CP Violation and Lightest Neutrino Mass Effects in Thermal Leptogenesis

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Abstract. Effects of the lightest neutrino mass in “flavoured” leptogenesis 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 $U$ are discussed. 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 reviewed.

1. Introduction
We discuss the effects of the lightest neutrino mass in “flavoured” leptogenesis [1, 2] where lepton flavor dynamics [3–8] plays 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 investigation of these effects was performed in reference [10]. We review some of the results obtained in [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 flavor 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 $U_{\text{PMNS}} \equiv U$. In this case the predicted value of 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

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conservethe CP-symmetry if its elements are real or purely imaginary \(^2\). Weremark that for
a CP-conserving matrix \(R\) and at temperatures \(T \sim M_1 \gtrsim 10^{12}\) GeV, the leptonflavours are indistinguishable (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 [5–7]).

In the present article we discuss the effects of the lightest neutrino mass on “flavoured”
(thermal) leptogenesis. We consider 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 \(U\). The results we review correspond to
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 orthogonal parametrisation of neutrino
Yukawa couplings of \(N_1\). As was already mentioned previously, this parametrisation involves an
orthogonal matrix \(R, R^T R = R R^T = 1\). Although, in general, the matrix \(R\) can be complex,
i.e. CP-violating, in [10] we were primarily interested in the possibility that \(R\) conserves the
CP-symmetry. We report results of the two types of light neutrino mass spectrum allowed by the
data [18]: i) with normal ordering \((\Delta m_A^2 > 0), m_1 < m_2 < m_3\), and ii) with inverted ordering
\((\Delta m_A^2 < 0), m_3 < m_1 < m_2\). The case of inverted hierarchical (IH) spectrum and real (and
CP-conserving) matrix \(R\) is reviewed in detail \(^3\).

The analysis in [10] was 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 \(\text{min}(m_j)\) [19,20], e.g., for \(\text{min}(m_j) \lesssim 0.10\)
eV. The latter condition is fulfilled for the NH and IH neutrino mass spectra, as well as for
spectrum with partial hierarchy [21]. Under the indicated condition \(m_j\), and correspondingly
\(\Delta m_A^2\) and \(\Delta m_\odot^2\), and \(U\) can be taken at the scale \(\sim M_Z\), at which the neutrino mixing parameters
are measured.

2. “Low Energy” CP-Violation and CP-Asymmetry in Flavoured Leptogenesis

Following the discussion in [12], we introduce combinations between the elements of the neutrino
mixing matrix \(U\) and the orthogonal matrix \(R\) that appears in the Casas-Ibarra parametrisation
[15] of the matrix of neutrino Yukawa couplings:

\[
P_{jkml} \equiv R_{jk} R_{jm} U_{lk}^* U_{lm}, \quad k \neq m.
\]

If CP-invariance doesn’t hold, then one can easily prove that \(P_{jkml}\) is not a real quantity:

\[
\text{Im}(P_{jkml}) \neq 0.
\]

In the parametrisation of the neutrino Yukawa couplings considered, the condition (2) triggers
CP-violation in the thermal leptogenesis scenario, when the dynamics of the flavour states plays a
role in the generation of the baryon asymmetry of the Universe. In particular, from (1) it is

\(^2\) The more general case in which CP-violation arises from the combined effect between the “low energy” Majorana
and/or Dirac phases in \(U_{\text{PMNS}}\), and the “high energy” CP-violating phases in a complex orthogonal matrix \(R\), in
thermal “flavoured” leptogenesis scenario, was addressed in [16] and [17].

\(^3\) New material, not published in [10], is presented in figures 2 and 3.
possible to understand what is the interplay between the “low energy” CP violation, encoded in the Majorana and/or Dirac phases present in the neutrino mixing matrix \( U \), and the “high energy” CP-violating phases of the matrix \( R \) and to disentangle the two contributions. In the present article we are primarily interested in the situation in which the CP-violation necessary for having successful leptogenesis can arise exclusively from “low energy” physics in the lepton sector. For this reason, we impose the orthogonal matrix \( R \) to satisfy CP-invariance constraints, i.e. all the matrix elements, \( R_{ij} \), are real or purely imaginary. If this is the case, CP-violation, and therefore condition (2), is accomplished through the neutrino mixing matrix \( U \) (“low energy” CP-violation). For real or purely imaginary \( R_{1j}R_{1k} \), \( j \neq k \), the CP-asymmetries \( \epsilon_i \) is given by

\[
\epsilon_i = \frac{3M_1}{16\pi^2} \sum_k \sum_{j>k} \left( m_j - m_k \right) \rho_{jk} |R_{1k}R_{1j}| \text{Im} \left( U_{1i}^* U_{1j} \right), \quad \text{Im} \left( R_{1i} R_{1j} \right) = 0
\]  

(3)

\[
\epsilon_i = -\frac{3M_1}{16\pi^2} \sum_k \sum_{j>k} \left( m_j + m_k \right) \rho_{jk} |R_{1k}R_{1j}| \text{Re} \left( U_{1i}^* U_{1j} \right), \quad \text{Re} \left( R_{1i} R_{1j} \right) = 0
\]  

(4)

with \( R_{1j}R_{1k} = \rho_{jk} |R_{1j}R_{1k}| \) and \( R_{1j}R_{1k} = i\rho_{jk} |R_{1j}R_{1k}| \), \( \rho_{jk} = \pm 1, j \neq k \). Note that, according to condition (2), real (purely imaginary) \( R_{1k}R_{1j} \) and purely imaginary (real) \( U_{1i}^* U_{1j} \), \( j \neq k \), implies violation of CP-invariance by the matrix \( R \) [12]. An interesting possibility is for example when the Dirac phase \( \delta \) and the effective Majorana phases \( \alpha_{31}, \alpha_{21} \) take the CP-conserving values: \( \delta = 0, \alpha_{31} = \pi \) and \( \alpha_{21} = 0 \). Then, for real \( R_{1j} \), \( j = 1, 2, 3 \), condition (2) is fulfilled and the CP-asymmetry \( \epsilon_i \) is different from zero. We say in this case that both the PMNS matrix and the orthogonal matrix are CP-conserving, but the neutrino Yukawa couplings still violate CP-symmetry. More specifically, it is impossible to construct a high energy observable that is sensitive to CP-symmetry breaking and depends only on the matrix \( R \). The only possibility to break the symmetry at high energy scales is to couple the matrix \( R \) to the PMNS neutrino mixing matrix, as in \( \epsilon_i \).

In order for the CP-symmetry to be broken at low energies, we should have both \( \text{Re}(U_{1k}^* U_{1j}) \neq 0 \) and \( \text{Im}(U_{1k}^* U_{1j}) \neq 0 \) (see [12] for further details on this point).

3. Light Neutrino Mass Spectrum with Inverted Ordering and Real \( R_{1j} \)

The case of inverted hierarchical (IH) neutrino mass spectrum, \( m_3 \ll m_1 < m_2, \ m_{1,2} \simeq \sqrt{\Delta m^2_{\odot}} \), is of particular interest since, as was already mentioned, for real \( R_{1j} \), \( j = 1, 2, 3 \), IH spectrum and negligible lightest neutrino mass \( m_3 \approx 0 \), it is impossible to generate the observed baryon asymmetry \( Y_B \approx 8.6 \times 10^{-11} \) 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 PMNS matrix. It can be proven that for \( m_3 = 0 \) and \( R_{13} = 0 \), the resulting baryon asymmetry is always suppressed by the factor \( \Delta m^2_{\odot}/(2\Delta m^2_{\odot}) \simeq 1.6 \times 10^{-2} \). 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, \( 10^9 \text{ GeV} \lesssim M_1 \lesssim 10^{12} \) GeV. Under these conditions the terms \( \propto \sqrt{m_3} \) in \( \epsilon_i \) will be dominant provided [12]

\[
2 \left( \frac{m_3}{\sqrt{\Delta m^2_{\odot}}} \right)^2 \left( \frac{\Delta m^2_{\odot}}{\Delta m^2_{\odot}} \right)^2 \frac{|R_{13}|}{|R_{11(12)}|} \gg 1.
\]  

(5)

This condition can be easily satisfied if \( R_{11} \rightarrow 0 \), or \( R_{12} \rightarrow 0 \), and if \( m_3 \) is sufficiently large. The neutrino mass spectrum is still hierarchical for \( m_3 \) having a value \( m_3 \lesssim 5 \times 10^{-3} \text{ eV} \ll \sqrt{|\Delta m^2_{\odot}|} \). The general analysis is performed for values of \( m_3 \) from the interval \( 10^{-10} \text{ eV} \lesssim m_3 \lesssim 5 \times 10^{-2} \text{ eV} \).

\[ We use the standard parametrisation of the PMNS matrix as defined in [12].
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 $R_{ij}$ 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$^2$, $\Delta m^2_{A} = 2.5 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

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 $U_{PMNS}$. 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, $R_{ij}$, $j = 1, 2, 3$, 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 $\theta_{13}$, corresponding to $\sin \theta_{13} = 0; 0.1; 0.2$. In the cases of $\sin \theta_{13} \neq 0$, the Dirac phase $\delta$ 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 $m_3$, $m_3 \ll \sqrt{|\Delta m^2_{A}|}$, the generated baryon asymmetry $|Y_B|$ can be strongly enhanced in comparison with the asymmetry $|Y_B|$ produced if $m_3 \approx 0$. The enhancement can be by a factor of $\sim 100$, 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 $R_{ij}$ 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 $5 \times 10^{-6}$ eV $\lesssim m_3 \lesssim 5 \times 10^{-2}$ eV. The results of our analysis show that for Majorana CP-violation from $U_{PMNS}$, successful
 leptogenesis can be obtained for $M_1 \gtrsim 3.0 \times 10^{10}$ GeV. Larger values of $M_1$ are typically required if the CP-violation is due to the Dirac phase $\delta$: $M_1 \gtrsim 10^{11}$ 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 $J_{\text{CP}}$ which controls the magnitude of CP-violation effects in neutrino oscillations: $|\sin \theta_{13} \sin \delta|, |\sin \theta_{13} \gtrsim (0.04 - 0.09), |J_{\text{CP}}| \gtrsim (0.009 - 0.020)$, where the precise value of the limit within the intervals given depends on the sign($R_{11}R_{13}$) and on $\sin^2 \theta_{32}$.

In Fig 2 the dependence of the generated baryon asymmetry with respect to the Majorana phase $\alpha_{31}$ is reported. The case analysed corresponds to the limit $R_{12} \cong 0$, for which condition (5) is fulfilled and the lightest neutrino mass $m_3$ gives an important contribution to the corresponding CP-asymmetry in the range $5 \times 10^{-6}$ eV $\lesssim m_3 \lesssim 5 \times 10^{-2}$ eV. The neutrino mixing angle $\theta_{13}$ is set to zero and no CP-violation arising from the Dirac phase is assumed. The values of $m_3$ and $|R_{11}|$ are computed in order to maximise the baryon asymmetry $|Y_B|$ at $\alpha_{31} = \pi/2$ for the two possible choices: $\text{sign}(R_{11}R_{13}) = \pm 1$.

The case in which the observed baryon asymmetry arises from the CP-violating contribution of the Dirac phase $\delta$ is presented in the two plots in Fig 3. We set $\sin \theta_{13} = 0.2$ and $R_{11} \cong 0$, $R_{12} \cong 0$ in the left and right panel, respectively. The effective Majorana phase is CP-conserving in both cases. The values of the lightest neutrino mass and the elements $|R_{1j}|$, $j = 1, 2$, are chosen in such a way as to maximise the baryon asymmetry $|Y_B|$. We remark that a value of $\delta \neq 0, \pi$, Majorana CP-conserving phases $\alpha_{31} = \pi$ and $\alpha_{21} = 0$ and real matrix $R$ imply “low energy” CP-violation due to the neutrino mixing matrix, but a “high energy” contribution associated with the matrix $R$ is still present, as already discussed in section 2. For this reason we didn’t consider this possibility in the reported results.

4. Light Neutrino Mass Spectrum with Normal Ordering and Real $R_{1j}$
A light neutrino mass spectrum with normal ordering (hierarchy) gives very different predictions with respect to the previous one. The case of negligible $m_1$ and real (CP-conserving) elements

Figure 2. The dependence of $|Y_B|$ on $\alpha_{31}$ (Majorana CP-violation), in the case of IH spectrum, real $R_{1j}R_{1k}$, $R_{12} = 0$, $s_{13} = 0$, $M_1 = 10^{11}$ GeV, and for i) $|R_{11}| = 0.18$, $m_3 = 5.6 \times 10^{-3}$ eV, sign($R_{11}R_{13}$) = $+1$ (left panel), and ii) $|R_{11}| = 0.48$, $m_3 = 9.3 \times 10^{-3}$ eV, sign($R_{11}R_{13}$) = $-1$ (right panel). The values of $m_3$ and $|R_{11}|$ used maximise $|Y_B|$ at $\alpha_{31} = \pi/2$. The horizontal dotted lines indicate the allowed range of $|Y_B|$ $(8.0 - 9.2) \times 10^{-11}$. 
The dependence of $|Y_B|$ on $\delta$ (Dirac CP-violation), in the case of IH spectrum, real $R_{ij}R_{ik}$, $s_{13} = 0.2$ and for i) $M_1 = 3 \times 10^{11}$ GeV, $\alpha_{32} \equiv \alpha_{31} - \alpha_{21} = 0$, $R_{11} = 0$, $|R_{12}| = 0.29$, $m_3 = 6.7 \times 10^{-3}$ eV, sign$(R_{12}R_{13}) = -1$ (left panel), and ii) $M_1 = 5 \times 10^{11}$ GeV, $\alpha_{31} = 0$, $R_{12} = 0$, $|R_{11}| = 0.22$, $m_3 = 8.6 \times 10^{-3}$ eV, sign$(R_{11}R_{13}) = +1$ (right panel). The values of $m_3$ and $|R_{1j}|$, $j = 1, 2$, used maximise $|Y_B|$ at $\delta = \pi/2$. The horizontal dotted lines indicate the allowed range of $|Y_B| = (8.0 - 9.2) \times 10^{-11}$.

Figure 3. The dependence of $|Y_B|$ on $\delta$ (Dirac CP-violation), in the case of IH spectrum, real $R_{ij}R_{ik}$, $s_{13} = 0.2$ and for i) $M_1 = 3 \times 10^{11}$ GeV, $\alpha_{32} \equiv \alpha_{31} - \alpha_{21} = 0$, $R_{11} = 0$, $|R_{12}| = 0.29$, $m_3 = 6.7 \times 10^{-3}$ eV, sign$(R_{12}R_{13}) = -1$ (left panel), and ii) $M_1 = 5 \times 10^{11}$ GeV, $\alpha_{31} = 0$, $R_{12} = 0$, $|R_{11}| = 0.22$, $m_3 = 8.6 \times 10^{-3}$ eV, sign$(R_{11}R_{13}) = +1$ (right panel). The values of $m_3$ and $|R_{1j}|$, $j = 1, 2$, used maximise $|Y_B|$ at $\delta = \pi/2$. The horizontal dotted lines indicate the allowed range of $|Y_B| = (8.0 - 9.2) \times 10^{-11}$.

$R_{ij}$ of $R$ was analysed in detail in [12]. In searching for possible significant effects of non-negligible $m_1$ in leptogenesis we have considered values of $m_1$ as large as 0.05 eV, $m_1 \leq 0.05$ eV. For $3 \times 10^{-3}$ eV $\lesssim m_1 \lesssim 0.10$ eV, the neutrino mass spectrum is not hierarchical; the spectrum exhibits partial hierarchy (see, e.g. [21]), i.e. we have $m_1 < m_2 < m_3$.

These results are illustrated in Fig. 4, showing the correlated values of $M_1$ and $m_1$ for which one can have successful leptogenesis. The figure was obtained using the same general method of analysis we have employed to produce Fig. 1. For given $m_1$ from the interval $10^{-10} \leq m_1 \leq 0.05$ eV, a thorough scan of the relevant parameter space was performed in the calculation of $|Y_B|$, searching for possible non-standard features (enhancement or suppression) of the baryon asymmetry. The real elements $R_{ij}$ of interest of the matrix $R$, were allowed to vary in their full ranges determined by the condition of orthogonality of $R$: $R_{11}^2 + R_{12}^2 + R_{13}^2 = 1$. The Majorana and Dirac phases $\alpha_{21,31}$ and $\delta$ were varied in the interval $[0, 2\pi]$. The calculations were performed again for three values of the CHOOZ angle, $\sin \theta_{13} = 0$; 0.1; 0.2. The relevant heavy Majorana neutrino mass $M_1$ was varied in the interval $10^9$ GeV $\lesssim M_1 \lesssim 10^{12}$ GeV.

For given $m_1$, the minimal value of the mass $M_1$, for which the leptogenesis is successful generating $Y_B \approx 8.6 \times 10^{-11}$, was obtained for the values of the other parameters which maximise $|Y_B|$. The min$(M_1)$ thus calculated did not show any significant dependence on $s_{13}$. For $m_1 \approx 7.5 \times 10^{-3}$ eV we did not find any noticeable effect of $m_1$ in leptogenesis: the results we have obtained practically coincide with those corresponding to $m_1 = 0$ and derived in [12]. For $7.5 \times 10^{-3}$ eV $\lesssim m_1 \lesssim 5 \times 10^{-2}$ eV the predicted baryon asymmetry $Y_B$ for given $M_1$ is generically smaller with respect to the asymmetry $Y_B$ one finds for $m_1 = 0$. Thus, successful leptogenesis is possible for larger values of min$(M_1)$. The corresponding suppression factor increases with $m_1$ and for $m_1 \approx 5 \times 10^{-2}$ eV values of $M_1 \gtrsim 10^{11}$ GeV are required.

The results we have obtained for light neutrino mass spectrum with normal ordering can vary significantly if one of the elements $R_{1ij}$ is equal to zero. In particular, if $R_{11} \approx 0$, we did not find any significant enhancement of the baryon asymmetry $|Y_B|$, generated within “flavoured”
Figure 4. 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$^2$, $\Delta m^2_A = 2.5 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

leptogenesis scenario with real matrix $R$ and CP-violation provided by the neutrino mixing matrix $U_{\text{PMNS}}$, when the lightest neutrino mass was varied in the interval $10^{-10}$ eV $\leq m_1 \leq 0.05$ eV. If, however, $R_{12} \approx 0$, 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 (see [10] for a detailed discussion on this point). As a consequence, it is possible to reproduce the observed value of $Y_B$ if the CP-violation is due to the Majorana phase(s) in $U_{\text{PMNS}}$ provided $M_1 \gtrsim 5.3 \times 10^{10}$ GeV.

5. Conclusions
The analysis we have performed in [10] shows that within the thermal “flavoured” leptogenesis scenario, the value of the lightest neutrino mass can have non negligible 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 $\sim 100$ with respect to the value corresponding to $m_3 \approx 0$, thus allowing for the generation of a matter-antimatter asymmetry compatible with the experimental observation.

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