Leptogenesis And Neutrino Oscillations Within A Predictive G(224)/SO(10)-Framework

Jogesh C. Pati,
Department of Physics, University of Maryland, College Park MD 20742, USA\textsuperscript{1},
and
Stanford Linear Accelerator Center, Stanford University, Menlo Park, CA, 94025, USA.
August 15, 2002.

Abstract

A framework based on an effective symmetry that is either G(224)= SU(2)\textsubscript{L}×SU(2)\textsubscript{R}×SU(4)\textsuperscript{c} or SO(10) has been proposed (a few years ago) that successfully describes the masses and mixings of all fermions including neutrinos, with seven predictions, in good accord with the data. Baryogenesis via leptogenesis is considered within this framework by allowing for natural phases (∼\frac{1}{20}-\frac{1}{2}) in the entries of the Dirac and Majorana mass-matrices. It is shown that the framework leads quite naturally, for both thermal as well as non-thermal leptogenesis, to the desired magnitude for the baryon asymmetry. This result is obtained in full accord with the observed features of the atmospheric and solar neutrino oscillations, as well as with those of the quark and charged lepton masses and mixings, and the gravitino-constraint. Hereby one obtains a unified description of fermion masses, neutrino oscillations and baryogenesis (via leptogenesis) within a single predictive framework.

\textsuperscript{1}present address
1 Introduction

The observed matter-antimatter asymmetry of the universe \[1,2\] is an important clue to physics at truly short distances. A natural understanding of its magnitude (not to mention its sign) is thus a worthy challenge. Since the discovery of the electroweak sphaleron effect \[3\], baryogenesis via leptogenesis \[4,5\] appears to be the most attractive and promising mechanism to generate such an asymmetry \[6\]. In the context of a unified theory of quarks and leptons, leptogenesis involving decays of heavy right-handed (RH) neutrinos, is naturally linked to the masses of quarks and leptons, neutrino oscillations and, of course, CP violation.

In this regard, the route to higher unification based on an effective four-dimensional gauge symmetry of either G(224)=SU(2)\(_L\)×SU(2)\(_R\)×SU(4)\(_C\) \[7\], or SO(10) \[8\] (that may emerge from a string theory near the string scale and breaks spontaneously to the standard model symmetry near the GUT scale \[9\]) offers some distinct advantages, which are directly relevant to understanding neutrino masses and implementing leptogenesis. These in particular include: (a) the existence of the RH neutrinos as a compelling feature, (b) B-L as a local symmetry, and (c) quark-lepton unification through SU(4)-Color. These three features, first introduced in Ref. \[7\] in the context of the symmetry G(224), are of course available within any symmetry that contains G(224) as a subgroup; thus, they are available within SO(10) and E\(_6\) \[10\], though not in SU(5) \[11\]. Effective symmetries such as flipped SU(5)×U(1) \[12\] or [SU(3)]\(^3\) \[13\], or SU(2)\(_L\)×SU(2)\(_R\)×U(1)\(_{B-L}\)×SU(3)\(_C\) \[14\] possess the first two features (a) and (b), but not (c). Now, the combination of the four ingredients – that is (i) the existence of the RH neutrino as an integral member of each family, (ii) the supersymmetric unification scale \(M_X \sim 2 \times 10^{16} \text{ GeV} \[15\] (which provides the Majorana mass of the RH neutrinos), (iii) the symmetry SU(4)-color (which provides the Dirac mass of the tau neutrino in terms of the top quark mass), and (iv) the seesaw mechanism \[16\] – yields even quantitatively just about the right value of \(\Delta m^2(\nu_2-\nu_3)\), as observed at SuperKamiokande \[18\].

Furthermore, these three features (a)-(c) noted above also provide just the needed ingredients - that is superheavy \(\nu_R\)'s and spontaneous violation of B-L at high temperatures - for implementing baryogenesis via leptogenesis.

Now, in a theory with RH neutrinos having heavy Majorana masses, the magnitude of the lepton-asymmetry is known to depend crucially on both the Dirac as well as Majorana mass matrices of the neutrinos \[19\]. In this regard, a predictive G(224)/SO(10) framework, describing the masses and mixings of all fermions, including neutrinos, has been proposed \[20\] that appears to be remarkably successful. In particular it makes seven predictions including: 

\[
m_b(m_b) \approx 4.7 - 4.9 \text{ GeV}, \quad m(\nu_3) \sim (1/2) eV(1/2-2), \quad V_{cb} \approx 0.044, \quad \sin^2 2\theta_{\text{osc}} \approx 0.9 - 0.99, \quad V_{us} \approx 0.20, \quad V_{ub} \approx 0.003 \quad \text{and} \quad m_d \approx 8 \text{ MeV},
\]

all in good accord with observations, to within 10% (see Sec. 2). It has been noted recently \[21\] that the large angle MSW solution (LMA), which is preferred by experiments \[22\], can arise quite plausibly within the same framework through SO(10)-invariant higher dimensional operators which can contribute directly to the Majorana masses of the left-handed neutrinos (especially to the \(\nu_L^c\nu_L^d\) mixing mass) without involving the familiar seesaw.

As an additional point, it has been noted by Babu and myself \[23\] that the framework proposed in Ref. \[20\] can naturally accommodate CP violation by introducing complex phases in the entries of the fermion mass-matrices, which preserve the pattern of the mass-matrices suggested in Ref. \[20\] as well as its successes.

The purpose of the present paper is to estimate the lepton and thereby the baryon excess.
that would typically be expected within this realistic G(224)/SO(10)-framework for fermion masses and mixings \cite{20,23}, by allowing for natural CP violating phases (∼ 1/20 to 1/2, say) in the entries of the mass-matrices as in Ref. [23]. The goal would thus be to obtain a *unified description* of (a) fermion masses, (b) neutrino oscillations, and (c) leptogenesis within a single predictive framework \cite{24}.

It should be noted that there have in fact been several attempts in the literature \cite{25} at estimating the lepton and baryon asymmetries, many of which have actually been carried out in the context of SO(10) \cite{26}, though (to my knowledge) without an accompanying realistic framework for the masses and mixing of quarks, charged leptons as well as neutrinos \cite{27}. Also the results in these attempts as regards leptogenesis have not been uniformly encouraging \cite{28}.

The purpose of this letter is to note that the G(224)/SO(10) framework, proposed in Ref. \cite{20} and \cite{23}, leads quite naturally, for both thermal as well as non-thermal leptogenesis, to the desired magnitude for baryon asymmetry. This result is obtained in full accord with Ref. \cite{20} and \cite{23}, leads quite naturally, for both thermal as well as non-thermal leptogenesis, to the desired magnitude for baryon asymmetry. This result is obtained in full accord with the observed features of atmospheric and solar neutrino oscillations, as well as with those of quark and charged lepton masses and mixings, and the gravitino-constraint. To present the analysis it would be useful to recall the salient features of these prior works \cite{20,23} on fermion masses and mixings. This is what is done in the next section.

2 Fermion Masses and Neutrino Oscillations in G(224)/SO(10): A Brief Review of Prior Work

The 3 × 3 Dirac mass matrices for the four sectors \((u, d, l, \nu)\) proposed in Ref. \cite{20} were motivated in part by the notion that flavor symmetries \cite{29} are responsible for the hierarchy among the elements of these matrices (i.e., for "33" \(\gg\) "22" \(\gg\) "12" \(\gg\) "11", etc.), and in part by the group theory of SO(10)/G(224), relevant to a minimal Higgs system (see below). Up to minor variants \cite{30}, they are as follows:

\[
M_u = \begin{bmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & \zeta_{u22}^u & \sigma + \epsilon \\ 0 & \sigma - \epsilon & 1 \end{bmatrix} \mathcal{M}_u^0; \quad M_d = \begin{bmatrix} 0 & \eta' + \epsilon' & 0 \\ \eta' - \epsilon' & \zeta_{d22}^d & \eta + \epsilon \\ 0 & \eta - \epsilon & 1 \end{bmatrix} \mathcal{M}_d^0
\]

\[
M_{\nu}^D = \begin{bmatrix} 0 & -3\epsilon' & 0 \\ -3\epsilon' & \zeta_{u22}^u & \sigma - 3\epsilon \\ 0 & \sigma + 3\epsilon & 1 \end{bmatrix} \mathcal{M}_{u\nu}^0; \quad M_{\nu} = \begin{bmatrix} 0 & \eta' - 3\epsilon' & 0 \\ \eta' + 3\epsilon' & \zeta_{d22}^d & \eta - 3\epsilon \\ 0 & \eta + 3\epsilon & 1 \end{bmatrix} \mathcal{M}_{d\nu}^0
\]

(1)

These matrices are defined in the gauge basis and are multiplied by \(\bar{\Psi}_L\) on left and \(\Psi_R\) on right. For instance, the row and column indices of \(M_u\) are given by \((\bar{u}_L, c_L, \bar{t}_L)\) and \((u_R, c_R, t_R)\) respectively. Note the group-theoretic up-down and quark-lepton correlations: the same \(\sigma\) occurs in \(M_u\) and \(M_{\nu}^D\), and the same \(\eta\) occurs in \(M_d\) and \(M_{\nu}\). It will become clear that the \(\epsilon\) and \(\epsilon'\) entries are proportional to B-L and are antisymmetric in the family space (as shown above). Thus, the same \(\epsilon\) and \(\epsilon'\) occur in both \((M_u, M_d)\) and also in \((M_{\nu}^D, M_{\nu})\), but \(\epsilon \rightarrow -3\epsilon\) and \(\epsilon' \rightarrow -3\epsilon'\) as \(q \rightarrow l\). Such correlations result in enormous reduction of parameters and thus in increased predictivity. Such a pattern for the mass-matrices can be obtained, using a minimal Higgs system \(45_H, 16_H, 16_H\) and \(10_H\) and a singlet \(S\) of SO(10),
through effective couplings as follows [31]:

\[
\mathcal{L}_{\text{Yuk}} = h_{33}16_3\bar{16}_310_H
+ [h_{23}16_2\bar{16}_310_H(S/M) + a_{23}16_2\bar{16}_310_H(45_H/M')(S/M)^p + g_{23}16_2\bar{16}_316_H^d(16_H/M'')(S/M)^q]
+ [h_{22}16_2\bar{16}_210_H(S/M)^2 + g_{22}16_2\bar{16}_216_H^d(16_H/M'')(S/M)^{q+1}]
+ [g_{12}16_1\bar{16}_216_H^d(16_H/M'')(S/M)^{q+2} + a_{12}16_1\bar{16}_210_H(45_H/M')(S/M)^{p+2}]
\]

Typically we expect \( M', M'' \) and \( M \) to be of order \( M_{\text{string}} \) [32]. The VEV’s of \( \langle 45_H \rangle \) (along B-L), \( \langle 16_H \rangle \) (along standard model singlet sneutrino-like component) and of the SO(10)-singlet \( \langle S \rangle \) are of the GUT-scale, while those of \( 10_H \) and of the down type SU(2)_L-doublet component in \( 16_H \) (denoted by \( 16_H^d \)) are of the electroweak scale [20,33]. Depending upon whether \( M'(M'') \approx M_{\text{GUT}} \) or \( M_{\text{string}} \) (see footnote [32]), the exponent \( p(q) \) is either one or zero [34].

The entries 1 and \( \sigma \) arise respectively from \( h_{33} \) and \( h_{23} \) couplings, while \( \hat{\eta} \equiv \eta - \sigma \) and \( \eta' \) arise respectively from \( g_{23} \) and \( g_{12} \)-couplings. The (B-L)-dependent antisymmetric entries \( \epsilon \) and \( \epsilon' \) arise respectively from the \( a_{23} \) and \( a_{12} \) couplings. [Effectively, with \( \langle 45_H \rangle \propto \text{B-L} \), the product \( 10_H \times 45_H \) contributes as a \( 120 \), whose coupling is family-antisymmetric.] The small entry \( \zeta_{22}^u \) arises from the \( h_{33} \)-coupling, while \( \zeta_{22}^d \) arises from the joint contributions of \( h_{22} \) and \( g_{22} \)-couplings. As discussed in [20], using some of the observed masses as inputs, one obtains \( |\hat{\eta}| \sim |\sigma| \sim |\epsilon| \sim O(1/10), |\eta'| \approx 4 \times 10^{-3} \) and \( |\epsilon'| \sim 2 \times 10^{-4} \). The success of the framework presented in Ref. [20] (which set \( \zeta_{22}^u = \zeta_{22}^d = 0 \)) in describing fermion masses and mixings remains essentially unaltered if \( |(\zeta_{22}^u, \zeta_{22}^d)| \leq (1/3)(10^{-2}) \) (say).

Such a hierarchical form of the mass-matrices, with \( h_{33} \)-term being dominant, is attributed in part to flavor gauge symmetry(ies) that distinguishes between the three families [35], and in part to higher dimensional operators involving for example \( \langle 45_H \rangle/M' \) or \( \langle 16_H \rangle/M'' \), which are supressed by \( M_{\text{GUT}}/M_{\text{string}} \sim 1/10 \), if \( M' \) and/or \( M'' \sim M_{\text{string}} \).

To discuss the neutrino sector one must specify the Majorana mass-matrix of the RH neutrinos as well. These arise from the effective couplings of the form [36]:

\[
\mathcal{L}_{\text{Maj}} = f_{ij}16_i16_j \bar{16}_H \bar{16}_H / M
\]

where the \( f_{ij} \)'s include appropriate powers of \( \langle S/M \rangle \), in accord with flavor charge assignments of \( 16_i \) (see [35]). For the \( f_{33} \)-term to be leading, we must assign the charge \( -a \) to \( 16_H \). This leads to a hierarchical form for the Majorana mass-matrix [20]:

\[
M_R' = \begin{bmatrix}
x & 0 & z \\
0 & 0 & y \\
z & y & 1
\end{bmatrix} M_R
\]

Following the flavor-charge assignments given in footnote [35], we expect \( |y| \sim \langle S/M \rangle \sim (\langle S/M \rangle)^2 \sim O(1/200) \) (1 to 2/3, say), \( |x| \sim \langle S/M \rangle^4 \sim (10^{-4}-10^{-5}) \) (say). The ”22” element (not shown) is \( \sim \langle S/M \rangle^2 \) and its magnitude is taken to be \( < |y|^2/3 \), while the ”12” element (not shown) is \( \sim \langle S/M \rangle^3 \). We expect

\[
M_R = f_{33} \langle \bar{16}_H \rangle^2 / M_{\text{string}} \approx (10^{15} \text{ GeV})(1/2 - 2)
\]

for \( \langle 16_H \rangle \approx 2 \times 10^{16} \text{ GeV}, M_{\text{string}} \approx 4 \times 10^{17} \text{ GeV} \) [37] and \( f_{33} \approx 1 \). Allowing for 2-3 mixing, this value of \( M_R \) [together with the SU(4)-color relation \( m(\nu_3^{\text{Dirac}}) = m(\nu_3^{\text{GUT}}) \approx 120 \text{ GeV} \)] leads to \( m(\nu_3) \approx (1/24 \text{ eV})(1/2-2) \) [20,17,38], in good accord with the SuperK data.
Ignoring possible phases in the parameters and thus the source of CP violation for a moment, as was done in Ref. [20], the parameters \((\sigma, \eta, \epsilon, \epsilon', \eta', \mathcal{M}_u^0, \mathcal{M}_D^0, y)\) can be determined by using, for example, \(m_t^{\text{phys}} = 174\) GeV, \(m_e(m_e) = 1.37\) GeV, \(m_S(1\) GeV) = 110-116 MeV, \(m_u(1\) GeV) = 6 MeV, the observed masses of \(e, \mu, \text{ and } \tau\) and \(m(\nu_2)/m(\nu_3) \approx 1/(7 \pm 1)\) (as suggested by a combination of atmospheric and solar neutrino data, the latter corresponding to the LMA MSW solution, see below) as inputs. One is thus led, for this CP conserving case, to the following fit for the parameters, and the associated predictions [20]. [In this fit, we drop \(|\zeta_{22}^a| \leq (1/3)(10^{-2})\) and leave the small quantities \(x\) and \(z\) in \(M_R^U\) undetermined and proceed by assuming that they have the magnitudes suggested by flavor symmetries (i.e., \(x \sim (10^{-4}-10^{-5})\) and \(z \sim (1/200)(1\) to 1/2) (see remarks below Eq. (11)):

\[
\begin{align*}
\sigma & \approx 0.110, \quad \eta \approx 0.151, \quad \epsilon \approx -0.095, \quad |\eta'| \approx 4.4 \times 10^{-3}, \\
\epsilon' & \approx 2 \times 10^{-4}, \quad \mathcal{M}_u^0 \approx m_t(M_X) \approx 120\text{ GeV,} \\
\mathcal{M}_D^0 & \approx m_b(M_X) \approx 1.5\text{ GeV,} \\
y & \approx -1/17.
\end{align*}
\]

These in turn lead to the following predictions for the quarks and light neutrinos [20, 38]:

\[
\begin{align*}
m_b(m_b) & \approx (4.7-4.9)\text{ GeV,} \\
\sqrt{\Delta m_{23}^2} & \approx m(\nu_3) \approx (1/24\text{ eV})(1/2-2), \\
V_{cb} & \approx \left| \frac{m_s}{m_b} \frac{\eta + \epsilon}{\eta - \epsilon} \right|^{1/2} - \left| \frac{m_c}{m_b} \frac{\sigma + \epsilon}{\sigma - \epsilon} \right|^{1/2} \approx 0.044, \\
\theta^{\text{osc}}_{\nu_\mu\nu_\tau} & \approx \left| \sqrt{\frac{m_\mu}{m_\tau}} \frac{\eta - 3\epsilon}{\eta + 3\epsilon} \right|^{1/2} + \sqrt{\frac{m_\mu}{m_\tau}} \approx |0.437 + (0.378 \pm 0.03)|, \\
\text{Thus, } \sin^2 2\theta^{\text{osc}}_{\nu_\mu\nu_\tau} & \approx 0.99, \quad \text{(for } m(\nu_2)/m(\nu_3) \approx 1/7), \\
V_{us} & \approx \left| \sqrt{\frac{m_d}{m_s}} \frac{\eta - 3\epsilon}{\eta + 3\epsilon} \right| \approx 0.20, \\
\left| \frac{V_{ub}}{V_{cb}} \right| & \approx \sqrt{\frac{m_s}{m_c}} \approx 0.07, \\
m_d(1\text{ GeV}) & \approx 8\text{ MeV,} \\
\theta^{\text{osc}}_{\nu_\mu\nu_\nu} & \approx 0.06 \text{ (ignoring non-seesaw contributions); see remarks below.}
\end{align*}
\]

The Majorana masses of the RH neutrinos \((N_{iR} \equiv N_i)\) are given by [38]:

\[
\begin{align*}
M_3 & \approx M_R \approx 10^{15}\text{ GeV (1/2-1),} \\
M_2 & \approx |y|^2 M_3 \approx (2.5 \times 10^{12}\text{ GeV})(1/2-1), \\
M_1 & \approx |x - z^2| M_3 \approx (1/2-2)10^{-5} M_3 \approx 10^{10}\text{ GeV (1/4-2).}
\end{align*}
\]

Note that we necessarily have a hierarchical pattern for the light as well as the heavy neutrinos (see discussions below on \(m_{\nu_3}\)). Leaving out the \(\nu_e-\nu_2\) oscillation angle for a moment, it seems remarkable that the first seven predictions in Eq. (7) agree with observations, to within 10%. Particularly intriguing is the (B-L)-dependent group-theoretic correlation between the contribution from the first term in \(V_{cb}\) and that in \(\theta^{\text{osc}}_{\nu_\mu\nu_\tau}\), which explains simultaneously why one is small \((V_{cb})\) and the other is large \((\theta^{\text{osc}}_{\nu_\mu\nu_\tau})\) [40]. That in turn provides some degree of confidence in the gross structure of the mass-matrices.

As regards \(\nu_e-\nu_\mu\) and \(\nu_e-\nu_\tau\) oscillations, the standard seesaw mechanism would typically lead to rather small angles as in Eq. (7), within the framework presented above [20]. It has, however, been noted recently [21] that small intrinsic (non-seesaw) masses \(\sim 10^{-3}\) eV of the LH neutrinos can arise quite plausibly through higher dimensional operators of the
form [41]: $W_{12} \supset k_{12} 16, 16, 16_H 16_H 10_H 10_H / M_{\text{eff}}^3$, without involving the standard seesaw mechanism [16]. One can verify that such a term would lead to an intrinsic Majorana mixing mass term of the form $m_{12}^0 \nu_L \nu_L^d$, with a strength given by $m_{12}^0 \approx k_{12} \langle 16_H \rangle^2 (175 \text{ GeV})^2 / M_{\text{eff}}^3 \sim (1.5-6) \times 10^{-3}$ eV, for $\langle 16_H \rangle \approx (1-2) M_{\text{GUT}}$ and $k_{12} \sim 1$, if $M_{\text{eff}} \sim M_{\text{GUT}} \approx 2 \times 10^{16}$ GeV [42]. Such an intrinsic Majorana $\nu_\mu \nu_\mu$ mixing mass $\sim \text{few} \times 10^{-3}$ eV, though small compared to $m(\nu_3)$, is still much larger than what one would generically get for the corresponding term from the standard seesaw mechanism [as in Ref. [20]]. Now, the diagonal $(\nu_\mu \nu_\mu)$ mass-term, arising from standard seesaw can naturally be $\sim (3-8) \times 10^{-3}$ eV for $|y| \approx 1/20-1/15$, say [20]. Thus, taking the net values of $m_{22}^0 \approx (6-7) \times 10^{-3}$ eV, $m_{12}^0 \sim 3 \times 10^{-3}$ eV as above and $m_{11}^0 \ll 10^{-3}$ eV, which are all plausible, we obtain $m_{\nu_2} \approx (6-7) \times 10^{-3}$ eV, $m_{\nu_1} \sim (1 \text{ to few}) \times 10^{-3}$ eV, so that $\Delta m_{12}^2 \approx (3.6-5) \times 10^{-5}$ eV$^2$ and $\sin^2 2\theta_{\nu_\mu} \approx 0.6 - 0.7$. These go well with the LMA MSW solution of the solar neutrino puzzle.

In summary, the intrinsic non-seesaw contribution to the Majorana masses of the LH neutrinos can possibly have the right magnitude for $\nu_\mu - \nu_\mu$ mixing so as to lead to the LMA solution within the G(224)/SO(10)-framework, without upsetting the successes of the first seven predictions in Eq. [7]. [In contrast to the near maximality of the $\nu_\mu-\nu_\mu$ oscillation angle, however, which emerges as a compelling prediction of the framework [20], the LMA solution, as obtained above, should, be regarded as a consistent possibility, rather than as a compelling prediction, within this framework.]

Before discussing leptogenesis, we need to discuss the origin of CP violation within the G(224)/SO(10)-framework presented above. The discussion so far has ignored, for the sake of simplicity, possible CP violating phases in the parameters ($\sigma$, $\eta$, $\epsilon$, $\eta'$, $\epsilon'$, $\zeta_{22}^u$, $y$, $z$, and $x$) of the Dirac and Majorana mass matrices [Eqs. [11], and [4]]. In general, however, these parameters can and generally will have phases [13]. Some combinations of these phases enter into the CKM matrix and define the Wolfenstein parameters $\rho_W$ and $\eta_W$ [44], which in turn induce CP violation by utilizing the standard model interactions. As observed in Ref. [23], an additional and potentially important source of CP and flavor violations (as in $K^0 \leftrightarrow \bar{K}^0$, $B_{d,s} \leftrightarrow \bar{B}_{d,s}$, $b \rightarrow sss$, etc. transitions) arise in the model through supersymmetry [15], involving squark and gluino loops (box and penguin), simply because of the embedding of MSSM within a string-unified G(224) or SO(10)-theory near the GUT-scale, and the assumption that primordial SUSY-breaking occurs near the string scale ($M_{\text{string}} > M_{\text{GUT}}$) [46]. It is shown that complexification of the parameters ($\sigma$, $\eta$, $\epsilon$, $\eta'$, $\epsilon'$, etc.), through introduction of phases $\sim 1/20-1/2$ (say) in them, can still preserve the successes of the predictions as regards fermion masses and neutrino oscillations shown in Eq. [7], as long as one maintains nearly the magnitudes of the real parts of the parameters and especially their relative signs as obtained in Ref. [20] and shown in Eq. [13] [17]. Such a picture is also in accord with the observed features of CP and flavor violations in $\epsilon_K$, $\Delta m_{B_d}$, and asymmetry parameter in $B_d \rightarrow J/\Psi + K$, while predicting observable new effects in processes such as $B_s \rightarrow B_s$ and $B_d \rightarrow \Phi + K_s$ [24].

We therefore proceed to discuss leptogenesis concretely within the framework presented above by adopting the Dirac and Majorana fermion mass matrices as shown in Eqs. [11] and [4] and assuming that the parameters appearing in these matrices can have natural phases $\sim 1/20-1/2$ (say) with either sign up to addition of $\pm \pi$, while their real parts have the relative signs and nearly the magnitudes given in Eq. [7].
3 Leptogenesis

In the context of an inflationary scenario \[^{18}\], with a plausible reheat temperature \(T_{RH} \sim (1 \text{ to few}) \times 10^9 \text{ GeV} \) (say), one can avoid the well known gravitino problem if \(m_{3/2} \sim (1 \text{ to } 2) \text{ TeV} \[^{49}\] and yet produce the lightest heavy neutrino \(N_1\) efficiently from the thermal bath if \(M_1 \sim (3 \text{ to } 5) \times 10^9 \text{ GeV} \) (say), in accord with Eq. \[^{3}\] \([N_2 \text{ and } N_3 \text{ are of course too heavy to be produced at } T \sim T_{RH}].\) Given lepton number (and B-L) violation occurring through the Majorana mass of \(N_1\), and C and CP violating phases in the Dirac and/or Majorana fermion mass-matrices as mentioned above, the out-of-equilibrium decays of \(N_1\) (produced from the thermal bath) into \(l + H\) and \(\bar{l} + \bar{H}\) and into the corresponding SUSY modes \(\tilde{l} + \tilde{H}\) and \(\bar{\tilde{l}} + \bar{\tilde{H}}\) would produce a B-L violating lepton asymmetry; so also would the decays of \(\tilde{N}_1\) and \(\bar{\tilde{N}}_1\). Part of this asymmetry would of course be washed out due to inverse decays and lepton number violating 2↔2-scatterings. We will assume this commonly adopted mechanism for the so-called thermal leptogenesis (At the end, we will, however, consider an interesting alternative that would involve non-thermal leptogenesis). This mechanism has been extended to incorporate supersymmetry by several authors (see e.g., \[^{50, 51, 52}\]). The net lepton asymmetry of the universe \([Y_L \equiv (n_L - n_{\bar{L}})/s]\) arising from decays of \(N_1\) into \(l + H\) and \(\bar{l} + \bar{H}\) and likewise from \((\tilde{N}_1, \tilde{N}_1)\)-decays \[^{50, 51, 52}\] is given by:

\[
Y_L = \kappa \epsilon_1 \left( \frac{n_{N_1} + n_{\tilde{N}_1} + n_{\tilde{N}_1}}{s} \right) \approx \kappa \epsilon_1 / g^* \tag{9}
\]

where \(\epsilon_1\) is the lepton-asymmetry produced per \(N_1\) (or \((\tilde{N}_1 + \tilde{N}_1)\)-pair) decay (see below), \(\kappa\) is an efficiency or damping factor that represents the washout effects mentioned above (thus \(\kappa\) incorporates the extent of departure from thermal equilibrium in \(N_1\)-decays; such a departure is needed to realize lepton asymmetry), and \(g^* \approx 228\) is the number of light degrees of freedom in MSSM.

The lepton asymmetry \(Y_L\) is converted to baryon asymmetry, by the sphaleron effects, which is given by:

\[
Y_B = \frac{n_B - n_{\bar{B}}}{s} = C Y_L, \tag{10}
\]

where, for MSSM, \(C \approx -1/3\). Taking into account the interference between the tree and loop-diagrams for the decays of \(N_1 \rightarrow lH\) and \(\tilde{l}\bar{H}\) (and likewise for \(N_1 \rightarrow \tilde{l}\bar{H}\) and \(\tilde{l}\bar{H}\) modes and also for \(\tilde{N}_1\) and \(\tilde{N}_1\)-decays), the CP violating lepton asymmetry parameter in each of the four channels (see e.g., \[^{51}\] and \[^{52}\]) is given by

\[
\epsilon_1 = \frac{1}{8\pi v^2 (M_D^TM_D)_{11}} \sum_{j=2,3} \text{Im} \left[ (M_D^TM_D)_{j1} \right]^2 f \left( M_j^2 / M_1^2 \right) \tag{11}
\]

where \(M_D\) is the Dirac neutrino mass matrix evaluated in a basis in which the Majorana mass matrix of the RH neutrinos \(M_R\) [see Eq. \(^{[1]}\)] is diagonal, \(v = (174 \text{ GeV}) \sin \beta\) and the function \(f \approx -3(M_1/M_j)\) for the case of SUSY with \(M_j \gg M_1\).

The efficiency factor mentioned above, is often expressed in terms of the parameter \(K \equiv [\Gamma(N_1)/2H]_{T=M_1}\). \[^{[18]}\] Assuming initial thermal abundance for \(N_1\), \(\kappa\) is normalized so that it
is 1 if \( N_1 \)'s decay fully out of equilibrium corresponding to \( K < 1 \) (in practice, this actually requires \( K < 0.1 \)). Including inverse decays as well as \( \Delta L \neq 0 \)-scatterings in the Boltzmann equations, a recent analysis [53] shows that in the relevant parameter-range of interest to us (see below), the efficiency factor (for the SUSY case) is given by [54]:

\[
\kappa \approx (0.7 \times 10^{-4})(eV/\tilde{m}_1)
\]

where \( \tilde{m}_1 \) is an effective mass parameter (related to \( K [55] \)), and is given by [56]:

\[
\tilde{m}_1 \equiv (m^\dagger_mD_D)^{11}/M_1.
\]

Eq. (13) should hold to better than 20% (say), when \( \tilde{m}_1 \gg 5 \times 10^{-4} \text{ eV} \) [53] (This applies well to our case, see below).

Given the Dirac and Majorana mass matrices of the neutrinos [Eqs. (11) and (14)], we are now ready to evaluate lepton assymetry by using Eqs. (9)-(13).

The Majorana mass matrix [Eq. (14)] describing the mass-term \( \nu_R^{T}CM_R^{*}\nu_R \) is diagonalized by the transformation \( \nu_R = U_R^{(1)}U_R^{(2)}N_R \), where (to a good approximation)

\[
U_R^{(1)} \approx \begin{bmatrix} 1 & 0 & z \\ 0 & 1 & y \\ -z & -y & 1 \end{bmatrix},
\]

and \( U_R^{(2)} = \text{diag}(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}) \) is a diagonal phase matrix that ensures real positive eigenvalues. The phases \( \phi_i \) can of course be derived from those of the parameters in \( M_R^{(2)} \) [see Eq. (1)]. Applying this transformation to the neutrino Dirac mass-term \( \bar{\nu}_LM_D^\nu\nu_R \) given by Eq. (11), we obtain \( M_D = M_D^{(1)}U_R^{(1)}U_R^{(2)} \), which appears in Eqs. (11) and (13). In turn, this yields:

\[
\frac{(M_D^\dagger M_D)_{21}}{(M_D^{(1)})^2} = e^{i(\phi_1 - \phi_2)}\{(-3\epsilon' - \zeta_{13}y')(\zeta_{11} - z\zeta_{13}) + [\zeta_{22}^* - y^*(\sigma' - 3\epsilon^*)][3\epsilon' - z(\sigma - 3\epsilon)] + (\zeta_{31} - z)[(\sigma^* + 3\epsilon^*) - y^*]\} \quad (15)
\]

\[
\frac{(M_D^\dagger M_D)_{11}}{(M_D^{(1)})^2} = |3\epsilon' - z(\sigma - 3\epsilon)|^2 + |\zeta_{31} - z|^2 \quad (16)
\]

In writing Eqs. (15) and (16), we have allowed, for the sake of generality, the relatively small “11”, “13”, and “31” elements in the Dirac mass-matrix \( M_D \), denoted by \( \zeta_{11}, \zeta_{13} \) and \( \zeta_{31} \) respectively, which are not excluded in Eq. (1). Guided by considerations of flavor symmetry (see footnote [35]), we would expect \( |\zeta_{11}| \sim (\langle S \rangle/M)^4 \sim 10^{-4} - 10^{-5}, \) and \( |\zeta_{13}| \sim |\zeta_{31}| \sim (\langle S \rangle/M)^2 \sim 10^{-2} \) (1 to 1/3) (say). These small elements (neglected in [20]) would not, of course, have any noticeable effects on the predictions of the fermion masses and mixings given in Eq. (7), except possibly on \( m_d \).

We now proceed to make numerical estimates of lepton and baryon-asymmetries by taking the magnitudes and the relative signs of the real parts of the parameters (\( \sigma, \eta, \epsilon, \eta', \epsilon' \), and \( y \) approximating the same as in Eq. (6), but allowing in general for natural phases in them. As mentioned before [see for example the fit given in footnote [47] and Ref. [23] (to appear)] such a procedure introduces CP violation in accord with observation, while preserving the success of the framework as regards its predictions for fermion masses and neutrino oscillations [23] [20].
Given the magnitudes of the parameters (see Eqs. (6) and Ref. [47]), which are obtained from considerations of fermion masses and neutrino oscillations [20,23]—that is $|\sigma| \approx |\epsilon| \approx 0.1, |y| \approx 0.06, |\epsilon'| \approx 2 \times 10^{-4}, |z| \approx (1/200)(1 \text{ to } 1/2), |\zeta_{22}| \approx 10^{-3}(1 \text{ to } 3), |\zeta_{13}| \approx |\zeta_{31}| \approx (1/200)(1 \text{ to } 1/2),$ with the real parts of $(\sigma, \epsilon \text{ and } y)$ having the signs $(+, - , -)$ respectively, we would expect the typical magnitudes of the three terms of Eq. (15) to be as follows:

$$|1^{\text{st}} \text{ Term}| = \left| (-3\epsilon' - \zeta_{13}y^*) (\zeta_{11} - z\zeta_{13}) \right|$$

$$\approx \left[ (6 \text{ to } 8) \times 10^{-4} \right] \left[ (2.5 \times 10^{-5}) (1 \text{ to } 1/4) \right] \approx 10^{-8}$$

$$|2^{\text{nd}} \text{ Term}| = \left| \zeta_{22} - y^* (\sigma^* - 3\epsilon^*) \right|$$

$$\approx (2 \times 10^{-2}) \left[ 2 \times 10^{-3} (1 \text{ to } 1/2) \right] \approx (4 \times 10^{-5}) (1 \text{ to } 1/2)$$

$$|3^{\text{rd}} \text{ Term}| = \left| (\zeta_{31} - z) \{ (\sigma^* + 3\epsilon^*) - y^* \} \right|$$

$$\approx \left[ (1/200)(1/2 \text{ to } 1/5) \right] (0.13) \approx (0.7 \times 10^{-3}) (1/2 \text{ to } 1/5)$$

Thus, assuming that the phases of the different terms are roughly comparable, the third term would clearly dominate. The RHS of Eq. (16) is similarly estimated to be:

$$\left( \frac{M_D^\dagger M_D}{M_u^0} \right)_{11} = |3\epsilon' - z(\sigma - 3\epsilon)|^2 + |\zeta_{31} - z|^2$$

$$\approx \left| 6 \times 10^{-4} + 2 \times 10^{-3} (1 \text{ to } 1/2) \right|^2 + \left| 5 \times 10^{-3} (1/2 \text{ to } 1/5) \right|^2$$

$$\approx 2.5 \times 10^{-5} (1/4 \text{ to } 1/6)$$

Since $|\zeta_{31}|$ and $|z|$ are each expected to be of order $(1/200)(1 \text{ to } 1/2)$, we have allowed in Eqs. (17) and (18) for a possible mild cancellation between their contributions to $|\zeta_{31} - z|$ by putting $|\zeta_{31} - z| \approx (1/200)(1/2 \text{ to } 1/5)$ (say). In going from the second to the third step of Eq. (18) we have assumed (for simplicity) that the second term of $(M_D^\dagger M_D)_{11}/(M_u^0)^2$ given by $|\zeta_{31} - z|^2$ dominates over the first. This in fact holds for a large part of the expected parameter space, especially for values of $|z| \approx (1/200)(1/2 \lesssim |\zeta_{31}| \approx (1/200)(1 \text{ to } 3/4)$ (say). Note that the combination $|\zeta_{31} - z|$ also enters into the dominant term [i.e., the third term in Eq. (17)] of $(M_D^\dagger M_D)_{21}/(M_u^0)^2$. As a result, to a good approximation (in the region of parameter space mentioned above), the lepton-asymmetry parameter $\epsilon_1$ [given by Eq. (11)] becomes independent of the magnitude of $|\zeta_{31} - z|^2$, and is given by:

$$\epsilon_1 \approx \frac{1}{8\pi} \left( \frac{M_u^0}{v} \right)^2 |(\sigma + 3\epsilon^* - y^*) \sin (2\phi_{21}) (3 \left( \frac{M_1}{M_2} \right) \right) \approx - (2.0 \times 10^{-6}) \sin (2\phi_{21}),$$

where, $\phi_{21} = \text{arg}[((\zeta_{31} - z)(\sigma^* + 3\epsilon^* - y^*)) + (\phi_1 - \phi_2)],$ and we have put $(M_u^0/v)^2 \approx 1/2$, $|\sigma + 3\epsilon - y| \approx 0.13$ (see Eq. (6) and Ref. [47]), and for concreteness (for the present case of thermal leptogenesis) $M_1 \approx 4 \times 10^9 \text{ GeV}$ and $M_2 \approx 2 \times 10^{12} \text{ GeV}$ [see Eq. (8)]. The parameter $m_1$, given by Eq. (13), is (approximately) proportional to $|\zeta_{31} - z|^2$ [see Eq. (15)]. It is given by:

$$m_1 \approx |\zeta_{31} - z|^2 (M_u^0)^2/M_1 \approx (1.9 \times 10^{-2} \text{ eV})(1 \text{ to } 1/6) \left( \frac{4 \times 10^9 \text{ GeV}}{M_1} \right)$$

where, as before, we have put $|\zeta_{31} - z| \approx (1/200)(1/2 \text{ to } 1/5)$. The corresponding efficiency factor $\kappa$ [given by Eq. (12)], lepton and baryon-asymmetries $Y_L$ and $Y_B$ [given by Eqs. (9) and (10)] and the requirement on the phase-parameter $\phi_{21}$ are listed in Table 1.
The constraint on $\phi_{21}$ is obtained from considerations of Big-Bang nucleosynthesis, which requires $3.7 \times 10^{-11} \lesssim (Y_B)_{BBN} \lesssim 9 \times 10^{-11}$ [1]; this is consistent with the CMB data [2], which suggests somewhat higher values of $(Y_B)_{CMB} \approx (7 - 10) \times 10^{-11}$ (say). We see that the first case $|\zeta_{31} - z| \approx 1/200(1/3)$ leads to a baryon asymmetry $Y_B$ that is on the low side of the BBN-data, even for a maximal $\sin(2\phi_{21}) \approx 1$. The other cases with $|\zeta_{31} - z| \approx (1/200)(1/4$ to 1/5), which are of course perfectly plausible, lead to the desired magnitude of the baryon asymmetry for natural values of the phase parameter $\phi_{21} \sim (\pi/18$ to $\pi/4)$. We see that, for the thermal case, the CMB data, requiring higher values of $Y_B$, would suggest somewhat smaller values of $|\zeta_{31} - z| \sim 10^{-3}$. This constraint would be eliminated for the case of non-thermal leptogenesis.

We next consider briefly the scenario of non-thermal leptogenesis [57,58]. In this case the inflaton is assumed to decay, following the inflationary epoch, directly into a pair of heavy RH neutrinos (or sneutrinos). These in turn decay into $l + H$ and $\bar{l} + \bar{H}$ as well as into the corresponding SUSY modes, and thereby produce lepton asymmetry, during the process of reheating. It turns out that this scenario goes well with the fermion mass-pattern of Sec. 2 [in particular see Eq. (3)] and the observed baryon asymmetry, provided $2M_2 > m_{infl} > 2M_1$, so that the inflaton decays into $2N_1$ rather than into $2N_2$ (contrast this from the case proposed in Ref. [57]). In this case, the reheating temperature ($T_{RH}$) is found to be much less than $M_1 \sim 10^{10}$ GeV (see below); thereby (a) the gravitino constraint is satisfied quite easily, even for a rather low gravitino-mass $\sim 200$ GeV (unlike in the thermal case); at the same time (b) while $N_1$'s are produced non-thermally (and copiously) through inflaton decay, they remain out of equilibrium and the wash out process involving inverse decays and $\Delta L \neq 0$-scatterings are ineffective, so that the efficiency factor $\kappa$ is 1.

To see how the non-thermal case can arise naturally, we recall that the VEV’s of the Higgs fields $\Phi = (1, 2, 4)_{H}$ and $\tilde{\Phi} = (1, 2, 4)_{H}$ have been utilized to (i) break SU(2)$_R$ and B-L so that G(224) breaks to the SM symmetry [7], and simultaneously (ii) to give Majorana masses to the RH neutrinos via the coupling in Eq. (4) (see e.g., Ref. [20]; for SO(10), $\Phi$ and $\tilde{\Phi}$ would be in $16_H$ and $\bar{16}_H$, respectively). It is attractive to assume that the same $\Phi$ and $\tilde{\Phi}$ (in fact their $\nu^c_{RH}$ and $\bar{\nu}^c_{RH}$-components), which acquire GUT-scale VEV’s, also drive inflation [57]. In this case the inflaton would naturally couple to a pair of RH neutrinos by the coupling of Eq. (6). To implement hybrid inflation in this context, let us assume following Ref. [57], an effective superpotential $W_{\text{eff}} = \lambda S(m_{\Phi} - M^2) + \text{(non-ren. terms)}$, where $S$ is a singlet field [59]. It has been shown in Ref. [57] that in this case a flat potential with a radiatively generated slope can arise so as to implement inflation, with $G(224)$ broken during the inflationary epoch to the SM symmetry. The inflaton is made of two complex scalar fields (i.e., $\theta = (\delta \bar{\nu}^C_{RH} + \delta \nu^C_{RH})/\sqrt{2}$) that represents the fluctuations of the Higgs fields around the SUSY minimum, and the

| $\zeta_{31} - z$ | (1/200)(1/3) | (1/200)(1/4) | (1/200)(1/5) |
|-----------------|--------------|--------------|--------------|
| $\tilde{m}_1$ (eV) | $0.83 \times 10^{-2}$ | $0.47 \times 10^{-2}$ | $0.30 \times 10^{-2}$ |
| $\kappa$ | $1/73$ | $1/39$ | $1/24$ |
| $Y_L/\sin(2\phi_{21})$ | $-11.8 \times 10^{-11}$ | $-22.4 \times 10^{-11}$ | $-36 \times 10^{-11}$ |
| $Y_B/\sin(2\phi_{21})$ | $4 \times 10^{-11}$ | $7.5 \times 10^{-11}$ | $12 \times 10^{-11}$ |

Table 1: Baryon Asymmetry for the Case of Thermal Leptogenesis
singlet S). Each of these have a mass $m_{\text{infl}} = \sqrt{2} \lambda M$, where $M = \langle (1, 2, 4)_H \rangle \approx 2 \times 10^{16}$ GeV and a width $\Gamma_{\text{infl}} = \Gamma(\theta \to \Psi_{\nu_H} \overline{\Psi}_{\nu_H}) = \Gamma(S \to \tilde{\nu}H\tilde{\nu}H) \approx [1/(8\pi)](M_1/M)^2 m_{\text{infl}}$ so that

$$T_{\text{RH}} \approx (1/7)(\Gamma_{\text{infl}}M_{\text{Pl}})^{1/2} \approx (1/7)(M_1/M)[m_{\text{infl}}M_{\text{Pl}}/(8\pi)]^{1/2} \tag{21}$$

For concreteness, take $M_2 \approx 2 \times 10^{12}$ GeV, $M_1 \approx 2 \times 10^{10}$ GeV (1 to 2) [in accord with Eq. (18)], and $\lambda \approx 10^{-4}$, so that $m_{\text{infl}} \approx 3 \times 10^{12}$ GeV. We then get: $T_{\text{RH}} \approx (1.7 \times 10^8$ GeV)(1 to 2), and thus (see e.g., Sec. 8 of Ref. [18]):

$$(Y_B)_{\text{Non-Thermal}} \approx - (Y_L/3) \approx (-1/3)(n_{\bar{N}_1} + n_{\bar{S}_1} + n_{\bar{S}_2})/s \epsilon_1 \approx (-1/3)(3/2)(T_{\text{RH}}/m_{\text{infl}}) \epsilon_1 \approx (3 \times 10^{-11})(\sin 2\phi_{21})(1 \to 2)^2 \tag{22}$$

Here we have used Eq. (19) for $\epsilon_1$ with appropriate $(M_1/M_2)$, as above. Setting $M_1 \approx 2 \times 10^{10}$ for concreteness, we see that $Y_B$ obtained above agrees with the (nearly central) observed value of $(Y_B)_{\text{BBN}(\text{CMB})} \approx (6(9)) \times 10^{-11}$, again for a natural value of the phase parameter $\phi_{21} \approx \pi/30(\pi/20)$. As mentioned above, one possible advantage of the non-thermal over the thermal case is that the gravitino-constraint can be met rather easily, in the case of the former (because $T_{\text{RH}}$ is rather low $\sim 10^8$ GeV), whereas for the thermal case there is a significant constraint on the lowering of the $T_{\text{RH}}$ (so as to satisfy the gravitino-constraint) via a vis a raising of $M_1 \sim T_{\text{RH}}$ so as to have sufficient baryon asymmetry (note that $\epsilon_1 \propto M_1$, see Eq. (19)). Furthermore, for the non-thermal case, the dependence of $Y_B$ on the parameter $|\zeta_{31} - z|^2$ (which arises through $\kappa$ and $\mathbf{m}_1$ in the thermal case, see Eqs. (12), (13), and (18)) is largely eliminated. Thus the expected magnitude of $Y_B$ (Eq. (22)) holds without a significant constraint on $|\zeta_{31} - z|$ (in contrast to the thermal case).

To conclude, we have considered two alternative scenarios (thermal as well as non-thermal) for inflation and leptogenesis. We see that the $G(224)/SO(10)$ framework provides a simple and unified description of not only fermion masses and neutrino oscillations (consistent with maximal atmospheric and large solar oscillation angles) but also of baryogenesis via leptogenesis, treated within either scenario, in accord with the gravitino-constraint. Each of the features – (a) the existence of the right-handed neutrinos, (b) B-L local symmetry, (c) quark-lepton unification through SU(4)-color, (d) the magnitude of the supersymmetric unification-scale and (e) the seesaw mechanism – plays a crucial role in realizing this unified and successful description. These features in turn point to the relevance of either the G(224) or the SO(10) symmetry being effective between the string and the GUT scales, in four dimensions [9]. While the observed magnitude of the baryon asymmetry seems to emerge naturally from within the framework, understanding its observed sign (and thus the relevant CP violating phases) remains a challenging task [61].

**Acknowledgements**

I would like to thank Kaladi S. Babu for collaborative discussions on CP violation, and Pasquale Di Bari and Qaisar Shafi for most helpful correspondences and clarifications of their work. I have also benefitted from discussions with Gustavo Branco and Tsutomo Yanagida on aspects of this work. The sabbatical support by the University of Maryland during the author’s visit to SLAC, as well as the hospitality of the Theory Group of SLAC, where this
work was carried out, are gratefully acknowledged. The work is supported in part by DOE grant no. DE-FG02-96ER-41015.

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[23] K. S. Babu and J. C. Pati, “Link Between Neutrino Oscillations and CP Violation within Supersymmetric Unification”, Abstract in Proceedings of NATO Advanced Study Institute, “Recent Developments in Particle Physics and Cosmology”, June 6-July 7, 2000, Cascais, Portugal, Pages 215-217, Ed. by G. Branco, Q. Shafi and J. I. Silva-Marcos; K. S. Babu and J. C. Pati, “Linking CP and Flavor Violations To Neutrino Oscillations Within Supersymmetric Unification” paper to appear.

[24] By combining these results with the analysis of the forthcoming paper [23], one would incorporate CP violation into this unified picture as well.
Many of these are based on phenomenological models just for neutrino masses, which are not linked to the masses and mixings of quarks and charged leptons. See e.g., S. F. King, [hep-ph/0204360] for a recent analysis along these lines and references therein.

For attempts within SO(10) models, see e.g., E. Nezri and J. Orloff, [hep-ph/0004227]; F. Bucella, D. Falcone, F. Tramontano, [hep-ph/0108172]; G. C. Branco, F. Gonzales Felipe, F. R. Joaquim and M. N. Rebelo, [hep-ph/0202030]. For a variant attempt within left-right symmetric model, see A. Joshipura, E. A. Paschos and W. Rodejohann, [hep-ph/0104228].

For example, many of the attempts in [26] assume that the Dirac mass-matrix of the neutrinos is equal to that of the up-flavor quarks ($M^D_\nu = M_u$) at GUT-scale. This simple equality would be true for SO(10) if only $10_H$ contributes to the fermion masses. However, the minimal Higgs system permits a (B-L)-dependent antisymmetric "$23"$ and "$32"$ entry [20] (as discussed later), which plays a crucial role in explaining why $m_\mu \neq m_s$ and why $V_{cb}$ is so small and yet $\theta_{\nu_{2\nu_3}}^{\text{osc}}$ is rather maximal. Such entries do not respect $M^D_\nu = M_u$.

For instance, in the first paper of Ref. [26], it is found that only the solar vacuum oscillation solution gives acceptable baryon asymmetry. In the second paper, it is noted that SUSY models with full quark-lepton symmetry gives too small an asymmetry, while in the third paper it is found that the just-so and SMA solutions give viable leptogenesis, but the LMA solution is strongly disfavored [based on their assumption of $M^D_\nu = M_u$, (see comments in Ref. [27])]. In the fourth paper, it is observed that the SMA and vacuum solutions produce reasonable asymmetry, but the LMA solution produces too large an asymmetry.

These have been introduced in various forms in the literature. For a sample, see e.g., C. D. Frogatt and H. B. Nielsen, Nucl. Phys. B147, 277 (1979); L. Hall and H. Murayama, Phys. Rev. Lett. 75, 3985 (1995); P. Binetruy, S. Lavignac and P. Ramond, Nucl. Phys. B477, 353 (1996). In the string theory context, see e.g., A. Faraggi, Phys. Lett. B278, 131 (1992).

The zeros in "$11"$, "$13"$ and "$31"$ elements signify that they are relatively small quantities (specified below). While the "$22"$ elements were set to zero in Ref. [20], because they are meant to be $<"23"$ "$32"$ "$33"$ $\sim 10^{-2}$ (see below), and thus unimportant for purposes of Ref. [20], they are retained here, because such small $\zeta_{22}^u$ and $\zeta_{22}^d$ [$\sim (1/3) \times 10^{-2}$ (say)] can still be important for CP violation and thus leptogenesis.

For G(224), one can choose the corresponding sub-multiplets – that is $(1, 1, 15)_H,(1, 2, 4)_H,(1, 2, 4)_H,(2, 2, 1)_H$ – together with a singlet $S$, and write a superpotential analogous to Eq. (2).

If the effective non-renormalizable operator like $16_216_310_H45_H/M'$ is induced through exchange of states with GUT-scale masses involving renormalizable couplings, rather than through quantum gravity, $M'$ would, however, be of order GUT-scale. In this case $\langle 45_H \rangle/M' \sim 1$, rather than $1/10$.

While $16_H$ has a GUT-scale VEV along the SM singlet, it turns it can also have a VEV of EW scale along the "$\tilde{\nu}_L$" direction due to its mixing with $10_H^d$, so that the $H_d$
of MSSM is a mixture of $10^d_H$ and $16^c_H$. This turns out to be the origin of non-trivial CKM mixings (see Ref. [20]).

[34] The flavor charge(s) of $45_H(16_H)$ would get determined depending upon whether $p(q)$ is one or zero (see below).

[35] The basic presumption here is that effective dimensionless couplings allowed by SO(10)/G(224) and flavor symmetries are of order unity [i.e., $(h_{ij}, g_{ij}, a_{ij}) \approx 1/3$-3 (say)]. The need for appropriate powers of $(S/M)$ with $\langle S \rangle /M \sim M_{GUT}/M_{\text{string}} \sim (1/10-1/20)$ in the different couplings leads to a hierarchical structure. As an example, consider just one U(1)-flavor symmetry with one singlet S. The hierarchical form of the Yukawa couplings exhibited in Eqs. (1) and (2) would be allowed, for the case of $p = 1, q = 0$, if $(16_3, 16_2, 16_1, 10_H, 16_H, 45_H$ and S) are assigned U(1)-charges of $(a, a + 1, a + 2, -2a, -a - 1/2, 0, -1)$. It is assumed that other fields are present that would make the U(1) symmetry anomaly-free. With this assignment of charges, one would expect $|\zeta_{22}^d| \sim (\langle S \rangle /M)^2$; one may thus take $|\zeta_{22}^d| \sim (1/3) \times 10^{-2}$ without upsetting the success of Ref. [20]. In the same spirit, one would expect $|\zeta_{13}, \zeta_{31}| \sim (\langle S \rangle /M^2 \sim 10^{-2}$ and $|\zeta_{11}| \sim (\langle S \rangle /M^3 \sim 10^{-4}$ (say). The value of “a” would get fixed by the presence of other operators (see later).

[36] These effective non-renormalizable couplings can of course arise through exchange of (for example) $45$ in the string tower, involving renormalizable $16, 16_H 45$ couplings. In this case, one would expect $M \sim M_{\text{string}}$.

[37] P. Ginsparg, Phys. Lett. B197, 139 (1987); V. S. Kaplunovsky, Nucl. Phys. B307, 145 (1988); Erratum: ibid B382, 436 (1992).

[38] J. C. Pati, “Probing Grand Unification Through Neutrino Oscillations, Leptogenesis and Proton Decay”, hep-ph/0305221. To appear in the Proceedings of the Erice 2002 School.

[39] The range in $M_3$ and $M_2$ is constrained by the values of $m(\nu_3)$ and $m(\nu_2)$ suggested by the atmospheric and solar neutrino data.

[40] Note that the magnitudes of $\eta, \epsilon$ and $\sigma$ are fixed by the input quark masses. Furthermore, one can argue that the two contributions for $\theta_{\nu_2\nu_3}^{\text{osc}}$ [see Eq. (1)] necessarily add to each other as long as $|y|$ is hierarchical ($\sim 1/10$) [20]. As a result, once the sign of $\epsilon$ relative to $\eta$ and $\sigma$ is chosen to be negative, the actual magnitudes of $V_{cb} \approx (0.044)$ and $\sin^2 2\theta_{\nu_2\nu_3}^{\text{osc}} \approx 0.99$ emerge as predictions of the model [20].

[41] Note that such an operator would be allowed by the flavor symmetry defined in Ref. [35] if one sets $a = 1/2$. In this case, operators such as $W_{23}$ and $W_{33}$ that would contribute to $\nu^c_i \nu_1^i$ and $\nu^c_i \nu^c_i$ masses would be suppressed relative to $W_{12}$ by flavor symmetry. As pointed out by other authors (see e.g., S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979) and Proc. XXVI Int’l Conf. on High Energy Physics, Dallas, TX, 1992; E. Akhmedov, Z. Berezhiani and G. Senjanovic, Phys. Rev. D47, 3245 (1993),), non-seesaw Majorana masses of the LH neutrinos can arise directly, even in the standard model, through operators of the form $L_L L_L \Phi_H \Phi_H /M$, by utilizing quantum gravity. [For SO(10), two $16_H$’s are needed additionally to violate B-L by two units.] In the case of the standard model, ordinarily, one would expect $M \sim M_{\text{Planck}}$. Thus one would still need to find a
As an example, one such fit with complex parameters assigns $\tilde{\sigma} \delta \delta$ and $\lambda \sigma \delta$ and mass terms $M_S \tilde{S} \tilde{S}$ and $\tilde{M}_{10} 1010$. In this case $\kappa_{12}/M_{\text{eff}} \approx a_1 a_2 b_2/(\tilde{M}_{10}^2 M_S)$. Setting the charge $a = 1/2$ (see Ref. 35 and 41), and assigning charges $(-3/2, 5/2)$ to $(10, \tilde{S})$, the couplings $a_1$, and $b$ would be flavor-symmetry allowed, while $a_2$ would be suppressed but so also would be the mass of $10$ compared to the GUT-scale. One can imagine that $\tilde{S}$ on the other hand acquires a GUT-scale mass through for example the Dine-Seiberg-Witten mechanism, violating the U(1)-flavor symmetry. One can verify that in such a picture, one would obtain $\kappa_{12}/M_{\text{eff}}^3 \approx 1/M_{\text{GUT}}^3$.

For instance, consider the superpotential for $\mathbf{45}_{H}$ only: $W(\mathbf{45}_{H}) = M_{45} \mathbf{45}_{H}^2 + \lambda \mathbf{45}_{H}^4 / M$, which yields (setting $F_{\mathbf{45}_{H}} = 0$), either $\langle \mathbf{45}_{H} \rangle = 0$, or $\langle \mathbf{45}_{H} \rangle^2 = -2 M_{\mathbf{15}}^3 M/\lambda$. Assuming that “other physics” would favor $\langle \mathbf{45}_{H} \rangle \neq 0$, we see that $\langle \mathbf{45}_{H} \rangle$ would be pure imaginary, if the square bracket is positive, with all parameters being real. In a coupled system, it is conceivable that $\langle \mathbf{45}_{H} \rangle$ in turn would induce phases (other than “0” and $\pi$) in some of the other VEV’s as well, and may itself become complex rather than pure imaginary.

L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983).

Within the framework developed in Ref. 23, the CP violating phases entering into the SUSY contributions (for example those entering into the squark-mixings) also arise entirely through phases in the fermion mass matrices.

An intriguing feature is the prominence of the $\delta_{RR}^{\nu_2}\eta_R \to \tilde{\sigma}$-parameter which gets enhanced in part because of the largeness of the $\nu_2-\nu_3$ oscillation angle. This leads to large departures from the predictions of the standard model, especially in transitions such as $B_s \to B_s$ and $B_d \to \Phi K_s (b \to s s s)$ 23. This feature has independently been noted recently by D. Chang, A. Massiero, and H. Murayama (hep-ph/0205111).

As an example, one such fit with complex parameters assigns 23: $\sigma = 0.10 - 0.012 i$, $\eta = 0.12 - 0.05 i$, $\epsilon = -0.095$, $\eta' = 4.0 \times 10^{-3}$, $\epsilon' = 1.54 \times 10^{-3} e^{i\pi/4}$, $\zeta_{22}^{u} = 1.25 \times 10^{-3} e^{i\pi/9}$ and $\zeta_{22}^{d} = 4 \times 10^{-3} e^{i\pi/2}$, $\mathcal{M}_{u}^{0} \approx 110$ GeV, $\mathcal{M}_{d}^{0} \approx 1.5$ GeV, $y \approx -1/17$ (compare with Eq. 4 for which $\zeta_{22}^{u} = 0$). One obtains as outputs: $m_{b,s,d} \approx (5 \text{ GeV, } 132 \text{ MeV, } 8 \text{ MeV})$, $m_{c,u} \approx (1.2 \text{ GeV, } 4.9 \text{ MeV})$, $m_{u,e} \approx (102 \text{ MeV, } 0.4 \text{ MeV})$ with $m_{t,\tau} \approx (167 \text{ GeV, } 1.777 \text{ GeV})$, $(V_{us}, V_{ub}, |V_{ub}|, |V_{td}|) \approx (0.217, 0.044, 0.0029, 0.011)$, while preserving the predictions for neutrino masses and oscillations as in Eq. 7. The above serves to demonstrate that complexification of parameters of the sort presented above can preserve the successes of Eq. 7 (20). This particular case leads to $\eta_W = 0.29$ and $\rho_W = -0.187$ 23, to be compared with the corresponding standard model values (obtained from $\epsilon_K, V_{ub}$ and $\Delta m_{BD}$) of $(\eta_W)_{\text{SM}} \approx 0.33$ and $(\rho_W)_{\text{SM}} \approx +0.2$. The consistency of such values for $\eta_W$ and $\rho_W$ (especially reversal of the sign of $\rho_W$ compared to the SM value), in the light of having both standard model and SUSY-contributions to CP and flavor-violations, and their distinguishing tests, are discussed in Ref. 23.
For reviews, see chapters 6 and 8 in E. W. Kolb and M. S. Turner, “The Early Universe”, Addison-Wesley, 1990.

J. Ellis, J. E. Kim and D. Nanopoulos, Phys. Lett. 145B, 181 (1984); M. Yu. Khlopov and A. Linde, Phys. Lett. 138B, 265 (1984); E. Holtmann, M. Kawasaki, K. Kohri and T. Moroi, hep-ph/9805405

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The factor 0.7 in Eq. (12) [instead of 1 in Eq. (14) of Ref. [53]] is an estimate that incorporates the modification needed for SUSY corresponding to a doubling of $N_1$-decay width owing to the presence of both $l + H$ and $l + \tilde{H}$-modes and an increase of $g^*$ from 106 for the standard model to 228 for SUSY.

One can verify that $K \equiv (\Gamma(N_1)/2H)_{T=M_1} \approx (0.37)[M_{Pl}/(1.66\sqrt{g^*(8\pi v^2)})]\tilde{m}_1 \approx 234(\tilde{m}_1/eV)$, where 0.37 denotes the usual time-dilatation factor, $g^*(for\ SUSY) \approx 228$ and $v \approx 174$ GeV. For comparison, we note that if one includes only inverse decays (thus neglecting $\Delta\ell \neq 0$-scatterings) in the Boltzmann equations, one would obtain: $\kappa \approx 0.3/[K(\ln K)^{0.6}]$ for $K > 10$ [53], and $\kappa \approx 1/2K$ for $1 \lesssim K \lesssim 10$. As pointed out in Ref. [53], these expressions, frequently used in the literature, however, tend to overestimate $\kappa$ by nearly a factor of 7. In what follows, we will therefore use Eq. (12) to evaluate $\kappa$.

M. Plumacher, Z. Phys. C74, 549 (1997).

For a specific scenario of inflation and leptogenesis in the context of SUSY G(224), see R. Jeannerot, S. Khalil, G. Lazarides and Q. Shafi, JHEP 010, 012 (2000) (hep-ph/0002151), and references therein. As noted in this paper, with the VEV’s of $(1, 2, 4)_H$ and $(1, 2, 4)_{\tilde{H}}$ breaking G(224) to the standard model, and also driving inflation, just the COBE measurement of $\delta T/T \approx 6.6 \times 10^{-6}$, interestingly enough, implies that the relevant VEV should be of order $10^{16}$ GeV. In this case, the inflaton made of two complex scalar fields (i.e., $\theta = (\delta \tilde{v}_{\tilde{H}} + \delta \tilde{v}_{H})/\sqrt{2}$, given by the fluctuations of the Higgs fields, and a singlet $S$), each with a mass $\sim 10^{12}-10^{13}$ GeV, would decay directly into a pair of heavy RH neutrinos – that is into $N_2N_2$ (or $N_1N_1$) if $m_{infl} > 2M_2$ (or $2M_1$). The subsequent decays of $N_2$’s (or $N_1$’s), thus produced, into $l + \Phi_H$ and $\tilde{l} + \tilde{\Phi}_H$ would produce lepton-asymmetry during the process of reheating. I will comment later on the consistency of this possibility with the fermion mass-pattern exhibited in Sec. 2. I would like to thank Qaisar Shafi for a discussion on these issues.

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Incorporating such an effective superpotential in accord with the assignment of flavor-changes suggested in Refs. [35] and [42] would involve two additional singlets with appropriate charges. The $(\text{VEV})^2$ of one or both of these may represent $M^2$. Derivation of such a picture with appropriate flavor-charge assignments from an underlying (string/M) theory is of course beyond the state of the art at present.

Note that for this non-thermal case, since the gravitino-constraint is relaxed, $N_1$ can be chosen heavier than for the case considered before (the thermal case), still in accord with Eq. [5]. Since $Y_B \propto \epsilon_1 T_{RH}/M_{\text{infl}}$, while $\epsilon_1 \propto (M_1/M_2)$, $T_{RH} \propto M_1(M_{\text{infl}})^{1/2}$ and $M_{\text{infl}} \propto \lambda$, we see that $Y_B \propto (M_1^2/M_2)/\sqrt{\lambda}$, for a constant $M$, for the case of non-thermal leptogenesis.

Note that the effective phase $\phi_{21}$, relevant to leptogenesis, depends on the phases in both the Dirac ($M_{D\nu}$) and the Majorana ($M_{R\nu}$) mass matrices of the neutrinos. Thus, in general, it is quite distinct from the phase(s) entering into observed CP violations in the K and the B-systems.