

Baryogenesis in a supersymmetric model without R -parity

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Abstract

We propose a simple scenario for baryogenesis in supersymmetric models where baryon number is broken alongwith R-parity. The lightest supersymmetric particle (neutralino) decays to three quarks and CP - violation comes from interference of tree and one loop box diagrams. The bounds on the R -parity breaking couplings from the out-of-equilibrium condition are considerably relaxed in this scenario.

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The observable universe contains more matter than antimatter although the ratio is very small for baryons. This asymmetry of the universe [1] can be generated at a very high energy, but in most likelihood it will be washed out at a later stage [2]. So a great deal of interest started in scenarios where the baryon asymmetry is generated during the electroweak phase transition [3, 4] by making the phase transition to be a weakly first order. However the condition for survival of the generated baryon asymmetry after the phase transition gives a strong bound on the mass of the higgs doublet [5], which rule out this scenario. This motivates for alternative scenarios for baryogenesis [6-10].

In this article we propose a simple supersymmetric model to generate baryon asymmetry of the universe at low energy. Baryon number violation arises from R-parity breaking. R-parity violating couplings, which also violate lepton number, is assumed to be small (or even zero if lepton number is conserved). The lightest supersymmetric particle (LSP), which is one of the neutralinos χ_1^0 , is now unstable since R-parity is broken. There exist new box-type diagrams for the decay of χ_1^0 , which interferes with the tree level diagram to give enough CP -violation, which generates the baryon asymmetry of the universe. The mass of χ_1^0 is much less than the sfermion masses and as a result when χ_1^0 decays the sfermions has already decayed away, so it does not matter if the sfermions decay in equilibrium and have erased the primordial baryon asymmetry. This relaxes the bounds on the R-parity breaking B-violating couplings considerably.

In supersymmetric models, R-parity was introduced as a matter of convenience to prevent fast proton decay. It is now realised that the proton lifetime can be made consistent with experiment without invoking R-parity symmetry. If we don't impose R-parity in the model, then the minimal supersymmetric standard model allows the following B and L violating terms

in the superpotential

$$W = \lambda_{ijk} L^i L^j (E^k)^c + \lambda'_{ijk} L^i Q^j (D^k)^c + \lambda''_{ijk} (U^i)^c (D^j)^c (D^k)^c \quad (1)$$

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 and i, j, k are the generation indices. In the above the first two terms are lepton number violating while the third term violates baryon number. For the stability of the proton, we assume that λ_{ijk} and λ'_{ijk} are extremely small or even zero (if some symmetry like lepton number is present). The couplings λ''_{ijk} can now be considerably large. They are antisymmetric in the last two indices and in general complex.

We consider one of the neutralinos (χ_1^0) as the lightest supersymmetric particle having mass of the order of 100 – 200 GeV and the sfermions have higher mass of the order of 250 GeV to a few TeV. So before the universe cools down to the temperature of the electroweak symmetry breaking scale the sfermions have already decayed away. Since R-parity is broken, some of the sfermions will have baryon number violating decay channels, which may even wash out the primordial baryon asymmetry of the universe.

Near the electroweak scale the neutralinos χ_1^0 are the only superparticles left to be decayed. If R-parity is not broken, these particles are stable. However, since R-parity is now broken, the neutralino can also decay to ordinary quarks and leptons. In these decays at least one of the vertex should not conserve R-parity and hence baryon number is broken. In figures 1(a) and 2(a) the tree level diagrams for the processes $\chi_1^0 \rightarrow u_{iL} d_{jR} d_{kR}$ and $u_{iR} d_{jL} d_{kR}$ are given, while in figures 1(b) and 2(b) we present the new type of one loop box diagrams. The interference of the tree level and the one loop diagrams give rise to the CP violation. The advantage of the box diagrams is that two of the vertices contains couplings of the higgs and hence elements of the CKM matrix contributes to the baryon asymmetry. This gives a

large enhancement and hence we can get a large baryon asymmetry even for considerably smaller R-parity breaking couplings.

As the B -violating couplings are antisymmetric with the interchange of the d-type quark indices, the indices j and k are always different for a particular type of decay mode where i, j and k are fixed. Thus with the interchange of j and k there will be an extra diagram at the tree level corresponding to figure 2a and two other box diagrams corresponding to figures 1b and 2b.

The thermally averaged decay width for such baryon number violating decays are given by

$$\langle \Gamma(\chi_1^0 \rightarrow u_i d_j d_k) \rangle \approx \frac{g^2 |\lambda''_{ijk}|^2 m_{\chi_1^0}^5}{10^4 \pi^4 (m_{\tilde{q}}^2 + T_0^2)^2} A^2 \quad (2)$$

where the factor A for the couplings $\bar{u}_R \tilde{u}_R \chi_1^0$ and $\bar{d}_R \tilde{d}_R \chi_1^0$ are

$$A = [\pm N_{12}/2 + \tan \theta_w / 6 N_{11}]$$

respectively. We have followed the notations of Haber and Kane [11] for the MSSM type squark-quark-neutralino interaction.

The decay of the neutralino should now satisfy the out-of-equilibrium condition near $T = m_{\chi_1^0}$, which is $\langle \Gamma(\chi_1^0 \rightarrow u_i d_j d_k) \rangle < 1.7 \sqrt{g_*} (T^2/M_P)$. This can be satisfied with $A \sim 10^{-2}$ to 10^{-3} , which is possible for a wide range of MSSM parameters for neutralino mass ranging from about 100 to 200 GeV with $|\mu|$ about 200 to 1000 GeV and $\tan \beta$ from 2 to 12, and with $\lambda'' < 10^{-1}$ to 10^{-2} .

For the decay modes of figures 1(a) and 2(a), we require $\bar{u}_L \tilde{u}_R \chi_1^0$ and $\bar{d}_L \tilde{d}_R \chi_1^0$ couplings, which comes from the higgsino component of the neutralino. In ref [11] these couplings are not present since they assumed $m_q = 0$. In general, the neutralino will have a higgsino component, coming from the mixing at the one loop level with the internal lines as quarks and squarks. The mass insertion for the quarks will allow a change in helicity. The dominant

contribution comes from the top quark in the loop and hence the suppression factor is proportional to m_t . The coupling of the neutralino $\bar{q}_L \tilde{q}_R \chi_1^0$ will thus be suppressed by a factor of

$$F = \frac{1}{2\pi} \frac{m_t}{m_{\tilde{q}}} \quad (3)$$

compared to the couplings A of $\bar{q}_R \tilde{q}_R \chi_1^0$. Instead of considering the coupling $\bar{q}_L \tilde{q}_R \chi_1^0$ of the higgsino component of the neutralino with the suppression factor F it is also possible to take the neutralino coupling $\bar{q}_R \tilde{q}_R \chi_1^0$ and then change the helicity of the quark by a mass insertion. But that will then introduce a suppression by $m_q/m_{\tilde{q}}$ and hence we do not consider this later possibility.

While calculating the baryon asymmetry in the decay of the neutralino χ_1^0 , one has to take into consideration the fact that some of the neutralinos may thermalize before they decay through the $\chi_1^0 q \rightarrow \chi_1^0 q$ scattering. This will introduce an additional suppression factor

$$S = \frac{5}{4\pi^2 g^2} \frac{|\lambda''_{ijk}|^2}{A^2} \left(\frac{m_{\chi_1^0}}{T_0} \right)^5. \quad (4)$$

Taking the suppression factors S and F into account we can now calculate the baryon asymmetry ϵ generated through the interference of the various possible tree level diagrams [figures 1(a) and 2(a)] with the box diagrams [figures 1(b) and 2(b)]

$$\epsilon = \frac{5}{2\pi^3} \frac{(m_{d_j} m_{d_l} + m_{u_i} m_{u_n})}{m_W^2} \frac{m_t^2}{m_{\tilde{q}}^2} \frac{m_{\chi_1^0}^5}{T_0^5} \frac{\tan^2 \beta}{A^2} [\text{Im}(\lambda''_{ijk} \lambda''_{nlk} V_{n^*j} V_{i^*l})] I\left(\frac{m_{\chi_1^0}}{m_{\tilde{q}}}\right) \quad (5)$$

where $I(m_{\chi_1^0}/m_{\tilde{q}})$ comes from the absorptive part of the loop integral. For $m_{\chi_1^0} \ll m_{\tilde{q}}$ it may be approximated as,

$$I\left(\frac{m_{\chi_1^0}}{m_{\tilde{q}}}\right) = \frac{1}{32\pi} \frac{m_{\chi_1^0}}{m_{\tilde{q}}}. \quad (6)$$

V_{a^*b} is the CKM matrix, which enters from the higgs coupling. It is clear from the expression that the imaginary part of the product of the couplings is invariant under rephasing of all the quark phases. We have assumed that the neutralino couplings are diagonal since the off diagonal couplings will be further suppressed. It can be noticed that it is possible to choose a phase convention, so that the λ 's are real and hence the CP -violating phase comes entirely from the CKM matrix. In this basis, there will not be any constraint coming from the electron dipole moment of the neutron on the complex part of the couplings of λ . This will reduce one more uncertain parameter in the problem.

In equation (5) it is possible to choose the parameters so that the amount of asymmetry generated in this scenario is large enough. As a representative set of values we consider $T_0 \approx m_{\chi_1^0}$. We consider $\tan\beta \sim 3$; mass of the neutralino of the order of 200 GeV and the mass of squarks are in the range of a few TeV. Since top quark in the decay product will be phase space suppressed, we consider the decay products to be $c_R b_L d_L$. The internal lines have top and strange quarks and hence the two CKM matrix elements are V_{tb} and V_{cs} . Then for $A^2 \sim 10^{-5}$ we get $\epsilon \sim 10^{-2} \times \lambda''_{ijk} \lambda''_{nlk}$. In this case large enhancement comes from the mass of the top quarks and diagonal CKM elements. For several other choices of parameters also we can have a large ϵ in this scenario.

We shall now discuss the constraints on the B -violating R-parity breaking coupling constant λ'' . In general one requires that all B -violating decays of the sfermions should be slow enough so as not to erase the baryon asymmetry before the electroweak phase transition [13]. However, in the present model these constraints are no longer valid since we generate baryon asymmetry at the electroweak scale when all the sfermions have already decayed away.

The constraint coming from the out of equilibrium condition for the in-

teraction $u_i d_j \rightarrow \bar{d}_k \chi_1^0$ is usually very severe [13]

$$\lambda''_{ijk} < 3 \times 10^{-6} \left(\frac{\tilde{m}}{1TeV} \right)^{1/2} \left[\sqrt{2} g \frac{\tan \theta_w}{3} N_{12} \right]^{-1}. \quad (7)$$

For the mass of neutralino of the order of 100 to 200 GeV this bound of λ''_{ijk} is of the order of 10^{-3} for some region of the parameter space independent of the generation indices. However, in the present scenario the CP violating part of this diagram will also contribute to the generation of baryon asymmetry. This means that even if this constraint is not satisfied, the suppression will be linear in λ''_{ijk} and this constraint is also relaxed.

Another source of constraint on λ''_{ijk} comes from the non-observation of $n\bar{n}$ oscillations. The earlier bound [14, 15] was $\lambda''_{11k} \ll 2 \times 10^{-7} [\tilde{m}/100GeV]^{5/2}$. However these constraints are highly model dependent and may be evaded [16, 17] and the upper bound may be of the order of 10^{-3} or higher depending on the choice of SUSY parameters. The coupling λ''_{113} is almost free of any constraint, when a suppression factor coming from the flavor changing neutral current is included [17]. For λ''_{112} the upper bound may vary from 10^{-4} to 10^{-1} depending on the stop mass from 100 GeV to 500 GeV [17]. In our case the upper bound on these couplings will be still higher.

The product of two B violating couplings are constrained from the rare two body non-leptonic decays of B and D mesons [17]. However those constraints are much weaker. For higher squark mass in the TeV range most stringent constraint essentially comes from the out of equilibrium conditions [17, 18] for most of the B -violating couplings, which is of the order of 10^{-2} to 10^{-3} . But these constraints are not applicable in the present scenario as discussed earlier.

Satisfying all the constraints it is thus possible to have λ'' as high as 10^{-1} . However for the choice of parameters we considered, we require only $\lambda'' \sim 10^{-3}$ to get ϵ as high as 10^{-8} . This gives us enough freedom to relax some other constraints and still have enough baryon asymmetry. In this

scenario this baryon asymmetry will be a $(B - L)$ asymmetry, and hence this is not washed out due to sphaleron transition. On the other hand since the baryon asymmetry is not related to the lepton asymmetry of the universe, all constraints on the lepton number violating interactions arising due to the Majorana masses of the neutrinos are no longer valid.

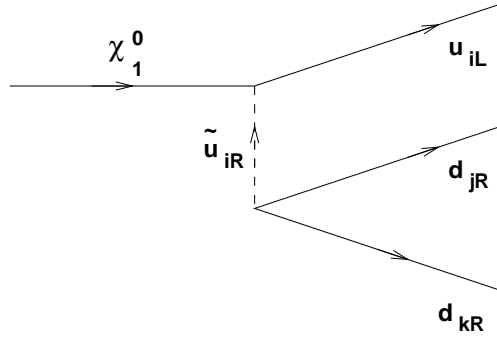
To summarize, we presented a simple supersymmetric model of baryogenesis, where baryon number is violated alongwith R -parity. CP -violation comes from an interference of the tree level and the one loop box-type diagrams, such that two of the elements enters from the CKM matrix. The constraints on the B -violating (R -parity violating) couplings are considerably relaxed in this scenario.

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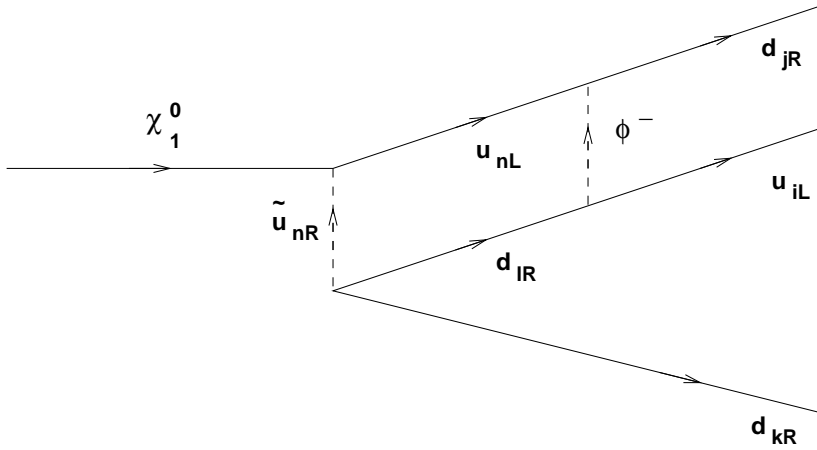
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(a)



(b)

Figure 1: Tree level and box diagrams for the decay $\chi_1^0 \rightarrow u_{iL}d_{jR}d_{kR}$.

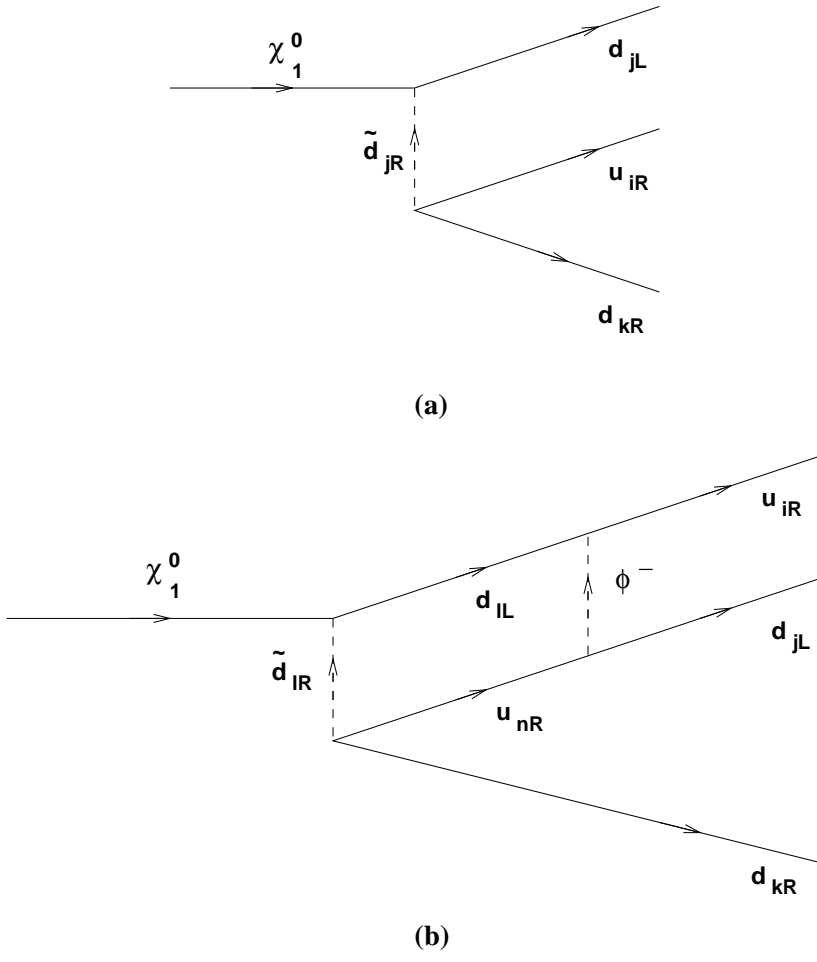


Figure 2: Tree level and box diagrams for the decay $\chi_1^0 \rightarrow d_{iL}u_{jR}d_{kR}$.