Nucleosynthesis

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Overview

Introduction

- Primordial Nucleosynthesis remains as one of the pillars of modern cosmology.
- Only probe of Universe during the epoch dominated by radiation in the first few minutes of cosmic expansion.
- Abundance of elements most convincing piece of evidence supporting Hot Big Bang Theory.
- Younger stars approach to non-zero abundances $\rightarrow$ "Primordial Gas"
- Can these abundances be explained by Hot Big Bang Theory ?

Hydrogen and Helium

Three pieces of physics:

- Neutron about 0.2% more massive than protons (Q = 1.293 Mev)
- Free Neutron will decay with a half-life of about 10.3 minutes.
- Existence of stable isotopes of light elements, and neutrons bound to them do not decay.

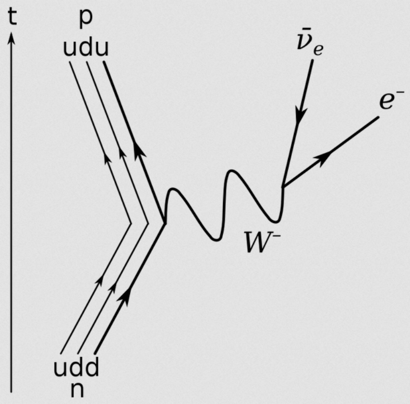

Figure 1: neutron decay

Hydrogen and Helium

At high temperatures protons and neutrons in thermal equilibrium at high energies.

$$N \propto m^{\frac{3}{2}} e^{\frac{-mc^2}{k_B T}} \tag{1}$$

Relatives densities :

$$\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{\frac{3}{2}} e^{-\frac{(m_n - m_p)c^2}{k_B T}} \tag{2}$$

while $k_B T \gg (m_n - m_p)c^2$ the number of protons and neutrons in the Universe will be almost identical. Reactions of converting neutrons to protons :

$$n + \nu_e \rightleftharpoons p + e^- \qquad n + e^+ \rightleftharpoons p + \bar{\nu}_e \tag{3}$$

Interactions proceed quickly until temperature reaches $k_B T \simeq 0.8$ MeV.

At this temperature slightly less than Q Ec (2) gives:

$$\frac{N_n}{N_p} \simeq e^{-\frac{1.3Mev}{0.8MeV}} \simeq \frac{1}{5} \tag{4}$$

Now onwards, only process that can change abundances is :

$$n \rightleftharpoons p + e^- + \bar{\nu}_e \tag{5}$$

Light Elements

The production of light elements then has to go through a complex reaction chain.

$$p + n \rightarrow D \tag{6}$$

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

$$D + D \rightarrow {}^4\mathrm{He} \tag{8}$$

This Happens at an energy of ~ 0.1 MeV. Once neutrons manage to form nuclei they become stable.
Delay until 0.1Mev (before helium-4 appear) is long enough that neutron decay is not negligible. How many neutrons decay ?. First , how old at that temperature ? Eq. (11.11) $(\frac{1sec}{t})^{0.5} = \frac{k_B T}{2MeV}$ gives t = 400 s:

$$\frac{N_n}{N_p} \simeq \frac{1}{5} e^{\frac{400 \cdot ln2}{614}} \simeq \frac{1}{8} \tag{9}$$

Primordial Abundance

All neutrons end up in helium and the number density of helium-4 is N(He4)=Nn/2. Each Helium weighs about four proton masses. Fraction of total mass in helium-4.

$$Y_4 = \frac{2N_n}{N_n + N_p} = 0.22 \tag{10}$$

About 22% of matter in the Universe is in the form of ^{4}He
keeping track of the whole network of nuclear reactions, allows one to estimate the trace abundances of all the other nuclei which form in the early Universe.

Comparing with observations

Two important parameters which affect abundances:

- The number of massless neutrino species in Universe $\rightarrow$ affects how nuclear reactions go out of thermal equilibrium
- The density of baryonic matter in the Universe $\rightarrow$ $\Omega_B h^2$ constrained

In agreement with observations, there is a tight bound of baryonic matter in the Universe.

$$0.016 \leq \Omega_B h^2 \leq 0.024 \tag{11}$$

Comparing with observations

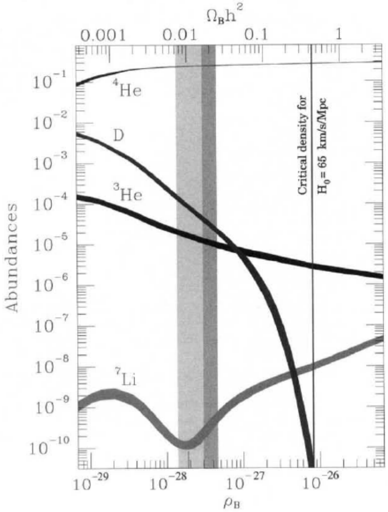

Figure 2: Predicted abundances of light nuclei

Contrasting decoupling and nucleosynthesis

- huge difference in energy scales between atomic and nuclear processes.
- Universe hot enough to destroy nuclei for first minutes of its existence. (while capable of destroying atoms for more than a hundred thousand years)
- Only decoupling leads to CMB. After nucleosynthesis the photons are still able to interact with both nuclei and electrons.

	Nucleosynthesis	Decoupling
Time	a few minutes	300 000 yrs
Temperature	10^{10} K	3000 K
Typical energy	1 MeV	1 eV
Process	Protons and neutrons form nuclei. Electrons remain free.	Nuclei and electrons form atoms.
Radiation	continues to interact with nuclei and electrons.	ceases interaction and forms microwave background.

Figure 3: Comparison of nucleosynthesis and decoupling

Baryogenesis

Sakharov conditions:

- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

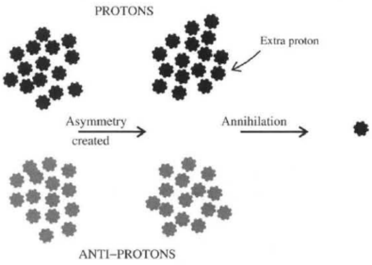

Figure 4: matter-anti-matter asymmetry

Referencias

An introduction to modern cosmology
Andrew R. Liddle

Thanks for your attention