Lec 13: 03/02/2010

Big-Bang Nucleosynthesis:

As we discussed in the last lecture, weak interactions freeze out (drop out of equilibrium) at $T \sim 1\,MeV$ (when the universe is ~ 1 second old).

Very interesting things happen from this moment on. As we will see shortly, this is the onset of big-bang nucleosynthesis. First lets focus on the hadrons (bound states of quarks and antiquarks). The quark-hadron phase transistion happens much earlier than one second (at $T \sim 200\,MeV$). At $T \sim 1\,MeV$ all hadrons have already decayed except for the proton and neutron. We note that protons are practically stable (the experimental limit on the proton lifetime is

$> 10^{33}$ years). Free neutrons decay, but they have a lifetime $\tau_n \simeq 887$ sec. Therefore, at $T \sim 1$ MeV ($t \sim 1$ sec) almost all of the existing neutrinos in the universe have not undergone the decay process.

The following interactions between proton and neutron (all weak interactions) maintain relative equilibrium between them until $T \sim 1$ MeV:

$n \leftrightarrow p + e^- + \bar{\nu}_e$ $\qquad m_n \simeq 939.57$ MeV, $m_p \simeq 938.27$ MeV

$p + e^- \leftrightarrow n + \nu_e$ $\qquad \Delta E = 0.8$ MeV

$p + \bar{\nu}_e \leftrightarrow n + e^+$ $\qquad \Delta E = 1.8$ MeV

These interactions proceed in both directions until $t \sim 1$ sec. At this time weak interactions (in the form of scattering processes that are mediated by weak gauge bosons $Z, W^\pm$) drop out of equilibrium. Henceforth, the only interaction (from those in above) that will still proceed is the neutron decay $n \to p + e^- + \bar{\nu}_e$.

At $T \sim 1\,\mathrm{MeV}$, the ratio of neutrons to protons (their number densities) follows the equilibrium value:

$$\left(\frac{n}{p}\right)_{1\,\mathrm{sec}} = \exp\left(-\frac{\Delta m}{T}\right) \sim \frac{1}{6}$$

After one second neutrons keep decaying while processes that convert p back to n are not efficient. As a result, the ratio $\frac{n}{p}$ will decrease in time as a result of the exponential decay of neutrons.

In addition, protons and neutrons can also bind together through strong interactions and form deutron D (which is ionized at these temperatures):

$n + p \leftrightarrow D + \gamma$

The inverse process (photo-dissociation of D) will be very efficient until the temperature drops below 100 keV. The binding energy of D is very low ~2 MeV. This implies that the number of energetic photons in the Wien tale of the black body spectrum of CMB is comparable to the number of baryons (neutrons + protons) down to a temperature given by:

$$T \sim \frac{2\,\mathrm{MeV}}{\ln\left(\frac{n_\gamma}{n_B}\right)}$$

Here $\eta \equiv \frac{n_B}{n_\gamma}$ is the ratio of the number density of baryons and photons. As we will see, big bang nucleosynthesis (BBN) determines $\eta \sim 5 \times 10^{-10}$ (which is in good agreement with ou independent determination from CMB).

For $\eta \sim O(10^{-10})$, it is easy to see that the photo-dissociation of D is efficient down to $T < 100$ keV. This is called the Deuterium bottleneck.

Once D can form, heavier elements like ^3He and ^4He are also made through strong interactions:

$D + D \rightarrow {}^4He + \gamma$

$D + D \rightarrow {}^3He + n$

${}^3He + D \rightarrow {}^4He + p$

$D + D \rightarrow {}^3H + p$

${}^3H + D \rightarrow {}^4He + n$

Almost all of the protons and neutrons end up in H and ^4He. A tiny fraction will be in the form of primordial D, ^3He. Even a tinier fractio will be in the form of ^7Li. There are no stable nuclei with atomic number $A=5$ and $A=8$. Also, ^6Li formation is suppressed because of the associated threshold energy. Elements heavier than ^7Li will not form because the rates for strong interactions drop out of equilibrium by that time, and also the Coulomb barrier for their formation will be too high to overcome at those temperatures.

We can make a quick estimate on the relative number of H and ^4He for $\eta \sim O(10^{-10})$. It turns out that at the time D can form we have:

$$\boxed{\frac{n}{p} \sim \frac{1}{7}}$$

This shows a slight drop from the equilibrium value $\left(\frac{n}{p}\right)_{1\,sec} \sim \frac{1}{6}$, which is due to neutron decay as we go through the Deuterium bottleneck.

This implies that there are two neutrons for every 14 protons. The two neutrons bind with two protons to form one ^4He, hence for every ^4He we will have 12 protons (12 Hydrogen). This results in:

$$\frac{n_{^4He}}{n_H} \sim \frac{1}{12}$$

The mass fraction of ^4He, denoted by $Y_{^4He}$, defined as the ratio of mass in primordial ^4He to the total baryonic mass is then found to be:

$\boxed{Y_{^4He} \sim 0.25}$

This is in very good agreement with the measurements. We then have:

$\boxed{Y_H \sim 0.75}$

And:

$$\boxed{\frac{^2D}{H}, \frac{^3He}{H} \sim \mathcal{O}(10^{-5}) \qquad \frac{^7Li}{H} \sim \mathcal{O}(10^{-19})}$$

Next we will see how we can infer η from the primordial abundance of light elements. Also, how BBN can constrain physics beyond the Standar Model (including the effective number of particle with a mass < 1 MeV).