Big Bang Nucleosynthesis (BBN)

Where do elements come from?

In general the synthesis of nuclei happens through production of elements in

1. BBN,
2. in stars by fusion for elements up to Fe,
3. in stars by r- and s- processes (neutron capture),
4. in supernovae explosions.

All elements heavier than Li have been produced in stars or supernovae.

Stars: production of all elements up to Fe by fusion. Why only up to Fe?

→ Remember "Bethe-Weizsäcker mass formula" (highest binding energy per nucleon for Fe)!

Could fusion in stars be responsible for abundance of all elements?´

→ Estimate helium production in stars in Milky Way within 10^{10} years. Current radiation: $L_* = 4 \cdot 10^{36}$ W. Conversion of 1 kg H to He yields $6 \cdot 10^{14}$J

→$E_{He} = 4 \cdot 10^{36} W \cdot 10^{10} yr = 1.2 \cdot 10^{54} J$

→$M_{He} = \frac{1.2 \cdot 10^{54}}{6 \cdot 10^{14}} kg = 2 \cdot 10^{39} kg$

The total mass of our galaxy $M_{Gal} \sim 3 \cdot 10^{41}$kg

→ Helium abundance expected from fusion in stars ~ 1%.

Measured He of abundance: ~ 24%

→ Stars cannot explain observed He abundance. Same holds for all light elements up to ^{7}Li

Look at "old metal poor stars": abundances of elements up to ^{7}Li are independent of abundance of heavier elements (Plateau). Metal in astrophysics: Everything heavier than He!

- ➔ Production of light elements in early universe!

Hot big bang model: correct prediction of the abundances of light stable isotopes

H, D, ^{3}He, ^{4}He and ^{7}Li in the universe

using well understood standard model physics calculations. Note that the different abundances span a range of **nine orders of magnitude** (^{4}He/H~0.1, ^{7}Li/H~10^{-10}), hence allowing to give powerful constraints on beyond standard model processes.

There is a dependence of the calculated abundances on the Baryon density of the universe ($\Omega_b h^2$), usually for BBN calculations normalized to photon density obtained from CMB η_b

and on the expansion rate of the universe at time of BBN. → Complementary cosmological information to CMB.

The term η_b is often quoted as

$$\eta_{10} = 10^{10} \cdot \eta_b \ .$$

The main reactions for isotope production in the early universe are neutron-, proton- as well as deuteron- and later ^{4}He capture by the already existing nuclei. During BBN also the unstable isotopes ^{7}Be and tritium were produced, however, these decayed into ^{7}Li and ^{3}He, respectively.

<u>Schematic derivation of ^{4}He abundance</u>:

In the early universe neutrinos, electrons and positrons were in thermal equilibrium through the weak reactions

a. $n \leftrightarrow p + e^- + \bar{\nu}_e$
b. $\nu_e + n \leftrightarrow p + e^-$
c. $e^+ + n \leftrightarrow p + \bar{\nu}_e$

For temperatures $T \gg \Delta m = m_n - m_p = 1.29\ MeV$ reactions were proceeding in both directions with the same rate.

The density of non-relativistic particles is given by

$$n_{non-rel} = g_i \left(\frac{mT}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m}{T}}$$

with g_i the number of internal degrees of freedom of the particle

$$\rightarrow \qquad \frac{n_n}{n_p} = e^{-\frac{\Delta m}{T}}$$

which in turn means that for $T \gg \Delta m \ \ n_n \cong n_p$.

At temperature $T_d \cong \Delta m = 0.8\ eV$ neutrons are frozen out as reactions b. and c. cannot happen anymore (reaction rates Γ(a.) and Γ(b.) fall below the expansion rate).

The half-life of neutrons $T_{\frac{1}{2}}(n) = (880.3 \pm 1.1)s$ is, however, bigger than the age of the universe at this time.

→ The neutron to proton ratio is frozen to

$$\frac{n_n}{n_p} \cong e^{-\frac{1.29\ MeV}{0.8\ MeV}} = 0.2$$

Before neutrons can decay back to protons they will be captured in ^{4}He nuclei by the reaction sequence

(1) $p+n \to \mathrm{d}+\gamma$
(2) $\mathrm{d}+\mathrm{d} \to {}^3\mathrm{He}+n$
(3) $\mathrm{d}+\mathrm{d} \to {}^3\mathrm{H}+p$
(4) ${}^3\mathrm{He}+\mathrm{d} \to {}^4\mathrm{He}+p$
(5) ${}^3\mathrm{H}+\mathrm{d} \to {}^4\mathrm{He}+n$

Process (1) leaves thermal equilibrium at $T \lesssim 0.1\, MeV$, when number of photons above threshold for deuterium disintegration 2.2MeV per baryon falls below unity.

→ Dependence on baryon density: $\frac{\Gamma_{pn\to d\gamma}}{H} \sim 2 \cdot 10^3 \left(\frac{T}{0.1\, MeV}\right)^5 \cdot \frac{n_p}{n_p+n_n}\Omega_b h^2$

→ Photo-disintegration d+$\gamma \to p+n$ becomes inefficient,

→ Increase of deuterium abundance,

→ Rapid d + d fusion to ^{4}He,

→ Most neutrons are "eaten up" by ^{4}He synthesis: $n_{He} \cong \frac{n_n}{2}$

The synthesis stops once all neutrons have been bound in deuterium.

Estimation of ^{4}He abundance:

$$Y(^4\mathrm{He}) = \frac{M_{He}}{M_{tot}} \cong \frac{4 \cdot n_{He} m_p}{n_p m_p + n_n m_p} = \frac{4 \cdot n_{He}}{n_n+n_p} = \frac{2 \cdot n_n}{n_n+n_p} = \frac{2}{1+\frac{n_p}{n_n}} \cong \frac{1}{3}$$

The time scale during which ^{4}He synthesis took place is not negligible with respect to half-life of the neutron → decay of neutrons resulting in decreasing $\frac{n_n}{n_p}$ ratio has to be taken into account.

This considered: $Y(^4\mathrm{He}) \cong 0.24$

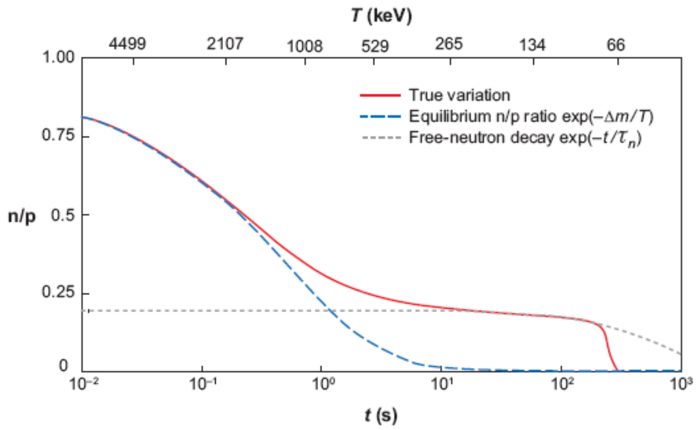
This is a rough estimate not considering details of neutron freeze out. The real challenge (complication) is in the details of thermodynamics.

Slight dependence of $Y(^4\mathrm{He})$ on η_{10} due to balance between D formation and disintegration: moves to higher T → The earlier D forms, the more neutrons available (don't decay) to form ^{4}He!

Final result also depends on $\Omega_b h^2$ and $T_{\frac{1}{2}}(n)$ → Comparison with measured abundances: determination of $\Omega_b h^2$!

Largest uncertainty is neutron half-life!

Note: dependence of ratio on decoupling temperature T_d given by ratio of reaction rate to Hubble expansion → dependence on number of neutrino families!

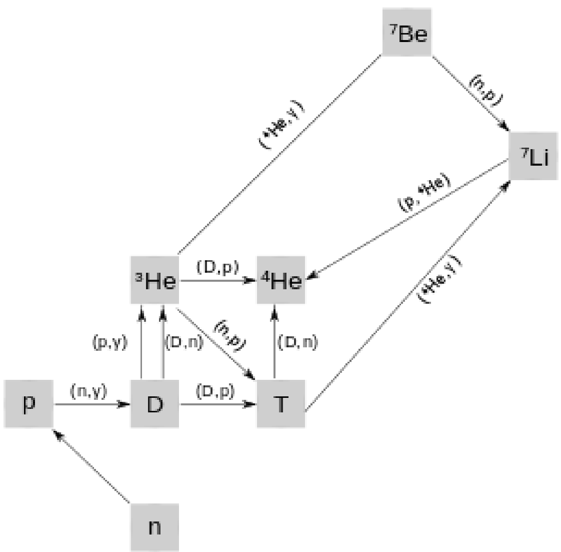


Neutron to proton ratio as a function of time after singularity. Shown are the contributions from thermal equilibrium (blue), from free neutron decay (gray) and the real evolution including BBN (red).

The heavier nuclei are produced mainly by the reactions

(6) $^{4}\text{He} + {}^{3}\text{H} \rightarrow {}^{7}\text{Li} + \gamma$
(7) $^{4}\text{He} + {}^{3}\text{He} \rightarrow {}^{7}\text{Be} + \gamma$
(8) $^{7}\text{Be} + n \rightarrow {}^{7}\text{Li} + p$

The production of heavier isotopes is strongly suppressed as there are no stable isotopes with mass numbers 5 and 8 (this also suppresses the ^{7}Li abundance); All nuclei with mass number $A = 5$ have half-lives smaller than ~10^{-23} s, while the longest lived $A = 5$ nuclei have half-lives shorter than 1 s.



Overview of reactions involved in the synthesis of elements in BBN

Calculations of the abundances are compared with observations to derive η_{10}.

Abundances are measured in unprocessed matter, i.e. systems with low metallicity (metallicity is the abundance of elements heavier than helium).

Abundances can be obtained from He and H, …. absorption lines: column density: Correlation between line depth to amount of intervening matter!

The ^{4}He abundance is measured in stars as a function of metallicity. The higher the metallicity, the higher the ^{4}He of the star (processing of primordial matter in stars) → extrapolation to zero metallicity gives the primordial value.

There is a remarkably good agreement between measured abundances over five orders of magnitude.

The baryon to photon ratio thus derived from BBN alone is:

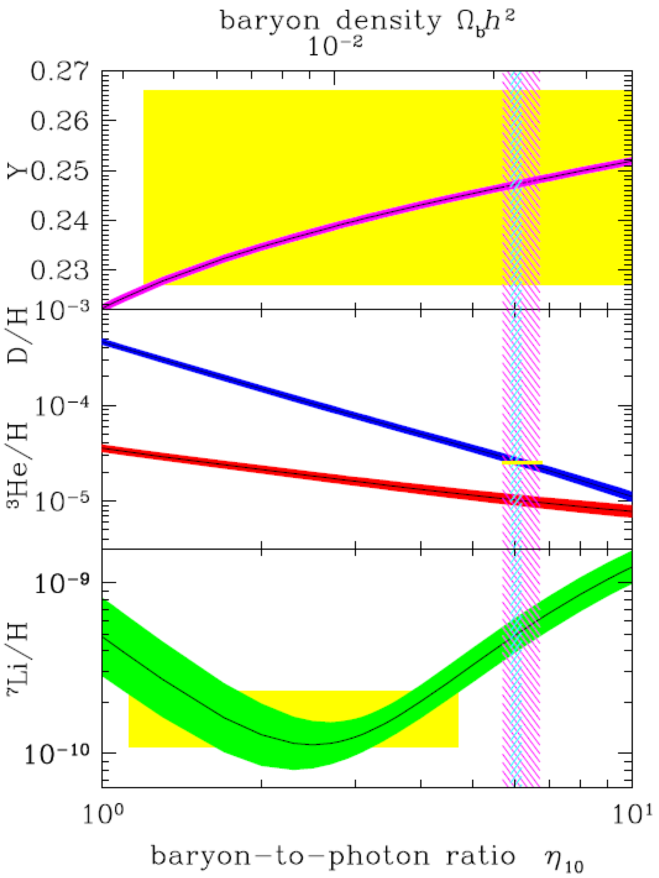
$$5.7 < \eta_{10,BBN} < 6.7$$

This is in very good agreement with the value derived from CMB alone

$$\eta_{10,CMB} = 6.047 \pm 0.074.$$

The Lithium abundance is systematically off by 5σ! This is so far an unresolved problem. It could have several explanations:

- ➔ Systematic errors in observed abundances,
- ➔ Uncertainties in stellar physics (Li destruction in stars),
- ➔ Uncertainties in nuclear inputs (poorly measured resonances), but latest updates have increased the tension!
- ➔ New Physics, must leave abundances of other isotopes unchanged → Difficult, but there are some



Abundance of light elements as a function of η_{10}. Shown are also the results from measurements (yellow boxes) and from CMB (blue shaded 68% C.L. interval). The 68% C.L. interval best fit to BBN only is shown as purple shaded area.