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Leptogenesis and low energy CP-violation

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Abstract. Within the context of the see-saw mechanism, we review the possible connection between the CP-violating phases which appear in the lepton unitary mixing matrix and are measurable in neutrino oscillations and other low-energy processes, with the ones which play a role in the generation of the baryon asymmetry of the universe through the leptogenesis mechanism.

1. Introduction

The origin of the matter-antimatter asymmetry is one of the most important questions in cosmology. Leptogenesis [1] has emerged as one of the favoured mechanisms to explain the baryon asymmetry. It relies on the fact that while $B - L$ is conserved both at the perturbative and non-perturbative level, the baryon and lepton number are non conserved separately. This implies that if one creates a net $B - L$, (e.g., a lepton number), the sphaleron processes would leave both baryon and lepton number comparable to the original $B - L$.

The possibility of establishing a connection between the low energy neutrino mixing parameters and high energy leptogenesis parameters has been studied extensively (see, e.g. [2, 3, 4, 5, 6, 7, 8]). As the number of parameters of seesaw models is significantly larger than the number of "low energy" quantities measurable in neutrino experiments, a one-to-one connection between these parameters is not possible in a model independent way. In particular, in a large number of studies which used the so-called "one-flavor approximation", it was shown that no direct link exists between the leptogenesis CP-violating parameters and the CP-violating Dirac and Majorana phases in the PMNS neutrino mixing matrix, measurable at low energies. Therefore, in the one-flavour case, the observation of leptonic low energy CP-violating phases would not automatically imply a nonvanishing baryon asymmetry through leptogenesis. This conclusion, however, does not universally hold [9, 10, 11]. In fact, if lepton flavour effects [9, 10, 11] are taken into account in the leptogenesis mechanism, the low-energy Dirac and/or Majorana CP-violating phases in $U_{\rm PMNS}$, which enter into the expressions respectively of the leptonic CP-violating rephasing invariant $J_{\rm CP}$ [12], controling the magnitude of the CP-violation effects in neutrino oscillations, and of the effective Majorana mass $| < m > |$ [13, 14, 15], can be the CP-violating parameters responsible for the generation of the baryon asymmetry of the Universe [7, 8] (see also [16]). Consequently, barring fine-tuned cancellations, the observation of CP-violation in the lepton (neutrino) sector would generically ensure the existence of a baryon asymmetry.

2. The see-saw mechanism and leptogenesis

Leptogenesis is particularly appealing because it takes place in the context of see-saw models [17], which naturally explain the smallness of neutrino masses. Heavy right-handed (RH) Majorana neutrinos, N_i, completely neutral under the Standard Theory gauge symmetry group are added to the Standard Theory. The Lagrangian reads

$$-\mathcal{L} = \overline{N_i}\,(m_D)_{ij}\,\nu_{Lj} \; + \text{h.c.} + \frac{1}{2}\,\overline{(N_i)^c}\,(M_R)_{ij}\,N_j \; , \tag{1}$$

where ν_{Lj} are the Standard Theory neutrinos, m_D and M_R are the Dirac and Majorana mass matrices, respectively. For sufficiently large M_R, N_i decouple and one finds the see–saw [17] formula for the low-energy neutrino mass matrix m_ν

$$m_\nu = U^*_{\text{PMNS}}\; D_m\; U^\dagger_{\text{PMNS}} \simeq m_D^T\; M_R^{-1}\; m_D \; . \tag{2}$$

D_m is a diagonal matrix containing the masses $m_{1,2,3}$ of the three light massive Majorana neutrinos and U_{PMNS} is the unitary Pontecorvo–Maki–Nagakawa–Sakata mixing matrix.

The CP-violating and out-of-equilibrium decays of RH neutrinos produce a lepton asymmetry [1] that is then converted into a baryon asymmetry through anomalous electroweak processes [18]. In the so-called "one-flavour approximation" all the lepton flavours are treated on the same footing and only one CP-asymmetry is relevant [1, 19, 20] :

$$\varepsilon_1 = \frac{\Gamma(N_1 \to \Phi^-\,\ell^+) - \Gamma(N_1 \to \Phi^+\,\ell^-)}{\Gamma(N_1 \to \Phi^-\,\ell^+) + \Gamma(N_1 \to \Phi^+\,\ell^-)} \simeq \frac{3}{16\,\pi\,v^2} \sum_{j\neq 1} \frac{\text{Im}(m_D\,m_D^\dagger)^2_{1j}}{(m_D\,m_D^\dagger)_{11}}\,\frac{M_1}{M_j} \; , \tag{3}$$

where we have assumed hierarchical N_i. Φ and ℓ indicate the Higgs field and the charged leptons, respectively. Here $v \simeq 174$ GeV is the electroweak symmetry breaking scale. $\Gamma(N_1 \to \Phi\,\ell)$ indicates the N_1 decay rate. The final lepton asymmetry depends on one additional single parameter which takes into in account the washout of the CP-asymmetry, $\widetilde{m_1} \propto (m_D\; m_D^\dagger)_{11}$, which is proportional to the total decay rate of the heavy RH Majorana neutrino N_1. Notice again that $\widetilde{m_1}$ is obtained by computing the total decay rate of the N_1, that is by summing over all the flavours. The asymmetry in the total baryon charge is then given by

$$Y_B \simeq -\frac{1}{2}\frac{\epsilon_1}{g_*}\eta\,(\widetilde{m_1}) \; , \tag{4}$$

where $\eta\,(\widetilde{m_1})$ accounts for the washing out due to inverse decays.

The final baryon asymmetry in the "one flavour approximation" depends always upon the trace of the CP asymmetries over flavours, ϵ_1, times a function of the trace over flavours of the decay rate of the RH neutrino N_1. Notice that, in this approximation, the lepton asymmetry, say, in the electron lepton number can be washed out by inverse decays involving the second and/or the third family (which erase only the muon and/or tau lepton charges). This approximation holds as far as lepton flavours are indistinguishable.

2.1. Flavour effects

The 'one-flavour' approximation is rigourously correct only when the interactions mediated by charged lepton Yukawa couplings are out of equilibrium. For a leptogenesis temperature $T \sim M_1$, the 'one-flavour' approximation holds only for $T \sim M_1 > 10^{12}$ GeV, where there is no notion of flavour. However, for $T \sim M_1 \sim 10^{12}$ GeV, the interactions mediated by the τ-lepton Yukawa couplings come into equilibrium, followed by those mediated by the muon Yukawa couplings at $T \sim M_1 \sim 10^9$ GeV, and the notion of lepton flavour becomes physical.

When flavour effects are accounted for, the final value of the baryon asymmetry is the sum of three contributions [21, 9, 10, 11, 6]. Each term is given by the CP asymmetry in a given lepton flavour l, properly weighted by a wash-out factor induced by the same lepton number violating processes. Therefore, the asymmetries in each lepton flavour are washed out differently. The asymmetry in each flavour l is given by

$$\epsilon_l = \frac{3}{16\pi v^2} \frac{1}{(m_D m_D^\dagger)_{11}} \, \mathrm{Im}\Big(\sum_j \Big((m_D)_{1l} (m_D m_D^\dagger)_{1j} (m_D^*)_{jl} \Big) \Big) \frac{M_1}{M_j} \,. \tag{5}$$

Obviously, the trace over the flavours of ϵ_l coincides with ϵ_1.

Similarly, one has to define a "wash-out mass parameter" for each flavour l [9, 11], $\widetilde{m_l} \propto |(m_D)_{1l}|^2$, which parametrizes the decay rate of N_1 to the leptons of flavour l. The trace $\sum_l \widetilde{m_l}$ coincides with the $\widetilde{m_1}$ parameter defined in the previous section.

What is more relevant is that the total baryon asymmetry is the sum of each individual lepton asymmetry. In the rest of the paper we will be concerned with temperatures ($10^9 \leq T \sim M_1 \leq 10^{12}$) GeV. In this range only the interactions mediated by the τ Yukawa coupling are in equilibrium and the final baryon asymmetry is well approximated by [11]

$$Y_B \simeq -\frac{12}{37 g_*} \left(\epsilon_2 \, \eta \left(\frac{417}{589} \widetilde{m_2} \right) + \epsilon_\tau \, \eta \left(\frac{390}{589} \widetilde{m_\tau} \right) \right) , \tag{6}$$

where $\epsilon_2 = \epsilon_e + \epsilon_\mu$, $\widetilde{m_2} = \widetilde{m_e} + \widetilde{m_\mu}$ and $\eta\left(\widetilde{m_l}\right)$ is a function of $\widetilde{m_l}$ [11]. From the generic expression for the baryon asymmetry, we deduce that the CP asymmetry in each flavour is weighted by the corresponding wash-out parameter. Therefore, the total baryon number is generically not proportional to ϵ_1.

3. The connection between the low-energy leptonic CP-violating phases and the leptogenesis one

As leptogenesis requires lepton number non-conservation, the possible observation of neutrinoless double beta ($(\beta\beta)_{0\nu}$)-decay in the present and future experiments would play an important role in understanding the origin of the baryon asymmetry as it would imply that lepton number indeed is not conserved. The observation of CP-violation in the lepton sector, in neutrino oscillation experiments and/or $(\beta\beta)_{0\nu}$-decay, would suggest the existence of CP-violation at high energy, which might be related to the one responsible for leptogenesis. Establishing a connection between the parameters at low energy (in particular, the CP-violating phases), measurable in principle in present and future experiments, and at high energy (relevant in leptogenesis) is of great importance.

It should be noticed that the number of parameters in the full Lagrangian of models which implement the see-saw mechanism is larger than the ones in the low-energy sector: in the case of 3 light neutrino generations and three heavy ones, at high energy the theory contains in the neutrino sector 18 parameters of which 12 real ones and 6 phases, while at low energy only 9 are accessible - 3 angles, 3 masses and 3 phases. The decoupling of the heavy right-handed neutrinos implies the loss of information on 9 parameters, of which three phases. It follows that a "one-to-one connection" between the low-energy and the high energy parameters is not possible in a model independent way. However, typically models implementing symmetries, textures or other tools to explain the low energy flavour structure have a reduced number of parameters and might allow such a connection.

Using the basis in which both M_R and the charged lepton mass matrix are real and diagonal, we consider the orthogonal parametrization for the Dirac mass [22]:

$$m_D \simeq \sqrt{M_R}\,\mathbf{R}\,D_m^{1/2}\,U_{\text{PMNS}}^\dagger\ , \tag{7}$$

where D_m is the diagonal real matrix which contains the low-energy light neutrino masses, and $\mathbf{R}$ is a complex orthogonal matrix. $\mathbf{R}$ contains 3 real parameters and 3 phases and can be represented as $\mathbf{R} = e^{i\mathbf{A}}\mathbf{O}$ [23], where $\mathbf{A}$ and $\mathbf{O}$ are respectively real antisymmetric and real orthogonal matrices.

In the "one-flavour" approximation, the CP asymmetry depends upon the trace of the CP asymmetries over flavours:

$$\epsilon_1 = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_{\alpha\beta\rho} m_\rho^{1/2} m_\beta^{3/2} U_{\alpha\rho}^* U_{\alpha\beta} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta\, |R_{1\beta}|^2} = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta\, |R_{1\beta}|^2}\,. \tag{8}$$

We can notice that the PMNS unitary mixing matrix U does not enter explicitly into the expression for the lepton asymmetry. Therefore in general it is not possible to obtain a direct connection between the leptogenesis phases with the ones measurable at low-energy.

At $T < 10^{12}$ GeV, flavours are distinguishable and the asymmetry in each flavour is given by

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{\alpha\beta}^* U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta\, |R_{1\beta}|^2}\,. \tag{9}$$

Since the CP asymmetry in each flavour is weighted by the corresponding wash out parameter, the total baryon number is not proportional to ϵ_1. It should be clear from Eq. (9) that we can have $\epsilon_l \neq 0$ even if, e.g., R is a real matrix and $R \neq \mathbf{1}$. If, however, R is a diagonal matrix, e.g., if $R = \mathbf{1}$, all three lepton number asymmetries vanish: $\epsilon_l = 0$, $l = e, \mu, \tau$. Since the PMNS matrix elements are explicitly present in the expression of ϵ_α, CP violating phases in low energy neutrino phenomena enter *directly* in the determination of the baryon asymmetry through leptogenesis [7, 8, 10, 11].

4. Leptogenesis uniquely from low-energy CP-violation.

We consider for definiteness hierarchical heavy Majorana neutrinos, with $M_1 \ll M_2 \ll M_3$. We take the matrix R to be real [10, 11, 7, 8] corresponding to the class of models where CP is an exact symmetry in the right-handed neutrino sector. Notice that, as $\epsilon_1 = 0$, we have $\epsilon_2 = -\epsilon_\tau$ and only one flavour CP-asymmetry needs to be studied. The flavour CP asymmetries and, consequently, the baryon asymmetry depend *exclusively on the low energy phases*. Leptogenesis is maximally connected to the low energy phases: the observation of low energy CP violation in the neutrino sector ensures the existence of a baryon asymmetry. For concreteness, we choose to consider the normal hierarchical mass spectrum for light neutrinos, characterised by $m_1 \ll m_2 \ll m_3$. We take the simplest case of decoupling of the heaviest right-handed neutrinos, corresponding to $R_{11} = 0$. Detailed results for generic R and for the other choices of neutrino mass spectrum can be found in Ref. [8].

Let's consider the interesting possibility of Majorana CP-violation due to $\alpha_{32} \neq 0, 2\pi$ in U_{PMNS}. By taking into account also the wash-out factors, we can express the dependence of the baryon asymmetry on α_{32} [8]:

$$|Y_B| \cong 2.0\, \times 10^{-10} \left(\frac{M_1}{10^{11}\ \text{GeV}}\right) |\sin\left(\alpha_{32}/2\right)|\ . \tag{10}$$

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Here, we have taken $\theta_{13} = 0$, $R_{12} = 0.92$ and $R_{13} = 0.39$, and used the best fit values for the oscillation parameters. We find that the observed baryon asymmetry, having a value in the interval $8.0 \times 10^{-11} \leq |Y_B| \leq 9.2 \times 10^{-11}$, can be reproduced for $M_1 \geq 3.6 \times 10^{10}$ GeV.

We turn now to study the case in which low energy CP-violation is only due to the Dirac phase, with $\alpha_{32} = 0, 2\pi$. In this case, the asymmetry depends on the δ phase and is suppressed by the $\sin\theta_{13}$ term. The baryon asymmetry is then given by [8]:

$$|Y_B| \cong 2.8 \times 10^{-11} \, |\sin\delta| \left(\frac{s_{13}}{0.2}\right) \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right) . \tag{11}$$

Thus, the maximal asymmetry $|Y_B|$ in the case of CP-violation due only to the Dirac phase δ in U_{PMNS} is approximately by a factor of 7 smaller than the maximal asymmetry due to violation of the CP-symmetry by the Majorana phase α_{32} of U_{PMNS}.

In order to reproduce the observed baryon asymmetry, taken to lie in the interval $8.0 \times 10^{-11} \leq |Y_B| \leq 9.2 \times 10^{-11}$, $s_{13}|\sin\delta|$ and M_1, in the case analised, should satisfy [8]:

$$2.9 \leq |\sin\delta| \left(\frac{s_{13}}{0.2}\right) \left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right) \leq 3.3 . \tag{12}$$

Given that $s_{13}|\sin\delta| \leq 0.2$, the lower bound in this inequality can be satisfied only for $M_1 \geq 2.9 \times 10^{11}$ GeV. Recalling that the flavour effects in leptogenesis are fully developed for $M_1 \leq 5 \times 10^{11}$ GeV, we obtain a *lower bound on the values of* $|s_{13}\sin\delta|$ *and* s_{13} *for which we can have successful leptogenesis in the case considered* [8]:

$$|\sin\theta_{13}\,\sin\delta| \geq 0.11 , \quad \sin\theta_{13} \geq 0.11 . \tag{13}$$

Values of s_{13} in the range given in Eq. (13) can be probed in the forthcoming Double CHOOZ [24] and future reactor neutrino experiments [25]. CP-violation effects with magnitude determined by $|\sin\theta_{13}\,\sin\delta|$ satisfying Eq. (13) are within the sensitivity of the next generation of neutrino oscillation experiments, designed to search for CP- or T- symmetry violations in neutrino oscillations [26].

5. Conclusions

The possible observation of $(\beta\beta)_{0\nu}$-decay would play an important role in understanding the origin of the baryon asymmetry as it would imply that lepton number (one of the main conditions for leptogenesis) indeed is not conserved. In addition, the observation of CP-violation in the lepton sector, in neutrino oscillation experiments and/or $(\beta\beta)_{0\nu}$-decay, would suggest the existence of CP-violation at high energy, which might be related to the one responsible for leptogenesis. Due to the complicated way in which the high energy phases and real parameters enter in m_ν, if there is CP-violation at high energy, as required by the leptogenesis mechanism, we can expect in general to have CP-violation at low-energy, as a complete cancellation would require some fine-tuning or special forms of m_D and M_R. Conversely, it was shown recently that, once lepton flavour effects are relevant and properly taken into account, the phases in the PMNS mixing matrix enter explicitly in the CP-asymmetry and consequently in the baryon asymmetry. Therefore, the observation of low-energy CP-violation would generically imply a non-vanishing baryon asymmetry. Even more, it is possible that the only source of CP-violation in leptogenesis comes from the low-energy Majorana and Dirac CP-violating phases. In conclusion, the observation of lepton number violation in $(\beta\beta)_{0\nu}$-decay and, possibly, of leptonic CP-violation would be a strong indication, even if not a proof (as it is not possible to reconstruct in a model indipendent way the high energy parameters from m_ν), of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

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