Physikalisches Institut
Universität Bonn
Theoretische Physik

Exercise 8
7th June 2013
SS 13

Exercises on Theoretical Particle Astrophysics

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Due 14th June

8.1 Big Bang Nucleosinthesis (BBN) *12 points*

The temperature of the universe 10^{-4} s after the big bang was about 100 MeV. At this moment, apart from electrons, neutrinos and photons, already bound quark states existed in form of protons and neutrons. Due to the high temperature protons and neutrons were in thermal equilibrium with electrons and electron neutrinos. The number densities of protons and neutrons in the non-relativistic case is given by

$$n_{p,n} = 2\left(\frac{m_{p,n}}{2\pi T}\right)^{3/2} \exp\left\{-\frac{m_{p,n}}{T}\right\} . \tag{1}$$

(a) What was the temperature (in Kelvin) at that moment? (*1 point*)

(b) What are the reactions which convert p into n and vice versa? (*1 point*)

(c) If the reaction rate drops below the Hubble parameter, the assumption of thermal equilibrium does not hold anymore. For the reactions you found in (b) this occurred about 1 s after the big bang, at a temperature of roughly 0.8 MeV . Compute the neutron-proton ratio at this moment. (*3 points*)

(d) About 300 s after the big bang the temperature dropped below the critical temperature for deuteron photo-disintegration ($^2\mathrm{H}+\gamma \to p+n$) such that stable helium nuclei could form. What was the neutron-proton ratio at this point in time? (*3 points*)

(e) Compute the expected amount of helium ^{4}He with respect to the total mass of visible matter in the universe, under the assumption that the predominant part of the neutrons were bound in helium. What would have been the consequences for the further development of the universe if the lifetime of the free neutron would be much smaller than 100 s? (*4 points*)

8.2 Baryogenesis

8 points

In the present time universe antimatter seems to be very rare, this observation is explained by a matter-antimatter asymmetry created in the early universe. Here we explore how could this asymmetry be originated.

(a) Estimate the baryon number density at $T \gg m_p$ if the universe contained equal numbers of baryons and antibaryons. *(Hint: You can assume a constant baryon antibaryon annihilation cross section which is about* $3 \cdot 10^{-27}$ cm^2 *(*$= 30$ *mb).* (*2 points*)

(b) Evidently this baryon density is much too small to explain BBN. We conclude that the (visible part of the) universe must have a baryon asymmetry

$$A_b = \frac{n_b - n_{\bar{b}}}{n_b + n_{\bar{b}}}\,. \tag{2}$$

How large would this asymmetry have been at $T \geq m_p$? *Hint: Recall that the baryon-to-photon ration at BBN was* 10^{-9}. (*2 points*)

(c) It still remains as a question how the finite A_b was generated in the very early universe. Sakharov showed in 1967 that any would-be *baryogenesis* mechanism must satisfy three conditions:

- It must violate baryon number.
- It must violate both C and CP.
- It must have occurred out of thermal equilibrium.

Show that these conditions are indeed necessary. (*4 points*)