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Neutrino processes in the lepton era of the universe and hot big bang cosmology

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Abstract. The neutrino interactions in the lepton era of the universe have been studied here according to the photon–neutrino coupling theory. It is found that neutrinos were decoupled from electrons from the beginning of the universe and remained so throughout the lepton era of the universe in hot big bang cosmology.

Zeldovich (1965) and Graaf (1970) have investigated the interactions $\nu_e + \bar{\nu}_e \rightleftharpoons e^- + e^+$ and $\nu_e + e^- \rightarrow \nu_e + e^-$ in the early stage of cosmic evolution in hot big bang cosmology. Both have studied the interactions according to the current–current coupling theory. Graaf (1970) also considered the problem assuming the existence of a neutral lepton current as well.

In a recent paper Bandyopadhyay (1968) has suggested an alternative theory to the current–current coupling theory which has been called the photon–neutrino weak coupling theory, in which photons are considered to interact weakly with neutrinos. It is of some interest to see how the results of Zeldovich and Graaf change in the new theory.

According to the photon–neutrino coupling theory we have for the process $\nu_e + \bar{\nu}_e \rightleftharpoons e^- + e^+$, a rate of neutrino energy loss $\mathrm{d}\epsilon_{\nu\bar{\nu}}/\mathrm{d}t$ given by the relation (Bandyopadhyay 1968)

$$\frac{\mathrm{d}\epsilon_{\nu\bar{\nu}}}{\mathrm{d}t} = 1{\cdot}75 \times 10^{15} T_9{}^5 \qquad (T_9 = T/10^9). \tag{1}$$

The neutrino energy density $\epsilon_{\nu\bar{\nu}}$ is given by (Zeldovich 1965)

$$\epsilon_{\nu\nu} = 7{\cdot}8 \times 10^{21} T_9{}^4. \tag{2}$$

From this we find the characteristic time

$$\tau_{\nu\bar{\nu}} = \frac{7{\cdot}8 \times 10^{21} T_9{}^4}{1{\cdot}75 \times 10^{15} T_9{}^5} = 4{\cdot}4 \times 10^6 T_9{}^{-1}. \tag{3}$$

This is to be compared with the characteristic time $\tau_{\nu\bar{\nu}}$ obtained according to the current–current coupling theory

$$\tau_{\nu\bar{\nu}} = 1{\cdot}7 \times 10^6\ T_9{}^{-5}. \tag{4}$$

For the interaction $\nu_e + e^- \rightarrow \nu_e + e^-$, the total cross section $\sigma_{\nu e}$ in the relativistic region according to the photon–neutrino coupling theory is given by (Bandyopadhyay and Ray Chaudhuri 1969)

$$\sigma_{\nu e} = \frac{\sigma_0}{\omega^2} \tag{5}$$

where $\sigma_0 = 3{\cdot}53 \times 10^{-47}\ \mathrm{cm}^2$ and $\omega = q/m_e c^2$; q being the energy of the initial neutrino in the centre of mass system. The number density of free electrons in thermal equilibrium is given by

$$n = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp(-\psi + E/kT) + 1} \tag{6}$$

where ψ is the Gibbs free energy per electron divided by kT. In the case of non-degeneracy ($\psi \ll -1$), we have

$$n = \frac{1}{\pi^2} \left(\frac{mc}{\hbar}\right)^3 f(\beta) \tag{7}$$

where $\beta = mc^2/kT$ and $f(\beta) = K_2(\beta)/\beta$. In the extreme relativistic case $\beta \rightarrow 0$, $f(\beta) \rightarrow 2/\beta^3$. From the relations (5) and (7), we find

$$\tau_{\nu e} = (\sigma_{\nu e} n_e c)^{-1} = 1{\cdot}6 \times 10^6\ T_9{}^{-1}\ \mathrm{s}. \tag{8}$$

Comparing $\tau_{\nu e}$ with the expansion time of the universe, in hot big bang cosmology $t = 230/T_9{}^2$ (Zeldovich 1965), we see that the characteristic time is greater than the expansion time of the universe for $T_9 \gtrsim 10^{-4}$ s, that is, $t \lesssim 10^{10}$ s. This may be compared with the case of the current–current coupling theory where the characteristic time is found to be greater than the expansion time for $T_9 \lesssim 20$ s, that is, $t > 0{\cdot}5$ s. Thus according to the photon–neutrino coupling theory neutrinos were decoupled from the beginning of the universe and remained so throughout the lepton era ($1{\cdot}6 \times 10^3 \gtrsim T_9 \gtrsim 6$). This is in sharp contrast to the result obtained according to the conventional current–current coupling theory.

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