Nuclear Astrophysics

VI: Nucleosynthesis beyond iron

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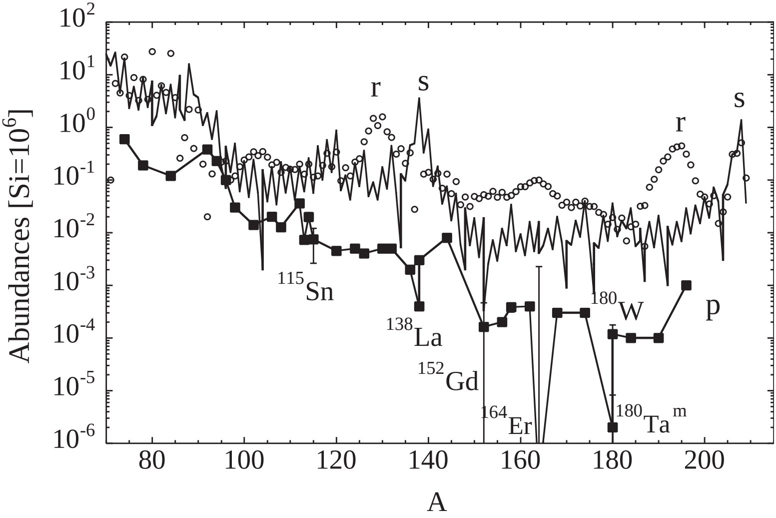
Otranto, may 30-june 3, 2011

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.)

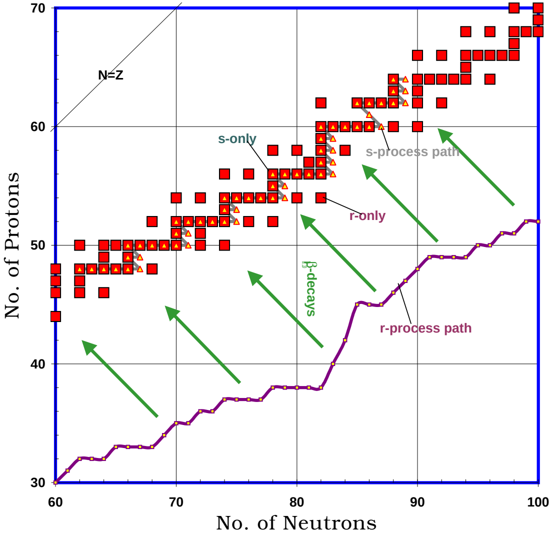
Consider the two cases:

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

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.

R- and s-process only nuclei



The classical s-process model

The classical model of B[2]FH 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:

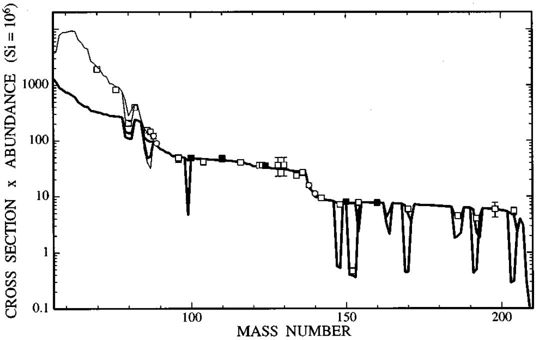
$$\frac{dN_A}{dt} = -N_n \langle \sigma v \rangle_A N_A + N_n \langle \sigma v \rangle_{A-1} N_{A-1}$$

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!

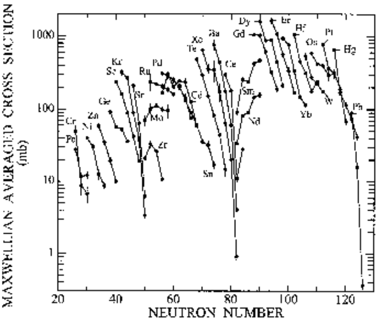
However, two components are required to make medium-mass and heavier s-process nuclei.

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.

There might be need for a third component, with $\tau_0 \approx 7$ mb^{-1} to explain the abundances around $A = 204 - 209$.
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

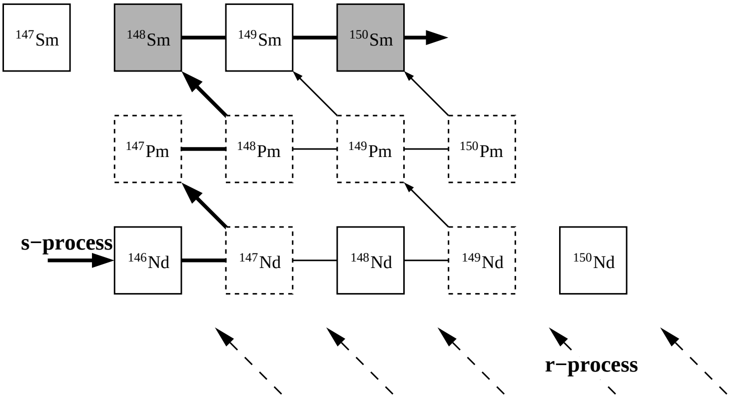
the s-process abundances have maxima at the neutron magic numbers, in agreement with observation.

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

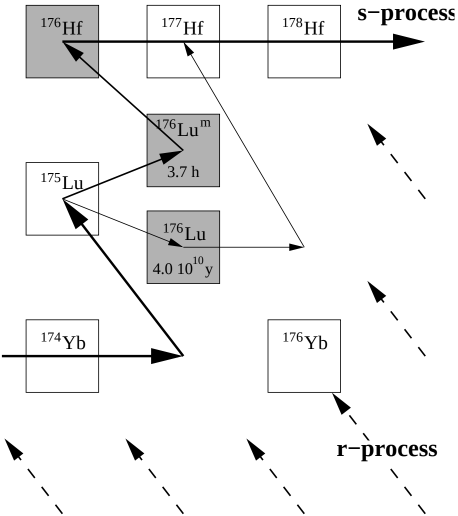


Branching at ^{148}Pm:

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

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

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, in a good approximation, the process proceeds in $(n, \gamma) \leftrightarrow (\gamma, n)$ equilibrium.
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 $Z + 1$ requires a β decay
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

$(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium

In equilibrium

$$\mu_n + \mu(Z,A) = \mu(Z,A+1)$$

This gives:

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

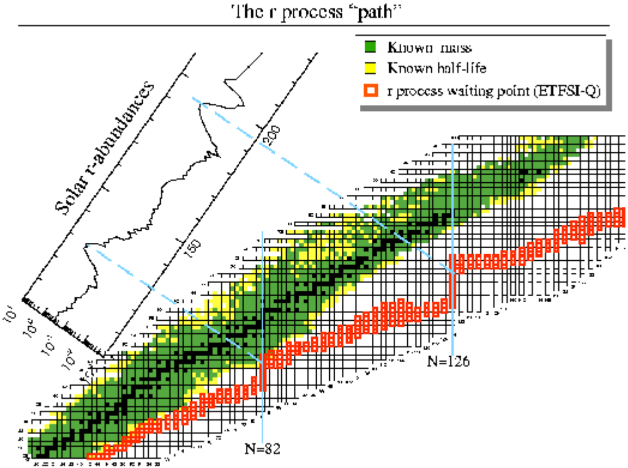
Taking left side ≈ 1:

$$\begin{aligned}\bar{S}_n &= kT \ln\left[\frac{2}{N_n}\left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2}\right] \\ &= \left(\frac{T}{10^9\ \mathrm{K}}\right)\left\{2.79 + 0.198\left[\log\left(\frac{10^{20}\ \mathrm{cm}^{-3}}{N_n}\right) + \frac{3}{2}\log\left(\frac{T}{10^9\ \mathrm{K}}\right)\right]\right\}\ \mathrm{MeV}.\end{aligned}$$

For $N_n = 10^{22}\ \mathrm{cm}^{-3}$ and $T_9 = 1.35$, $\bar{S}_n = 3.28$

But $\bar{S}_n$ depends on N_n and T and will change in a dynamical environment.

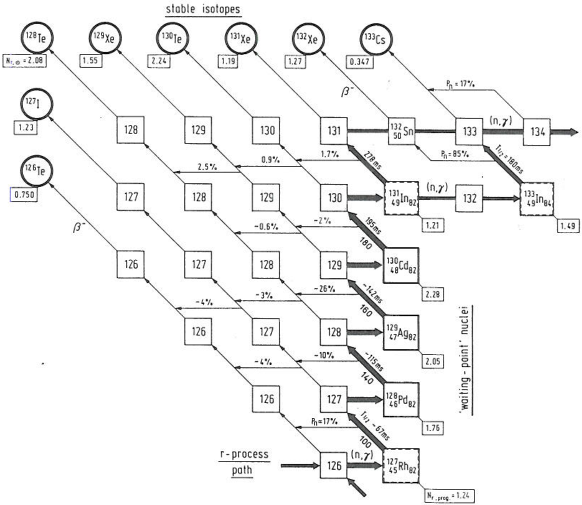
r-process



$T \approx 100$ 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



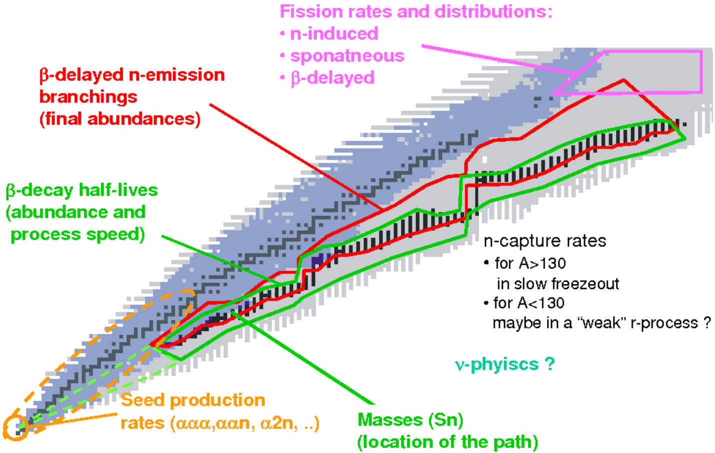
Why are there r-process peaks?

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).

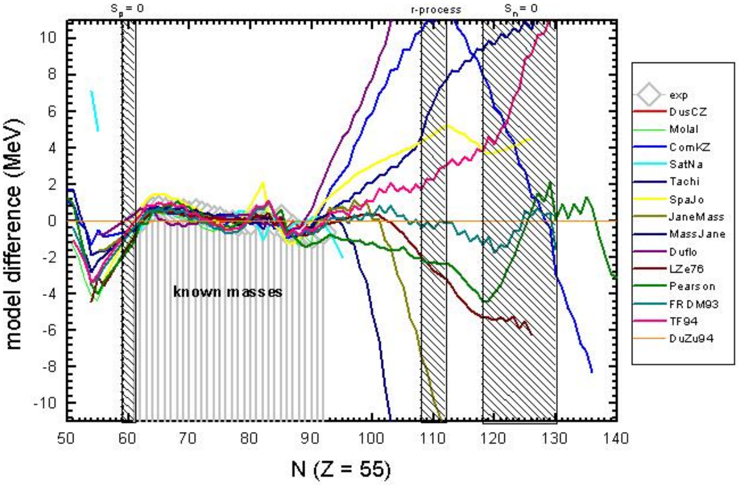
Thus, the r-process flow halts at the magic neutron numbers. Due to the extra binding energy of magic nuclei, the Q_β values of these nuclei are usually smaller than those for other r-process nuclei. This makes the lifetimes of the magic nuclei longer than lifetimes of other r-process nuclei. Furthermore, 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.

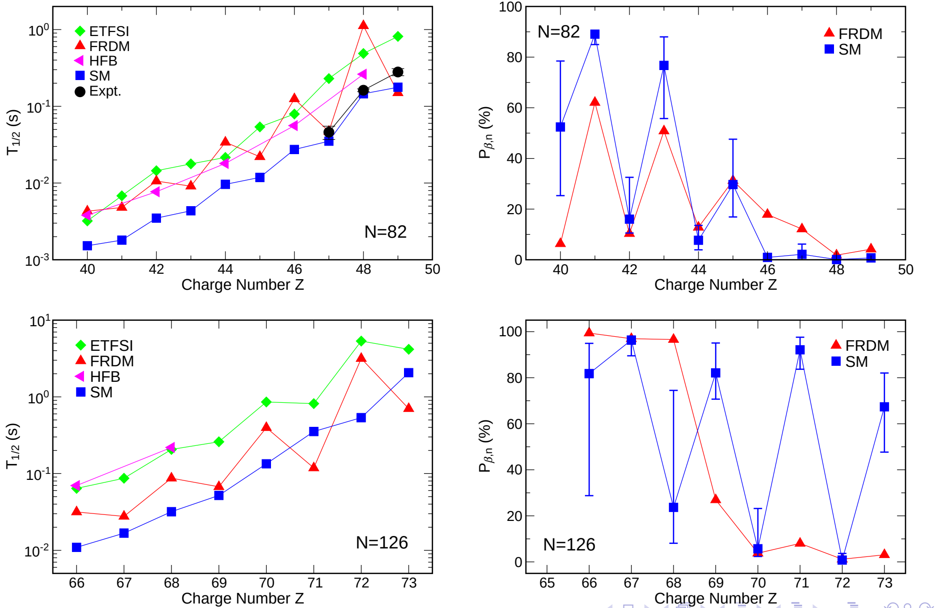
Which nuclear ingredients are needed?



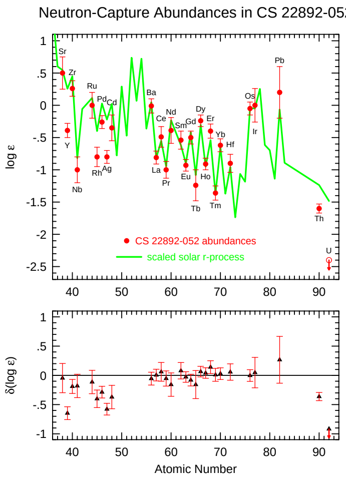
Mass predictions

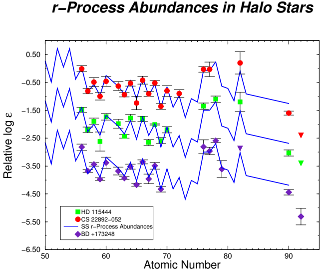


Half-lives for r-process nuclei



Abundances observed in metal-poor stars





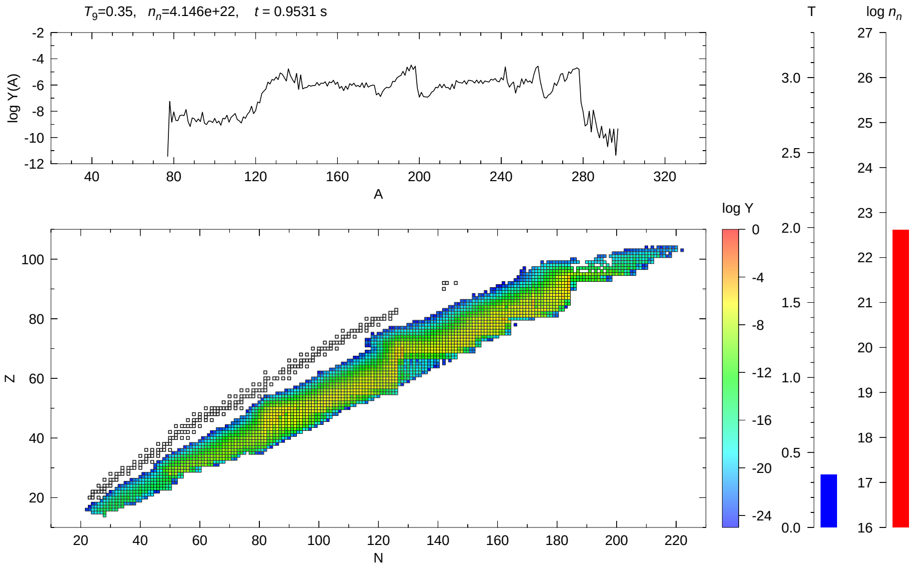
- Abundances for nuclei $Z \geq 56$ consistent with normalized solar distribution.
- U/Th ratio can be used to estimate age of the galaxy. (CS 22892-052, 15.6 ± 4.6 Gyr)

R-process simulations and needs

- neutrino-driven wind model (trajectories from supernova simulation)
- coupled to nuclear network
- neutron separation energies
- halflives, β-delayed neutron emission probabilities
- neutron-capture rates
- various fission processes (neutron-induced, β-induced, spontaneous)
- neutrino-induced processes

G. Martinez-Pinedo, D. Mocelj, F.-K. Thielemann, A. Kelic, K.-H. Schmidt

R-process network



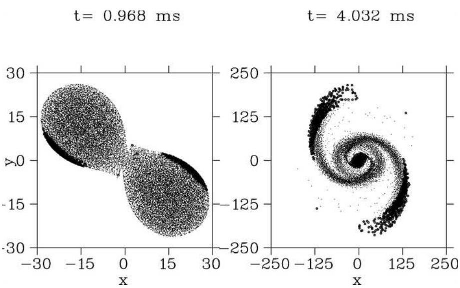
Where does the r-process occur in nature?

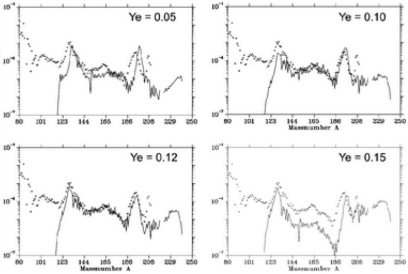
This has been named one of the 11 fundamental questions in science. Recent observational evidence in metal-poor (very old) stars point to two distinct r-process sites. One site appears to produce the r-process nuclides above $A \sim 130$; another one has to add to the abundance of r-process nuclides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

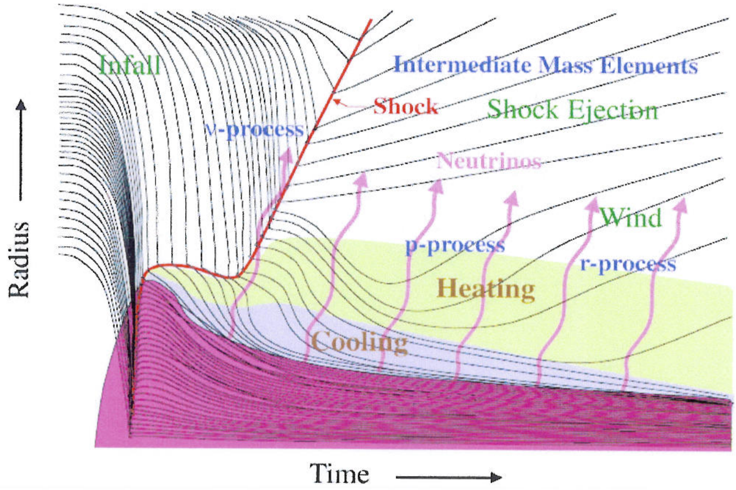
Sites: neutron-star mergers





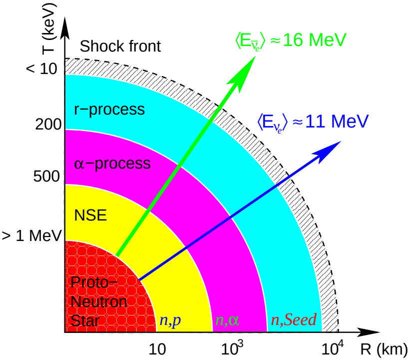
Problem: the frequency of neutron star mergers is too low to produce the entire solar r-process matter

Sites: neutrino-driven wind scenario

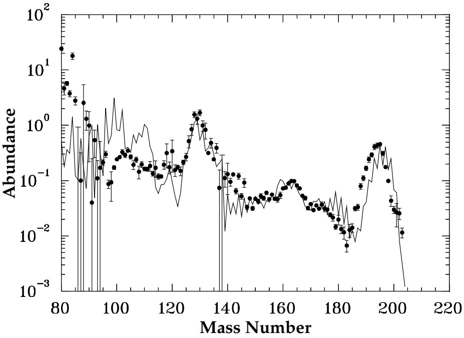


Sites: neutrino-driven wind scenario

Neutrino-driven wind

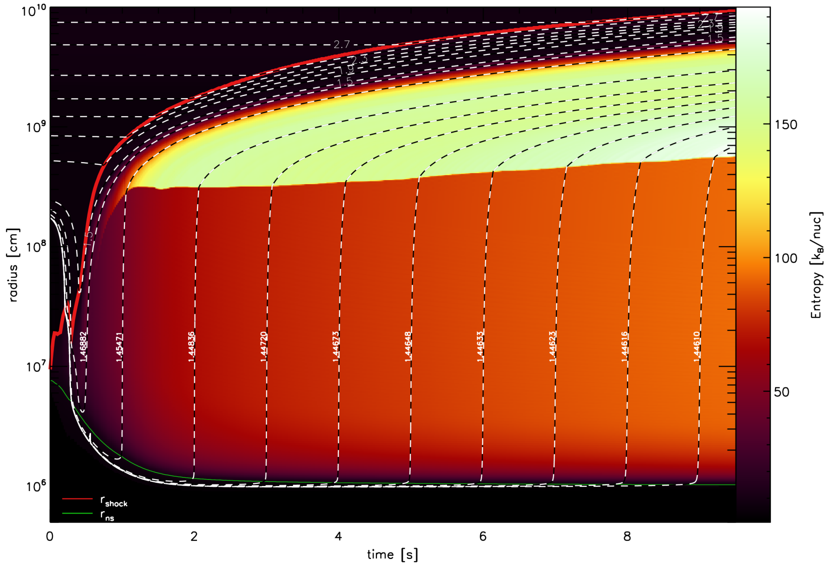


(S. Woosley *et al*)



- 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

Supernova trajectories



Galactical evolution of r- and s-process

The r-process is a primary process, while the s-process is a secondary. Hence, r-process material should have been made already in the first galactical supernovae, while s-process nuclides had to wait until sufficient seed nuclei were available. This can be seen in studying the time-dependence of abundances of characteristic r- and s-process nuclides.

Typical examples are Ba for the s-process and Eu for the r-process. In stars the abundances of these nuclides are observed relative to the ratio of iron to hydrogen. As Fe has to be produced in stars during the age of the galaxy, the ratio [Fe/H] increases with time and can be used as an indicator for the age of the star. (The symbol [A/B] measures the log of the ratio, normalized to the solar ratio, [A/B]=0 is the solar ratio.)

The Ba-Eu ratio during the galactical history

If the r-process is a primary and the s-process a secondary process, then the abundance ratio of s-process (Ba) to r-process (Eu) nuclides and the Ba-Fe abundance ratio must have increased with time: