Big Bang Nucleosynthesis - Summary

by Dr. Helga Dénes (hdenes@yachaytech.edu.ec)

This summary is based on the book Chapters 9.5, 9.6 and 10.1-10.6 from Klaus Grupen: Astroparticle Physics.

1 The thermal history of the first 10μs

one can find the times and energy densities, at which different temperatures were reached. By combining this with the knowledge of particle physics, one will see what types of particle interactions were taking place at what time.

10^{16} GeV the different interactions separate into strong and electroweak interactions. This is the scale of Grand Unified Theories (GUT scale). One expects that this phase transition is related to the Higgs field. The vacuum expectation value of the Higgs field above the GUT scale should be zero. Up to this moment the masses of elementary particles were zero. During the transition the vacuum expectation value of the Higgs field will adopt non-zero values. This phenomenon is called spontaneous symmetry breaking (SSB). As a result, the hypothetical X and Y bosons from earlier times go from being massless to having very high masses on the order of the GUT scale. So, at lower temperatures, baryon-number-violating processes mediated by exchange of X and Y bosons are highly suppressed.

The hypothetical X and Y bosons couple quarks to leptons, allowing violation of the conservation of baryon number thus permitting proton decay. Grand Unified Theory (GUT) is any model in particle physics that merges the electromagnetic, weak, and strong forces into a single force at high energies. It raises the possibility that there was a grand unification epoch in the very early universe in which these three fundamental interactions were not yet distinct.

10^{-11} s and a 100 GeV, **'electroweak scale'**: SSB phase transition is expected to occur, whereby the electroweak Higgs field acquires a non-zero vacuum expectation value. As a result, W and Z bosons as well as the quarks and leptons acquire their masses.

10^{-5} s 0.2 GeV (the **'QCD scale'**): quarks and gluons become confined into colour-neutral hadrons. This process, called **hadronization**.

Two major issues with our knoledge of the earliest Universe:
- Why the universe appears to be composed of matter, rather than a mixture of matter and antimatter?
- Horizon problem and Inflation

2 The Baryon Asymmetry of the Universe

The universe known to us seems to consist of matter only. how this asymmetry could evolve from a state that initially contained equal amounts of matter and antimatter, a process called **baryogenesis**. For every proton there is an electron, so the universe also seems to have a non- zero lepton number (**leptogenesis**). The Standard Model as it stands cannot explain the observed baryon asymmetry of the universe.

If antiparticles were to exist in significant numbers locally, one would see **evidence of** this from proton-antiproton or electron-positron **annihilation**. $p\bar{p}$ annihilation produces typically several mesons including neutral pions, which decay into two photons. So, one would see γ **rays in an energy range up to around 100 MeV**. No such gamma rays are observed in significant quantities to indicate large amounts of antimatter.

Some antiprotons bombarding the Earth as cosmic rays at a level of around 10^{-4} compared to cosmic-ray protons $\rightarrow$ compatible with production in collisions of ordinary high-energy protons with interstellar gas or dust.

If there would exist appreciable numbers of **positrons** in the universe and in the Milky Way, one would also expect to find evidence for the **511 keV annihilation**. There is such a line in the gamma-ray spectrum from our galaxy, however it can also be understood by the annihilation of locally produced positrons.

In the high-energy regime a positron flux, which cannot easily be understood by local positron production, but it could be particles from a local supernova or it may be a signature of dark matter decay.

There is no evidence for antimatter from the distant regions of the Universe.

We think that the laws of nature allow that a baryon asymmetry would arise from a state that began with a net baryon number of zero. Although the universe today seems completely dominated by baryons and not antibaryons, the relative asymmetry was very much smaller at earlier times. The baryon-antibaryon asymmetry A can be described with the barion to photon ratio:

$$A \approx \frac{n_{b,0}}{n_{\gamma,0}}$$

The baryon-number-to-photon ratio:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

This ratio remains constant as long as there are no further baryon-number-violating processes. The baryon-antibaryon asymmetry A is roughly equal to the current baryon-to-photon ratio η. The current photon density $n_{\gamma,0}$ is well determined from the CMB temperature. In principle, one could determine $n_{b,0}$ by adding up all of the baryons, however this is not easy.

A more accurate determination of η comes from the model of Big Bang Nucleosynthesis combined with measurements of the ratio of **abundances of deuterium to hydrogen**. From this the baryon asymmetry can be expressed as: $A \approx 6\eta \approx 4 \times 10^{-9}$

2.1 The Sakharov conditions

three conditions must exist in order for a universe with non-zero baryon number to evolve from an initially baryon-symmetric state.

- baryon-number-violating processes
- violation of C and CP symmetry
- departure from thermal equilibrium

The baryon asymmetry is one of the clearest indications from cosmology that the Standard Model is incomplete and that other particles and interactions must exist.

3 Big Bang Nucleosynthesis

At times from around 10^{-2} s through the first several minutes after the Big Bang, the temperature passed through the range from around **10 to below 10^{-1} MeV.** During this period protons and neutrons combined to produce a significant amount of ^{4}He plus smaller amounts of deuterium (^{2}H), tritium (^{3}H), ^{3}He, ^{6}Li, ^{7}Li, and ^{7}Be. Further synthesis of nuclei in stars accounts for all of the heavier elements plus only a relatively small (1 to 2%) additional amount of helium. This is an important support of the Big Bang model.

The two main ingredients of BBN are the equations of cosmology and thermal physics, plus the rates of nuclear reactions. Of crucial importance is the rate of the reaction $\nu_e + n \Leftrightarrow e^- + p$, which allows transformations between neutrons and protons. At a temperature around 0.7 MeV the reaction is no longer fast enough to keep up and the neutron-to-proton ratio 'freezes out' at a value of around 1/6. To first approximation one can estimate the helium abundance simply by assuming that all of the available neutrons end up in ^{4}He.

The one free parameter of BBN is the baryon density Ω_b or, equivalently, the baryon-to-photon ratio η. By comparing the observed abundances of the light elements with those predicted by BBN, the value of η can be estimated. The result is of fundamental importance for the dark-matter. $\rightarrow$ Based on Ω_b we can get the density of dark matter Ω_{DM}.

The neutron to proton ratio depends how fast the Universe expands and cools at the time when the equilibrium between the p - n transformation is broken. We need to compare the expansion rate of the Universe H to the reaction rate Γ. Γ = H:

$$G_F^2 T^5 \sim \frac{T^2}{m_{Pl}}$$

This determines the freeze-out temperature $T_f \approx 0.7$ MeV. Under this temperature there is no more equilibrium between the p and n and the neutron-to-proton ratio freeze-out to

$$\frac{n_n}{n_p} \approx 0.13$$

In the next few minutes, essentially all of the neutrons become bound into ^{4}He, and thus the neutron-to-proton ratio at the freeze-out temperature is the dominant factor in determining the amount of helium produced. The nucleosynthesis is completed after three minutes (t = 180 s). After about several minutes the temperatures are insufficient to fuse heavier nuclei.

The more detailed calculations need to consider the average lifetime of the n and the additional heating from electron-positron annihilation. If τ_n were less, then essentially all of the neutrons would decay before they could be bound up into deuterium. On the other hand, if it had been at a temperature much higher than $m_n - m_p$, then there would have been equal amounts of protons and neutrons. Then the entire universe would have been made of helium. Usual hydrogen-burning stars would be impossible.

We can predict elemental abundances based on nucleosynthesis models, which we can then compare to observations. Abundances depend on η so we can use the abundances to determine η. This is also not straight forward since abundances change as a result of stellar nucleosynthesis. For this we generally try to observe 'metal-poor' galaxies or high redshift intergalactic gas.

The created elements:

- 23% ^{4}He mass fraction means that the number fraction of ^{4}He is about 6% with respect to hydrogen.
- ^{2}H/H $\sim 10^{-5}$
- ^{3}He/H $\sim 10^{-5}$
- ^{7}Li/H $\sim 10^{-10}$

The measured D/H provides the most accurate determination of η. η can be converted into the energy density of baryons.

The **CMB** is created when the electrons **recombine** with nuclei and form neutral atoms. This happens much later than the primary nucleosynthesis.

4 Neutrino Families

The comparison of the measured and predicted ^{4}He mass fractions can result in constraints on the particle content of the Universe.

The exact value of the **decoupling temperature** of p-n is also a complicated mixture of effects, being sensitive to the **degrees of freedom**, which **depends on the number of relativistic particle species** (at the nucleosynthesis time: $\nu's, \gamma, e^-, e^+$) in thermal equilibrium $\rightarrow$ the number of neutrino types. Cosmology measurements support 3 types of 'light' neutrinos and do not support more than 3 types.

An independent measurement comes from the Large Electron-Positron (LEP) collider from the total width of the Z resonance, which also supports 3 types of neutrinos.