Primordial Elements' Abundances in a Non-Standard Big Bang Nucleosynthesis

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General View of the Big Bang Nucleosynthesis

When the Universe was about a fraction of a second old, it was very hot and dense.

At this temperatures some particles were in thermal equilibrium:

- Photons
- Neutrinos
- $e^{\pm}$
- Nucleons

Universe expansion $\Longrightarrow$ lower temperatures

Lower temperatures $\Longrightarrow$ no thermal equilibrium

The Neutron to Proton Ratio

For T $\sim$ 1 MeV the protons and neutrons are still in equilibrium with the fluid.

$\Longrightarrow$ n/p ratio $\sim$ n^{eq}/p^{eq} ratio

The n^{eq}/p^{eq} ratio can be expressed as:

$$\left(\frac{n_n}{n_p}\right)_{eq} = \left(\frac{m_n}{m_p}\right)^{3/2} e^{-(m_n-m_p)/T} \tag{1}$$

Where the relative abundances of neutrons and protons depend on the β and inverse β decay:

$$\begin{aligned} n + \nu_e &\Leftrightarrow p^+ + e^- \\ n + e^+ &\Leftrightarrow p^+ + \bar{\nu}_e \end{aligned} \tag{2}$$

The Neutron to Proton Ratio

If an asymmetry of neutrinos exists:

$$\left(\frac{n_n}{n_p}\right)_{eq} = \left(\frac{m_n}{m_p}\right)^{3/2} e^{-(m_n - m_p - \mu_{\nu_e})/T} = e^{-\xi_{\nu_e}} (n/p)_{eq} \qquad (3)$$

At a certain point (T $\sim$ 0.8 MeV), the weak interactions can no longer maintain the protons and neutrons in equilibrium.

As the Universe continues to expand, the protons are favored over the neutrons ($\Delta m = m_n - m_p = 1.29$ MeV).

The n/p ratio depends not only in the weak-interaction rates but also the Universe expansion rate.

The non-Standard Big Bang Nucleosynthesis can be approached through the parameter "S": S = H$'$/H.

The Deuterium role in BBN

The production of deuterium can be represented by the following reaction:

$$n + p^{+} \Leftrightarrow D + \gamma \tag{4}$$

Any n/p ratio deviation from the standard model $\Longrightarrow$ different relative number of neutrons and protons available.

At high T, deuterium is photodissociated before capturing another neutron or proton $\Longrightarrow$ more complex nuclei cannot be built.

$$\left(\frac{n_D}{n_p}\right)_{eq} \approx \eta \left(\frac{T}{m_p}\right)^{3/2} e^{B_D/T} \tag{5}$$

Where $B_D \equiv m_n + m_p - m_D = 2.22$ MeV (binding energy).

The Deuterium role in BBN

As the BNN begins, neutrons and protons combine forming: D, ^{3}He and ^{4}He.

The formation of these nuclides can be represented by:

$$D + p^+ \Leftrightarrow {}^3\mathrm{He} + \gamma \tag{6}$$

$$D + {}^3\mathrm{He} \Leftrightarrow {}^4\mathrm{He} + p^+ \tag{7}$$

Although the heavier nuclides have larger binding energies, they cannot be formed until there is enough deuterium.

$\Longrightarrow$ deuterium acts as a bottleneck.

Heavier Nuclides

Helium (^{4}He) acts as a new bottleneck because:

- Is the most tightly bound out of the light nuclides
- There are no stable mass-5 nuclides

The nuclear reactions incorporate the available neutrons into ^{4}He.

$\Longrightarrow$ The ^{4}He abundance is highly depends on the amount of available neutrons.

The only reactions that manage to jump the mass-5 gap form ^{7}Li and ^{7}Be. Another gap emerges at mass-8.

Predicted Primordial Abundances (SBBN)

Standard Big Bang Nucleosynthesis (SBBN):

$\Longrightarrow$ BBN-predicted primordial abundances depend only in: η

$$X_A = F(A) \left(\frac{T}{m_B}\right)^{3(A-1)/2} \eta^{A-1} X_p^Z X_n^{A-Z} e^{B_A/T} \qquad (8)$$

With $F(A) = g_A A^{5/2} \zeta(3)^{A-1} \pi^{(1-A)/2} 2^{(3A-5)/2}$.

But the heavier nuclear species are only effectively produced after the lighter ones.

Predicted Primordial Abundances (SBBN)

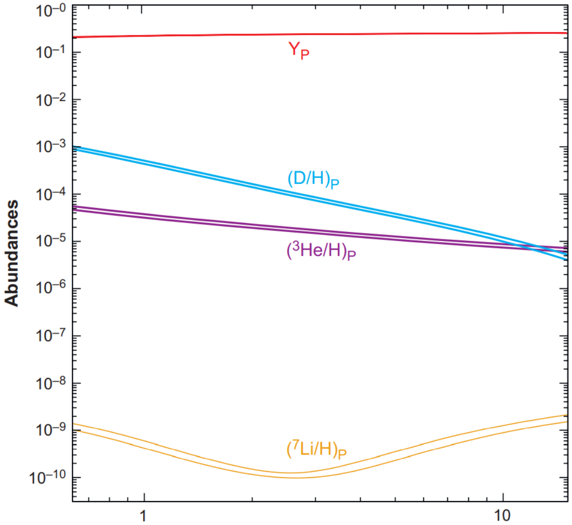

Figure: SBBN-predicted primordial abundances of D, ^{3}He, ^{7}Li and the ^{4}He mass fraction as functions of η_{10} (Steigman, 2007)

Primordial Abundances: SBBN

How do we know the value of η_{10} ?

- CMB temperature fluctuation
- Distribution of the Large-Scale Structure (LSS)

With a $\sim$ 95% confidence: $5.7 \lesssim \eta_{10} \lesssim 6.5$

With this values range:

$$
\begin{aligned}
y_{D} &\equiv 10^{5}(D/H) = 2.68(1 \pm 0.03)(6/\eta_{10})^{1.6} \\
y_{3} &\equiv 10^{5}(^{3}He/H) = 1.06(1 \pm 0.03)(6/\eta_{10})^{0.6} \\
Y_{P} &\equiv 0.2483 \pm 0.0005 + 0.0016(\eta_{10} - 6) \\
y_{Li} &\equiv 10^{10}(^{7}Li/H) = 4.30(1 \pm 0.1)(\eta_{10}/6)^{2}
\end{aligned}
$$

Primordial Abundances: non-SBBN ($S \neq 1$)

The Non-Standard Big Bang Nucleosynthesis (Non-SBBN) can be explored through the parameter S:

- $S > 1 \Longrightarrow$ faster Universe expansion
- $S < 1 \Longrightarrow$ slower Universe expansion

If $S > 1$:

- D and ^{3}He abundances increase
- The ^{4}He abundance increases
- The abundance of mass-7 depends on η

Primordial Abundances: Non-SBBN ($S \neq 1$)

Primordial abundances as a function of η_{10} and S ($4 \lesssim \eta_{10} \lesssim 8$, $0.85 \lesssim S \lesssim 1.15$) (Steigman, 2007):

$$y_D \equiv 46.5(1 \pm 0.03)\eta_D^{-1.6} \tag{9}$$

$$Y_P \equiv (0.2386 \pm 0.0006) + \eta_{He}/625 \tag{10}$$

$$y_{\mathrm{Li}} \equiv \frac{(1 \pm 0.1)}{8.5}\eta_{\mathrm{Li}}^2 \tag{11}$$

Where η_D and η_{He} are defined as:

$$\eta_D \equiv \eta_{10} - 6(S - 1) \tag{12}$$

$$\eta_{He} \equiv \eta_{10} + 100(S - 1) \tag{13}$$

$$\eta_{\mathrm{Li}}^2 \equiv \eta_{10} - 3(S - 1) \tag{14}$$

Note that η_D and η_{Li} have similar dependencies with η_{10} and S: $\eta_{\mathrm{Li}} = \eta_{\mathrm{D}} + 3(S - 1) \approx \eta_{\mathrm{D}}$

Primordial Abundances: Non-SBBN ($\xi_{\nu_e} \neq 0$)

Another way to discuss the non-SBBN is through the ξ_{ν_e} parameter.

A n/p ratio deviation affects the primordial abundances.

If $\xi_{\nu_e} \neq 0$:

- $\xi_{\nu_e} > 0$: greater n/p ratio
- $\xi_{\nu_e} < 0$: smaller n/p ratio

Steigman (2007) also obtained analytical fits for η_{10} and ξ_{ν_e} ($4 \lesssim \eta_{10} \lesssim 8$, $-0.1 \lesssim S \lesssim 0.1$):

$$\eta_D = \eta_{10} + 5\xi_{\nu_e}/4 \tag{15}$$

$$\eta_{He} = \eta_{10} - 574\xi_{\nu_e}/4 \tag{16}$$

$$\eta_{\mathrm{Li}} = \eta_{10} - 7\xi_{\nu_e}/4 \tag{17}$$

High discrepancy from the observational data.

$\Longrightarrow$ accuracy of the data remains questionable.

For comparison purposes:

$$y_{\rm DP} = 2.68^{+0.27}_{-0.25} \quad (18)$$

$$y_{\rm 3P} = 1.1 \pm 0.2 \quad (19)$$

$$Y_{\rm P} = 0.240 \pm 0.006 (< 0.251 \pm 0.002) \quad (20)$$

$$[{\rm Li}]_{\rm P} = 2.1 \pm 0.1 (2.5 \pm 0.1) \quad (21)$$

Data vs Theory: SBBN

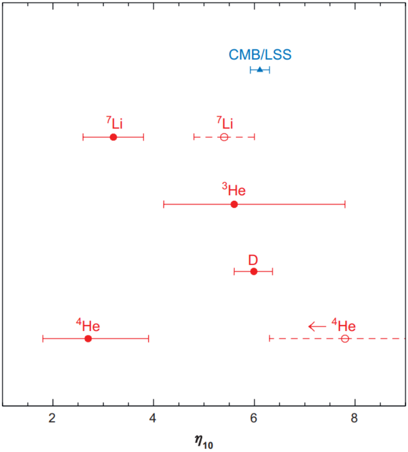

Figure: SBBN-predicted values of η_{10}, 1σ uncertainties) (red filled circles), corresponding to the abundances adopted, the non-BBN value inferred from CMB radiation LSS data (blue triangle) and also the alternative values (open circles) (Steigman, 2007).

Data vs Theory: Non-SBBN

To obtain the observationally inferred values:

- Use the D abundance to fix η_{10}
- Adopt the value from the CMB radiation and the LSS

If we use D to fix η_{10}:

$$S = 0.952 \pm 0.036 (< 1.017 \pm 0.013) \quad (22)$$

$$\xi_{\nu_e} = 0.034 \pm 0.026 (> -0.012 \pm 0.009) \quad (23)$$

However, we still cant solve the lithium problem...

References

Steigman, G. 2007, Annual Review of Nuclear and Particle Science, 57, 463–491, doi: 10.1146/annurev.nucl.56.080805.140437