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A new bridge between leptonic *CP* violation and leptogenesis

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Abstract

Flavour effects due to lepton interactions in the early Universe may have played an important role in the generation of the cosmological baryon asymmetry through leptogenesis. If the only source of high-energy *CP* violation comes from the left-handed leptonic sector, then it is possible to establish a bridge between flavoured leptogenesis and low-energy leptonic *CP* violation. We explore this connection taking into account our present knowledge about low-energy neutrino parameters and the matter–antimatter asymmetry observed in the Universe. In this framework, we find that leptogenesis favours a hierarchical light neutrino mass spectrum, while for quasi-degenerate and inverted hierarchical neutrino masses there is a very narrow allowed window. The absolute neutrino mass scale turns out to be $m \lesssim 0.1$ eV.

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1. Introduction

The possibility of relating low-energy neutrino physics with the baryon asymmetry of the Universe (BAU) produced via the mechanism of thermal leptogenesis [1] has received a great deal of attention in the last few years [2]. In the simplest extension of the standard model (SM) where heavy neutrino singlets are added to the particle content, light neutrino masses arise through the seesaw mechanism [3]. Besides providing a natural mechanism to suppress neutrino masses, the seesaw mechanism puts at our disposal the necessary ingredients to explain the matter–antimatter asymmetry observed in our Universe. Indeed, the out-of-equilibrium decays of heavy Majorana neutrinos, under the presence of *CP*-violating interactions, produce a lepton asymmetry which is partially converted into a baryon asymmetry by the $(B + L)$-violating electroweak sphaleron interactions [4].

Recently, it has been noted that charged-lepton flavour effects play a crucial role on the dynamics of the thermal leptogenesis mechanism [5–9]. In particular, for temperatures below $\sim 10^{12}$ (10^9) GeV the interactions mediated by the τ (μ) are non-negligible and, therefore, their effects should be properly taken into account in the computation of the final value of the BAU. In the limit of hierarchical heavy Majorana neutrinos $M_1 \ll M_2 < M_3$, the leptogenesis temperature is typically around $T \sim M_1$. Consequently, depending on the actual value of M_1 and on which charged-lepton Yukawa interactions are in equilibrium, one has different possible scenarios.

In the one-flavour limit where all the charged-leptons are equally treated, one can show that a necessary condition for the mechanism of leptogenesis to work is the presence of a nonvanishing high-energy *CP* violation in the right-handed neutrino sector. In the flavoured leptogenesis perspective, this remains true if $M_1 \gtrsim 10^{12}$ GeV, which corresponds to the temperature above which all the charged-lepton Yukawa interactions are out of equilibrium. In this temperature regime, the *CP* asymmetry generated in the decays of the heavy Majorana neutrinos is summed up over all flavours and its *CP*-violating part does not depend in general on the low-energy *CP*-violating quantities which could be potentially measured in future neutrino experiments. Therefore, in the one-flavour approximation, the observation of low-energy leptonic *CP* violation does not necessarily imply the existence of a nonvanishing BAU.

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One may ask whether the above conclusions remain valid when flavour effects are accounted for. In this Letter we show that, in a general class of models where *CP* is an exact symmetry in the high-energy right-handed neutrino sector, it is indeed possible to establish a direct link between low-energy leptonic *CP* violation and the generation of the cosmological baryon asymmetry. In these models, the baryon asymmetry only depends on the left-handed leptonic *CP* phases, which in turn are determined by the low-energy Dirac and Majorana neutrino phases [6,8]. We shall also briefly address the question on the possibility of naturally preserving *CP* as a good symmetry of the right-handed neutrino sector.

2. Leptogenesis and *CP* violation: a new perspective

We work in the simple framework of the SM extended with three right-handed neutrinos N_i $(i = 1, 2, 3)$ with hierarchical heavy Majorana masses $M_1 \ll M_2 < M_3$. Working in the basis where the charged-lepton Yukawa couplings and the heavy Majorana neutrino mass matrix are diagonal, the relevant Dirac neutrino Yukawa interaction is $\mathbf{Y}_{i\alpha} N_i \ell_\alpha H$, where ℓ_α $(\alpha = e, \mu, \tau)$ are the SM lepton doublets and H is the Higgs doublet. We take advantage of the so-called Casas–Ibarra parametrization [10]

$$\mathbf{Y}_{i\alpha} = \sqrt{M_i}\mathbf{R}_{ik}\sqrt{m_k}\mathbf{U}^*_{\alpha k}/v, \tag{1}$$

where $\mathbf{U}$ is the low-energy leptonic mixing matrix, which diagonalizes the effective neutrino mass matrix $\mathbf{m}_\nu$ in such a way that

$$\mathbf{m}_\nu = v^2 \mathbf{Y}^T \mathbf{M}^{-1} \mathbf{Y} = \mathbf{U}^* \operatorname{diag}(m_1, m_2, m_3)\mathbf{U}^\dagger. \tag{2}$$

Here m_i are the effective light neutrino masses and $v \equiv \langle H^0 \rangle \simeq 174$ GeV. The matrix $\mathbf{R}$ in Eq. (1) is an orthogonal matrix, in general complex. In what follows, we consider a class of seesaw models where $\mathbf{R}$ is real,[1] corresponding to the cases where *CP* is conserved in the right-handed neutrino sector [6,8].

In this special case, the flavoured *CP* asymmetries generated in the decays $N_1 \to \ell_\alpha H$ are simply given by [8]

$$\varepsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{\sum_{k,j} m_k^{1/2} m_j^{3/2} \mathbf{R}_{1k}\mathbf{R}_{1j} \mathrm{I}_{\alpha kj}}{\sum_k m_k \mathbf{R}_{1k}^2}, \tag{3}$$

where $\mathrm{I}_{\alpha kj} \equiv \mathrm{Im}(\mathbf{U}^*_{\alpha k}\mathbf{U}_{\alpha j})$. Summing up over all flavours, $\varepsilon_1 = \sum_\alpha \varepsilon_\alpha$, one recovers the standard one-flavour result [11]. It is straightforward to show that if $\mathbf{R}$ is real, then $\varepsilon_1 = 0$ due to the unitarity of $\mathbf{U}$. Thus, at temperatures where all lepton flavours are out of equilibrium and the one-flavour approximation is valid, no lepton asymmetry can be generated. This in turn implies an upper bound on the lightest heavy Majorana neutrino mass, $M_1 \lesssim 10^{12}$ GeV, for the present scenario to be viable.

Clearly, the *CP* asymmetries ε_α are very sensitive to the type of light neutrino mass spectrum. Three distinct cases are usually considered: hierarchical (HI), inverted hierarchical (IH) and quasi-degenerate (QD) neutrinos,

$$\begin{aligned}
&\text{HI:} \quad m_1 \ll m_2 \simeq (\Delta m^2_\odot)^{1/2}, \quad m_3 \simeq (\Delta m^2_@)^{1/2},\\
&\text{IH:} \quad m_3 \ll m_1 \simeq m_2 \simeq (\Delta m^2_@)^{1/2},\\
&\text{QD:} \quad m \equiv m_1 \simeq m_2 \simeq m_3 > (\Delta m^2_@)^{1/2},
\end{aligned} \tag{4}$$

where $\Delta m^2_\odot = (7.9 \pm 0.6) \times 10^{-5}$ eV^2 and $\Delta m^2_@ = (2.6 \pm 0.4) \times 10^{-3}$ eV^2 are the *solar* and *atmospheric* neutrino mass squared differences at 2σ level [12]. The leptonic mixing matrix $\mathbf{U}$ can be parametrized in the form $\mathbf{U}_\delta \operatorname{diag}(1, e^{i\alpha}, e^{i\beta})$, where $\mathbf{U}_\delta$ contains the Dirac-type *CP*-violating phase δ and α, β are Majorana phases [13]. For the leptonic mixing angles θ_{ij} of the matrix $\mathbf{U}_\delta$, the presently available neutrino oscillation data yield $\sin^2\theta_{12} = 0.30^{+0.06}_{-0.04}$, $\sin^2\theta_{23} = 0.50^{+0.13}_{-0.12}$ and $s^2_{13} \equiv \sin^2\theta_{13} \leqslant 0.025$.

Using the orthogonality condition of the matrix $\mathbf{R}$, one can show that the *CP* asymmetries (3) are bounded from above:

$$\begin{aligned}
\text{HI:} \quad |\varepsilon_\alpha| &\leqslant \frac{3M_1(\Delta m^2_@)^{1/2}}{32\pi v^2}(1-\rho)|\mathrm{I}_{\alpha 32}|\\
&\simeq 4 \times 10^{-7}|\mathrm{I}_{\alpha 32}|\left(\frac{M_1}{10^{10}\ \text{GeV}}\right),\\
\text{IH:} \quad |\varepsilon_\alpha| &\leqslant \frac{3M_1(\Delta m^2_\odot)^{1/2}}{32\pi v^2}\rho|\mathrm{I}_{\alpha 21}|\\
&\simeq 1.5 \times 10^{-8}|\mathrm{I}_{\alpha 21}|\left(\frac{M_1}{10^{10}\ \text{GeV}}\right),\\
\text{QD:} \quad |\varepsilon_\alpha| &\leqslant \frac{3M_1\Delta m^2_@}{64\pi v^2 m}\left(|\mathrm{I}_{\alpha 32}|^2 + |\mathrm{I}_{\alpha 31}|^2\right)^{1/2}\\
&\simeq 1.3 \times 10^{-7}\left(|\mathrm{I}_{\alpha 32}|^2 + |\mathrm{I}_{\alpha 31}|^2\right)^{1/2}\\
&\quad \times \left(\frac{M_1}{10^{10}\ \text{GeV}}\right)\left(\frac{0.1\ \text{eV}}{m}\right),
\end{aligned} \tag{5}$$

where $\rho = (\Delta m^2_\odot/\Delta m^2_@)^{1/2} \simeq 0.17$. It is interesting to note that in the case of a real matrix $\mathbf{R}$, the *CP* asymmetries ε_α vanish for exactly degenerate light neutrinos (see Eq. (3)). Therefore, for QD neutrinos, the quantities ε_α turn out to be suppressed by the absolute neutrino mass scale m, contrarily to what occurs in the case of a complex $\mathbf{R}$, where the upper bound on the flavour asymmetries is proportional to m [7]. We also remark that for a heavy Majorana mass $M_1 < 10^9$ GeV, the above asymmetries will be typically too small to account for the BAU. Thus, in the present framework, flavoured leptogenesis could be viable if

$$10^9\ \text{GeV} \lesssim M_1 \lesssim 10^{12}\ \text{GeV}. \tag{6}$$

Since in this mass window only the τ Yukawa coupling is in thermal equilibrium, the final value of the baryon asymmetry per entropy density can be written as [8]

$$Y_B \equiv \frac{n_B}{s} = -\frac{12}{37}\left(\frac{115}{36}Y_2 + \frac{37}{9}Y_\tau\right), \tag{7}$$

where Y_2 is a combined density coming from the indistinguishable e and μ asymmetries. The individual flavour densities Y_2 and Y_τ can be found by solving the corresponding system of

[1] Notice that although $\mathbf{R}$ is real, one must ensure that $\mathbf{R} \neq \mathbf{1}$ since a misalignment in the right-handed neutrino sector is necessary to obtain nonvanishing *CP* asymmetries.

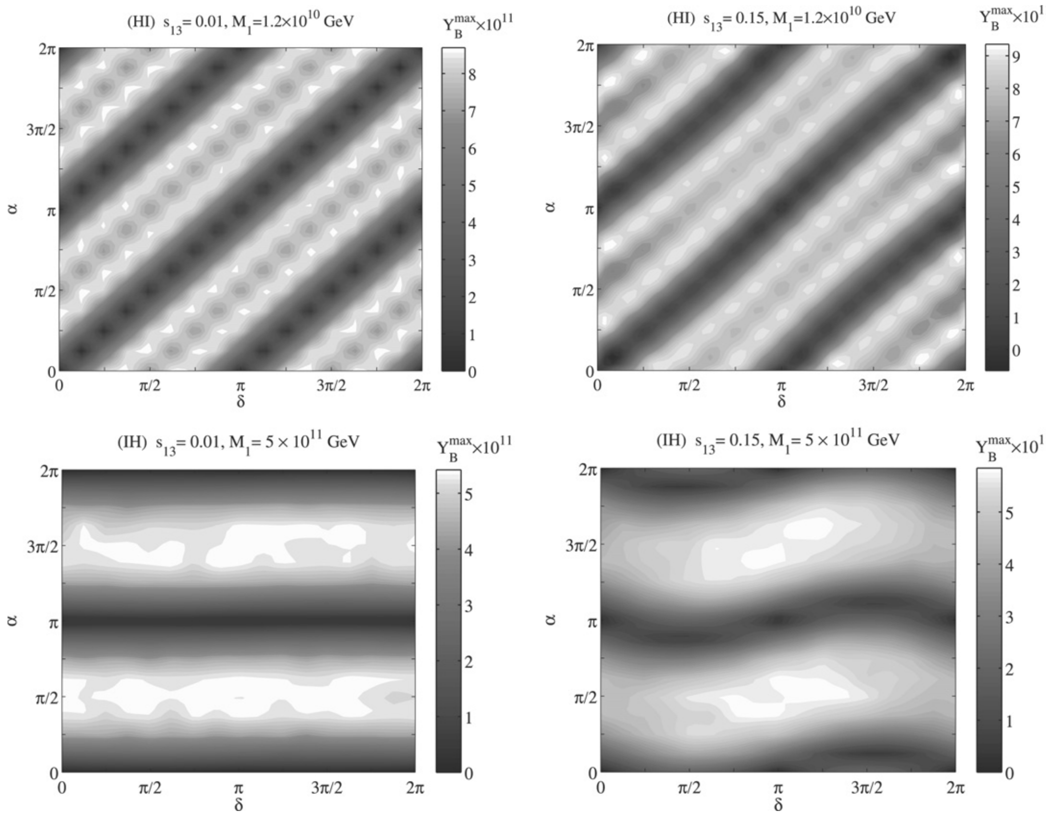

Fig. 1. The correlation between the low-energy Dirac (δ) and Majorana (α) phases for different neutrino spectra: normal hierarchy (HI) (upper panels) and inverted hierarchy (IH) (lower panels). The shaded contours correspond to the maximum of the baryon asymmetry that can be generated in models where *CP* is an exact symmetry of the right-handed neutrino sector. We consider $s_{13} = 0.01, 0.15$. The remaining low-energy neutrino parameters are taken at their present central values.

Boltzmann equations. In the mass region (6), it suffices to consider the leptonic *CP* asymmetry ε_τ, since $\varepsilon_2 \equiv \varepsilon_e + \varepsilon_\mu = -\varepsilon_\tau$ when $\mathbf{R}$ is real.

In Fig. 1 we present the correlation between the low-energy Dirac (δ) and Majorana (α) phases for different neutrino spectra: normal hierarchy (upper panels) and inverted hierarchy (lower panels). The shaded contours correspond to the maximum of the baryon asymmetry that can be generated in models where *CP* is an exact symmetry of the right-handed neutrino sector.[2] The curves were obtained by solving numerically the relevant Boltzmann equations and maximizing over all the possible values of the orthogonal real matrix $\mathbf{R}$. It is assumed in all cases that right-handed neutrinos are not initially present in the thermal plasma, but instead are created by inverse decays and scattering processes. The plots are given for two different values of the leptonic mixing angle s_{13}, namely, $s_{13} = 0.01$ and 0.15. The remaining low-energy neutrino parameters are taken at their present central values. A similar plot is presented in Fig. 2 for the case of quasi-degenerate neutrinos. In the latter case, the correlation between the low-energy Majorana phases, α and β, is shown for maximal low-energy Dirac *CP* violation, i.e. when $\delta = \pi/2$. We also remark that all the results can be easily extrapolated to any value of M_1 in the range of Eq. (6),

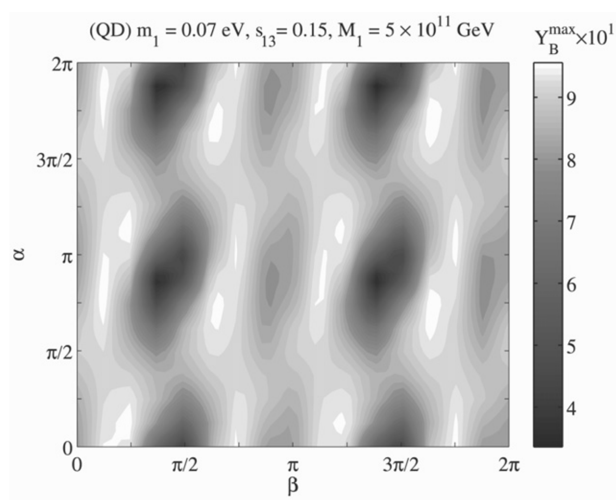

Fig. 2. The correlation between the low-energy Majorana phases, α and β, for the case of a quasi-degenerate (QD) neutrino mass spectrum and maximal low-energy Dirac *CP* violation ($\delta = \pi/2$).

since as can be readily seen from the maximal *CP* asymmetries in Eqs. (5), there is essentially a linear dependence between this parameter and the final baryon asymmetry.

Comparing the results of Figs. 1 and 2 with the experimentally observed value $Y_B = (8.7 \pm 0.3) \times 10^{-11}$ [14], it becomes clear that for IH and QD neutrinos there is a very small allowed window for leptogenesis to be viable in the present framework

[2] Our results do not contemplate some special forms of the matrix $\mathbf{R}$ for which the asymmetries in the decays of N_2 could be large and the washout effects due to N_1 small.

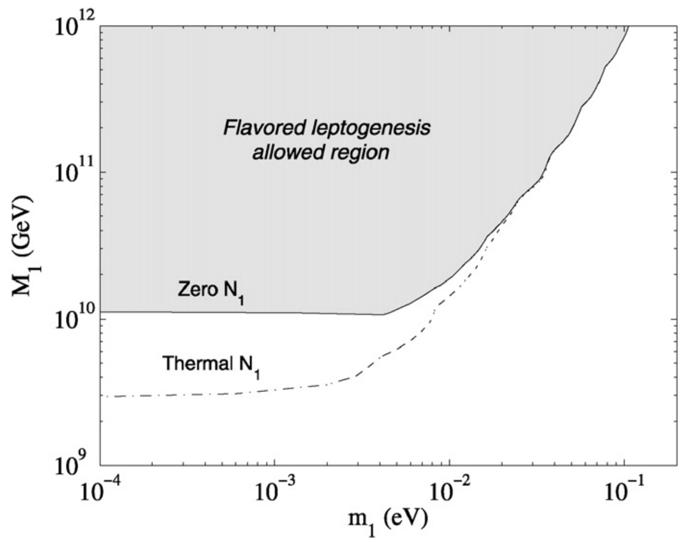

Fig. 3. The region allowed for flavoured leptogenesis in the (m_1, M_1)-plane. The cases of zero and thermal initial N_1 abundance are shown. The contour lines correspond to the lower bound $Y_B = 8.4 \times 10^{-11}$.

(i.e when no *CP* violation arises from the right-handed neutrino sector). Moreover, as expected from the expression of the *CP* asymmetries given in Eq. (5), we find an upper bound on the absolute neutrino mass scale. In Fig. 3 we present the regions of the (m_1, M_1)-plane where flavoured leptogenesis can produce the observed cosmological baryon asymmetry. The solid (dot-dashed) line corresponds to a vanishing (thermal) initial N_1 abundance. From the figure we obtain the lower bound $M_1 > 10^{10}$ GeV (3×10^9 GeV), as well as the upper bound $m_1 \lesssim 0.1$ eV.

3. Conclusion

We have studied the correlation between low-energy leptonic *CP* violation and thermal leptogenesis in a class of seesaw models where *CP* is an exact symmetry of the high-energy right-handed neutrino sector. In this case, and taking into account the role played by flavour effects on the dynamics of the leptogenesis mechanism, one can establish a correlation between low-energy *CP* violation and the cosmological baryon asymmetry. We have shown that for hierarchical light neutrino masses a successful flavoured leptogenesis requires $M_1 > 10^{10}$ GeV (3×10^9 GeV) for a zero (thermal) initial abundance of the lightest right-handed neutrino N_1. On the other hand, values of M_1 close to the upper bound of 10^{12} GeV (above which the present scenario is not viable) are needed for the inverted hierarchy and quasi-degenerate neutrino masses, thus leaving a very narrow window for these neutrino mass spectra. We find an upper bound on the absolute neutrino mass scale: $m \lesssim 0.1$ eV.

Regarding the correlation between the low-energy *CP*-violating phases and the value of the BAU, our analysis has shown that there are certain combinations of phases which are excluded for all values of M_1 (see plots). Furthermore, in this class of models, the observation of low-energy leptonic *CP* violation would in general indicate that the observed baryon asymmetry could have indeed been created through the leptogenesis mechanism. Future information about low-energy *CP* violation either from neutrino oscillations or neutrinoless double beta decay searches could further constrain the present scenario.

Finally, we briefly address the question of how to construct, in the seesaw framework, a model where *CP* violation only occurs in the left-handed neutrino sector. In general, once one allows for *CP* violation through the introduction of complex Yukawa couplings, *CP* arises both in the left-handed and right-handed sectors, so both matrices $\mathbf{U}_\delta$ and $\mathbf{R}$ are complex. The simplest way of restricting the number of *CP*-violating phases is through the assumption that *CP* is a good symmetry of the Lagrangian, only broken by the vacuum. A model can actually be constructed, where one has in a natural way $\mathbf{U}_\delta$ complex while $\mathbf{R}$ is real. Let us consider the seesaw framework and impose *CP* invariance at the Lagrangian level. Now we introduce three Higgs doublets, together with a Z_3 symmetry under which the left-handed fermion doublets ψ_{Lj} transform as $\psi_{Lj} \to e^{i2\pi j/3}\psi_{Lj}$ and the Higgs doublets as $\phi_j \to e^{-i2\pi j/3}\phi_j$, while all other fields transform trivially. It can be readily shown that there is a region of parameters where the vacuum violates *CP* through complex vacuum expectation values $\langle \phi_i^0 \rangle = v_i e^{i\theta_i}$. Due to the Z_3 restrictions on Yukawa couplings, the combination $\mathbf{YY}^\dagger$ is real, thus implying a real $\mathbf{R}$ (cf. Eq. (1)), but a complex $\mathbf{U}_\delta$ is generated. The drawback of such a scheme is that in order to generate the required baryon asymmetry, leptogenesis would have to take place at the TeV scale.

Note added

While this work was in preparation, a related preprint appeared [15], where some of the aspects analysed in this Letter are also studied.

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