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Scalar triplet leptogenesis without right-handed neutrino decoupling

D. Aristizabal Sierra

IFPA, Dep. AGO, Universite de Liege, Bat B5, Sart Tilman B-4000 Liege 1, Belgium

Abstract

We discuss leptogenesis in the context of type-II seesaw in the case in which in addition to the scalar electroweak triplet decays the lepton asymmetry is also induced by right-handed neutrino decays (mild hierarchical scenarios). We show that within this setup, depending on the relative sizes of the relevant parameters, one can identify three classes of generic models, each one with its own consequences for leptogenesis.

Keywords: Neutrino masses, baryogenesis, leptogenesis

1. Introduction

Going beyond standard leptogenesis means going beyond type-I seesaw. Certainly the most simple frameworks for such a task are provided by type-II seesaw, type-III seesaw or interplays among them (a full analysis can be found in [1]). In particular the "hybrid" type-I plus type-II scenario has been discussed in the limit of right-handed (RH) neutrino decoupling[2][1], so we here aim to extend upon this consideration by discussing scenarios were a net non-zero baryon asymmetry is builded up from the dynamics of both, the electroweak triplet and the lightest RH neutrino, scenarios we dub as *mild hierarchical scenarios*.

This paper is mostly based on references [5, 6].

2. Type II seesaw and leptogenesis

Extending the standard model with a scalar electroweak triplet induces a new set of interactions determined by

$$\mathcal{L}^{II} = -Y_{ij}\ell^T_{L_i} C i\tau_2 \boldsymbol{\Delta}\ell_{L_j} - M^2_\Delta \mathrm{Tr}\boldsymbol{\Delta}^\dagger\boldsymbol{\Delta} + \mu H^T i\tau_2 \boldsymbol{\Delta} H + \text{H.c.}\,, \tag{1}$$

with $\boldsymbol{\Delta}$ given by

$$\boldsymbol{\Delta} = \begin{pmatrix} \Delta^{++} & \Delta^{+}/\sqrt{2} \\ \Delta^{+}/\sqrt{2} & \Delta^{0} \end{pmatrix}. \tag{2}$$

These interactions solely can account for neutrino masses and mixings, with the effective light neutrino mass matrix given by

$$\boldsymbol{m}_\nu^{\boldsymbol{II}} = 2\, v_\Delta\, \boldsymbol{Y}\,, \tag{3}$$

where $\langle\Delta\rangle = v_\Delta$. Successful leptogenesis, however, requires going beyond the interactions in (1). Here we will consider RH neutrinos as the new degrees of freedom allowing the generation of a baryon asymmetry consistent with data *i.e.* scenarios with interplay between type-I and type-II seesaw. The interactions induced by the RH neutrinos,

$$\mathcal{L}^{I} = -\lambda_{ij}\overline{N}_{R_i}\ell_{L_j}\tilde{H}^\dagger - \frac{1}{2}\overline{N}_{R_i} C M_{R_i}\overline{N}^T_{R_i} + \text{H.c.}\,, \tag{4}$$

lead to the standard type-I CP asymmetry parameter in N_k decays, ϵ_{N_k}, while the combination of interactions in (1) and (4) yield a new contribution, $\epsilon^\Delta_{N_k}$, to the total CP asymmetry, $\epsilon^{\text{tot}}_{N_k}$ [7]. While N_k decays receive contributions from wave-function as well as vertex one-loop corrections, in the setup considered here triplet decays are subject only to vertex corrections. Thus, the CP asymmetry parameter in triplet decays, ϵ_Δ, arises solely from

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Email address: `daristizabal@ulg.ac.be` ()

[1] Leptogenesis in type-III scenarios was discussed for the first time in [3] and subsequently discussed in [4].

the interference between the tree-level and vertex correction.

2.1. *Kinetic equations for triplet and RH neutrino dynamics*

Depending on the mass spectrum of the mixed type-I plus type-II scenario, the lepton asymmetry can be produced by RH neutrino decays, triplet decays or both. When writing the Boltzmann equations accounting for the dynamics of the state producing the lepton asymmetry those states which are decoupled can be ignored and—in general—only the lightest state interactions have to be included. In *mild hierarchical scenarios*, where $M_\Delta \sim M_{N_1}$, both the triplet and lightest RH neutrino reactions play a crucial role.

The full network of kinetic equations for the case under consideration consist of five coupled differential equations for the following densities: Y_{N_1}, Y_Σ, Y_{Δ_L}, Y_{Δ_H}, Y_{Δ_Δ}. The resulting equations satisfy the constraint

$$2\,Y_{\Delta_\Delta} + Y_{\Delta H} - Y_{\Delta_L} = 0 \qquad (5)$$

as a consequence of hypercarge conservation[2]. With this constraint at hand and in the one-flavor approximation the final network of Boltzmann equations can be written according to [5]

$$\begin{aligned}
\dot{Y}_{N_1} &= -\,(y_{N_1} - 1)\,\gamma_{D_{N_1}}\,,\\
\dot{Y}_{\Sigma} &= -\,(y_\Sigma - 1)\,\gamma_{D_\Delta} - 2(y_\Sigma^2 - 1)\,\gamma_A\,,\\
\dot{Y}_{\Delta_L} &= \Big[(y_{N_1} - 1)\,\epsilon_{N_1}^{\rm tot} - \Big(y_{\Delta_L} - y_{\Delta_\Delta}^H\Big)\Big]\,\gamma_{D_{N_1}}\\
&\quad + \left[(y_\Sigma - 1)\,\epsilon_\Delta - 2K_\ell\,(y_{\Delta_L} + y_{\Delta_\Delta})\right]\,\gamma_{D_\Delta}\,,\\
\dot{Y}_{\Delta_\Delta} &= -\Big[y_{\Delta_\Delta} + (K_\ell - K_H)\,y_{\Delta_L} + 2K_H\,y_{\Delta_\Delta}^H\Big]\,,
\end{aligned} \qquad (6)$$

where the following conventions are used: $\dot{Y} \equiv sHz\,dY/dz$, $y_X \equiv Y_X/Y_X^{\rm Eq}$ (the exception being $y_{\Delta_\Delta}^H \equiv Y_{\Delta_\Delta}/Y_H^{\rm Eq}$ and $y_{\Delta_L} = Y_{\Delta_L}/Y_\ell^{\rm Eq}$), $\Sigma \equiv \Delta + \Delta^\dagger$, $\epsilon_{N_1}^{\rm tot} \equiv \epsilon_{N_1} + \epsilon_{N_1}^\Delta$ and $\gamma_{D_{N_1}}$, γ_{D_Δ} and γ_A are the reaction densities for: RH neutrino and triplet decays and triplet annihilations. The factors $K_{\ell,H}$ resemble the flavor projectors defined in standard flavored leptogenesis [8, 9] as they project triplet decays into the Higgs or the lepton doublet directions. They are given by

$$K_\ell = \frac{\tilde{m}_\Delta^\ell}{\tilde{m}_\Delta^\ell + \frac{\tilde{m}_\Delta^2}{4\,\tilde{m}_\Delta^\ell}} \quad \text{and} \quad K_H = \frac{\tilde{m}_\Delta^2}{4\,\tilde{m}_\Delta^\ell\left(\tilde{m}_\Delta^\ell + \frac{\tilde{m}_\Delta^2}{4\,\tilde{m}_\Delta^\ell}\right)}\,, \qquad (7)$$

where the parameters $\tilde{m}_\Delta^\ell$ and $\tilde{m}_\Delta^2$ are given by

$$\tilde{m}_\Delta^\ell = \frac{v^2\,|\boldsymbol{Y}|^2}{M_\Delta} \quad \text{and} \quad \tilde{m}_\Delta^2 = {\rm Tr}[\boldsymbol{m_\nu^{II}}\boldsymbol{m_\nu^{II}}^\dagger]\,, \qquad (8)$$

with $v = \langle H\rangle \simeq 174$ GeV and $|\boldsymbol{Y}|^2 = {\rm Tr}[\boldsymbol{Y}\,\boldsymbol{Y}^\dagger]$.

Since we are dealing with a *mild hierarchical scenario* we asumme $r = M_\Delta/M_{N_1} \subset [10^{-1}, 1]$ and so while $z = M_\Delta/T$, $z_N = r\,z$. Accordingly, the problem of studying the generation of a lepton asymmetry through eqs. (6), once the CP asymmetries $\epsilon_{N_1}^{\rm tot}$ and ϵ_Δ are fixed, reduces to a five parameter problem, namely $\tilde{m}_{N_1} = v^2(\boldsymbol{\lambda}\boldsymbol{\lambda}^\dagger)_{11}/M_{N_1}$, $\tilde{m}_\Delta$, $\tilde{m}_\Delta^\ell$, M_Δ and r [3].

3. Results

The details of the generation of the lepton asymmetry are determined by the relative size of the different parameters intervening in eqs. (6), which fix the size of the corresponding Yukawa, Higgs and gauge reaction densities and also fix the direction in the "lepton-Higgs space" through which the triplet, Higgs and lepton asymmetries are projected (see eqs. (7)). Three possible scenarios can be defined [5]:

A. Purely triplet scalar leptogenesis models:
The relevant parameters follow the hierarchy $\tilde{m}_1 \ll \tilde{m}_\Delta^\ell, \tilde{m}_\Delta$. The L asymmetry is generated through the processes $\boldsymbol{\Delta} \to \bar{\ell}\bar{\ell}$ or $\boldsymbol{\Delta} \to HH$ and the details strongly depend on whether $\tilde{m}_\Delta^\ell \gg \tilde{m}_\Delta$, $\tilde{m}_\Delta^\ell \ll \tilde{m}_\Delta$ or $\tilde{m}_\Delta^\ell \sim \tilde{m}_\Delta$. Interestingly, when $\tilde{m}_\Delta^\ell \gg \tilde{m}_\Delta$ the Higgs asymmetry—being weakly washed out—turns out to be large and implies a large lepton asymmetry.

B. Singlet dominated leptogenesis models:
These scenarios are defined according to $\tilde{m}_1 \gg \tilde{m}_\Delta^\ell, \tilde{m}_\Delta$ thus leptogenesis is mainly determined by N_1 dynamics. The relative difference between the parameters $\tilde{m}_\Delta^\ell$ and $\tilde{m}_\Delta$ determines whether either the Higgs asymmetry or the L asymmetry are strongly or weakly washed out, thus three cases can be distinguished: $\tilde{m}_\Delta^\ell \gg \tilde{m}_\Delta$, $\tilde{m}_\Delta^\ell \ll \tilde{m}_\Delta$ or $\tilde{m}_\Delta^\ell \sim \tilde{m}_\Delta$. Each of them exhibit different features.

C. Mixed leptogenesis models:
In these models the parameters controlling the gauge reaction densities strengths are all of the same order i.e. $\tilde{m}_1 \sim \tilde{m}_\Delta^\ell \sim \tilde{m}_\Delta$.

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[2] The same relation is found to hold in the case when the RH neutrino is decoupled [2]. This is expected since the RH neutrino is a vanishing hypercharge state.

[3] In contrast to the pure triplet leptogenesis case [2] where the determination of the L asymmetry depends only on three parameters: $\tilde{m}_\Delta$, $\tilde{m}_\Delta^\ell$, M_Δ.

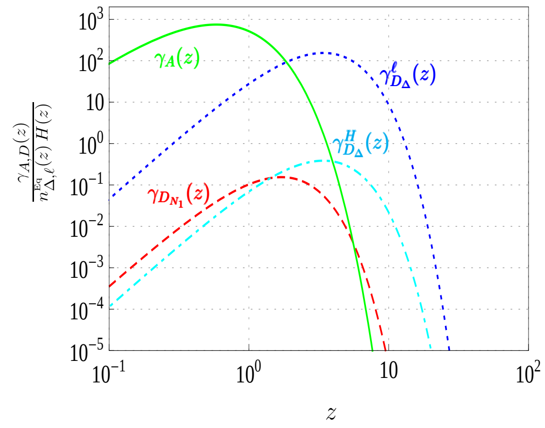

Figure 1: Reaction densities for triplet and RH neutrino processes.

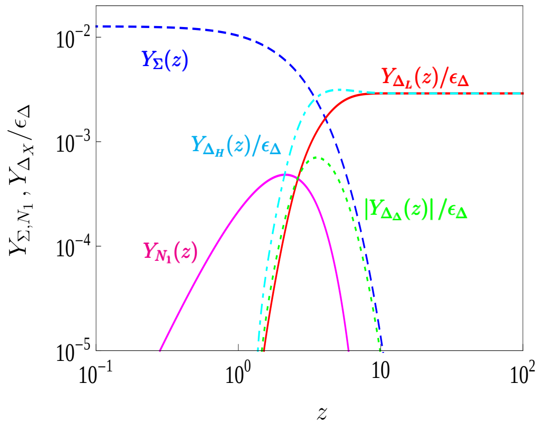

Figure 2: Evolution of the different densities as a function of $z = M_\Delta/T$.

A full discussion of these schemes can be found in [5]. Here in order to illustrate the main features of leptogenesis in these scenarios we show in fig. 1 the different gauge reaction densities obtained by choosing P_I=($\tilde{m}_1$, $\tilde{m}_\Delta$, $\tilde{m}^\ell_\Delta$,M_Δ,r) =(10^{-4} eV, 10^{-2} eV, 10^{-1} eV, 10^{10} GeV,2) and fixing $\epsilon^{\rm tot}_{N_1} = 10^{-6}$ and $\epsilon_\Delta = 10^{-5}$. As expected, at high temperature gauge reactions dominate and start rapidly falling at $z \sim 1$. Above that value they are overcomed by Higgs related reactions which although large do not imply a strong washout of the Higgs asymmetry (due to $\gamma^H_{D_\Delta} \ll \gamma^\ell_{D_\Delta}$) as demonstrated in fig. 2. Indeed the large Higgs asymmetry allows the development of a large triplet and lepton asymmetry at values slightly above $z \sim 1$, as required by condition (5). At higher values the triplet asymmetry is diluted and transferred to the lepton asymmetry which accordingly increases, and matches the Higgs asymmetry when the triplet asymmetry is entirely depleted. This effect (storing a large asymmetry in certain lepton-Higgs direction) resembles what can happen in standard leptogenesis when flavor effects are taken into account.

4. Conclusions

We discussed scenarios where leptogenesis takes place due to interplay between type-I and type-II seesaws. In particular, we have analysed scenarios where the lepton asymmetry is generated through the CP violating decays of the lightest RH neutrino and the electroweak triplet. Working in the one-flavor approximation, it has been shown that three scenarios for the generation of a baryon asymmetry via leptogenesis can be identified. Even under this assumption we have found that in some of the scenarios discussed, the simultaneous presence of triplet and RH neutrino interactions allows an enhancement of the lepton asymmetry produced via leptogenesis.

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