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)

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 \( (Z = N = 28) \)

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**Big Bang Nucleosynthesis**

**Neutrino Decoupling**

- initially at \( T > 1 \text{MeV} \), all weak interactions occur in statistical equilibrium
  \[
  \nu + n \leftrightarrow p + e; \quad \bar{\nu} + p \leftrightarrow n + e; \quad n \leftrightarrow p + e + \bar{\nu}
  \]
  → the neutron-proton ratio is determined by statistical equilibrium, i.e. the Boltzmann distribution \( n/p = \exp(-\Delta M/kT) \), where \( \Delta M = 1.293 \text{MeV} \).

- 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: \( t_{\text{weak}} \propto T^{-5} \),
  → neutrinos decouple at \( T \simeq 10^{10} \text{K} \simeq 0.86 \text{MeV} \)
  → \( n/p \approx 0.223 \)
• the deuterium reaction $p + n \leftrightarrow ^2D + \gamma$ 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 $\beta$ decay with a half life of 617 s
  
  $\rightarrow$ n/p drops to $\sim 0.164$

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

• primordial reactions:
  
  $p + n \rightarrow ^2D + \gamma$
  $^2D + p \rightarrow ^3He + \gamma$
  $^2D + n \rightarrow ^3H + \gamma$
  $^3He + ^3He \rightarrow ^4He + 2p$

• there are no stable nuclides with mass 5 or 8 $\rightarrow$ limits buildup of heavier elements

• some light elements form through reactions like
  
  $^4He + ^3H \rightarrow ^7Li + \gamma$
  $^4He + ^3He \rightarrow ^7Be + \gamma$
  $^7Be + e \rightarrow ^7Li + \nu$

• the final abundance ratios depend on
  
  ▶ the n/p ratio determined by the decoupling temperature
  ▶ the competition of $\beta$ decays and the rate of n + p reactions, which depends on the the nucleon to photon ratio $\eta$ (the n + p rate depends on the nucleon/baryon density)
  ▶ at low nucleon density ($\eta$): neutrons $\beta$ 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:
  
  $Y = \frac{4 \times 1/2n}{4 \times 1/2n + (p - n)} = \frac{2n}{p + n} = \frac{2n/p}{1 + n/p} = 0.28$
  
  (for n/p = 0.164)
- The production of deuterium and hence all other light nuclides depends strongly on the baryon density
  - At high $\eta$, deuterium is efficiently destroyed by $p$ or $n$ captures (to produce nuclides of mass number 3)
  - Astronomical observations fix $\eta$ in the standard model to $3 - 15 \times 10^{-10}$ (assumes $n/p$ ratio is fixed by standard particle physics; Universe is homogeneous)
- 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: $4H \rightarrow \text{He}$, $3\text{He} \rightarrow \text{C}$, $2\text{C} \rightarrow \text{Mg}$, $2\text{O} \rightarrow \text{S, Si, Si} \rightarrow \text{Fe}$
- 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 $T \sim 2 \times 10^9$ K, elements start to photodisintegrate and eject light particles, in particular p’s ($\gamma$, p), n’s ($\gamma$, n) and $\alpha$’s ($\gamma$, $\alpha$) 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) → abundance pattern approaches nuclear statistical equilibrium (NSE)

- there is a net excess of $\alpha$ capture reactions which build up alpha-rich elements ($\alpha$-process)
- $^{28}$Si + $\alpha$ → $^{32}$S + $\alpha$ → $^{36}$Ar + $\alpha$ → $^{40}$Ca
  + $2\alpha$ → $^{48}$Ti + $\alpha$ → $^{52}$Cr + $\alpha$ → $^{56}$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 establish 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 ~ 0.1 M☉ can be ejected)
  - large ejection of oxygen
  - thermonuclear explosions: dominant producers of Ni (which decays into Fe; ~ 0.6 M☉)
  - different timescales for core collapse supernovae (~ 10⁷ yr) and thermonuclear explosions (up to ~ 10⁹ 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

\[ (Z, A) + n \rightarrow (Z, A + 1) + \gamma \]

- consider neutron-capture reactions (on Fe-peak seed nuclei)

\[ (Z, A) + n \rightarrow (Z, A + 1) + \gamma \]

- if (Z, A+1) is stable, it waits until it captures another neutron
- if (Z, A+1) is unstable to \( \beta \) decay (typically \( t_{\text{decay}} \sim 10^5 - 10^7 \) s), the further chain depends on \( t_{\text{decay}} \) and \( t_{\text{capture}} \)

\[ t_{\text{decay}} \ll t_{\text{capture}}: \text{s-process} \]

(slow neutron-capture process)

\( \beta \) decay, s-process follows the “valley of \( \beta \) stability”

\[ t_{\text{decay}} \gg t_{\text{capture}}: \text{r-process} \]

(rapid neutron-capture process)

- if (Z, A+1) can capture further neutrons and produce elements (far) away from the valley of \( \beta \) stability
- eventually these elements \( \beta \) decay and produce stable neutron-rich isotopes
Astrophysical Sites for the s- and r-process

- **s-process** requires relatively low neutron densities \( (n \lesssim 10^{26} \text{ m}^{-3}) \)

- **r-process** requires relatively high neutron densities \( (n \gtrsim 10^{26} \text{ m}^{-3}) \)

- **s-process**
  - possible neutron sources (during stellar He burning) \(^{13}\text{C}(\alpha, n)^{16}\text{O}\) or \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\)
  - first reaction requires \(^{13}\text{C}\) which is relatively rare, but produced during hydrogen burning via \(^{12}\text{C}(p, \gamma)^{13}\text{N} (e^+ \nu)^{13}\text{C}\) (CN cycle)
  - requires simultaneous hydrogen/helium burning or injection of freshly produced \(^{13}\text{C}\) into He-burning layers
  - promising site: thermally pulsing AGB stars (with alternating hydrogen and helium burning)
  - s-stars, barium stars
  - \(^{22}\text{Ne} + \alpha\) 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.
  \[
  \begin{align*}
  (A, Z) + p &\rightarrow (A + 1, Z + 1) + \gamma \\
  (A, Z) + \gamma &\rightarrow (A - 1, Z) + n
  \end{align*}
  \]
- possible site: Thorne-Żytkow objects (red supergiants with neutron cores) where protons are injected into the burning region at very high temperature \((T \sim 10^9 \text{ K})\)

Production of light elements

- by **spallation** of intermediate nuclei (e.g. O, N, C) by cosmic rays
  \[
  \{p, \alpha\} + \{C, N, O\} \rightarrow ^{6}\text{Li}, ^{7}\text{Li}, ^{7}\text{Be}, ^{9}\text{Be}, ^{10}\text{Be}, ^{10}\text{B}, ^{11}\text{B}
  \]

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

→ explosive H/He burning in giants?