UCRHEP-T406
March 2006

Leptogenesis Below the Davidson-Ibarra Bound

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Abstract

The observed baryon asymmetry of the Universe is suitably created in thermal leptogenesis through the out-of-equilibrium decay of N_1, the lightest of the three heavy singlet neutral fermions which anchor the seesaw mechanism to obtain small Majorana neutrino masses. However, this scenario suffers from the incompatibility of a generic lower bound on the mass of N_1 and the upper bound on the reheating temperature of the Universe after inflation. A modest resolution of this conundrum is proposed.

The canonical seesaw mechanism [1] for small Majorana neutrino masses requires the existence of three heavy singlet neutral fermions N_i so that

$$\mathcal{M}_\nu = -\mathcal{M}_D \mathcal{M}_N^{-1} \mathcal{M}_D^T \tag{1}$$

where $\mathcal{M}_D$ is the 3×3 Dirac mass matrix linking ν_α with N_i through the Yukawa interactions $h_{\alpha i}(\nu_\alpha \phi^0 - l_\alpha \phi^+)N_i$, where (ϕ^+, ϕ^0) is the Higgs doublet of the Standard Model (SM). In the early Universe, a lepton asymmetry may be generated [2] by the out-of-equilibrium decay of the lightest N_i (call it N_1), which gets converted into a baryon asymmetry through the interactions of the SM sphalerons [3] which conserve $B-L$, but violate $B+L$, where B and L are baryon and lepton number respectively. The existence of N_i explains thus at the same time why both neutrino masses as well as the observed baryon asymmetry of the Universe (BAU) are nonzero and small.

In the context of cosmology, the Universe goes through a period of inflation and then gets reheated to a certain maximum temperature T_h which is limited by the possible overproduction of gravitinos [4], if the underlying theory of matter is supersymmetric. It has been shown [5] that the generic lower bound on the mass M_1 of N_1 for successful thermal leptogenesis is dangerously close to being higher than T_h. This means that N_1 is not likely to be produced in enough abundance to generate the BAU.

To avoid this problem, several ideas have been discussed in the literature [6]. In particular, a more recent proposal is to consider the flavour issues in thermal leptogenesis [7]. Here a new and very simple solution is proposed. In addition to the three N_i $(i = 1, 2, 3)$, we add one more singlet fermion S together with a discrete Z_2 symmetry, under which S is odd and all other fields are even. This Z_2 symmetry prevents the Yukawa coupling of S to the usual lepton and Higgs doublets, but is allowed to be broken softly and explicitly by the $N_i S$ terms. Thus S mixes with N_i and its (indirect) couplings to the leptons are naturally suppressed. Specifically, the 7×7 mass matrix spanning $(\nu_e, \nu_\mu, \nu_\tau, N_1, N_2, N_3, S)$ is given by

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & 0 & m_{e1} & m_{e2} & m_{e3} & 0 \\ 0 & 0 & 0 & m_{\mu 1} & m_{\mu 2} & m_{\mu 3} & 0 \\ 0 & 0 & 0 & m_{\tau 1} & m_{\tau 2} & m_{\tau 3} & 0 \\ m_{e1} & m_{\mu 1} & m_{\tau 1} & M_1 & 0 & 0 & d_1 \\ m_{e2} & m_{\mu 2} & m_{\tau 2} & 0 & M_2 & 0 & d_2 \\ m_{e3} & m_{\mu 3} & m_{\tau 3} & 0 & 0 & M_3 & d_3 \\ 0 & 0 & 0 & d_1 & d_2 & d_3 & M_S \end{pmatrix}. \tag{2}$$

In canonical leptogenesis without S, the lightest right-handed neutirno N_1 decays into either $l^-\phi^+$ and $\nu\phi^0$, or $l^+\phi^-$ and $\bar{\nu}\bar{\phi}^0$. Thus a CP asymmetry may be established from the interference of the tree-level amplitudes with the one-loop vertex and self-energy corrections [8]. The decay rate

$$\Gamma_1 = \frac{(h^\dagger h)_{11}}{8\pi} M_1 \tag{3}$$

is compared against the expansion rate of the Universe

$$H(T) = 1.66 g_*^{1/2} \frac{T^2}{M_{Planck}} \tag{4}$$

at $T \sim M_1$, where $g_* \simeq 230$ is the effective number of relativistic degrees of freedom in the Minimal Supersymmetric Standard Model (MSSM) and $M_{Planck} = 1.2 \times 10^{19}$ GeV. This means that a <u>lower</u> bound on M_1 may be established by first considering the out-of-equilibrium condition

$$H(T = M_1) > \Gamma_1. \tag{5}$$

Let $K_1 = \Gamma_1 / H(T = M_1)$, then the above condition requires $K_1 < 1$, but even if $K_1 > 1$, a reduced lepton asymmetry may still be generated, depending on the details of the Boltzmann equations which quantify the deviation from equilibrium of the process in question.

The baryon-to-photon ratio of number densities has been measured [9] with precision, i.e.

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}. \tag{6}$$

In canonical leptogenesis, the thermal production of N_1 in the early Universe after reheating implies [10]

$$\eta_B \sim \frac{\epsilon_1}{10 g_*}\,, \tag{7}$$

where a typical washout factor of 10 has been inserted, and the CP asymmetry ϵ_1 is given by

$$\epsilon_1 \simeq -\frac{3}{8\pi}\left(\frac{M_1}{M_2}\right)\frac{Im[(h^\dagger h)^2]_{12}}{(h^\dagger h)_{11}}\,, \tag{8}$$

assuming $M_1 << M_2 << M_3$. To get the correct value of η_B, ϵ_1 should be of order 10^{-6}. However, using the Davidson-Ibarra upper bound on the CP asymmetry [5]

$$|\epsilon_1| \leq \frac{3M_1}{8\pi v^2}\sqrt{\Delta m^2_{atm}}. \tag{9}$$

this would imply $M_1 > 4 \times 10^9$ GeV. Since T_h is not likely to exceed 10^9 GeV, this poses a problem for canonical leptogenesis.

In the present model, the addition of S allows the choice of $M_S < M_1$. Since the mixing of S with N_i comes from the breaking of the assumed Z_2 symmetry of the complete Lagrangian, the parameters d_i are naturally small compared to M_i. The induced couplings of S to leptons are suppressed by factors of d_i/M_i compared to those of N_i, with its decay rate given by

$$\Gamma_S = \sum_i \frac{(h^\dagger h)_{ii}}{8\pi}\left(\frac{d_i}{M_i}\right)^2 M_S\,. \tag{10}$$

The condition for the departure from equilibrium, i.e. Eq. (5), during the decays of S can then be satisfied at a much lower mass.

The CP asymmetry generated by the decays of S comes from the interference of the tree-level and one-loop diagrams of Figure 1. Consider the case where S mixes only with N_1. Both the numerator and denominator of Eq. (8) are then suppressed by the same $(d_1/M_1)^2$ factor, and we obtain

$$\epsilon_{S_1} \simeq -\frac{3}{8\pi}\left(\frac{M_S}{M_2}\right)\frac{Im[(h^\dagger h)^2]_{12}}{(h^\dagger h)_{11}}\,. \tag{11}$$

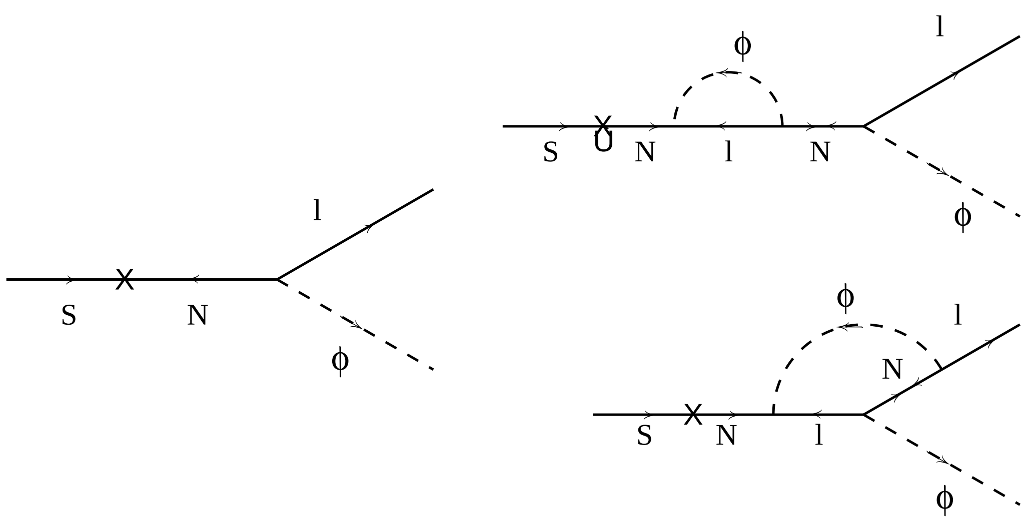

Figure 1: Tree-level and one-loop (self-energy and vertex) diagrams for S decay, which interfere to generate a lepton asymmetry.

Comparing Eq. (11) with Eq. (8), we see that we have not gained anything because M_S is subject to the same lower bound as M_1 through Eq. (9). Of course, we can adjust (d_1/M_1) to make $K_S < 1$ to avoid any washout, but then the thermal production of S through its inverse decay (which prefers $K_S > 1$) will be suppressed and we have again the typical reduction by about a factor of ten, as shown in Ref. [10].

To reduce M_S below the Davidson-Ibarra bound of 4×10^9 GeV, we may consider the case where S mixes only with N_2, then

$$\epsilon_{S_2} \simeq -\frac{3}{8\pi}\left(\frac{M_S}{M_1}\right)\frac{Im[(h^\dagger h)^2]_{21}}{(h^\dagger h)_{22}}\,. \tag{12}$$

This would allow M_S to be smaller by a large factor, as shown below. Consider the following approximate Yukawa matrix

$$h_{\alpha i} \simeq \begin{pmatrix} 0 & 0 & 0 \\ h_1 & -ih_2 & 0 \\ h_1 & -ih_2 & 0 \end{pmatrix}, \tag{13}$$

where $h_{1,2}$ are real, from which we obtain

$$(h^\dagger h)_{22} \simeq 2h_2^2, \quad [(h^\dagger h)^2]_{21} \simeq 4ih_1h_2(h_1^2+h_2^2)\,. \tag{14}$$

As for the neutrino mass matrix, it is given by

$$\mathcal{M}_\nu = h_{\alpha i} M_i^{-1} h_{\beta i} v^2 = m_0 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}, \tag{15}$$

where $m_0/v^2 = h_1^2 M_1^{-1} - h_2^2 M_2^{-1}$. This neutrino mass matrix has maximal $\nu_\mu - \nu_\tau$ mixing and $m_3 \simeq \sqrt{\Delta m^2_{atm}}$ and $m_{1,2} \simeq 0$, which is a reasonable approximation of the present data on neutrino oscillations. Since M_2 is assumed much greater than M_1, we have thus

$$m_3 \simeq 2h_1^2 v^2/M_1 \,. \tag{16}$$

Now Eq. (12) can be expressed as

$$\epsilon_{S_2} \simeq -\frac{3M_S m_3}{8\pi v^2}\left(\frac{h_1^2 + h_2^2}{h_1 h_2}\right). \tag{17}$$

Comparing this to the bound of Eq. (9), we see that M_S may be lowered by the factor $h_1 h_2/(h_1^2 + h_2^2)$. It may thus be reduced by, say a factor of 10 to 4×10^8 GeV, below the reheating temperature of 10^9 GeV.

In conclusion we have shown that the simple addition of an extra singlet to the usual three heavy neutral singlet fermions responsible for the seesaw mechanism in the MSSM offers a modest solution to the gravitino problem in canonical leptogenesis.

This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837. EM thanks the Physical Research Laboratory, Ahmedabad, India for hospitality during a recent visit.

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