

Lecture 3: Big Bang Nucleosynthesis

Last time:

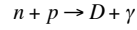
- particle anti-particle soup
- > quark soup
- > neutron-proton soup.

Today:

- Form ${}^2\text{D}$ and ${}^4\text{He}$
- Form heavier nuclei?
- Discuss primordial abundances X_p, Y_p, Z_p .
- Constrain baryon density

Big Bang Nucleosynthesis

Starts with Deuterium formation



when the high energy tail of blackbody photons no longer breaks up D. Binding energy $E=2.2$ MeV.

$$E / k T \sim \ln(N_\gamma / N_B) = \ln(10^9) \sim 20$$

$$k T \sim 0.1 \text{ MeV} \quad (T \sim 10^9 \text{ K} \quad t \sim 100 \text{ s})$$

LTE+neutron decay: $N_p / N_n \sim 7$

Thus, at most, $N_D / N_p = 1/6$

Deuterium readily assembles into heavier nuclei.

Key Fusion Reactions

	product:	binding energy:
$n + p \rightarrow D + \gamma$	Deuterium (pn)	2.2 MeV
$D + D \rightarrow {}^3\text{He}^{++} + n$	${}^3\text{He}$ (ppn)	7.72 MeV
$p + D \rightarrow {}^3\text{He}^{++} + \gamma$		
$n + D \rightarrow T + \gamma$	Tritium (pnn)	8.48 MeV
$D + D \rightarrow T + p$		
$n + {}^3\text{He}^{++} \rightarrow T + p$		
$n + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + \gamma$	${}^4\text{He}$ (ppnn)	28.3 MeV
$D + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + p$		
$p + T \rightarrow {}^4\text{He}^{++} + \gamma$		
$D + T \rightarrow {}^4\text{He}^{++} + n$		
${}^3\text{He}^{++} + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + 2p$		

Deuterium Bottleneck

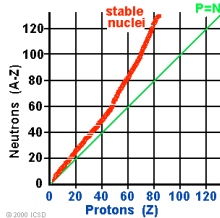
Note:

- D has the lowest binding energy (2.2 MeV) (D easy to break up)
- Nuclei with $A > 2$ can't form until D is produced. (requires 3-body collisions)

→ Deuterium bottleneck

- Nucleosynthesis waits until D forms.
- Then nuclei immediately form up to ${}^4\text{He}$.

What about Heavier Nuclei?

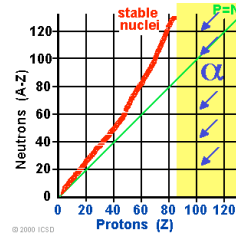


Z = number of protons
A = atomic weight
= protons + neutrons

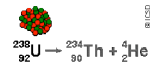
As protons increase, neutrons must increase faster for stable nuclei.

Nuclei with $Z > 83$ or > 126 neutrons UNSTABLE.

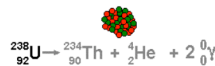
e.g. α -decay (emit ${}^4\text{He}$)
 β -decay (emit e^-)

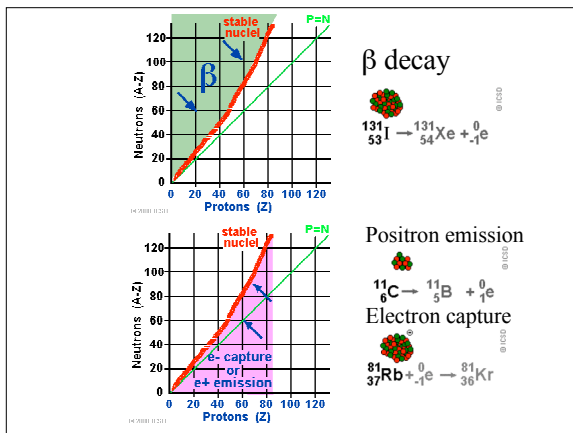


α decay



Photon emission





BBN stalls

The main problem:
 ${}^4\text{He}$ very stable, 28 MeV binding energy.
 Nuclei with $A = 5$ are unstable!

Further fusion is rare (lower binding energies):

$${}^3\text{He}^{++} + {}^4\text{He}^{++} \rightarrow {}^7\text{Li}^{+++} + e^+ + \gamma$$

$${}^3\text{He}^{++} + {}^4\text{He}^{++} \rightarrow {}^7\text{Be}^{4+} + \gamma$$

$${}^7\text{Be}^{4+} + n \rightarrow {}^7\text{Li}^{+++} + p$$

$${}^7\text{Li}^{+++} + p \rightarrow 2\ {}^4\text{He}^{++}$$

In stars, fusion proceeds because high density and temperature overcome the ${}^4\text{He}$ binding energy.

Primordial Abundances

Because ${}^4\text{He}$ is so stable, all fusion pathways lead to ${}^4\text{He}$, and further fusion is rare.
 Thus almost all neutrons end up in ${}^4\text{He}$, and residual protons remain free. [i.e., p+p does not occur]

To first order, with $N_p / N_n \sim 7$,

$$X_p = \frac{\text{mass in H}}{\text{total mass}} = \frac{N_p - N_n}{N_p + N_n} = \frac{6}{8} = 0.75$$

$$Y_p = \frac{\text{mass in He}}{\text{total mass}} = \frac{2N_n}{N_p + N_n} = \frac{2}{8} = 0.25$$

Primordial abundances of H & He (by mass, not by number).

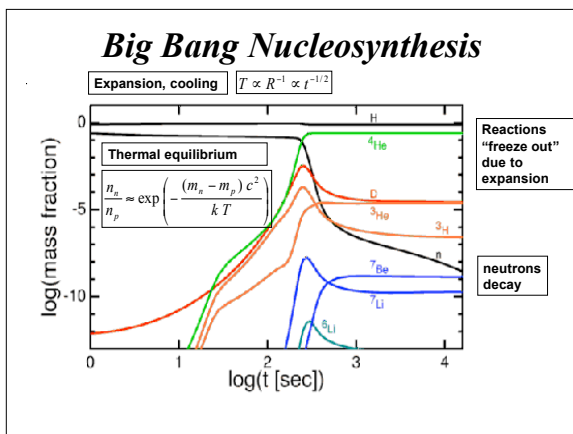
Primordial Metals

Residual D, T, ${}^7\text{Li}$, ${}^7\text{Be}$.

$$Z_p \equiv \frac{\text{mass of metals}}{\text{total mass}} \sim 0$$

Note: *In astronomy all nuclei with $A > 4$ are known as metals.*

Since the 1960's, computers simulating Big Bang Nucleosynthesis using known reaction rates give detailed abundance predictions:

$$X_p = 0.75 \quad Y_p = 0.25 \quad Z_p = 5 \times 10^{-5}$$


Sensitivity to Parameters

Abundances depend on two parameters:

- 1) cooling time vs neutron decay time (proton - neutron ratio)
- 2) photon-baryon ratio (T at which D forms)

If cooling much faster, no neutrons decay and $N_p / N_n \sim 5$

$$\rightarrow X_p = 4/6 = 0.67 \quad Y_p = 2/6 = 0.33.$$

If cooling much slower, all neutrons decay

$$\rightarrow X_p = 1 \quad Y_p = 0.$$

Baryon Density Constraint

Abundances (especially D) sensitive to these 2 parameters.

Why?

Fewer baryons/photon, D forms at lower T , longer cooling time, more neutrons decay, less He.

Also, lower density, lower collision rates, D burning incomplete, more D.

Conversely, higher baryon/photon ratio
 → more He and less D.

Photon density is well known, but baryon density is not.

→ The measured D abundance constrains the baryon density!!

A very important constraint.

$$\Omega_b \approx 0.04$$

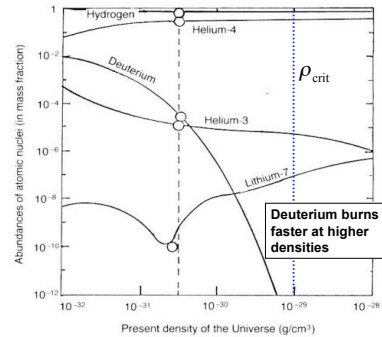
Baryon Density Constraint

Observed abundances require

$$\Omega_b \left(\frac{H_0}{70} \right)^2 = 0.040 \pm 0.004$$

~4% baryons

consistent with CMB



Observations can check the predictions, but must find places not yet polluted by stars.

- Lyman-alpha clouds

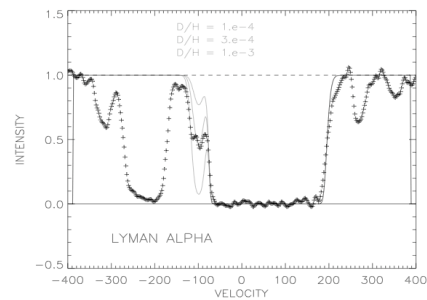


Quasar spectra show absorption lines. Line strengths give abundances in primordial gas clouds (where few or no stars have yet formed).

- nearby dwarf galaxies

High gas/star ratio and low metal/H in gas suggest that interstellar medium still close to primordial.

D/H measurement



Summary

Mostly H (75%) and ^4He (25%) emerge from the Big Bang, plus a few metals (~0%) up to ^7Li . The strong binding energy of ^4He largely prevents formation of heavy metals. Observed primordial abundances confirm predictions, and measure the baryon density $\Omega_b \approx 0.04$

Next time: *Matter-radiation decoupling*
Formation of the CMB