The Origin of the Elements

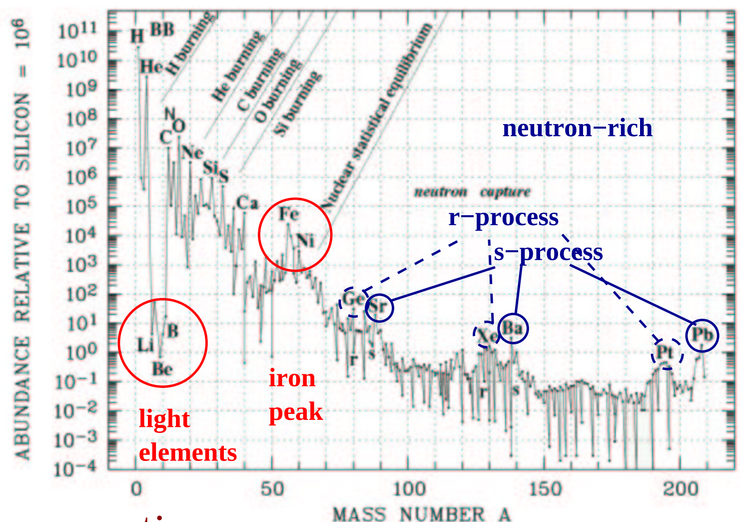
Literature:

- H. Reeves, Online lectures on Primordial Nucleosynthesis, http://nedwww.ipac.caltech.edu/level5/Sept01/Reeves/Reeves2.html
- Principles of Stellar Evolution and Nucleosynthesis, Donald Clayton (University of Chicago Press), classical standard graduate text
- Supernovae and Nucleosynthesis, David Arnett (Princeton University Press)

I. Big Bang Nucleosynthesis

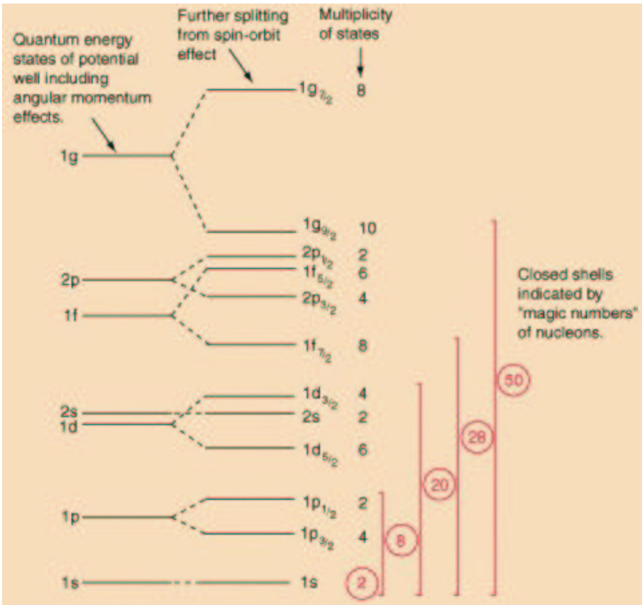
II. Stellar Nucleosynthesis

III. Explosive Nucleosynthesis



Main properties

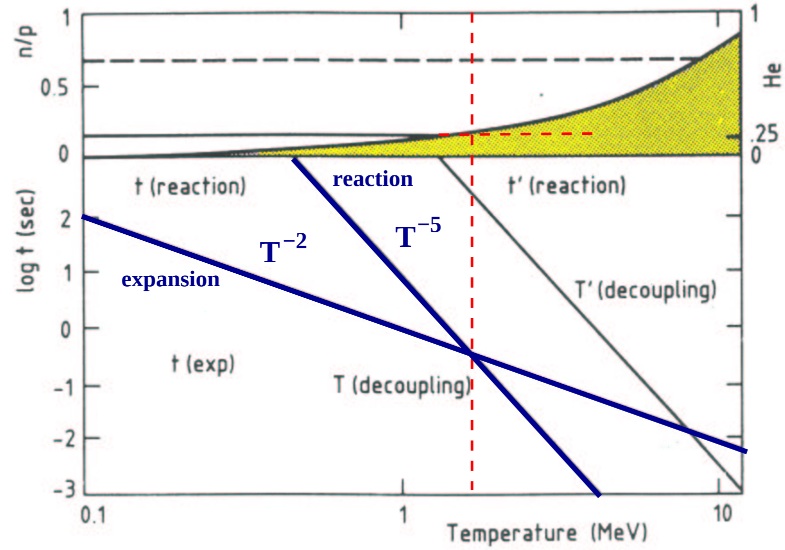
- heavier elements are more difficult to form because of the larger Coulomb barrier, i.e. require higher energies (temperatures) during nuclear-burning phases in stars
- iron peak: most tightly bound nuclei
- the origin of light elements? (Li, Be, B are less tightly bound than He, C)
- neutron-rich elements beyond the iron peak require neutron captures



- **the odd-even effect:** elements with odd Z are rarer
- **magic numbers:** (from nuclear shell structure) elements with $Z,\ N = 2, 8, 20, 28, 50, 82, 126$ are more stable → doubly magic nuclei are particularly stable: e.g. He $(Z = N = 2)$, O $(Z = N = 8)$, Ca $(Z = N = 20)$, Ni $(Z = N = 28)$

Big Bang Nucleosynthesis

Neutrino Decoupling



- initially at $T > 1\,\mathrm{MeV}$, all weak interactions occur in statistical equilibrium
  $\nu + n \rightleftharpoons p + e; \quad \bar{\nu} + p \rightleftharpoons n + e; \quad n \rightleftharpoons p + e + \bar{\nu}$

→ the neutron-proton ratio is determined by statistical equilibrium, i.e. the Boltzmann distribution $n/p = \exp(-\Delta M/kT)$, where $\Delta M = 1.293\,\mathrm{MeV}$.

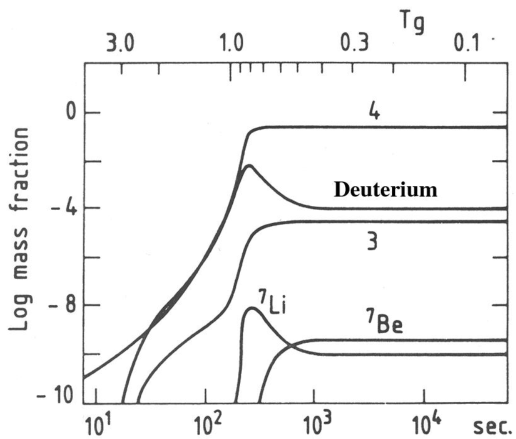
- the n/p ratio is determined by the temperature at which neutrinos decouple
  - ▹ expansion timescale: $t_{exp} \propto (G\rho)^{-1/2} \propto T^{-2}$, (since $\rho \propto T^4$ in the radiation-dominated phase)
  - ▹ weak reaction timescale: $t_{weak} \propto T^{-5}$.

  → neutrinos decouple at $T \simeq 10^{10}\,\mathrm{K} \simeq 0.86\mathrm{MeV}$

  → $n/p \simeq 0.223$

- the deuterium reaction $p + n \rightleftharpoons {}^2D + \gamma$ remains in equilibrium till the temperature has dropped to about 0.1 MeV (10^9 K), reached after about 4 minutes
  - ▷ during this period, the n's undergo β decay with a half life of 617 s
  - → n/p drops to ~ 0.164

The Phase of Primordial Nucleosynthesis ($T < 0.1$ MeV)



- primordial reactions:

$$
\begin{aligned}
p + n &\rightarrow D + \gamma \\
D + p &\rightarrow {}^3He + \gamma \\
D + n &\rightarrow {}^3H + \gamma \\
{}^3He + {}^3He &\rightarrow {}^4He + 2p
\end{aligned}
$$

- there are no stable nuclides with mass 5 or 8 → limits buildup of heavier elements

- some light elements form through reactions like

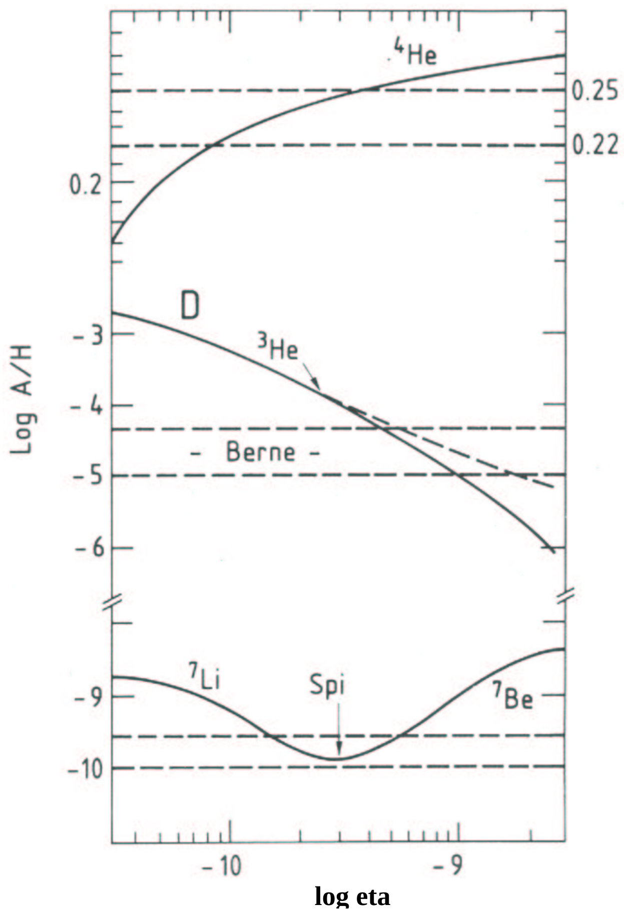
$$
\begin{aligned}
{}^4He + {}^3H &\rightarrow {}^7Li + \gamma \\
{}^4He + {}^3He &\rightarrow {}^7Be + \gamma \\
{}^7Be + e &\rightarrow {}^7Li + \nu
\end{aligned}
$$

- the final abundance ratios depend on
  - ▷ the n/p ratio determined by the decoupling temperature
  - ▷ the competition of β decays and the rate of $n + p$ reactions, which depends on the nucleon to photon ratio η (the $n + p$ rate depends on the nucleon/baryon density)
  - ▷ at low nucleon density (η): neutrons β decay
  - ▷ at high nucleon density (the realistic case): most neutrons are incorporated into He
    - o number of He nuclei: 1/2 n (n: number of initial neutrons; 2 neutrons/He nucleus)
    - o number of H nuclei: $p - n$ (p: number of initial protons)
    - o helium mass fraction:
      $$Y = \frac{4 * 1/2n}{4 * 1/2n + (p - n)} = \frac{2n}{p + n} = \frac{2n/p}{1 + n/p} = 0.28$$
      (for $n/p = 0.164$)

• the production of deuterium and hence all other light nuclides depends strongly on the baryon density

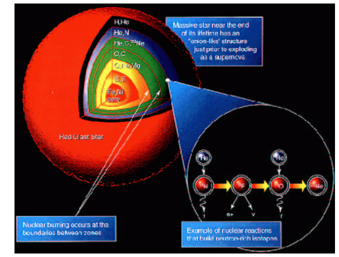
- ▷ at high η, deuterium is efficiently destroyed by p or n captures (to produce nuclides of mass number 3)
- ▷ astronomical observations fix η in the standard model to $3 - 15 \times 10^{-10}$ (assumes n/p ratio is fixed by standard particle physics; Universe is homogeneous)

$\rightarrow$ baryon mass fraction: $\Omega \sim 0.01 - 0.02$



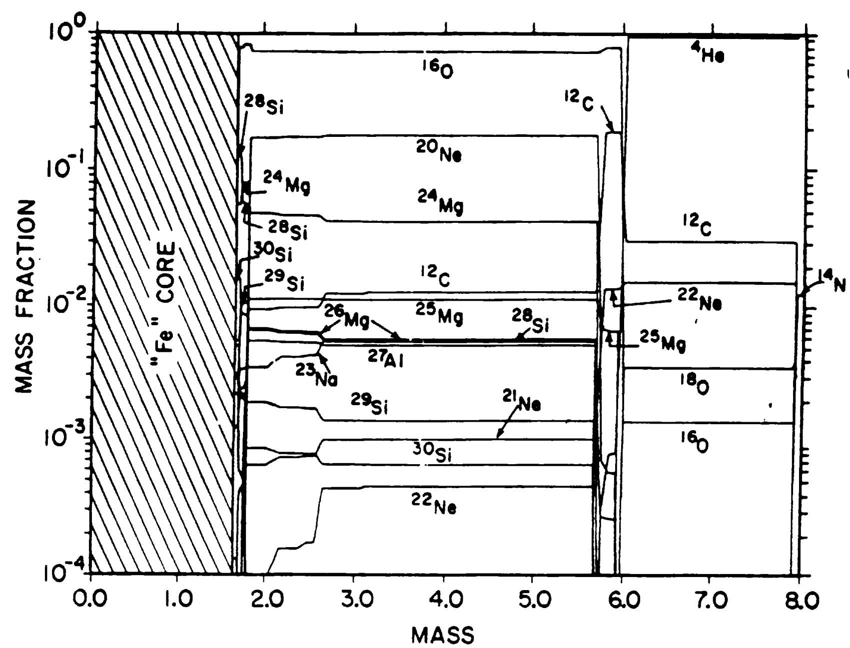
Stellar Nucleosynthesis

- ▷ Hydrostatic burning during the core evolution of the star builds up most elements up to Fe at ever higher temperatures
- ▷ schematically: $4\,\mathrm{H} \rightarrow \mathrm{He}$, $3\,\mathrm{He} \rightarrow \mathrm{C}$, $2\,\mathrm{C} \rightarrow \mathrm{Mg}$, $2\,\mathrm{O} \rightarrow \mathrm{S, Si}$, $\mathrm{Si} \rightarrow \mathrm{Fe}$
- ▷ onion-like presupernova structure

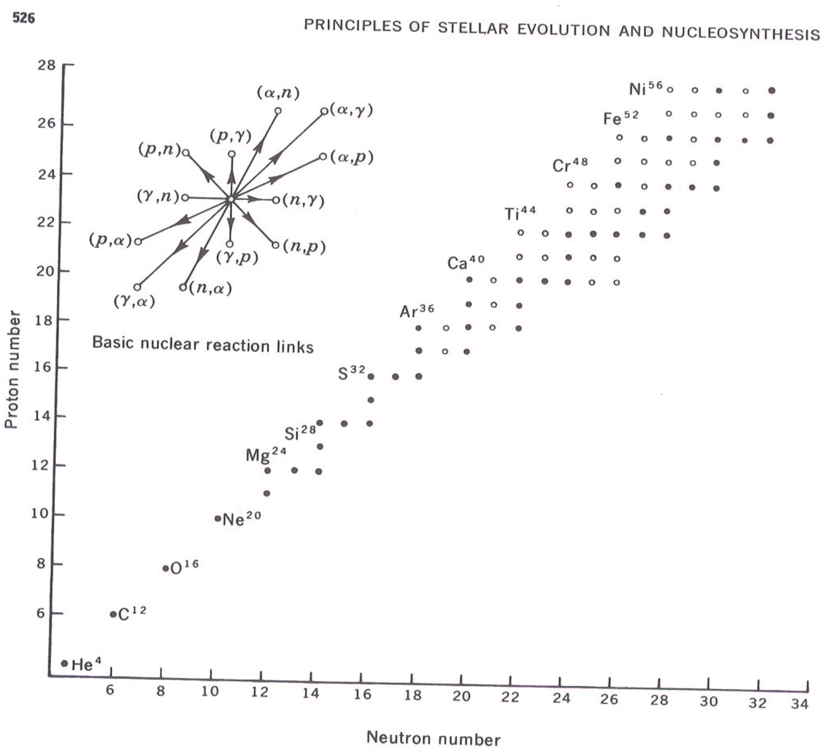


- ▷ core collapses and elements in core are locked up, rest is ejected into the ISM (in particular O)
- ▷ also stellar wind ejection during AGB/supergiant phases

Final Structure of $8\,M_\odot$ Helium Core (Nomoto)



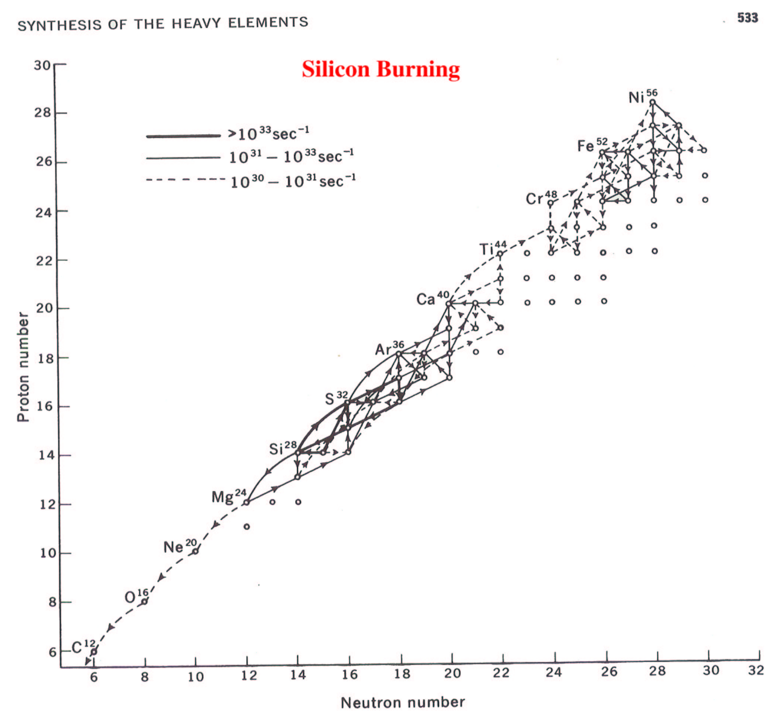
Silicon Burning and Explosive Nucleosynthesis



- after oxygen burning: mainly S, Si
- at $\mathrm{T} \sim 2 \times 10^9\,\mathrm{K}$, elements start to photodisintegrate and eject light particles, in particular p's (γ, p), n's (γ, n) and α's (γ, α) that can react with other nuclei
- the least tightly bound nuclei are stripped more easily
- all reactions occur in both directions (i.e. forward and reverse reaction) $\rightarrow$ abundance pattern approaches nuclear statistical equilibrium (NSE)

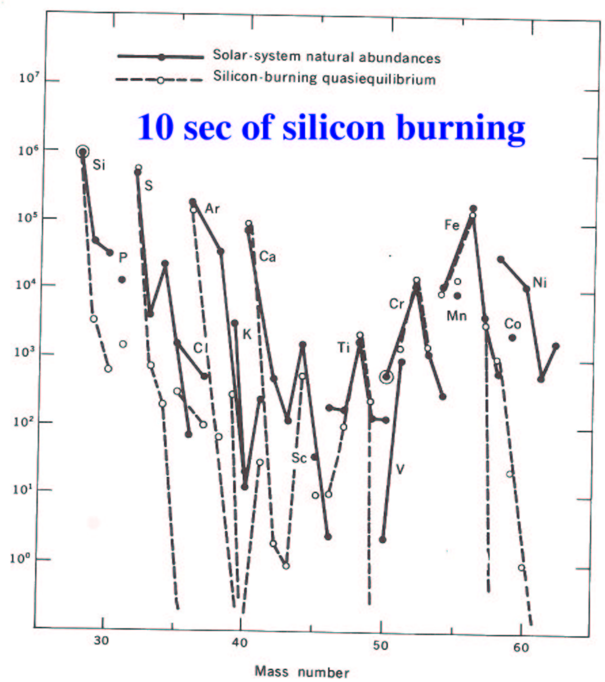
- there is a net excess of α capture reactions which build up alpha-rich elements (α-process)
- $^{28}\mathrm{Si} + \alpha \rightarrow {}^{32}\mathrm{S} + \alpha \rightarrow {}^{36}\mathrm{Ar} + \alpha \rightarrow {}^{40}\mathrm{Ca}$

  $+2\,\alpha \rightarrow {}^{48}\mathrm{Ti} + \alpha \rightarrow {}^{52}\mathrm{Cr} + \alpha \rightarrow {}^{56}\mathrm{Fe}$
- builds up the most stable elements ^{54}Fe or ^{56}Fe (depends on neutron excess)
- how far the "flow" proceeds depends on the temperature (which determines the flow rate) and the duration of the phase



Explosive Burning (e.g. during a supernova)

- carbon burning close to hydrostatic equilibrium
- but: oxygen and silicon burning do not necessarily estabilish statistical equilibrium
- at high densities: close to NSE
- at low densities (after expansion): incomplete burning, abundance pattern freezes out → intermediate-mass elements
- reproduces the solar abundance pattern reasonably well (by nuclear physics standards)



Supernova Nucleosynthesis

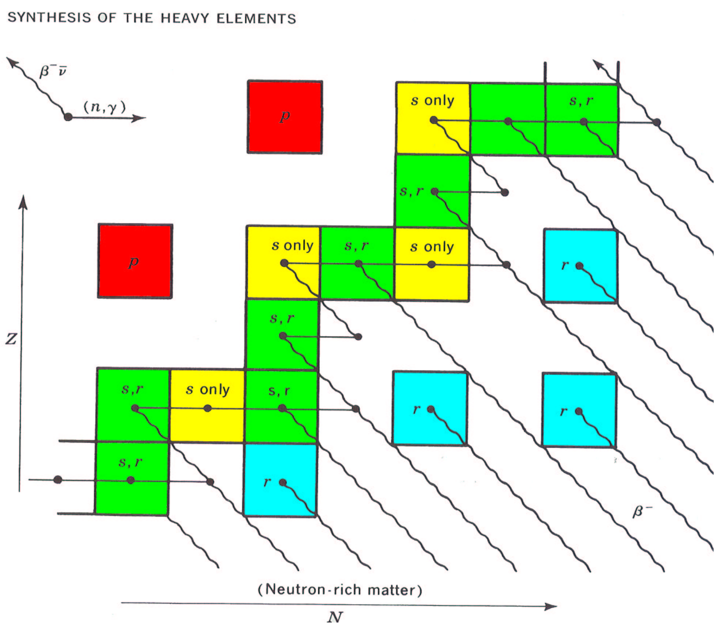
- different supernova types produce, different abundance patterns
  - ▷ core-collapse supernovae: most Fe is locked up in the core (at most $\sim 0.1\,M_\odot$ can be ejected)
  - ▷ large ejection of oxygen
  - ▷ thermonuclear explosions: dominant producers of Ni (which decays into Fe; $\sim 0.6\,M_\odot$)
  - ▷ different timescales for core collapse supernovae ($\sim 10^7$ yr) and thermonuclear explosions (up to $\sim 10^9$ yr)

  → oxygen/iron ratio evolves with time

  → observational constraint on supernova explosions?
- complication: hypernovae eject both Fe and O and a lot of α-rich elements (Ca, Ti), but are probably not as common at early times (?)

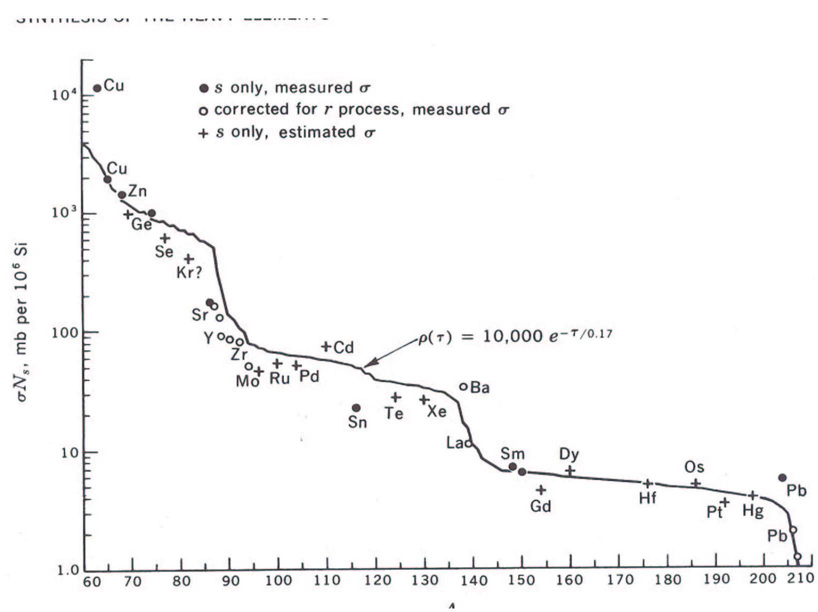
Production of Heavy Nuclei ($A \geq 60$)

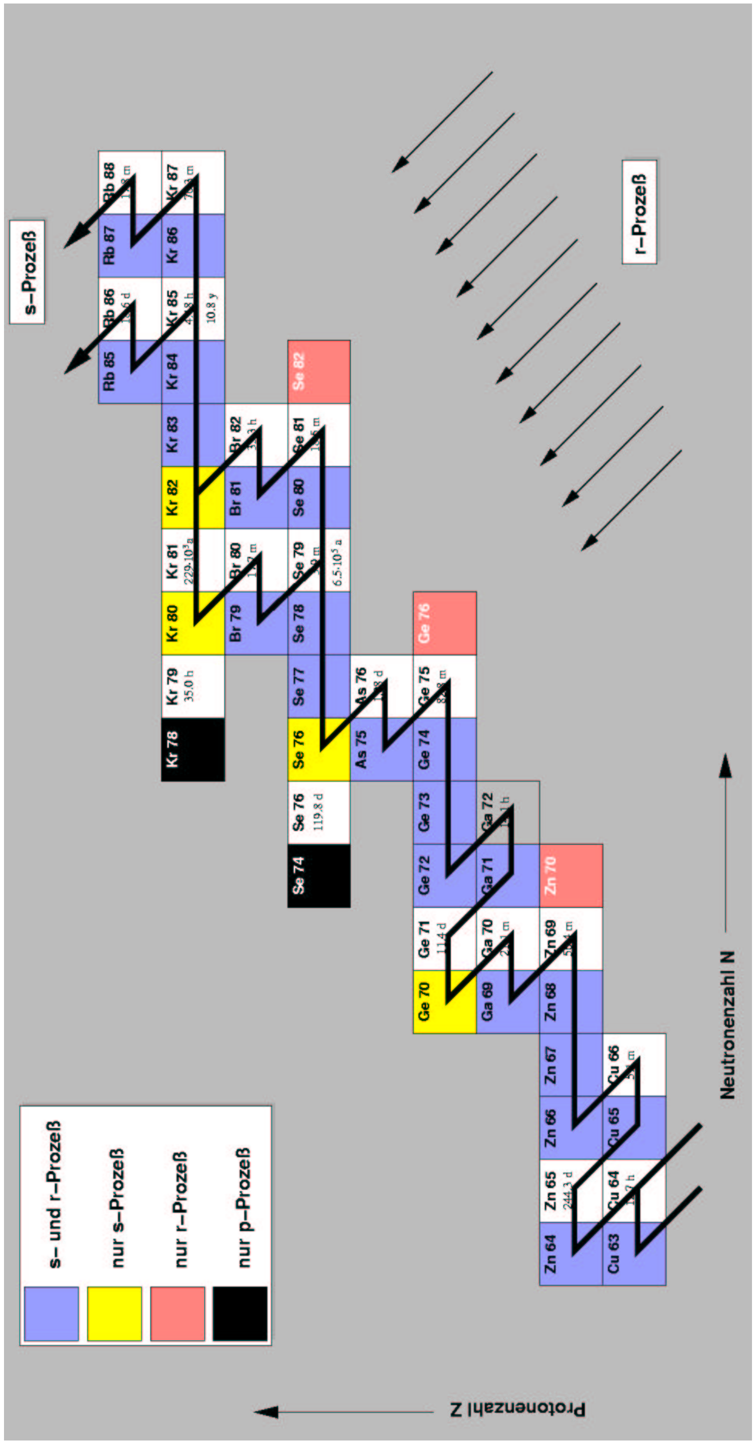
- produced by endothermic reactions



- consider neutron-capture reactions (on Fe-peak seed nuclei)
  $(\mathbf{Z}, \mathbf{A}) + \mathbf{n} \rightarrow (\mathbf{Z}, \mathbf{A}+1) + \gamma$
  - ▷ if (Z,A+1) is stable, it waits until it captures another neutron
  - ▷ if (Z,A+1) is unstable to β decay (typically $t_{decay} \sim 10^5 - 10^7$ s), the further chain depends on t_{decay} and $t_{capture}$

- $t_{decay} \ll t_{capture}$: s-process (slow neutron-capture process)
  - ▷ β decay, s-process follows the "valley of β stability"
- $t_{decay} \gg t_{capture}$: r-process (rapid neutron-capture process)
  - ▷ (Z,A+1) can capture further neutrons and produce elements (far) away from the valley of β stability
  - ▷ eventually these elements β decay and produce stable neutron-rich isotopes





Astrophysical Sites for the s- and r-process

- s-process requires relatively low neutron densities ($n \lesssim 10^{26}\,m^{-3}$)
- r-process requires relatively high neutron densities ($n \gtrsim 10^{26}\,m^{-3}$)
- s-process
  - ▷ possible neutron sources (during stellar He burning) $^{13}C(\alpha, n)^{16}O$ or $^{22}Ne(\alpha, n)^{25}Mg$
  - ▷ first reaction requires ^{13}C which is relatively rare, but produced during hydrogen burning via $^{12}C(p, \gamma)^{13}N(e^{+}\nu)^{13}C$ (CN cycle)

  → requires simultaneous hydrogen/helium burning

  or injection of freshly produced ^{13}C into He-burning layers
  - ▷ promising site: thermally pulsing AGB stars (with alternating hydrogen and helium burning)

  → s-stars, barium stars
  - ▷ $^{22}Ne + \alpha$ only occurs at very high temperatures (e.g. in the cores of massive stars)
- r-process
  - ▷ requires explosive burning
  - ▷ e.g. in supernova explosion behind the supernova shock (probably not, conditions are only suitable for too short a time)
  - ▷ neutron star/neutron star or neutron star/black hole mergers accompanied with very high neutron densities and the formation of neutron-rich nuclei

The p process:

- the origin of proton-rich elements is not well understood
- need e.g.

  ▷ $(A, Z) + p \rightarrow (A+1, Z+1) + \gamma$

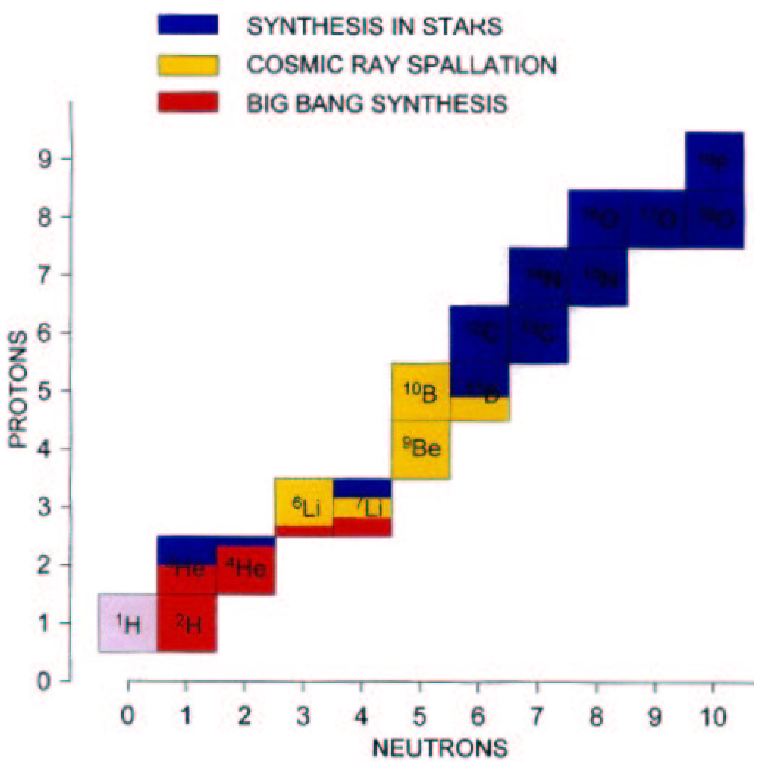
  ▷ $(A, Z) + \gamma \rightarrow (A-1, Z) + n$

- possible site: Thorne-Żytkow objects (red supergiants with neutron cores) where protons are injected into the burning region at very high temperature ($T \sim 10^9$ K)

Production of light elements

- by spallation of intermediate nuclei (e.g. O, N, C) by cosmic rays

  $\{p, \alpha\} + \{C, N, O\} \rightarrow {}^6Li,\ {}^7Li,\ {}^7Be,\ {}^9Be,\ {}^{10}Be,\ {}^{10}B,\ {}^{11}B$



- origin of solar ^{7}Li unknown, big bang nucleosynthesis and cosmic-ray spallation cannot produce the observed solar abundance

→ explosive H/He burning in giants?

The Chemical Lifecycle of Stars