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A fuller flavour treatment of N_2-dominated leptogenesis

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Abstract

We discuss N_2-dominated leptogenesis in the presence of flavour dependent effects that have hitherto been neglected, in particular the off-diagonal entries of the flavour coupling matrix that connects the total flavour asymmetries, distributed in different particle species, to the lepton and Higgs doublet asymmetries. We derive analytical formulae for the final asymmetry including the flavour coupling at the N_2-decay stage as well as at the stage of wash-out by the lightest right-handed neutrino N_1. Moreover, we point out that in general part of the electron and muon asymmetries (phantom terms), can completely escape the wash-out at the production and a total $B - L$ asymmetry can be generated by the lightest RH neutrino wash-out yielding so-called phantom leptogenesis. However, the phantom terms are proportional to the initial N_2 abundance and in particular they vanish for initial zero N_2-abundance. Taking any of these new effects into account can significantly modify the final asymmetry produced by the decays of the next-to-lightest RH neutrinos, opening up new interesting possibilities for N_2-dominated thermal leptogenesis.

Keywords: Neutrino physics; Early universe; Leptogenesis

1. Introduction

Leptogenesis [1] is based on a popular extension of the Standard Model, where three right-handed (RH) neutrinos N_{Ri}, with a Majorana mass term M and Yukawa couplings h, are added to the SM Lagrangian,

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$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_{Ri}\gamma_\mu\partial^\mu N_{Ri} - h_{\alpha i}\bar{\ell}_{L\alpha}N_{Ri}\tilde{\Phi} - \frac{1}{2}M_i\bar{N}^c_{Ri}N_{Ri} + h.c.$$
$$(i = 1, 2, 3,\ \alpha = e, \mu, \tau). \tag{1}$$

After spontaneous symmetry breaking, a Dirac mass term $m_D = vh$, is generated by the vev $v = 174$ GeV of the Higgs boson. In the see-saw limit, $M \gg m_D$, the spectrum of neutrino mass eigenstates splits in two sets: 3 very heavy neutrinos N_1, N_2 and N_3, respectively with masses $M_1 \leqslant M_2 \leqslant M_3$, almost coinciding with the eigenvalues of M, and 3 light neutrinos with masses $m_1 \leqslant m_2 \leqslant m_3$, the eigenvalues of the light neutrino mass matrix given by the see-saw formula [2]

$$m_\nu = -m_D\frac{1}{M}m_D^T. \tag{2}$$

Neutrino oscillation experiments measure two neutrino mass-squared differences. For normal schemes one has $m_3^2 - m_2^2 = \Delta m^2_{\rm atm}$ and $m_2^2 - m_1^2 = \Delta m^2_{\rm sol}$, whereas for inverted schemes one has $m_3^2 - m_2^2 = \Delta m^2_{\rm sol}$ and $m_2^2 - m_1^2 = \Delta m^2_{\rm atm}$. For $m_1 \gg m_{\rm atm} \equiv \sqrt{\Delta m^2_{\rm atm} + \Delta m^2_{\rm sol}} = (0.050 \pm 0.001)$ eV [3] the spectrum is quasi-degenerate, while for $m_1 \ll m_{\rm sol} \equiv \sqrt{\Delta m^2_{\rm sol}} = (0.0088 \pm 0.0001)$ eV [3] it is fully hierarchical (normal or inverted). The most stringent upper bound on the absolute neutrino mass scale comes from cosmological observations. Recently, quite a conservative upper bound,

$$m_1 < 0.2\ \text{eV} \quad (95\%\ \text{CL}), \tag{3}$$

has been obtained by the WMAP Collaboration combining CMB, baryon acoustic oscillations and supernovae type Ia observations [4].

The CP violating decays of the RH neutrinos into lepton doublets and Higgs bosons at temperatures $T \gtrsim 100$ GeV generate a $B - L$ asymmetry one third of which, thanks to sphaleron processes, ends up into a baryon asymmetry that can explain the observed baryon asymmetry of the Universe. This can be expressed in terms of the baryon-to-photon number ratio and a precise measurement comes from the CMBR anisotropies observations of WMAP [4],

$$\eta_B^{\rm CMB} = (6.2 \pm 0.15) \times 10^{-10}. \tag{4}$$

The predicted baryon-to-photon ratio η_B is related to the final value of the $(B - L)$ asymmetry $N^{\rm f}_{B-L}$ by the relation

$$\eta_B \simeq 0.96 \times 10^{-2} N^{\rm f}_{B-L}, \tag{5}$$

where we indicate with N_X any particle number or asymmetry X calculated in a portion of co-moving volume containing one heavy neutrino in ultra-relativistic thermal equilibrium, so that e.g. $N^{\rm eq}_{N_2}(T \gg M_2) = 1$.

If one imposes that the RH neutrino mass spectrum is strongly hierarchical, then there are two options for successful leptogenesis. A first one is given by the N_1-dominated scenario, where the final asymmetry is dominated by the decays of the lightest RH neutrinos. The main limitation of this scenario is that successful leptogenesis implies quite a restrictive lower bound on the mass of the lightest RH neutrino. Imposing independence of the final asymmetry of the initial RH neutrino abundance and barring phase cancellations in the see-saw orthogonal matrix entries the lower bound is given by [5–7]

$$M_1 \gtrsim 3 \times 10^9\ \text{GeV}. \tag{6}$$