Big Bang Nucleosynthesis (BBN)

One of the most important evidences for the hot big bang model comes from the 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 strong dependence of the calculated abundances on the Baryon to Photon ratio η_b and on the expansion rate of the universe at time of BBN. This gives complementary information to CMB.

The term η_b is often quoted as

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

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.

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 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 $T \cong \Delta m = 0.8\, eV$ neutrons are frozen out as reactions b. and c. cannot happen anymore (reaction rates Γ(a.) and Γ(b.) fall below the expansion rate). This freeze out temperature depends on the baryon to photon ratio η_b(compare to CMB temperature).

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

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

Process (1) leaves thermal equilibrium at $T \lesssim 0.1\, MeV$

→ photo-disintegration d+$\gamma \rightarrow p + n$ becomes inefficient,

→ increase of deuterium abundance,

→ rapid d + d fusion to ^{4}He,

→ Nearly all 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.

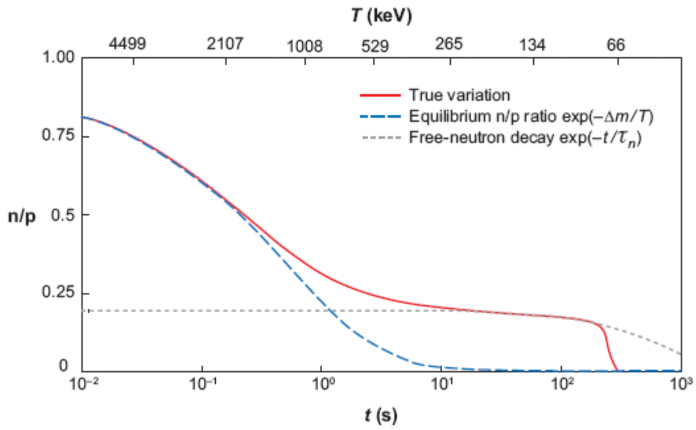
Estimation of ^{4}He abundance:

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

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

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

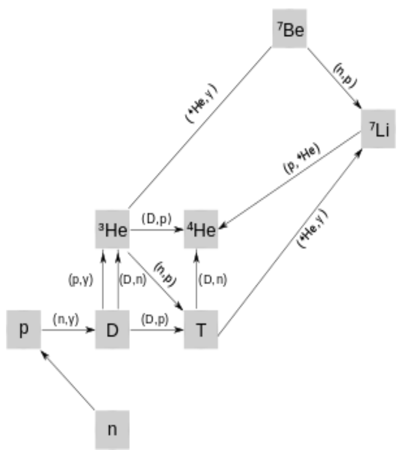


Neutron to proton ratio as a function of time after singularity. Shown are the contributions from thermal equilibrium (blue), from free neutron decay (gray) and the real evolution including BBN (red).

The heavier nuclei are produced mainly by the reactions

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

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 lives $A = 5$ 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).

As all deuterium is destroyed when cycled in stars, the measurement of its abundance gives the most precise value for η_{10}.

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:

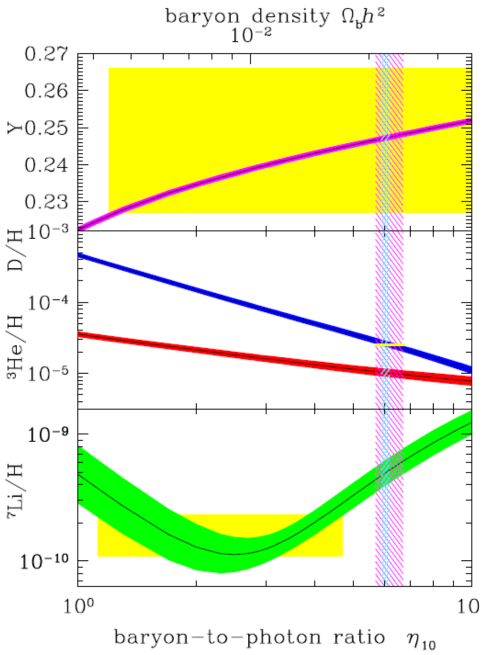
$$5.7 < \eta_{10,BBN} < 6.7$$

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),
- ➔ New Physics, must leave abundances of other isotopes unchanged.



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.