

Lecture 3: Big Bang Nucleosynthesis "The First Three Minutes"

Last time:

particle anti-particle soup

--> quark soup

--> neutron-proton soup

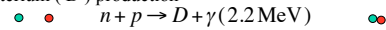
p / n ratio at onset of ${}^2\text{D}$ formation

Today:

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

Onset of Big Bang Nucleosynthesis

Deuterium (D) production



Delayed until the high energy tail of blackbody photons can no longer break up D. Binding energy: $E = 2.2 \text{ MeV}$.

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

$$kT \sim 0.1 \text{ MeV} \quad (T \sim 10^9 \text{ K} \quad t \sim 400 \text{ s})$$

Thermal equilibrium

$$+ \text{neutron decay: } N_p / N_n \sim 7$$

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

But: **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
$D + D \rightarrow T + p$		
$n + {}^3\text{He}^{++} \rightarrow T + p$	${}^4\text{He}$ (ppnn)	28.3 MeV
$n + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + \gamma$		
$D + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + p$		
$p + T \rightarrow {}^4\text{He}^{++} + \gamma$		
$D + T \rightarrow {}^4\text{He}^{++} + n$		
${}^3\text{He}^{++} + {}^3\text{He}^{++} \rightarrow {}^4\text{He}^{++} + 2p$		

Deuterium Bottleneck

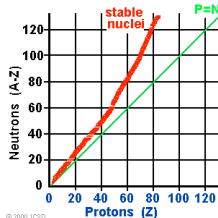
Note:

- 1) D has the lowest binding energy (2.2 MeV)
(D easy to break up)
- 2) Nuclei with $A > 2$ cannot form until D is produced.
(would require 3-body collisions)

→ **Deuterium bottleneck**

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

What about Heavier Nuclei?

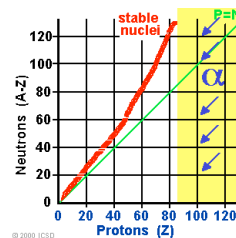


Z = number of protons
A = atomic weight
= protons + neutrons

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

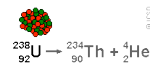
Nuclei with $Z > 83$ or > 126 neutrons UNSTABLE.

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

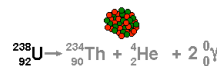


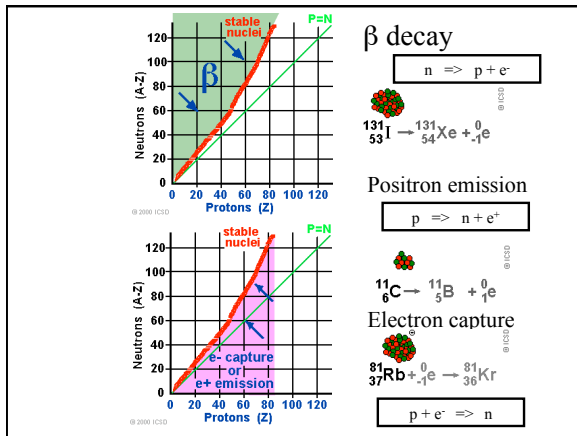
Lose 2 neutrons and 2 protons

α decay



Photon emission





BBN stalls

The main problem:
⁴He is very stable, (28 MeV binding energy).
 No stable nuclei with A = 5.
 So can't use ⁴He + p or ⁴He + n, only much rarer ⁴He + ⁴He collisions make progress.
 Thus further fusion is slow (low binding energies), leading to only traces of heavier nuclei, up to ⁷Li.

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

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

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

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

(In stars, fusion proceeds because high density and temperature overcome the ⁴He binding energy.)

Primordial Abundances

Because ⁴He is so stable, all fusion pathways lead to ⁴He, and further fusion is rare.
 Thus almost all neutrons end up in ⁴He, and residual protons remain free. [p+p -> ²He 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).

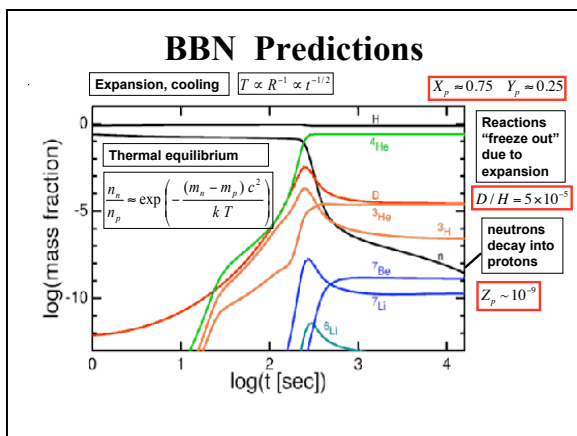
Primordial Metals

In astronomy, all nuclei with A > 4 (or with Z > 2) are called metals (Li, Be, ...)

BBN yields H, He, and traces of D, T, ⁶Li, ⁷Li, ⁷Be.

$$Z_p = \frac{\text{mass of metals}}{\text{total mass}} \approx 0$$

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

$$X_p = 0.75 \quad Y_p = 0.25 \quad Z_p \sim 10^{-9}$$


Sensitivity to Parameters

Abundances depend on two parameters:

- 1) photon/baryon ratio (sets T at which D forms)
- 2) cooling time / neutron decay time (determines the proton / neutron ratio)

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) are sensitive to these 2 parameters.

Why?

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

At lower density, lower collision rates, D burning incomplete \Rightarrow more D.

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

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

\rightarrow The measured D abundance constrains the baryon density!!

A very important constraint.

$$\Omega_b \approx 0.04$$

Baryon Density Constraint

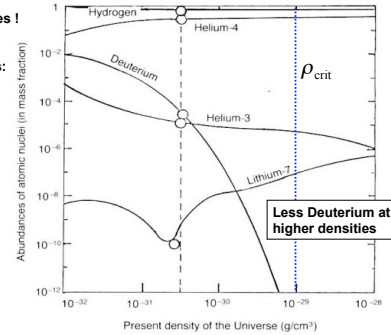
Observed He/H matches!

Observed D/H requires:

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

~4% baryons

Confirmed by an independent result from the CMB ripples.



Can we find primordial gas ?

Observations can check the BBN predictions.

But we **must find primordial gas, not yet polluted by stars.**

1) D/H ratio from "Lyman-alpha clouds":



Quasar spectra show a "forest" of $\text{Ly}\alpha$ absorption lines, formed in gas clouds at various redshifts along the line of sight.

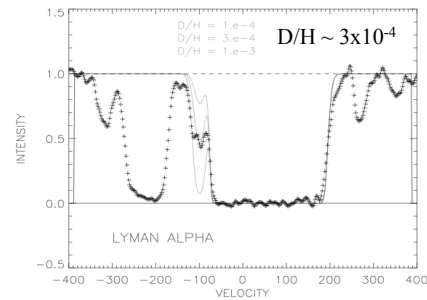
Line strengths give D/H abundance in primordial gas clouds (where few or no stars have yet formed).

2) He/H ratio from nearby low-metallicity dwarf galaxies:

High gas/star ratio and low metal/H from emission lines in HII regions suggest that interstellar medium still close to primordial

Primordial D/H from $\text{Ly}\alpha$ clouds

$\text{Ly}\alpha$ (+Deuterium $\text{Ly}\alpha$) line in quasar spectrum:



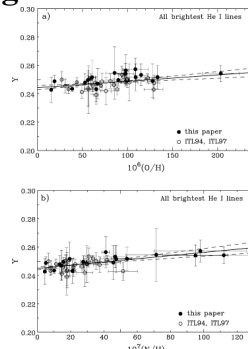
$Y_p =$ primordial He/H from dwarf galaxies

• Emission lines from H II regions in low-metallicity galaxies.

• Measure abundance ratios: He/H, O/H, N/H, ...

• Stellar nucleosynthesis increases He along with metal abundances.

• Find $Y_p = 0.245$ by extrapolating to zero metal abundance.



Summary of BBN

Mostly H (75%) and ^4He (25%) emerge from the Big Bang, plus traces of 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