Leptogenesis and Low-energy Observables

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We address the question of how to establish a connection between leptogenesis and low energy observables. We emphasize that such a connection only exists in the framework of flavour models. A particular example is the case of texture zeros in some of the Yukawa couplings.

1. Introduction

The experimental discovery of neutrino masses and leptonic mixing is one of the most important recent developments in Particle Physics. It is well known that in the Standard Model (SM), neutrinos are strictly massless, due to the absence of right-handed neutrinos, together with exact \( B-L \) conservation. Therefore, the discovery of non-vanishing neutrino masses is a clear indication of physics beyond the SM.

One of the simplest ways of accommodating neutrino masses is through the introduction of at least two right-handed neutrinos, leading to the seesaw mechanism. Apart from offering an elegant explanation for the smallness of neutrino masses, the seesaw mechanism also provides a framework to create the observed baryon asymmetry of the Universe (BAU). This is achieved through leptogenesis, a mechanism first suggested in Ref. [1], where out-of-equilibrium decays of heavy right-handed neutrinos create a lepton asymmetry which in turn is converted into a baryon asymmetry, through sphaleron interactions [2], [3]. Since leptogenesis, together with neutrino masses, leptonic mixing and leptonic CP violation, all arise from the seesaw mechanism, it is natural to ask whether there is a connection between leptogenesis and low energy observables. Furthermore, such a connection would be necessary in order to test leptogenesis, assuming the heavy neutrinos masses lie outside the reach of future experiments.

2. Low-energy observables

Let us assume that lepton number is violated at a high energy scale, leading to the generation at low energies of an effective left-handed Majorana neutrino mass matrix. In the mass eigenstate basis, the charged weak current can be written:

\[
L_W = -\frac{g}{\sqrt{2}} l_L \gamma^\mu U_{jk} \nu_k \gamma_L + h.c.,
\]

where \( U \) denotes the leptonic mixing matrix at low energies, usually named the Pontecorvo, Maki, Nakagawa and Sakata (PMNS) matrix. Although in the see-saw framework \( U \) is not exactly unitary, in the standard seesaw type I framework, \( U \) is unitary to a high degree of accuracy. Once 3×3 unitarity is assumed, \( U \) is characterized by six parameters which are usually taken as three mixing angles and three CP violating phases. Due to the assumed Majorana nature of neutrinos, the simplest rephasing invariant functions of \( U_{ij} \) are the bilinears \( U_{i\alpha} U_{j\beta}^\ast \) (no summation on repeated indices implied). Using unitarity, it has been shown [4] that the full matrix \( U \) can be constructed from six independent Majorana-type phases \( \phi_{i\beta} \equiv \arg (U_{i\alpha} U_{j\beta}^\ast) \). There are nine low energy observables, namely the three light neutrino masses and the six parameters characterizing \( U \) [5]. The question is then whether it is possible to relate leptogenesis to the low energy observables.
3. Leptogenesis and the relation to Low-energy Observables

Let us consider the SM with the addition of three right-handed (r.h.) neutrinos. In this case, one can write an $SU(2) \times U(1)$ invariant Majorana mass term for r.h. neutrinos, denoted $M_R$, assumed to be of a scale much higher than the electroweak scale, $v$. After spontaneous $SU(2) \times U(1)$ breaking, a neutrino Dirac mass matrix $m_D$ is also generated. This leads to an effective $3 \times 3$ neutrino Dirac mass matrix in the weak basis (WB) where $M_R$ is diagonal and real. In this case, the PMNS matrix.

It can be shown that, to an excellent, approximation $G = m_D D^{-1}$ in the WB where $M_R$ is also diagonal and real and where $D = \text{diag}(M_1, M_2, M_3)$ with $M_i$ denoting the masses of the three heavy neutrinos $N_i$. $K$ coincides very approximately, up to corrections of order $v/M_R$, with the unitary matrix that diagonalizes $m_{\text{eff}}$, in the WB where the charged lepton mass matrix is already real and diagonal, i.e., the PMNS matrix.

The lepton number asymmetry generated through CP violating decays of the $j$-th heavy Majorana neutrino into the different leptonic families has been computed $[7,8,9,10]$ in the single flavour approximation, and shown to be proportional to:

$$A^j \alpha \sum_{k \neq j} \text{Im}(m_D^\dagger m_D)_{jk}(m_D^\dagger m_D)_{kj}$$

(3)

in the weak basis (WB) where $M_R$ is diagonal. In the seesaw framework the matrix $m_D$, in this WB, can be written $[11]$

$$m_D = iU\sqrt{dR}\sqrt{D}$$

(4)

where $D$ stands for $M_R$ and $R$ is a general complex orthogonal matrix. The matrix $R$ is relevant for leptogenesis since:

$$m_D^\dagger m_D = -\sqrt{D}R^\dagger dR\sqrt{D}.$$  

(5)

Eq. (4) shows that in general unflavoured leptogenesis is independent of the presence of CP violation at low energies $[12]$. Notice that in the WB where the charged lepton mass matrix and $M_R$ are real and diagonal, all CP violating phases appear in $m_D$.

It is possible to impose constraints on $m_D$ in the context of special flavour models. A particular example is the imposition of zero textures on $m_D$ in the WB where the charged lepton mass matrix and $M_R$ are real and diagonal. In this case one has

$$\langle m_D \rangle_{ij} = 0 \Rightarrow (U)_{ik} \sqrt{d_{kk}} R_{kj} = 0.$$  

(6)

corresponding to an orthogonality condition between one column of the matrix $R$ and one row of the matrix $U \sqrt{d}$. Imposing texture zeros on $m_D$ reduces the number of CP violating phases and in some cases, allows to fully relate the matrix $R$ to low energy parameters while at the same time imposing constraints on low energy physics $[13,14]$. The expression written above relating the mixing matrix $G$ to the matrix $m_D$ also shows how constraints on $m_D$ may affect high energy physics.

It is important to notice that textures are not WB independent and symmetries are only explicit in specially chosen WB. On the other hand it may be convenient to analyse specific flavour models without the requirement of being in a particular WB or going to the physical basis. CP-odd WB invariants can be useful to study CP violation both in the quark and leptonic sector. The technique to obtain CP-odd WB invariant conditions was developed for the first time in $[15]$ for the study of CP violation in the quark sector of the Standard Model. This is a powerful tool, and the fact that constraints imposed on the mass matrices will in general reduce the number of CP violating phases, also allows to use this type of conditions in particular cases, to recognize models with texture zeros when written in a WB where these are not present $[13]$. Weak basis invariant conditions relevant for CP violation in the leptonic sector at low energies must be sensitive to the Dirac-type phase as well as to Majorana-type
phases. These were given in [16, 17, 18]. Weak basis invariant conditions relevant in the case of unflavoured leptogenesis were first presented in [19], [18]. Details and further analysis are given in [20], [21].

Leptogenesis in the single flavour approximation relies on the assumption that washout effects are not sensitive to the different flavours of charged leptons into which the heavy neutrino decays. It was pointed out that flavour matters in leptogenesis whenever the mass of the lightest heavy neutrino is lower than $10^{12}$ GeV [22, 23, 24, 25, 26, 27].

The separate lepton $i$ family asymmetry generated from the decay of the $k$th heavy Majorana neutrino depends on the combination [21] $\text{Im} \left( (m_D^† m_D)_{kk'} \left( m_D^* \right)_{ik} (m_D)_{ik'} \right)$ as well as on $\text{Im} \left( (m_D^† m_D)_{k'k} \left( m_D^* \right)_{ik} (m_D)_{ik'} \right)$. It is clear from these expressions that in the case of flavoured leptogenesis there are additional sources of CP violation since the PMNS matrix does not cancel out. This gives rise to the new possibility of having viable leptogenesis even in the case of $R$ being a real matrix. For some of the early attempts see [28, 29, 30, 31]. In the case of real $R$, the phases relevant for leptogenesis are arguments of the Majorana bilinears introduced in section 2.

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