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BIG BANG NUCLEOSYNTHESIS

Big Bang Nucleosynthesis (BBN), together with the CMB and the recession fo galaxies provide compelling evidence that the early universe was dense and hot. BBN is the sequence of nuclear reactions that led to the synthesis of the light elements of D: ^{3}He ^{4}He and ^{7}Li in the "First Three Minuets" (more precisely between t=0.01 and 200 sec). Heavier elements were produced in stars. The difficulty to produce Helium in stars led Alpher, Bethe and Gamow ("α, β, γ") in the late 1940's to suggest a cosmological origin.
The observed abundances of these light elements provide a very powerful test of the Hot Big Bang since there are only two parameters which affect the predicted abundances:

1. The number of neutrino species since this affects the temperature-age relation and the way in which the nuclear reactions go out of thermal equilibrium.
2. The density of baryonic matter ρ_B in the Universe. If the density of baryons (i.e. protons and neutrons) changes, then their formation into nuclei will also be altered such that the ratio of the abundances will change. This is particularly critical for D because if ρ_B is high, all the D will be converted to ^{4}He and there will be no D left. Usually, ρ_B is expressed using the density parameter and since the critical density ρ_c contains a factor of h^2, this means the combination $\Omega_B\, h^2$ is constrained.

1 The Physics of BBN

The underlying assumption is FRW cosmology. The early universe was dominated by relativistic matter, so the Friedmann equation can be written as:

$$H^2 = (8\pi/3)G\ \rho_r$$

where

$$\rho = (g_*/2)a_B\ T_r^4,$$

a_B is the Boltzmann radiation constant and g_* counts the total number of spin states of all relativistic particle species. If there are 3 Neutrino species then $g_* = 10.75$.

The time scale of the reaction is dictated by the half-life time of the neutron, 614 seconds. the reactions converting neutrons to protons and vice versa are

$$n + \nu_e \Longleftrightarrow p + e^-$$

$$n + e^+ \Longleftrightarrow p + \bar{\nu}_e.$$

At temperature $T \sim 2$ MeV energies and densities have dropped sufficiently so that neutrinos cease to interact. Calculations show that the ratio of the number of neutrons to protons was frozen at

$$N_n/N_p = 1/8$$

The reactions that lead to ^{4}He are:

$$n + p \Longrightarrow D + \gamma \tag{1}$$

$$D + D \Longrightarrow\ {}^3He + n \tag{2}$$

$$^3He + D \Longrightarrow\ {}^4He + p \tag{3}$$

We can now estimate the fraction of mass in Helium. Assuming $N_{He} = N_n/2$ (all neutrons ended up in Helium):

$$Y = m_{He}/m_{tot} = 4N_{He}/(N_n + N_p) = 2N_n/(N_n + N_p) = 2(N_n/N_p)/(1 + N_n/N_p) \approx 0.22$$

where we assumed $N_n/N_p = 1/8$ from above.

More detailed calculations give $Y = 0.248$ and observations are in the range Y = 0.22-0.25.

2 Results and implications

Agreement with the observed element abundances is only possible if the number of neutrino species is 3. This has been confirmed by experiments at CERN. This leaves $\Omega_B\, h^2$ as the only input parameter. Comparison with observations (see figure) shows that the Hot Big Bang can reproduce the abundances of the light elements for a narrow range in $\Omega_B\, h^2$:

$$0.016\ \leq\ \Omega_B\, h^2\ \leq\ 0.024$$

where the range corresponds to errors and differences in the observations.

This agrees with results from the CMB anisotropies and from baryon fraction in clusters. Putting results from these probes it emerges that

$$\Omega_B\, h^2 \approx 0.02.$$

With a Hubble Constant $h = 0.7$ this means that the baryon density parameter is $\Omega_B = 0.04$. This has important implications: (i) Baryons cannot provide the closure density. (ii) Most of the baryons are dark. (iii) Most of the dark matter is non-baryonic.

3 Matter/Anti-Matter Asymmetry

(LJS version)

Earlier we saw that the photon-to-baryon ratio $\eta = 10^9$. In quantum mechanics, every particle should have an anti-particle but we know there is no significant quantity of anti-matter in our Universe (we would have seen the signals of annihilation).

There must therefore be a matter/anti-matter asymmetry such that $10^9 + 1$ particles of matter collided with 10^9 particles of anti-matter to give us 10^9 photons for every baryon.

When the mean photon energy $k_B\, T >> m_p\, c^2$, baryons and anti-baryons will be in thermal equilibrium:

$$\gamma\, +\, \gamma \Longleftrightarrow p\, +\, p^-$$

During this epoch, a process must have occurred to create one extra proton for every billion existing but left anti-protons untouched. The Universe then cools and once $k_B\, T << m_p\, c^2$ the protons and anti-protons annihilate each other for good. One proton will be left for every 10^9 annihilations. We are made of this small initial asymmetry favouring matter. At present there are only highly speculative particle physics theories to explain this.