 2003)  \( Y(n) \) not high enough
- Jets in core-collapse supernovae (Cameron 2001)  entropic not high enough
- \( \nu \)-driven wind (Woosley et al. 1992, Terasava et al. 2001)  entropy not high enough
- Neutrino-induced in He-shells (Epstein et al. 1988, Banerjee et al. 2011)
ν-driven wind scenario

- shock
- reverse shock
- neutron star

Entropy [kB/nuc]

Arcones et al. 2007
Here we analyze the impact of the reverse shock on different trajectories [26, 42]. Some of the deficiencies discussed in the next section. However, there are features that depend on the dynamical evolution. In order to understand the abundances under different trajectories together with solar r-process abundances (dots) [72]. None of the calculations reproduce mainly the third r-process peak (2c), produce the solar abundances around the second peak (2b), and the first r-process peak (2a).

\[ \rho \propto \rho_0 \exp \left( -\frac{\gamma_1}{\gamma_1-1} \right) \]

\[ \gamma_1 = \frac{1}{n_{\text{He}} \sigma_{\text{H-S}}} \]

\[ \langle N \rangle = \sum_{Z,A} \frac{1}{Y_{\text{be}}} \]

\[ \tau = \frac{n_{\beta}}{\rho v} \]

\[ \beta = \frac{n_{\beta}}{n_{\gamma}} \]

\[ Y_{\text{be}} \sim \frac{1}{2} \]

\[ Y_{\text{be}} \sim \frac{1}{2} + \frac{1}{2} \]

FIG. 1: (Color online) Temperature and density evolution of the v-driven wind simulation model.

FIG. 2: (Color online) Final abundances for the different evolutions of Fig. 1 compared to solar r-process abundances.
Hot r-process

**Location of path**

\[ S_n = \frac{T_9}{5.04} \times (34.08 + 1.5 \log T_9 - 1.5 \log n_n) \]

= 2.5-4 MeV

**Need:**

- Masses (traps)
- Half-lives (Si detector stacks, combine with \( \gamma \)-spectroscopy)
- Neutron capture rates after neutron freeze-out
- Neutron emission probabilities (neutron detector)
- Maybe fission and neutrino interaction rates

The evolution takes place under \((n,\gamma)-(\gamma,n)\) equilibrium (classical r-process, Seeger, Fowler and Clayton 1965, Kratz et al. 1993)

Equilibrium favors “waiting points”
Cold r-process

Location of path
$S_n = 2-4$ MeV

Need:
- Neutron capture rates (masses)
- Half-lives
- Neutron emission probabilities
- Maybe fission and neutrino interaction rates

Competition between beta decay and neutron capture (Blake & Schramm 1976, Wanajo 2007, Janka & Panov 2009)
Sensitivity of r-process to astro and nuclear physics

**Sensitivity to astrophysics**

- FRDM
  - Hot r-process
  - Cold r-process
- Comparison to observations:
  - Obtain neutron density, temperature, time
  - Neutrino interactions
  - Determines which model is correct
  - Convoluted with nuclear physics

**Sensitivity to nuclear physics**

- ETFSI-Q masses
- ETFSI-I masses
- Hot r-process
Shell quenching effect on masses/r-process

Neutron number

$S_{2n}$ [MeV]

r-process path

ETFSI-I

- 40
- 42
- 44
- 46
- 48
Shell quenching effect on masses/r-process

Neutron number $S_{2n}$ [MeV]

ETFSI-I
- 40
- 42
- 44
- 46
- 48

ETFSI-Q
(N=82 quenched)

CARIBU reach

Diff. in models
Possible CARIBU half-life measurements

Known half-lives
CARIBU reach

Direct effect on r-process path
Summary

- New observations will require similar advances in nuclear physics to address the many compelling scientific questions of the r-process
- Neutron-rich nuclei far from stability are important in the r-process
- CARIBU rates will enable the study of nuclei relevant for r-process nucleosynthesis

- Mass measurements ($\delta<10\text{-}100\text{ keV}$) will have a direct effect on r-process calculations and will address the question about shell-quenching at the $N=82$ shell closure
- Half-lives and $P_n$ measurements will put the nuclear physics in the r-process responsible for Sr, Y and Zr abundances in a solid basis

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