DESY 11-174
March 2012

Spontaneous $B-L$ Breaking as the Origin of the Hot Early Universe

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Abstract

The decay of a false vacuum of unbroken $B-L$ symmetry is an intriguing and testable mechanism to generate the initial conditions of the hot early universe. If $B-L$ is broken at the grand unification scale, the false vacuum phase yields hybrid inflation, ending in tachyonic preheating. The dynamics of the $B-L$ breaking Higgs field and thermal processes produce an abundance of heavy neutrinos whose decays generate entropy, baryon asymmetry and gravitino dark matter. We study the phase transition for the full supersymmetric Abelian Higgs model. For the subsequent reheating process we give a detailed time-resolved description of all particle abundances. The competition of cosmic expansion and entropy production leads to an intermediate period of constant 'reheating' temperature, during which baryon asymmetry and dark matter are produced. Consistency of hybrid inflation, leptogenesis and gravitino dark matter implies relations between neutrino parameters and superparticle masses. In particular, for a gluino mass of 1 TeV, we find a lower bound on the gravitino mass of 10 GeV.

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Contents

1 Introduction

Neutrino masses, baryogenesis, dark matter and the acoustic peaks in the power spectrum of the cosmic microwave background (CMB) radiation require an extension of the Standard Model of particle physics. The supersymmetric standard model with right-handed neutrinos and spontaneously broken $B-L$, the difference of baryon and lepton number, provides a minimal framework which can account for all these phenomena [1]. $B-L$ breaking at the grand unification (GUT) scale leads to an elegant explanation of the small neutrino masses via the seesaw mechanism and explains baryogenesis via leptogenesis [2]. The lightest supersymmetric particle is an excellent candidate for dark matter [3–5] and the spontaneous breaking of $B-L$ requires an extended scalar sector, which automatically yields hybrid inflation [6, 7], explaining the inhomogeneities of the CMB.

Recently, we have suggested that the decay of a false vacuum of unbroken $B-L$ symmetry generates the initial conditions of the hot early universe: nonthermal and thermal processes produce an abundance of heavy neutrinos whose decays generate primordial entropy, baryon asymmetry via leptogenesis and gravitino dark matter from scatterings in the thermal bath [8,9]. In this context, tachyonic preheating after hybrid inflation [10] sets the stage for a matter dominated phase whose evolution is described by Boltzmann equations, finally resulting in a radiation dominated phase. It is remarkable that the initial conditions of this radiation dominated phase are not free parameters but are determined by the parameters of a Lagrangian, which in principle can be measured by particle physics experiments and astrophysical observations.

Our work is closely related to previous studies of thermal leptogenesis [11, 12] and nonthermal leptogenesis via inflaton decay [13–16], where the inflaton lifetime determines the reheating temperature. In supersymmetric models with global $B-L$ symmetry the scalar superpartner $\widetilde{N}_1$ of the lightest heavy Majorana neutrino N_1 can play the role of the inflaton in chaotic [17,18] or hybrid [19,20] inflation models. One of the main motivations for nonthermal leptogenesis has been that the 'gravitino problem' for heavy unstable gravitinos [21–25] can be avoided by means of a low reheating temperature. In the following we shall assume that the gravitino is the lightest superparticle. Gravitino dark matter can then be thermally produced at a reheating temperature compatible with leptogenesis [26].

The present work is an extension of Ref. [9]. We discuss in detail the effect of all supersymmetric degrees of freedom on the reheating process and restrict the parameters of the Lagrangian such that they are compatible with hybrid inflation and the production of cosmic strings during spontaneous symmetry breaking. This implies in particular that $B-L$ is broken at the GUT scale. The consistency of hybrid inflation, leptogenesis and gravitino dark matter entails an interesting connection between the lightest neutrino mass m_1 and the gravitino mass $m_{\widetilde{G}}$. As we shall see, the final results for baryon asymmetry and dark matter are rather insensitive to the effects of superparticles and details of the reheating process. Due to the restrictions on the parameter space compared to Ref. [9] the lower bound on the gravitino mass increases to about 10 GeV.

The paper is organized as follows. In Section 2 we briefly recall field content and superpotential of our model, in particular the Froggatt-Nielsen flavour structure on which our analysis is based. We then discuss the time-dependent masses of all particles during the spontaneous breaking of $B-L$ symmetry in the supersymmetric Abelian Higgs model, the restrictions of hybrid inflation and cosmic strings on the parameters, and the particle abundances produced during tachyonic preheating. Section 3 deals with the time evolution after preheating and the required set of Boltzmann equations for all particles and superparticles. The detailed description of the reheating process is given in Section 4 with emphasis on the various contributions to the abundance of N_1 neutrinos, the lightest of the heavy Majorana neutrinos, whose decays eventually generate entropy and baryon asymmetry. Particularly interesting is the emerging plateau of a reheating temperature which determines the final gravitino abundance. In Section 5 a systematic scan of the parameter space is carried out, and relations between neutrino and superparticle masses are determined. Three appendices deal with important technical aspects: The full supersymmetric Lagrangian for an Abelian gauge theory in unitary gauge, which is used to describe the time-dependent $B-L$ breaking (Appendix A), CP violation in all supersymmetric $2 \to 2$ scattering processes (Appendix B) and the definition of the reheating temperature (Appendix C).

2 $B-L$ breaking at the GUT scale

2.1 Field content and superpotential

Our study is based on an extension of the minimal supersymmetric standard model (MSSM) which offers solutions to a series of problems in particle physics and cosmology. Its main features are right-handed neutrinos, a $U(1)_{B-L}$ factor in the gauge group and three chiral superfields, needed for $B-L$ breaking and allowing for supersymmetric hybrid inflation. In this section, we give a review of this model, presented earlier in Ref. [9], thereby focussing on the aspects which are especially relevant for this paper.

A characteristic feature of the model is that inflation ends in a phase transition which breaks the extra $U(1)$ symmetry. During this phase transition the system experiences the decay from the false into the true vacuum. At the same time, this phase transition is responsible for the production of entropy, matter and dark matter through tachyonic preheating and subsequent leptogenesis. Finally, it yields masses for the right-handed neutrinos, thereby setting the stage for the seesaw mechanism, which can explain the observed light neutrino masses. The superpotential is given by

$$W = \frac{\sqrt{\lambda}}{2}\,\Phi\,(v_{B-L}^2 - 2\,S_1 S_2) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^\nu \mathbf{5}_i^* n_j^c H_u + W_{\mathrm{MSSM}}\,, \tag{1}$$

where S_1 and S_2 are the chiral superfields containing the Higgs field responsible for breaking $B-L$, Φ contains the inflaton, i.e. the scalar field driving inflation, and n_i^c denote the superfields containing the charge conjugates of the right-handed neutrinos. In the following, we will refer to the components of S_1, S_2 and Φ as the symmetry breaking sector, whereas the components of n_i^c form the neutrino sector. v_{B-L} is the scale at which $B-L$ is broken. The $B-L$ charges are $q_S \equiv q_{S_2} = -q_{S_1} = 2$, $q_\Phi = 0$, and $q_{n_i} = -1$. h and λ denote coupling constants, and W_{MSSM} represents the MSSM superpotential,

$$W_{\mathrm{MSSM}} = h_{ij}^u \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^d \mathbf{5}_i^* \mathbf{10}_j H_d\,. \tag{2}$$

For convenience, all superfields have been arranged in $SU(5)$ multiplets, $\mathbf{10} = (q,\, u^c,\, e^c)$ and $\mathbf{5}^* = (d^c,\, l)$, and $i, j = 1, 2, 3$ are flavour indices. We assume that the colour triplet partners of the electroweak Higgs doublets H_u and H_d have been projected out. The vacuum expection values $v_u = \langle H_u \rangle$ and $v_d = \langle H_d \rangle$ break the electroweak symmetry. In the following we will assume large $\tan\beta = v_u/v_d$, implying $v_d \ll v_u \simeq v_{\mathrm{EW}} = \sqrt{v_u^2 + v_d^2}$. For notational convenience, we will refer to H_u as H from now on.

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$	n^c_3	n^c_2	n^c_1	$H_{u,d}$	$S_{1,2}$	Φ
Q_i	0	1	2	a	a	$a+1$	$d-1$	$d-1$	d	0	0	$2(d-1)$

Table 1: Froggatt-Nielsen flavour charge assignments.

In addition to these chiral superfields, the model also contains a vector supermultiplet V ensuring invariance under local $B{-}L$ transformations and the gravity supermultiplet consisting of the graviton G and the gravitino $\tilde{G}$.

2.2 Froggatt-Nielsen flavour model

The flavour structure of the model is parametrized by a Froggatt-Nielsen flavour model based on a global $U(1)_{\mathrm{FN}}$ group, following Refs. [27, 28]. According to this model, the couplings in the superpotential can be estimated up to $\mathcal{O}(1)$ factors as powers of a common hierarchy parameter η, with the exponent given by the sum of the flavour charges Q_i of the fields involved in the respective operators. Setting the charges of all Higgs fields to zero, this implies

$$h_{ij} \sim \eta^{Q_i+Q_j}\,, \quad \sqrt{\lambda} \sim \eta^{Q_\Phi}\,. \tag{3}$$

The numerical value of the parameter $\eta \simeq 1/\sqrt{300}$ is deduced from the quark and lepton mass hierarchies. This remarkably simple flavour model can reproduce the experimental data on Standard Model masses and mixings, while at the same time it remains flexible enough to incorporate the phenomena beyond the Standard Model mentioned above. Further details on the predictive power of this model can be found in Ref. [29], where we recently performed a Monte-Carlo study to examine the impact of the $\mathcal{O}(1)$ factors.

In the following, we will restrict our analysis to the case of a hierarchical heavy (s)neutrino mass spectrum, $M_1 \ll M_2, M_3$, where $M = h^n\, v_{B-L}$. Furthermore we assume the heavier (s)neutrino masses to be of the same order of magnitude as the common mass m_S of the particles in the symmetry breaking sector, for definiteness we set $M_2 = M_3 = m_S$. With this, the Froggatt-Nielsen flavour charges are fixed as denoted in Tab. 1. Taking the $B{-}L$ gauge coupling to be $g^2 = g^2_{GUT} \simeq \pi/6$, the model can now, up to $\mathcal{O}(1)$ factors, be parametrized by the $U(1)_{\mathrm{FN}}$ charges a and d. The $B{-}L$ breaking scale v_{B-L}, the mass of the lightest of the heavy (s)neutrinos M_1, and the effective light neutrino mass parameter $\widetilde{m}_1$ are related to these by

$$v_{B-L} \sim \eta^{2a}\frac{v^2_{\mathrm{EW}}}{\overline{m}_\nu}\,, \qquad M_1 \sim \eta^{2d} v_{B-L}\,, \qquad \widetilde{m}_1 \equiv \frac{(m^\dagger_D m_D)_{11}}{M_1} \sim \eta^{2a}\frac{v^2_{\mathrm{EW}}}{v_{B-L}}\,. \tag{4}$$

Here, $\overline{m}_\nu = \sqrt{m_2 m_3}$, the geometric mean of the two light neutrino mass eigenvalues m_2 and m_3, characterizes the light neutrino mass scale, which, with the charge assignments above, can be fixed to 3×10^{-2} eV. To obtain this result, we exploited the seesaw formula $m_\nu = -m_D M^{-1} m_D^T$ with $m_D = h^\nu v_{\mathrm{EW}}$. Furthermore, it can be shown that $\widetilde{m}_1$ is bounded from below by the lightest neutrino mass m_1 [30].

In the following, we will study the model in terms of the more physical quantities v_{B-L} and M_1 instead of the $U(1)_{\mathrm{FN}}$ charges. To partly account for the $\mathcal{O}(1)$ uncertainties in the neutrino mass matrices, we will additionally vary $\widetilde{m}_1$. Apart from this, we ignore any further uncertainties of the model and simply set the $\mathcal{O}(1)$ prefactors to one. Furthermore, when considering the production of dark matter in form of gravitinos, cf. Section 3.2, the gravitino ($m_{\tilde{G}}$) and gluino ($m_{\tilde{g}}$) masses will be additional parameters.

2.3 Spontaneous symmetry breaking

Before the spontaneous breaking of $B-L$, supersymmetry is broken by the vacuum energy density $\rho_0 = \frac{1}{4}\lambda v_{B-L}^4$, which drives inflation. During this time, the dynamics of the system is governed by the slowly rolling scalar component ϕ of the inflaton multiplet Φ. The scalar components of the Higgs superfields $S_{1,2}$ are stabilized at zero. The right-handed sneutrinos and the scalar MSSM particles obtain their masses due to supergravity contributions. As the field value of the inflaton decreases, so do the effective masses in the Higgs sector, until a tachyonic direction develops in the effective scalar potential. The subsequent phase transition can best be treated in unitary gauge, in which the physical degrees of freedom are manifest. In particular, performing a super-gauge transformation relates the Higgs superfields $S_{1,2}$ and the vector superfield V to the respective fields S' and Z in unitary gauge,

$$S_{1,2} = \frac{1}{\sqrt{2}} S' \exp(\pm iT) \,, \qquad V = Z + \frac{i}{2gq_S}(T - T^*) \,. \tag{5}$$

Note that the chiral superfield T playing the role of the gauge transformation parameter is chosen such that S_1 and S_2 are mapped to the same chiral superfield S'. This reflects the fact that one chiral superfield is 'eaten' by the vector superfield in order to render it massive. The supermultiplet S' contains two real scalar degrees of freedom, $s' = \frac{1}{\sqrt{2}}(\sigma' + i\tau)$, where τ remains massive throughout the phase transition and σ' is the actual symmetry-breaking Higgs field. It acquires a vacuum expectation value proportional to $v(t) = \frac{1}{\sqrt{2}}\langle \sigma'^2(t,\vec{x})\rangle_{\vec{x}}^{1/2}$ which approaches v_{B-L} at large times. In the Lagrangian, we account for symmetry breaking by making the replacement $\sigma' \to \sqrt{2}v(t) + \sigma$, where σ denotes the fluctuations around the homogeneous Higgs background.

The fermionic component $\tilde{s}$ of the supermultiplet S' pairs up with the fermionic component $\tilde{\phi}$ of the inflaton supermultiplet Φ to form a Dirac fermion ψ, the higgsino, which becomes massive during the phase transition. Due to supersymmetry, the corresponding scalar fields (σ, τ and inflaton ϕ) end up having the same mass as the higgsino in the supersymmetric true vacuum. Likewise, the gauge supermultiplet Z (gauge boson A, real scalar C, Dirac gaugino $\tilde{A}$) and the (s)neutrinos N_i ($\tilde{N}_i$) acquire masses. Note that the choice of unitary gauge, cf. Eq. (5), forbids us to use the Wess-Zumino gauge, so Z denotes a full massive gauge multiplet with four scalar and four fermionic degrees of freedom. The capital N refers to the physical Majorana particle $N = (n, \bar{n})^T$ built from the two Weyl spinors contained in the superfields n^c and n. $\tilde{N}$ denotes the complex scalar superpartner of the left-chiral fermion n. For an overview of the particle spectrum, see Fig. 1.

At the end of the phase transition, supersymmetry is restored. An explicit calculation of the Lagrangian describing this phase transition is given in Appendix A. We can read off the mass eigenvalues during the phase transition, cf. Eqs. (106) to (110):

$$
\begin{aligned}
&m_\sigma^2 = \frac{1}{2}\lambda(3v^2(t) - v_{B-L}^2)\,, \qquad m_\tau^2 = \frac{1}{2}\lambda(v_{B-L}^2 + v^2(t))\,, \\
&m_\phi^2 = \lambda v^2(t)\,, \qquad m_\psi^2 = \lambda v^2(t)\,, \\
&m_Z^2 = 8g^2 v^2(t)\,, \\
&M_i^2 = (h_i^n)^2 v^2(t)\,.
\end{aligned} \tag{6}
$$

Here we have ignored corrections which arise due to thermal effects and due to supersymmetry breaking before the end of inflation in some hidden sector, leading to a mass for the gravitino.

2.4 Hybrid inflation and cosmic strings

The spontaneous breaking of $B-L$ discussed in the previous section marks the end of a stage of hybrid inflation, which is governed by the first term in the superpotential in Eq. (1). As the symmetry breaking proceeds very rapidly and abruptly, it represents what is often referred to as a 'waterfall' phase transition. It is accompanied by the production of local topological defects in the form of cosmic strings as well as the nonadiabatic production of particles coupled to the Higgs field, a process commonly