Nuclear Astrophysics

V: Nucleosynthesis beyond iron

Karlheinz Langanke

GSI & TU Darmstadt

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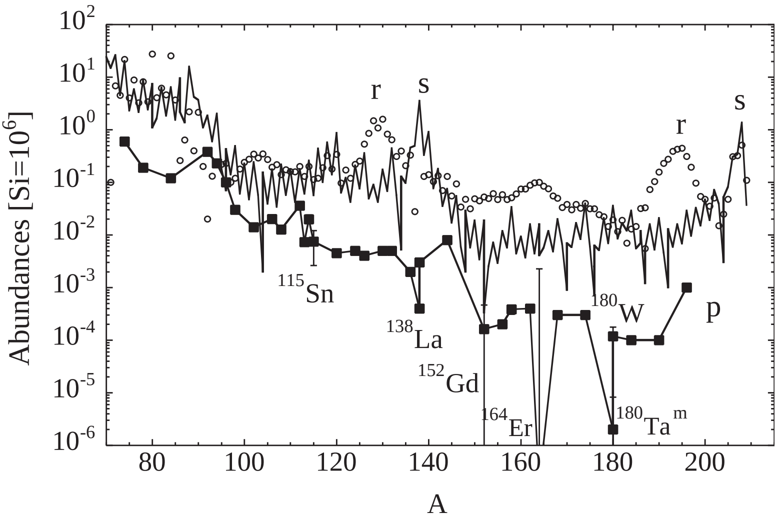
Abundances of heavy nuclei



Two main processes (s-process, r-process) plus the p-process.

Why several processes?

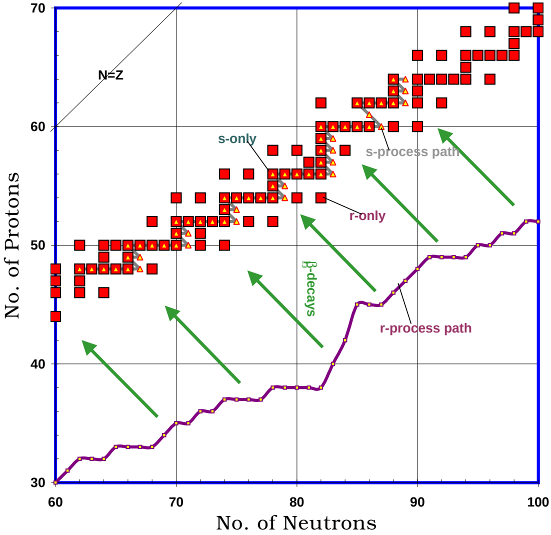
- double-peak structures which are related to magic neutron numbers $N = 50, 82, 126$
- the upper peaks occur in accordance with mass numbers of stable double-magic nuclei (A=87, 138, 208); they are associated with the s-process
- the lower peaks occur at mass numbers which are shifted compared to the stable double-magic nuclei (A=80, 130, 195); they are associated to very neutronrich, magic nuclei which are produced by the r-process
- for some (even-even) mass numbers there exist 2 or even 3 stable nuclides (in principle, only one nucleus per mass number is stable, the others then decay by double-beta decay which has extremely long half-lives); the neutronrich nuclide is produced by the r-process, the 'middle-one' in the valley of stability by the s-process. For the neutron-deficient nuclide one needs an extra process, which is called p-process.

Neutron captures vs beta decays

R- and s-process are a sequence of neutron captures, interrupted by beta decays, which are needed to progress in charge number. The beta decays are characterized by lifetimes τ_β, which usually do not depend on the environment. The neutron captures are characterized by lifetimes $\tau_n = 1/(N_n \langle \sigma_n v \rangle)$, which depend on the neutron number densities N_n. (We note that τ_β and τ_n can both also depend on temperature.)
Consider the two cases:

1. If $\tau_\beta < \tau_n$, then an unstable nucleus, reached on the path, will beta-decay before it captures another neutron. The path runs through the valley of stability. This is the s-process.
2. If $\tau_\beta >> \tau_n$, several neutron captures will occur, before a nucleus is reached which beta-decays. The path runs through very neutronrich nuclei. This is the r-process. To achieve the short neutron capture times one needs very high neutron densities.

R- and s-process only nuclei



R- and s-process

Both, r- and s-process contribute to abundances of heavy elements, in fact many nuclides are made by both processes. However, some nuclides are only made by r-process (**r-process only**), while some are made only by the s-process (**s-process only**).

How does this happen?

The r-process path runs through very neutronrich nuclei far away from stability.These nuclides are unstable and decay to stability once the r-process neutron source is used up. This decay chain stops once a stable nucleus is reached. However, if there are two stable nuclei with the same A number, the decay stops at the neutronrich nucleus $A = (Z, N)$ and there is no contribution to the other stable nucleus $A = (Z + 2, N - 2)$. The latter, which is in the valley of stability, is only made by the s-process, while the first has no s-process contribution. S-only and r-only nuclides play important roles to disentangle the two processes. In general, there are also minor p-process contributions which have to be considered.

The classical s-process model

The classical model of B²FH is based on the following idea:
If a nucleus is β-unstable following a neutron capture in the s-process, it will almost always β-decay to the first available stable isotope before the next neutron capture occurs. Then it generally suffices in the s-process to follow only the abundances as function of mass numbers, which only changes by neutron captures:

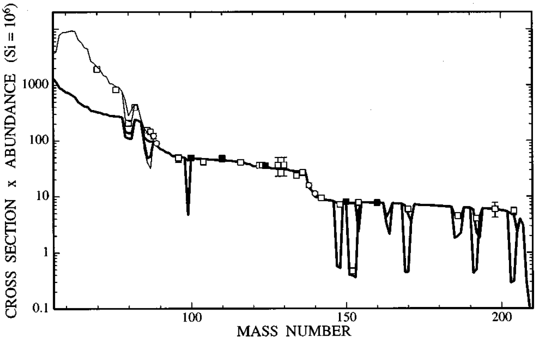
$$\frac{dN_A}{dt} = -N_n \langle \sigma v \rangle_A N_A + N_n \langle \sigma v \rangle_{A-1} N_{A-1}$$

As for neutron capture $\sigma \sim \frac{1}{v}$, one can write $\langle \sigma v \rangle_A = \sigma_A v_T$, where v_T is the thermal velocity of neutrons and σ_A the thermal capture cross section. Defining a neutron exposure $\tau = \int N_n v_T dt$, one has

$$\frac{dN_A}{d\tau} = -\sigma_A N_A + \sigma_{A-1} N_{A-1}.$$

If the s-process achieves a steady state, $\frac{dN_A}{d\tau} = 0$ and $\sigma_A N_A = const$.

Abundance vs cross section



abundance × cross sections indeed constant between magic numbers!

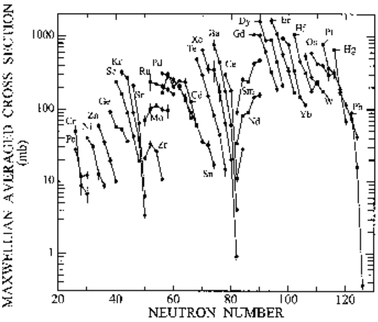
However, two components are required to make medium-mass and heavier s-process nuclei.

The main and the weak s-process component

- **Main component.** Produces most of the nuclei in the mass range $90 < A < 204$. It occurs in AGB (Asymptotic Giant Branch) stars. The main neutron source is ^{13}C(α,n)^{16}O. The temperature is of order 3×10^8 K, the neutron number density of order 10^8/cm^3.
- **Weak component.** This component contributes significantly to the production of s-nuclides in the $A \sim 90$ mass range. It operates in core-helium burning in more massive stars. The main neutron source is ^{22}Ne(α,n)^{25}Mg.

The s-process stops at ^{208}Pb, ^{209}B, where the s-process path hits the region of α-instability.

Neutron capture cross sections



(n, γ) cross section have minima at magic neutron numbers. As the product (abundance $\times$ cross sections) is about constant follows that

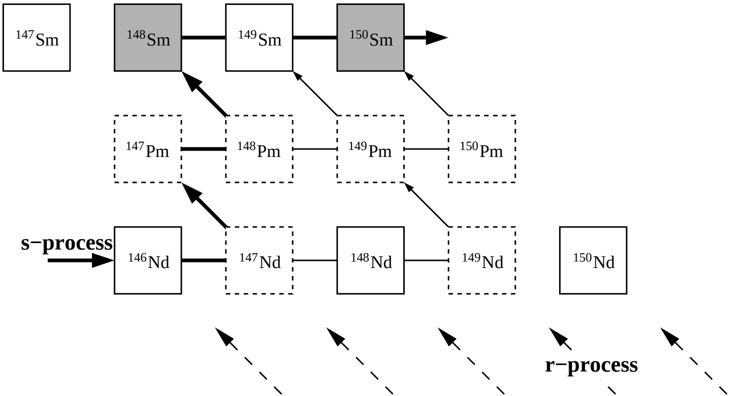
the s-process abundances have maxima at the neutron magic numbers, in agreement with observation.

S-process branchings

Usually $\tau_\beta < \tau_n$ for nuclei on the s-process path. As the neutron capture rate ($r = \tau_n^{-1} = N_n \langle \sigma v \rangle$) depends on the neutron number density N_n, the inequality $\tau_\beta < \tau_n$ gives first constraints on the s-process environment. However, much better constraints can be derived from the **s-process branching points**, where $\tau_\beta \approx \tau_n$. In particular one can use the facts that the lifetimes depend on temperature, neutron and mass density.

- β-decay rates are temperature sensitive; then branchings allow the determination of the stellar temperature
- sometimes also electron captures are important; these rates depend on the mass density
- branchings obviously also allow to determine the neutron number density

Branching at ^{150}Sm

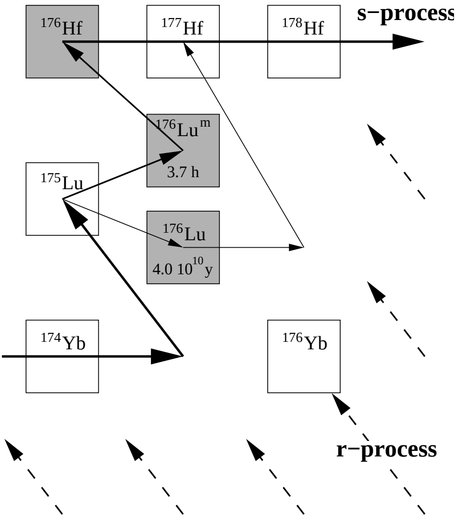


Branching at ^{148}Pm:

$$f_\beta = \frac{\lambda_\beta}{\lambda_\beta + \lambda_n} = \frac{\langle \sigma v \rangle N(^{148}Sm)}{\langle \sigma v \rangle N(^{150}Sm)} \approx 0.9$$

The neutron density is estimated to be: $(4.1 \pm 0.6) \times 10^8\ \mathrm{cm}^{-3}$

Branching at ^{176}Lu



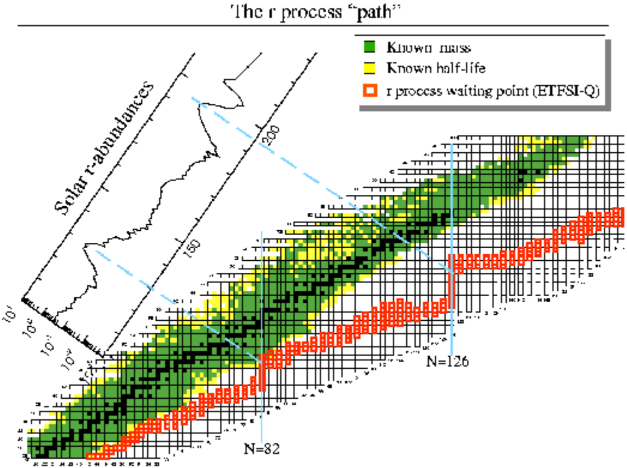
Branching depends on temperature, resulting in $T = (2.5 - 3.5) \times 10^8$ K.

R-process: the general idea

R-process simulations indicate that the process proceeds at finite temperature where, in a good approximation, $(n, \gamma) \leftrightarrow (\gamma, n)$ equilibrium holds.
This will imply that

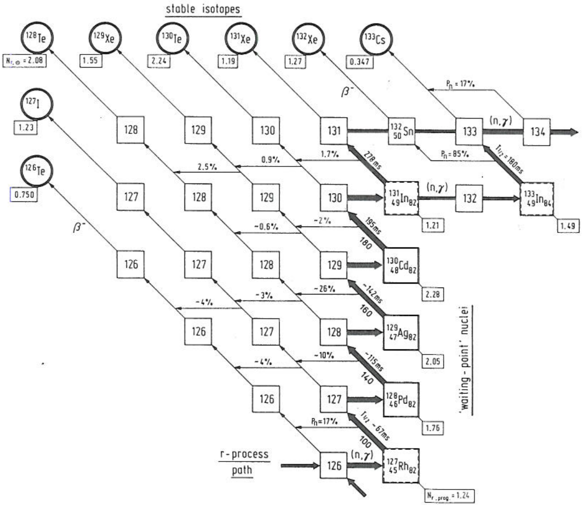
1. the process runs along a path of approximately constant neutron separation energy S_n.
2. for a given Z value, the abundance flow resides basically in a single isotope, which is the one with a neutron separation energy closest to S_n
3. for the mass flow to proceed from Z to $Z + 1$ a β decay is required
4. if β-decays are fast enough, β-flow equilibrium might establish and the abundances might be indirectly proportional to the halflives
5. after the neutron source is exhausted, the r-process freezes out and the unstable nuclei decay back to stability
6. if the r-process reaches nuclei in the uranium region, fission can occur possibly bringing part of the mass flow back to lighter nuclei (fission cycling)
7. if the r-process occurs in strong neutrino fluxes, neutrino-induced reactions can influence the r-process dynamics and abundances

r-process



$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$
$(n, \gamma) \rightleftarrows (\gamma, n)$ implies $S_n \approx 2$ MeV

The r-process at magic neutron numbers



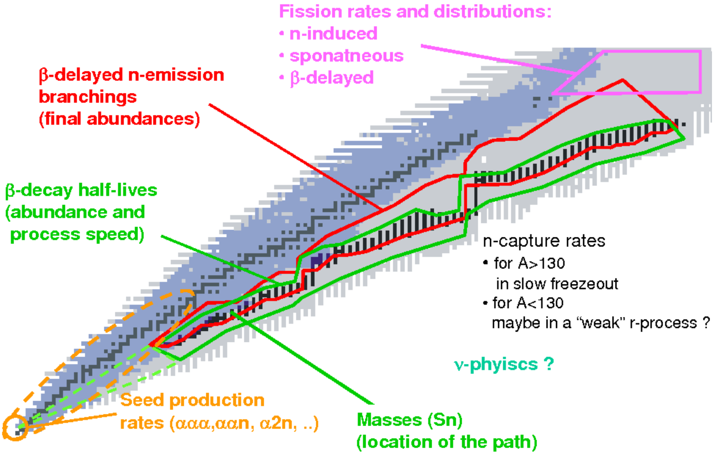
Why are there r-process peaks?

Once the path reaches nuclei with magic neutron numbers (Z, N_{mag}), the neutron separation energy for the nucleus $(Z, N_{mag}+1)$ decreases strongly. Thus, (γ, n) hinders the process to continue and (Z, N_{mag}) *beta*-decays to $(Z+1, N_{mag}-1)$, which is followed immediately by n-capture to $(Z+1, N_{mag})$. This sequence of alternative β-decays and n-captures repeat itself, until n-capture on a magic nucleus can compete with destruction by (γ, n).

Thus, the r-process flow halts at the magic neutron numbers. Due to the extra binding energy of magic nuclei, the Q_β values of these nuclei are usually smaller than those for other r-process nuclei. This makes the lifetimes of the magic nuclei longer than lifetimes of other r-process nuclei. Furthermore, the lifetimes of the magic nuclei increase significantly with decreasing neutron excess. For example, the halflive of the r-process nucleus ^{130}Cd has been measured as 195 ± 35 ms, while typical halflives along the r-process are about 10 ms.

Thus, material is enhanced in nuclei with N_{mag}, which after freeze-out, results in the observed r-process abundance peaks.

Which nuclear ingredients are needed?

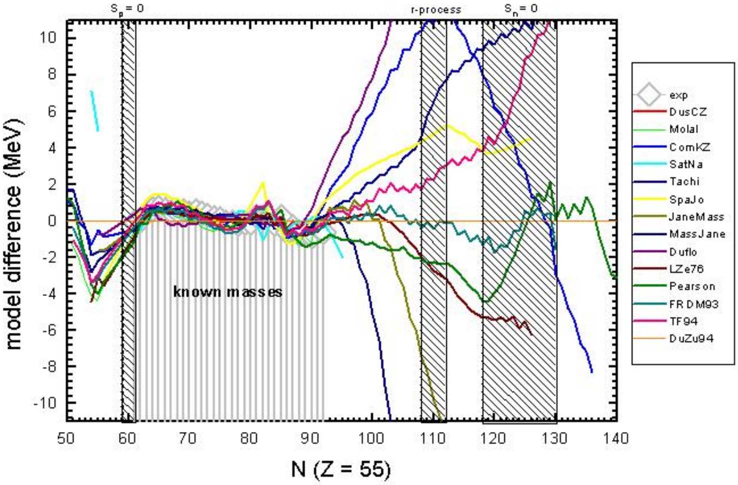


Masses

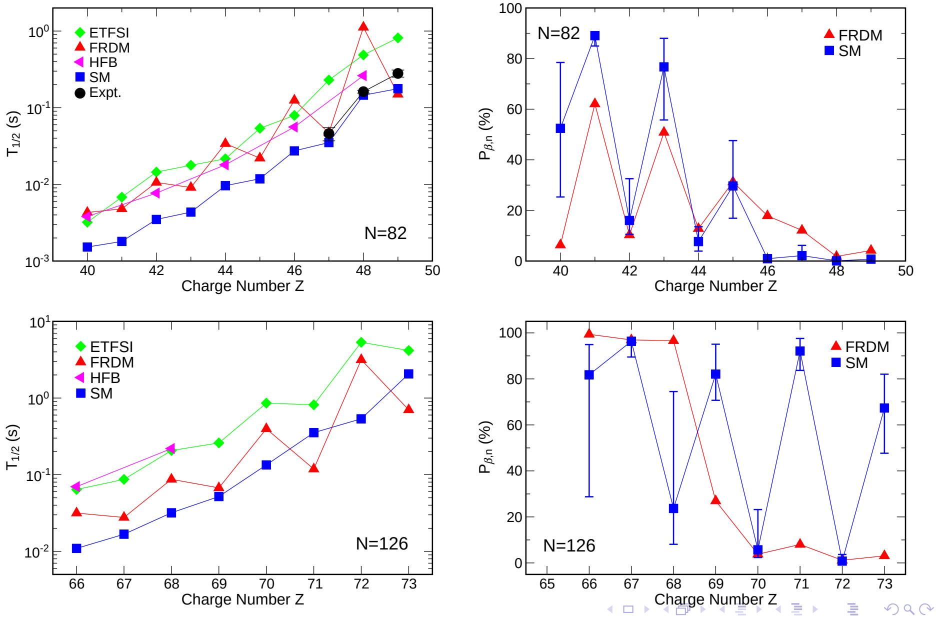
The most important nuclear input are neutron separation energies as they determine the r-process path. However, the nuclei are so neutronrich that for most the masses are experimentally not known. They are modelled where one distinguishes

- **empirical mass parametrizations** which are fitted to known masses and then are used to predict the unknown masses. The best-known models are the Finite-Range Droplet Model (FRDM) and the Extended Thomas-Fermi with Strutinski Integral (ETFSI) model. The known masses are reproduced with an uncertainty of about 700 keV.
- **microscopic models** based on nuclear models like Hartree-Fock (with BCS pairing) or Hartree-Fock-Bogoliubov, where the interactions (Skyrme) are fitted to the masses of selected nuclei. The best obtained uncertainty to all known masses is also of order 700 keV.

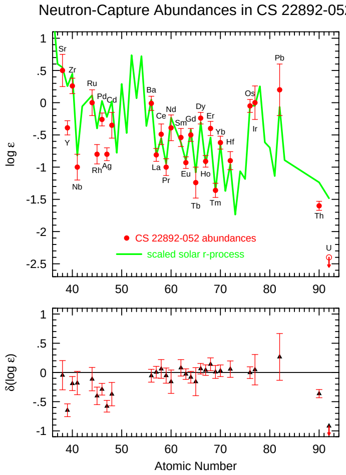
Mass predictions

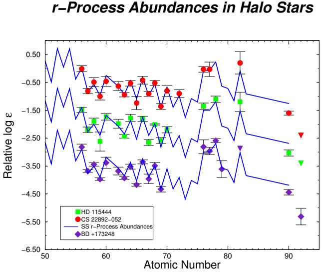


Half-lives for r-process nuclei



Abundances observed in metal-poor stars





- Abundances for nuclei $Z \geq 56$ consistent with normalized solar distribution.
- U/Th ratio can be used to estimate age of the galaxy. (CS 22892-052, 15.6 ± 4.6 Gyr)

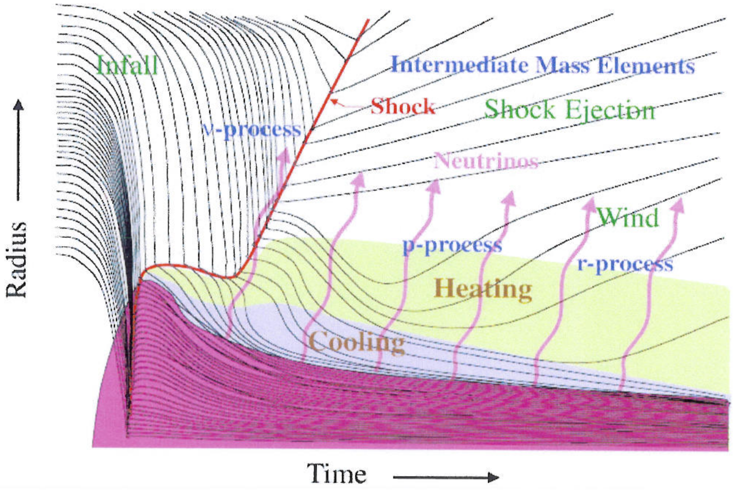
Where does the r-process occur in nature?

This has been named one of the 11 fundamental questions in science. Recent observational evidence in metal-poor (very old) stars point to two distinct r-process sites. One site appears to produce the r-process nuclides above $A \sim 130$; another one has to add to the abundance of r-process nuclides below $A = 130$.

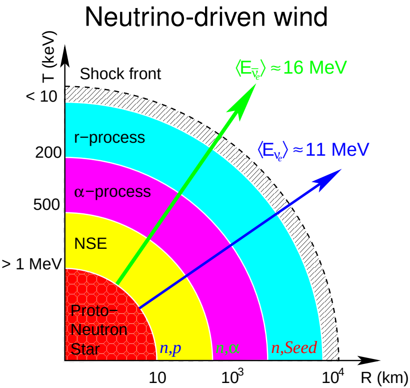
The two favorite sites are:

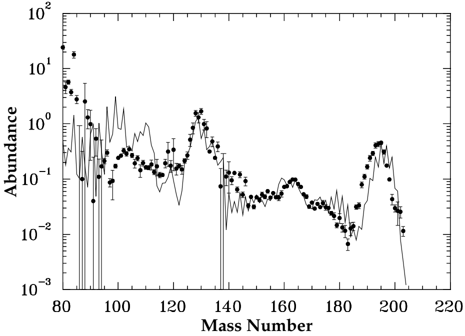
1. neutrino-driven wind above the proto-neutron star in a core-collapse supernova
2. neutron star mergers

Sites: neutrino-driven wind scenario in supernova



Sites: neutrino-driven wind scenario

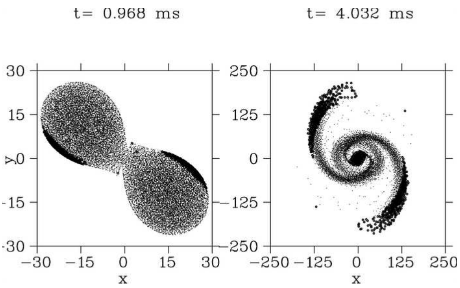


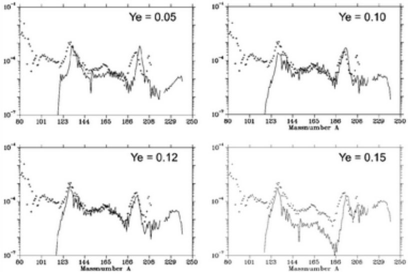


- Neutrino-wind from (cooling) NS
  $\nu_e + n \rightarrow e^- + p$
  $\bar{\nu}_e + p \rightarrow e^+ + n$
- α-process (formation seed nuclei)
  $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be} + \gamma$
  $\alpha + {}^9\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$

- Expansion adiabatic (Entropy constant) and $r \sim e^{t/\tau}$.
- Main parameter determining the nucleosynthesis is the neutron to seed ratio n/s
- supernova simulations usually give too small n/s for production of r-process peak around $A \sim 195$

Sites: neutron-star mergers





Problem: the frequency of neutron star mergers is too low to produce the entire solar r-process matter