1.8 Nucleosynthesis

It follows from the equation of continuity (6) that the mass contained in the Universe had a large density and hence probably also a large temperature when the radius R of the Universe was small. The conditions in the whole Universe could then be similar to those in stellar interiors, and there could take place some thermonuclear reactions. For each reaction (either chemical, thermonuclear or a reaction of elementary particles, or for a ionization process, a radiative transition, etc.) there exists also the inverse process. In the thermodynamic equilibrium, the ratio of abundances of the products of these reactions is determined by the temperature and the density. Because the relaxation time τ_r for reaching this equilibrium usually decreases fast with increasing density, it was much smaller than the age t of the Universe at that time when R was small, and hence the chemical composition of the Universe corresponded to the equilibrium one. At the moment when the density decreased due to the cosmological expansion and τ_r became larger than t, the detailed equilibrium was broken. In the first approximation, the nowadays chemical composition of the Universe is a frozen picture of the situation at that instant. For a more accurate calculation, it is necessary to solve the appropriate kinetic equations. However, in principle, the chemical composition of the Universe is determined by the value of the temperature in the epoch with given density. An ionized matter is in thermodynamic equilibrium with the radiation, hence the temperature is described by the density of photons. The resulting chemical composition is thus dependent on the ratio of the photon density n_γ and the baryon density n_B, i.e., on the entropy per baryon, because the entropy of the equilibrium photon gas, which is proportional to the density of photons, is dominant. The resulting abundance of He^4 (which is $\simeq 0.25$ by mass in a good agreement with the observations) is poorly sensitive to n_B/n_γ because it is determined mainly by the relative abundance of neutrons and protons ($\simeq 0.2$) at the moment when their mutual transmutations finished due to the drop of the temperature. After the plasma recombination, the relaxation time τ_r of the radiative processes becomes larger than the age t of the Universe and the radiation decouples from the mass. It means that it is freely cooling with the temperature $T \sim R^{-1}$ (while the non-relativistic particles of the mass are cooling faster with $T \sim R^{-2}$). This radiation is now observed as the cosmic background radiation, the density (temperature) of which is well measured. The mean density of baryons in the Universe can thus be calculated from the observed chemical composition of the mass in the Universe. This method determines the density of the baryonic matter including the contribution of dark matter also. However, it is influenced by the subsequent enrichment of the primordial chemical composition by heavy elements produced in the nucleosynthesis in stellar interiors. The determination of the mean chemical composition is also hampered by the increase of its local inhomogeneities. The best agreement with the observations gives the baryon density $n_\mathrm{B} \simeq 10^{-9} n_\gamma$, which corresponds to $\rho \simeq 0.1 \rho_\mathrm{crit}$.

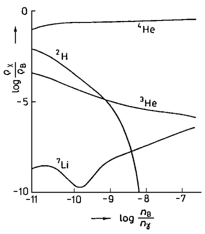

Figure 7: Relative abundance of elements as a function of entropy per baryon.

A mutual transmutation took place between the photons and the pairs of particles and antiparticles in the early epochs of the evolution of the Universe, when the mean energy of the γ-photons was higher than the corresponding threshold value. In the equilibrium of creation and annihilation processes, the numbers of photons and particles with $mc^2 < h\nu$ were approximately equal (nonetheless the dynamics of the Universe was still 'dominated by radiation' because the particles were highly relativistic like the photons). In the course of the cooling, the baryons annihilated first and then the leptons also. Because we now observe a non-zero density of particles and practically no antiparticles, there must have been a small excess of particles in comparison with antiparticles (in ratio approximately $(1+10^{-9})$:1) – the so-called *baryon asymmetry*.