Baryogenesis through $R-$parity violation

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Abstract

We consider generation of baryon asymmetry of the universe through $R-$parity violation in a scenario in which out-of-equilibrium condition is satisfied by making the electroweak phase transition to be first order. We study all the $R-$parity violating interaction which can generate $(B-L)$ asymmetry which then converts to baryon asymmetry of the universe. We demonstrate that CP–violating sfermion decays contribute more than that of the neutralino decays in the generation of $(B-L)$ asymmetry.

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1 Introduction

The baryon asymmetry of the universe [1] can be generated at a very high energy, but in most likelyhood it will be washed out at a later stage [2, 3]. So a great deal of interest started in scenarios where the baryon asymmetry is generated during the electroweak phase transition [4, 5, 6]. The most popular one tries to generate the baryon asymmetry in the standard model or its minimal extension with two higgs doublets, where the electroweak phase transition is required to be a weakly first order. The anomalous baryon number violation [2] in the standard model due to quantum effect becomes very fast at the electroweak scale in the presence of the sphaleron fields[3]. There is provision for enough $CP-$violation in the two higgs doublet models. Out-of-equilibrium condition is satisfied by making the phase transition to be first order. However, the condition that after the electroweak phase transition this asymmetry will not be washed out constrains these models most severely [7]. This requires the higgs mass to be less than about 80 GeV. So if the experimental lower bound on the higgs mass is increased beyond this value, then this scenario will fail to explain baryogenesis.

Another interesting scenario has recently been proposed by Masiero and Riotto [8], where they also generate baryon asymmetry at around the time of electroweak phase transition. They work in the context of supersymmetric model. They first generte lepton number asymmetry through R-parity violating decays of the lightest neutralino. Interference of the tree level diagram and the one loop diagram with superparticles in the loop gives rise to rephasing invariant $CP-$violation in this model. The out-of-equilibrium condition is satisfied by considering the electroweak symmetry breaking phase transition to be first order. Unlike the other class of models [4, 5, 6], here the anomalous baryon number violation converts the lepton number asymmetry [9, 10] (and hence $(B-L)$ asymmetry) to baryon asymmetry during the electroweak phase transition. As a result anomalous baryon number violation is required to be present even after the electroweak phase transition and hence there is no upper bound on the higgs mass.

In this model since lepton number asymmetry is generated at the electroweak scale, the bounds [11] on the mass of the heavy right handed neutrinos from baryogenesis, which arise from the decay of these particles are not valid. The direct bound on the masses of the left-handed neutrinos and the bound on the right handed neutrinos arising from the scattering processes involving the right handed neutrinos are still valid [12]. Otherwise the lepton asymmetry generated by the decay of neutralinos or sfermions would be washed out by these processes before they are converted to baryon asymmetry.

In this article we point out that in addition to the lightest neutralino, the sfermions can also contribute to the generation of the lepton asymmetry and hence baryon asymmetry of the universe in the model of ref. [8]. We assume that the sfermions are not too heavy compared to the mass of the lightest neutralino. As a result when the neutralinos are generated through the decay of the false vacuum, it also produces sfermions, which in turn, contributes to the generation of baryon asymmetry. We shall not repeat the details of the model [8]. We shall study all possible diagrams which can generate lepton number asymmetry in the $R-$parity violating models and hence can contribute to the generation of the baryon asymmetry.

In the next section we review the model in brief pointing out how the decay of the sfermions can contribute to the generation of baryon asymmetry. In the following section we describe all the diagrams contributing to the generation of lepton asymmetry in this scenario. The amplitudes for these diagrams are then computed and it is shown that in many cases the contribution of the decay of the superparticles are more than that of the lightest neutralino. We then summarize our result in the last section.

2 The Model

In this section we shall describe only the relevant features of the model of ref. [8] in brief and then point out why the decay of the sfermions can also contribute to the generation of the baryon asymmetry of the universe. The electroweak phase transition is assumed to be first order. This means that if T_0 is the temperature at which the potential is flat at the origin, and $v(T_0)$ is the vacuum expectation value (*vev*) of the lightest higgs at $T = T_0$, then $v(T_0)/T_0$ is non-zero. Supersymmtry is broken at a scale much larger than the electroweak symmetry breaking scale. As a result only one combination of the higgs fields (h) remains light, whose *vev* breaks the electroweak symmetry.

In this case baryogenesis is not generated before the electroweak phase transition is over. $(B - L)$ asymmetry is generated from a lepton number violating (through $R-$parity violation) decay of neutralinos or sfermions. Due to anomalous baryon number violation this $(B - L)$ asymmetry will be converted to baryon asymmetry of the universe. In models where baryon number is generated using anomalous baryon number violation, it generates $(B + L)$ asymmetry. Since any $(B + L)$ asymmetry is then washed out by the anomalous baryon number violation, they require that anomalous baryon number violation after the electroweak phase transition is too weak to wash out the generated baryon asymmetry of the universe. In the present model under discussion the generated $(B - L)$ asymmetry is not washed out by anomalous baryon number violation and hence even after the electroweak phase transition anomalous electroweak baryon number violation should be present, and there is no lower bound on $v(T_0)/T_0$. Because of this the generated baryon asymmetry will not be washed out soon after the electroweak phase transition and hence there is no lower bound on the higgs mass.

At a very high temperature compared to the electroweak phase transition temperature, there is only one phase and the universe is in the symmetric phase. At the critical temperature T_c, the free energy of the $SU(2)_L \times U(1)_Y$ broken phase is same as the symmetry restored phase, and both the vacuum co-exist. However, at this temperature the phase transition does not occur since the tunnelling probability through the barrier is very small. The phase transition takes place at a temperature $T_0 < T_c$, when the bubbles of true vacuum start growing very fast and the barrier separating the two phases nearly vanishes. During this time the bubbles collide releasing energy, which produces particles with a distribution far from equilibrium. This means that although the lepton number violating intraction is otherwise in equilibrium at the electroweak phase transition temperature (T_0), the out-of-equilibrium distribution of the particles allows to generate enough lepton asymmetry if there is $CP-$violation.

Taking the co-efficient of the quartic term in the light neutral higgs boson h to be of the order of $\lambda_T \sim 10^{-2}$ the bubble nucleation temperature (T_0)will be about 150 GeV for a higgs mass of about 100 GeV. Because of the difference between the false and the true vacuum energy densities (ρ_v), the false vacuum ($\langle h \rangle = 0$) will decay and the bubbles with true vacuum will expand very fast at temperature $T < T_0$. When these bubbles collide, the energy releases through direct particle production due to quantum effects. In ref [8] it was considered that at this stage only the neutralinos will be generated and their distribution will be far from equilibrium. However, as we shall argue, since in many supersymmetric models the masses of the other sfermions are comparable, all these sfermions may also be produced when the bubbles collide. Since all these particles have decayed away long before the nucleation temperature T_0, the number density of the particles produced in this process are very low and far from equilibrium. Depending on the mass of these particles, the number density will be suppressed. This suppression is only logarithmic and hence slightly heavier particles will also be produced along with the lightest neutralinos almost in equal number. As a result, in these models if there are other lepton number violating interactions which also allows enough $CP-$violation, then they can also contribute to the generation of lepton number asymmetry. In fact, if the mass of the neutralinos are not too small compared to the sfermions, then the lepton number asymmetry generated through the decay of the sfermions can be much larger than the lepton number asymmetry generated by the decay of the neutralinos.

If f_q fraction of particles of type q is produced during a bubble collision, then the number density of q particles produced in the collision would be,

$$n_q \approx \frac{f_q \rho_v \Delta}{\gamma} \tag{1}$$

where, $\Delta \approx 6\sqrt{2}(\lambda_T/\alpha T_0)$ is the size of the wall moving with a velocity v_w and $\gamma \approx (1 - v_w^2)^{-1/2}$. An estimate of f_q is given in ref [8] to be,

$$f_q \approx g_q^4 \ \ln\left(\frac{\gamma}{2\Delta m_q}\right). \tag{2}$$

where, g_q is the Yukawa coupling constants for the higgs with the fermions of species q. With this estimate of the number density of the particle of type q produced in the collision it is possible to calculate the amount of lepton number asymmetry generated from the decay of these particles of species q.

From this expression one can guess that it is possible to create particles of mass upto $\frac{1}{2}\gamma\Delta^{-1}$ when energy is released during the collision of bubbles. In ref. [8] the mass of the lightest neutralino has been taken to be about 500 GeV, for the choice of parameters considered. However, while assuming an order of magnitude of λ_T a factor of two is not very crucial and hence particles of masses of about 1 TeV are equally probable. In most supersymmetric models it is assumed that several of the sfermions will have mass less than 1 TeV. All these particles will then be created when energy is released during the collision of bubbles after the nucleation temperature (T_0).

Let us assume that CP is violated in the decay of these particles q, and the amount of CP violation is ϵ_L^q. Then the total amount of lepton asymmetry created when these particles q are created in collisions and then they decay is,

$$\frac{n_L}{s} = \frac{45}{2} \frac{\epsilon_L^q n_q}{\pi^2 g_* T_0^3}. \tag{3}$$

Taking $\alpha \sim 10^{-2}$, $\gamma \sim 10^2$, $g_* \sim 10^2$ and $\lambda_T \sim 10^{-2}$, one obtains

$$\frac{n_L}{s} \approx 10^{-5} \epsilon_L^q \tag{4}$$

The logarithmic suppression factor due to the mass difference of the lightest neutralino and the other sfermions are almost negligible. Thus depending on the couplings of the sfermions and the amount of CP violation in their decay, the other superparticles can generate more lepton asymmetry than the amount generated by the lightest neutralino. In fact, as we shall show although the neutralino decays can generate barely enough lepton asymmetry, the sfermion decay can generate quite large lepton asymmetry, which makes this model more attractive.

3 Lepton asymmetry in decays of sfermions

We shall now list all the lepton number violating $R-$parity violating decays of the sfermions, which can interfere with suitable one loop diagram, which allows $CP-$violation and also an imaginary integral. For this purpose we shall not include processes, in which the decay products are any superparticles or other heavy particles like the right handed neutrino. The decaying particles are taken to be the sfermions, which, through their decay to light quarks and leptons generate lepton asymmetry if there is enough $CP-$violation. There is always another sfermion in the loop to ensure the absorptive part of the diagram to be non-vanishing. Lepton number is violated in all these decays through $R-$parity violation. These leaves us with not too many choices for the tree level and the one loop diagrams contributing to the generation of lepton asymmetry. These diagrams are presented in figs [1-8].

We start with the $R-$parity violating part of the superpotential,

$$W = \lambda_{ijk} L^i L^j \left(E^k\right)^c + \lambda'_{ijk} L^i Q^j \left(D^k\right)^c + \lambda''_{ijk} \left(U^i\right)^c \left(D^j\right)^c \left(D^k\right)^c \tag{5}$$

which gives all the $R-$parity violating decays of the sfermions. Here L and Q are the lepton and quark doublet superfields. E^c is the lepton singlet superfield and U^c and D^c are the quark singlet superfields. i, j, k are the generation indices and $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda'_{ijk} = -\lambda'_{ikj}$. In the above the third term is a baryon number violating term. This one cannot generate any baryon asymmetry simply because there are no one loop diagrams, which can allow $CP-$violation. Furthermore, for the stability of the proton, we can either have baryon number violating $R-$parity breaking terms or the lepton number violating $R-$parity breaking terms, but not both types of terms. So, in the present scenario we only consider the lepton number violating $R-$parity breaking terms.

In the four component Dirac notation we can write the Yukawa interactions of the lepton number violating R-breaking Lagrangian generated by equation (5) as

$$\begin{aligned} \mathcal{L} &= \lambda_{ijk} \left[\tilde{\nu}^i_L \bar{e}^k_R e^j_L + \tilde{e}^j_L \bar{e}^k_R \nu^i_L + \left(\tilde{e}^k_R\right)^* \left(\bar{\nu}^i_L\right)^c e^j_L - (i \leftrightarrow j) \right] \\ &+ \lambda'_{ijk} [\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L + \left(\tilde{d}^k_R\right)^* \left(\bar{\nu}^i_L\right)^c d^j_L - \tilde{e}^i_L \bar{d}^k_R u^j_L \\ &+ \tilde{u}^j_L \bar{d}^k_R e^i_L + \left(\tilde{d}^k_R\right)^* \left(\bar{e}^i_L\right)^c u^j_L] + h.c. \end{aligned} \tag{6}$$

These give all the $R-$parity violating decays of the sfermions. There are stringent bounds on different λ_{ijk} and λ'_{ijk} from low energy processes [13] and very recently the product of two of such couplings has been constrained significantly from the neutrinoless double beta decay [14] and from rare leptonic decays of the long-lived neutral kaon, the muon and the tau as well as from the mixing of neutral K and B meson [15]. In most cases it is found that the upper bound on λ'_{ijk} and λ_{ijk} may be of the order of 10^{-1} and in some cases this bound may be of the order of 10^{-2} for the sfermion mass of order 100 GeV. For higher sfermion masses these values are even higher. Recently H1 Collaboration [16] has claimed that the existence of first generation squarks is excluded for masses up to 240 GeV for coupling values $\lambda' \geq \sqrt{4\pi\alpha_{em}}$. The upper bound of the product of two such couplings may vary from 10^{-3} to 10^{-4} except a few cases where it may be as low as 10^{-8}. However in our cases in the expression of the lepton number asymmetry the λ and λ' couplings with various possible combinations of the generation indices will be involved and to make an estimate of the asymmetry we can consider the contributions mainly coming from the λ and λ' couplings with higher values. We have considered λ_{ijk} and λ'_{ijk} to be complex in our discussion.

Let us first consider the two body decay $\tilde{d}^j_L \to d^k_R \bar{\nu}^i_L$ (figure 1). The amount of asymmetry ϵ^q_L is defined by

$$\epsilon^j_L = \sum_{ki} \Delta L \frac{\Gamma\left(\tilde{d}^j_L \to d^k_R \bar{\nu}^i_L\right) - \Gamma\left(\left(\tilde{d}^j_L\right)^* \to \bar{d}^k_R \nu^i_L\right)}{\Gamma\left(\tilde{d}^j_L \to \mathrm{a}ll\right)} \tag{7}$$

where ΔL is the lepton number generated in the decay $\tilde{d}^j_L \to d^k_R \bar{\nu}^i_L$. Here and in our subsequent discussions for other decay processes also the magnitude of ΔL is 1.

The L-violating two body decay rate of squark for $\tilde{d}^j_L \to d^k_R \bar{\nu}^i_L$ is given by

$$\Gamma\left(m_q, m_{\tilde{q}}\right) = \frac{\left(\lambda'_{ijk}\right)^2}{16\pi} m_{\tilde{q}} \left(1 - \frac{m_q^2}{m_{\tilde{q}}^2}\right)^2 \tag{8}$$

where m_q and $m_{\tilde{q}}$ are the quark mass and the squark mass respectively. Now to get an idea of the order of the total decay width for squarks in the R-parity violating scenario we like to mention that in MSSM the main decay modes are expected to be $\tilde{q}_{L,R} \rightarrow q\chi_1^0; \tilde{u}_L \rightarrow d\chi_1^+; \tilde{d}_L \rightarrow u\chi_1^-$ with mass of neutralinos and charginos much lighter than that of squarks. However in our case the mass of neutralinos and charginos are very near to the mass of squarks and the L-violating two body decay modes we are considering has much higher phase space in comparison to those MSSM decay modes. Particularly when say λ'_{122} coupling which may be of the order of 4×10^{-1} is there in equation (8) the branching ratio for L-violating decay modes may be higher than that for those MSSM decay modes. So to estimate the value of ϵ_L we may consider the order of the total decay width to be equal to the order of the decay width for such L-violating two body decays. Otherwise we have to include a suppression factor given by the ratio of R–parity breaking decay rate to the decay rate through neutralinos.

To find ϵ_L^j for the decay $\tilde{d}_L^j \rightarrow d_R^k \bar{\nu}_L^i$ we shall consider the tree level diagram (figure 1a) and one loop diagram (figure 1b). In the loop diagram for this decay and for other decay processes considered by us there are MSSM type couplings at two vertices. Unless we consider flavour violation at one of those vertices ϵ_L will be zero as the imaginary part of the product of the four couplings associated with the four vertex in tree and loop diagram can be made zero by suitable redefinition of the phase associated with the fields. Now the flavour violation is possible in quark-squark-neutralino (or quark-squark-gluino) interactions [18] as the quark and squark mass matrices are not simultaneously diagonal. For example, in a basis where the charge-1/3 quark mass matrix is diagonal, the charge -1/3 left squark mass matrix is given by

$$M^2_{L_{\tilde{d}}} = \left(m_L^2 \, \mathbf{1} + m_{\hat{d}}^2 + c_0 \, K \, m_{\hat{u}}^2 \, K^\dagger \right) \qquad (9)$$

where $m_{\hat{d}}, m_{\hat{u}}$ are the diagonal down-and up-quark mass matrix respectively, and K is the Kobayashi-Maskawa matrix. m_L is a flavour-blind SUSY breaking parameter that sets the scale of squark masses. We neglect here left-right mixing among squarks which can potentially contribute to the off-diagonal blocks. The term proportional to $m_{\tilde{u}}^2$ arises as a one loop contributions induced by up-type Yukawa coupling with charged higgsinos. So $m_{\tilde{d}}^2$ cannot be simultaneously diagonal with $m_{\tilde{d}}^2$ and flavour violation occurs in squark-quark-neutralino interactions. The coefficient c_0 is obtained from solving the renormalization group equations for the evolution of the SUSY parameters and the value of which is model-dependent and needs to be restricted by SUSY contributions to various FCNC processes.

In estimating ϵ_L for the decay in figure 1 and in other cases also we shall consider the flvaour violation only in one of the two MSSM-type vertices. For such flavor violation as for example the left-squark-quark-neutralino interaction term in the down sector is

$$\begin{aligned} \mathcal{L}_{q\tilde{q}\chi_i^0} &= -\sqrt{2}\, g \sum_{ij} \left[\tilde{q}_{iL}^{\dagger}\, \bar{\chi}_j^0 \, \frac{1-\gamma_5}{2}\, q_k \Gamma_{ik} \;\; \{T_{3i}\, N_{j2} - \tan\theta_w \,(T_{3i} - e_i)\; N_{j1}\} \right] \\ &+ \;\; h.c. \end{aligned} \tag{10}$$

where Γ_{ik} is the (ik)-th element of the unitary matrix that diagonalises the upper 3×3 block of $m_{\tilde{d}}^2$ in equation (9). N is the neutralino mixing matrix, and T_{3i} the third component of the the isospin of the i-th flavour. One may consider the left-right mixing among squarks while considering the flavor-changing right-squark-quark-neutralino interaction.

For a top-quark mass $m_t = 170GeV$, the third term in the upper-left block of $m_{\tilde{d}}^2$ is important from the viewpoint of diagonalisation, so that for a not-too-small value of c_0, the elements of Γ are close to those of K in magnitude. If we parametrize Γ_{ik} by writing $\frac{\Delta m_{\tilde{q}}{}^2}{m_{\tilde{q}}{}^2}\Gamma_{ik} = cK_{ik}$ where $\Delta m_{\tilde{q}}{}^2$ is the mass-square seperation between the two squarks of different flavor say $\tilde{b}$ and $\tilde{s}$. The value of c_0 can lie anywhere between O(0.01) to O(0.1) according to various model dependent estimates [19]. For higher $\Delta m_{\tilde{q}}{}^2$ the value of c_0 also can be higher. Thus with average squark mass in the 200 GeV range c can lie in the range $0.05-0.5$. Now the factor $\frac{\Delta m_{\tilde{q}}{}^2}{m_{\tilde{q}}{}^2}$ in parametrizing Γ_{ik} has been considered to take into account the GIM-like cancellations. However in our case in estimating ϵ_L we really need not consider this kind of cancellations as what matters is the product of four couplings as for example in figure 1(a) and figure 1(b) and as the similar diagrams with different flavor of quarks and squarks may have quite different order of values of λ' couplings for which such cancellations will not be operative. In our case we shall approximate Γ_{ik} as K_{ik} without GIM-like suppression.

$$\begin{aligned} \epsilon_L^j &= \sum_{ikm} \frac{1}{2\pi} \,\mathrm{Im}\left(\lambda'^*_{ijk}\lambda'_{imk}A_{jm}B\right)\left(\sum_{ik} \mid \lambda'_{ijk} \mid^2 \left(1-\frac{m^2_{d^k}}{m^2_{\tilde{d}^j}}\right)^2\right)^{-1} F(\tilde{d}^j_L \tilde{d}^k_R) \\ &\approx \sum_{ikm} \frac{1}{2\pi} \,\mathrm{Im}\left(\lambda'^*_{ijk}\lambda'_{imk}A_{jm}B\right)\left(\sum_{ik} \mid \lambda'_{ijk} \mid^2\right)^{-1} F(\tilde{d}^j_L \tilde{d}^k_R) \end{aligned} \qquad (11a)$$

where A_{jm} and B are given by

$$A_{jm} = \sqrt{2} g K_{jm}\left[-\frac{1}{2}N_{12} + \frac{1}{6}\ \tan\theta_w\ N_{11}\right] \qquad (11b)$$

$$B = \left(\frac{-\sqrt{2}}{3}\right)\ g \tan\theta_w\ N_{12}{}^* \qquad (11c)$$

In (11a), $F(\tilde{d}^j_R \tilde{e}^l_L)$ comes from the absorbtive part of the loop integral.

To estimate the order of ϵ_L in (11a) we first like to mention that it depends highly on the order of A_{jm} and B which comes from the left-d-squark, quark, neutralino coupling and the right-d-squark, quark, neutralino coupling of the MSSM type rather than depending on the values of λ' couplings which are both in numerator and denominator of (11a). For a wide range of MSSM parameters for neutralino mass ranging from about 100 to 700 GeV with

$\mid \mu \mid$ about 200 to 1000 GeV and $\tan\beta$ from 2 to 12 the product of left-d-squark, quark, neutralino coupling with flavor violation and right-d-squark, quark, neutralino coupling is of the order of $K_{jm} \times 10^{-7}$ to $K_{jm} \times 10^{-2}$ and the left-d-squark, quark, neutralino coupling is higher in general than the similar coupling with the right-d-squark. Particularly with neutralino mass of the order of 270 GeV and $\tan\beta = 4$ and $\mu = -400$ GeV this product is about $4K_{jm} \times 10^{-2}$ and with neutralino mass of the order of 200 GeV and $\mu = -200$ GeV and $\tan\beta = 2.5$ this product is of the order of $K_{jm} \times 10^{-7}$. If we consider the higher value of this product the order of ϵ_L^j may be as high as of the order of 10^{-4} and hence $\frac{n_L}{s} \sim 10^{-9}$. If one considers all the generation indices in place of j in e_L^j the asymmetry will be even higher. We may consider the higher values of λ' allowed by the present experiments with its' value of the order of 10^{-1}.

In the reference [8] ϵ_L is generated from the three body decay $\chi_1^0 \to t l_i d_k^c$ which depends highly on the λ' parameters and according to the reference [8] if all λ' couplings are considered of similar order then λ' are expected to be of the order of 8×10^{-3} to explain the baryon asymmetry through lepton asymmetry. But the decay processes which we are considering in this case and elsewhere the ϵ_L depends highly on MSSM type couplings and the out of equilibrium condition does not give bound on the MSSM couplings as the decay width is controlled by λ or λ' couplings at the tree level. For higher values of the product of two MSSM type couplings one may get higher lepton asymmetry from the L-violating two body decay modes of squarks, sneutrino or charged leptons than that from the three body decay of neutralino as mentioned in reference [8].

In case of the decay $\tilde{d}_R^k \to \nu_L^i d_L^j$ from the interference of the tree level and the one loop level diagrams in figures 2a and 2b one obtains

$$\epsilon_L^k \approx \frac{\sum_{ijm} \mathrm{Im}\left(A_{mj} B \lambda'_{ijk} \lambda'^*_{imk}\right) F(\tilde{d}_R^k \tilde{d}_L^m)}{4\pi \ \sum_{ij} \mid \lambda'_{ijk} \mid^2} \tag{12}$$

The contribution to lepton asymmetry from this kind of interference will be like our previous case of left-squark decay as same MSSM type couplings are involved.

For the decay $\tilde{d}_R^k \to e_L^i u_L^j$ there are two one loop diagrams (figures 3b and 3c) which can interfere with the tree level diagram (figure 3a). In the loop diagram in figure 3b we shall consider the generation mixing in the slepton-lepton-neutralino interaction which is very similar to the flavor changing squark-quark-neutralino interaction considered in earlier cases. If the neutrinos have non-vanishing masses, the charged slepton mass matrix in the left sector is given by

$$M_{\tilde{l}}^2 = \mu^2 + M_l M_l^\dagger + c'_0 M_\nu {M_\nu}^\dagger \tag{13}$$

where the third term comes as radiative corrections due to the Yukawa couplings of left sleptons with charged Higgsinos. c'_0 is a model-dependent parameter to be specified by the renormalization group equations. For this term the generation mixing is induced in the slepton mass matrix [18] and that leads to generation mixing in the slepton-lepton-neutralino interactions also. If the neutrinos are Dirac particles the matrix m_ν is constrained to have small elements . However see-saw type scenarios with large Majorana mass entail the possibility of neutrino mass parameters appearing in the Yukawa couplings to be of the order of tau mass [20]. So the mixing particularly involving third generation will be strongest in such cases. In this scenario the left-slepton-lepton-neutralino interaction is

$$\mathcal{L}_{l\tilde{l}\chi_i^0} = -\sqrt{2}\, g \sum_{ij} \left[\tilde{l}_{iL}^{\dagger}\, \bar{\chi}_j^0 \frac{1-\gamma_5}{2}\, l_k \Gamma'_{ik} \;\; \{ T_{3i}\, N_{j2} - \tan\theta_w \,(T_{3i} - e_i)\; N_{j1} \} \right] + \; h.c. \tag{14}$$

where Γ'_{ik} is a function of c'_0 and the slepton mixing matrix and is constrained from the experimental limits on rare decays like $\mu \to e\gamma$ and $\tau \to \mu\gamma$ [21]. Using the bounds on such decays [22] and suitably translating the limits given in reference [21] it is seen that μ decay gives the constraint on the upper limit of $\frac{\Gamma'_{12}\, \Delta m_{\tilde{l}}{}^2}{m_{\tilde{l}}^2}$ as 10^{-3} and from the tau decay such constraint on $\frac{\Gamma'_{23}\, \Delta m_{\tilde{l}}{}^2}{m_{\tilde{l}}^2}$ is $0.2 - 0.3$.

From the interference of the diagrams in figure 3a with those in figure 3b and figure 3c we get

$$\epsilon_L^k \approx \frac{\sum_{ijm} \mathrm{Im}\left(C_{im} B \lambda'_{ijk} \left(-\lambda'^*_{mjk} \right) \right) F(\tilde{d}_R^k \tilde{e}_L^m)}{2\pi \sum_{ij} \mid \lambda'_{ijk} \mid^2} + \frac{\sum_{ijm} \mathrm{Im}\left(B_{kl} D \lambda'_{ijk} \lambda'^*_{ijl} \right) F(\tilde{d}_R^k \tilde{u}_L^m)}{2\pi \sum_{ij} \mid \lambda'_{ijk} \mid^2} \tag{15a}$$

where

$$C_{ij} = \Gamma'_{ij}\; C \tag{15b}$$

$$C = \sqrt{2}\; g \left[-\frac{1}{2} N_{12} - \frac{1}{2} \tan\theta_w \; N_{11} \right] \tag{15c}$$

$$D = \sqrt{2} g \;\; \left[\frac{1}{2} N_{12} + \frac{1}{6} \tan\theta_w \; N_{11} \right] \tag{15d}$$

and

$$B_{kl} = B \; K_{kl} \tag{15e}$$

C_{ij} characterizes the flavor violating slepton-lepton-neutralino interaction in figure 3b and B_{kl} characterizes flavor violating right-squark-quark-neutralino interaction in figure 3c and D corresponds to up-squark-quark-neutralino vertex. For flavor violation with right-squark we have considered similar order of suppression as in the case of left squark. The first term in (15a) comes from interference of figures 3a and 3b, while the second term comes from interference of figures 3a and 3c. In the same range of MSSM parameter space discussed in the earlier case we find the product of two MSSM type couplings B and C_{ij} varies from $\Gamma'_{ij} \times 10^{-7}$ to $\Gamma'_{ij} \times 10^{-2}$ and for the product of two MSSM type couplings B_{kl} and D it varies from $K_{kl} \times 10^{-7}$ to $K_{kl} \times 10^{-2}$ and as the higher values of Γ'_{ij} may be somewhat higher than 0.2 the order of ϵ_L^k can be as high as 10^{-3} from (15a).

In case of the decay $\tilde{u}_L^j \to d_R^k \bar{e}_L^i$ there are again two one loop diagrams (figures 4b and 4c) interferring with the tree level diagram (figure 4a) contributing to ϵ_L. The sum of these two contributions is given by

$$\begin{aligned} \epsilon_L^j &\approx \frac{\sum_{ikm} \mathrm{Im}\left(DC_{im}{}^* \lambda'^*_{ijk} \left(-\lambda'_{mjk}\right)\right) F(\tilde{u}_L^j \tilde{e}_L^m)}{2\pi \sum_{ik} \mid \lambda'_{ijk} \mid^2} \\ &+ \frac{\sum_{ikm} \mathrm{Im}\left(\lambda'^*_{ijk} D B_{mk} \lambda'_{ijm}\right) F(\tilde{u}_L^j \tilde{d}_R^m)}{2\pi \sum_{ik} \mid \lambda'_{ijk} \mid^2} \end{aligned} \tag{16}$$

The order of the product of two MSSM type couplings in equation (16) is like earlier cases. However the higher value of this product in the first term in (16) may be even $\Gamma'_{im} \times 10^{-1}$ for neutralino mass of the order of 650 GeV, $\tan\beta = 12$ and $\mu = -1000$ GeV for which higher value of ϵ_L from (16) may be even more than 10^{-3}.

There is two body sneutrino decay $\tilde{\nu}_L^i \to d_R^k \bar{d}_L^j$ shown in figure 5 leading to the contribution to ϵ_L. Now to get an idea of the order of the total decay width for sneutrino we note like the case of squark decays here also for light neutralinos much lighter than sneutrino in MSSM the main decay modes are expected to be $\tilde{\nu} \to \nu \chi_1^0$. However we shall consider the mass of the lightest neutralino to be nearer to the mass of the sneutrino and similarly like our cases for squark decays we shall consider the total decay width for sneutrino to be highly dominated by the R-parity violating decay widths for sneutrino decaying to $d_R^k \bar{d}_L^j$ and $e_R^k \bar{e}_L^j$.

From the interference of diagrams in figure 5a and figure 5b one obtains

$$\epsilon_L^i \approx \frac{\sum_{jkm} \mathrm{Im}\left(\lambda'^{*}_{ijk} A_{mj}{}^{*}(-C)\lambda'_{imk}\right) F(\tilde{\nu}_L^i \tilde{d}_L^m)}{2\pi \sum_{jk}\left(\mid \lambda_{ijk} \mid^2 + \mid \lambda'_{ijk} \mid^2\right)} \tag{17}$$

For a wide range of parameter space mentioned in the beginning of this section it is found that the product of two MSSM type couplings is of the order of $K_{mj} \times 10^{-1}$. So from this sneutrino decay one may expect the higher possible value of ϵ_L for a wide range of MSSM parameter space. The lepton asymmetry thus generated can be as high as , $\frac{n_L}{s} \sim 10^{-8}$.

Next we shall consider L-violating decays of selectron like $\tilde{e}_L^i \rightarrow d_R^k \bar{u}_L^j$. About the total decay width here we like to mention like our earlier cases that the main decay mode in MSSM is expected to be $\tilde{l}^{\pm} \rightarrow l^{\pm}\chi_1^0$ for light neutralino mass. But in our following discussion we shall consider its' mass to be nearer to the mass of selectron for which one may expect that the total L-violating decay width for selectron decaying to $d_R^k \bar{u}_L^j$ and $e_R^k \bar{\nu}_L^i$ will dominate the total decay width for selectron.

From the interference of the diagrams in figures 6a and 6b one obtains

$$\epsilon_L^i \approx \frac{\sum_{jkl} \mathrm{Im}\left(\left(-\lambda'^{*}_{ijk}\right) BC_{li}\lambda'_{ljk}\right) F(\tilde{e}_L^i \tilde{d}_R^k)}{2\pi \sum_{jk}\left(\mid \lambda_{ijk} \mid^2 + \mid \lambda'_{ijk} \mid^2\right)} \tag{18}$$

The product of two MSSM type couplings is same as in the case of the interference of figures 3a and 3b. The order of ϵ_L may be as high as 10^{-3}.

In our discussion we have mentioned the mass of lightest neutralino to be nearer to the mass of squarks or charged slepton and sneutrino. But if it is somewhat lighter than the squark, charged slepton or sneutrino mass, other heavier neutralino may also be lighter than squarks or charged slepton or sneutrino. Then for various decay processes one may get further one loop diagrams replacing the lightest neutralino by the other heavier neutralino in the loop diagrams and those will give some further contributions to ϵ_L.

Taking into account those probable extra diagrams and with relatively higher values of the product of MSSM type couplings one may get a significant amount of lepton asymmetry in the scenario of ref. [8].

4 Summary

We studied the model proposed by Masiero and Riotto [8] to generate baryon asymmetry of the universe through lepton asymmetry where the electroweak symmetry breaking phase transition is of first order. In contrast to their consideration of only the three body decay of lightest neutralino we have considered various L-violating two body decays of sfermions to generate lepton asymmetry because the sfermions may not be light and may be generated during the decay of false vacuum. The order of lepton asymmetry coming from these two body decays depends highly on the choice of various MSSM parameters and to some extent on the values of λ and λ' and may easily vary from the order of 10^{-8} to 10^{-11} in the presently allowed region of MSSM parameter space. Particularly for the decays $\tilde{\nu}_L^i \rightarrow d_R^k \bar{d}_L^j$ one may expect quite high lepton asymmetry of the order of 10^{-8} for a wide range of parameter space. On the other hand the lepton asymmetry coming from neutralino decay as mentioned in ref. [8] depends highly on the values of λ' couplings and with $\lambda' \approx 8 \times 10^{-3}$ it can be atmost of the order of 10^{-11}. As the lepton asymmetry from the decays of squarks, sneutrino or charged slepton mainly depends on the values of the product of MSSM type couplings which are not constrained by the out of equilibrium condition and may be quite high so even for lower values of λ or λ' of the order of 10^{-4} say where MSSM type decays may dominate the total decay width of sfermions one can still hope for higher lepton asymmetry. Taking into account the lepton asymmetry generated by sfermion decay alongwith the neutralino decays this scenario can produce large baryon asymmetry of the universe.

Acknowledgement One of us (US) acknowledges a fellowship from the Alexander von Humboldt Foundation and hospitality from the Institut für Physik, Univ Dortmund during his research stay, where part of this work was done.

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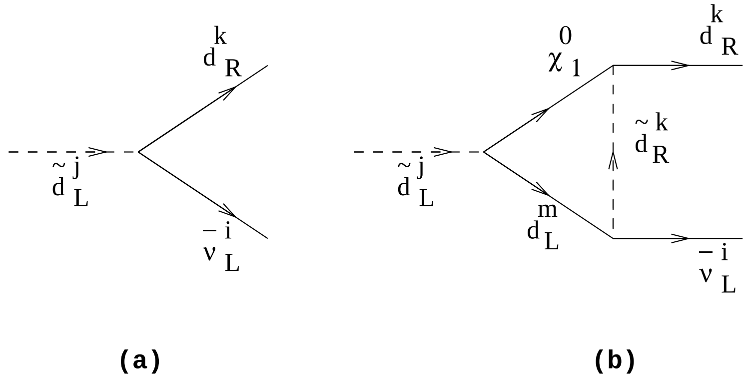

Figure 1: Tree level and one loop diagram for the decay $\tilde{d}_L^j \rightarrow d_R^k \bar{\nu}_L^i$.

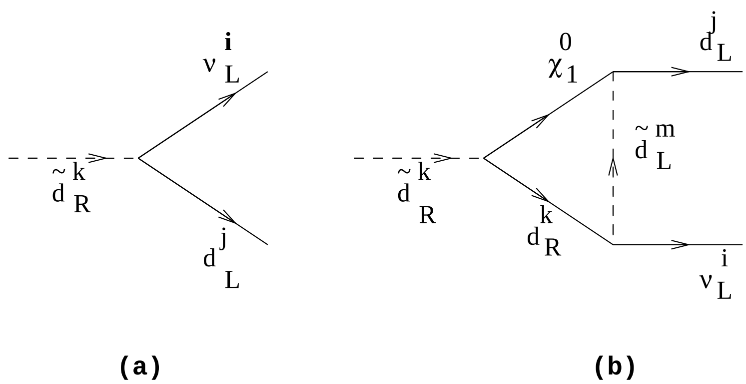

Figure 2: Tree level and one loop diagram for the decay $\tilde{d}_R^k \rightarrow \nu_L^i d_L^j$.

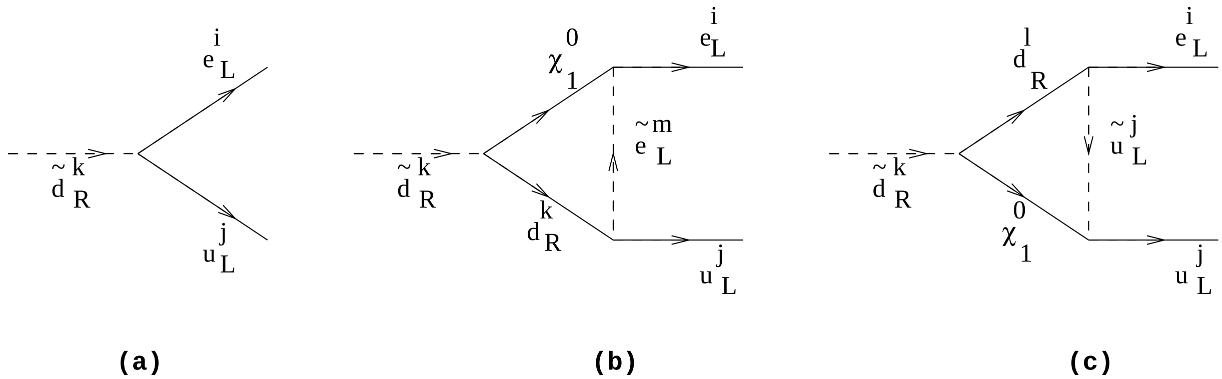

Figure 3: Tree level and one loop diagram for the decay $\tilde{d}^k_R \to e^i_L u^j_L$.

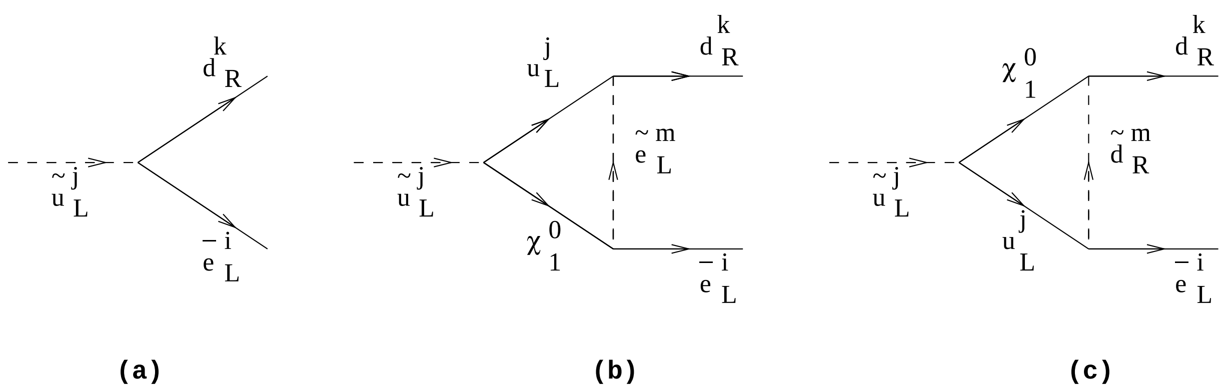

Figure 4: Tree level and one loop diagram for the decay $\tilde{u}^j_L \to d^k_R \bar{e}^i_L$.

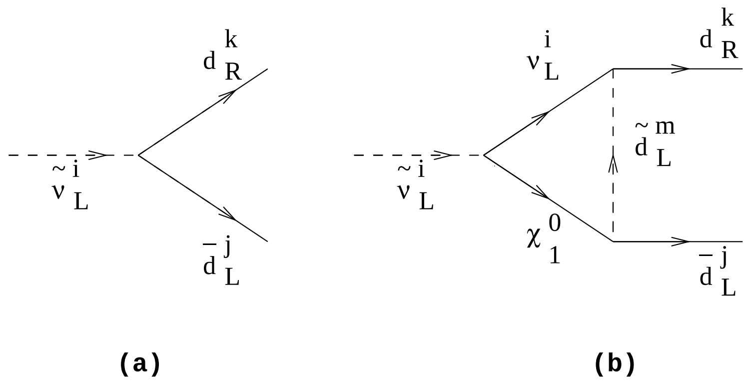

Figure 5: Tree level and one loop diagram for the decay $\tilde{\nu}_L^i \to d_R^k \bar{d}_L^j$.

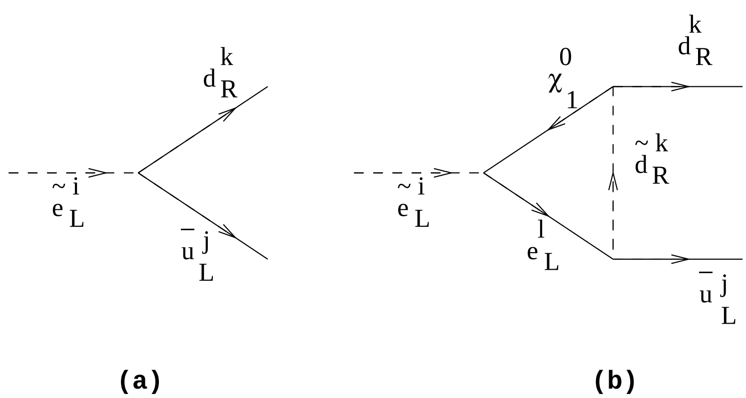

Figure 6: Tree level and one loop diagram for the decay $\tilde{e}_L^i \to d_R^k \bar{u}_L^j$.