PROCEEDINGS OF SCIENCE

Low-scale leptogenesis with Dirac phase CP-violation

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The freeze-in scenario of leptogenesis via oscillations within the type-I seesaw model with two quasi-degenerate heavy Majorana neutrinos $N_{1,2}$ can be viable in the mass range $M \sim (0.1 - 100)$ GeV even when the Dirac phase δ of the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix is the only source of CP-violation in the leptonic sector and in leptogenesis. In particular, viable leptogenesis with Dirac phase CP-violation is compatible with $N_{1,\,2}$ total squared coupling to the Standard Model leptons within the reach of future planned and proposed experiments. Moreover, the parameter space differs from the one associated with the Casas-Ibarra sources of CP-violation. Future precise determination of δ and/or the $N_{1,2}$ couplings to the Standard Model leptons could establish whether, within the context of low-scale leptogenesis, the Dirac phase alone can be responsible for the present baryon asymmetry of the Universe.

1st General Meeting of the COST Action, COSMIC WSIPers
5^{th} – 8^{th} *September 2023*
Bari, Italy

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PoS(COSMICWISPers)008

1. Introduction

There is compelling astrophysical and cosmological evidence of a *baryon asymmetry of the Universe* (BAU). Fits to the independent data on the cosmic microwave background anisotropies and the abundances of light primordial elements give today a best-fit value of $\eta_B \simeq 6.1 \times 10^{-10}$ [1, 2], where $\eta_B = (n_B - n_{\bar{B}})/n_\gamma$ is the difference between the number densities of baryons n_B and antibaryons $n_{\bar{B}}$ normalised to that of photons n_γ.

A notable mechanism to generate the BAU is that of *leptogenesis* (LG) [3] in which a lepton asymmetry generated through some non-standard mechainsm is converted into the present BAU by the non-perturbative sphaleron processes, which are predicted by the Standard Model (SM) to be in thermal equilibrium at temperatures in the range $132 \lesssim T/\mathrm{GeV} \lesssim 10^{12}$ [4, 5]. The simplest LG realisation arises within the type-I seesaw extension of the SM, which also provides an explanation for the origin of the SM neutrinos' masses. Its minimal version augments the SM particle content with two sterile right-handed neutrinos, taken to be singlets under the SM gauge group. The right-handed neutrinos enter in the Lagrangian with a Majorana mass term and a Yukawa coupling to the Higgs Φ and left-handed charged lepton doublets $\psi_{\alpha L}$ of flavour $\alpha = e, \mu, \tau$ as follows

$$\mathcal{L}_{\mathrm{Seesaw}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\left(i\,\overline{N_j}\partial\!\!\!/ N_j - M_j\overline{N_j}N_j\right) - \left(Y_{\alpha j}\overline{\psi_{\alpha L}}\,i\sigma_2\,\Phi^*\,N_{jR} + \mathrm{h.c.}\right), \tag{1}$$

written in the basis for which the Majorana mass matrix M for the right-handed neutrinos is diagonal, so that N_j stands for a massive Majorana neutrino with mass $M_j > 0$, $j = 1, 2$ [1].

The Yukawa interaction in Eq. (1) allows for lepton number violating processes (decays, inverse decays, scatterings) involving the heavy Majorana neutrinos, the Higgs boson and the left-handed leptons. These can also violate CP if the Yukawa couplings satisfy the proper requirements. With these processes happening out-of-equilibrium in the expanding Universe in conjunction with sphalerons, all the three Sakharov's condition for a dynamical generation of a baryon asymmetry are satisfied [6]. Thus, the type-I seesaw extension incorporates all the necessary ingredients for LG.

What couples to the charged leptons and Higgs doublet is a superposition of mass eigenstates. Hence, CP-violating oscillations of heavy Majorana neutrinos can occur during LG, affecting the generation of the lepton asymmetry. The "freeze-in" mechanism of LG in which oscillations of quasi-degenerate heavy Majorana neutrinos dominate the generation of the BAU during their out-of-equilibrium production has been extensively studied after its proposal [7, 8]. Such scenario of *LG via oscillations* is viable in reproducing the present observed BAU for masses of two quasi-degenerate heavy Majorana neutrinos $M_1 \simeq M_2$ as low as 100 MeV. The existence of heavy Majorana neutrinos with masses below the electroweak scale, i.e. hundreds of GeV, and couplings compatible with viable LG can be probed in low-energy experiments (see, e.g., [9, 10] and references therein), making the scenario of LG via oscillations testable.

An intriguing possibility is when the requisite CP-violation in LG is uniquely due to the Dirac phase δ of the light neutrino mixing matrix. In this case, there would be a direct link between the BAU and CP-violating phenomena in low-energy neutrino oscillations. At present, only indications

[1]The values of $M_{1,2}$ are generally much larger than the eV scale of the light neutrino masses, and so we will refer to $N_{1,2}$ further on as *heavy Majorana neutrinos*.

for CP-violation from δ exist, with CP-conserving values that are not yet excluded by global fit analyses [11, 12]. Provided the Dirac phase is proven to be CP-violating by, e.g., T2K [13] and NOνA [14] or the planned DUNE [15] and T2Hyper-Kamiokande (T2HK) [16] experiments, it could be the only responsible for the predominance of matter over antimatter in our Universe. LG with solely Dirac CP-violation has been shown to work in the thermal high-scale scenarios and only recently also in the context of LG via oscillations [17]. In what follows, after setting the necessary notation, we will briefly summarise the main results of [17].

2. The Type-I Seesaw Mechanism for Light Neutrino Mass Generation

The type-I seesaw extension embeds a mechanism to generate the masses of the light neutrinos. With the Higgs field acquiring a non-vanishing vacuum expectation value $v/\sqrt{2} \simeq 174\,\text{GeV}$, diagonalisation of the seesaw Lagrangian in Eq. (1) leads to the seesaw formula for the light neutrino masses: $U\hat{m}_\nu U^T \simeq -(v^2/2)\,YM^{-1}Y^T$, valid at tree level and up to second-order corrections in the heavy Majorana neutrino couplings to the SM $\Theta_{\alpha j} \equiv (v/\sqrt{2})Y_{\alpha j}/M_j$, $|\Theta_{\alpha j}| \ll 1$. In the seesaw formula, $\hat{m}_\nu = \text{diag}(m_1, m_2, m_3)$, with $m_{1,2,3}$ being the masses of the light SM neutrinos, while the matrix U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix. The typical seesaw mechanism consists of taking M_j at scales that are high enough to obtain the light neutrino masses. However, the smallness of the light neutrino masses can also be accounted for by the smallness of the Yukawa couplings or by cancellations occurring between the various terms – note that the seesaw formula is a matrix relation. The latter situation can be, e.g., justified in terms of a mildly broken symmetry. Consequently, the masses of the heavy Majorana neutrinos are unconstrained from the point of view of explaining the light neutrino masses and can lie, e.g., even below the electroweak scale.

The PMNS matrix in the type-I seesaw extension is, to a very good approximation, unitary and can be parameterised in terms of three neutrino mixing angles θ_{12}, θ_{23} and θ_{13}, the Dirac phase δ, and two Majorana phases α_{21} and α_{31} [18], which are undetermined at present. As it is well known, in the case of just two heavy Majorana neutrinos, the lightest neutrino is massless at tree and one loop level and the light neutrino mass spectrum has either a normal hierarchy (NH) or an inverted hierarchy (IH), with $m_1 \simeq 0 \ll m_2 < m_3$ or $m_3 \simeq 0 \ll m_1 < m_2$, respectively. In the numerical analysis of [17], the best-fit values of the three neutrino mixing angles θ_{12}, θ_{23} and θ_{13}, and the two neutrino mass squared differences obtained in the latest `NuFit 5.2` analysis [11, 12] were used: $\theta_{12} = 33.41^\circ\ (33.41^\circ)$, $\theta_{13} = 8.58^\circ\ (8.57^\circ)$, $\theta_{23} = 42.2^\circ\ (49.0^\circ)$, $\Delta m^2_{21} = 7.41\ (7.41)\times 10^{-5}\ \text{eV}^2$ and $\Delta m^2_{31(32)} = 2.507\ (-2.486) \times 10^{-3}\ \text{eV}^2$ in the NH (IH) case. Given the relatively large uncertainty in its determination, the Dirac phase δ can been considered as a free parameter. Finally, only the combination $\alpha_{23} = \alpha_{21} - \alpha_{31}$ (the phase α_{21}) is physical in the NH (IH) case.

The Yukawa matrix is given in terms of the relevant low-energy observables under the Casas-Ibarra (CI) parameterisation [19]: $Y_{\alpha j} = \pm i(\sqrt{2}/v)U_{\alpha a}\sqrt{m_a}O_{ja}\sqrt{M_j}$, $a = 1, 2, 3$. The *CI matrix O* is complex with orthonormal rows and entries $O_{11(13)} = O_{21(23)} = 0$, $O_{23(22)} = \varphi\, O_{12(11)} = \varphi \cos\theta$ and $O_{13(12)} = -\varphi\, O_{22(21)} = \varphi \sin\theta$ in the NH (IH) case, with $\theta \equiv \omega + i\xi$, ω and ξ being free real parameters and $\varphi = \pm 1$. Working with $\varphi = +1$ while extending the range of the Majorana phases $\alpha_{23(21)}$ from $[0, 2\pi]$ to $[0, 4\pi]$ allows to consider the same full sets of CI and Yukawa matrices [20].

In general, the CI matrix contains CP-violating phases. The CI matrix can be taken to be CP-conserving – as, for instance, in flavour models based on sequential dominance [21] or with residual CP-symmetries [22, 23] – choosing $\omega = k\pi$, $k = 0, 1/2, 1, \ldots$, and $\xi \neq 0$, while allowing for an overall exponential enhancement of the couplings $\Theta_{\alpha j}$. In this case, CP-violation uniquely from δ is obtained by setting also the Majorana phases to $\alpha_{23(21)} = \pi$ or 3π, avoiding CP-violation from the Majorana phases and from any interplay between CP-conserving PMNS and CI matrices [24].

3. The Parameter Space of Leptogenesis with Dirac Phase CP-Violation

The evolution of the lepton asymmetry and the abundances of the heavy Majorana neutrinos is customarily studied by solving sets of momentum-averaged Boltzmann-like differential equations. To properly take the effects of oscillations into account, the equations for the density matrix of the heavy Majorana neutrinos should be considered. The density matrix equations for LG via oscillations have been obtained with various approaches and different levels of refinements (see, e.g., [25]). In [17], the Python package `ULYSSES` [26, 27] was used to solve numerically the relevant equations and perform a scan of the parameter space of viable LG considering solely Dirac CP-violation.

The results of the parameter scan for the NH case is depicted in the left panel of Fig. 1 (similar results hold for the IH case but not shown). The plot indicates quite remarkably that LG with low-energy CP-violation solely from δ is viable in the mass range $0.1 \leq M_1/\text{GeV} \leq 100$, for mass splittings $\Delta M/M_1 \equiv (M_2 - M_1)/M_1 \in [10^{-11}, 10^{-4}]$ and rather large values of $\Theta^2 \equiv \sum_{\alpha j} |\Theta_{\alpha j}|^2$, entering the sensitivity regions of planned and proposed experiments looking for heavy neutral leptons (purple dashed line) or the discussed FCC-ee facility (green dashed line). Moreover, the results in [17] have revealed the existence of a gap between the parameter spaces of LG with solely Dirac phase CP-violation and that associated to extra CP-violating phases (either CI and/or Majorana), with the separation depending on δ and M_1. A precise measurement of δ and Θ^2 at a certain mass scale in the associated gap would indicate the necessity of having additional sources of CP-violation other than δ.

The triangular plot in the right panel of Fig. 1 shows the flavour couplings $\Theta^2_\tau : \Theta^2_\mu : \Theta^2_e$, with $\Theta^2_\alpha \equiv \sum_j |\Theta_{\alpha j}|^2$, that are compatible with LG with either Dirac phase CP-violation (solid triangles) or with additional sources of CP-violation (surrounding fainter regions) – either CI or Majorana phases. With experiments suggesting a flavour structure outside the green and blue (yellow and red) triangles of the plot in the NH (IH) case, but still inside the light-blue (light-red) regions, LG would necessitate of additional sources of CP-violation in order to generate the present BAU.

Finally, in [17], a correspondence between the sign of the BAU and that of $\sin\delta$ in the NH case was found. This is reflected in differences between the flavour hierarchies. More specifically, LG with Dirac phase CP-violation is successful in reproducing the positive BAU for either $0 < \delta < \pi$ ($\pi < \delta < 2\pi$), $\xi > 0$ and $\Theta^2_\mu > \Theta^2_\tau > \Theta^2_e$ or $\pi < \delta < 2\pi$ ($0 < \delta < \pi$), $\xi < 0$ and $\Theta^2_\tau > \Theta^2_\mu > \Theta^2_e$ for $\omega = 0, \pi, 2\pi$ ($\pi/2, 3\pi/2$). With possible future signatures favouring a certain flavour hierarchy and measurements of δ determining whether $0 < \delta < \pi$ or $\pi < \delta < 2\pi$, one could discriminate between the aforementioned cases.

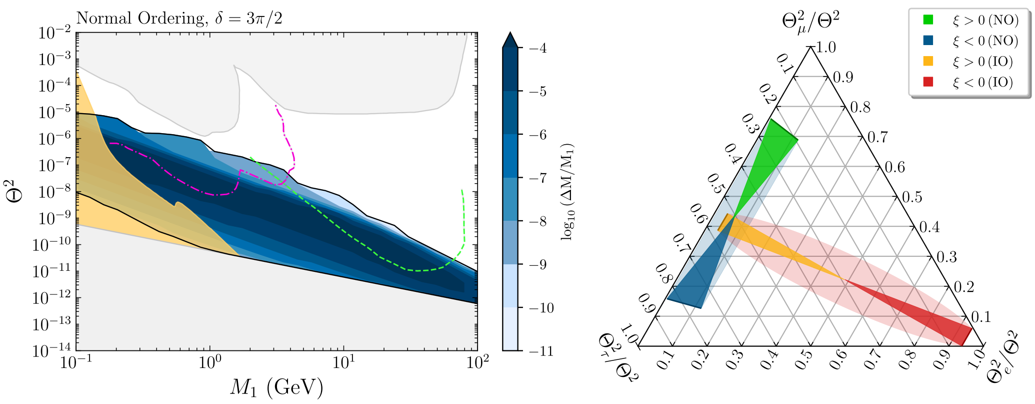

Figure 1: *Left.* The parameter space of viable (in blue) of LG via oscillations with CP-violation solely from δ. The plot is obtained for $\delta = 3/2$ and NH (similar results hold for IH) and several mass splittings. The shaded grey and yellow areas are currently excluded. The dashed curves are sensitivity lines of future planned and proposed experiments. *Right.* A ternary plot illustrating the flavour ratios compatible with LG. Inside the solid triangles LG with Dirac phase CP-violation can be successful. In the fainter blue (red) regions LG can be viable with additional sources of CP-violation. See the text and [17] for further details.

4. Conclusion

LG via oscillations with the CP-violation provided exclusively by the Dirac phase δ is feasible for masses of the two quasi-degenerate heavy Majorana neutrinos as low as 100 MeV, rather large coupling of the heavy Majorana neutrinos to the SM and with the possibility of either supporting or falsifying the scenario in future low-energy experiments. Future high-precision measurements of δ and the couplings Θ_α^2 could determine whether, within the scenario of LG considered, the Dirac phase can be the unique responsible for the present BAU, or if other sources of CP-violation are necessary.

Acknowledgements

This article is based upon work from COST Action COSMIC WISPers CA21106, supported by COST (European Cooperation in Science and Technology).

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