Non-thermal leptogenesis and a prediction of inflaton mass in a supersymmetric $SO(10)$ model

Takeshi Fukuyama, Tatsuru Kikuchi and Toshiyuki Osaka

Department of Physics, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan
E-mail: fukuyama@se.ritsumei.ac.jp, rp009979@se.ritsumei.ac.jp and rp006002@se.ritsumei.ac.jp

Received 22 March 2005
Accepted 4 June 2005
Published 14 June 2005

Online at stacks.iop.org/JCAP/2005/i=06/a=005
doi:10.1088/1475-7516/2005/06/005

Abstract. The gravitino problem gives a severe constraint on the thermal leptogenesis scenario. This problem leads us to consider some alternatives to it if we try to keep the gravitino mass around the weak scale $m_{3/2} \sim 100$ GeV. We consider, in this paper, the non-thermal leptogenesis scenario in the framework of a minimal supersymmetric $SO(10)$ model. Even if we start with the same minimal $SO(10)$ model, we have different predictions for low-energy phenomenologies dependent on the types of see-saw mechanism. This is the case for leptogenesis: it is shown that the type-I see-saw model gives a consistent scenario for the non-thermal leptogenesis but the type-II one does not. The predicted inflaton mass needed to produce the observed baryon asymmetry of the universe is found to be $M_I \sim 5 \times 10^{11}$ GeV for the reheating temperature $T_R = 10^6$ GeV.

Keywords: neutrino properties, baryon asymmetry, inflation

ArXiv ePrint: hep-ph/0503201
1. Introduction

The supersymmetric (SUSY) grand unified theory (GUT) provides an attractive implication for the understanding of the low-energy physics. In fact, for instance, the anomaly cancellation between the several matter multiplets is automatic in the GUT, since the matter multiplets are unified into a few multiplets, and the experimental data support the fact of unification of three gauge couplings at the GUT scale, $M_{\text{GUT}} = 2 \times 10^{16}$ GeV assuming the particle contents of the minimal supersymmetric standard model (MSSM) [1,2]. The right-handed neutrino that appeared naturally in the $SO(10)$ GUT provides a natural explanation of the smallness of the neutrino masses through the see-saw mechanism [3], and also the baryon asymmetry of the universe may have its origin in the same dimension-five operator relevant to the neutrino masses through the leptogenesis scenario [4] that would provide a natural explanation for the observed value of the baryon asymmetry [5]

$$4.9 \times 10^{-11} \leq Y_B \left( = \frac{n_B}{s} \right) \leq 9.9 \times 10^{-11} \text{ (95% C.L.).} \quad (1)$$

In a series of papers, we have discussed a minimal $SO(10)$ model [6,7] and its applications to low-energy phenomenologies like neutrino oscillations, neutrinoless double beta decay, leptogenesis [8], lepton flavour violation [9] and proton decay [10]. (For the minimal $SO(10)$ models done by other groups, see [11].) In these applications, we achieved rather good coincidences with observations. The only exceptional case is leptogenesis where our theory gives overproduction of baryon asymmetry in its naive form [8]. In order to relieve this pathology, we were forced to make the second pair of doublets play some roles unlike the conventional case where these doublets are decoupled at the electro-weak scale. However, the so-called gravitino problem [12] gives a severe constraint on the reheating temperature; though this problem has had a long history [13] and there are many studies on this subject [14], recent progress including the hadronic decay processes shed a new doubt on the high reheating temperature $T_R$ [15]. If we take this seriously and adopt low $T_R$, the thermal leptogenesis becomes impossible. This may be good news for us since the minimal $SO(10)$ model in its naive form may survive in the new scenario. The new scenario is not unique and we consider in this paper non-thermal leptogenesis, where the inflaton decays to the right-handed neutrinos and the successive $B-L$ violating decays of the right-handed neutrinos produce the baryon asymmetry.

In a series of papers, we have discussed a minimal $SO(10)$ model [6,7] and its applications to low-energy phenomenologies like neutrino oscillations, neutrinoless double beta decay, leptogenesis [8], lepton flavour violation [9] and proton decay [10]. (For the minimal $SO(10)$ models done by other groups, see [11].) In these applications, we achieved rather good coincidences with observations. The only exceptional case is leptogenesis where our theory gives overproduction of baryon asymmetry in its naive form [8]. In order to relieve this pathology, we were forced to make the second pair of doublets play some roles unlike the conventional case where these doublets are decoupled at the electro-weak scale. However, the so-called gravitino problem [12] gives a severe constraint on the reheating temperature; though this problem has had a long history [13] and there are many studies on this subject [14], recent progress including the hadronic decay processes shed a new doubt on the high reheating temperature $T_R$ [15]. If we take this seriously and adopt low $T_R$, the thermal leptogenesis becomes impossible. This may be good news for us since the minimal $SO(10)$ model in its naive form may survive in the new scenario. The new scenario is not unique and we consider in this paper non-thermal leptogenesis, where the inflaton decays to the right-handed neutrinos and the successive $B-L$ violating decays of the right-handed neutrinos produce the baryon asymmetry.

In a series of papers, we have discussed a minimal $SO(10)$ model [6,7] and its applications to low-energy phenomenologies like neutrino oscillations, neutrinoless double beta decay, leptogenesis [8], lepton flavour violation [9] and proton decay [10]. (For the minimal $SO(10)$ models done by other groups, see [11].) In these applications, we achieved rather good coincidences with observations. The only exceptional case is leptogenesis where our theory gives overproduction of baryon asymmetry in its naive form [8]. In order to relieve this pathology, we were forced to make the second pair of doublets play some roles unlike the conventional case where these doublets are decoupled at the electro-weak scale. However, the so-called gravitino problem [12] gives a severe constraint on the reheating temperature; though this problem has had a long history [13] and there are many studies on this subject [14], recent progress including the hadronic decay processes shed a new doubt on the high reheating temperature $T_R$ [15]. If we take this seriously and adopt low $T_R$, the thermal leptogenesis becomes impossible. This may be good news for us since the minimal $SO(10)$ model in its naive form may survive in the new scenario. The new scenario is not unique and we consider in this paper non-thermal leptogenesis, where the inflaton decays to the right-handed neutrinos and the successive $B-L$ violating decays of the right-handed neutrinos produce the baryon asymmetry.

In a series of papers, we have discussed a minimal $SO(10)$ model [6,7] and its applications to low-energy phenomenologies like neutrino oscillations, neutrinoless double beta decay, leptogenesis [8], lepton flavour violation [9] and proton decay [10]. (For the minimal $SO(10)$ models done by other groups, see [11].) In these applications, we achieved rather good coincidences with observations. The only exceptional case is leptogenesis where our theory gives overproduction of baryon asymmetry in its naive form [8]. In order to relieve this pathology, we were forced to make the second pair of doublets play some roles unlike the conventional case where these doublets are decoupled at the electro-weak scale. However, the so-called gravitino problem [12] gives a severe constraint on the reheating temperature; though this problem has had a long history [13] and there are many studies on this subject [14], recent progress including the hadronic decay processes shed a new doubt on the high reheating temperature $T_R$ [15]. If we take this seriously and adopt low $T_R$, the thermal leptogenesis becomes impossible. This may be good news for us since the minimal $SO(10)$ model in its naive form may survive in the new scenario. The new scenario is not unique and we consider in this paper non-thermal leptogenesis, where the inflaton decays to the right-handed neutrinos and the successive $B-L$ violating decays of the right-handed neutrinos produce the baryon asymmetry.

In a series of papers, we have discussed a minimal $SO(10)$ model [6,7] and its applications to low-energy phenomenologies like neutrino oscillations, neutrinoless double beta decay, leptogenesis [8], lepton flavour violation [9] and proton decay [10]. (For the minimal $SO(10)$ models done by other groups, see [11].) In these applications, we achieved rather good coincidences with observations. The only exceptional case is leptogenesis where our theory gives overproduction of baryon asymmetry in its naive form [8]. In order to relieve this pathology, we were forced to make the second pair of doublets play some roles unlike the conventional case where these doublets are decoupled at the electro-weak scale. However, the so-called gravitino problem [12] gives a severe constraint on the reheating temperature; though this problem has had a long history [13] and there are many studies on this subject [14], recent progress including the hadronic decay processes shed a new doubt on the high reheating temperature $T_R$ [15]. If we take this seriously and adopt low $T_R$, the thermal leptogenesis becomes impossible. This may be good news for us since the minimal $SO(10)$ model in its naive form may survive in the new scenario. The new scenario is not unique and we consider in this paper non-thermal leptogenesis, where the inflaton decays to the right-handed neutrinos and the successive $B-L$ violating decays of the right-handed neutrinos produce the baryon asymmetry.
2. Leptogenesis in a minimal SUSY $SO(10)$ model

Let us first briefly review the conventional leptogenesis scenario [4]. In the following, our discussion is always based on the effective Lagrangian at energies lower than the right-handed neutrino masses such that

$$\mathcal{L}_{\text{eff}} = - \int d^2 \theta \left( Y_\nu^i N_i^c L_j H_u + \frac{1}{2} \sum_i M_{Ri} N_i^c N_i^c \right) + \text{h.c.,}$$

(2)

where $i, j = 1, 2, 3$ denote the generation indices, $Y_\nu$ is the Yukawa coupling, $L$ and $H_u$ are the lepton and the Higgs doublets chiral supermultiplets, respectively, and $M_{Ri}$ is the lepton-number-violating mass term of the right-handed neutrino $N_i$ (we are working on the basis of the right-handed neutrino mass eigenstates). The peculiar properties of minimal $SO(10)$ are that we can fix $Y_\nu^{ij}$ and $M_{Ri}$ unambiguously from the low-energy phenomenologies of quarks and leptons [6, 7].

The lepton asymmetry in the universe is generated by CP-violating out-of-equilibrium decay of the heavy neutrinos, $N \rightarrow \ell_L H_u^0$ and $N \rightarrow \ell_L H_u^-$. The leading contribution is given by the interference between the tree level and one-loop level decay amplitudes, and the CP-violating parameter is found to be [16]

$$\epsilon = \frac{1}{8\pi(Y_\nu^\dagger Y_\nu)^{11}} \sum_{j=2,3} \text{Im} \left[(Y_\nu^\dagger Y_\nu)^{1j}\right] \left\{ f(M_{Rj}^2/M_{R1}^2) + 2g(M_{Rj}^2/M_{R1}^2) \right\}.$$

(3)

Here $f(x)$ and $g(x)$ correspond to the vertex and the wavefunction corrections,

$$f(x) \equiv \sqrt{x} \left[ 1 - (1 + x) \ln \left( \frac{1 + x}{x} \right) \right],$$

$$g(x) \equiv \frac{\sqrt{x}}{2(1 - x)},$$

(4)

respectively, and both are reduced to $\sim -(1/2\sqrt{x})$ for $x \gg 1$. So in this approximation, $\epsilon$ becomes

$$\epsilon = -\frac{3}{16\pi(Y_\nu^\dagger Y_\nu)^{11}} \sum_{j=2,3} \text{Im} \left[(Y_\nu^\dagger Y_\nu)^{1j}\right] \frac{M_{R1}}{M_{Rj}}.$$

(5)

Using the type-I see-saw mass of the neutrino, $M_\nu = -Y_\nu^T M_{\text{R}}^{-1} Y_\nu \langle H_u \rangle^2$, $\epsilon$ is further written as [17]

$$\epsilon = \frac{3}{16\pi} \frac{M_{R1} \text{Im} [(Y_\nu^\dagger Y_\nu M_\nu^T)_{11}]}{\langle H_u \rangle^2} \equiv \frac{3}{16\pi} \frac{m_{\nu3} M_{R1} \delta_{\text{eff}}}{\langle H_u \rangle^2}.$$

(6)

In the minimal $SO(10)$ model we have the definite form of $Y_\nu$ and estimate these values unambiguously. We have assumed that the lightest $N_1$ decay dominantly contributes to the resultant lepton asymmetry. In fact, this is confirmed by numerical analysis in the case of hierarchical right-handed neutrino masses [18]. Using the above $\epsilon$, the generated $Y_B$ is described as

$$Y_B \sim \frac{\epsilon}{g_s} d.$$

(7)
where $g_* \sim 100$ is the effective degrees of freedom in the universe at $T \sim M_{R1}$, and $d \leq 1$ is the so-called dilution factor. This factor parameterizes how the naively expected value $Y_B \sim \epsilon / g_*$ is reduced by washing-out processes.

We can classify the washing-out processes into two cases, with and without the external leg of the heavy right-handed neutrinos, respectively. The former includes the inverse-decay process and the lepton-number-violating scatterings mediated by the Higgs boson \cite{19} such as $N + \ell_L \leftrightarrow q_R + q_L$, where $q_L$ and $q_R$ are quark doublet and singlet, respectively. The latter case is the one induced by the effective dimension-five interaction,

$$\mathcal{L}_N = \frac{1}{2} (Y_{\nu}^T M_R^{-1} Y_{\nu})_{ij} (L_i H_u)^T C^{-1} (L_j H_u),$$

after integrating out the heavy right-handed neutrinos. This term is nothing but the one providing the see-saw mechanism \cite{3}. The importance of this interaction was discussed in \cite{20}, where the interaction was shown to be necessary to avoid the false generation of the lepton asymmetry in thermal equilibrium. While numerical calculations \cite{18,19} are necessary in order to evaluate the dilution factor precisely, $Y_B \sim \epsilon / g_*$ roughly gives a correct answer, and the washing-out process is mostly not so effective. Note that this is the consequence from the current neutrino oscillation data as explained in \cite{8}.

The lepton asymmetry parameter $\epsilon$ has been evaluated by using the results of the minimal $SO(10)$ model \cite{7}, and the results are listed in the following table.

| $\tan \beta$ | $\epsilon$         |
|--------------|--------------------|
| 40           | $7.39 \times 10^{-5}$ |
| 45           | $6.80 \times 10^{-5}$ |
| 50           | $6.50 \times 10^{-5}$ |
| 55           | $11.2 \times 10^{-5}$ |

Unfortunately, the CP-violating parameter $\epsilon$ is too large to be consistent with the observed baryon asymmetry. In order to circumvent this problem we made use of another pair of $SU(2)$ doublets appearing in the minimal $SO(10)$ model. We solved the Boltzman equation and obtained the consistent $Y_B$ \cite{8}. However, in this case we need the extra Higgs doublets other than those in the MSSM, which may raise other problems. So it is worth considering an alternative solution to this overproduction. On the other hand, the gravitino problem forces us to use a low reheating temperature less than the mass of $M_{R1}$. If we believe this, the above problem becomes fake, since thermal $N_R$ are not generated in the reheating era. So the minimal $SO(10)$ model itself drives us to use other approaches such as non-thermal leptogenesis scenario \cite{21} or the Affleck–Dine mechanism \cite{22}. In the next section, we discuss the non-thermal leptogenesis scenario in the minimal $SO(10)$ model.

3. Non-thermal leptogenesis

Now we turn to the discussions of the non-thermal leptogenesis scenario \cite{21}. In the non-thermal leptogenesis scenario, the right-handed neutrinos are produced through the direct non-thermal decay of the inflaton.
Non-thermal leptogenesis and a prediction of inflaton mass in a supersymmetric \( SO(10) \) model

Here we give a concrete model to specify the inflaton. We add a singlet chiral supermultiplet which plays the role of an inflaton \( I \).\(^1\) The interaction Lagrangian relevant for the inflaton and the right-handed neutrinos is given by

\[
\mathcal{L}_I = -\frac{1}{2} \int d^2\theta \left( M_I I^2 + \sum_i \lambda_i I N_i^c N_i^c \right). \tag{9}
\]

When the inflaton gets a vacuum expectation value (VEV), it gives rise to the Majorana masses for the right-handed neutrinos in addition to the VEV of \([10, 1, 3] \) in \( \mathbf{126} \) under \( SU(4)_P \times SU(2)_{L,R} \)\(^6\). However, the VEV \( \langle I \rangle \) is posted around the GUT scale and \( \lambda_i \) is found to be \( 10^{-8} \) later, and this contribution gives a tiny correction to \( M_R \). Also the first term in equation (9) dominates over the second, and is reduced to the chaotic inflationary model \(^{24}\).

In such a superpotential, the inflaton decay rate is given by

\[
\Gamma(I \rightarrow N_i N_i) \approx \frac{|\lambda_i|^2}{4\pi M_I}. \tag{10}
\]

Then the consequently produced reheating temperature is obtained by

\[
T_R = \left( \frac{45}{2\pi^2 g_\ast} \right)^{1/4} (\Gamma M_P)^{1/2}. \tag{11}
\]

If the inflaton dominantly couples to \( N \), the branching ratio of this decay process is, of course, \( BR \sim 1 \). Then the produced baryon asymmetry of the universe can be calculated by using the following formula,

\[
\left( \frac{n_B}{s} \right) = -0.35 \times \left( \frac{n_{N_i}}{s} \right) \times \left( \frac{n_L}{n_{N_1}} \right) = -0.35 \times \frac{3}{2} BR(I \rightarrow N_1 N_1) \left( \frac{T_R}{M_I} \right) \times \epsilon. \tag{12}
\]

With the hierarchical mass spectra for the right-handed neutrinos, it can be approximated as

\[
\left( \frac{n_B}{s} \right) = -1.95 \times 10^{-10} \times BR \times \left( \frac{T_R}{10^6 \text{ GeV}} \right) \left( \frac{M_{R1}}{M_I} \right) \left( \frac{m_{\nu_3}}{0.065 \text{ eV}} \right) \times \delta_{\text{eff}}, \tag{13}
\]

where \( \delta_{\text{eff}} \equiv \text{Im}[(Y_\nu M_\nu^T Y_\nu)^{11}]/[m_{\nu_3}(Y_\nu Y_\nu^T)^{11}] \) denotes the effective value of the CP-violating phase parameter relevant for the leptogenesis, and it can be estimated as \( \delta_{\text{eff}} = -0.166 \) in our model. As can easily be seen, it is possible to produce the baryon asymmetry of the universe by using a reheating temperature as low as \( T_R \lesssim 10^6 \) GeV. Hence, a very wide range of the gravitino mass can be allowed, \( m_{3/2} \gtrsim 10^6 \) MeV. The result of the detailed numerical calculation based on equation (12) is shown in figure 1. As shown in figure 1(a), the predicted inflaton mass is heavier than the lightest right-handed neutrino \( (M_{R1} = 1.6 \times 10^{11} \text{ GeV}) \) in our model \(^7\). Hence the non-thermal leptogenesis

\(^1\) There is an alternative scenario in which we regard one of the scalar partners of the right-handed neutrinos as an inflaton \(^{23}\). But in this case, we obtained a reheating temperature \( T_R \sim 4 \times 10^{12} \) (GeV) that is too high for the weak scale gravitino. So it is driven by necessity to consider the other possibility like the model presented in this paper if we keep the gravitino mass at the weak scale.
Non-thermal leptogenesis and a prediction of inflaton mass in a supersymmetric SO(10) model

Figure 1. The predicted baryon asymmetry of the universe $Y_B = n_B/s$ as a function of the inflaton mass $M_I$ (GeV) with the reheating temperature $T_R = 10^6$ GeV and BR = 1. In (a), the vertical blue line represents the kinematical cut for the inflaton to have enough energy to decay, $E \geq 2M_{R1}$, i.e., the right-hand side of this line is allowed from the kinematics. Two horizontal green lines represent the upper and the lower bounds on the observed value of the baryon asymmetry at 95% C.L. (a) The lepton asymmetry parameter $\epsilon$ has been taken from [7]; (b) the lepton asymmetry parameter $\epsilon$ has been taken from [25].

is well workable. But using the model given in [25], it can be seen from figure 1(b) that the calculated inflaton mass is lighter than the lightest right-handed neutrino mass ($M_{R1} = 2.7 \times 10^{13}$ GeV), and the non-thermal leptogenesis scenario is prohibited by the kinematics. We hasten to add that this conclusion is valid under the non-thermal leptogenesis under the gravity-mediated SUSY-breaking scenario.

It can be read off from figure 1(a) that the observed value of the baryon asymmetry leads to an inflaton mass around $M_I \sim 5 \times 10^{11}$ GeV. This corresponds to the coupling constant of the inflaton to the right-handed neutrinos as $\lambda_i \sim 10^{-8}$. Such a small coupling indicates that the model can naturally fit into the chaotic inflationary model [24] based on a minimal supersymmetric SO(10) model.
4. Summary

In confronting the recent progress on the gravitino problem [15], the usual thermal leptogenesis scenario encounters some problems. In this paper, we have explored the non-thermal leptogenesis as an alternative scenario to the thermal one. We have estimated the baryon asymmetry of the universe based on a minimal supersymmetric SO(10) model with a type-I see-saw mechanism. The result of our analysis shows that the non-thermal scenario well works within the minimal SO(10) model, and we have found that an inflaton mass around $M_I \sim 5 \times 10^{11}$ GeV gives the observed value of the baryon asymmetry of the universe. In this analysis, we have used the reheating temperature $T_R = 10^6$ GeV, which was chosen so as to realize the weak scale gravitino mass $m_{3/2} \sim 100$ GeV without causing the gravitino problem. Even if these values are relaxed by one order of magnitude ($m_{3/2} \lesssim 10$ TeV, $T_R = 10^7$ GeV), the result is still valid.

In this paper, we have assumed that full thermalization occurs soon after the inflation. Although there is a discussion on this point [26], the main motivation of this paper is to give a quantitative estimation for the non-thermal leptogenesis scenario in the minimal SO(10) model. Therefore, we leave the consideration of thermalization processes for a future study.

Acknowledgments

The work of TF is supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan (No 16540269). He is also grateful to Professors D Chang and K Cheung for their hospitality at NCTS. The work of TK is supported by a Research Fellowship of the Japan Society for the Promotion of Science (No 7336).

References

[1] Giunti C, Kim C W and Lee U W, 1991 Mod. Phys. Lett. A 6 1745 [SPIRES]
Langacker P and Luo M X, 1991 Phys. Rev. D 44 817 [SPIRES]
Amaldi U, de Boer W and Furstenau H, 1991 Phys. Lett. B 260 447 [SPIRES]

[2] As early works before LEP experiments, see
Dimopoulos S, Raby S and Wilczek F, 1981 Phys. Rev. D 24 1681 [SPIRES]
Ibañez L E and Ross G G, 1981 Phys. Lett. B 105 439 [SPIRES]
Einhorn M B and Jones D R, 1982 Nucl. Phys. B 196 475 [SPIRES]
Marciano W and Senjanović G, 1982 Phys. Rev. D 25 3092 [SPIRES]

[3] Yanagida T, Horizontal gauge symmetry and masses of neutrinos, 1979 Proc. Workshop on the Unified Theory and Baryon Number in the Universe (KEK, Tsukuba) ed O Sawada and A Sugamoto
Gell-Mann M, Ramond P and Slansky R, The family group in grand unified theories, 1979 Supergravity ed D Freedman and P van Niewenhuizen (Amsterdam: North-Holland)
Mohapatra R N and Senjanović G, 1980 Phys. Rev. Lett. 44 912 [SPIRES]

[4] Fukugita M and Yanagida T, 1986 Phys. Lett. B 174 45 [SPIRES]
For a recent review, see for instance Buchmuller W, Peccei R D and Yanagida T, 2005 Preprint hep-ph/0502169

[5] Eidelman S et al (Particle Data Group), 2004 Phys. Lett. B 592 1 [SPIRES]

[6] Matsuda K, Koide Y and Fukuyama T, 2001 Phys. Rev. D 64 053015 [SPIRES]
Matsuda K, Koide Y, Fukuyama T and Nishiura H, 2002 Phys. Rev. D 65 033008 [SPIRES]

[7] Fukuyama T and Okada N, 2002 J. High Energy Phys. JHEP11(2002)011 [SPIRES] [hep-ph/0205066]

[8] Fukuyama T and Okada N, 2002 Mod. Phys. Lett. A 17 1725 [SPIRES] [hep-ph/0202214]

[9] Fukuyama T, Kituchi T and Okada N, 2003 Phys. Rev. D 68 033012 [SPIRES] [hep-ph/0304190]
Non-thermal leptogenesis and a prediction of inflaton mass in a supersymmetric $SO(10)$ model

[10] Fukuyama T, Ilakovac A, Kikuchi T, Meljanac S and Okada N, 2004 J. High Energy Phys. JHEP09(2004)052 [SPIRES] [hep-ph/0406068]

[11] Babu K S and Mohapatra R N, 1993 Phys. Rev. Lett. 70 2845 [SPIRES]

[12] Weinberg S, 1982 Phys. Rev. Lett. 48 1303 [SPIRES]

[13] Khlopov M Y and Linde A D, 1984 Phys. Lett. B 138 265 [SPIRES]

[14] See for instance Roszkowski L and Ruiz de Austri R, 2004 Preprint hep-ph/0408227

[15] Kawasaki M, Kohri K and Moroi T, 2004 Preprint astro-ph/0402490

[16] Covi L, Roulet E and Vissani F, 1996 Phys. Lett. B 384 169 [SPIRES]

[17] Buchmuller W and Yanagida T, 1999 Phys. Lett. B 445 399 [SPIRES]

[18] Plamauer M, 1997 Z. Phys. C 74 549

[19] Luty M A, 1992 Phys. Rev. D 45 455 [SPIRES]

[20] Kolb E W and Wollfram S, 1980 Nucl. Phys. B 172 224 [SPIRES]

[21] Lazarides G and Shafi Q, 1991 Phys. Lett. B 258 305 [SPIRES]

[22] Affleck I and Dine M, 1985 Nucl. Phys. B 249 361 [SPIRES]

[23] Fukuyama T and Kikuchi T, 2005 J. High Energy Phys. JHEP05(2005)017 [SPIRES] [hep-ph/0412373]

[24] Linde A, 1983 Phys. Lett. B 129 177 [SPIRES]

[25] Dutta B, Mimura Y and Mohapatra R N, 2004 Phys. Rev. D 69 115014 [SPIRES] [hep-ph/0402113]

[26] Allahverdi R and Mazumdar A, 2005 Preprint hep-ph/0505050