Leptonic CP Violation and Baryon Asymmetry

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The observation of neutrino masses leads to the possibility of leptonic mixing and CP violation. One of the simplest extensions of the Standard Model giving rise to neutrino masses consists of the introduction of one righthanded neutrino field per generation, singlet of SU(2). In the context of the seesaw mechanism this leads to three light and three heavy neutrinos. The charged current interactions couple the charged leptons to both the light and the heavy physical neutrinos and leptonic CP violation may occur at low energies as well as at high energies giving rise to the possibility of leptogenesis. There are special scenarios where it is possible to establish a connection between CP violation at the two different scales, an interesting example is included in this work. Furthermore, we describe how the conjecture that all phenomena of CP violation present in nature could have a common origin can be realized in the framework of a further minimal extension of the Standard Model with CP broken through the phase of the vacuum expectation value of a complex Higgs singlet.

1 Introduction

At present there is strong evidence for nonzero neutrino masses and nontrivial leptonic mixing implying for the first time the existence of physics beyond the Standard Model. In fact in the Standard Model (SM) neutrinos are strictly massless and any extension giving rise to neutrino masses will contain new ingredients not present before in the SM. The simplest way of extending the SM in order to take into account neutrino masses is the inclusion of righthanded neutrino singlets, in analogy with all other fermions in the theory. Yet once righthanded neutrinos are included both Dirac mass terms and Majorana mass terms for righthanded neutrinos are allowed. The scale of the Dirac mass terms is the electroweak scale, v, whilst there are no constraints on the scale of the righthanded Majorana mass terms. In Grand Unified models it
is natural to assume this scale, V, to be of the order of the Grand Unification scale. Mixing and CP violation in the leptonic sector naturally arise once righthanded neutrinos are included. In what follows we generally assume their number to be three although, in fact, the number of righthand neutrino fields could differ from the number of lefthanded fields. When the two scales v and V are very different, with V much larger than v, the seesaw mechanism \cite{seesaw} operates providing an elegant explanation for the smallness of the observed neutrino masses. In the context of seesaw there are three light neutrinos with small masses and an additional number of very heavy neutrinos (the number of heavy neutrinos equals the number of righthanded neutrinos included) with masses that can be of the order of the Grand Unification scale. As a result there can be leptonic CP violation at low energies as well as at high energies. Leptonic CP violation at high energies could be the explanation for the generation of the observed baryon asymmetry of the Universe (BAU) via the leptogenesis mechanism \cite{leptogenesis} where a CP asymmetry generated through the out-of-equilibrium L-violating decays of the heavy Majorana neutrinos leads to a lepton asymmetry which is subsequently transformed into a baryon asymmetry by (B+L)-violating sphaleron processes \cite{sphalerons}. In general there is no connection between CP violation at low and high energies \cite{connection} yet this connection can be established in special frameworks \cite{special-frameworks}. One can go further and ask whether there is a framework where all CP violations have a common origin. In Ref. \cite{common-origin} it was shown that this is indeed possible in a small extension of the Standard Model with neutrino righthanded singlets, a vectorial quark isosinglet and a complex Higgs scalar.

\section{Framework}

We work in the context of a minimal extension of the SM which consists of adding to the standard spectrum one right-handed neutrino per generation. After spontaneous gauge symmetry breaking, the following leptonic mass terms can be written:

\begin{equation}
\mathcal{L}_m = -\overline{\nu}_L^0 m_D \nu_R^0 + \frac{1}{2} \nu_R^0 C M_R \nu_L^0 + \overline{\nu}_R^0 m_l^0 \nu_R^0 + h.c. = \\
= -\frac{1}{2} n_L^T C M^* n_L + \overline{\nu}_R^0 m_l^0 \nu_R^0 + h.c. \quad (1)
\end{equation}

where $m_D$, $M_R$ and $m_l$ denote the neutrino Dirac mass matrix, the righthanded neutrino Majorana mass matrix and the charged lepton mass matrix, respectively, and $n_L = (\nu_L^0, (\nu_R^0)^\dagger)$ (should be interpreted as a column matrix). In order to study CP violation in a weak basis (WB) it is necessary to consider the most general CP transformation which leaves the gauge interaction invariant:

\begin{align}
\text{CP} \nu_L (\text{CP})^\dagger &= U_{\gamma} \nu_L^0 C m_L^T \\
\text{CP} \nu_R (\text{CP})^\dagger &= V_{\gamma} \nu_R^0 C m_R^T \\
\text{CP} \nu_L (\text{CP})^\dagger &= U_{\gamma} \nu_R^0 C \nu_L^T \\
\text{CP} \nu_R (\text{CP})^\dagger &= V_{\gamma} \nu_L^0 C \nu_R^T \quad (2)
\end{align}
where \( U, V, W \) are unitary matrices acting in flavour space and where for notation simplicity we have dropped here the superscript 0 in the fermion fields. Invariance of the mass terms under the above CP transformation, requires that the following relations have to be satisfied:

\[
W^T M_R W = -M^*_R \tag{3}
\]
\[
U^\dagger m_D W = m_D^* \tag{4}
\]
\[
U^\dagger m_l V = m_l^* \tag{5}
\]

In \cite{7}, it was shown, making use of these equations, that the number of independent CP violating phases which appear in general in this model is \((n^2 - n)\), with \( n \) the number of generations. The same result was obtained in \cite{8} through an analysis performed in the physical basis. In the general case where a Majorana mass term for lefthanded neutrinos is also present the number of CP violating phases would be \( (n^2 + n(n - 1)/2) \).

In the case of three generations (three lefthanded and three righthanded neutrinos), the full neutrino mass matrix, \( \mathcal{M} \) in Eq. (1), is 6 \times 6, and has the following form:

\[
\mathcal{M} = \begin{pmatrix}
0 & m
m^T & M
\end{pmatrix} \tag{6}
\]

We have dropped the subscript in \( m_D \) and \( M_R \) in order to simplify the notation. Starting from a weak basis where \( m_l \) is already diagonal and real the neutrino mass matrix is diagonalized by the transformation:

\[
V^T \mathcal{M}^* V = \mathcal{D} \tag{7}
\]

where \( \mathcal{D} = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, M_{\nu_1}, M_{\nu_2}, M_{\nu_3}) \), with \( m_{\nu_i} \) and \( M_{\nu_i} \) denoting the physical masses of the light and heavy Majorana neutrinos, respectively. It is convenient to write \( V \) and \( \mathcal{D} \) in the following form:

\[
V = \begin{pmatrix}
K & R
S & T
\end{pmatrix}; \tag{8}
\]
\[
\mathcal{D} = \begin{pmatrix}
d & 0
0 & D
\end{pmatrix}. \tag{9}
\]

It can be easily verified that both \( S \) and \( R \) are of order \( \frac{m_D}{M} \) (with \( R = mT^*D^{-1} \)) and that \( K \) is, to an excellent approximation, the unitary matrix that diagonalizes \( m_{\text{eff}} \equiv m \frac{1}{M} m^T \):

\[
-K^\dagger m \frac{1}{M} m^T K^* = d \tag{10}
\]

which is the usual seesaw formula. In this approximation \( K \) is a unitary matrix which coincides with the Maki, Nakagawa and Sakata matrix \( (V_{MNS}) \) \cite{10}.

The neutrino weak-eigenstates are related to the mass eigenstates by:
\[ \nu_{iL}^0 = V_{i\alpha} \nu_{\alpha L} = (K, R) \left( \begin{array}{c} \nu_{iL} \\ N_{iL} \end{array} \right) \left( \begin{array}{c} i = 1, 2, 3 \\ \alpha = 1, 2, \ldots 6 \end{array} \right) \] (11)

and thus the leptonic charged current interactions are given by:

\[-\frac{g}{\sqrt{2}} \left( \overline{l_i} \gamma_\mu K_{ij} \nu_{jL} + \overline{l_i} \gamma_\mu R_{ij} N_{jL} \right) W^{\mu} + h.c. \] (12)

From Eqs. (11), (12) it follows that K and R give the charged current couplings of charged leptons to the light neutrinos \( \nu_j \) and to the heavy neutrinos \( N_j \), respectively. In the exact decoupling limit, R can be neglected and only K is relevant. In this case two of the phases that can be factored out of K (in the approximation of exact unitarity) cannot be rotated away due to the Majorana character of the neutrino fields and, as a result, K is left with three CP violating phases (one of Dirac type and two of Majorana character). However, since we want to study the connection between CP violation relevant to leptogenesis and that observable at low energies (e.g., in neutrino oscillations) we have to keep both K and R.

The present knowledge of leptonic masses and mixing is still incomplete despite great recent progress. The evidence for solar and atmospheric neutrino oscillations is now solid and it is already established that the pattern of the leptonic mixing matrix \( V_{MNS} \) is very different from that of the quark sector \( V_{CKM} \), since only one of the leptonic mixing angles, \( \theta_{13} \), is small (the notation is that of the standard parametrization of \( V_{CKM} \) in [11]). Recent KamLAND results [12], a terrestrial long baseline experiment which has great sensitivity to the square mass difference relevant for solar oscillations, \( \Delta m^2_{21} \), combined with those of SNO [13] and previous solar experiments [14] lead, for the 1\( \sigma \) range [15], to:

\[ \Delta m^2_{21} \equiv |m^2_2 - m^2_1| = 8.2^{+0.3}_{-0.4} \times 10^{-5} \text{ eV}^2 \] (13)

\[ \tan^2 \theta_{12} = 0.39^{+0.05}_{-0.04} \] (14)

and corresponds to the large mixing angle solution (LMA) of the Mikheev, Smirnov and Wolfenstein (MSW) effect [16]. On the other hand, atmospheric neutrino results from Superkamiokande [17] and recent important progress by K2K [18], which is also a terrestrial long baseline experiment, are consistent with, for the 1\( \sigma \) range [15]:

\[ \Delta m^2_{32} \equiv |m_3^2 - m_2^2| = 2.2^{+0.6}_{-0.4} \times 10^{-3} \text{ eV}^2 \] (15)

\[ \tan^2 \theta_{23} = 1.0^{+0.35}_{-0.26} \] (16)

Assuming the range for \( \Delta m^2_{32} \) from SuperKamiokande and K2K, the present bounds for \( \sin^2 \theta_{13} \) from the CHOOZ experiment [19] at 3\( \sigma \) lie [15] in \( \sin^2 \theta_{13} < 0.05 - 0.07 \). The value for the angle \( \theta_{13} \) is critical for the prospects of detection of low energy leptonic CP violation, mediated through a Dirac-type phase, \( \delta \), whose strength is given by \( J_{CP} \):
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\[ \mathcal{J}_{CP} \equiv \text{Im} \left[ (V_{11}V_{22}V_{12}^*V_{21}) \right] = \frac{1}{8} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \cos(\theta_{13}) \sin \delta, \]

(17)

Direct kinematic limits on neutrino masses \[20\] from Mainz and Troitsk and neutrinoless double beta decay experiments \[21\] when combined with the given square mass differences exclude light neutrino masses higher than order 1 eV. Non-vanishing light neutrino masses also have an important impact in cosmology. Recent data from the Wilkinson Microwave Anisotropy Probe, WMAP \[22, 23\], together with other data, put an upper bound on the sum of light neutrino masses of 0.7 eV.

3 General Conditions for Leptogenesis

The lepton-number asymmetry resulting from the decay of heavy Majorana neutrinos, \( \varepsilon_{N_j} \), was computed by several authors \[24\]. The evaluation of \( \varepsilon_{N_j} \), involves the computation of the interference between the tree level diagram and one loop diagrams for the decay of the heavy Majorana neutrino \( N^j \) into charged leptons \( l^k_i \) \((i = e, \mu, \tau)\) leading to:

\[
\varepsilon_{N_j} = \frac{g^2}{M_W^2} \sum_{k \neq j} \left[ \text{Im} \left( (m^\dagger m)_{jk} (m^\dagger m)_{jk} \right) \frac{1}{16\pi} \left( I(x_k) + \frac{\sqrt{x_k}}{1 - x_k} \right) \right] \frac{1}{(m^\dagger m)_{jj}}
\]

\[
= \frac{g^2}{M_W^2} \sum_{k \neq j} \left[ (M_k)^2 \text{Im} \left( (R^\dagger R)_{jk} (R^\dagger R)_{jk} \right) \frac{1}{16\pi} \left( I(x_k) + \frac{\sqrt{x_k}}{1 - x_k} \right) \right] \frac{1}{(R^\dagger R)_{jj}}
\]

(18)

where \( M_k \) denote the heavy neutrino masses, the variable \( x_k \) is defined as \( x_k = \frac{M_k^2}{M_j^2} \) and \( I(x_k) = \sqrt{x_k} \left( 1 + (1 + x_k) \log \left( \frac{x_k}{1 + x_k} \right) \right) \). From Eq. (18) it can be seen that the lepton-number asymmetry is only sensitive to the CP-violating phases appearing in \( m^\dagger m \) in the WB, where \( M_R \equiv M \) is diagonal (notice that this combination is insensitive to rotations of the left-hand neutrinos).

The simplest leptogenesis scenario corresponds to heavy hierarchical neutrinos where \( M_1 \) is much smaller than \( M_2 \) and \( M_3 \). In this limit only the asymmetry generated by the lightest heavy neutrino is relevant, due to the existence of washout processes, and \( \varepsilon_{N_1} \) can be simplified into:

\[
\varepsilon_{N_1} \simeq -\frac{3}{16 \pi v^2} \left( I_{12} \frac{M_1}{M_2} + I_{13} \frac{M_1}{M_3} \right),
\]

(19)

where

\[
I_{1i} = \text{Im} \left[ \frac{(m^\dagger m)_{1i}}{(m^\dagger m)_{11}} \right].
\]

(20)

Thermal leptogenesis is a rather involved thermodynamical non-equilibrium process and depends on additional parameters. In the hierarchical case the
baryon asymmetry only depends on four parameters \[25\]: the mass \(M_1\) of the lightest heavy neutrino, together with the corresponding CP asymmetry \(\varepsilon_{N_1}\) in their decays, as well as the effective neutrino mass \(\tilde{m}_1\) defined as

\[
\tilde{m}_1 = (m^\dagger m)_{11}/M_1
\]

in the weak basis where \(M\) is diagonal, real and positive and, finally, the sum of all light neutrino masses squared, \(\tilde{m}^2 = m_1^2 + m_2^2 + m_3^2\). It has been shown that this sum controls an important class of washout processes. Successful leptogenesis would require \(\varepsilon_{N_1}\) of order \(10^{-8}\), if washout processes could be neglected, in order to reproduce the observed ratio of baryons to photons \[22\]:

\[
\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}.
\]

Leptogenesis is a non-equilibrium process that takes place at temperatures \(T \sim M_1\). This imposes an upper bound on the effective neutrino mass \(\tilde{m}_1\) given by the “equilibrium neutrino mass” \[26\]:

\[
m_* = \frac{16\pi^{5/2}}{3\sqrt{3}} g_*^{1/2} \frac{v^2}{M_{Pl}} \simeq 10^{-3} \text{ eV},
\]

where \(M_{Pl}\) is the Planck mass (\(M_{Pl} = 1.2 \times 10^{19} \text{ GeV}\), \(v = \langle \phi^0 \rangle / \sqrt{2} \simeq 174\) GeV is the weak scale and \(g_*\) is the effective number of relativistic degrees of freedom in the plasma and equals 106.75 in the SM case. Yet, it has been shown \[27\], \[28\] that successful leptogenesis is possible for \(\tilde{m}_1 < m_*\) as well as \(\tilde{m}_1 > m_*\), in the range from \(\sqrt{\Delta m^2_{12}}\) to \(\sqrt{\Delta m^2_{23}}\). The square root of the sum of all neutrino masses squared \(\tilde{m}\) is constrained, in the case of normal hierarchy, to be below 0.20 eV \[24\], which corresponds to an upper bound on light neutrino masses very close to 0.10 eV. This result is sensitive to radiative corrections which depend on top and Higgs masses as well as on the treatment of thermal corrections. In \[28\] a slightly higher value of 0.15 eV is found. From Eq. 19 a lower bound on the lightest heavy neutrino mass \(M_1\) is derived. Depending on the cosmological scenario, the range for minimal \(M_1\) varies from order \(10^7\) Gev to \(10^9\) Gev \[24\] \[28\].

4 Weak Basis Invariants and CP Violation

In this section we present WB invariants which must vanish if CP invariance holds. Non-vanishing of any of these WB invariants signals CP violation. Weak basis invariant conditions are very useful since they allow us to determine whether or not a Lagrangean violates CP without the need to go to the physical basis. Clearly they can be very useful for instance in the study of mass models with particular textures or symmetries. The strategy to build these conditions was first applied in the context of the Standard Model \[29\].
The starting point are Eqs. (3) to (5). The technique proposed allows to build several different conditions. Different conditions may be sensitive to different CP violating phases. Furthermore some of them are identically zero under particular circumstances. This requires a careful choice of invariants.

Since leptogenesis only depends on the product $m^\dagger m$ this combination must appear in the conditions relevant for leptogenesis. From Eqs. (4), (3), one obtains:

\begin{align}
W^\dagger hW &= h^* \\
W^\dagger HW &= H^*
\end{align}

(24)

where $h = m^\dagger m$, $H = M^\dagger M$. It can be then readily derived, from Eqs. (3), (24), that CP invariance requires [7]:

\begin{equation}
I_1 \equiv \text{ImTr}[hHM^*h^*M] = 0
\end{equation}

(25)

Analogously several other different conditions can be derived [7]:

\begin{align}
I_2 &\equiv \text{ImTr}[hH^2M^*h^*M] = 0 \\
I_3 &\equiv \text{ImTr}[hH^2M^*h^*MH] = 0
\end{align}

(26, 27)

It has been shown [7] that if none of the heavy neutrino masses vanish and furthermore there is no degeneracy among them these conditions are independent and do not automatically vanish. Since there are six independent CP violating phases, one may wonder whether one can construct other three independent WB invariants, apart from $I_i$, which would describe CP violation in the leptonic sector. This is indeed possible, a simple choice are the WB invariants $\tilde{I}_i(i = 1, 2, 3)$, obtained from $I_i$, through the substitution of $h$ by $\tilde{h} = m^\dagger h_l m$, where $h_l = m_l m_l^\dagger$. For example one has:

\begin{equation}
\tilde{I}_1 = \text{ImTr}(m^\dagger h_l m H M^* m^\dagger h_l^* m^\dagger M)
\end{equation}

(28)

and similarly for $\tilde{I}_2, \tilde{I}_3$. As it was the case for $I_i$, CP invariance requires that $\tilde{I}_i = 0$.

Since low energy physics is sensitive to $m_{\text{eff}}$ it is possible to show that the strength of CP violation at low energies, observable for example through neutrino oscillations, can be obtained from the following low-energy WB invariant:

\begin{equation}
Tr[h_{\text{eff}}, h_l]^3 = 6i\Delta_{21}\Delta_{32}\Delta_{31} \text{Im}\{(h_{\text{eff}})_{12}(h_{\text{eff}})_{23}(h_{\text{eff}})_{31}\}
\end{equation}

(29)

where $h_{\text{eff}} = m_{\text{eff}} m_{\text{eff}}^\dagger$, $h_l = m_l m_l^\dagger$ and $\Delta_{21} = (m_\mu^2 - m_\tau^2)$ with analogous expressions for $\Delta_{31}, \Delta_{32}$.

5 Relating CP Violation at low energies with CP Violation required for Leptogenesis

It is clear from Eq. (1) that it is possible to choose a weak basis where the matrices $m_l$ and $M$ are simultaneously diagonal. In this case all CP violating
phases appear in $m$. There is no loss of generality in parametrizing the Dirac neutrino mass matrix by $\Delta$:

$$m = U Y_\Delta$$  \hspace{1cm} (30)$$

with $U$ a unitary matrix and $Y_\Delta$ a matrix with triangular form:

$$Y_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ |y_{21}| \exp(i \phi_{21}) & y_2 & 0 \\ |y_{31}| \exp(i \phi_{31}) & |y_{32}| \exp(i \phi_{32}) & y_3 \end{pmatrix}$$  \hspace{1cm} (31)$$

where the $y_i$ are real. Since $U$ is unitary, it contains in general six phases. However, three of these phases can be rephased away through the transformation:

$$m \rightarrow P_\xi m$$  \hspace{1cm} (32)$$

where $P_\xi = \text{diag}(\exp(i \xi_1), \exp(i \xi_2), \exp(i \xi_3))$. In a WB, this corresponds to a simultaneous phase transformation of the left-handed charged lepton fields and the left-handed neutrino fields. Furthermore, $Y_\Delta$ defined by Eq. (31) can be written as:

$$Y_\Delta = P_\beta^\dagger \hat{Y}_\Delta P_\beta$$  \hspace{1cm} (33)$$

where $P_\beta = \text{diag}(1, \exp(i \beta_1), \exp(i \beta_2))$ and

$$\hat{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ |y_{21}| \exp(i \phi_{21}) & y_2 & 0 \\ |y_{31}| \exp(i \phi_{31}) & |y_{32}| \exp(\sigma) & y_3 \end{pmatrix}$$  \hspace{1cm} (34)$$

with $\sigma = \phi_{32} - \phi_{31} + \phi_{21}$. It follows from Eqs. (30), (33) that the matrix $m$ can then be written as

$$m = \hat{U}_\rho \rho P_\alpha \hat{Y}_\Delta P_\beta$$  \hspace{1cm} (35)$$

where $P_\alpha = \text{diag}(1, \exp(i \alpha_1), \exp(i \alpha_2))$ and $\hat{U}_\rho$ contains only one phase $\rho$ as, for example, in the standard parametrization of $V_{CKM}$. Therefore, in this WB, where $m_l$ and $M$ are diagonal and real, the phases $\rho$, $\alpha_1$, $\alpha_2$, $\sigma$, $\beta_1$, $\beta_2$ are the only physical phases and can be used to characterize CP violation in this model. It follows from here that leptogenesis is controlled by the phases $\sigma$, $\beta_1$, $\beta_2$. If these three phases vanish there is no possibility of leptogenesis, still the remaining three phases can be responsible for low energy CP violation thus it is possible to have no CP violation at high energies responsible for leptogenesis and still have leptonic low energy CP violation $\mathbf{7}$. Conversely one may ask whether it is possible to have leptogenesis with no low energy CP violation either of Dirac or Majorana type $\mathbf{4}$. The answer to this question can be given by going to the weak basis where both $m_l$ and $M$ are real and diagonal. Then from Eq. (10) one can derive:
where \( \sqrt{d} \) and \( \sqrt{D} \) are diagonal real matrices such that \( \sqrt{d}\sqrt{d} = d \), \( \sqrt{D}\sqrt{D} = D \) and \( O^c \) is an orthogonal complex matrix, i.e. \( O^c O^{cT} = I \) but in general \( O^c O^{c\dagger} \neq I \). It is clear that with this parametrization the product \( m^\dagger m \), relevant for leptogenesis, is insensitive to \( K \). It is also clear from Eq. (10) that \( K \) is insensitive to the matrix \( O \). Yet, although a connection cannot be established in general, it can be established in special frameworks.

Here we present an interesting illustrative example of such a connection [31]. Starting from the parametrization of Eqs. (30) and (31) it follows that \( U \) does not play any role for leptogenesis since it cancels out in the product \( m^\dagger m \). This suggests the simplifying choice of taking \( U = I \). With this choice several texture zeros were studied for the matrix \( Y_\Delta \). Two patterns with one additional zero in \( Y_\Delta \) were found to be consistent with low energy physics (either with hierarchical heavy neutrinos or two-fold quasi degeneracy):

\[
\begin{pmatrix}
 y_{11} & 0 & 0 \\
y_{21} e^{i \phi_{21}} & y_{22} & 0 \\
y_{31} & 0 & y_{33}
\end{pmatrix}, \quad
\begin{pmatrix}
 y_{11} & 0 & 0 \\
y_{22} & 0 & y_{32} e^{i \phi_{32}} \\
y_{31} e^{i \phi_{31}} & y_{32} e^{i \phi_{32}} & y_{33}
\end{pmatrix}
\] (37)

Still it is possible to eliminate one of the two remaining phases and obtain viable leptogenesis together with specific predictions for low energy physics consistent with the known experimental constraints. In Ref. [31] special examples were built with strong hierarchies in the entries of \( Y_\Delta \) parametrized in terms of powers of a small parameter.

The question of whether the sign of the baryon asymmetry of the Universe can be related to CP violation in neutrino oscillation experiments was addressed by considering models with only two heavy neutrinos [32]. In this case the Dirac mass matrix has dimension \( 3 \times 2 \). The interesting examples correspond to textures of the form given above in Eq. (37) with the third column eliminated and corresponds to the most economical extension of the SM leading to leptogenesis. In this case the number of parameters is further reduced and the remaining non zero parameters are strongly constrained by low energy physics. This fact leads to a definite relative sign between \( \text{Im} (m^\dagger m)_{12} \) and \( \sin 2\delta \).

6 A common Origin for all CP violations

CP violation has been observed both in the Kaon sector [34] and in the B-sector [35] [36]. The existence of a matter dominated Universe constitutes indirect evidence for CP violation. It has been established that within the framework of the SM it is not possible to generate the observed size of BAU, due in part to the smallness of CP violation in the SM. This provides motivation for considering new sources of CP violation beyond the KM mechanism.
The question of whether it is possible to find a framework where all these manifestations of CP violation have a common origin has been addressed in [6] in the context of a small extension of the Standard Model and also in [33] in the framework of a SUSY SO(10) model. In [6] a minimal model is proposed with spontaneous CP violation, where CP breaking both in the quark and leptonic sectors arises solely from a phase $\alpha$ in the vacuum expectation value of a complex scalar singlet $S$, with $\langle S \rangle = \frac{V}{\sqrt{2}} \exp(i\alpha)$. Since $S$ is an $SU(2) \times U(1) \times SU(3)_c$ singlet, $V$ can be much larger than the electroweak breaking scale. Therefore, in this framework CP violation is generated at a high energy scale. In order for the phase $\alpha$ to generate a non-trivial phase at low energies in the Cabibbo, Kobayashi and Maskawa matrix, one is led to introduce at least one vector-like quark, whose lefthanded and righthanded components are singlets under $SU(2)$. In the leptonic sector, righthanded neutrinos play the rôle of the vector-like quarks, establishing the connection between CP breaking at high and low energies, and allowing also for the possibility of leptogenesis.

The model considered consists of adding to the SM the following fields: one singlet charge $-\frac{1}{3}$ vectorial quark $D^0$, three righthanded neutrino fields $\nu_R^0$ (one per generation) and a neutral scalar singlet field, $S$. A $Z_4$ symmetry is imposed, under which the fields $D^0$, $S$, $\psi_0^l$ (the lefthanded lepton doublets), $\nu_R^0$ and $\nu_R^0$ transform non trivially, all other fields remain invariant under the $Z_4$ symmetry.

The scalar potential will contain terms in $\phi$ and $S$ with no phase dependence, together with terms of the form $(\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^\dagger \phi)(S^2 + S^{*2}) + \lambda_3 (S^4 + S^{*4})$ which, in general, lead to the spontaneous breaking of T and CP invariance [37] with $\phi$ and $S$ acquiring vacuum expectation values (vevs) of the form:

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}, \quad \langle S \rangle = \frac{V \exp(i\alpha)}{\sqrt{2}}$$

and the $Z_4$ symmetry is also broken.

After spontaneous symmetry breaking the leptonic mass terms are given by Eq. (1). In the model a bare Majorana mass term for the righthanded neutrinos would break the $Z_4$ symmetry yet, a term of this form is generated through the couplings of $\nu_R^0$ to the scalar singlet $S$, after $Z_4$ breaking. It was shown in Ref.[6] that leptogenesis is possible in this framework. Furthermore, whenever the matrix $m^\dagger m$ is real there is also no CP violation at low energies. On the other hand the matrix $mm^\dagger$ is always real in this framework.

In the hadronic sector the phase $\delta_{KM}$, generated through spontaneous CP violation in general is not suppressed and the $Z_4$ symmetry allows to find a solution [38] of the strong CP problem of the type proposed by Nelson [39] and Barr [40].
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