Neutrinos masses in the Supersymmetric $B - L$ model with three non-identical right-handed neutrinos.

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Abstract

We build a supersymmetric version with $SU(2)_L \otimes U(1)_{Y'} \otimes U(1)_{B-L}$ where the three right-handed neutrinos have non identical $B - L$ charges in the superfield formalism. We calculate the masses to all usual leptons of this model at the tree level.

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1 Introduction

The generation of neutrino masses is an important issue in any realistic extension of the standard model (SM) and in general, the values of these masses that are needed to explain all neutrino oscillation data are not enough to put strong constraints on model building. It means that several models can induce neutrino masses and mixing compatible with experimental data [1]. So, instead of proposing models built just to explain the neutrino properties, it is more useful to consider what are the neutrino masses that are predicted in any particular model which has motivation other than the explanation of neutrino physics.

Recently, it was proposed an interesting model where the symmetry $U(1)_{B-L}$ where we introduce three right-handed neutrinos must be added to the matter representation content. Explicit solutions for the $B - L$ parameters show that at least two types of model arise: i) the model with three right-handed neutrinos having $B - L = -1$; ii) the model with two right-handed neutrinos having $B - L = -4$ and the third one having $B - L = 5$ [2].

The supersymmetric version of this model with three identical neutrinos was presented in Ref. [3]. In this article we are going to present the supersymmetric version for this kind of model with three non identical neutrinos where two right-handed neutrinos having $B - L = -4$ and the third one having $B - L = 5$ [2].

The outline of this paper is as follows: In Sec.(2) we present the model, in Sec.(3) we define a $R$-Parity in such way that neutrinos and neutralinos are distinguish particles. At Sec.(4) we present the lagrangian of this model in the superfield formalism and after it we calculate the masses to the all usual leptons and at the end we present our conclusions.
2 The Model.

The symmetry in this model is

$$SU(2)_L \otimes U(1)_{Y'} \otimes U(1)_{B-L},$$

and the charge operator is given by

$$Q = I_3 + \frac{1}{2} [Y' + (B - L)].$$

We also assume that $L$ assignment is restricted to the integer numbers, the anomaly cancellation imply only three right-handed neutrinos can be added to the minimal representation of SM.

We will build the supersymmetric case of the three non identical neutrinos and we will not discuss the quarks because, they are the same as presented at [2, 3, 4].

We start introducing the leptons of our model, as usual in supersymmetric models, in the following chiral superfields ($i=1,2,3$, is a familly indices):

$$\hat{L}_{iL} = \left( \begin{array}{c} \hat{\nu}_i \\ \hat{l}_i \end{array} \right)_L \sim (2,0,-1), \quad \hat{E}_{iR} \sim (1,1,1),$$

in parenthesis it appears the transformations properties under the respective factors ($SU(2)_L, U(1)_{Y'}, U(1)_{B-L}$).

We will introduce three right-handed (they are also known as “Sterile Neutrinos”, for more detail see 5.) neutrinos

$$\hat{N}_{1R} \sim (1,5,-5), \quad \hat{N}_{\beta R} \sim (1,-4,4),$$

where $\beta = 2,3$.

The Higgs sector of this model, we have the usual doublet $\hat{H}_{1,2}$

$$\hat{H}_1 = \left( \begin{array}{c} \hat{h}^+_1 \\ \hat{h}^0_1 \end{array} \right) \sim (2,1,0), \quad \hat{H}_2 = \left( \begin{array}{c} \hat{h}^0_2 \\ \hat{h}^-_2 \end{array} \right) \sim (2,-1,0),$$

while their vev as usual are given by:

$$\langle H_1 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle H_2 \rangle = \frac{v_2}{\sqrt{2}}.$$

We need to enlarge the scalar doublet sector adding four new scalars

$$\hat{\phi}_1 = \left( \begin{array}{c} \hat{\phi}^0_1 \\ \hat{\phi}^-_1 \end{array} \right) \sim (2,5,-6), \quad \hat{\phi}_1' = \left( \begin{array}{c} \hat{\phi}^+_1 \\ \hat{\phi}^0_1 \end{array} \right) \sim (2,-5,6),$$

$$\hat{\phi}_2 = \left( \begin{array}{c} \hat{\phi}^0_2 \\ \hat{\phi}^-_2 \end{array} \right) \sim (2,-4,3), \quad \hat{\phi}_2' = \left( \begin{array}{c} \hat{\phi}^+_2 \\ \hat{\phi}^0_2 \end{array} \right) \sim (2,4,-3).$$

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The vevs of the new scalars can be written in the following form:

\[ \langle \Phi_1 \rangle = \frac{u_1}{\sqrt{2}}, \langle \Phi'_1 \rangle = \frac{u'_1}{\sqrt{2}}, \langle \Phi_2 \rangle = \frac{u_2}{\sqrt{2}}, \langle \Phi'_2 \rangle = \frac{u'_2}{\sqrt{2}}. \] (8)

In order to obtain an arbitrary mass matrix for the neutrinos we have to introduce the following additional singlet

\[ \hat{\varphi}_1 \sim (1, 8, -8), \quad \hat{\varphi}_2 \sim (1, -10, 10). \] (9)

The vevs of the new scalars can be written in the following form:

\[ \langle \varphi_1 \rangle = \frac{w_1}{\sqrt{2}}, \langle \varphi_2 \rangle = \frac{w_2}{\sqrt{2}}. \] (10)

We could introduce

\[ \hat{\varphi}_3 \sim (1, -1, 1), \] (11)

and this new scalar would induce mixing in the neutrinos sector, we can avoid this term with R-Parity, as we will discuss at Sec.(3) and Eq.(23).

Concerning the gauge bosons and their superpartners, they are introduced in vector superfields. See Table 1 the particle content together with the gauge coupling constant of each group.

| Group    | Vector | Gauge | Gaugino | Auxiliar | constant |
|----------|--------|-------|---------|----------|----------|
| SU(2)_L  | W_i    | W'    | W'      | D_W      | g        |
| U(1)_Y_  | b_Y    | b_Y'  | b_Y'    | D_Y'     | g_Y'     |
| U(1)_B-L | b_BL   | b_BL  | b_BL    | D_BL     | g_BL     |

Table 1: Information on fields contents of each vector superfield of this model and their gauge constant.

These are the minimal fields, we need to construct this supersymmetric model.

### 3 R-Parity.

Let us begin defining the R-parity in the model with the particle content listed above. We define at Tab.(2) the R-charge (n_Φ) of each superfield in our model. Using these R-charges we can get the R-Parity of each fermion field contained in these chiral superfield these results we shown at Tab.(3).

The connection between R-parity, spin (S), baryon number (B) and lepton number (L) conservation laws can be made explicitly by writing

\[ \text{R-parity} = (-1)_S^2(-1)^{3(B-L)}. \] (12)

Therefore the R-parity is conserved as a consequence of the B − L symmetry.

\footnote{Here Φ means chiral superfield as defined at \[7, 8, 9\].}
| Superfield | $L_iL$  | $E_iR$  | $N_{1R}$ | $N_{\beta R}$ | $S$  |
|------------|--------|--------|----------|--------------|-----|
| $R-$ charge | $n_L = (1/2)$ | $n_E = (-1/2)$ | $n_{N_1} = (1/2)$ | $n_{N_\beta} = 0$ | $n_S = 0$ |

Table 2: Information about the $R$-charge ($n_\Phi$) of all the chiral superfields of this model, our notation here $S = H_{1,2}, \Phi_{1,2}, \Phi'_{1,2}, \varphi_{1,2}$.

| $(B - L)$ | $-5$ | $4$ | $-6$ | $6$ | $3$ | $-3$ | $-8$ | $10$ |
|------------|------|-----|-----|----|---|-----|----|----|
| Fermion $N_{1R}$ | $-1$ | $-1$ | $-1$ | $-1$ | $-1$ | $-1$ | $-1$ | $-1$ |
| $R-$ Parity | $+1$ | $+1$ | $+1$ | $+1$ | $+1$ | $+1$ | $+1$ | $+1$ |

Table 3: Information about the $B - L$ quantum number and $R$-Parity of new fields, fermions and scalars, of this model.

4 The Lagrangian

With the superfields presented at Sec.(2), we can built a supersymmetric invariant lagrangian in the superfield formalism [7]. It has the following form

$$L = L_{SUSY} + L_{soft}.$$ (13)

Here, as usual, $L_{SUSY}$ is the supersymmetric piece, see Sec.(4.1), while $L_{soft}$ explicitly breaks SUSY, see Sec.(4.2).

4.1 The Supersymmetric Term.

We can rewrite each term appearing in Eq.(13), in the following way

$$L_{SUSY} = L_{lepton} + L_{scalar} + L_{gauge} + L_{quark},$$ (14)

the last two terms above, $L_{gauge}, L_{quark}$, are the same as presented at the supersymmetric model with three identical neutrinos presented in [3].

The first term, $L_{lepton}$, written at Eq.(14) is given by:

$$L_{lepton} = \left[ \int d^4 \theta \left( L_{\text{char}}^{N_1} + L_{\text{char}}^{N_\beta} \right) \right],$$ (15)

where we have defined

$$L_{\text{char}}^{N_1} = \sum_{i=1}^{3} \left[ \tilde{L}_{iL} \tilde{e}_{2}[g_W + g_{BL}(-\frac{1}{2})]b_{BL} L_{iL} + \tilde{E}_{iL} \tilde{e}_{2}[g_{Y'}(\frac{5}{2})]b_{Y'} + g_{BL}(\frac{5}{2})]b_{BL} E_{iL} \right],$$

$$L_{\text{char}}^{N_\beta} = \tilde{N}_{1L} \tilde{e}_{2}[g_{Y'}(\frac{5}{2})]b_{Y'} + g_{BL}(\frac{5}{2})]b_{BL} N_{1L},$$

$$L_{\text{char}}^{N_\beta} = \sum_{\beta=2}^{3} \tilde{N}_{\beta L} \tilde{e}_{2}[g_{Y'}(\frac{5}{2})]b_{Y'} + g_{BL}(\frac{5}{2})]b_{BL} N_{\beta L}.$$
In the expressions above we have used $\hat{W} = T^a \hat{W}^a$ where $T^a = \sigma^a / 2$ (with $a = 1, 2, 3$) are the generators of $SU(2)_L$ while $g_Y$ and $g_B$ are the gauge constant constants of the $U(1)_Y$ and the $U(1)_{B-L}$ and those gauge coupling constants are related by the following relation

$$\frac{1}{g_Y^2} = \frac{1}{g_Y^2} + \frac{1}{g_B^2},$$

(17)

as presented at \[2, 3\].

The second term $L_{\text{scalar}}$, written at Eq.(14), is rewritten in following way

$$L_{\text{scalar}} = \left[ \int d^4\theta \left( L^{H_1, H_2} + L^\phi + L^\sigma \right) \right] + \left( \int d^2\theta W + hc \right),$$

(18)

where we have defined

$$L^{H_1, H_2} = \hat{H}_1 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{H}_1 + \hat{H}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{H}_2,$$

$$L^\phi = \hat{\phi}_1 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\phi}_1 + \hat{\phi}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\phi}_2 + \hat{\phi}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\phi}_1 + \hat{\phi}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\phi}_2,$$

$$L^\sigma = \hat{\sigma}_1 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\sigma}_1 + \hat{\sigma}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\sigma}_2 + \hat{\sigma}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\sigma}_1 + \hat{\sigma}_2 e^{2[g_{Y'}+g_{Y'}(\hat{2})]b_{Y'}+g_{B}b_{BL}} \hat{\sigma}_2.$$  

(19)

$W$ is the superpotential of this model.

### 4.1.1 The Superpotential

The superpotential of our model is given by

$$W = \frac{W_2}{2} + \frac{W_3}{3},$$

(20)

where

$$W_2 = \mu_H \left( \hat{H}_1 \hat{H}_2 \right) + \mu_{\Phi_1} \left( \hat{\Phi}_1 \hat{\Phi}_1' \right) + \mu_{\Phi_2} \left( \hat{\Phi}_2 \hat{\Phi}_2' \right),$$

(21)

Remember $\left( \hat{H}_1 \hat{H}_2 \right) \equiv \epsilon_{\alpha\beta} H_1^\alpha H_2^\beta$ is the usual doublet contraction as done in the MSSM. The free parameter $\mu_H, \mu_{\Phi_1}, \mu_{\Phi_2}$ are, in general, complex numbers and we can have CP violation interactions \[3, 4\].

The case of three chiral superfields the terms are\[3\]

$$W_3 = \sum_{i=1}^3 \sum_{j=1}^3 f_{ij}^L (\hat{H}_2 \hat{L}_{iL}) \hat{E}_{jR} + f_{i}^\nu (\hat{\Phi}_1' \hat{L}_{iL}) \hat{N}_{1R} + \sum_{\beta=2}^3 f_{i\beta}^N (\hat{\Phi}_2' \hat{L}_{iL}) \hat{N}_{\beta R}$$

$$+ f^N \hat{\phi}_2 \hat{N}_{1R} \hat{N}_{1R} + \sum_{\alpha, \beta=2}^3 f_{\alpha \beta}^N \hat{\phi}_1 \hat{N}_{\alpha R} \hat{N}_{\beta R}.$$  

(22)

\[3\] The terms with quarks were omitted but they are the same ones given at \[3\].
In general all the Yukawa terms defined above are complex numbers; they are symmetric in $ij$ exchange and they are dimensionless [8, 9].

We see that the neutrinos $N_1$ and $N_\beta$, their $B-L$ quantum number are not equal and they have opposite $R$-parity, therefore we can not introduce the following term

$$\bar{\phi}_3 \tilde{N}_{1R} \tilde{N}_{\beta R},$$

because it will violate our $R$-Parity introduced at Sec.(3).

The superpotential, defined at Eq.(20), forbid the term like $\hat{u} \hat{d} \hat{d}$ it is good because they generate the following processes, at tree-level, that contributes to the nucleon instability:

1. proton decay;
2. neutron-antineutron oscillation.

Leptogenesis [10] is a term for a scenario where new physics generates a lepton asymmetry in the Universe which is partially converted to a baryon asymmetry. In the review [11] we learned that the introduction of singlet neutrinos with Majorana masses and Yukawa couplings to the doublet leptons fulfills Sakharov conditions. Then we can expected in explain the matter asymmetry with this new model as done in [10, 12].

### 4.2 Soft Terms

The soft terms, as defined at [13], are given by:

$$L_{soft} = L_{GMT} + L_{SMT} + L_{Int},$$

where

$$L_{GMT},$$ known as gaugino mass term, is identical as presented at [3].

The term $L_{SMT},$ known as scalars mass term, is given by:

$$L_{SMT} = - \left( \sum_{i=1}^{3} \left[ M_L^2 |\tilde{L}_i|^2 + M_{\tilde{E}}^2 |\tilde{E}_i|^2 \right] + \sum_{\beta=2} M_{N_\beta}^2 |\tilde{N}_\beta|^2 \right)
+ \left[ M_L^2 |H_1|^2 + M_{H_1}^2 |H_2|^2 + M_{\bar{\Phi}}^2 |\Phi_1|^2 + M_{\bar{\Phi}'}^2 |\Phi_1'|^2 + M_{\bar{\Phi}_2}^2 |\Phi_2|^2 + M_{\bar{\Phi}_2'}^2 |\Phi_2'|^2 \right] + \left[ \beta_H (H_1 H_2) + \beta_{\Phi_1} (\Phi_1 \Phi_1') + \beta_{\Phi_2} (\Phi_2 \Phi_2') + hc \right],$$

where $|H_1|^2 \equiv H_1^\dagger H_1$ and we can redefine

$$\beta_H = B_H \mu_H, \quad \beta_{\Phi_1} = B_{\Phi_1} \mu_{\Phi_1}, \quad \beta_{\Phi_2} = B_{\Phi_2} \mu_{\Phi_2}.$$
Notice that in the last line at equation above has the same term as introduced at Eq.\((21)\) with the the Chiral Superfield replaced by their scalars.

Before we continue, it is useful to remember that the scalar mass terms \(M^2_L\) and \(M^2_l\) are in general hermitean \(3\times3\) matrices in generation space \([8, 9]\). It is very well known that the SUSY flavor problem occurs because the transformation that diagonalizes the fermion mass matrix does not simultaneously diagonalize the corresponding sfermion mass squared matrices.

The last term defined at Eq.\((24)\), \(\mathcal{L}_{\text{Int}}\) has the same term as introduced at Eq.\((22)\) with the the Chiral Superfield replaced by their scalars, is written as

\[
\mathcal{L}_{\text{Int}} = \left\{ \sum_{i=1}^{3} \sum_{j=1}^{3} A_{ij}^f f_{ij}^l \left( H_2 \tilde{L}_iL \right) \tilde{E}_jR + A_{11}^\nu f_{1}^\nu \left( \Phi'_1 \tilde{L}_iL \right) \tilde{N}_{1R} \right. \\
+ \sum_{\beta=2}^{3} A_{i\beta}^\nu f_{1\beta}^l \left( \Phi'_2 \tilde{L}_iL \right) \tilde{N}_{1\beta} + A_{11}^M f^N \varphi_2 \tilde{N}_1 \tilde{N}_1 \\
+ \sum_{\alpha=2}^{3} \sum_{\beta=2}^{3} A_{\alpha\beta}^N f_{\alpha\beta}^N \varphi_1 \tilde{N}_\alpha \tilde{N}_\beta + h\text{c} \right\}. \tag{27}
\]

The \(A\)-terms are known to play an important role in Affleck-Dine baryogenesis \([14]\), as well as in the inflation models based on supersymmetry \([15, 16, 17]\).

5 Charged Fermion Masses

The masses of the charged leptons is given by:

\[
f_{ij}^l h_{i}^{0} l_i E_j + h\text{c}. \tag{28}\]

This expression is using Weyl-spinors. We are going to define the following Dirac four components spinors

\[
\mathcal{E}_a = \begin{pmatrix} l_a \\ E_a \end{pmatrix}, \tag{29}\]

where \(a = e, \mu, \tau\) means the physical eigenstates while \(i = 1, 2, 3\) are the symmetry eigenstates and thei are relationed by

\[
l_a = V_{a1}^l l_i, \quad E_a = V_{a1}^R E_i. \tag{30}\]

Using the spinors defined at Eq.\((29)\) the mass term become

\[
M^l_{i\alpha} \tilde{\mathcal{E}}_{aR} \mathcal{E}_{aL} + h\text{c}. \tag{31}\]

where \(M^l_{i\alpha} = \text{diag}(m_e, m_\mu, m_\tau)\) is the diagonal mass matrix of the charged leptons.
5.1 Neutrino masses

The terms contributing to the neutrino masses are:

\( - \left[ f_1^\nu (\Phi_1^L L_{1L}) N_{1R} + f_2^\nu N (\Phi_2^L L_{1L}) N_{\beta R} + f_3^N \varphi_2 N_{1R} N_{1R} + f_4^N \varphi_1 N_{\alpha R} N_{\beta R} + h c \right] \). (32)

The first two terms give Dirac masses term, while the last two terms give Majorana masses terms to the neutrinos.

Using the base

\( \Psi^0 = (\nu_1 L \nu_2 L \nu_3 L N_{1R} N_{2R} N_{3R})^T \),

we can write the mass matrix to neutrino as

\( \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \), (34)

and we see that this matrix generates the type I seesaw mechanism [?]. The mass matrix leads to the following mass, for light \( M_L^\nu \) and heavy \( M_P^\nu \), neutrinos we can write the following expressions

\( M_L^\nu \approx - (M_D)^T (M_M)^{-1} M_D, \quad M_P^\nu \approx M_M \). (35)

Using angle \( \Xi \) defined as

\( \tan \Xi = \frac{u_{12}'}{u_1'} \),

we can write \( M_D \) in the following way

\( M_D = \frac{u_1'}{2\sqrt{2}} \begin{pmatrix} f_1^\nu & f_{12}^N \tan \Xi & f_{13}^N \tan \Xi \\ f_{21}^\nu & f_{22}^N \tan \Xi & f_{23}^N \tan \Xi \\ f_{31}^\nu & f_{32}^N \tan \Xi & f_{33}^N \tan \Xi \end{pmatrix} \), (37)

if \( \Xi = (\pi/2) \) rad our matrix is identical to the \( M_D \) presented at Ref. [6].

In order to write \( M_M \), first we have to defined \( \Gamma, \Omega \) though the following ratios

\( \tan \Gamma = \frac{w_1}{u_1}, \quad \tan \Omega = \frac{w_2}{u_1} \), (38)

using these new parameters we get

\( M_M = \frac{u_1'}{2\sqrt{2}} \begin{pmatrix} f_N \tan \Omega & 0 & 0 \\ 0 & f_{22}^N \tan \Gamma & f_{23}^N \tan \Gamma \\ 0 & f_{32}^N \tan \Gamma & f_{33}^N \tan \Gamma \end{pmatrix} \), (39)

our matrix is identical to the \( M_M \) presented at Ref. [6].

We can conclude our model is also compatible with the observed solar and atmospheric mass scales and the tribimaximal mixing matrix, for more details see Ref. [6], their Sec.IV.
6 Conclusions

We presented the Supersymmetric version of the model with three distinctics right handed neutrinos presented at [2]. This model has some interesting facts such as we can generate neutrinos masses via see-saw mechanism; they preserve the $R$-parity, therefore the neutrinos and neutralinos are distinct particles and due this fact the lightest supersymmetric particle (LSP) is stable and the particles are pair produced in any collider experiment and it is also a good candidate for Dark Matter in Universe; we can generate a viable Leptogenesis scenario due the Majorana phases in the sneutrino mass matrix that will induce the decay of Heavy Neutrinos in leptons plus usual scalars generating in this way more leptons than antileptons. We think that these models have some nice predictions that could be explored in the near future.

References

[1] M. C. Rodriguez and I. V. Vancea, arXiv:1603.07979 [hep-ph].
[2] J. C. Montero and V. Pleitez, Phys. Lett. B675, 64, (2009).
[3] J. C. Montero, V. Pleitez, M. C. Rodriguez and B. L. Sánchez-Vega, arXiv:1609.08129 [hep-ph].
[4] A. C. B. Machado and V. Pleitez, Phys. Lett. B698, 128, (2011).
[5] R. R. Volkas, Prog. Part. Nucl. Phys. 48, 161, (2002); [hep-ph/0111326].
[6] J. C. Montero and B. L. Sánchez-Vega, Phys. Rev. D84, 053006, (2011).
[7] J. Wess and J. Bagger, Supersymmetry and Supergravity, 2nd edition, Princeton University Press, Princeton NJ, (1992).
[8] M. Drees, R. M. Godbole and P. Roy, Theory and Phenomenology of Particles, 1st edition, World Scientific Publishing Co. Pte. Ltd., Singapore, (2004).
[9] H. Baer and X. Tata, Weak Scale Supersymmetry, 1st edition, Cambridge University Press, United Kingdom, (2006).
[10] J. Pelto, I. Vilja and H. Virtanen, Phys. Rev. D83, 055001, (2011).
[11] Y. Nir, [hep-ph/0702199].
[12] S. Iso, N. Okada and Y. Orikasa, arXiv:1011.4769 [hep-ph].
[13] L. Girardello and M. T. Grisaru, Nucl. Phys. B194, 65, (1982).
[14] M. Dine, L. Randall and S. Thomas, Phys. Rev. Lett. 75, 398, (1995); M. Dine, L. Randall and S. Thomas, Nucl. Phys. B458, 291, (1996); T. Gherghetta, C. Kolda and S. P. Martin, Nucl. Phys. B468, 37, (1996).
[15] R. Allahverdi, K. Enqvist, A. Jokinen and A. Mazumdar, *JCAP* **0610**, 007, (2006).

[16] R. Allahverdi, K. Enqvist, J. Garcia-Bellido and A. Mazumdar, *Phys. Rev. Lett.* **97**, 191304, (2006).

[17] D. H. Lyth, arXiv:hep-ph/0605283; R. Allahverdi and A. Mazumdar, arXiv:hep-ph/0610069