Right-Handed Sector Leptogenesis

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Abstract

Instead of creating the observed baryon asymmetry of the universe by the decay of right-handed (RH) neutrinos to left-handed leptons, we propose to generate it dominantly by the decay of the RH neutrinos to RH leptons. This mechanism turns out to be successful in large regions of parameter space. It may work, in particular, at a scale as low as \(\sim\) TeV, with no need to invoke quasi-degenerate RH neutrino masses to resonantly enhance the asymmetry. Such a possibility can be probed experimentally by the observation at colliders of a singlet charged Higgs particle and of RH neutrinos. Other mechanisms which may lead to successful leptogenesis from the RH lepton sector interactions are also briefly presented. The incorporation of these scenarios in left-right symmetric and unified models is discussed.

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1 Introduction

In view of the recent evidence for non-vanishing neutrino masses and the belief that these masses are associated with lepton number violation, the leptogenesis mechanism has become the leading candidate to explain the baryon asymmetry of the universe. In the type I seesaw mechanism \(\frac{1}{2}\) the lepton asymmetry is generated through the decay of heavy Majorana right-handed (RH) neutrinos \(N_{1,2,3}\). This scenario is naturally accommodated in the framework of theories that predict the existence of RH neutrinos, such as \(SO(10)\)

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Pati-Salam in general. Another possible source of neutrino masses, which is well motivated in these frameworks, is the type II seesaw, which involves the interactions of a heavy $SU(2)_L$ triplet Higgs $\Delta_L$. Also this mechanism can lead to successful leptogenesis in agreement with the neutrino mass constraints. Other seesaw possibilities of successful leptogenesis arise if there are two or more heavy Higgs triplets or if self-conjugate triplets of fermions $\Sigma$ exist.

All the seesaw models above have the attractive feature that neutrino masses and baryogenesis are both generated from the same interactions. This nice feature has nonetheless a price to pay: due to the smallness of the neutrino masses, leptogenesis can be generically successful only at a very high scale (i.e. if $M_{N_1} \gtrsim 4 \cdot 10^8$ GeV or if $M_{\Delta_L} \gtrsim 2.5 \cdot 10^{10}$ GeV or if $M_{\Sigma_1} \gtrsim 1.5 \cdot 10^{10}$ GeV). Only in the special scenario where two heavy states have a quasi-degenerate mass spectrum, leptogenesis can be successful at much lower scales, thanks to the resonant enhancement of the lepton asymmetry occurring in this case. Not considering this last possibility, beside the fact that these bounds are in tension with the gravitino constraint in supergravity theories, basically they imply that leptogenesis could never be tested directly.

In this connection, one may ask if the minimal theories incorporating the seesaw mechanism contain other sources of lepton asymmetry, which are not suppressed by the smallness of neutrino masses and, in this case, if leptogenesis could be successful at a lower scale. More generally it is phenomenologically interesting to determine what are the basic mechanisms which can induce successful leptogenesis at the low scale (independently of specific grand-unified realizations). Note that this does not necessarily require two sources of lepton number violation, one for neutrino masses and a different one for leptogenesis. In fact, in this paper we consider the case where the source of lepton number violation remains the same (i.e. the Majorana masses of RH neutrinos $N_i$), but where the interactions at the origin of the decays, instead of involving the left-handed Standard Model (SM) leptons, involve the right-handed SM leptons.

We consider a basic mechanism where the $N_i$’s decay to a charged RH lepton and a scalar charged $SU(2)_L$ singlet $\delta^+$ (section 2). The case where the $\delta^+$ is accompanied by a $\delta^0$ and a $\delta^{++}$ to form an $SU(2)_R$ triplet is similar and discussed in section 3. The issue of the incorporation of these two basic leptogenesis mechanisms in left-right symmetric and/or unified models is discussed in section 4. In section 5 we identify other possible sources of lepton asymmetry involving RH leptons. In section 6 the perspectives to observe a $\delta^+$ (and a RH neutrino) with mass of the order of TeV are briefly outlined.

Let us notice that there is a very small number of possibilities to generate leptogenesis at the low scale from two-body decays involving the SM fermions in the final state. In particular, the decaying particle has to be a SM gauge singlet in order to avoid very large washout from gauge scattering at low scale. With seesaw interactions to generate the neutrino masses, the mechanism we consider in sections 2 and 3 appears to be the most economical non-resonant one (in terms of particle content and assumptions). Other

Moreover, the lower bounds on seesaw particle masses are saturated for specific structures of the neutrino Yukawa couplings, while generic structures require higher values of the masses. In particular, if the neutrino Yukawa couplings are analog to the charged fermion ones (as in most unified models), the produced lepton asymmetry in type I models is in general too small. In this case, even leptogenesis at high scale is successful only if a resonant enhancement of the asymmetry occurs.
non-resonant possibilities of inducing low scale thermal leptogenesis arise if the neutrino masses are not induced by seesaw interactions but radiatively (from 3-body decays \cite{14} or from $L$ violating soft terms in the seesaw extended MSSM \cite{21}) or by considering more than 3 generations of right- and left-handed neutrinos \cite{22}. Resonant possibilities have been considered e.g. in \cite{23}.

2 The simplest model: a charged $SU(2)_L$ singlet scalar

We first consider the minimal case where in addition to the SM particles there exist two or more RH neutrinos $N_i$ and a charged scalar $SU(2)_L$ singlet $\delta^+$. In full generality the relevant interactions are:

$$
L \ni -M_2^2 \delta^+ \overline{\delta}^+ + \left[ -\frac{1}{2} M_{N_1} N_{iR}^T C N_{iR} - H^+ N_{iR}(Y_N)_{ij} \psi_{jL} \
-(Y_R)_{ij} N_{iR}^T C \delta^+ l_{jR} - (Y_L)_{ij} \psi_{iL}^T C i\tau_2 \delta^+ \psi_{jL} + \text{h.c.} \right],
$$

with $\psi_{iL} = (\nu_{iL} \: l_{iL})^T$ and $H = (H^0 \: H^-)^T$.

We consider the possibility that the scalar singlet is lighter than the RH neutrinos and we neglect, at this stage, the effects of the $Y_N$ couplings, which are not relevant to achieve our main results. Their effect will be quantified later. In this case leptogenesis can be induced by replacing in the standard diagrams, both in the loop and in the final state, the left-handed lepton doublet with the RH charged lepton and the Higgs doublet with the scalar singlet, as shown in Fig. 1. For the lightest RH neutrino $N_1$, the relevant CP asymmetry is:

$$
\epsilon_{N_1} = \sum_i \frac{\Gamma(N_1 \rightarrow l_{iR} + \delta^+) - \Gamma(N_1 \rightarrow \bar{l}_{iR} + \delta^-)}{\Gamma_{N_1}} \cdot C_L,
$$

with

$$
\Gamma_{N_1} = \frac{1}{16\pi} M_{N_1} \sum_i |(Y_R)_{1i}|^2.
$$

In Eq. (2), $C_L$ is the lepton number produced in the decay $N_1 \rightarrow l_{iR} + \delta^+$. Unlike the Higgs doublet in the standard leptogenesis case, $\delta^+$ does not have a vanishing lepton number. Once produced from the decay of the RH neutrinos, it decays to 2 left-handed antileptons, via the $Y_L$ couplings, so that it has $L = -2$ which gives $C_L = -1$. One finds

$$
\epsilon_{N_1} = \frac{1}{8\pi} C_L \sum_j \frac{\text{Im}[\sum_i |(Y_R)_{1i} |^2]}{\sum_i |(Y_R)_{1i} |^2} \sqrt{x_j} \left[ 1 - (1 + x_j) \log \left( 1 + \frac{1}{x_j} \right) + \frac{1}{2} \frac{1}{1 - x_j} \right],
$$

3
where \( x_j = M_{N_j}^2 / M_{N_1}^2 \). For this calculation we neglected \((M_3 / M_{N_1})^2\) corrections which are small as soon as the \( \delta^+ \) is a few times lighter than \( N_1 \) as we assume here. In the limit where we also neglect the \( M_{N_1}^2 / M_{N_2,3}^2 \) corrections, we get

\[
\varepsilon_{N_1} = -C_L \frac{1}{8\pi} \sum_j \frac{\text{Im}[\langle Y_R Y_R^\dagger \rangle_{1j}^2]}{\sum_i |(Y_R)_{ii}|^2} \frac{M_{N_1}}{M_{N_j}}.
\] (5)

Apart for the \( C_L \) factor and for a combinatoric factor of two in the self-energy contribution, this asymmetry is the same as in the standard case, replacing the ordinary Yukawa couplings \( Y_N \) by the \( Y_R \) scalar singlet ones. Contrary to the standard case, however, the \( RH \) Yukawa couplings \( Y_R \) do not induce any neutrino masses and so are not constrained by them. As a result this mechanism may easily lead to successful leptogenesis and may also work at a much lower scale, as explained below, which is phenomenologically interesting.

Considering for simplicity only 2 RH neutrinos \( N_{1,2} \) (the effect of \( N_3 \) can be straightforwardly incorporated), numerically the constraints for successful leptogenesis are the following:

- The total baryon asymmetry produced is given by:

\[
\frac{n_B}{s} = \frac{28}{79} n_L = -\frac{135 \zeta(3) 28}{4|\pi|^4 g_* 79} \varepsilon_{N_1} \eta = -1.36 \cdot 10^{-3} \varepsilon_{N_1} \eta ,
\] (6)

where \( \eta \) is the efficiency factor and \( g_* = 108.75 \). For a maximal efficiency, \( \eta = 1 \), the requirement to reproduce the data (i.e. \( \frac{n_B}{s} = 9 \cdot 10^{-11} \)) implies that

\[
Y_R^{(2)} \equiv \sqrt{\frac{\text{Im} \left[ \sum_i (Y_R)_{1i} (Y_R^\dagger)_{2i} \right]^2}{\sum_i |(Y_R)_{1i} (Y_R^\dagger)_{1i}|^2}} \geq 1.3 \cdot 10^{-3} \sqrt{\frac{M_{N_2}}{M_{N_1}}},
\] (7)

which means that at least one of the \( (Y_R)_{2i} \) coupling is of order \( 10^{-3} \cdot \sqrt{M_{N_2}/M_{N_1}} \) or larger.

- To avoid washout from the \( N_1 \) inverse decays the constraint on the decay width reads:

\[
\Gamma_{N_1} < H(T)|_{T=M_{N_1}} = \sqrt{\frac{4|\pi|^3 g_*}{45 M_{\text{Planck}}}} \frac{T^2}{M_{N_1}}.
\] (8)

Using Eq. (3), the corresponding upper bound on the \( (Y_R)_{1i} \) couplings reads

\[
Y_R^{(1)} \equiv \sqrt{\sum_i |(Y_R)_{1i}|^2} < 3 \cdot 10^{-4} \sqrt{\frac{M_{N_1}}{10^9 \text{GeV}}}.
\] (9)

Larger values of \( Y_R^{(1)} \) lead to suppression of the efficiency which, for successful leptogenesis, has to be compensated by larger values of the \( (Y_R)_{2i} \) couplings in the numerator of the asymmetry \( \varepsilon_{N_1} \).

- If Eq. (3) is satisfied, the washout from \( \Delta L = 2 \) scattering mediated by \( N_1 \) is negligible, see e.g. [16]. Taking values for \( (Y_R)_{2i} \) consistent with Eq. (7), the washout from \( \Delta L = 2 \) scatterings mediated by \( N_2 \) is generically negligible, except possibly

Therefore, leptogenesis is possible with a lower scale. A detailed analysis of the constraints and the implications of this mechanism can provide insights into the early universe and the generation of baryon asymmetry.
for $M_{N_1}$ as low as a few TeV. In fact, this depends on the interplay of $Y_R^{(1)}$, $M_{N_1}$, $M_{N_2}/M_{N_1}$ as well as of the $(Y_R)_{2i}$ couplings. Large $(Y_R)_{2i}$ couplings lead to a large CP asymmetry but also to large $\Delta L = 2$ washout. Large $M_{N_2}/M_{N_1}$ leads to suppressed washout but also to a small CP asymmetry. Small $Y_R^{(1)}$ leads to late $N_1$ decay, and therefore to suppressed $N_2$ washout at the temperature of the decay, i.e. to a large Boltzmann suppression of the on-shell $N_2$ contribution and to a large suppression of the off-shell $N_2$ scatterings (through $T/M_{N_2}$ powers and also a Boltzmann factor below the $M_\beta + m_l$ threshold). The interplay of all these effects can be determined from the Boltzmann equations. Considering them explicitly, we have checked that even at scales as low as a few TeV, an efficiency of order one can be obtained easily (see also [14, 21, 24]).

Combining the 3 constraints above, successful leptogenesis can be achieved in a large region of parameter space. The scale at which the lepton asymmetry may be produced depends on the hierarchy between the $Y_R$ couplings of $N_2$ and $N_1$. This can be quantified by combining Eqs. (7) and (9):

$$\frac{Y_R^{(1)}}{Y_R^{(2)}} < 0.2 \cdot \sqrt{\frac{M_{N_1}}{M_{N_2}} \frac{M_{N_1}}{10^9 \text{GeV}}}.$$  

(10)

This condition is easily satisfied for $M_{N_1} \sim 10^{9-15}$ GeV. When, for example, $M_{N_1}/M_{N_2} \sim 0.1$ and $M_{N_1} = 10^7$ GeV, at least one of the $(Y_R)_{2i}$ couplings needs to be about two orders of magnitude larger than the $(Y_R)_{1i}$. At scale as low as 1-10 TeV the hierarchy needed is more substantial, of about 4 orders of magnitude, but this is not unrealistic for Yukawa couplings (the hierarchy needed is of the order of the one in the SM Yukawa couplings). An example of a set of parameters leading to an efficiency of order one and to a baryon asymmetry in agreement with the observed one is: $M_{N_1} = 2$ TeV, $M_{N_2} = 6$ TeV, $(Y_R)_{2i}^{\text{max}} \sim 4 \cdot 10^{-3}$, $Y_R^{(1)} \sim 10^{-7}$ and $M_\beta \sim 750$ GeV. We find that successful leptogenesis can be generated with $M_{N_1}$ as low as $\simeq 1$ TeV and with $M_{N_2}$ as low as $\simeq 4$ TeV.2

So far we have neglected the effects of the ordinary $Y_N$ Yukawa couplings. Switching them on leads to more tree-level and one-loop diagrams. In addition to the usual pure $Y_N$ diagrams there are self-energy diagrams involving both $Y_R$ and $Y_N$ couplings. This leads to the full asymmetry $\varepsilon_{N_1} = \varepsilon_{N_1}^V + \varepsilon_{N_1}^S$ where the vertex and self-energy contributions are:

$$\varepsilon_{N_1}^V = \frac{1}{8\pi} \sum_j \frac{\left| C_L (Y_R Y_R^\dagger)^2_{1j} + 2(Y_N Y_N^\dagger)^2_{1j} \right|}{\sum_i \left| (Y_R)_{1i} \right|^2 + 2 \sum_i \left| (Y_N)_{1i} \right|^2} \sqrt{\frac{1 - (1 + x_j) \log \left( 1 + \frac{1}{x_j} \right)}{x_j}},$$

(11)

$$\varepsilon_{N_1}^S = \frac{1}{16\pi} \sum_j \frac{\left| C_L (Y_R Y_R^\dagger)^2_{1j} + 2(C_L + 1)(Y_R Y_R^\dagger)_{1j}(Y_N Y_N^\dagger)_{1j} + 4(Y_N Y_N^\dagger)^2_{1j} \right|}{\sum_i \left| (Y_R)_{1i} \right|^2 + 2 \sum_i \left| (Y_N)_{1i} \right|^2} \frac{1}{1 - x_j}.$$  

(12)

As it is well-known, at scales above $\simeq 4 \cdot 10^8$ GeV, the $Y_N$ couplings can lead to successful leptogenesis and may dominate the asymmetry of Eqs. (11) and (12). At a lower scale, the

2If there is an additional resonance effect, $M_{N_2}$ ($\simeq M_{N_1}$) can be lowered down to $\sim 1$ TeV as well.
light neutrino mass constraints generically require that the $Y_N$ couplings are smaller than $10^{-3}$, barring cancellations between different $Y_N$ entries. Therefore the asymmetry of Eqs. (11) and (12) can lead to successful leptogenesis only from large enough $Y_R$ couplings of $N_2$ (and/or $N_3$) as explained above. In this case the $Y_N$ couplings to $N_2$ and $N_3$ have a negligible effect in the numerator of Eqs. (11) and (12), but still the $Y_N$ couplings of $N_1$ may have a significant effect, in particular from their contribution to the tree level decay width of $N_1$:

$$\Gamma_{N_1} = \frac{1}{16\pi} M_{N_1} \sum_i |(Y_R)_{i1}|^2 + \frac{1}{8\pi} M_{N_1} \sum_i |(Y_N)_{i1}|^2.$$  

(13)

Just as in the standard leptogenesis mechanism, there will be no inverse decay washout effect if $N_1$ contributes to light neutrino masses by less than $10^{-3}$ eV, that is to say if the solar and atmospheric mass splittings are dominated by the contributions of $N_2$ and $N_3$. In fact, Eq. (8) now implies the constraint (9) as well as

$$\frac{v^2 \sum_i |(Y_N)_{i1}|^2}{M_{N_1}} < 10^{-3} \text{eV}.$$  

(14)

In the opposite case, larger $Y_R$ couplings to $N_2$ and/or $N_3$ are required for successful leptogenesis, in order to increase $\epsilon_{N_1}$ thus compensating for the washout factor $\eta < 1$.

Note finally that, as we have assumed only one Higgs doublet $H$, the scalar singlet $\delta^+$ has no coupling bilinear in $H$. For the case where there would be more than one Higgs doublet, $\delta^+$ can couple antisymmetrically to two different $H_i$ (just as in the Zee model [25]). Such a coupling would be dangerous because, combined with the $Y_L$ coupling, it could induce a fast $\Delta L = 2$ scattering. As a consequence, the basic mechanism above works safely if there is only one Higgs doublet lighter than $M_{N_1}$. In the opposite case, leptogenesis may still work but only if these $\delta^+$ couplings to two different Higgs doublets are forbidden or suppressed, or if instead the $Y_L$ couplings are forbidden or suppressed. Note that in the later situation the $\delta^+$ has to be considered as having $L = 0$ so that in all equations above $C_L = 1$. Models with or without extra Higgs doublets and mechanisms to suppress dangerous $\delta^+$ couplings are discussed in section 4.1.

3 The right-handed scalar triplet case

If the theory of particle interactions beyond the Standard Model contains left-right symmetry, the gauge symmetry has to be extended to include the group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. In order to realize leptogenesis in this framework, the role of the charged singlet $\delta^+$ may be played by the charge-one component of an $SU(2)_R$ triplet $\Delta_R$. In this case the leptogenesis mechanism discussed in section 2 is slightly modified. The relevant interactions are:

$$\mathcal{L} \ni -M_\Delta^2 Tr \Delta_R^\dagger \Delta_R + \left[ -\frac{1}{2} M_{N_i} N_{Ri}^T C N_{Ri} - H^\dagger \bar{N}_{Ri} (Y_N)_{ij} \psi_{jL} 
- (Y_\Delta)_{ij} \bar{\psi}_{iR} C i\tau_2 \Delta_R \psi_{jR} + \text{h.c.} \right],$$  

(15)

\footnote{This follows from the seesaw formula [2], $m_\nu = -v^2 Y_N^T M_N^{-1} Y_N$, where $m_\nu$ is the mass matrix of light neutrinos and $M_N = \text{diag}(M_{N_1}, M_{N_2}, M_{N_3})$.}
with $\psi_L = (\nu_L l_L)^T$, $\psi_R = (N_i l_i R)^T$, $H = (H^0 H^-)^T$ and

$$\Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}} \delta^+ & \delta^{++} \\ \frac{1}{\sqrt{2}} \delta^0 & -\frac{1}{\sqrt{2}} \delta^+ \end{pmatrix}.$$ (16)

Here we assume that $\delta^0$ has zero vacuum expectation value, that is, its contribution to RH neutrino masses is already reabsorbed in $M_{N_i}$ (see also section 4.2).

The diagrams in Fig. 1, in this case, lead to the same asymmetry as in Eq. (4), and successful leptogenesis leads to the same constraints, replacing everywhere the $(Y_R)_{ij}$ couplings by $\sqrt{2} (Y_\Delta)_{ij}$. In addition, as there is no coupling of the $\Delta_R$ to two left-handed leptons, the $\delta^+$ does not have $L = -2$ as above and $C_L$ is modified. Since we assume that the $\delta^+$ is lighter than the RH neutrinos, the $\delta^+$ cannot decay to two particles but instead to three, either to a Higgs doublet and a lepton-antilepton pair which have $L = 0$, or into a Higgs doublet and a pair of antileptons which have $L = -2$. Summing over flavors of final-state leptons as well as of the virtual RH neutrinos $N_i$, we get

$$\Gamma(\delta^+ \rightarrow l_L^+ l_L^+ H^+) = \frac{1}{192\pi^3} \frac{M^3_\delta}{4} \sum_{ij} (Y_\Delta Y^\dagger_\Delta)_{ij} (Y_N Y^\dagger_N)_{ij} M_{N_i} M_{N_j}$$ (17)

and

$$\Gamma(\delta^+ \rightarrow l_L^+ l_R^+ H^-) = \frac{1}{192\pi^3} \frac{M^5_\delta}{16} \sum_{ij} (Y_\Delta Y^\dagger_\Delta)_{ij} (Y_N Y^\dagger_N)_{ij} M^2_{N_i} M^2_{N_j}.$$ (18)

Since the second decay mode is suppressed by two extra powers of $M_\delta/M_{N_i}$, the first one is dominant, so that $\delta^+$ has $L \simeq 0$ and $C_L \simeq +1$. Note that it may be unnecessary to know what is the lepton number of $\delta^+$ to determine that the value $C_L = +1$ must be taken in the CP asymmetry. The reason is that Eq. (17) (and a fortiori Eq. (18)) may lead generically to a $\delta^+$ decay lifetime larger than the age of the Universe $t$ at the electroweak scale (i.e. at $T \simeq 150$ GeV [26] with $1/t \approx 2H$ for a radiation dominated universe):

$$\Gamma_{\delta^+} < \sqrt{\frac{16\pi^3 g_*}{45}} \frac{T^2}{M_{Planck}} \bigg|_{T \approx 150\, \text{GeV}}.$$ (19)

Assuming realistic values of the $Y_N$ couplings from solar and atmospheric data, taking for the $Y_\Delta$ couplings the values necessary for successful leptogenesis estimated in section 2 and taking $M_\delta$ at least a few times smaller than $M_{N_i}$, one finds that Eq. (19) is satisfied for $M_{N_1}$ below $\sim 10^7$ GeV.

The presence of the two extra states $\delta^{++}$ and $\delta^0$ does not play any significant role for leptogenesis. The $\delta^{++}$ couples only to two RH charged leptons and does not bring any source of L-violation, it has $L = -2$ lepton number. The $\delta^0$ component couples either to $N_1 N_i$ with suppressed couplings (see Eq. (9) with $Y_R$ replaced by $Y_\Delta$) or to two $N_{2,3}$, which have masses above the temperature of the production of the asymmetry.

In summary, leptogenesis works in the same way in the case of Eq. (11), by means of a charged scalar singlet, and in the case of Eq. (15), by means of a RH triplet scalar, provided we replace everywhere $Y_R$ by $\sqrt{2} Y_\Delta$ and $C_L = -1$ by $C_L = +1$.

\footnote{At most, if the $\delta^{++}$ is still active at $T \sim M_{N_i}$, it will change the produced baryon asymmetry by about one percent changing the number of active degrees of freedom by about one percent.}
4 Incorporating right-handed leptogenesis in unified gauge theories

4.1 The case of a charged singlet $\delta^+$

Let us consider the embedding of an $SU(2)_L$ singlet Higgs boson with charge one in the simplest gauge extensions of the Standard Model.

In the presence of left-right symmetry, the RH leptons $\psi_R = (N_l R)^T$ have quantum numbers $(1, 2, -1)$ under the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Since $(1, 2, -1) \times (1, 2, -1) = (1, 1, -2)_a + (1, 3, -2)_s$, a scalar $\delta^+ \sim (1, 1, 2)$ has (antisymmetric) Yukawa couplings to RH leptons. In the same way, it also couples to the left-handed leptons $\psi_L \sim (2, 1, -1)$. In these models, other Higgs bosons in addition to $\delta^+$ are needed in order to break spontaneously $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ as well as to give Majorana masses to RH neutrinos.

If the minimal left-right group is further extended to a Pati-Salam model, $\delta^+$ is accommodated into a $(1, 1, 10)$-multiplet under $SU(2)_L \times SU(2)_R \times SU(4)_c$, which couples bilinearly to RH fermions $\sim (1, 2, \varepsilon)$. The Pati-Salam group may be naturally embedded in unified models based on $SO(10)$, with all fermions in a 16-dimensional spinor representation. In this case $\delta^+$ is part of a 120 Higgs multiplet, which has renormalizable Yukawa couplings to fermions.

Alternatively, one can consider the $SU(5)$ option for gauge coupling unification. In this case, leptons are assigned as follows to $SU(5)$ representations: $\psi_L \in \tilde{5}_f$, $\psi_R \in 10_f$ and $N^c \sim 1_f$. In order to introduce $\delta^+$, one needs to add to the model a 10-dimensional Higgs multiplet, which has the proper couplings required in section 2 to achieve RH leptogenesis: $Y_R 1_\tilde{f} 10_H$ and $Y_L 5_f 5_f 10_H$.

At the end of section 2 we discussed possible “Zee-like” trilinear couplings between $\delta^+$ and two different Higgs doublets $H_i$ with hypercharge -1. In the left-right symmetric models, only one $H_i$ is contained in the bidoublet field $(2,2,0)$ which provides the usual Dirac-type Yukawa couplings. In Pati-Salam models, there are two such doublets, one in $(2,2,1)$ and one in $(2,2,15)$, but $SU(4)_c$ invariance prevents them to couple to $\delta^+ \in (1,1,10)$. Similarly, in $SO(10)$ context, $10_H$, $\overline{126}_H$, $120_H$, contain, respectively, one, one and two fields $H_i$, but $\delta^+ \in 120$ has no trilinear coupling to them. Therefore, the “Zee-like” coupling requires the introduction of at least one extra Higgs multiplet with no Yukawa couplings to fermions, e.g., $210_{SO(10)} \supset (2, 2, 10)_{SU(2)_L} \supset (2, 2, -2)_{SU(2)_L}$. In $SU(5)$ models, one $H_i$ is contained either in 5 or in $\overline{45}$ and any choice of two such doublets is sufficient to couple to $\delta^+ \in 10$.

Even in models where the couplings $\delta^+ H_i H_j$ are present, they become dangerous for leptogenesis only if both Higgs doublets are lighter than $M_N$, which generically requires fine-tuning. In this case these couplings must be suppressed or alternatively the coupling $Y_L$ must be forbidden. This last option may be naturally realized requiring that lepton number is broken only softly, by RH neutrino Majorana masses.

4.2 The case of a right-handed triplet $\Delta_R$

In the case of leptogenesis via a RH triplet $\Delta_R = (\delta^+, \delta^+, \delta^0)$, it is understood that the gauge symmetry includes, at least, the minimal left-right symmetric group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. A RH triplet is naturally present in left-right models since the VEV of its neutral component $\delta^0$ provides the correct symmetry breaking to the Standard
Model and, moreover, it gives a Majorana mass to the RH neutrinos. In fact, \( \Delta_R \sim (1,3,2) \) couples symmetrically to two RH lepton doublets \( \psi_R \sim (1,2,-1) \). In Pati-Salam models, \( \Delta_R \) is contained in the \((1,3,10)\) multiplet which, in turn, belongs to \( 126 \) Higgs representation in \( SO(10) \).

Let us discuss limits and merits of the minimal left-right symmetric framework, in order to realize the RH leptogenesis scenario we proposed in section 3.\(^5\) The mass of the \( \delta^+ \) can be smaller than the \( SU(2)_R \) breaking scale (as well as the RH neutrino masses) since they are determined by independent scalar potential couplings. The left-right model has the nice feature that \( \delta^+ \) undergoes only three-body decays, since \( \Delta_R \) does not couple to left-handed lepton doublets nor to two Higgs bosons, as long as \( SU(2)_L \) is unbroken (these last couplings can come only from the interaction \( \lambda_{ij}Tr(\Delta_R^i \Phi_i \Delta_L \Phi_j^i) \), where \( \Phi_i \) are bidoublet Higgs bosons). These couplings if present would induce fast \( \Delta_L = 2 \) scattering washout effects. The presence of the left-handed triplet \( \Delta_L \) might also induce washout effects, which are suppressed, however, if \( \Delta_L \) is heavier or has small \( \lambda_{ij} \) couplings. The effect of the RH gauge bosons are suppressed because they have a mass naturally of the order of or heavier than the heaviest RH neutrino.

Notice that, in section 3, we introduced a Majorana mass term \( M_R \) for RH neutrinos in addition to the Yukawa coupling \( Y_\Delta \) between \( \Delta_R \) and RH lepton doublets. In the minimal left-right model, the two terms can be identified, so that only one source of flavor breaking is present: the matrices \( M_R \) and \( Y_\Delta \) are proportional to each other. As a consequence, in the \( N_i \) mass eigenstate basis, the \( Y_\Delta \) coupling matrix is also diagonal and the diagrams of Fig. 1 with two different RH neutrinos are simply vanishing. Therefore, for this leptogenesis mechanism to be effective we need to extend the minimal model in order to distinguish \( M_R \) from \( Y_\Delta \). For example, one may introduce a second RH triplet (a second \( 126 \) in \( SO(10) \)), or consider extra (e.g. non-renormalizable) sources of RH neutrino mass. Alternatively, one could resort to the singlet leptogenesis mechanism, adding a \((1,1,2)\) Higgs multiplet (\( 120 \) in \( SO(10) \) context).

The dangerous couplings between \( \delta^+ \) and two Higgs doublets \( H_i \), absent in the minimal left-right model, could appear in more general theories. The discussion is completely parallel to the singlet case of the previous section: such couplings are forbidden as long as one considers only \( H_i \) contained in Higgs multiplets with Yukawa couplings to fermions. However they appear, for example, if a 210 Higgs is introduced in \( SO(10) \) models (and similarly for smaller gauge groups).

Note finally that in Grand-Unified models, although one generally expects the right-handed neutrinos as well as the scalar singlet \( \delta^+ \) to be very massive, it is not excluded that these particles are present at the TeV scale. One may worry in this case that the charged singlet scalar (at the intermediate scale) affects the running of the \( U(1)_Y \) gauge coupling (with a contribution \( \Delta b_1 = 1/5 \) to the \( \beta \)-function, in the usual normalization). However, the full particle spectrum at the intermediate scale is highly model-dependent. In particular, the scale of the left-right symmetry breaking \( v_R \) can be as small as a few TeV and be consistent with unification (for a recent analysis see Ref. [28]).

\(^5\)For more standard realizations of leptogenesis in the minimal left-right model based on RH neutrino decay to left-handed leptons or on \( SU(2)_L \) triplet scalar decay, see Refs. [7, 27].
5 Other possible leptogenesis contributions from the RH sector

In this section we identify other minimal mechanisms to induce a lepton asymmetry from the RH lepton sector.

One possibility is to have two RH neutrinos quasi-degenerate in mass. In this case the self-energy diagram of Fig. 1(b) leads to resonant enhancement of the asymmetry pretty much as in the ordinary leptogenesis model. One may expect that this enhancement allows to achieve successful leptogenesis at low scale relaxing the hierarchy between the couplings $(Y_R)_{ij}$ discussed in section 2. However, in order to have observable consequences, in addition to requiring strongly degenerate RH neutrino masses, this scenario still needs a hierarchy of couplings [24], similar to (or slightly smaller than) the one considered above (i.e. small $N_1$ couplings in order to avoid too large washout from inverse decays and larger $N_{2,3}$ couplings to lead to direct observations of RH neutrinos). Only very close to the resonance larger $(Y_R)_{1j}$ couplings (up to few $10^{-5}$) can be taken for $M_{N_1} \sim$ few TeV. The improvement with respect to the resonant case in the usual leptogenesis model is that the Yukawa couplings leading to observable consequences do not require cancellation between them to avoid the generation of too large neutrino masses.

Another possibility of successful leptogenesis we want to mention, and which could work in the minimal left-right model or SO(10), occurs at high scale if the $\delta^+$ is lighter than the RH neutrinos. In this case, the lepton number violating 3-body decay of the $\delta^+$, Eq. (18), can induce leptogenesis considering the ordinary vertex and self-energy one loop diagrams of the virtual $N_i$ in this decay. This leads to asymmetries of the order $\varepsilon_{N_1} \cdot (M_\delta/M_{N_1})^2$ (where $\varepsilon_{N_1}$ is the ordinary two body decay asymmetry of $N_1$ decaying to left-handed leptons). As a result, and taking into account the fact that the $\delta^+$ can be thermalized by gauge scatterings, we estimate that this 3-body decay can lead to successful leptogenesis for $M_\delta \gtrsim 10^{11}$ GeV. Note that, due to the fact that the 3-body decay of the $\delta^+$ is quite slow, in general it will not washout preexisting lepton asymmetries, in particular the asymmetry which could have been produced by the decay of the $N_i$ at a higher scale.

Finally, we consider other possible mechanisms of successful leptogenesis driven by the other components of an $SU(2)_R$ triplet $\Delta_R$, that is $\delta^0$ and $\delta^{++}$. The neutral component $\delta^0$, if lighter than RH neutrinos $N_i$, undergoes 4-body decay into two left-handed leptons and two Higgs doublets, via two virtual $N_i$. The lepton asymmetry generated by these decays comes from the ordinary one-loop diagrams of both virtual $N_i$. It is therefore proportional to $\sim \varepsilon_{N_i}$ but is suppressed by extra powers of $M_{N_i}/M_{\delta^0}$. The decay width is extremely suppressed and therefore satisfies easily the out-of-equilibrium condition. We estimate that leptogenesis can be successful only at very high scale, $M_{\delta^0} \gtrsim 10^{11}$ GeV.

The $\delta^{++}$ decays into two RH charged leptons. Such a decay can produce a lepton asymmetry only if there are at least two different $\delta^{++}$, via the self-energy diagram involving two charged Higgs bosons (just like with two left-handed triplets [10, 11]). The extra scalars in the loop are naturally given by the $\delta^+$, since the scalar potential term $Tr(\Delta_R \Delta_R) Tr(\Delta_R^\dagger \Delta_R^\dagger)$ provides, after $SU(2)_R$ breaking, the trilinear coupling $\delta^{++} \delta^- \delta^- + h.c.$ This mechanism requires triplets with mass above $\sim 10^{10}$ GeV (except if they are quasi-degenerate). This model does not present any particular advantage with respect to the more straightforward type I and/or II seesaw models of leptogenesis. It illustrates once more the fact that there are many possible leptogenesis models at a high scale, but only very few working at low scale.
6 Phenomenology of a TeV scale charged $SU(2)_L$ singlet scalar

The observation of a light $SU(2)_L$ singlet $\delta^+$ at colliders would imply that, in the presence of RH neutrinos, the $Y_R$ interactions occur naturally. This would render our leptogenesis mechanism as plausible as the standard one. Moreover the fact that this model can work at scales as low as the TeV scale opens the possibility to produce directly a RH neutrino through the relatively large $Y_R$ couplings of the $N_2$ and/or $N_3$, which can have a mass as low as few TeV.\(^6\) This would leave in general no other choice for leptogenesis (and baryogenesis) than to be produced at low scale below $M_{N_{2,3}}$, as allowed by our model.\(^7\)

Note that to produce a $\delta^+$ at colliders, the Drell-Yan $\delta^+\delta^-$ pair production process (from $e^+e^-$ or $q\bar{q}$ annihilation with an intermediate photon or $Z$) is the most effective way. For definiteness, consider the differential cross-section for $e^+e^-\rightarrow \gamma \rightarrow \delta^+\delta^-$:

$$\frac{d\sigma}{d\cos \theta} = \frac{\pi \alpha^2}{4Q^2} \left(1 - \frac{4M_\delta^2}{Q^2}\right)^{3/2} \sin^2 \theta,$$

where $Q^2$ is the center-of-mass energy squared, $\alpha$ is the electromagnetic constant and $\theta$ the angle between the collision axis and the outgoing $\delta^+$. For $Q^2 = 500$ GeV (as foreseen at the International Linear Collider) a $\delta^+$ of about 200 GeV would be produced with a total cross section of about 20 femtobarns. For any scalar with given weak isospin and hypercharge, the pair production cross section from $q\bar{q}$ annihilation can be found e.g. in [32]. In particular, this paper studies the $pp\rightarrow \Delta^{++}\Delta^{--}$ cross section relevant for LHC with $\Delta^{++}$ a doubly charged particle member of a $SU(2)_L$ scalar triplet. This cross section has been found to be large enough by far to observe a $\Delta^{++}$ with a mass as large as 1 TeV. The LHC $pp\rightarrow \delta^+\delta^-$ pair production is similar, up to factors of order unity due to different charges.

The identification of $\delta^+$ relies on the comparison of its dominant decay channels with background, which is beyond the scope of this article. Just note that, as we discussed above, if $\delta^+$ couples (antisymmetrically) to left-handed leptons as in Section 2, it should mainly decay into anti-lepton and antineutrino. The decay into anti-$\tau$ is actually the more interesting one, because it can be used to identify at the LHC a relatively light MSSM charged Higgs $H^+$ (see, e.g., [33]). The two particle decays can be distinguished by analyzing the angular distribution of the outgoing antilepton, since it is left-handed in the case of $H^+$ and right-handed in the case of $\delta^+$. In case the $Y_L$ couplings would be in addition suppressed (below $\sim 10^{-7}$), the lifetime of the $\delta^+$ would be much longer than for $H^+$, leading to a displaced vertex when it decays.

Note also that the $\delta^+$ singlet can induce, through its $Y_L$ couplings, a $\mu\rightarrow e\gamma$ transition with branching ratio $\text{Br}(\mu\rightarrow e\gamma) \approx (\alpha/48\pi)|(Y_L)_{e\tau}(Y_L)_{\mu\tau}|^2 / (M_Y^4 G_F^2)$ (see e.g. [34]). With $M_Y$ below TeV, a branching ratio of the order of the experimental limit ($\text{Br}(\mu\rightarrow e\gamma) < 1.2 \cdot 10^{-11}$ at 90% C.L. [35]) can be easily obtained. Similarly the $Y_R$ couplings can induce this transition with $\text{Br}(\mu\rightarrow e\gamma) \approx (\alpha/192\pi)|(Y_R)_{e\tau}(Y_R)_{\mu\tau}|^2 / (M_Y^4 G_F^2)$, where we assumed that the exchange of the RH neutrino $N_i$ gives the main contribution and we

\(^6\)The production of TeV scale RH neutrinos through the Yukawa couplings to left-handed leptons has been discussed e.g. in [29] for LHC, [30] for a high energy $e^+e^-$ linear collider and [31] for an $e\gamma$ collider.

\(^7\)A possible exception is the case where the observed $N_i$ has suppressed couplings to a given flavor, so that it cannot washout any preexisting lepton asymmetry associated to that flavor.
neglected $M_\delta/M_{N_1}$ corrections. In this case the sets of parameters which lead to successful leptogenesis give rise to a smaller branching ratio, below $\sim 10^{-17}$, therefore unobservable.

The case of the triplet $(\delta^0, \delta^+, \delta^{++})$ has a similar phenomenology for what concerns the production of the $\delta^+$ and $N_{2,3}$. However, here $\delta^+$ does not have 2-body decays since it has no $Y_L$ coupling and it can decay only very slowly to three bodies (see Section 3). Therefore, the Drell-Yan produced $\delta^+\delta^-$ pair will leave in the detector a pair of long curved charged particle tracks which could be distinguished from a muon pair by the fact that they would be less relativistic. In this case the decay to a charged lepton pair and a $H^+$ (see Eq. (17)) will occur in general outside the detector and cannot be seen. In this scenario a $\delta^{++}$ could also be produced electromagnetically in colliders. As there is no $Y_L$ couplings, the $\mu \to e\gamma$ process in this case can be induced only through the $Y_\Delta$ couplings, with suppressed branching ratios as for the singlet case with $Y_R$ couplings.

7 Summary

We have considered a new mechanism to induce leptogenesis successfully, by the decay of the RH neutrino $N_1$ to a RH charged lepton and a scalar $SU(2)_L$ singlet $\delta^+$. In the presence of left-right symmetry the $\delta^+$ may or may not be a member of an $SU(2)_R$ triplet. In both versions one achieves successful leptogenesis easily in a similar way. This mechanism can work at scales as low as few TeV with no need of resonant enhancement of the asymmetry. Such a low scale realization requires that $N_1$ Yukawa couplings to RH charged leptons are about 4 orders of magnitude smaller than the ones of heavier RH neutrinos.

In grand-unified theories this mechanism can be realized, for the singlet case, both in SO(10), if there exists a 120 scalar multiplet, and in SU(5) with a 10 scalar multiplet. The $SU(2)_R$ scalar triplet case can be incorporated in SO(10) models with a $\overline{126}$ scalar multiplet. However, in this case, in order for leptogenesis to work, the model should contain a source of RH neutrino masses independent from this $\overline{126}$ representation.

Phenomenologically, the observation of a light $SU(2)_L$ singlet $\delta^+$ at colliders would be a strong evidence in favor of our proposal. The additional production of a RH neutrino at few TeV scale, through the large couplings to RH charged leptons, would make the case for low scale leptogenesis.

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