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Dirac and Majorana Leptonic CP-Violation and Leptogenesis

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Abstract. We briefly review the results showing that the CP-violation necessary for the generation of the baryon asymmetry of the Universe in leptogenesis with "hierarchical" heavy Majorana neutrinos can be due exclusively to the Dirac and/or Majorana CP-violating phase(s) in the neutrino mixing matrix U. One can have successful leptogenesis, in particular, even if the only source of CP-violation is the Dirac phase δ in U. For light ν-mass spectrum with normal (inverted) hierarchy, this requires $|\sin\theta_{13}\sin\delta| \geq 0.09$ (0.02), θ_{13} being the CHOOZ angle.

1. Introduction

It was shown recently in [1] that the CP-violation necessary for the generation of the observed baryon asymmetry of the Universe Y_B in the thermal leptogenesis scenario [2] can be due exclusively to the Dirac and/or Majorana CP-violating (CPV) phases in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix [3], and thus can be directly related to the low energy CP-violation in the lepton sector (observable, e.g. in neutrino oscillations, etc.). The baryon asymmetry is generated in the regime of large lepton flavour effects in leptogenesis ("flavoured" leptogenesis) [4, 5]. In ref. [6] the baryon asymmetry Y_B produced in "flavoured" leptogenesis, with the requisite CP-violation provided by the PMNS matrix U, was found to depend strongly in certain physically interesting cases on the value of the lightest neutrino mass, $\min(m_j)$, $j = 1, 2, 3$. For specific values of $\min(m_j)$ the asymmetry $|Y_B|$ can be significantly enhanced (by a factor of ~ 100 or more) with respect to that predicted for $\min(m_j) \cong 0$. This enhancement can make the predicted Y_B compatible with the observations even when this is not the case for $\min(m_j) \cong 0$. Here we review briefly some of the results obtained in [1, 6].

Following [1, 6], we consider the the simplest scheme in which leptogenesis can be implemented - the minimal "seesaw"(type I) model of ν-mass generation [7], which includes the Standard Model (SM) plus three heavy right-handed (RH) Majorana neutrinos, N_j. The latter are assumed to have a hierarchical mass spectrum [2], $0 < M_1 \ll M_2 \ll M_3$. We limit our discussion here to the cases of light neutrinos having normal hierarchical (NH), $m_1 \ll m_2 < m_3$, or inverted hierarchical (IH), $m_3 \ll m_1 < m_2$, mass spectrum [3] (see, e.g. [8]). In thermal leptogenesis with "hierarchical" heavy Majorana neutrinos N_j, the CPV lepton asymmetry is produced in out-of-equilibrium lepton number and CP-nonconserving decays of the lightest one, N_1. At later epoch the lepton asymmetry is converted into a baryon asymmetry by $(B - L)$-conserving but $(B + L)$-violating sphaleron interactions [9].

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[2] Results for quasi-degenerate in mass heavy Majorana neutrinos were also obtained in [1].
[3] A rather detailed discussion of the case of quasi-degenerate light neutrino mass spectrum is given in [1].

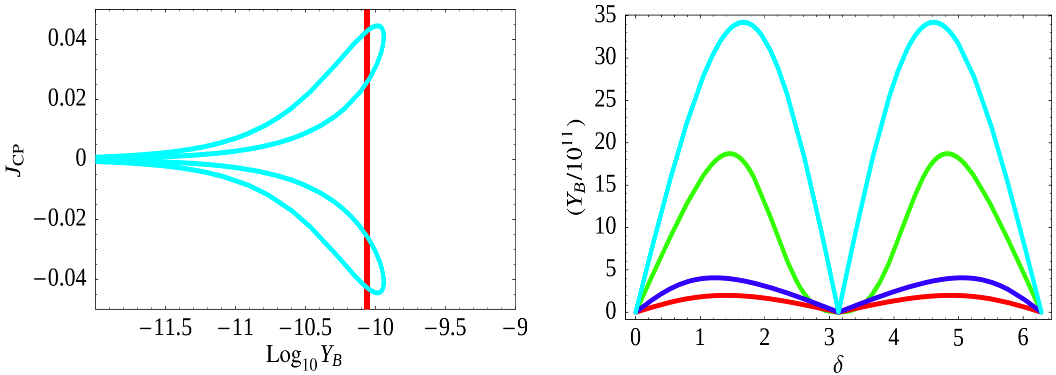

Figure 1. Baryon asymmetry from the CPV Dirac phase δ in U. Left panel: the correlation between $J_{\rm CP}$ and $Y_{\rm B}$ for NH spectrum, s_{13}=0.2, α_{32}=0, R_{12}=0.86, and M_1=5×10^{11} GeV. Right panel: $|Y_B|$ as a function of δ for IH spectrum, $R_{11}R_{12} = i\ \kappa\ |R_{11}R_{12}|$ $(|R_{11}|^2 - |R_{12}|^2 = 1)$, $\kappa = -1$ (red and dark blue lines), $\kappa = +1$ (light blue and green lines), for $M_1 = 2\times10^{11}$ GeV, and $s_{13} = 0.1$ (red and green lines) and $s_{13} = 0.2$ (dark blue and light blue lines). (From [1].)

2. Baryon Asymmetry from CPV Dirac and Majorana Phases in $U_{\rm PMNS}$

The matrix of neutrino Yukawa couplings, λ, together with the Majorana mass matrix of the RH neutrinos, M_R, and the matrix of charged lepton Yukawa couplings, λ^{lep}, plays a crucial role both in the see-saw mechanism and in leptogenesis. In the basis in which M_R and λ^{lep} are diagonal, λ is the only source of CP-violation in the lepton sector. The "orthogonal" parametrisation allows to relate in a rather simple manner λ with the PMNS matrix [10]: $\lambda = v^{-1}\sqrt{M}\,R\,\sqrt{m}U^{\dagger}$, where R is a complex orthogonal matrix, $R\ R^T = R^T\ R = \mathbf{1}$, $M \equiv \mathrm{Diag}(M_1, M_2, M_3)$, $m \equiv \mathrm{Diag}(m_1, m_2, m_3)$, $M_j > 0$, $m_k \geq 0$, and $v = 174$ GeV is the vacuum expectation value of the Higgs doublet field. We are interested in the case when the matrix R conserves the CP-symmetry. Therefore we will assume that R has real and/or purely imaginary elements [1].

Suppose the baryon asymmetry Y_B is produced in the "two-flavour" regime in leptogenesis [4, 5]. 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 leptogenesis can be written as [4, 5] $|Y_B| \cong 3\times10^{-3}\ |\epsilon_\tau\ \eta|$, where ϵ_τ is the CPV asymmetry in the τ flavour (lepton charge) produced in N_1-decays [4], η is the efficiency factor [5], $|\eta| \cong |\eta(0.71\widetilde{m_2}) - \eta(0.66\widetilde{m_\tau})|$, $\widetilde{m_{2,\tau}}$ being the wash-out mass parameters $\widetilde{m_2} = \widetilde{m_e} + \widetilde{m_\mu}$, $\widetilde{m_l} = |\sum_j m_j\ R_{1j}\ U^*_{lj}|^2$. For real R we have [1]:

$$\epsilon_\tau = -\frac{3M_1}{16\pi v^2}\frac{\sum_k\sum_{j>k}\sqrt{m_k m_j}\,(m_j - m_k)\,\rho_{kj}|R_{1k}R_{1j}|\,\mathrm{Im}\ (U^*_{\tau k}\,U_{\tau j})}{\sum_i m_i\,|R_{1i}|^2}\ ,\ \mathrm{Im}\,(R_{1k}R_{1j}) = 0\,, \qquad (1)$$

where $\rho_{jk} \equiv \mathrm{sgn}(R_{1j}R_{1k}) = \pm1$, $j \neq k$. If $R_{1j}R_{1k} = i\rho_{jk}\ |R_{1j}R_{1k}|$, then $\mathrm{Im}(R_{1k}R_{1j})$ and $(m_j - m_k)$ in eq. (1) should be replaced [5] by $\mathrm{Re}(R_{1k}R_{1j})$ and $(m_j + m_k)$ [1].

We shall summarise next briefly some of the results obtained in [1, 6]. Consider the case of NH Spectrum, $m_1 \ll m_2 \ll m_3 \cong (\Delta m^2_{\rm A})^{1/2}$, $\Delta m^2_{\rm A} \cong 2.5\times10^{-3}$ eV^2 being the "atmospheric" neutrino mass squared difference. Suppose that $m_1 \cong 0$, $R_{11} \cong 0$ (N_3 decoupling), $R_{12}R_{13}$ is real and the only source of CP-violation is the Dirac phase δ in U. In this case $\epsilon_\tau \propto s_{13}\sin\delta$, $s_{13} \equiv \sin\theta_{13}$. For, e.g. $R_{12}R_{13} > 0$, s_{13}=0.2, δ=$\pi/2$, and $R_{12} \cong 0.86$ (which maximises $|Y_B|$), we have [1]: $|Y_B| \cong 3.6\times10^{-13}$ $((\Delta m^2_{\rm A})^{1/2}/0.05\ {\rm eV})(M_1/10^9\ {\rm GeV})$. The observed baryon asymmetry $|Y_B| \cong (8.0 - 9.2)\times10^{-11}$ can be reproduced for $M_1 \lesssim 5\times10^{11}$ GeV if $|\sin\theta_{13}\sin\delta| \gtrsim 0.09$, or $|J_{\rm CP}| \gtrsim 2.0\times10^{-2}$, $J_{\rm CP}$ being the rephasing invariant controlling the magnitude of CP-violation in neutrino oscillations [11]. Given the experimental limit

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[4] The expression for Y_B we have given is normalised to the entropy density, see, e.g. [1].

[5] Note that real (purely imaginary) $R_{1k}R_{1j}$ and purely imaginary (real) $U^*_{lk}U_{lj}$, $j \neq k$, implies violation of CP-invariance by the matrix R [1]. In order for the CP-symmetry to be broken at low energies, we should have both $\mathrm{Re}(U^*_{lk}U_{lj}) \neq 0$ and $\mathrm{Im}(U^*_{lk}U_{lj}) \neq 0$ (see [1] for further details).

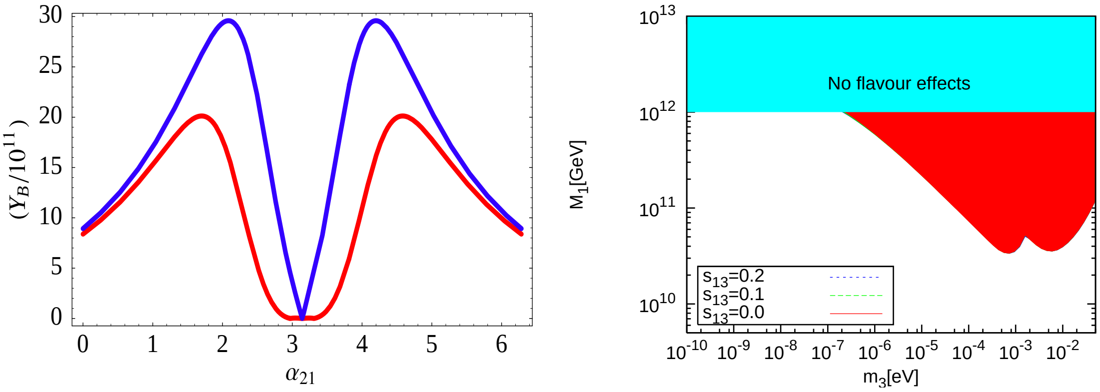

Figure 2. The asymmetry $|Y_B|$ in the case of IH spectrum. Left panel: $|Y_B|$ versus the Majorana phase $\alpha_{21} \equiv \alpha$ of U for purely imaginary $R_{11}R_{12} = -i|R_{11}R_{12}|$, $R_{13} = 0$, $\delta = 0$, $M_1 = 2 \times 10^{11}$ GeV and $s_{13} = 0,\ 0.2$ - black/blue and gray/red lines. Right panel: 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) in the case of real R (see [1, 6] for further details).

$\sin\theta_{13} \leq 0.22$, leptogenesis can be successful provided $M_1 \gtrsim 1.9 \times 10^{11}$ GeV. The ranges of values of $\sin\theta_{13}$ and of $|J_{\rm CP}|$ we find are within the sensitivity of the planned θ_{13} reactor neutrino experiments Double CHOOZ and Daya Bay and of the neutrino oscillation experiments on CP- (T-) violation. Since both Y_B and $J_{\rm CP}$ depend on s_{13} and δ, for given values of the other relevant parameters there exists a correlation between the values of $|Y_B|$ and $J_{\rm CP}$ (Fig. 1). In the analogous case of IH spectrum, Dirac CP-violation, $m_3 \cong 0$ and N_3 decoupling ($R_{13} \cong 0$), we find that the observed baryon asymmetry $|Y_B| \cong (8.0 - 9.2) \times 10^{-11}$ can be reproduced if $|\sin\theta_{13}\sin\delta| \gtrsim 0.02$, or $|J_{\rm CP}| \gtrsim 4.6 \times 10^{-3}$ (Fig 1). However, leptogenesis can be successful for $M_1 \lesssim 10^{12}$ GeV only if $R_{11}R_{12}$ is not real [1, 12]. The quoted results correspond to $R_{11}R_{12}{=}i\kappa|R_{11}R_{12}|$, $\kappa{=}\pm1$. We can still have successful leptogenesis for real R, CP-violation due to the CPV phases in U and $M_1 \lesssim 10^{12}$ GeV, provided m_3 is significantly different from 0 [6]. Typically values of 5×10^{-4} eV $\lesssim m_3 \lesssim 5 \times 10^{-2}$ eV are required. If, however, $R_{1j} \neq 0$, $j = 1, 2, 3$, one can have successful leptogenesis even for $m_3 \sim 10^{-5}$ eV (Fig. 2).

In conclusion, the results presented in the present article underline, in particular, the importance of understanding the status of the CP-symmetry in the lepton sector and, correspondingly, of the experiments aiming to measure the CHOOZ angle θ_{13} and of the experimental searches for Dirac and/or Majorana leptonic CP-violation at low energies.

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