The Origin of the Elements

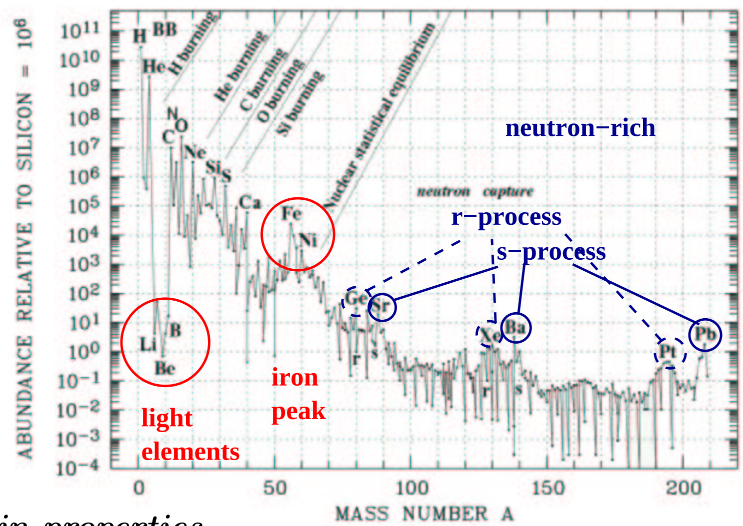
Literature:

- 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

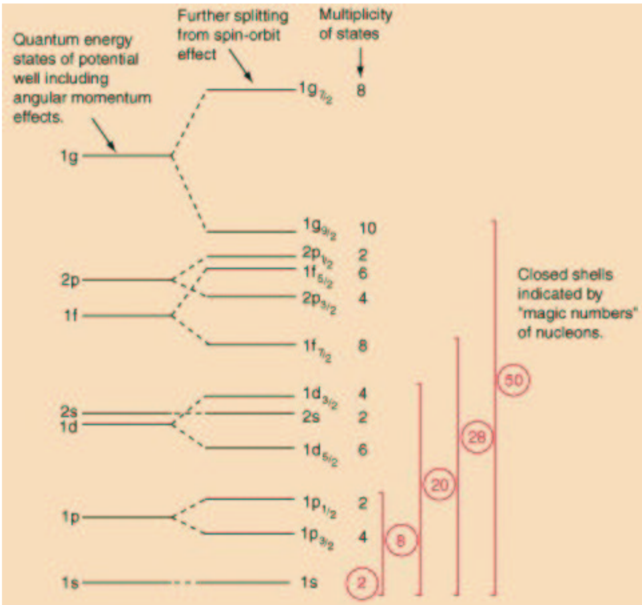
II. Stellar Nucleosynthesis

III. Explosive Nucleosynthesis



Main properties

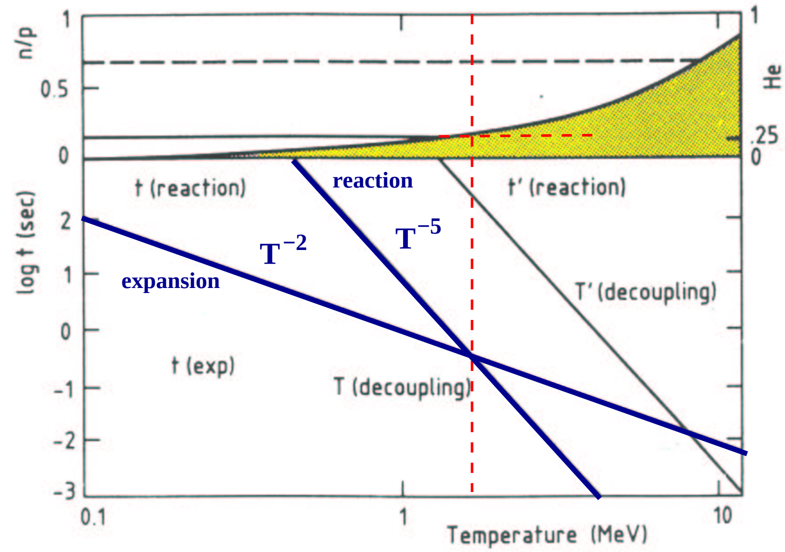
- heavier elements are more difficult to form because of the larger *Coulomb barrier*, i.e. require higher energies (temperatures) during nuclear-burning phases in stars
- *iron peak:* most tightly bound nuclei
- the origin of *light elements?* (Li, Be, B are less tightly bound than He, C)
- *neutron-rich 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 $\rightarrow$ *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 $T > 1\,\text{MeV}$, all weak interactions occur in *statistical equilibrium*
  $\nu + n \rightleftharpoons p + e; \quad \bar{\nu} + p \rightleftharpoons n + e; \quad n \rightleftharpoons p + e + \bar{\nu}$

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

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

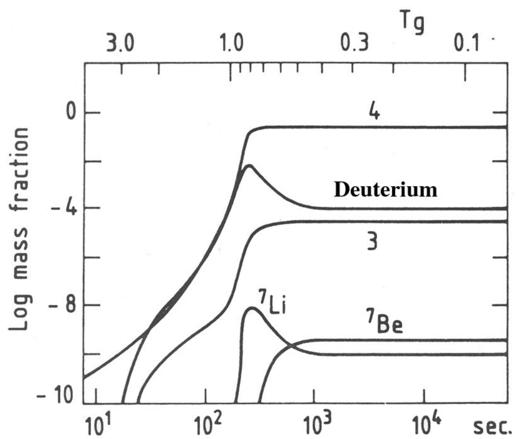
  $\rightarrow$ neutrinos decouple at $T \simeq 10^{10}\,\text{K} \simeq 0.86\text{MeV}$

  $\rightarrow$ $n/p \simeq 0.223$

- 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

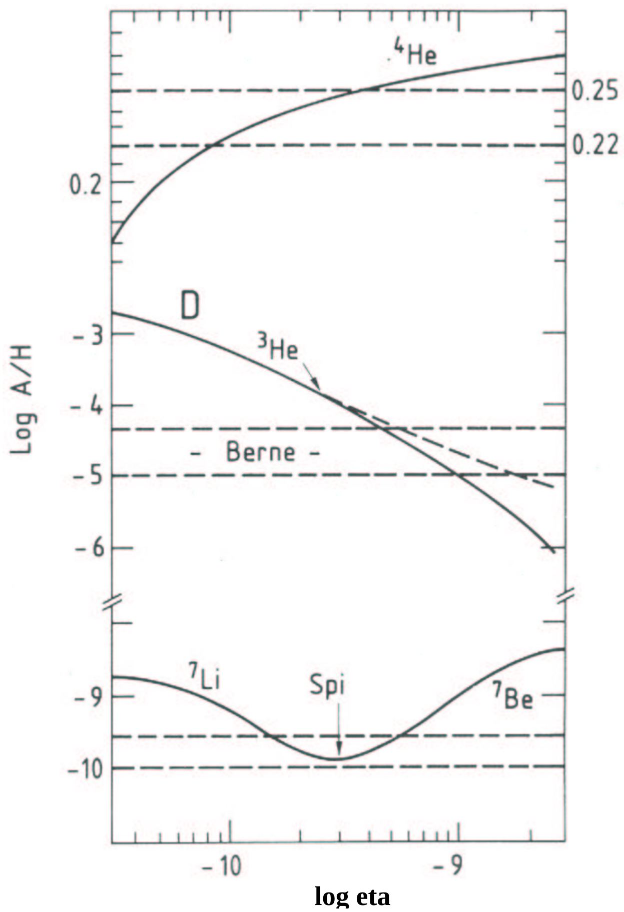
- some *light elements* form through reactions like

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

- 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 *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 $n/p = 0.164$)

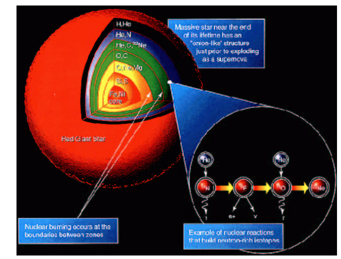
- the production of *deuterium* and hence all other light nuclides depends strongly on the baryon density
  - ▹ at high η, deuterium is efficiently destroyed by p or n captures (to produce nuclides of mass number 3)
  - ▹ *astronomical observations* fix η in the standard model to $3 - 15 \times 10^{-10}$ (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



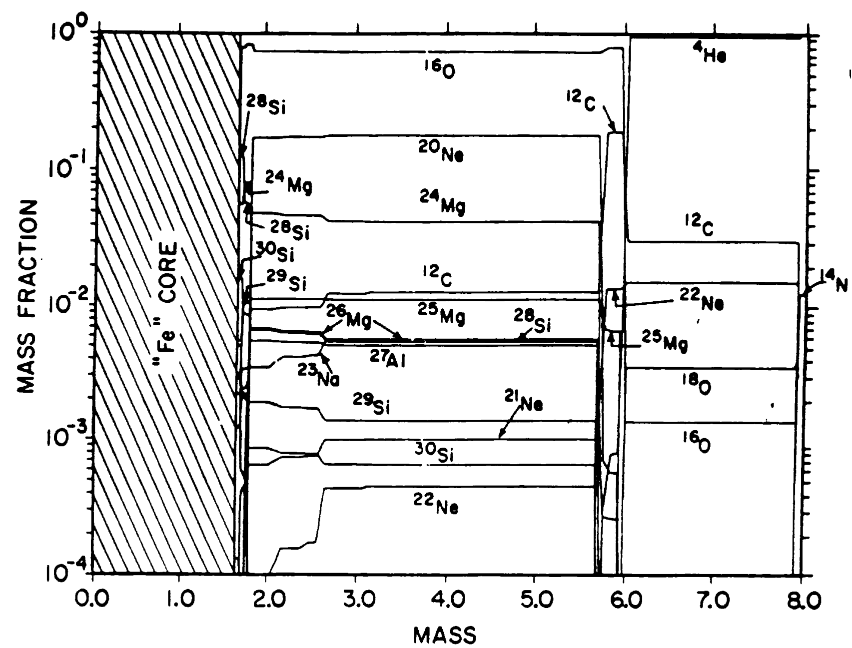
▹ schematically: $4\,\mathrm{H} \rightarrow \mathrm{He}$, $3\,\mathrm{He} \rightarrow \mathrm{C}$, $2\,\mathrm{C} \rightarrow \mathrm{Mg}$, $2\,\mathrm{O} \rightarrow \mathrm{S}, \mathrm{Si}$, $\mathrm{Si} \rightarrow \mathrm{Fe}$

▹ *onion-like* presupernova structure

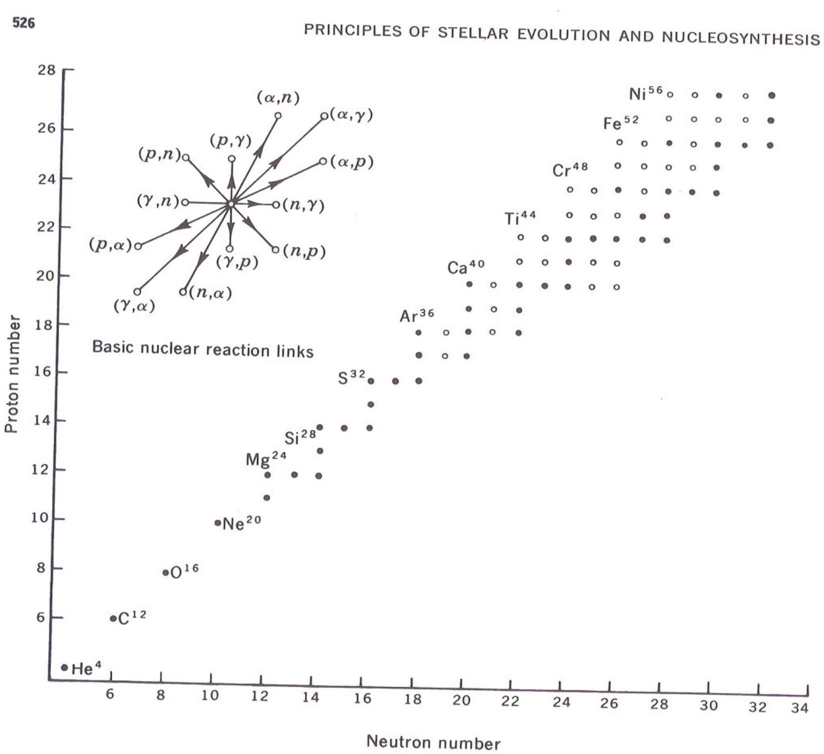
▹ core collapses and elements in core are locked up, rest is *ejected into the ISM* (in particular O)

▹ also *stellar wind ejection* during *AGB/supergiant phases*

Final Structure of $8\,\mathrm{M}_\odot$ *Helium Core* (Nomoto)



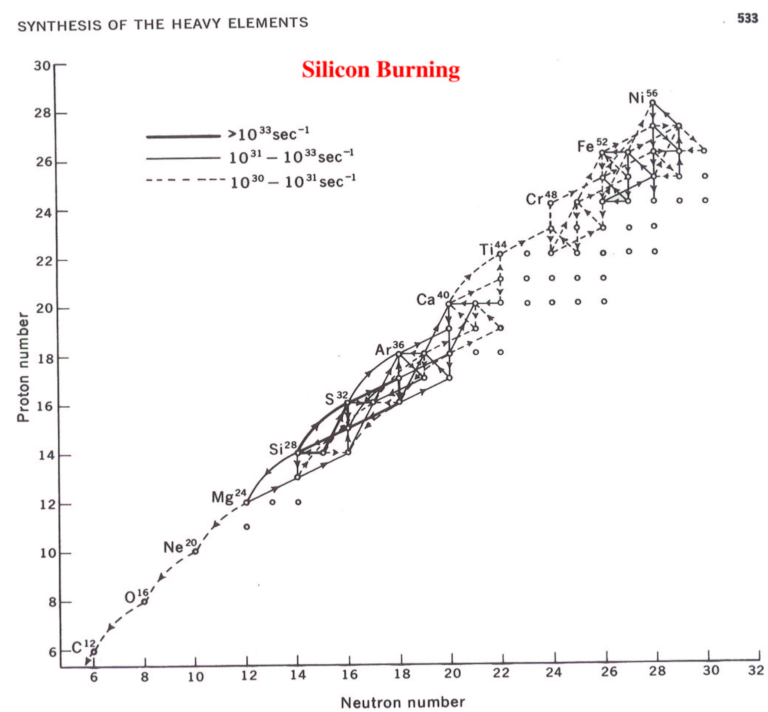
Silicon Burning and Explosive Nucleosynthesis



- 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)***

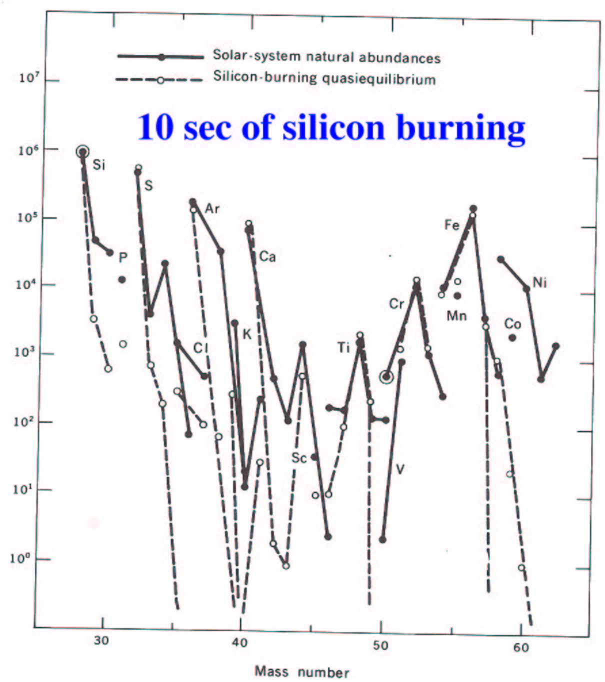
- there is a net excess of α capture reactions which build up ***alpha-rich*** elements ***(α-process)***
- $^{28}\mathrm{Si} + \alpha \rightarrow {}^{32}\mathrm{S} + \alpha \rightarrow {}^{36}\mathrm{Ar} + \alpha \rightarrow {}^{40}\mathrm{Ca}$

  $+2\,\alpha \rightarrow {}^{48}\mathrm{Ti} + \alpha \rightarrow {}^{52}\mathrm{Cr} + \alpha \rightarrow {}^{56}\mathrm{Fe}$
- 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 $\sim 0.1\,\mathrm{M}_\odot$ can be ejected)
  - ▷ large ejection of *oxygen*
  - ▷ *thermonuclear explosions:* dominant producers of *Ni* (which decays into Fe; $\sim 0.6\,\mathrm{M}_\odot$)
  - ▷ different *timescales* for core collapse supernovae ($\sim 10^7$ yr) and thermonuclear explosions (up to $\sim 10^9$ yr)

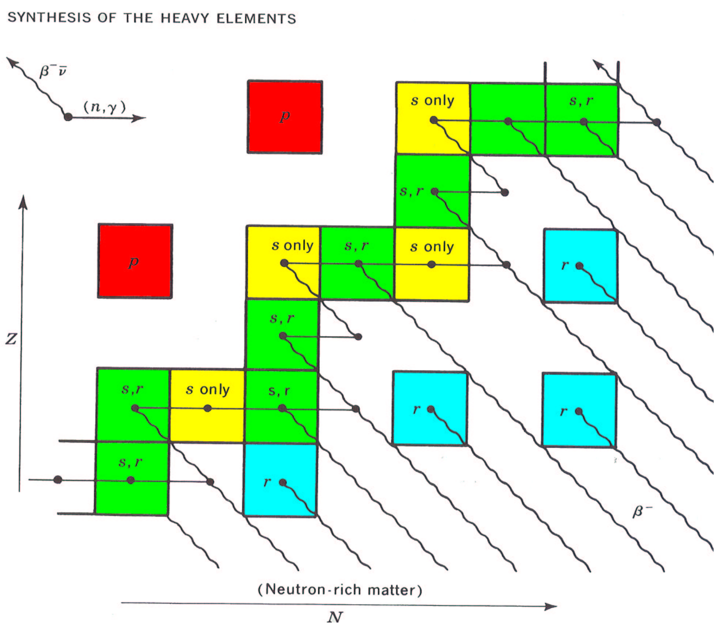
→ *oxygen/iron ratio* evolves with time

→ *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 (?)

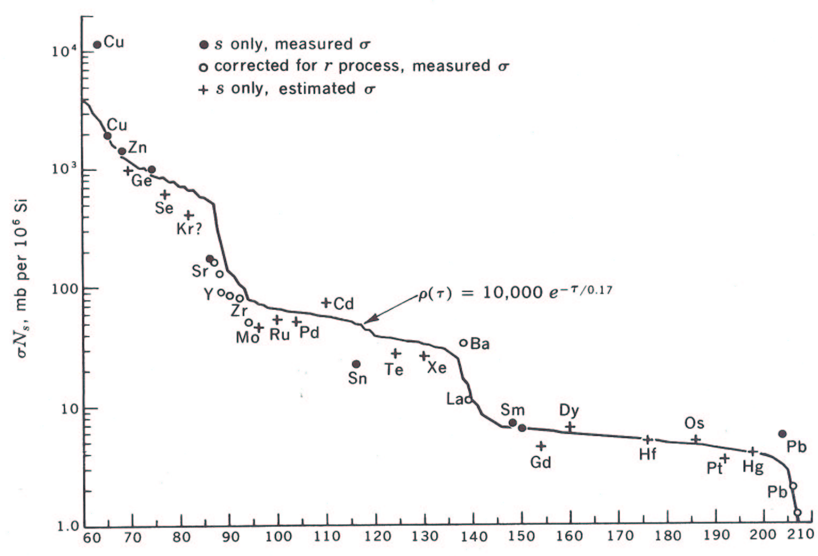
Production of Heavy Nuclei (A $\geq$ 60)

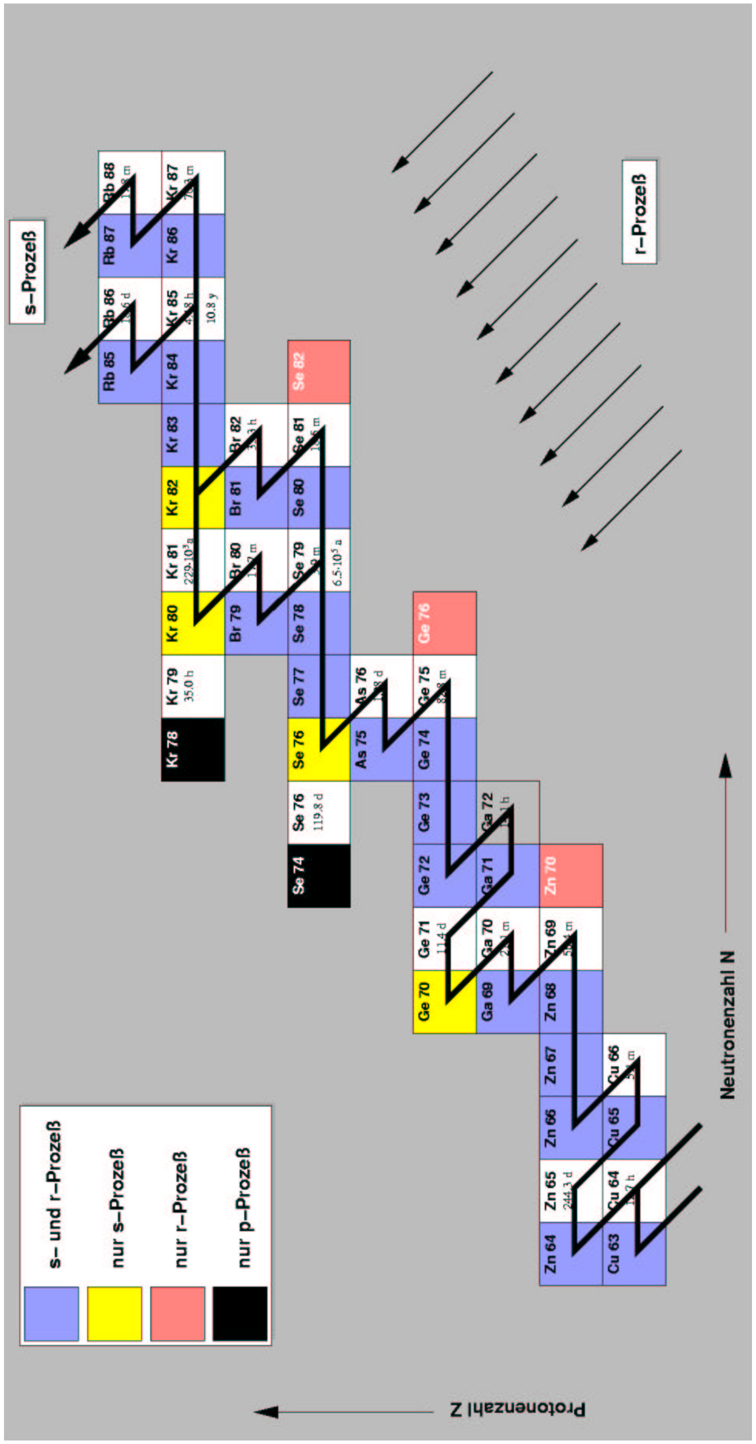
- produced by *endothermic reactions*



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

- $t_{\rm decay} \ll t_{\rm capture}$: ***s-process***
  (slow neutron-capture process)
  - ▷ ***β decay,*** s-process follows the ***"valley of β stability"***
- $t_{\rm decay} \gg t_{\rm capture}$: ***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 ($n \lesssim 10^{26}\,\mathrm{m}^{-3}$)
- r-process requires relatively high neutron densities ($n \gtrsim 10^{26}\,\mathrm{m}^{-3}$)
- *s-process*
  - ▷ possible neutron sources (during stellar He burning) $^{13}\mathrm{C}(\alpha, \mathrm{n})^{16}\mathrm{O}$ *or* $^{22}\mathrm{Ne}(\alpha, \mathrm{n})^{25}\mathrm{Mg}$
  - ▷ first reaction requires $^{13}\mathrm{C}$ which is relatively rare, but produced during hydrogen burning via $^{12}\mathrm{C}(\mathrm{p}, \gamma)^{13}\mathrm{N}(\mathrm{e}^{+}\nu)^{13}\mathrm{C}$ (CN cycle)

  → requires *simultaneous hydrogen/helium burning*

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

  → s-stars, barium stars
  - ▷ $^{22}\mathrm{Ne} + \alpha$ 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

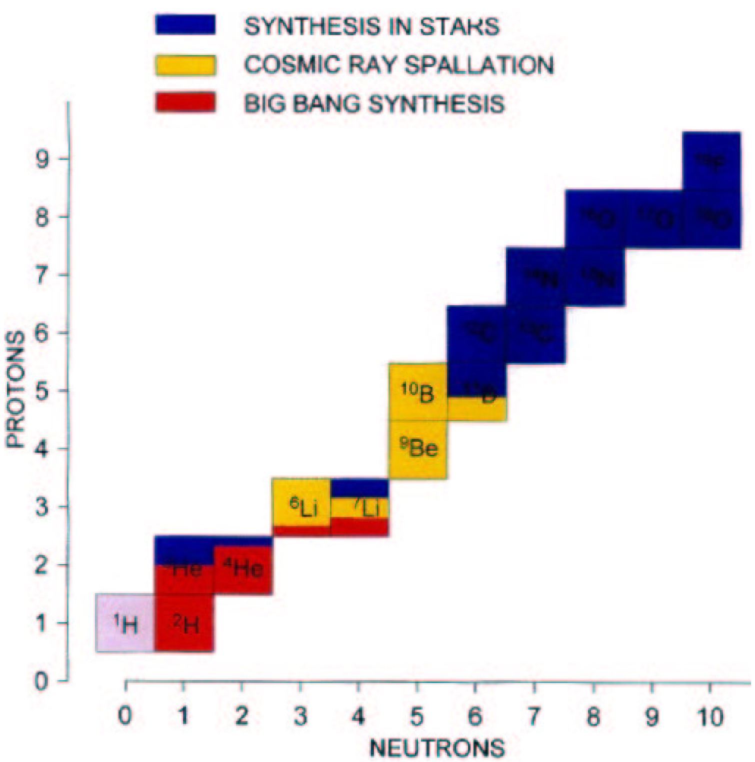
The p process:

- the origin of *proton-rich* elements is not well understood
- need e.g.
  - ▷ $(\mathbf{A}, \mathbf{Z}) + \mathbf{p} \rightarrow (\mathbf{A}+1, \mathbf{Z}+1) + \gamma$
  - ▷ $(\mathbf{A}, \mathbf{Z}) + \gamma \rightarrow (\mathbf{A}-1, \mathbf{Z}) + \mathbf{n}$
- possible site: *Thorne-Żytkow objects* (red supergiants with neutron cores) where protons are injected into the burning region at very high temperature ($\mathrm{T} \sim 10^9\,\mathrm{K}$)

Production of light elements

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

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



- 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