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Big-Bang Nucleosynthesis (Cont'd);

As we discussed, most of the neutrons end up in the form of ^4He, and only a tiny fraction in ^2D and ^3He (even a smaller number in ^7Li).

The ratio of the number of neutrons to protons $\frac{n}{p}$ is given by the equilibrium value $(\frac{n}{p})_{eq}$ once the weak interactions freeze out;

$$\left(\frac{n}{p}\right)_{eq} = \exp\left(\frac{-(m_n - m_p)}{T_{f.o.}}\right)$$

Where:

$$T^3_{f.o.} \sim G_F^{-2} M_p^{-1} \sqrt{\frac{\pi^2}{90} g_*}$$

Here $g_* = 2 + \frac{7}{8} \times 4 + \frac{7}{8} \times 2 \times N_{\nu,eff}$, where N_ν is the effective number of light neutrinos (the meaning of "effective" will be explained later on).

Note that $T_{f.o.}$ depends on $N_{\nu,eff}$ (it is larger for a larger $N_{\nu,eff}$ and smaller for a smaller $N_{\nu,eff}$). A small change in $T_{f.o.}$ (corresponding to a small change in g_*) affects $\left(\frac{n}{p}\right)_{eq}$ significantly because of its exponential dependence on $T_{f.o.}$.

Throughout the Deuterium bottleneck (until $T \lesssim$ key) neutrons freely decay. At the time ^2D can form without being dissociated we have:

$$X \equiv \frac{n}{p} = \left(\frac{n}{p}\right)_{eq} \exp\left(-\frac{\Delta t}{\tau_n}\right)$$

Here τ_n is neutron lifetime and Δt is the time interval of Deuterium bottleneck.

As we mentioned earlier, Δt depends on $\eta \equiv \frac{n_B}{n_\gamma}$. The larger η is, the smaller Δt will be (and vice versa). Note, however, that $\Delta t \ll \tau_n$. Thus X is not very sensitive to η (but it is to g_*). The mass fraction of ^4He is given by:

$$Y_{^4He} \simeq \frac{2X}{1+X}$$

We therefore conclude that $Y_{^4He}$ is very sensitive to g_*, but has mild dependence on η. One can find an expression for it as follows:

$$\boxed{Y_{^4He} = 0.230 + 0.025 \log\left(\frac{\eta}{10^{-10}}\right) + 0.0075\,(g_* - 10.75) + 0.014\,(\tau_{\frac{1}{2}} - 10.6\ \text{min})} \quad (*)$$

Here $\tau_{\frac{1}{2}}$ is the neutron half life. It is evident from this expression that $Y_{^4He}$ is a good measure of g_* ($g_* = 10.75$ for three light neutrinos).

On the other hand, the abundance of ^2D is sensitive to η. The reason being that only those ^2D that do not participate in nuclear reactions leading to formation of ^4He (discussed in the previous lecture) survive. The reaction rate is sensitive to η.

The larger η is, the sooner we will be through the Deuterium bottleneck. The ^2D number density will be higher as well as its mean kinetic energy. In consequence ^4He formation will be more efficient which implies in a much smaller number of ^2D not participating in the process.

The sensitivity of ^2D abundance on η is evident from the approximate expression that can be derived;

$$\boxed{\frac{^2D}{H} \sim \eta^{-1.6}} \quad (**)$$

The two expressions (*), (**) suggest that ^2D abundance is a good baryometer, while

$Y_{^4He}$ is a good measure of light degrees of freedom g_* at the freeze out of weak interaction.

An important point is that the light element abundance is affected by stellar processes. Therefore, we have to make sure that the primordial abundance of these elements are measured through observations, in order to be able to make comparison with BBN predictions. The observations that are used to measure primordial abundance of light elements are:

- ^2D: High redshift Quasi Stellar Objects (QSO's), through absorption line of ^2D (which is in the UV part of the spectrum).
- ^3He: InterStellar Matter (ISM), through emission

line of singly ionized ^3He (which is in the radio part of the spectrum).

^4He: Low metalicity extragalactic HII regions (regions with hot ionized gas), through the emission line of ^4He (which is in the optical part of the spectrum).

^7Li: Very metal poor stars (Pop III stars), through the absorption line of ^7Li (which is in the optical part of the spectrum).

We look for old (hence metal poor) systems that are not significantly affected by stellar evolution. Astrophysical processes destroy ^2D and produce ^4H. As of now, we don't quite know whether stars are not producers or destroyers of ^3He. We als seem to have difficulty in deducing the primordial abundance of ^7Li from metal poor stars.

High redshift QSO's observations yield a value of η that is in remarkable agreement with that inferred from CMB (the latter will be discussed in detail later on). This is a great achievement of big-bang cosmology that two measurement from vastly different times (few minutes for BBN, $\sim 400{,}000$ years for CMB) are in excellent agreement. Nowadays, the ^2D abundance is used to infer the value of η, and then $Y_{^4He}$ is used to constrain g_* (or $N_{\nu, eff}$).

We find $\underline{\underline{\eta \sim 6 \times 10^{-10}}}$ from ^2D measurement (as well as CMB). Until recently, ^4He measurements were systematically on the lower side resulting in $N_{\nu,\text{eff}} < 3$. However, the more recent measurements are higher (though they have large error bars) and we currently have $\underline{\underline{N_{\nu,\text{eff}} < 3.2}}$ (at the 2σ level).

As we will see later, this bound can be used to constrain the number of new light degrees of freedom that arise in physics beyond the standard model.

Let us briefly summarize the three important things that BBN has achieved:

1- First and foremost, it confirms hot big bang universe as early as ~ 1 sec. The (overall) consistency between predictions for the abundance of light elements and their **measured** values is one of the observational pillars that the universe was a hot bath of elementary particles at about one second. At the moment, we do not have direct observational evidence of the hot big bang at (much) earlier times.

This puts an important constraint on theories of the universe. For example, in the inflationary universe scenorio, which is the dominant paradigm of the early universe currently, the universe undergoes a brief period of very rapid expansion. This leaves the universe cold and empty, and all particles are created during transition from the inflationary phase to the hot big bang phase. The success of BBN requires that this transition occurs prior to one second.

2- The inference of η from the measured values of the light element abundances gives important information on the content of the universe. Comparing $\eta \sim 6\times10^{-10}$ with the amount of baryonic mass implies that about half of the baryons in the universe is dark. These "dark baryons" are thought to be in the form of MACHO's (MAssive Compact Halo Objects), Jupiter like objects, etc.

Moreover, when combined with other observations it turns out that most of the matter in the universe is non-baryonic and dark. The identity of dark matter is one of the most important problems is cosmology, and is the center of a lot of experimental and theoretical efforts.

3 _ The bound on g_* from BBN gives rise to tight constraints on new physics beyond the standard model. In fact, this bound can be much stronger than these from earthbound experiments. For example, it can rule out particle that interact with ordinary particles very weakly (much weaker than weak interactions). It will be very difficult to see these particles in the lab directly.

We will discuss this in more length later on.