SOFT LEPTOGENESIS IN THE INVERSE SEESAW

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We consider "soft leptogenesis" in the context of the inverse seesaw mechanism. In this model there are lepton number (L) conserving and L-violating soft supersymmetry-breaking B-terms involving the singlet sneutrinos which, together with the – generically small– L-violating parameter responsible of the neutrino mass, give a small mass splitting between the four singlet sneutrino states of a single generation. In combination with the trilinear soft supersymmetry breaking terms they also provide the CP violation needed to generate a lepton asymmetry in the singlet sneutrino decays. We obtain that the lepton asymmetry is proportional to the L-conserving soft supersymmetry-breaking B-term, and it is not suppressed by the L-violating parameters. As in the standard see-saw case, we find that this mechanism can lead to sucessful leptogenesis only for relatively small value soft bilinear B-term. The right-handed neutrino masses can be sufficiently low to elude the gravitino problem. Also the corresponding Yukawa couplings involving the lightest of the right-handed neutrinos are constrained to be $\sum |Y_{1k}|^2 \lesssim 10^{-7}$, which generically implies that the neutrino mass spectrum has to be strongly hierarchical.

1 Introduction

The discovery of neutrino oscillations makes leptogenesis a very attractive solution to the baryon asymmetry problem [1]. In the standard framework the tiny neutrino masses are generated via the (type I) seesaw mechanism and thus the new singlet neutral leptons with heavy Majorana masses can produce dynamically a lepton asymmetry through out of equilibrium decay. Eventually, this lepton asymmetry is partially converted into a baryon asymmetry due to fast $B-L$ violating sphaleron processes.

For a hierarchical spectrum of right-handed neutrinos, successful leptogenesis requires generically quite heavy singlet neutrino masses [2], of order $M > 2.4(0.4) \times 10^9$ GeV for vanishing (thermal) initial neutrino densities. The stability of the hierarchy between this new scale and the electroweak one is natural in low-energy supersymmetry, but in the supersymmetric seesaw scenario there is some conflict between the gravitino bound on the reheat temperature and the thermal production of right-handed neutrinos [3].

Once supersymmetry has been introduced, leptogenesis is induced also in singlet sneutrino decays. If supersymmetry is not broken, the order of magnitude of the asymmetry and the basic mechanism are the same as in the non-supersymmetric case. However, supersymmetry-breaking terms can play an important role in the lepton asymmetry generated in sneutrino decays [4,5] because they induce effects which are essentially different from the neutrino ones. In brief, soft supersymmetry-breaking terms involving the singlet sneutrinos remove the mass degeneracy between the two real sneutrino states of a single neutrino generation, and provide new sources of lepton number and CP violation. As a consequence, the mixing between the two sneutrino states generates a CP asymmetry in the decay, which can be sizable for a certain range of parameters. In particular the asymmetry is large for a right-handed neutrino mass scale relatively low, in the range $10^5 - 10^8$ GeV, well below the reheat temperature limits, what solves the cosmological gravitino problem. Moreover, contrary to the traditional leptogenesis scenario, where at least two generations of right-handed neutrinos are required to generate a CP asymmetry in (s)neutrino decays, in this new mechanism for leptogenesis the CP asymmetry in sneutrino decays is present even if a single generation is considered. This scenario has been termed "soft leptogenesis", since the soft terms and not flavour physics provide the necessary mass splitting and CP-violating phase.

We have studied[6] soft leptogenesis in the framework of an alternative mechanism to generate small neutrino masses, namely the inverse seesaw scheme[7]. This scheme is characterized by a *small* lepton number violating Majorana mass term μ, while the effective light neutrino mass is $m_\nu \propto \mu$. Small values of μ are technically natural, given that when $\mu \to 0$ a larger symmetry is realized: lepton number is conserved and neutrinos become massless. In the inverse seesaw scheme lepton flavour and CP violation can arise even in the limit where lepton number is strictly conserved, due to the mixing of the SU(2) doublet neutrinos with new SU(2) × U(1) singlet leptons.

As opposite to the standard seesaw case, these singlet leptons do not need to be very heavy[8], and, as a result, lepton flavour and CP violating processes are highly enhanced. In Ref.[9] it was studied the possibility that the baryon asymmetry is generated in this type of models during the electroweak phase transition, in the limit $\mu = 0$. A suppression was found due to the experimental constraints on the mixing angles of the neutrinos. Therefore we considered the supersymmetric version of the model and the soft leptogenesis mechanism, since (*i*) in this case we expect that a CP asymmetry will be generated in sneutrino decays even with a single-generation and no suppression due to the mixing angles is expected, and (*ii*) this scheme provides a more natural framework for the relatively low right-handed neutrino mass scale.

2 Inverse Seesaw Mechanism

In this type of models[7], the lepton sector of the Standard Model is extended with two electroweak singlet two-component leptons per generation, i.e.,

$$L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}, e_R^i, \nu_R^i, s_L^i \tag{1}$$

We assign lepton number $L = 1$ to the singlets s_L^i and ν_R^i. The (9×9) mass matrix of the neutral lepton sector in the ν_L, ν_R^c, s_L basis is given by

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M^T \\ 0 & M & \mu \end{pmatrix} \tag{2}$$

where m_D, M are arbitrary 3×3 complex matrices in flavour space and μ is complex symmetric. The matrix $\mathcal{M}$ can be diagonalized by a unitary transformation, leading to nine mass eigenstates n_a: three of them correspond to the observed light neutrinos, while the other three pairs of two component leptons combine to form three quasi-Dirac leptons.

In this "inverse seesaw" scheme, assuming $m_D, \mu \ll M$ the effective Majorana mass matrix for the light neutrinos is approximately given by

$$m_\nu = m_D^T {M^T}^{-1} \mu M^{-1} m_D \ , \tag{3}$$

while the three pairs of heavy neutrinos have masses of order M, and the admixture among singlet and doublet $SU(2)$ states is suppressed by m_D/M. Although M is a large mass scale suppressing the light neutrino masses, in contrast to the Majorana mass ($\Delta L = 2$) of the right-handed neutrinos in the standard seesaw mechanism, it is a Dirac mass ($\Delta L = 0$), and it can be much smaller, since the suppression in Eq. 3 is quadratic and moreover light neutrino masses are further suppressed by the small parameter μ which characterizes the lepton number violation scale.

We consider the supersymmetric version of this model. The above neutral lepton mass matrix (Eq. 2) is described by the following superpotential:

$$W = Y_{ij} N_i L_j H + \frac{1}{2}\mu_{ij} S_i S_j + M_{ij} S_i N_j \ , \tag{4}$$

where $i, j = 1, 2, 3$ are flavour indices, H, L_i, N_i, S_i are the superfields corresponding to the $SU(2)$ up-Higgs and lepton doublets, and ν_R^{ic} and s_L^i singlets respectively, and Y_{ij} denote the neutrino Yukawa couplings. After spontaneous electroweak symmetry breaking, the neutrino Dirac masses are given by $(m_D)_{ij} = Y_{ij}\langle H\rangle$.

The relevant soft supersymmetry breaking terms are the bilinear and trilinear scalar couplings involving the singlet sneutrino fields. We consider a simplified one generation model because a single generation of singlet sneutrinos is sufficient to generate the CP asymmetry.

$$-L_{soft} = AY_{1i}\widetilde{L}_i\widetilde{N}H + \widetilde{m}_S^2\widetilde{S}\widetilde{S}^\dagger + \widetilde{m}_N^2\widetilde{N}\widetilde{N}^\dagger + \widetilde{m}_{SN}^2\widetilde{S}\widetilde{N}^\dagger + B_S\widetilde{S}\widetilde{S} + B_{SN}\widetilde{S}\widetilde{N} + h.c. \tag{5}$$

With our lepton number assignments, the soft SUSY breaking terms which violate L are $\widetilde{m}_{SN}^2$ and B_S. The lagrangian describing sneutrino interactions has three independent physical CP violating phases. Furthermore, if we assume conservative values of the soft breaking terms:

$$\begin{gathered} A \sim \mathcal{O}(m_{SUSY}) \\ \widetilde{m}_N \sim \widetilde{m}_S \sim \widetilde{m}_{SN} \sim \mathcal{O}(m_{SUSY}) \\ B_S \sim \mathcal{O}(m_{SUSY}\mu) \\ B_{SN} \sim \mathcal{O}(m_{SUSY}M) \end{gathered} \tag{6}$$

with both, $\mu, m_{SUSY} \ll M$, we see that $B_S, \widetilde{m}_N^2, \widetilde{m}_S^2, \widetilde{m}_{SN}^2 \ll B_{SN}$ and $\widetilde{M}_{SN}^2 \sim \mu M^*$. Neglecting these small soft terms, there is still one physical CP violating phase,

$$\phi = \arg(AB_{SN}^* M) \ . \tag{7}$$

In this limit the mass degeneracy among the four sneutrino states is removed by both the L-violating mass μ and L-conserving supersymmetry breaking term B_{SN}. Together with the trilinear A term they also provide a source of CP violation, and the mixing among the four sneutrino states leads to a CP asymmetry in their decay.

3 The CP Asymmetry

Here we present the CP asymmetry in the singlet sneutrino decays. We assume that the sneutrinos are in a thermal bath with a thermalization time Γ^{-1} shorter than the typical oscillation times, ΔM_{ij}^{-1}, therefore coherence is lost and it is appropriate to compute the CP asymmetry in terms of the mass eigenstates.

We define a fermionic and a scalar CP asymmetry in the decay of each $\widetilde{N}_i$ in terms of decay amplitudes as:

$$\epsilon_{s_i} = \frac{\sum_k |\hat{A}_i(\widetilde{N}_i \to \widetilde{L}_k H)|^2 - |\hat{A}_i(\widetilde{N}_i \to \widetilde{L}_k^\dagger H^\dagger)|^2}{\sum_k |\hat{A}_i(\widetilde{N}_i \to \widetilde{L}_k H)|^2 + |\hat{A}_i(\widetilde{N}_i \to \widetilde{L}_k^\dagger H^\dagger)|^2} \tag{8}$$

$$\epsilon_{f_i} = \frac{\sum_k |\hat{A}_i(\widetilde{N}_i \to L_k h)|^2 - |\hat{A}_i(\widetilde{N}_i \to \bar{L}_k \bar{h})|^2}{\sum_k |\hat{A}_i(\widetilde{N}_i \to L_k h)|^2 + |\hat{A}_i(\widetilde{N}_i \to \bar{L}_k \bar{h})|^2} \; . \tag{9}$$

To compute ϵ_{s_i} and ϵ_{f_i} we follow the effective field theory approach described in [10], which consideres the CP violation due to mixing of nearly degenerate states by using resumed propagators for unstable (mass eigenstate) particles. We neglect thermal corrections to the CP asymmetry from loops. We obtain the following fermionic and scalar CP asymmetries at $T = 0$:

$$\epsilon_{s_i} = -\epsilon_{f_i} = \bar{\epsilon}_i = -\frac{4\,|B_{SN}\,A|\,\Gamma}{4|B_{SN}|^2 + |M|^2\Gamma^2} \sin\phi \; . \tag{10}$$

As long as we neglect the zero temperature lepton and slepton masses and small Yukawa couplings, the phase-space factors of the final states are flavour independent.

The total asymmetry ϵ_i generated in the decay of the singlet sneutrino $\tilde{N}_i$ can be written in the approximate decay at rest as:

$$\epsilon_i = \frac{\epsilon_{s_i} c_s + \epsilon_{f_i} c_f}{c_s + c_f} = \bar{\epsilon}_i \left[\frac{(1+n_B)^2 - (1-n_F)^2}{(1+n_B)^2 + (1-n_F)^2}\right] \; , \tag{11}$$

where c_s, c_f are the phase-space factors of the scalar and fermionic channels respectively, and $n_{B(F)}$ is the Bose(Fermi) distribution.

We find that this leptogenesis scenario presents many features analogous to soft leptogenesis in seesaw models [4,5]: (*i*) The CP asymmetry (Eq. 11) vanishes if $c_s = c_f$, because then there is an exact cancellation between the asymmetry in the fermionic and bosonic channels. Finite temperature effects break supersymmetry and make the fermion and boson phase-spaces different $c_s \neq c_f$, mainly because of the final state Fermi blocking and Bose stimulation factors. (*ii*) It also displays a resonance behaviour with the maximum placed at $2B_{SN}/M \sim \Gamma$. (*iii*) The CP asymmetry is due to the presence of supersymmetry breaking and irremovable CP violating phases, thus it is proportional to $|B_{SN}\,A| \sin\phi$.

We obtain that the CP asymmetry is not suppressed by the lepton number violating scale μ. This may seem counterintuitive. However if $\mu = 0$ the four sneutrino states are pair degenerate, and we can choose a lepton number conserving mass basis, made of the $(L = 1)$ states

$$\begin{aligned} \widetilde{N}_1' &= \frac{1}{\sqrt{2}}\left(\widetilde{S}^\dagger - \widetilde{N}\right) \\ \widetilde{N}_2' &= \frac{1}{\sqrt{2}}\left(\widetilde{S}^\dagger + \widetilde{N}\right) \end{aligned} \tag{12}$$

and their hermitian conjugates, with $L = -1$, $\widetilde{N}_1'^\dagger, \widetilde{N}_2'^\dagger$. Although there is a CP asymmetry in the decay of these sneutrinos, it is not a lepton number asymmetry (since in the limit $\mu = 0$ total lepton number is conserved) but just a redistribution of the lepton number stored in heavy sneutrinos and light lepton and slepton $SU(2)$ doublets. At very low temperatures, $T \ll M$, when no heavy sneutrinos remain in the thermal bath, all lepton number is in the light species and obviously if we started in a symmetric Universe with no lepton number asymmetry it will not be generated.

4 Results

Finally we quantified the conditions on the parameters which can be responsible for a successful leptogenesis: WMAP measurements in the ΛCDM model imply[11] that $n_{\mathcal{B}}/s = (8.7^{+0.3}_{-0.4}) \times 10^{-11}$. Assuming thermal initial sneutrino distribution and the weak wash-out regime, the final value of the baryon asymmetry generated in sneutrino decays can be parameterized as:

$$\frac{n_{\mathcal{B}}}{s} = -\frac{8}{23}\frac{n^{eq}_{\tilde{N}}}{s}\kappa \sum_i \epsilon_i(T_d), \tag{13}$$

where $8/23$ is the fraction of $\mathcal{B} - \mathcal{L}$ asymmetry converted into baryon asymmetry by sphaleron processes, $n^{eq}_{\tilde{N}}/s$ is the equilibrium number density of sneutrinos normalized to the entropy density, $\epsilon_i(T)$ is given in Eq. 11 and T_d is the temperature at the time of decay ($\Gamma = H(T_d)$). Finally, $\kappa \lesssim 1$ is a dilution factor which takes into account the possible inefficiency in the production of the singlet sneutrinos, the erasure of the generated asymmetry by L-violating scattering processes and the temperature dependence of the CP asymmetry $\epsilon_i(T)$. The precise value of κ can only be obtained from numerical solution of the Boltzmann equations. In what follows we will use an approximate constant value $\kappa = 0.2$.

Some constraints arise from the timing of the decay. First, successful leptogenesis requires the singlet sneutrinos to decay out of equilibrium: its decay width must be smaller than the expansion rate of the Universe $\Gamma < H\,|_{T=M}$. Second, in order for the generated lepton asymmetry to be converted into a baryon asymmetry via the B-L violating sphaleron processes, the singlet sneutrino decay should occur before the electroweak phase transition ($\Gamma > H(T \sim 100$ GeV$)$). These two conditions determines a range for the possible values of $\sum |Y_{1k}|^2$ for a given M:

$$2.6 \times 10^{-21} \left(\frac{10^8\,\text{GeV}}{M}\right) < \sum_k |Y_{1k}|^2 < 5 \times 10^{-9} \left(\frac{M}{10^8\,\text{GeV}}\right) \tag{14}$$

Eq.14 implies that the contribution of the lightest pseudo-Dirac singlet neutrino generation to the neutrino mass is negligible. Consequently, to reproduce the observed mass differences $\Delta m^2_{\odot}$ and Δm^2_{atm}, the dominant contribution to the neutrino masses must arise from the exchange of the heavier singlet neutrino states.

In Fig.1 we plot the range of parameters $\sum |Y_{1k}|^2$ and B_{SN} for which enough asymmetry is generated. We show the ranges for three values of M and for a generic value of $A = m_{SUSY} = 10^3$ GeV and $\sin\phi = 1$. We see that this mechanism works for relatively small values of M ($< 10^9$ GeV). The smaller is M, the smaller are the yukawas $\sum |Y_{1k}|^2$. Also, in total analogy with the standard seesaw [4,5], the value of the soft susy-breaking bilinear B_{SN}, is well bellow the expected value $M m_{SUSY}$. The reason is that, in order to generate an asymmetry large enough $B_{SN} \sim M\Gamma$, but Γ is very small if the sneutrinos decay out of equilibrium, $\Gamma \leqslant 1\text{ GeV}\,\left(\frac{M}{10^9\text{ GeV}}\right)^2$.

Given the small required values of B_{SN} one can question the validity of our results. In order to verify their stability we checked that as long as $|B_{SN}| \gg |B_S|, |\mu|^2$ the total CP asymmetry is always proportional to B_{SN}, and presents the same resonant behaviour, so that it is still significant only for $B_{SN} \ll M m_{SUSY}$.

In summary in this work [6] we studied the conditions for successful soft leptogenesis in the context of the supersymmetric inverse seesaw mechanism. This scheme is characterized by a small lepton number violating Majorana mass term μ with the effective light neutrino mass being $m_\nu \propto \mu$.

The relevant lepton asymmetry is proportional to the L-conserving term B_{SN} and is not suppressed by any L-violating parameter. As in the standard see-saw case, the asymmetry displays a resonant behaviour, and can lead to successful leptogenesis only for relatively small values of B_{SN}. The right-handed neutrino masses are low enough to elude the gravitino problem.

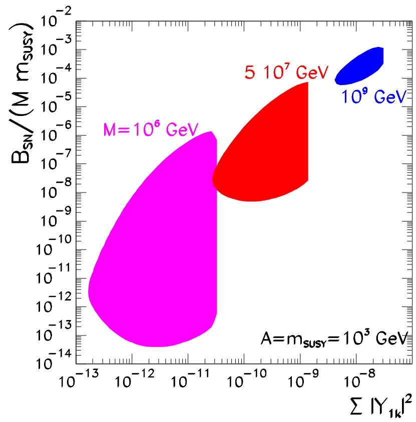

Figure 1: $\sum_k |Y_{1k}|^2 - B_{SN}$ regions in which enough CP asymmetry can be generated, and the non-equilibrium decay and decay before the electroweak phase transition conditions are verified. We take $A = m_{SUSY} = 10^3$ GeV, $\sin\phi = 1$. The regions correspond to $M = 10^6,\ 5 \times 10^7$, and 10^9 GeV.

Also, the out of equilibrium decay condition implies that the Yukawa couplings involving the lightest of the right-handed neutrinos are constrained to be very small. This means that the contribution of the lightest pseudo-Dirac singlet neutrino generation to the neutrino mass is negligible, so the dominant contribution to the neutrino masses must arise from the exchange of the heavier singlet neutrino states. Generically this leads to a neutrino mass spectrum strongly hierarchical.

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