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CP violation effects on the neutrino degeneracy parameters in the Early Universe

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Abstract

We explore possible CP violating effects, coming from the Dirac phase of the Maki–Nakagawa–Sakata–Pontecorvo matrix, on the neutrino degeneracy parameters, at the epoch of Big-Bang nucleosynthesis. We first demonstrate the conditions under which such effects can arise. In particular it requires that the initial muon and tau neutrino degeneracy parameters ξ_ν differ. Then we solve numerically the kinetic equations for the three flavor neutrino density matrix with the goal of quantifying the impact of the Dirac phase on the electron neutrino degeneracy parameter ξ_{ν_e}. The calculations include the vacuum term, the coupling to matter, the $\nu\nu$ interaction and the collisions. Effects on ξ_{ν_e} up to almost 1% and on Y_p of about 0.1% are found, depending on the initial conditions.

Keywords: Physics of the early Universe; Neutrino physics; CP violation

1. Introduction

One of the major open questions in modern cosmology is the origin of the matter–antimatter asymmetry in our Universe. The bayon asymmetry is nowadays known to be $\eta_B \equiv (n_B - n_{\bar{B}})/n_\gamma = 6.14 \times 10^{-10}(1.00 \pm 0.04)$ thanks to the measurement of the CMB anisotropies by WMAP [1]. In analogy with η_B related to the baryon asymmetry, the total neutrino asymmetry $L_\nu = L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$ can be quantified by the neutrino chemical potentials μ_{ν_α} ($\alpha \equiv e, \mu, \tau$) or, equivalently, the degeneracy parameters $\xi_{\nu_\alpha} \equiv \mu_{\nu_\alpha}/T_\nu$:

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$$L_{\nu_\alpha} = \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{n_\gamma} = \frac{\pi^2}{12\zeta(3)}\left(\frac{T_{\nu_\alpha}}{T_\gamma}\right)^3\left(\xi_{\nu_\alpha} + \frac{\xi^3_{\nu_\alpha}}{\pi^2}\right) \tag{1}$$

where n_{ν_α} ($n_{\bar{\nu}_\alpha}$) are the neutrinos (anti-neutrinos) number densities and $\zeta(3) \simeq 1.202$.

Sphalerons effects in baryogenesis and leptogenesis scenarios [2] can equilibrate cosmic lepton and baryon asymmetries at the same level. Since the lepton asymmetry is only possible in the neutrino sector because of charge conservation, the observation of a non-zero neutrino degeneracy parameter ξ can furnish important information to our understanding of the matter–antimatter asymmetry in the Universe.

Non-zero electron, muon and tau neutrino degeneracy parameters influence the abundance of light elements produced in Big-Bang Nucleosynthesis (BBN) in two aspects. While all flavors influence the expansion rate of the Universe, by modifying the effective number of degrees of freedom, only $\xi_{\nu e}$ impacts the neutron/proton ratio, a key parameter for the ^{4}He abundance. Indeed ^{4}He, among all the light elements formed during BBN, is the most sensitive one to the neutrino degeneracy parameters. Extensive work has been performed to extract information on the relic lepton asymmetries either from Big-Bang Nucleosynthesis, as in e.g. [3–11] or from the cosmic microwave background and large scale anisotropies, like in [12,13].

Major advances have been performed in neutrino physics in the last ten years. The change in neutrino flavor content due to oscillations is at present a well established phenomenon. This implies that the neutrino flavor basis is related to the mass basis

$$\psi_{\nu_\alpha} = \sum_i U_{\alpha i}\psi_i, \tag{2}$$

where the unitary Maki–Nakagawa–Sakata–Pontecorvo (MNSP) matrix can be written as a product of three matrices $U = T_{23}T_{13}T_{12}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{3}$$

with $c_{ij} = \cos\theta_{ij}$ ($s_{ij} = \sin\theta_{ij}$) and θ_{12}, θ_{23} and θ_{13} the three neutrino mixing angles. These oscillation parameters have been well determined, except for the third neutrino mixing angle θ_{13} and a possible Dirac CP violating phase.[1] If θ_{13} is close to the Chooz limit, i.e. $\sin^2 2\theta_{13} < 0.02$, reactor experiments (Double-Chooz, RENO and Daya-Bay) should soon measure this angle [14]. The two squared mass differences[2] have been measured with good precision [15]. Since the sign of Δm^2_{23} has not been determined yet, two mass hierarchies are possible: inverted ($\Delta m^2_{23} > 0$) or normal ($\Delta m^2_{23} < 0$). This is known as the mass hierarchy problem. The absolute neutrino mass scale is also still unknown, since neutrino oscillations are only sensitive to mass squared differences. The KATRIN experiment will soon reach the sub-eV sensitivity [16] while important indirect limits on the sum of the neutrino masses are obtained using CMB and LSS data (see e.g. [17–19]). Indeed, so far, only indirect effects of cosmological neutrinos have been observed. Their detection represents one of the major future challenges. An interesting possibility has been

[1] Note that Majorana phases can also be present. They can influence the neutrinoless double-beta decay half-lives, while neutrino oscillations are not affected by such phases. For this reason they will not be considered here.

[2] Although the existence of sterile neutrinos is an attractive possibility, here we consider three active neutrino families, in agreement with the ensemble of experimental data.