Non-thermal leptogenesis and baryon asymmetry in different neutrino mass models

G. Panotopoulos

Department of Physics, University of Crete, Heraklion, Crete, GREECE
email: panotop@physics.uoc.gr

Abstract

In the present work we study non-thermal leptogenesis and baryon asymmetry in the universe in different neutrino mass models discussed recently. For each model we obtain a formula relating the reheating temperature after inflation to the inflaton mass. It is shown that all but four cases are excluded and that in the cases which survive the inflaton mass and the reheating temperature after inflation are bounded from below and from above.
1 Introduction

The Standard Model (SM) of particle physics \[1\] is a very successful theoretical framework for all low-energy phenomena. However, it is widely considered to be a low-energy limit of some underline fundamental theory. Perhaps the most direct evidence for physics beyond the SM is the recent discovery that neutrinos have small but finite masses \[2, 3, 4\]. A simple and natural way to explain the tiny neutrino masses is via the seesaw mechanism \[5\]. According to that, the existence of super-heavy right-handed neutrinos is postulated and the smallness of the masses of the usual SM neutrinos is due to the largeness of the masses of the new neutrinos. Solar, atmospheric, reactor and accelerator neutrino experiments (for a summary of three-flavour neutrino oscillation parameters see e.g. \[6\]) seem to indicate neutrino masses in the sub-eV range \([0.001 \text{ eV} < m_\nu < 0.1 \text{ eV}]\), which implies that heavy right-handed neutrinos weigh \(~10^{10} GeV - 10^{15} GeV\) \[7\].

On the other hand, the baryon asymmetry in the universe (BAU) is one of the most challenging problems for modern cosmology. Both Big-Bang Nucleosynthesis \[8\] and CMB data (for example from WMAP \[9\]) show that in the universe one baryon corresponds approximately to one billion photons. This very small number should be computable in the framework of the theory of the elementary particles and their interactions we know today. Nowadays, the most popular way to obtain the BAU is through leptogenesis \[10\]. Initially a lepton asymmetry is generated through the out-of-equilibrium decays of right-handed neutrinos and then the lepton asymmetry is partially converted to baryon asymmetry through the non-perturbative “sphaleron” effects \[11\]. In general leptogenesis can be thermal or non-thermal. Thermal leptogenesis usually requires very high reheating temperature after inflation \[12\]. This can be problematic because of the gravitino constraint. In supersymmetric models (for reviews in supersymmetry see e.g. \[13\] and for supersymmetry in cosmology see e.g. \[14\]) with spontaneous supersymmetry breaking the superpartner of the graviton, the gravitino, gets a mass depending on how the supersymmetry is broken. In gravity mediated supersymmetry breaking the gravitino mass is in the range \(m_{3/2} = 100 \text{ GeV} - 1 \text{ TeV}\) and the gravitino (if not the lightest supersymmetric particle) is unstable with a lifetime larger than Nucleosynthesis time \(t_N \sim 1 \text{ sec}\) and dangerous for cosmology. This gravitino problem \[15\] can be avoided provided that the reheating temperature after inflation is bounded from above in a certain way, namely \(T_R \leq (10^6 - 10^7) \text{ GeV}\) \[16\].
Therefore one can see that heavy right-handed neutrinos can have important implications both for particle physics and cosmology. Various neutrino mass models \cite{17,18} have been proposed and their predictions on neutrino masses and mixings have been studied thoroughly. The requirement for the right baryon asymmetry in the universe as well as for the right phenomenology for light neutrino masses and mixings puts severe constraints on right-handed neutrinos. Recently six concrete neutrino mass models were discussed and a comparison of numerical predictions on baryon asymmetry for these models was presented \cite{19}. Two of the models were almost consistent with the observed BAU, while the rest of them predicted either a small ($\eta \leq 10^{-19}$) or a large ($\eta \geq 10^{-6}$) baryon asymmetry. The analysis was performed in the framework of thermal leptogenesis. The aim of the present work is to study the same models in the framework of non-thermal leptogenesis and derive the constraints on the inflaton mass and the reheating temperature after inflation.

Our work is organized as follows. After this introduction we review the six neutrino mass models in section 2 and we discuss non-thermal leptogenesis for these models in the third section. Our results are presented in section 4 and we conclude in the last section.

2 Review of the different neutrino mass models

Here we give a brief review of the six neutrino mass models \cite{18} discussed recently in \cite{19}. The interested reader can find more details in \cite{18,19}. In particular, all the information about the models are collected in Appendix A of \cite{19}. There is one normal hierarchical model (NHT3), two inverted hierarchical models (InvT2A, InvT2B) and three degenerate models (DegT1A, DegT1B, DegT1C). According to seesaw mechanism, the light left-handed neutrino mass matrix $m_\nu$, the heavy right-handed neutrino mass matrix $M_R$ and the Dirac neutrino mass matrix $m_D$ are related as follows

$$m_\nu = m_D M_R^{-1} m_D^T$$

where $M_R^{-1}$ is the inverse of $M_R$ and $m_D^T$ is the transpose of $m_D$. The predicted values of the neutrino mass-squared differences and mixing parameters are shown in table 1.
Case (ii):

| Type   |
|--------|
| DegT1A |
| DegT1B |
| DegT1C |
| InvT2A |
| InvT2B |
| NHT3   |

Case (i):

Table 1: Predicted values of the solar and atmospheric neutrino mass-squared differences and three mixing parameters (from [19]).

| Type   | $m^2_{21} [10^{-5} eV^2]$ | $m^2_{23} [10^{-5} eV^2]$ | $\tan^2 \theta_{12}$ | $\sin^2 2\theta_{23}$ | $\sin \theta_{13}$ |
|--------|---------------------------|---------------------------|-----------------------|-----------------------|---------------------|
| DegT1A | 8.80                      | 2.83                      | 0.98                  | 1.0                   | 0.0                 |
| DegT1B | 7.91                      | 2.50                      | 0.27                  | 1.0                   | 0.0                 |
| DegT1C | 7.91                      | 2.50                      | 0.27                  | 1.0                   | 0.0                 |
| InvT2A | 8.36                      | 2.50                      | 0.44                  | 1.0                   | 0.0                 |
| InvT2B | 9.30                      | 2.50                      | 0.98                  | 1.0                   | 0.0                 |
| NHT3   | 9.04                      | 3.01                      | 0.55                  | 0.98                  | 0.074               |

Table 2: The three right-handed Majorana neutrino masses in GeV (from [19]).

| Type   | Case (i): $|M_j|$ | Case (ii): $|M_j|$ |
|--------|----------------|-----------------|
| DegT1A | $4.28 \times 10^9, 1.16 \times 10^{10}, 3.84 \times 10^{10}$ | $3.47 \times 10^7, 9.42 \times 10^7, 3.81 \times 10^{13}$ |
| DegT1B | $4.05 \times 10^7, 6.16 \times 10^{10}, 7.6 \times 10^{13}$ | $3.28 \times 10^5, 4.98 \times 10^9, 7.6 \times 10^{13}$ |
| DegT1C | $4.05 \times 10^7, 6.69 \times 10^{12}, 6.99 \times 10^{12}$ | $3.28 \times 10^5, 4.85 \times 10^{11}, 7.81 \times 10^{11}$ |
| InvT2A | $3.28 \times 10^8, 9.70 \times 10^{12}, 6.79 \times 10^{10}$ | $2.64 \times 10^6, 7.92 \times 10^{10}, 6.70 \times 10^{16}$ |
| InvT2B | $5.6527 \times 10^{10}, 5.6532 \times 10^{10}, 5.38 \times 10^{16}$ | $4.5971 \times 10^8, 4.5974 \times 10^8, 5.34 \times 10^{16}$ |
| NHT3   | $6.51 \times 10^{10}, 7.97 \times 10^{11}, 1.01 \times 10^{15}$ | $5.27 \times 10^8, 6.45 \times 10^9, 1.01 \times 10^{15}$ |

Table 3: Calculation of $CP$ asymmetry $\epsilon$ and baryon asymmetry $\eta$ for each neutrino mass model (from [19]).
In thermal leptogenesis for the SM case the BAU \( \eta \equiv n_B/n_\gamma = 6.1 \times 10^{-10} \) is computed by the formula \[19\]
\[
\eta = 0.0216 \kappa \epsilon
\] (2)
where the \( CP \) asymmetry \( \epsilon \) is defined as
\[
\epsilon = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}
\] (3)
with \( \Gamma = \Gamma(N_1 \rightarrow l_L \phi^\dagger) \) and \( \bar{\Gamma} = \Gamma(N_1 \rightarrow \bar{l}_L \phi) \) the decay rates, while the dilution factor \( \kappa \) is determined by numerical integration of Boltzmann equations. However it can be estimated by \[19\]
\[
\kappa = \frac{1}{2\sqrt{9 + K^2}}
\] (4)
for \( 0 \leq K \leq 10 \) and by
\[
\kappa = \frac{0.3}{K(lnK)^{0.6}}
\] (5)
for \( 10 \leq K \leq 10^6 \), with \( K \) the decay parameter \( K = m_1/m^* \), where \( m^* \) is the equilibrium neutrino mass \( m^* = 1.08 \times 10^{-3} \) eV and \( \tilde{m}_1 \) is the effective neutrino mass defined as
\[
\tilde{m}_1 = \frac{v^2(hh^\dagger)_{11}}{M_1}
\] (6)
with \( v \) the electroweak scale, \( M_1 \) the mass of \( N_1 \) and \( h \) the matrix for the neutrino Yukawa couplings. The three right-handed neutrino masses for each model are shown in table 2 while the \( CP \) asymmetry and baryon asymmetry are shown in table 3. The Dirac neutrino mass matrix \( m_D \) can be either the charged lepton mass matrix \( m_l \) (case (i)) or the up-quark mass matrix \( m_u \) (case (ii)). We see that NHT3 and DegT1A models are almost consistent with the observed BAU, while the rest of the models lead either to very small baryon asymmetry, \( \eta \leq 10^{-19} \) (DegT1B, DegT1C, InvT2A), or to large baryon asymmetry, \( \eta \geq 10^{-6} \) (InvT2B).

3 Non-thermal leptogenesis

We start by introducing three heavy right-handed neutrinos (one for each family) \( N_i, i = 1, 2, 3 \) with masses \( M_1, M_2, M_3 \), which interact only with leptons and Higgs through Yukawa couplings. In supersymmetric models the superpotential that describes their interactions with leptons and Higgs is \[20\]
\[
W_1 = Y_{ia} N_i L_a H_u
\] (7)
where \( Y_{ia} \) is the matrix for the Yukawa couplings, \( H_u \) is the superfield of the Higgs doublet that couples to up-type quarks and \( L_a \) \( (a = e, \mu, \tau) \) is the superfield
of the lepton doublets. Furthermore, we assume that after the slow-roll phase of inflation, the inflaton decays dominantly to right-handed neutrinos through Yukawa couplings and for supersymmetric models the interaction is described by the superpotential [21]

$$W_2 = \sum \lambda_i S N_i^c N_i^c$$

(8)

where $\lambda_i$ are the couplings for this type of interaction and $S$ is a gauge singlet chiral superfield for the inflaton. With such a superpotential the inflaton decay rate $\Gamma_\phi$ is given by [21]

$$\Gamma_\phi \equiv \Gamma(\phi \rightarrow N_i N_i) = \frac{1}{4\pi} |\lambda_i|^2 M_I$$

(9)

The reheating temperature after inflation $T_R$ is given by [22]

$$T_R = \left( \frac{45}{4\pi^3 g_\star} \right)^{1/4} (\Gamma_\phi M_{pl})^{1/2}$$

(10)

where $M_{pl}$ is Planck mass and $g_\star$ is the effective number of relativistic degrees of freedom at the reheating temperature. For the reheating temperatures that we shall consider all the particles are relativistic and for MSSM $g_\star = 915/4 = 228.75$, while for SM $g_\star = 427/4 = 106.75$.

Any lepton asymmetry $Y_L \equiv n_L/s$ produced before the electroweak phase transition is partially converted into a baryon asymmetry $Y_B \equiv n_B/s$ via sphaleron effects [11]. The resulting $Y_B$ is

$$Y_B = C Y_L$$

(11)

with the fraction $C$ computed to be $C = -8/15$ in the MSSM and $C = -28/79$ in the SM [23]. The lepton asymmetry, in turn, is generated by the $CP$-violating out-of-equilibrium decays of the heavy neutrinos

$$N \rightarrow l H_u^*, \quad N \rightarrow \bar{l} H_u$$

(12)

In the framework of non-thermal leptogenesis the lepton asymmetry is given by [21]

$$Y_L = \frac{3}{2} BR(\phi \rightarrow N_1 N_1) \frac{T_R}{M_I} \epsilon$$

(13)

where $M_I$ is the inflaton mass, $T_R$ the reheating temperature after inflation, $\epsilon$ the $CP$ asymmetry and BR is the branching ratio for the decay of the inflaton to the lightest heavy right-handed neutrino. The decay is kinematically allowed provided that

$$M_I > 2M_1$$

(14)
We will assume that $BR \approx 1$, that is the inflaton decays practically only to the lightest of the right-handed neutrinos. This is possible even if the inflaton is heavy enough to decay to all right-handed neutrinos as long as $|\lambda_1|^2 \gg |\lambda_2|^2, |\lambda_3|^2$. Combining the above formulae we obtain

$$Y_B = CY_L = C \frac{3}{2} \frac{T_R}{M_I} \epsilon$$  \hspace{1cm} (15)$$

or

$$T_R = \left( \frac{2Y_B}{3C\epsilon} \right) M_I$$  \hspace{1cm} (16)$$

From the WMAP data \text{[9]} we know that

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6.1 \times 10^{-10}$$  \hspace{1cm} (17)$$

If we recall that the entropy density for relativistic degrees of freedom is $s = h_{\text{eff}} \frac{2\pi^2}{45} T^3$ and that the number density for photons is $n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$, one easily obtains for today that $s = 7.04 n_\gamma$. Thus for $Y_B$ we have

$$Y_B = 8.7 \times 10^{-11}$$  \hspace{1cm} (18)$$

Following \text{[24]} we shall consider that $M_I \geq 100 T_R$, because in that case the neutrino $N_1$ is always out of thermal equilibrium. Finally we recall that $M_I > 2 M_1$.

4 Results

Now we can present our results. We shall begin with the SM case first and we shall use for the fraction $C$ the SM value, namely $C = -28/79$. For each neutrino model (12 cases in total) the CP asymmetry $\epsilon$ as well as the right-handed neutrino mass $M_I$ are known. Therefore we have i) a formula relating the reheating temperature to the inflaton mass, ii) a lower bound for the inflaton mass $M_I > 2 M_1$, and iii) an upper bound for the reheating temperature $T_R \leq 0.01 M_I$. Furthermore, using the relationship between $T_R$ and $M_I$ we are able to convert the upper limit for $T_R$ to a corresponding upper limit for $M_I$ and also the lower limit for $M_I$ to a corresponding lower limit for $T_R$. So both $T_R$ and $M_I$ are bounded both from above and from below. Let $T_R^{\text{min}}$ and $T_R^{\text{max}}$ be the lower and higher value for the reheating temperature respectively. Then $T_R^{\text{min}} < T_R \leq T_R^{\text{max}}$ and obviously it is required that $T_R^{\text{max}} > T_R^{\text{min}}$, which is not satisfied for all cases. In fact most of the cases are excluded. The only cases for which the constraint is satisfied are:

- DegT1A, case (i), for which:

$$8.56 \times 10^9 \text{ GeV} < M_I \leq 5.49 \times 10^{11} \text{ GeV}$$  \hspace{1cm} (19)$$
6.67 \times 10^5 \text{ GeV} < T_R \leq 4.28 \times 10^7 \text{ GeV} \quad (20)

- NHT3, case (i), for which:

\[ 1.3 \times 10^{11} \text{ GeV} < M_I \leq 2.35 \times 10^{12} \text{ GeV} \quad (21) \]
\[ 3.6 \times 10^7 \text{ GeV} < T_R \leq 6.51 \times 10^8 \text{ GeV} \quad (22) \]

- InvT2B, case (i), for which:

\[ 1.13 \times 10^{11} \text{ GeV} < M_I \leq 5.09 \times 10^{16} \text{ GeV} \quad (23) \]
\[ 1.25 \times 10^3 \text{ GeV} < T_R \leq 5.65 \times 10^8 \text{ GeV} \quad (24) \]

- InvT2B, case (ii), for which:

\[ 9.2 \times 10^8 \text{ GeV} < M_I \leq 4.55 \times 10^{12} \text{ GeV} \quad (25) \]
\[ 9.29 \times 10^2 \text{ GeV} < T_R \leq 4.6 \times 10^6 \text{ GeV} \quad (26) \]

One can see from the results presented above that inflationary models in which 
\( M_I \sim 10^{13} \text{ GeV} \), like e.g. chaotic \cite{25} or natural \cite{26} inflation, are compatible
only with one neutrino model (InvT2B, case (i)). Furthermore, for a concrete
inflationary model with a given inflaton mass our results allow us to know what
the reheating temperature must be and also what the inflaton decay rate \( \Gamma_\phi \) is
and what the inflaton Yukawa coupling \( |\lambda_1| \) is. For example, in chaotic or natural
inflation we obtain

\[
\begin{align*}
M_I & \sim 10^{13} \text{ GeV} \quad (27) \\
T_R & \sim 10^5 \text{ GeV} \quad (28) \\
\Gamma_\phi & \sim 10^{-8} \text{ GeV} \quad (29) \\
|\lambda_1| & \sim 10^{-10} \quad (30)
\end{align*}
\]

At this point we should add a comment regarding the gravitino constraint. If we
add supersymmetry in order to address the gravitino problem, then the expression
for the baryon asymmetry in MSSM will change slightly by a numerical factor of
order one. So we could use the results obtained so far for the SM case. If we require
that \( T_R \leq (10^6 - 10^7) \text{ GeV} \) then we see that the models InvT2B and DegT1A are
already compatible with the gravitino constraint, the model NHT3 is marginally
compatible (for the lower values for \( T_R \)) with the gravitino constraint and finally
the model InvT2B can be made compatible with the gravitino constraint lowering
the upper bound for \( T_R \)

\[ 1.25 \times 10^3 \text{ GeV} < T_R \leq (10^6 - 10^7) \text{ GeV} \quad (31) \]
5 Conclusions

In the present work we have studied non-thermal leptogenesis in six neutrino mass models proposed earlier and discussed recently in the literature. For each model we have obtained a formula relating the inflaton mass $M_I$ to the reheating temperature after inflation $T_R$. In fact according to this formula $T_R$ is proportional to $M_I$. Hence, the bigger the inflaton mass the bigger the reheating temperature. In a concrete inflationary model (chaotic \cite{25}, natural \cite{26}, supersymmetric hybrid \cite{27} etc) with a given mass for the inflaton, the right baryon asymmetry implies a certain reheating temperature after inflation. This in turn implies a certain decay rate for the inflaton field and a certain value for the inflaton Yukawa coupling. Furthermore, kinematical reasons and the requirement for non-thermal leptogenesis lead to a lower and an upper bound both for $M_I$ and $T_R$. Our results show that in most of the neutrino models under study the lower bound is not compatible with the upper bound and therefore only four cases survive. If we also take into account the gravitino constraint $T_R \leq (10^6 - 10^7)$ GeV, then in one of these cases the reheating temperature is even more constrained.

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