The problem of testing leptogenesis from low energy experiments is discussed following three different perspectives. Firstly, we review the prospects that from low energy experiments we could reconstruct the neutrino Yukawa coupling matrix and hence constrain the leptogenesis mechanism. We emphasize the fact that the experimental determination of the phases and mixings in the light neutrino mass matrix is irrelevant for leptogenesis, unless additional information about the texture of the Yukawa coupling matrix is provided by other observables. Secondly, we show how the discovery of an extra gauge boson could bring us important indications for leptogenesis. Thirdly, we discuss the problems one encounters when attempting to build a leptogenesis mechanism at a directly testable scale, presenting an explicit model which avoids these problems.

1 Introduction

The matter-antimatter asymmetry of the universe is one of the most fascinating enigma of today’s particle physics and cosmology. The recent evidence for small but non-vanishing neutrino masses has established the leptogenesis mechanism with heavy singlet neutrinos as one of the most appealing explanation of this asymmetry. In the seesaw mechanism with heavy singlet neutrinos, the smallness of neutrino masses is naturally explained and the terms at their origin, (i.e. the Yukawa interactions involving the left-handed leptons and the singlet neutrinos, and the lepton number violating singlet neutrino Majorana mass term), are also expected to be at the origin of a cosmological lepton asymmetry produced at the epoch of the singlet neutrino decays. Once produced, the lepton asymmetry $Y_L$ is expected to be converted for a large fraction to a baryon asymmetry $Y_B$ by the effects of the sphalerons associated to the B+L anomaly

$$Y_B = -CY_L,$$

with $Y_{B,L} = n_{B,L}/s$, the baryon (lepton) number density over the entropy density. In the seesaw extended standard model and seesaw extended minimal supersymmetric standard model, $C$ is
equal to $28/79$ and $8/23$ respectively. From nucleosynthesis constraints, $Y_B$ has been determined to be within the range $3 \cdot 10^{-11} < Y_B < 9 \cdot 10^{-11}$, in agreement with recent results from CMB data. Qualitatively if the singlet neutrinos have masses between $\sim 10^{10}$ GeV and the GUT scale, the typical values of the Yukawa couplings we need for inducing the leptogenesis with the right order of magnitude are also the ones we need for inducing neutrino masses in agreement with the neutrino experiments and with the dark matter bound $m_\nu < \text{few eV}$. Moreover for such values of the singlet neutrino masses, the seesaw leptogenesis model can be embedded naturally in grand unified models such as the ones based on SO(10) which predicts the existence of singlet neutrinos.

For all these reasons this seesaw leptogenesis model is definitely very attractive. More pragmatically, however, this model has a major default: it’s very difficult to test it. With so large singlet neutrino masses, it is not possible to test it directly by producing those particles. The problem of how to test leptogenesis indirectly from low energy observables is therefore crucial. In these proceedings we will discuss this problem following three different perspectives. First, in section 2 the various observables from which we could build a program of low-energy tests of leptogenesis are discussed. The question we address is how we could reconstruct the Yukawa coupling matrix from these observables and from that how we could test leptogenesis. Secondly, in section 3, we emphasize the fact that the discovery of an extra gauge boson around the TeV scale would bring very interesting informations about leptogenesis, and discuss this question in particular in the context of a unified theory based on the $E_6$ group. Finally in section 4 we discuss the problems one encounters if, instead of considering leptogenesis models at a very high scale, we want to build a leptogenesis mechanism at a directly testable scale. We present an explicit leptogenesis model at the TeV scale which avoids these problems.

2 Low energy observables and leptogenesis

The seesaw mechanism is usually implemented in a minimal way by adding to the standard model (SM) three heavy singlet neutrinos $N_i$ coupling to the left-handed lepton doublet $L$ through Yukawa interactions:

$$\mathcal{L} = \mathcal{L}_S M + N_i^c (Y_\nu)_{ij} L_j H - \frac{1}{2} N_i^c (M_N)_{ij} N_j^c,$$

Without loss of generality, one can always work in the basis where the charged lepton and heavy singlet neutrino mass matrices are real and diagonal. In this basis we have also the freedom to redefine the three doublets of left-handed lepton fields by multiplying them by any phase without affecting the physical content of the model. In full generality the lagrangian above involves therefore 9 real parameters and 6 phases in $Y_\nu$ in addition to the 3 real singlet neutrino masses $M_{N_i}$. The light neutrino masses induced are given by the usual seesaw formula:

$$\mathcal{M}_\nu = Y_\nu^T (M_N)^{-1} Y_\nu v^2,$$

with $v = 174$ GeV. Being symmetric this matrix can be diagonalized by a unitary matrix $U$,

$$U^T \mathcal{M}_\nu U = \mathcal{M}_\nu^D,$$

with $\mathcal{M}_\nu^D = \text{diag}(m_\nu_1, m_\nu_2, m_\nu_3)$. $U$ can be written as $U = PV$ where $V$ is a CKM type matrix involving 3 angles and one phase $\delta$,

$$V = \begin{pmatrix} c_1 c_3 & -s_1 c_3 & -s_3 e^{-i\delta} \\ s_1 c_2 - c_1 s_2 s_3 e^{i\delta} & c_1 c_2 + s_1 s_2 s_3 e^{i\delta} & -c_3 s_2 \\ s_1 s_2 + c_1 c_2 s_3 e^{i\delta} & c_1 s_2 - s_2 c_3 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix},$$
and where the matrix \( P \equiv diag(e^{i\phi_1}, e^{i\phi_2}, 1) \) involves two Majorana phases \( \phi_{1,2} \) which cannot be absorbed in the \( N_i \) fields (i.e. without reappearing in the \( M_N \)'s).

In the thermal history of the universe, at temperature around \( T \sim M_N \), the \( N_i \)'s disappear decaying to left-handed leptons and scalar Higgs bosons. The averaged \( \Delta L \) produced per decay is given by the CP-asymmetry:

\[
\varepsilon_i = \frac{\Gamma(N_i \rightarrow lH) - \Gamma(N_i \rightarrow \bar{H}^*)}{\Gamma(N_i \rightarrow lH) + \Gamma(N_i \rightarrow \bar{H}^*)}.
\]  

(6)

At lowest order, \( \varepsilon_i \) is given by the interference of the tree and one loop (vertex\( ^\dagger \) and self-energy\( ^\ddagger \)) diagrams which gives:

\[
\varepsilon_i = -\frac{1}{8\pi} \sum_l \text{Im} \left[ \left( Y_{\nu l} Y_{\nu l}^T \right)^{il} \left( Y_{\nu l} Y_{\nu l}^T \right)^{il} \right] \sqrt{x_l} \left[ \log(1 + 1/x_l) + \frac{2}{x_l - 1} \right],
\]

(7)

with \( x_l = (M_{N_i}/M_{N_j})^2 \). If the out-of-equilibrium decay condition\( ^\dagger \)

\[
\Gamma_{N_i} = \frac{1}{8\pi} \sum_j |Y_{\nu j}^{ij}|^2 M_{N_i} < H(T = M_{N_i}) = \sqrt{\frac{4\pi^3 g_s}{45 M_{\text{Planck}}}} T^2 \bigg|_{T = M_{N_i}},
\]

(8)
is satisfied, then the lepton asymmetry density will be given by \( Y_L \sim \sum \varepsilon_i / g^* \) with \( g^* \) the number of active degrees of freedom at this temperature (\( g_s \sim 100 \)).

In order to determine the constraints on this leptogenesis mechanism we could obtain from low energy experiments, it is necessary to know how we could reconstruct the \( Y_\nu \) matrix from the knowledge we have on the light neutrino mass matrix. To this end, it is convenient to use the parametrization\( ^\ddagger \)

\[
Y_\nu = \frac{1}{v} (M_N)^{1/2} R (M_\nu^D)^{1/2} U^{-1},
\]

(9)

with \( R \) a complex matrix which from Eqs. \( ^\dagger \) and \( ^\ddagger \) turns out to be orthogonal (\( R^T R = 1 \)). This parametrization is interesting because by construction, putting Eq. \( ^\ddagger \) in Eq. \( ^\dagger \), the low energy neutrino mass matrix \( M_\nu \) is independent of \( R \), and by taking the full set of possible complex orthogonal matrices \( R \), we can determine the full set of possible matrices \( Y_\nu \) which give rise to the same low energy neutrino mass matrix \( M_\nu \). Therefore \( R \) contains all the information in \( Y_\nu \) which is not contained in \( M_\nu \) and is independent of it. Since a general complex orthogonal matrix can be parametrized in terms of 3 real angles and 3 phases, this information depends on 6 parameters as it should be (i.e. 15 in \( Y_\nu \) minus 9 in \( M_\nu \)). A convenient way to parametrize a complex orthogonal matrix is in terms of three complex angles:

\[
R = \pm \begin{pmatrix}
\hat{c}_2 \hat{c}_3 & -\hat{c}_1 \hat{s}_3 - \hat{s}_1 \hat{c}_2 \hat{c}_3 & \hat{s}_1 \hat{s}_3 - \hat{c}_1 \hat{s}_2 \hat{c}_3 \\
\hat{c}_2 \hat{s}_3 & \hat{c}_1 \hat{c}_3 - \hat{s}_1 \hat{s}_2 \hat{c}_3 & -\hat{s}_1 \hat{c}_3 - \hat{c}_1 \hat{s}_2 \hat{s}_3 \\
\hat{s}_2 & \hat{s}_1 \hat{c}_2 & \hat{c}_1 \hat{c}_2
\end{pmatrix},
\]

(10)

with the “±” in front of the matrix to account for possible reflections.

Having the full set of possible \( Y_\nu \) matrices for a given low energy matrix \( M_\nu \) one can now address the question: which constraints \( M_\nu \) gives on leptogenesis? In Eq. \( ^\ddagger \) the lepton asymmetry depends only on the \( M_{N_i} \) and on the combination \( Y_\nu Y_\nu^\dagger \) which from Eq. \( ^\dagger \) is:

\[
Y_\nu Y_\nu^\dagger = \frac{1}{v^2} (M_N)^{1/2} R (M_\nu^D) R^\dagger (M_N)^{1/2}
\]

(11)

This combination depends on the light and heavy neutrino mass eigenvalues as well as on \( R \) but turns out to be independent of \( U \)! This means that, in a model independent way, leptogenesis
is independent of the three mixing angles and phases in $U$ and can be expressed in such a way that it depends only on mixing angles and phases which decouple from the low energy neutrino mass matrix. Of course we could find other parametrization where $Y_\nu^T Y_\nu^\dagger$ has for example a dependence on the CKM phase $\delta$ in $U$ for fixed values of the other phases but this dependence is completely parametrization dependent and therefore meaningless. The fact that there exists one parametrization (i.e. Eq. (3)) where leptogenesis and $\delta$ are totally independent shows it clearly. In other words, to speak about a "phase overlap" between the leptogenesis phase and the phase $\delta$, i.e. to know if we expect that the observation of a large $\delta$ phase at neutrino factories would lead naturally to a large leptogenesis phase, is parametrization dependent and therefore arbitrary. Only by assuming specific textures on $Y_\nu$ relating the phases, the knowledge of $\delta$ might tell us something about the leptogenesis phase. To assume a specific texture on $M_\nu$ is not sufficient because it doesn’t tell anything about the phases appearing in Eqs. (7) and (11).

To constrain leptogenesis from low energy experiments we need observables which are sensitive to $R$. If on the one hand in the seesaw extended SM it is unlikely that some observables could give model independent constraints on $R$, on the other hand in the seesaw extended minimal supersymmetric model (which involves the same number of parameters in $Y_\nu$), one might get a chance to reconstruct $R$ and hence $Y_\nu$. The slepton mass matrices, the electric dipole moments of the electron $d_e$ and muon $d_\mu$, the CP-conserving flavor changing processes $\mu \to e\gamma$ and $\tau \to l\gamma$, the CP-violating and CP-conserving component of $\mu \to eee$ and $\tau \to 3l$, depend on $Y_\nu$ from the effects of $Y_\nu$ on the renormalization (RGE’s) of the soft supersymmetry breaking parameters they involve (i.e. the slepton doublet and charged singlet slepton mass terms as well as trilinear couplings, see Ref. 11). At lowest order, all these processes have the property to depend on $Y_\nu$ through an hermitian matrix which has the form $H = Y_\nu^T D Y_\nu$ with $D$ a diagonal real matrix. In particular the soft slepton mass matrices depend on $H$ with $D = \log(M_{GUT}/M_N)\delta_{ij}$. In Refs. 12-14 it has been pointed out that from these observables and $M_\nu$ one could reconstruct $Y_\nu$ and see the consequences for leptogenesis. Replacing first $\nu$ by $\nu \sin \beta$ in Eqs. (9), (9) and (11) for the MSSM, the explicit way to proceed is the following 15: From a given $H$ matrix determined from these observables and from a given set of parameters in $M_\nu$ one can calculate the matrix

$$H' = (M_\nu^D)^{-1/2}U^\dagger H U (M_\nu^D)^{-1/2}v^2 \sin^2 \beta.$$  

The matrix $R$ as well as $(M_N)$ can then be determined as the solution of the equation

$$H' = R^\dagger (D_{ii} M_N) R.$$  

Thus from the nine effective low energy neutrino parameters and from the nine parameters in the hermitian matrix $H$ one can determine $R$ and $(M_N)$ and hence $Y_\nu$ via Eq. (13).

It is worth to take few examples of matrices $H$ and $M$ which satisfy the various experimental neutrino constraints as well as give an asymmetry within its experimental range. In Table.1 are shown the values of the various observables which can be reached for some configurations of parameters satisfying these requirements. Also given are the present and expected (in the forthcoming years) experimental sensitivities. One observes that some of the experimental bounds (in particular $\mu \to e\gamma$ 15-17) can be already saturated for some configurations of the matrix $H$. With the experimental sensitivities expected in the future, a non-negligible fraction of the parameter space is expected to be covered, in particular for $\mu \to e\gamma$, $\tau \to l\gamma$ and the EDM of the electron $d_e$. Instead of considering chosen $H$ matrices, a more systematic way to scan the reachable theoretical values would be to take, in a random way, values of $c_{1,2,3}$ in $R$, Eq. (14).

Note that, as pointed out in Ref. 1, an hermitian matrix cannot always be diagonalized by a complex orthogonal matrix. In this procedure it is therefore necessary to exclude the ranges of values of $H$ which are for this reason not physical.
Current experimental sensitivity | Expected experimental sensitivity | Theoretical value reachable
---|---|---
\(\text{Br}(\mu \rightarrow e\gamma)\) | \(< 1.2 \times 10^{-11}\) | \(\sim 10^{-14} - 10^{-15}\) | \(\sim 10^{-10}\) |
\(\text{Br}(\tau \rightarrow \mu\gamma)\) | \(< 6 \times 10^{-7}\) | \(\sim 10^{-7} - 10^{-8}\) | \(\sim 10^{-6}\) |
\(\text{Br}(\tau \rightarrow e\gamma)\) | \(< 2.7 \times 10^{-6}\) | \(\sim 10^{-7} - 10^{-8}\) | \(\sim 10^{-6}\) |
\(d_e (\text{e cm})\) | \(< 1.6 \times 10^{-27}\) | \(\sim 10^{-32}\) | \(\sim 10^{-28}\) |
\(d_\mu (\text{e cm})\) | \((3.7 \pm 3.4) \times 10^{-19}\) | \(\sim 10^{-24} - 10^{-25}\) | \(\sim 10^{-25}\) |
\(d_\tau (\text{e cm})\) | \(< 4.5 \times 10^{-17}\) | \(\sim 10^{-17}\) | \(\sim 10^{-15} - 10^{-16}\) |
\(\text{Br}(\mu \rightarrow 3e)\) | \(< 1 \times 10^{-12}\) | \(\sim 10^{-15} - 10^{-16}\) | \(\sim 10^{-12}\) |
\(\text{Br}(\tau \rightarrow 3e)\) | \(< (2 - 4) \times 10^{-7}\) | \(\sim 10^{-8}\) | \(\sim 10^{-8}\) |
\(\text{Br}(\tau \rightarrow \mu 2e)\) | \(< (2 - 4) \times 10^{-7}\) | \(\sim 10^{-8}\) | \(\sim 10^{-8}\) |
\(\text{Br}(\tau \rightarrow 3\mu)\) | \(< (2 - 4) \times 10^{-7}\) | \(\sim 10^{-8}\) | \(\sim 10^{-9}\) |
\(\text{Br}(\tau \rightarrow e 2\mu)\) | \(< (2 - 4) \times 10^{-7}\) | \(\sim 10^{-8}\) | \(\sim 10^{-9}\) |

Table 1: Processes from which constraints on \(Y_\nu\) and the \(M_{N_i}\) could be obtained. The current and expected experimental sensitivity are compared to the larger theoretical values obtained for various textures of the matrix \(H\). We didn’t find this theoretical value for \(d_e\) in the literature but it is anyway much smaller than the experimental sensitivities.

Note also that the discovery of neutrinoless double beta decay would provide one additional important constraint on the neutrino mass matrix scale and Majorana phases. The discovery of supersymmetry and the measurements of the slepton masses would be of course crucial in this program. From all these observables one might get a chance to get constraints on \(Y_\nu\) important for leptogenesis. However, practically it’s very unlikely that we are going to be in a corner of the parameter space for which several observables are expected to be observed soon. Moreover even if the matrix \(H\) was determined with accuracy, the reconstruction of the \(Y_\nu\) matrix from it still relies in this framework on the assumption of universality of the soft mass terms at the grand unified scale. Would we relax this assumption, would we loose most of the model predictivity. But waiting for more experimental information about this assumption it’s definitely worth to proceed in this way!

3 **Extra low energy gauge boson and leptogenesis: the cases of SO(10) and \(E_6\)**

There exist other types of low energy indications one might get on the leptogenesis mechanism. If we embed the leptogenesis mechanism discussed above in a grand unified theory (GUT), many low energy informations relevant for the GUT can also be relevant for leptogenesis. Very important informations about the GUT group, the origin of neutrino masses and leptogenesis, would be furnished in particular by the discovery of an extra gauge boson at low energy (around \(\sim 1\) TeV). In the following we will discuss this possibility in the cases of \(SO(10)\) and \(E_6\) which are the two simplest groups which predict the existence of singlet neutrinos in the same representation than the other fermions (i.e. in the 16 and 27 representation respectively). In the \(SO(10)\) case, the discovery of an extra \(Z'\) or \(W'\) basically would rule out the seesaw mechanism of neutrino masses and leptogenesis with heavy singlet neutrinos. This is due to the fact that there are no subgroup of \(SO(10)\) larger than the SM group which doesn’t protect the \(N_i\) masses from being large. For example in the case where the left-right symmetry group \(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\) would be broken at a low scale \(\Lambda_{LR} \sim\) TeV, since the \(N_i\)’s are not singlets of this group they would acquire masses of the order of \(\Lambda_{LR}\). This model can still be made consistent with the
neutrino mass constraints, if the Yukawa couplings in $Y_{\nu}$ are taken sufficiently small in Eq. (8), but in this case a far too small asymmetry is produced in Eq. (9). Therefore to accommodate an extra low energy gauge boson we need to consider the next anomaly free group which is $E_6$. The group $E_6$ is quite interesting because the discovery of an extra gauge boson is in this case compatible with the neutrino mass and leptogenesis constraints, but only if this extra gauge boson is observed with given properties closely related to these constraints [4]. In fact since $E_6$ has rank 6 and the SM has rank 4, the SM can be extended at low energy by an extra $U(1)$, $SU(2)$ or $SU(3)$. With a $SU(3)$ we could think about the $SU(3)_{R,L}$ of the maximal subgroup $SU(3)_{c} \times SU(3)_{L} \times SU(3)_{R}$ of $E_6$. With a $SU(2)$ there are three subgroups which correspond to the three $SU(2)$ subgroups in $SU(3)_{R}$. With a $U(1)$ there is a continuum of possibilities (i.e. any combination of $U(1)_\psi$ and $U(1)_\chi$ which are defined by $E_6 \rightarrow SO(10) \times U(1)_\psi$ and $SO(10) \rightarrow SU(5) \times U(1)_\chi$). It turns out that among all these possible low energy extensions of the SM in $E_6$, only two have as singlets the $N_i$’s, that is to say allow the $N_i$’s to be heavy enough to satisfy both the neutrino mass and leptogenesis constraints. These are [3]:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_N,$$  \hfill (14)

$$SU(3)_C \times SU(2)_L \times SU(2)^A_R \times U(1)_{Y_L} + Y^*_R.$$  \hfill (15)

$U(1)_N$ is the combination of $U(1)_\psi$ and $U(1)_\chi$ for which the $N_i$’s are singlets (i.e. $Q_N = \cos \alpha Q_\psi + \sin \alpha Q_\chi$ with $\tan \alpha = \sqrt{15}$. $SU(2)^A_R$ is not the usual $SU(2)_R$ group of the left-right model but the one in which $u_R$ is in a doublet with $h_R$, the additional $SU(3)_c$ triplet in the 27 fundamental representation of $E_6$.

For these two subgroups one can show that the seesaw model works fine for leptogenesis as well as for neutrino masses. These two subgroups lead to a rich phenomenology at the TeV scale, in particular the presence of 11 extra degrees of freedom at this scale in addition to the 15 degrees of freedom of a full SM generation in each of the 3 generations of 27 multiplets. It also predicts relations between the partial decay widths of the extra gauge bosons to the various members of the 27 multiplets (i.e. of the $Z'$ for $U(1)_N$ and the $Z'$ and the 2 $W'_R$ for $SU(2)^A_R$). The observation at the LHC of this phenomenology, which is closely related to the neutrino mass and leptogenesis constraints, would provide strong indications for the seesaw model of neutrino masses and leptogenesis with heavy singlet neutrinos.

4 Leptogenesis at the TeV scale

So far we discussed the standard leptogenesis model based on the existence of singlet neutrinos with masses above $\sim 10^{10}$ GeV. We now want to address the question whether it is possible to build rather simple models at a directly testable scale (around $\sim 1$ TeV). In this case, instead of testing leptogenesis indirectly as discussed above, we could test it by producing directly the particles at its origin.

4.1 Problems occurring at the TeV scale

We first discuss the three main problems one has to face if we want to build such a low scale model:

- First, at such a low scale, the out-of-equilibrium condition for the decay width, Eq. (8), imposes the general condition that the couplings are very tiny. This is due to the fact that first, this condition is mediated by the very large Planck scale and secondly, the decay

---

There exists an exception to this statement which consists in singlet neutrinos having a huge mass degeneracy of order $10^{-10}$, in case the asymmetry is hugely enhanced by the terms in $1/(x_1 - 1)$ in Eq. (9), but we don’t consider this possibility here.
width is in general only linear in the mass of the decaying particle, see Eq. (8), in contrast to the Hubble constant which depends quadratically on this mass. This means that the product of couplings entering the decay width has to be as much as 10 orders of magnitude smaller at the TeV scale than at the $10^{13}$ GeV scale. Beyond the fact that the naturalness of such tiny couplings can be questionable, the major problem is that the associated produced asymmetry will be far too tiny, due to the fact that the asymmetry in most possible models is proportional to the same tiny couplings. For example in the Fukugita-Yanagida model with singlet neutrinos having masses around $\sim 1 - 10$ TeV, the produced asymmetry will be typically 6 orders of magnitude too small to account for $Y_B \sim 10^{-10}$.

- At the TeV scale, various scatterings can also be very fast with respect to the Hubble constant. This is particularly the case with gauge scatterings if the decaying particles producing the asymmetry are not neutral or SU(2)$_L$ singlets. As shown in Ref. 6, these scatterings easily wash out the asymmetry by 6 orders of magnitude. To avoid these effects, the particle at the origin of the asymmetry be better neutral and gauge singlet of any low-energy gauge symmetry. This restricts largely the possibilities.

- In the more ambitious and more interesting case where the source of lepton number violation at the origin of the asymmetry is also at the origin of the neutrino oscillations, an other problem could in general occur. Two cases have to be distinguished. First in the case where the neutrino masses are produced at tree level, as in the seesaw mechanism with singlet neutrinos, the values of the couplings which are needed to generate the neutrino masses are generally slightly larger than the ones allowed by the out-of-equilibrium condition. At the 1-10 TeV scale this will induce an additional damping effect of order $\sim 10^6$. Secondly in the case of neutrino masses generated by radiative processes, as in the Zee model or in R-parity violating supersymmetric model, it is quite difficult to generate the neutrino masses without violating largely the out-of-equilibrium condition. The couplings necessary to accommodate the experimental neutrino mass constraints are typically three order of magnitude larger than the values allowed by the out-of-equilibrium condition for the associated decays. This induce a huge damping of the produced asymmetry which exceeds $10^6$.

4.2 A simple mechanism based on three body decays

To avoid the three problems above one can think about three different asymmetry enhancement mechanisms. The first is based on a huge mass degeneracy between at least two of the $N_i$’s, which induces a resonant enhancement in Eq. (7) from the term in $1/(x_1 - 1)$. For $M_{N_i} \sim 1$ TeV the degree of degeneracy required is of order $\Delta M_N/M_N \sim 10^{-10}$, which might be very difficult to test. For more explanations we refer the reader to Ref. 7, 27, 28. A second mechanism consists in having a hierarchy among the couplings, taking all the couplings tiny (to satisfy the out-of-equilibrium condition) except the ones which intervene in the one-loop decay amplitude but not in the tree level amplitude, i.e. in the numerator but not in the denominator of Eq. (7). However, in the Fukugita-Yanagida model the neutrino constraints forbid this possibility. A third mechanism, which appears to our opinion to be more natural and definitely more testable, is based on three body decays. If in the thermal history of the universe the last L-violating decay turns out to have been a three body decay, and not a two body decay as usually considered in usual leptogenesis models, and if it occurs at a scale around $\sim 1 - 10$ TeV, then the lepton asymmetry produced can have the right order of magnitude without the need of any mass degeneracy. This can be easily seen from the fact that in this case, for a three body decay $A \rightarrow B + C^* \rightarrow B + D + E$, the numerator of the asymmetry will involve 6 couplings and the numerator will involve 4 couplings. In other words, if here for simplicity we take all these
couplings to be equal ($\equiv g$), the asymmetry will be in $\sim g^2$ with a decay width in $\sim g^4$. As a result, if the coupling $g$ is of order $\sim 10^{-3}$, the decay width is suppressed enough to satisfy the condition $\Gamma < H$, with a produced asymmetry large enough (i.e. $\varepsilon \sim 10^{-8}$ which is perfectly fine). Two body decays don’t have this interesting property because they display an asymmetry and a decay width which involve the same numbers of coupling (i.e. $\sim Y^2_\nu$ in Eqs. (2) and (3)). Moreover a L-violating coupling $g$ of order $10^{-3}$ is typically what we need to induce at the TeV scale the neutrino masses in a radiative way as in the Zee model and the models with R-parity violation. This three body decay radiative mechanism may provide therefore a general framework of neutrino masses and leptogenesis at the TeV scale which is an alternative to the usual high scale two-body decay seesaw framework.

In Ref. 6 we implemented this general framework with an explicit model. It is based on the three body decays of singlet neutrinos mediated by virtual charged scalar singlets. The particle content of this minimal model consists in three singlet neutrinos $N_i$ having masses $\sim 1-10$ TeV, plus two charged scalar singlets $S_{1,2}^+$ having similar masses (but heavier than the lightest singlet neutrino) plus two lighter Higgs doublets $H_{1,2}$. The tree level decays are represented in Fig. 1. In this model the (Majorana) neutrino masses are generated as in the Zee model at the one loop level from the L-violating couplings of the charged scalar singlets to two lepton doublets and to two Higgs doublets. The leptogenesis is induced by the interference of the tree level diagrams of Fig. 1 with one loop diagrams involving the self-energy of the virtual scalar singlets in Fig. 1 (with two leptons or two Higgs doublets in the loop). In this model the neutrino masses can also receive a contribution from the usual Yukawa couplings in Eq. (2). In order that this contribution doesn’t induce too large neutrino masses at this low scale through Eq. (3), it is required in this model that these Yukawa couplings are small enough. This neutrino condition insures also that the usual two-body decays of the $N_i$’s don’t over-dominate the three body decays, otherwise this would suppress the asymmetry. More details can be found in Ref. 6 where explicit set of values of parameters reproducing the data for neutrino masses as well as leptogenesis are given. This model shows what kind of minimal assumptions have to be made to build a leptogenesis mechanism at a directly testable scale. The main assumption is that a more involved particle content has to be considered.

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