On the Interplay between “High” and “Low” Energy CP Violation in Flavoured Leptogenesis

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Abstract. The possible interplay in “flavoured” leptogenesis between the “low energy” CP violation originating from the PMNS neutrino mixing matrix \( U \), and the “high energy” CP-violation which can be present in the matrix of neutrino Yukawa couplings, \( \lambda \), and can manifest itself only in “high” energy scale processes, is discussed. The results reported are obtained for type I see-saw model with three heavy right-handed Majorana neutrinos having hierarchical spectrum. It is shown that in the case of inverted hierarchical light neutrino mass spectrum, there exist regions in the corresponding leptogenesis parameter space where the relevant “high energy” phases have large CP-violating values, but the purely “high energy” contribution in \( Y_B \) plays a sub-dominant role in the production of baryon asymmetry compatible with the observations.

1. Introduction
There are three possible regimes of creation of the baryon asymmetry in the leptogenesis scenario [1–6] of generation of the matter-antimatter asymmetry of the Universe. At temperatures \( T > 10^{12} \) GeV, the lepton flavours (individual lepton charges) are indistinguishable and the one flavour approximation is valid. For \( 10^9 \) GeV \( \lesssim T \lesssim 10^{12} \) GeV, the Boltzmann evolution of the CP-asymmetry \( \epsilon_\tau \) in the \( \tau \)-flavour (lepton charge \( L_\tau \) of the Universe) is distinguishable from the evolution of the CP-asymmetry in the \( (e + \mu) \)-flavour (or lepton charge \( L_e + L_\mu \)), \( \epsilon_e + \epsilon_\mu \). This corresponds to the so-called “two-flavour regime” 2. At smaller temperatures, \( T \lesssim 10^9 \) GeV, the evolution of the \( \mu \)-flavour (lepton charge \( L_\mu \)) and of \( \epsilon_\mu \) also become distinguishable (three-flavour regime). The produced baryon asymmetry is a sum of the relevant CP-violating asymmetries in each of the three lepton flavours \( e, \mu \) and \( \tau \) (or lepton charges \( L_e, L_\mu \) and \( L_\tau \)), each weighted by the corresponding efficiency factor accounting for the wash-out processes.

In the regime in which the lepton flavour effects in leptogenesis are significant (“flavoured” leptogenesis), the CP-violation necessary for the generation of the observed matter-antimatter asymmetry can be provided exclusively [7] by the Dirac and/or Majorana [9] CP-violating phases in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix [10] \( U \). In the case of three hierarchical heavy right-handed (RH) Majorana neutrinos \( N_j, j = 1,2,3 \), and CP violation (CPV) due to the Majorana phases in \( U \), this typically requires that the mass of the lightest RH Majorana neutrino, \( N_1 \), satisfies \( M_1 \gtrsim 4 \times 10^{10} \) GeV [7]. One can have successful leptogenesis

1 Presented by S T Petcov.
2 As was suggested in [7] and confirmed in the more detailed study [8], in the two-flavour regime of leptogenesis the flavour effects are fully developed at \( M_1 \lesssim 5 \times 10^{11} \) GeV.
also if the only source of CP-violation is the Dirac phase $\delta$ in $U$, provided $|\sin \theta_{13} \sin \delta| \geq 0.09$, $\theta_{13}$ being the CHOOZ angle. In thermal leptogenesis with “hierarchical” spectrum of the heavy Majorana neutrinos $N_j$, CPV lepton asymmetry is produced in out-of-equilibrium lepton number and CP-nonconserving decays of the lightest one, $N_1$. The lepton asymmetry is converted into a baryon asymmetry by $(B-L)$-conserving but $(B+L)$-violating sphaleron interactions [2].

The CP-violation necessary for the generation of the baryon asymmetry $Y_B$ in “flavoured” leptogenesis can arise both from the “low energy” neutrino mixing matrix $U$ and/or from the “high energy” part of the matrix of neutrino Yukawa couplings, $\lambda$, which can mediate CP-violating phenomena only at some high energy scale. In the orthogonal parametrisation [11], the “high energy” part of $\lambda$ is represented by a complex orthogonal matrix $R$, $R R^T = R^T R = 1$:

\[
\lambda = v^{-1} \sqrt{M} R \sqrt{\mu} \dagger,
\]

where $M$ and $m$ are diagonal matrices formed by the masses of $N_j$ and of the light Majorana neutrinos $\nu_j$, $M \equiv \text{Diag}(M_1, M_2, M_3)$, $m \equiv \text{Diag}(m_1, m_2, m_3)$, $M_j > 0$, $m_\nu \geq 0$, and $v = 174$ GeV is the vacuum expectation value of the Higgs doublet field. The matrix $R$, as is well-known, does not affect the “low” energy neutrino mixing phenomenology.

Here we review some of the results derived in [12, 13] on the possible interplay in “flavoured” leptogenesis between contributions in $Y_B$ due to the “low energy” and “high energy” CP violation, originating from the PMNS matrix $U$ and the $R$-matrix, respectively. We consider the case of light Majorana neutrinos with inverted hierarchical (IH) spectrum $^3$ (see, e.g. [14]), $m_3 \ll m_{1,2} \equiv \sqrt{|\Delta m^2_{ij}|} \approx 0.05$ eV. It was shown in [12,13] that if the light Majorana neutrinos possess IH mass spectrum, there exist significant regions of the corresponding leptogenesis parameter space where the relevant “high energy” $R$–phases have large CP-violating values, but the purely “high energy” contribution in $Y_B$ plays a sub-dominant role in the production of baryon asymmetry compatible with the observations. The requisite dominant term in $Y_B$ can arise due to the “low energy” CP-violation in the neutrino mixing matrix $U$. In some of these regions the “high energy” contribution in $Y_B$ is so strongly suppressed that one can have successful leptogenesis only if the requisite CP-violation is provided by the Majorana CP-violating phase(s) in $U$.

2. Baryon Asymmetry from “Low” and “High” Energy CP Violation: a Case of Subdominant “High” Energy Contribution

Consider the simplest leptogenesis scenario based on the type I see-saw model with three heavy right-handed Majorana neutrinos having hierarchical mass spectrum. Suppose that the baryon asymmetry $Y_B$ is produced in the “two-flavour” regime in leptogenesis [5, 6]. This regime is realised at temperatures $10^9$ GeV \(\lesssim T \sim M_1 \lesssim 10^{12}$ GeV. Under the assumptions made, $|Y_B|$ generated via thermal leptogenesis can be written as [5,6]

\[
|Y_B| \approx 3 \times 10^{-3} |\epsilon \eta(0.66 \bar{m}_{\tau}) + \epsilon_2 \eta(0.71 \bar{m}_2)|,
\]

where $\epsilon_2 \equiv \epsilon_e + \epsilon_\mu$, $\epsilon_l$ being the CPV asymmetry in the $l$ flavour (lepton charge) produced in $N_1$-decays $^4$, $l = e, \mu, \tau$, and $\eta(0.66 \bar{m}_{\tau})$ and $\eta(0.71 \bar{m}_2)$ are the corresponding efficiency factors [6], $\bar{m}_{2, \tau}$ being the associated wash-out mass parameters $^5$, $\bar{m}_2 = \bar{m}_\mu + \bar{m}_\tau$,

\[
\bar{m}_l = \sum_j m_j R_{1j} U_{lj}^* |^2.
\]

$^3$ For a detailed analysis of the case of normal hierarchical spectrum see [12], were results for the IH spectrum were also presented.

$^4$ The expression for $Y_B$ we have given is normalised to the entropy density, see, e.g. [7].

$^5$ Approximate analytic expression for $\eta(\bar{m})$ is given in [6].
For complex $R$ we have:

$$\epsilon_r = -\frac{3M_1}{16\pi v^2} \frac{\text{Im}(\sum_{jk} m_{1j}^{1/2} m_k^{3/2} U_{j2}^* U_{rk} R_{ij} R_{ik})}{\sum_i |m_i R_{1i}|^2}.$$  

In what follows we use the standard parametrisation of the 3-neutrino mixing matrix:

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix} \text{diag}(1, e^{i\phi_{21}}, e^{i\phi_{31}})$$

where $c_{ij} \equiv \cos \theta_{ij}$, $s_{ij} \equiv \sin \theta_{ij}$, $\theta_{ij} = \{0, \pi/2\}$, $\delta = \{0, 2\pi\}$ is the Dirac CP-violating phase and $\alpha_{21}$ and $\alpha_{31}$ are the two Majorana CPV phases [9]. All numerical results discussed below are obtained for the best fit values of the solar and atmospheric neutrino oscillation parameters [15–17]: $\Delta m^2_{21} = 7.65 \times 10^{-5} \text{ eV}^2$, $\sin^2 \theta_{12} = 0.30$, $|\Delta m^2_{31}| = |\Delta m^2_{32}| = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{23} = 1$. The 3$\sigma$ limit on $\sin^2 \theta_{13}$, $\sin^2 \theta_{13} < 0.056$, is taken into account as well.

We shall discuss next some of the results obtained in [13]. Consider the case of IH spectrum, $m_3 \ll m_1 < m_2$, $m_{12} \equiv (|\Delta m^2_{31}|)^{1/2}$. Suppose for simplicity that $m_3=0$, and $R_{13}=0$ ($N_3$ decoupling). Suppose further that $R_{11(12)} = |R_{11(12)}| e^{i\varphi_{11(12)}}$ are complex and that $\delta = 0, \pi$. Under the conditions of $m_3=0$ and $\delta = 0, \pi$, the “low energy” CPV can only be due to the Majorana phase $\alpha_{21}$. The $R$-phases $\varphi_{11,12}$ will be a source of “high energy” CPV if $\varphi_{11,12} \neq k\pi/2$, $k=0,1,\ldots$. Using the orthogonality condition $R^2_{11} + R^2_{12} = 1$, it is possible to express $\varphi_{11,12}$ in terms of $|R_{11(12)}|^2$ [12, 13):

$$\cos 2\varphi_{11} = \frac{1 + |R_{11}|^4 - |R_{12}|^4}{2|R_{11}|^2},$$

$$\cos 2\varphi_{12} = \frac{1 - |R_{11}|^4 + |R_{12}|^4}{2|R_{12}|^2},$$

with $\text{sgn}(\sin 2\varphi_{11}) = -\text{sgn}(\sin 2\varphi_{12})$. The CP-violating asymmetry $\epsilon_r$ in the case considered is given by:

$$\epsilon_r \approx -\frac{3M_1}{16\pi v^2} \frac{\sqrt{\Delta m^2_{31}}}{|R_{11}|^2 + |R_{12}|^2} \left( |R_{11}|^2 \sin(2\varphi_{11}) \left( |U_{\tau\tau}|^2 - |U_{\tau\tau}|^2 \right) - \frac{\Delta m^2_{31}}{\Delta m^2_{31}} |U_{\tau\tau}|^2 \right)$$

$$+ \frac{|R_{11}||R_{12}|}{2} \left[ \frac{\Delta m^2_{31}}{\Delta m^2_{31}} \cos(\varphi_{11} + \varphi_{12}) \text{Im}(U_{\tau\tau}^* U_{\tau\tau}) + 2 \sin(\varphi_{11} + \varphi_{12}) \text{Re}(U_{\tau\tau}^* U_{\tau\tau}) \right]$$

For $\varphi_{11} = k\pi/2$, $\varphi_{12} = k'\pi/2$, $k, k' = 0, 1, 2, \ldots$, $R_{11}$ and $R_{12}$ are either real or purely imaginary and the expression for $\epsilon_r$ reduces to the one derived in [7]. Under these conditions we can have successful leptogenesis for $R_{13} = 0$ in the case considered only if $R_{11} R_{12}$ is purely imaginary, i.e. if $|\sin(\varphi_{11} + \varphi_{12})| = 1$, the requisite CP-violation being provided exclusively by the Majorana or Dirac phases in the PMNS matrix [7]. We remind the reader that i) the $R$-matrix will satisfy the CP-invariance constraint if its elements $R_{ij}$ are real or purely imaginary, 6 and ii) in order to have CP-violation, e.g. only due to the Majorana phase $\alpha_{21}$ in $U$, both $\text{Im}(U_{\tau\tau}^* U_{\tau\tau})$ and $\text{Re}(U_{\tau\tau}^* U_{\tau\tau})$ should be different from zero [18, 19], while the Dirac phase $\delta$ should have a CP-conserving value, $\delta = k\pi$, $k = 0, 1, 2, \ldots$ (i.e., the rephasing invariant $J_{CP}$ associated with $\delta$ [20] should satisfy $J_{CP} = 0$). Let us note also that purely imaginary $R_{11} R_{12}$, i.e. $|\sin(\varphi_{11} + \varphi_{12})| = 1$, and

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6 For the precise form of the CP-invariance constraint on the elements $R_{ij}$ of the $R$-matrix see [7].
Re($U_{13}^* U_{23}$) = 0, $J_{CP} = 0$, corresponds to the case of CP-invariance and $\epsilon_\tau = 0$. However, purely imaginary $R_{11} R_{12}$ and $J_{CP} = 0$, Im($U_{13}^* U_{23}$) = 0, but Re($U_{13}^* U_{23}$) $\neq$ 0 (i.e. $\delta = k \pi$, $\alpha_{21} = 2 \pi q$, $k, q = 0, 1, 2, \ldots$), corresponds to CP-violation due to the neutrino Yukawa couplings, i.e. due to the combined effect of the matrix $R$ and of the PMNS matrix $U$ [7], and $\epsilon_\tau \neq 0$. It is interesting that in this case both the $R$-matrix and the PMNS matrix $U$ satisfy the CP-invariance constraints (having real and/or purely imaginary elements), while the neutrino Yukawa couplings do not satisfy these constraints. As a consequence, under the indicated conditions i) there will be no CP-violation effects caused by PMNS matrix $U$ in the low energy neutrino mixing phenomena (neutrino oscillations, neutrinoless double beta decay, etc.), and ii) there will be no CP-violation effects in the “high energy” phenomena which depend only on the matrix $R$ (i.e. do not depend on the PMNS matrix $U$).

The analysis in [13] was performed actually under the following much weaker conditions: $|R_{13}|^2 |\sin 2 \varphi_{13}| \ll \min(|R_{11}|^2 |\sin 2 \varphi_{11}|, |R_{12}|^2 |\sin 2 \varphi_{12}|)$, and sufficiently small $m_3$, so that the terms $\propto m_3 |R_{13}|^2$ and $\propto m_3^2 |R_{13}|^2$ in the asymmetries $\epsilon_2$ and $\epsilon_\tau$ and in the wash-out mass parameters $\tilde{m}_\tau$ and $\tilde{m}_2$, are negligible. The first condition is satisfied even if $R_{13}^2$ is not zero, but is just real, i.e. if Im($R_{13}^2$) = 0. The second condition is naturally satisfied in the case of IH spectrum. Here we report results corresponding to $m_3 = 0$ and $R_{13} = 0$.

For the IH light neutrino mass spectrum under discussion, the following relation holds [13]: $\epsilon_2 = -\epsilon_\tau + O(\Delta m_{23}^2/|\Delta m_{31}^2|)$. Thus, the baryon asymmetry $Y_\beta$ can be written as a function of $\epsilon_\tau$ only, like in the case of the matrix $R$ satisfying the CP-invariance constraints [7]:

$$
Y_\beta \approx \frac{-12 \epsilon_\tau}{37 g_*} \left( \eta \left( \frac{390}{589} m_\tau^2 \right) - \eta \left( \frac{417}{589} \tilde{m}_2 \right) \right)
$$

$$
\equiv Y_\beta^0 (A_{HE} + A_{MIX})
$$

(8)

where $A_{HE(MIX)} \equiv C_{HE(MIX)} (\eta(0.66 \tilde{m}_\tau) - \eta(0.71 \tilde{m}_2))$, $\eta(0.66 \tilde{m}_\tau)$ and $\eta(0.71 \tilde{m}_2)$) being the

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Note that this relation is valid not only for $R_{13} = 0$, but also for nonzero real $R_{13}$, $R_{13} \neq 0$, Im($R_{13}^2$) = 0.
efficiency factors for the asymmetries $\epsilon_\tau$ and $\epsilon_2$ (see [5,6]), and

\[ Y_B^0 \approx 3 \times 10^{-10} \left( \frac{M_1}{10^9 \text{ GeV}} \right) \left( \frac{\sqrt{\Delta m^2_{\text{ew}}}}{5 \times 10^{-2} \text{ eV}} \right), \tag{9} \]

\[ C_{\text{HE}} = G_{11} \sin 2\varphi_{11} \left[ |U_{\tau 1}|^2 - |U_{\tau 2}|^2 \right], \tag{10} \]

\[ C_{\text{MIX}} \approx 2 G_{12} \sin(\varphi_{11} + \varphi_{12}) \Re(U_{\tau 1}^* U_{\tau 2}), \tag{11} \]

where $G_{11} \equiv |R_{11}|^2/(|R_{11}|^2 + |R_{12}|^2)$, $G_{12} \equiv |R_{11} R_{12}|/(|R_{11}|^2 + |R_{12}|^2)$ and we have neglected the contributions proportional to the factor $0.5 \Delta m^2_{\text{ew}}/|\Delta m^2_{\text{ew}}| \approx 0.016$ in the CP-asymmetry $\epsilon_\tau$. In Eq. (8), $Y_B^0 A_{\text{HE}}$ is the “high energy” term which vanishes in the case of a CP-conserving matrix $R$, while $Y_B^0 A_{\text{MIX}}$ is a “mixed” term which, in contrast to $Y_B^0 A_{\text{HE}}$, does not vanish when $R$ conserves CP: it includes the “low energy” CP-violation, e.g. due to the Majorana phase $\alpha_{21}$ in the neutrino mixing matrix. We recall that the phase $\alpha_{21}$ enters also into the expression for the neutrinoless double beta decay effective Majorana mass in the case of IH light neutrino mass spectrum [21]. In order to have CP-violation due to the Majorana phase $\alpha_{21}$, both $\Im(U_{\tau 1}^* U_{\tau 2})$ and $\Re(U_{\tau 1}^* U_{\tau 2})$ should be different from zero [18, 19].

The interplay between the CP-violation arising from the “high energy” phases of the matrix $R$ and the “low energy” CP-violating Dirac and/or Majorana phases in the neutrino mixing matrix, as well as the relative contributions of the “high energy” and the “mixed” terms $Y_B^0 A_{\text{HE}}$ and $Y_B^0 A_{\text{MIX}}$ in $Y_B$, have been studied in [12,13] using the formalism described above. It was found in [12,13] that there exist relatively large regions of the corresponding leptogenesis parameter space where the “high energy” contribution to $Y_B$ is subdominant, or even strongly suppressed. Below we discuss briefly one specific example of such a suppression for $R_{12} = 0$, which can take place even when the “high energy” $R$-phases possess large CP-violating values. In this case the asymmetry $\epsilon_\tau$ is produced in the regime of mild wash-out ($\tilde{m}_\tau \approx (1 - 3) \times 10^{-3} \text{ eV}$), while the asymmetry $\epsilon_2$ is generated with strong wash-out effects (see, e.g. [5,6]). In both cases one has $\epsilon_2 = -\epsilon_\tau + O(\Delta m^2_{\text{ew}}/|\Delta m^2_{\text{ew}}|)$. Under these conditions the two-flavour regime in leptogenesis is realised typically for $M_1 \lesssim 5 \times 10^{11} \text{ GeV}$. Consider the term $Y_B^0 A_{\text{HE}}$. One can convince oneself that for sufficiently large $\theta_{13}$, $Y_B^0 A_{\text{HE}}$ depends in a crucial way on the Dirac phase $\delta$ through the following combination of the elements of the neutrino mixing matrix [12,13]:

\[ |U_{\tau 1}|^2 - |U_{\tau 2}|^2 \approx (s_{12}^2 - c_{12}^2)s_{23}^2 - 4 s_{12} c_{12} s_{23} c_{23} s_{13} \cos \delta \]

\[ \approx -0.20 - 0.92 s_{13} \cos \delta, \tag{12} \]

where we have used $s_{12}^2 = 0.30$ and $s_{23}^2 = 0.5$. Indeed, for, e.g. $s_{13} = 0.2$ and the Dirac phase assuming the CP-conserving value $\delta = \pi$, we get $(|U_{\tau 1}|^2 - |U_{\tau 2}|^2) \approx -0.016$. At the same time we have $|Y_B^0 A_{\text{MIX}}| \propto |U_{\tau 1}^* U_{\tau 2}| \approx 0.27$. As a consequence, if the Majorana phase $\alpha_{21}$ has a sufficiently large CP-violating value, the contribution of $|Y_B^0 A_{\text{MIX}}|$ to $|Y_B|$ can be by an order of magnitude bigger than the contribution of the “high energy” term $|Y_B^0 A_{\text{HE}}|$. Actually, for $s_{12}^2 = 0.30$ and $s_{23}^2 = 0.5$, the “high energy” term in $Y_B$ will be strongly suppressed by the factor $(|U_{\tau 1}|^2 - |U_{\tau 2}|^2)$ if $(- \sin \theta_{13} \cos \delta) \gtrsim 0.15$, independently of the values of the “high energy” phases $\varphi_{11}$ and $\varphi_{12}$. Even if the latter assume large CP-violating values, the purely “high energy” contribution to $Y_B$ would play a sub-dominant role in the generation of the baryon asymmetry compatible with the observations if the above inequality holds. For $(- \sin \theta_{13} \cos \delta) > 0.17$ and $M_1 \lesssim 5 \times 10^{11} \text{ GeV}$, the observed value of the baryon asymmetry cannot be generated by the
“high energy” term $Y_{B}^{0}A_{\text{HE}}$ alone. One can have successful leptogenesis in this case only if there is an additional dominant contribution in $Y_{B}$ due to the CP-violating Majorana phase $\alpha_{21}$ in the PMNS matrix. This result is valid [13] in the whole range of variability of the parameter $|R_{12}|$, $|(1-|R_{11}|^{2})| \leq |R_{12}|^{2} \leq (1+|R_{11}|^{2})$, and for $|R_{11}|$ having values in the interval $0.3 \lesssim |R_{11}| \lesssim 1.2$. For values of $|R_{11}|$ outside the indicated interval we cannot have successful leptogenesis in the two-flavour regime for $M_{1} \lesssim 5 \times 10^{11}$ GeV. For the $3\sigma$ allowed values of $s_{12}^{2} = 0.38$ and $s_{23}^{2} = 0.36$, the same conclusion is valid if $0.06 \lesssim (-\sin \theta_{13} \cos \delta) \lesssim 0.12$. The values of $\sin \theta_{13}$ and $\sin \theta_{13} \cos \delta$, for which we can have the discussed strong suppression $^8$ of $Y_{B}^{0}A_{\text{HE}}$, can be probed by the Double CHOOZ and Daya Bay reactor neutrino experiments [24,25] and by the planned accelerator experiments on CP violation in neutrino oscillations [26].

The results in the case discussed above are illustrated in Fig. 1, where we show the dependence of $|Y_{B}^{0}A_{\text{HE}}|$, $|Y_{B}^{0}A_{\text{MIX}}|$ and $|Y_{B}|$ on $|R_{12}|$ for a fixed value of $|R_{11}| = 0.7 (R_{13} = 0)$ and $\alpha_{21} = \pi/2$, $s_{13} = 0.2, (-s_{13} \cos \delta) = 0.15$ and $M_{1} = 10^{11}$ GeV. Note that varying $|R_{12}|$ in its allowed range is equivalent to varying the “high energy” CP-violating phases, see eqs. (2) and (3). Shown is also the behavior of the “high energy” term for two additional values of $(-s_{13} \cos \delta)$. As is clearly seen in Fig. 1, for $(-s_{13} \cos \delta) \gtrsim 0.15, |A_{\text{HE}}|$ is strongly suppressed and is much smaller than $|A_{\text{MIX}}|$ in almost all the range of variability of $|R_{12}|$. The same conclusion holds if we allow $|R_{11}|$ to vary in the interval $0.3 \lesssim |R_{11}| \lesssim 1.2$. For the indicated ranges of values of $|R_{11}|$ and $|R_{12}|$, the “high energy” CP-violating phases are not necessarily small. However, reproducing the observed value of the baryon asymmetry is problematic (or can even be impossible) without a contribution due to the CP-violating phases in the PMNS matrix.

The “high energy” contribution can be sub-dominant also in the case of $\sin \theta_{13} = 0$. This possibility can be realised [13] for values of the Majorana phase in the PMNS matrix $0 < \alpha_{21} \lesssim 2\pi/3$ and roughly in half of the parameter space spanned by the relevant elements of the $R$ matrix. In both cases the observed value of the baryon asymmetry can be reproduced for values of the lightest RH Majorana neutrino mass lying in the interval $5 \times 10^{9}$ GeV $\lesssim M_{1} \lesssim 7 \times 10^{11}$ GeV. Similar results hold in the more general case of $|R_{13}| \neq 0, \text{Im}(R_{13}^{2}) = 0$, for $0 \leq |R_{13}| \lesssim 0.9, 1.05 \lesssim |R_{13}| \lesssim 1.5$, and $0.3 \leq |R_{13}| \lesssim 1.2$.

The results obtained in [12,13] show that in the “flavoured” leptogenesis scenario, the contribution to $Y_{B}$ due to the “low energy” CP-violating Majorana and Dirac phases in the neutrino mixing matrix, in certain physically interesting cases, like IH light neutrino mass spectrum, relatively large value of $(-\sin \theta_{13} \cos \delta)$, etc., can be indispensable for the generation of the observed baryon asymmetry of the Universe even in the presence of “high energy” CP-violation, generated by additional physical phases in the matrix of neutrino Yukawa couplings (e.g. by CP-violating phases in the complex orthogonal matrix $R$ appearing in the “orthogonal parametrisation” of neutrino Yukawa couplings).

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$^8$ It is interesting to note that in the recent analysis of the global neutrino oscillation data [22], a nonzero value of $\sin^{2}\theta_{13}$ was reported at 1.6$\sigma$. The best value and the 1$\sigma$ allowed interval of values of $\sin\theta_{13}$ found in [22], $\sin\theta_{13} = 0.126$ and $\sin\theta_{13} = (0.077-0.161)$, are in the range of interest for our discussion. In addition, $\cos\delta = -1$ is reported to be preferred over $\cos\delta = +1$ by the atmospheric neutrino data [22,23].
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