STRONG SO(10)-INSPIRED LEPTOGENESIS: PREDICTIONS AND MOTIVATION[a]

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We highlight the existence of regions in the parameter space associated to the SO(10)-inspired model of leptogenesis where, beside the current experimental constraints, also non-trivial strong thermal leptogenesis requirements are satisfied. These particular solutions guarantee the independence of the model from possible pre-existent asymmetries, motivating at the same time the value observed for baryon asymmetry of the Universe. Attracted by these features we insist on the strong thermal solutions of the SO(10)-inspired model, presenting sharp predictions on the low energy neutrino parameters which fall in the range of the next-generation experiments.

1 Introduction

Leptogenesis is a class of models in which neutrino masses and baryon asymmetry of the Universe share a common origin [3]. The model we consider is based on a type-I seesaw extension of the Standard Model, involving three Majorana right handed (RH) neutrinos N_{Ri} $(i = 1, 2, 3)$. More precisely, after the charged-lepton-Yukawa-coupling matrix has been diagonalised, the Lagrangian can be written as

$$\mathcal{L} = \mathcal{L}_{SM} + i\overline{N_{Ri}}\partial^{\mu}\gamma_{\mu}N_{Ri} - h_{\alpha i}\overline{\ell_{L\alpha}}N_{Ri}\tilde{\Phi} - \frac{1}{2}\overline{N^c_{Ri}}D_{M_i}N_{Rj} + \text{H.c.} \tag{1}$$

where D_X indicates the diagonal form of the matrix X, the subscript 'α' denotes the charged-lepton flavours $(\alpha = e, \mu, \tau)$ and the subscript 'i' refers to the RH neutrinos $(i = 1, 2, 3)$. With the setup in Eq. 1 a neutrino Dirac mass term, $m_D = hv$, is generated at the electro-weak symmetry breaking, where $v = 174$ GeV. Then, in the seesaw limit $M \gg m_D$, the neutrino spectrum splits effectively into two parts: on one hand we have three light neutrinos associated to the mass scale resulting from the famous seesaw formula

$$m_{\nu} = -m_D D_M^{-1} m_D^T. \tag{2}$$

On the other, in the high energy sector of the theory, three heavy neutrinos $N_i \simeq N_{Ri} + N^c_{Ri}$ generate the baryon asymmetry of the Universe through their CP-violating decays [4]. By net leptogenesis accounts for the production of a baryon asymmetry as large as $\eta_B^{lept} \simeq 10^{-2} N_{B-L}^{lept,f}$. Here $N_{B-L}^{lept,f}$ represents the final amount of $B - L$ asymmetry induced by the heavy neutrino decays, while N_X denotes the abundance of particle or asymmetry X calculated in a co-moving volume which contains one RH neutrino in ultra-relativistic regime and thermal equilibrium.

[a]This paper is based on the work in [1, 2] and its content was presented to the Electroweak Interaction and Unified Theories session of the 47th edition of the Recontres de Moriond.

2 The Model

The seesaw type-I extension in Eq. 1 introduces 18 new parameters: 15 in the Yukawa coupling matrix $h_{\alpha i}$ and the three heavy masses M_i. Considering now the Takagi factorisation of the light neutrino mass matrix by the PMNS matrix U

$$U^\dagger m_\nu U^* = -D_m \tag{3}$$

as well as the bi-unitary decomposition of the neutrino Dirac mass matrix m_D

$$m_D = V_L^\dagger D_{m_D} U_R. \tag{4}$$

by means of the seesaw formula in Eq. 2 it is: $D_{m_D}^{-1} V_L U D_m U^T V_L^T D_{m_D}^{-1} = U_R D_M^{-1} U_R^T = M^{-1}$. It is therefore clear that the unitary matrix U_R, appearing in Eq. 4, is determined by the diagonalisation of the Hermitian operator $M^{-1}(M^{-1})^\dagger \equiv U_R D_M^{-2} U_R^\dagger$.

As a consequence we can re-parameterise the model adopting the following inputs: 3 Dirac masses in D_{m_D}, 6 parameters in the PMNS matrix U, 6 in the unitary matrix V_L and 3 light neutrino masses in D_m. Then, beside the available experimental information which partially constrain the light neutrino mass spectrum in D_m and the mixing angles in the PMNS matrix, we impose further theoretical conditions that characterise the model. To this purpose we adopt the SO(10)-inspired relations[5 6], which set a similarity between the up-type quarks and neutrinos quantified by the following conditions:

1. the mixing angles in V_L are limited according to the ranges of the CKM counterparts[b]
2. each neutrino Dirac mass λ_i is proportional to the corresponding up-type quark mass, $\lambda_1 = \alpha_1 m_u$, $\lambda_2 = \alpha_2 m_c$ and $\lambda_3 = \alpha_3 m_t$. We also expect $\alpha_i \sim \mathcal{O}(1)$.

These assumptions completely specify the SO(10)-inspired model. In the next Section we describe the leptogenesis process within this framework and review the strong thermal leptogenesis conditions.

3 Leptogenesis in the SO(10)-inspired scenario

Through the seesaw formula in Eq. 2, the Dirac mass hierarchy induced by the SO(10)-inspired conditions is transferred to the RH neutrinos. Then, excluding particular choices of parameters which result in a degenerate mass spectrum [7], the RH neutrino masses obey the hierarchical relation

$$M_1 \ll 10^9 \text{ GeV} < M_2 < 10^{12} \text{ GeV} \ll M_3. \tag{5}$$

Notice that for the above conditions the CP asymmetries[8] of N_1 and N_3 are negligible, therefore the emerging leptogenesis scenario is purely N_2-dominated. As a result the B-L asymmetry generation proceeds according to the following steps:

- for $T \sim M_2$ the B-L asymmetry is generated by the N_2 decays in a two flavour $(\tau, \tilde{\tau}_2)$ regime[9 10 11]
- for $T \sim M_1$ the N_1 processes are active and the asymmetry created by N_2 is partially washed out in a three flavour (e, μ, τ) regime.

[b]This is because V_L would play here the same role as the CKM matrix does in the quark sector, if we had no seesaw mechanism.

In this way the generated B-L asymmetry is independent of α_1 and α_3 and at the end of the leptogenesis process it is

$$N_{B-L}^{lept,f} \simeq \frac{P_{2e}^0}{P_{\tilde{\tau}_2}^0}\varepsilon_{\tilde{\tau}_2}\kappa(K_2, K_{\tilde{\tau}_2})e^{-\frac{3\pi}{8}K_{1e}} + \frac{P_{2\mu}^0}{P_{\tilde{\tau}_2}^0}\varepsilon_{\tilde{\tau}_2}\kappa(K_2, K_{\tilde{\tau}_2})e^{-\frac{3\pi}{8}K_{1\mu}} + \varepsilon_{2\tau}\kappa(K_2, K_{2\tau})e^{-\frac{3\pi}{8}K_{1\tau}}. \quad (6)$$

where we adopted the same conventions as in [6].

3.1 Strong thermal leptogenesis

The N_2-dominated scenario is particularly relevant when considering the problem of initial conditions in leptogenesis. Due to the high re-heating temperature usually required by leptogenesis models and disregarding ad hoc inflation scenarios, it is natural to expect a certain amount of B-L asymmetries, N_{B-L}^{preex}, to be generated before the onset of leptogenesis by other mechanisms. This preexistent contribution would sum to the leptogenesis one, $N_{B-L}^{lept,f}$, and be in part responsible for the generation of the baryon asymmetry of the Universe through the sphaleron processes. Unfortunately a detailed calculation of N_{B-L}^{preex} is not viable at the moment, as it relies on an accurate description of the state of the Universe after the inflation era. On top of that, a priori there is no reason to exclude preexistent contributions large enough to dominate the final B-L asymmetry and even to impose a baryon asymmetry of the Universe much larger than $\eta_B^{cmbr} \sim 10^{-9}$ actually measured. In this sense N_{B-L}^{preex} represents an unknown and problematic initial condition for leptogenesis models.

A possible solution to the above problem is given by strong thermal leptogenesis [2]. In these scenarios the same leptogenesis processes wash out any possible preexistent contribution, so that after the leptogenesis era the B-L asymmetry is dominated by $N_{B-L}^{lept,f}$. In other words, strong thermal leptogenesis ensures the independence from possible preexistent asymmetries and the initial conditions therein encoded. Hence the baryon asymmetry of the Universe is necessarily a leptogenesis product, and models can recover their predictability. In this way strong thermal leptogenesis also provides a motivation for the coincidence that, given the low energy neutrino parameters in the ranges actually measured, leptogenesis naturally produces an amount of baryon asymmetry compatible with the one measured in our Universe.

Strong thermal leptogenesis within flavoured models with hierarchical RH neutrinos is realised under non-trivial constraints, fulfilled only by the tauon N_2-dominated scenario [2]. Specifically, beside the mass spectrum of Eq. 5, the tauon N_2-dominated scenario requires the following conditions on the flavoured decay efficiency parameter $K_{i\alpha}$: $K_{2\tau} \gg 1$, $K_{\tilde{\tau}_2} \gg 1$, $K_{1e} \gg 1$ $K_{1\mu}$, but $K_{1\tau} \leq 1$. These constraints ensure the washout of any preexistent contribution through the projection effect [12]. Hence the amount of preexistent asymmetry at the end of the leptogenesis process, $N_{B-L}^{preex,f}$, is necessarily negligible. Nevertheless, for the same conditions, a τ-lepton asymmetry is generated by the N_2 decays, resulting in the amount of B-L asymmetry required for leptogenesis to be successful.

4 Strong SO(10)-inspired leptogenesis and its predictions

From the discussion in Section 2 it should be clear that the SO(10)-inspired model of leptogenesis represents a natural embedding for N_2-dominated scenarios. Attracted by the features of strong thermal leptogenesis we therefore aim to verify the compatibility of the model with the conditions reported in Section 3. To this purpose we performed a scan of its parameter space, seeking the region where the strong leptogenesis condition $N_{B-L}^{preex,f} \ll N_{B-L}^{lept,f}$ is satisfied and a right amount of B-L asymmetry is produced. Restricting ourselves to the experimental 2σ-ranges [13], we repeated the analyses for different values of the initial pre-existent asymmetry $N_{B-L}^{preex,0}$. It should be stressed that the results presented in Figure 1 refer exclusively to normal-ordered light neutrinos: no strong thermal solutions have been found for inverted order within the current framework.

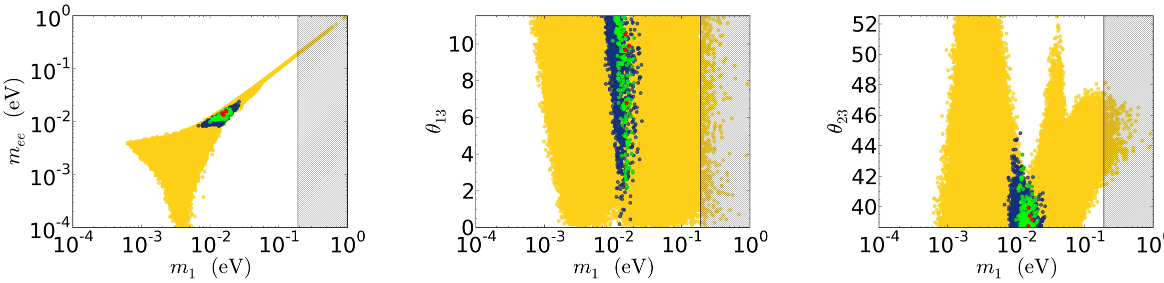

Figure 1: Predictions on the low energy neutrino parameters, $\alpha_2 = 5$. The colour code indicates the magnitude of the preexistent $B - L$ asymmetry washed out in the corresponding point of the parameter space. Yellow dots are for $\mathcal{O}(0)$, blue dots for $\mathcal{O}(10^{-3})$, green dots for $\mathcal{O}(10^{-2})$ and red pentagons are for $\mathcal{O}(10^{-1})$. The model correctly reproduces $\eta_B \sim 10^{-9}$ in all the coloured regions.

To conclude we highlight the main results emerging from our analyses, considering for sake of definiteness the green regions of Figure 1 which denote the washout of an initial pre-existent asymmetry as big as $N_{B-L}^{preex,0} \sim \mathcal{O}(10^{-2})$. A more exhaustive investigation involving the red regions is in preparation[1]. Focusing on the first panel, we can see how strong thermal leptogenesis constrains the lightest neutrino mass m_1 and the neutrinoless double beta decay mass scale m_{ee} to the range around 10^{-2} eV. This is our strongest prediction, which nicely falls within the declared sensitivities of next-generation experiments. The middle panel shows the agreement between the model and current observations, requiring a non-zero value for the lepton mixing angle θ_{13} and presenting the bulk of solutions for large values of the parameter. Finally the last panel is reserved for the signature of the model, encoded in θ_{23}. In fact the strong thermal solutions of the SO(10)-inspired model predict non-maximal values for the mixing angle, with an upper bound at $\theta_{23}^{max} \simeq 44^{\circ}$ and the majority of solution falling for $\theta_{23} \leq 42^{\circ}$.

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References

1. P. Di Bari, L. Marzola, *in preparation.*
2. E. Bertuzzo, P. Di Bari, L. Marzola, Nucl. Phys. **B849** (2011) 521-548.
3. M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).
4. W. Buchmuller, P. Di Bari, M. Plumacher, Annals Phys. **315** (2005) 305-351.
5. G. C. Branco *et al*, Nucl. Phys. B **640** (2002) 202 [hep-ph/0202030].
6. P. Di Bari, A. Riotto, Phys. Lett. **B671** (2009) 462-469; JCAP **1104** (2011) 037.
7. E. K. Akhmedov, M. Frigerio and A. Y. .Smirnov, JHEP **0309** (2003) 021.
8. L. Covi, E. Roulet and F. Vissani, Phys. Lett. B **384** (1996) 169
9. E. Nardi, Y. Nir, E. Roulet, J. Racker, JHEP **0601** (2006) 164.
10. A. Abada *et al*, JCAP **0604**, 004 (2006).
11. S. Blanchet, P. Di Bari, JCAP **0703** (2007) 018.
12. S. Blanchet, P. Di Bari, D. A. Jones and L. Marzola, arXiv:1112.4528 [hep-ph].
13. T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. **10** (2008) 113011.