Dirac phase leptogenesis

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Abstract. I present here a concise summary of the preprint arXiv:0707.3024, written in collaboration with A. Anisimov and P. Di Bari. There we discuss leptogenesis when CP violation stems exclusively from the Dirac phase in the PMNS mixing matrix. Under this assumption it turns out that the situation is very constrained when a hierarchical heavy right-handed (RH) neutrino spectrum is considered: the allowed regions are small and the final asymmetry depends on the initial conditions. On the other hand, for a quasi-degenerate spectrum of RH neutrinos, the CP asymmetry can be enhanced and the situation becomes much more favorable, with no dependence on the initial conditions. Interestingly, in the extreme case of resonant leptogenesis, in order to match the observed baryon asymmetry of the Universe, we obtain a lower bound on sin $\theta_{13}$ which depends on the lightest active neutrino mass $m_1$.

1. Introduction

With the understanding of the important role of flavor in leptogenesis [1, 2], it has become progressively clear that the link between low-energy CP violation and the size of the baryon asymmetry predicted by thermal leptogenesis [3] is considerably tighter than in the unflavored (or one-flavor) situation. In particular it was shown in [4] for a hierarchical RH neutrino spectrum that a non-zero Majorana phase can be the unique source of CP violation contributing to the generation of the baryon asymmetry of the Universe, although the allowed region in the parameter space was small, and mainly in the weak wash-out. The Dirac phase can also do the job, provided the angle $\theta_{13}$ is not too small [5].

Within the see-saw model [6], a nice way to see the different contributions to the CP violation required for leptogenesis is to choose the following parametrization of the Dirac mass matrix [7]:

$$m_D = U \sqrt{D_m} \Omega \sqrt{D_M},$$

where $m_i$ and $M_i$ ($i = 1, 2, 3$) denote the light and heavy neutrino masses, respectively, and $D_X \equiv \text{diag}(X_1, X_2, X_3)$. Among the 18 supplementary parameters brought by the see-saw, 6 are CP violating phases: 1 Dirac and 2 Majorana phases in the PMNS mixing matrix $U$, as well as 3 unobservable phases in the $\Omega$ matrix. The $\Omega$ matrix can be conveniently parametrized as a product of three complex rotations, $\Omega = R_{12}(\omega_{21})R_{13}(\omega_{31})R_{23}(\omega_{32})$.

In [8] we analysed in detail the role of the Dirac phase as the unique source of CP violation required for leptogenesis. The aim is here to summarize some important results obtained there.
2. Hierarchical spectrum for the heavy RH neutrinos

In the hierarchical limit (HL), $M_1 \ll M_2 \ll M_3$, one can safely study only the decay of the lightest RH neutrino $\nu_1$, $N_1$, and we anticipate that successful leptogenesis will occur for $10^9 \text{GeV} \lesssim M_1 \lesssim 10^{12} \text{GeV}$, where a two-flavor regime applies, with flavors denoted $\alpha = e + \mu, \tau$.

Since here we consider leptogenesis exclusively from one low-energy phase, namely the Dirac phase, we have that the total $CP$ asymmetry $\varepsilon_1 = \varepsilon_1^\tau + \varepsilon_{1,e+\mu} = 0$, so that the final asymmetry can be written as

$$N_f^{B-L} \simeq (\kappa_{1\tau}^f - \kappa_{1,e+\mu}^f)\varepsilon_1^\tau,$$

where $\kappa_{1\alpha}^f$ are the final efficiency factors, which include the effects of the wash-out and the production of the asymmetry.

Since the $CP$ asymmetry parameter $\varepsilon_1^\tau \propto M_1$, if one requires the final asymmetry, including the sphaleron conversion, to match the observed baryon asymmetry of the Universe, $\eta_{\nu_{\text{CMB}}} = (6.1 \pm 0.2) \times 10^{-10}$ [9], one obtains a lower bound on the lightest RH neutrino mass, $M_1$.

We show in Fig. 1 an example of lower bound $M_1^{\text{min}}$ vs. $K_1$ for $m_1/m_{\text{atm}} = 0.1$, $s_{13} = 0.2$, $\delta = -\pi/2$ and $\omega_{31} < 0$. The thin and thick solid lines denote thermal and vanishing initial abundance of RH neutrinos, respectively.

It was explicitly checked in [8] that, for all cases under study, the contribution from the heavier RH neutrinos was negligible.

2 This rigorously applies to the example shown in Fig. 1, but this statement turns out to apply for all cases studied in [8].
One way-out of this unfavorable situation is to go to a quasi-degenerate RH neutrino spectrum, where the \( CP \) asymmetry can be enhanced and where a strong wash-out is ensured.

3. Quasi-degenerate spectrum for the heavy RH neutrinos
In the degenerate limit (DL), \( M_1 \simeq M_2 \simeq M_3 \), we anticipate the mass \( M_1 \) to be below \( 10^9 \) GeV, so that a three-flavor problem arises, with flavors \( \alpha = e, \mu, \tau \). Contrary to the HL, the \( CP \) asymmetries, as well as the wash-outs, must be now summed over each RH neutrino:

\[
N_{B-L}^f \simeq \sum_\alpha (\varepsilon_{1\alpha} + \varepsilon_{2\alpha} + \varepsilon_{3\alpha}) \kappa_\alpha^f (K_{1\alpha} + K_{2\alpha} + K_{3\alpha}).
\]

(3)

In the DL, the \( CP \) asymmetries are inversely proportional to the degeneracy parameter \( \delta_{ji} \equiv (M_j - M_i)/M_i \). This implies a dependence on \( \delta_{ji} \) of the lower bound on \( M_1 \) for successful leptogenesis. For \( \Omega = R_{13} \) we obtained the following 3\( \sigma \) bounds for normal and inverted hierarchy, respectively:

\[
M_1 \gtrsim 5.5 \times 10^9 \text{GeV} \left| \frac{\delta_{31}}{\sin \theta_{13} \sin \delta} \right| \quad \text{and} \quad M_1 \gtrsim 5 \times 10^{11} \text{GeV} \left| \frac{\delta_{31}}{\sin \theta_{13} \sin \delta} \right|.
\]

(4)

It is interesting to notice how the degeneracy parameter is linked to the size of \( \sin \theta_{13} \) for successful leptogenesis at fixed \( M_1 \).

The enhancement for close RH neutrino masses is of course limited. Indeed, when \( \delta_{ij}^{\text{res}} \simeq dM_i m_{\text{atm}}/(16\pi v^2) \), one hits a resonance \([11, 12]\), where \( d = 1 \div 10 \) accounts for the present uncertainty in the location of the resonance. It is interesting to notice that in this extreme situation we obtained a lower bound on \( \theta_{13} \) which depends on the lightest active neutrino mass, \( m_1 \). This is shown in Fig. 2, for \( \Omega = R_{13} \) and a normal hierarchy. The corresponding constraint for an inverted hierarchy as well as for other \( \Omega \) matrices can be found in \([8]\). Note finally that for a vanishing \( m_1 \), successful Dirac phase leptogenesis demands \( \sin \theta_{13} \gtrsim 2.3 \times 10^{-7} \) and \( \sin \theta_{13} \gtrsim 3 \times 10^{-6} \) for normal and inverted hierarchy, respectively.

4. Conclusion
The possibility that the Dirac phase, which one hopes to measure in the next-generation neutrino experiments, might be the source of \( CP \) violation required for leptogenesis is interesting. We obtained that a degenerate RH neutrino spectrum is preferred and that in the extreme case of resonant leptogenesis a nice link between low-energy parameters, such as \( \sin \theta_{13}, m_1 \) and the mass hierarchy, is present.

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