r-process nucleosynthesis: conditions, sites, and heating rates

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The (solar) r-process abundance pattern

Uncertainties for r-process calculations:
- nuclear properties
- neutron capture cross sections
- $\beta$-decay rates
- fission rates & fragment distribution
- hydrodyn. conditions
  - $Y_e = \frac{n_p}{n_p + n_n}$
  - temperatures and densities
  - expansion timescales

Marius Eichler thoughts on the r-process
basic equations

\[ \dot{Y}_i = \sum_j N_i^j \lambda_j Y_j + \sum_{j,k} \frac{N_{j,k}^i}{1 + \delta_{jk}} \rho N_A \langle \sigma v \rangle_{j;k} Y_j Y_k + \sum_{j,k,l} \frac{N_{j,k,l}^i}{1 + \Delta_{jkl}} \rho^2 N_A^2 \langle \sigma v \rangle_{j;k;l} Y_j Y_k Y_l \]

nuclear statistical equilibrium:
\[ \bar{\mu}(Z, N) = Z \bar{\mu}_p + N \bar{\mu}_n \]

\[ Y(Z, N) = G_{Z,N}(\rho N_A)^{A-1} \frac{A^{3/2}}{2^A} \left( \frac{2\pi \hbar^2}{m_u kT} \right)^{3/2} (A-1) \exp \left( \frac{B_{Z,N}}{kT} \right) Y_n^N Y_p^Z \]

\[ \sum_i A_i Y_i = 1 \]
\[ \sum_i Z_i Y_i = Y_e \]
(n, \gamma) \rightarrow (\gamma, n) \text{ equilibrium}

\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{\langle \sigma v \rangle_{n,\gamma}(Z,A)}{\lambda_{\gamma,n}(Z,A)} \frac{n_n}{G(Z,A)} \left( \frac{A+1}{A} \right)^{3/2} \left( \frac{2 \pi \hbar^2}{m_u kT} \right)^{3/2} n_n \exp[S_n(Z, A + 1)/kT]

\lambda_{\gamma,n}(Z, A + 1) = \frac{2G(Z,A)}{G(Z,A+1)} \left( \frac{A}{A+1} \right)^{3/2} \left( \frac{m_u kT}{2 \pi \hbar^2} \right)^{3/2} \langle \sigma v \rangle_{n,\gamma}(Z, A) \exp[-S_n(Z, A + 1)/kT]
Hot and cold r-process

first defined by Wanajo (2007)

Eichler et al. (2015)

tidal ejecta are a hot r-process scenario if nuclear heating is taken into account
Late-time heating from radioactive decays

see also Metzger (2014), Lippuner & Roberts (2015), Fernandez & Metzger (2016), Rosswog et al. (2017), Wollaeger et al. (2017)

Barnes et al. (2016)
Survival timescales of heavy nuclei

Möller et al. (2003):

Marketin et al. (2015):

Marius Eichler thoughts on the r-process
Fission powering kilonova/macronova light curves

experimentally known SF rates with $1 \text{d} < T_{1/2} < 2$ weeks

log$_{10} \left( \min \left( T_{1/2(\alpha)}, T_{1/2(\beta)} \right) \right) \text{[s]}$
Phenomenological spontaneous fission rates

Petermann et al. (2012)
\[ \log(T_{1/2})[s] = 8.08B_f - 24.05 \]

Zagrebaev et al. (2011)
\[ \log(T_{1/2})[s] = 1146.4 - 75.3 \frac{Z^2}{A} + 1.638 \left( \frac{Z^2}{A} \right)^2 - 0.012 \left( \frac{Z^2}{A} \right)^3 + (7.24 - 0.095 \frac{Z^2}{A})B_f + C(Z, A) \]
Phenomenological spontaneous fission rates

Based on ETFSI barriers (sets from I. Panov)

\[ \log(T_{1/2})[s] = 7.77B_f - 33.3 \]

\[ \log(T_{1/2})[s] = 10.145B_f - 50.127 \]
Spontaneous fission rates

Based on BCPM EDF (Giuliani et al. 2017)

Based on these models, very unlikely that spontaneous fission occurs on timescales between 1 day and 2 weeks.
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Actinide abundances in Metal-poor stars

from Meng-Ru's presentation (10.08.2017)

solar like [Eu/Th]

HE1523-0901  CS22892-052

CS30315-029  CS22953-003  CS31082-001

HE1219-0312

actinide boost stars with enhanced Th abundances

from SAGA database

from Meng-Ru's presentation (10.08.2017)
MHD supernovae

Winteler et al. (2012)

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thoughts on the r-process
Other models

see also Takiwaki et al. (2009)

see also Takiwaki et al. (2009)
MHD supernovae in GCE

Wehmeyer et al. (2015)

thoughts on the r-process
Is there a demand for a reduced r-process network for hydro simulations?
Analytic formula for nuclear heating

Korobkin et al. (2012): 

$$f_{\text{tot}}(t) = 0.36 \left[ \exp(-at) + \frac{\ln(1+2bt^d)}{2bt^d} \right]$$

only valid for FRDM!

Barnes et al. (2016):

$\alpha \propto \text{const.}$

$\epsilon_{\text{th}} = 0.1$

$\epsilon_{\text{th}} = 0.5$

$\epsilon_{\text{th}} = 0.9$

$\alpha \propto t^n$

Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>$v_{ol}/c$</th>
<th>Coefficients</th>
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<th>$b$</th>
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<td>0.95</td>
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</table>
Starting point: waiting point approximation

\[ \dot{Y}(Z) = \lambda_\beta(Z - 1, N_{Z-1}) Y(Z - 1) - \lambda_\beta(Z, N_Z) Y(Z) \]

\[ \frac{Y(Z,A+1)}{Y(Z,A)} = \frac{G(Z,A+1)}{2G(Z,A)} \left( \frac{A+1}{A} \right)^{3/2} \left( \frac{2\pi \hbar^2}{m u kT} \right)^{3/2} n_n \exp[S_n(Z, A+1)/kT] = 1 \]

\[ S_n^{\text{crit}} = -kT \ln \left( n_n \frac{G(Z,N+1)}{2G(Z,N)} \left( \frac{A+1}{A} \frac{2\pi \hbar^2}{m u kT} \right)^{3/2} \right) ; \]

\[ S_n(Z, N_Z) > S_n^{\text{crit}} > S_n(Z, N_Z + 1) \]
(first) idea: look at isobars and distribute nuclei into bins according to their $\beta$-decay timescales

Abundances of isobars stay constant for $\beta$-decays with $P_n = 0$