EFFECTS OF LIGHTEST NEUTRINO MASS IN LEPTOGENESIS

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The effects of the lightest neutrino mass in "flavoured" leptogenesis are investigated in the case when the CP-violation necessary for the generation of the baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana phases in the neutrino mixing matrix U. The type I see-saw scenario with three heavy right-handed Majorana neutrinos having hierarchical spectrum is considered. The "orthogonal" parametrisation of the matrix of neutrino Yukawa couplings, which involves a complex orthogonal matrix R, is employed. Results for light neutrino mass spectrum with normal and inverted ordering (hierarchy) are obtained. It is shown, in particular, that if the matrix R is real and CP-conserving and the lightest neutrino mass m_3 in the case of inverted hierarchical spectrum lies the interval 5×10^{-4} eV $\lesssim m_3 \lesssim 7 \times 10^{-3}$ eV, the predicted baryon asymmetry can be larger by a factor of ~ 100 than the asymmetry corresponding to negligible $m_3 \cong 0$. As consequence, we can have successful thermal leptogenesis for 5×10^{-6} eV $\lesssim m_3 \lesssim 5 \times 10^{-2}$ eV even if R is real and the only source of CP-violation in leptogenesis is the Majorana and/or Dirac phase(s) in the neutrino mixing matrix.

1 Introduction

We investigate the effects of the lightest neutrino mass in thermal leptogenesis [1,2] where lepton flavor effects[3–8] play an important role in the generation of the observed baryon asymmetry of the Universe and the CP-violation required for the baryogenesis mechanism to work is due exclusively to the Dirac and/or Majorana CP-violating phases in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) [9] neutrino mixing matrix. A detailed analysis of these effects has been performed in reference [10].

The minimal scheme in which leptogenesis can be implemented is the non-supersymmetric version of the type I see-saw [11] model with two or three heavy right-handed (RH) Majorana neutrinos. Taking into account the lepton flavour effects in leptogenesis it was shown [12] (see also [4,13,14]) that if the heavy Majorana neutrinos have a hierarchical spectrum, the observed baryon asymmetry Y_B can be produced even if the only source of CP-violation is the Majorana and/or Dirac phase(s) in the PMNS matrix $U_{\rm PMNS} \equiv U$. In this case the predicted value of

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the baryon asymmetry depends explicitly (i.e. directly) on U and on the CP-violating phases in U. The results quoted above were demonstrated to hold both for normal hierarchical (NH) and inverted hierarchical (IH) spectrum of masses of the light Majorana neutrinos. In both these cases they were obtained for negligible lightest neutrino mass and CP-conserving elements of the orthogonal matrix R, present in the "orthogonal" parametrisation [15] of the matrix of neutrino Yukawa couplings. The CP-invariance constraints imply that the matrix R could conserve the CP-symmetry if its elements are real or purely imaginary [c]. We remark that for a CP-conserving matrix R and at temperatures $T \sim M_1 \gtrsim 10^{12}$ GeV, the lepton flavours are indistnguishible (one flavour approximation) and the total CP asymmetry is always zero. In this case no baryon asymmetry is produced. One can prove [12] that, for NH spectrum and negligible lightest neutrino mass m_1 successful thermal leptogenesis can be realised for a real matrix R. In contrast, in the case of IH spectrum and negligible lightest neutrino mass (m_3), the requisite baryon asymmetry was found to be produced for CP-conserving matrix R only if certain elements of R are purely imaginary: for real R the baryon asymmetry Y_B is strongly suppressed and leptogenesis cannot be successful for $M_1 \lesssim 10^{12}$ GeV (i.e. in the regime in which the lepton flavour effects are significant [5,6,7]).

In the present work we have analysed the effects of the lightest neutrino mass on "flavoured" (thermal) leptogenesis. We considered the case when the CP-violation necessary for the generation of the observed baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana CP-violating phases in the PMNS matrix U. Our study is performed within the simplest type I see-saw scenario with three heavy RH Majorana neutrinos N_j, $j = 1, 2, 3$. The latter are assumed to have a hierarchical mass spectrum, $M_1 \ll M_{2,3}$. As a consequence, the generated baryon asymmetry Y_B depends linearly on the mass of N_1, M_1, and on the elements R_{1j} of the matrix R, $j = 1, 2, 3$, present in the neutrino Yukawa couplings of N_1. Throughout the present study we employ the "orthogonal" parametrisation of the matrix of neutrino Yukawa couplings. As was already mentioned previously, this parametrisation involves an orthogonal matrix R, $R^T R = RR^T = \mathbf{1}$. Although, in general, the matrix R can be complex, i.e. CP-violating, in the present work we are primarily interested in the possibility that R conserves the CP-symmetry. We consider the two types of light neutrino mass spectrum allowed by the data [17]: i) with normal ordering ($\Delta m^2_{\rm A} > 0$), $m_1 < m_2 < m_3$, and ii) with inverted ordering ($\Delta m^2_{\rm A} < 0$), $m_3 < m_1 < m_2$. The case of inverted hierarchical (IH) spectrum and real (and CP-conserving) matrix R is investigated in detail.

Our analysis is performed for negligible renormalisation group (RG) running of m_j and of the parameters in the PMNS matrix U from M_Z to M_1. This possibility is realised for sufficiently small values of the lightest neutrino mass $\min(m_j)$ [18,19], e.g., for $\min(m_j) \lesssim 0.10$ eV. The latter condition is fulfilled for the NH and IH neutrino mass spectra, as well as for spectrum with partial hierarchy [20]. Under the indicated condition m_j, and correspondingly $\Delta m^2_{\rm A}$ and $\Delta m^2_{\odot}$, and U can be taken at the scale $\sim M_Z$, at which the neutrino mixing parameters are measured.

2 Light Neutrino Mass Spectrum with Inverted Ordering and Real R_{1j}

The case of inverted hierarchical (IH) neutrino mass spectrum, $m_3 \ll m_1 < m_2$, $m_{1,2} \cong \sqrt{|\Delta m^2_{\rm A}|}$, is of particular interest since, as was already mentioned, for real R_{1j}, $j = 1, 2, 3$, IH spectrum and negligible lightest neutrino mass $m_3 \cong 0$, it is impossible to generate the observed baryon asymmetry $Y_B \cong 8.6 \times 10^{-11}$ in the regime of "flavoured" leptogenesis [12], i.e. for $M_1 \lesssim 10^{12}$ GeV, if the only source of CP violation are the Majorana and/or Dirac phases in the

[c] The case in which CP-violation arises from the combined effect between the "low energy" Majorana and/or Dirac phases in $U_{\rm PMNS}$ and the "high energy" CP-violating phases in a complex orthogonal matrix R, in thermal "flavoured" leptogenesis scenario, has recently been addressed [16].

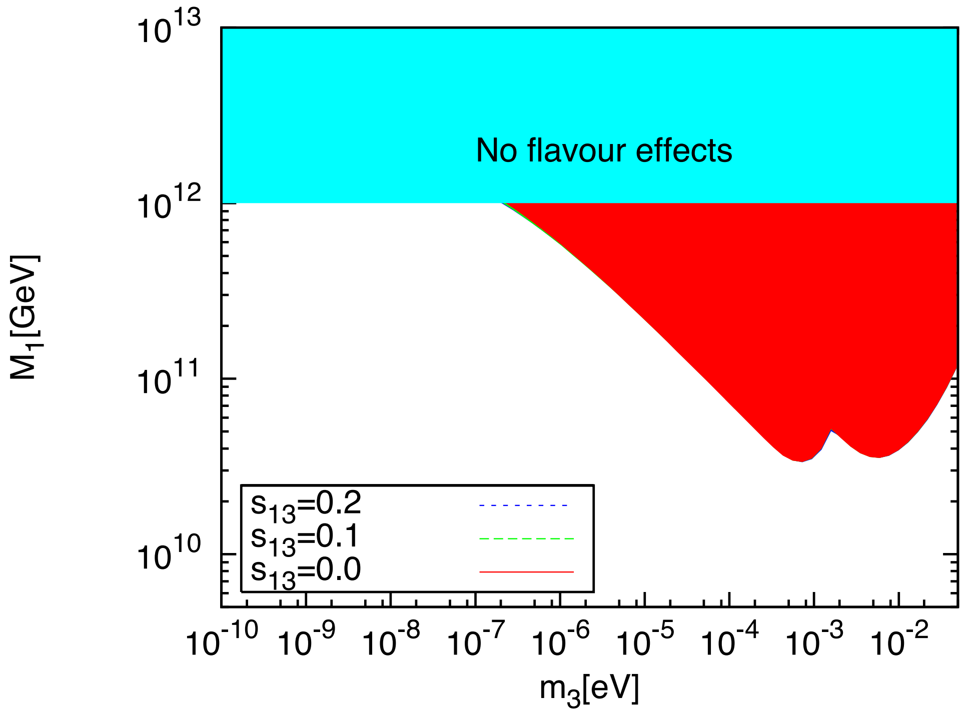

Figure 1: Values of m_3 and M_1 for which the "flavoured" leptogenesis is successful, generating baryon asymmetry $|Y_B| = 8.6 \times 10^{-11}$ (red/dark shaded area). The figure corresponds to hierarchical heavy Majorana neutrinos, light neutrino mass spectrum with inverted ordering (hierarchy), $m_3 < m_1 < m_2$, and real elements R_{1j} of the matrix R. The results shown are obtained using the best fit values of neutrino oscillation parameters: $\Delta m^2_\odot = 8.0 \times 10^{-5}$ eV^2, $\Delta m^2_{\rm A} = 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

PMNS matrix. It can be proved that for $m_3 = 0$ and $R_{13} = 0$, the resulting baryon asymmetry is always suppressed by the factor $\Delta m^2_\odot/(2\Delta m^2_{\rm A}) \cong 1.6 \times 10^{-2}$. We analyse the generation of the baryon asymmetry Y_B for real R_{1j}, $j = 1, 2, 3$, when m_3 is non-negligible. We assume that Y_B is produced in the two-flavour regime, 10^9 GeV $\lesssim M_1 \lesssim 10^{12}$ GeV.

In Fig. 1 we show the correlated values of M_1 and m_3 for which one can have successful leptogenesis in the case of neutrino mass spectrum with inverted ordering and CP-violation due to the Majorana and Dirac phases in $U_{\rm PMNS}$. The figure was obtained by performing, for given m_3 from the interval 10^{-10}eV $\leq m_3 \leq 0.05$ eV, a thorough scan of the relevant parameter space searching for possible enhancement or suppression of the baryon asymmetry with respect to that found for $m_3 = 0$. The real elements of the $R-$matrix of interest, R_{1j}, $j = 1, 2, 3$, were allowed to vary in their full ranges determined by the condition of orthogonality of the matrix R: $R^2_{11} + R^2_{12} + R^2_{13} = 1$. The Majorana phases $\alpha_{21,31}$ were varied in the interval $[0, 2\pi]$. The calculations were performed for three values of the CHOOZ angle θ_{13}, corresponding to $\sin\theta_{13} = 0;\ 0.1;\ 0.2$. In the cases of $\sin\theta_{13} \neq 0$, the Dirac phase δ was allowed to take values in the interval $[0, 2\pi]$. The heavy Majorana neutrino mass M_1 was varied in the interval 10^9 GeV $\leq M_1 \leq 10^{12}$ GeV. For given m_3, the minimal value of the mass M_1, for which the leptogenesis is successful, generating $|Y_B| \cong 8.6 \times 10^{-11}$, was obtained for the values of the other parameters which maximise $|Y_B|$. We have found that in the case of IH spectrum with non-negligible m_3, $m_3 \ll \sqrt{|\Delta m^2_{\rm A}|}$, the generated baryon asymmetry $|Y_B|$ can be strongly enhanced in comparison with the asymmetry $|Y_B|$ produced if $m_3 \cong 0$. The enhancement can be by a factor of ~ 100, or even by a larger factor. As a consequence, one can have successful leptogenesis for IH spectrum with $m_3 \gtrsim 5 \times 10^{-6}$ eV even if the elements R_{1j} of R are real and the requisite CP-violation is provided by the Majorana or Dirac phase(s) in the PMNS matrix. As a consequence, successful thermal leptogenesis is realised for 5×10^{-6} eV $\lesssim m_3 \lesssim 5 \times 10^{-2}$ eV. The results of our analysis show that for Majorana CP-violation from $U_{\rm PMNS}$, successful leptogenesis can be obtained for $M_1 \gtrsim 3.0 \times 10^{10}$ GeV. A somewhat larger values of M_1 are typically required if the CP-violation is due to the Dirac phase δ: $M_1 \gtrsim 10^{11}$ GeV. The requirement of successful "flavoured" leptogenesis in the latter case leads to the following lower limits on $|\sin\theta_{13}\sin\delta|$, and thus on $\sin\theta_{13}$ and on the rephasing invariant $J_{\rm CP}$ which controls the magnitude of CP-violation effects in neutrino oscillations: $|\sin\theta_{13}\sin\delta|, \sin\theta_{13} \gtrsim (0.04 - 0.09)$, $|J_{\rm CP}| \gtrsim (0.009 - 0.020)$, where the precise value of the limit within the intervals given depends on the ${\rm sgn}(R_{11}R_{13})$ (or ${\rm sgn}(R_{12}R_{13})$) and on $\sin^2\theta_{23}$.

The results we have obtained for light neutrino mass spectrum with normal ordering, $m_1 < m_2 < m_3$, can vary significantly if one of the elements R_{1j} is equal to zero. In particular, if $R_{11} \cong 0$, we did not find any significant enhancement of the baryon asymmetry $|Y_B|$, generated within "flavoured" leptogenesis scenario with real matrix R and CP-violation provided by the neutrino mixing matrix $U_{\rm PMNS}$, when the lightest neutrino mass was varied in the interval 10^{-10} eV $\leq m_1 \leq 0.05$ eV. If, however, $R_{12} \cong 0$, the dependence of $|Y_B|$ on m_1 exhibits qualitatively the same features as the dependence of $|Y_B|$ on m_3 in the case of neutrino mass spectrum with inverted ordering (hierarchy), although $\max(|Y_B|)$ is somewhat smaller than in the corresponding IH spectrum cases. As a consequence, it is possible to reproduced the observed value of Y_B if the CP-violation is due to the Majorana phase(s) in $U_{\rm PMNS}$ provided $M_1 \gtrsim 5.3 \times 10^{10}$ GeV.

The analysis we have performed shows that within the thermal "flavoured" leptogenesis scenario, the value of the lightest neutrino mass can have non negligibile effects on the magnitude of the baryon asymmetry of the Universe in the cases of light neutrino mass spectrum with inverted and normal ordering (hierarchy). In particular, as regards the IH spectrum, one can have an enhancement of the baryon asymmetry by a factor of ~ 100 with respect to the value corresponding to $m_3 \cong 0$, thus allowing for the generation of a matter-antimatter asymmetry compatible with the experimental observation.

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