Baryogenesis with scalar bilinears

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We show that if the baryon asymmetry of the universe is generated through the out-of-equilibrium decays of heavy scalar bilinears coupling to two fermions of the minimal standard model, it is necessarily an asymmetry conserving $(B-L)$ that cannot survive past the electroweak phase transition because of sphalerons. We then show that a surviving $(B-L)$ asymmetry may be generated if the heavy scalars decay into two fermions, and *into two light scalars* (which may be detectable at hadron colliders). We list all possible such trilinear scalar interactions, and discuss how our new baryogenesis scenario may occur naturally in supersymmetric grand unified theories. [S0556-2821(99)04019-9]

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A major success of grand unified theories (GUTs) is apparently the generation of the baryon asymmetry of the universe. After Sakharov [1] pointed out the three conditions required for baryogenesis, the first realization of this proposal was found in GUTs [2]. However, it was later recognized that the generated baryon asymmetry conserves $(B-L)$ and is therefore washed away by the sphaleron-induced, fast baryon-number violating processes [3] before the electroweak phase transition.

Restricting ourselves to the fermion content of the standard model (SM), we first prove that $(B-L)$ conservation of the baryon asymmetry, generated in GUTs through heavy particle decays to known fermions only, is a generic feature of any theory. We then propose a new mechanism for baryogenesis in GUTs in which a $(B-L)$ asymmetry is generated via heavy scalar bilinear decays into two fermions and into two light scalars. In this scenario the required CP violation comes from the interference between the tree-level and one-loop self-energy diagrams. We classify all possible trilinear operators of the scalar bilinears which can contribute to this type of baryogenesis. We demonstrate that in a wide class of GUTs, the new baryogenesis mechanism occurs naturally. A generic feature of these scenarios is the existence of light scalars. For example, in some supersymmetric (SUSY) GUTs, there are pseudo-Goldstone-type bilinears whose masses are given by seesaw-type relations and may be as low as $\mathcal{O}(1)$ TeV, giving rise to detectable signatures at future collider experiments. In particular, observation of an excess of same-sign lepton pairs or *s*-channel diquark resonances at the Fermilab Tevatron or the CERN Large Hadron Collider (LHC) would strongly support the proposed baryogenesis scenario with scalar bilinears.

In spite of the tremendous successes of the SM, there are now definite experimental indications for physics beyond it. With the positive evidence of neutrino masses in atmospheric [4] and solar neutrino [5] as well as the Liquid Scintillation Neutrino Detector (LSND) [6] experiments, it becomes apparent that we have to extend the SM. One important approach to understand the new physics beyond the SM is to study possible new particles whose existence may be indicated by the particle content of the SM. In the SM the quarks and leptons transform under the $SU(3)_C\times SU(2)_L\times U(1)_Y$ gauge group as $(u_i,d_i)_L\sim(3,2,1/6)$, $u_{iR}\sim(3,1,2/3)$, $d_{iR}\sim(3,1,-1/3)$; $(\nu_i,l_i)_L\sim(1,2,-1/2)$, $l_{iR}\sim(1,1,-1)$, where $i=1,2,3$ is the generation index, and there is only one doublet Higgs scalar, $(\phi^+,\phi^0)\sim(1,2,1/2)$, which couples $\overline{(u_i,d_i)_L}$ to u_{jR} and d_{jR}, as well as $\overline{(\nu_i,l_i)_L}$ to l_{jR}. However, other scalars which transform as bilinear combinations of the SM fermions (listed in Table I) are of great interest. There are several scenarios in which new scalar bilinears are added to explain the masses of neutrinos. Dileptons, leptoquarks, and diquarks inevitably occur

TABLE I. Scalar bilinears that can take part in the generation of a baryon asymmetry of the universe.

Representation	Notation	qq	$\overline{ql}$	$q\overline{l}$	ll
(1,1,−1)	χ^-				×
(1,3,−1)	ξ				×
(1,1,−2)	L^{--}				×
(3*,1,1/3)	Y_a	×	×		
(3*,3,1/3)	Y_b	×	×		
(3*,1,4/3)	Y_c	×	×		
(3*,1,−2/3)	Y_d	×			
(3,2,1/6)	X_a			×	
(3,2,7/6)	X_b			×	
(6,1,−2/3)	Δ_a	×			
(6,1,1/3)	Δ_b	×			
(6,1,4/3)	Δ_c	×			
(6,3,1/3)	Δ_L	×			

in all interesting GUTs [7]. They are classified and their phenomenology has been studied in comprehensive works [8,9]. In the following we show that they are also important for the generation of a baryon asymmetry of the universe.

To generate a baryon asymmetry it is necessary to have [1] (i) baryon number violation, (ii) C and CP violation, and (iii) out-of-equilibrium conditions. In early works it was noticed that baryogenesis is possible in GUTs because there exist new gauge and Higgs bosons whose decays violate baryon number. When these heavy particles (say X) decay into two quarks and into a quark and an antilepton, the baryon and lepton numbers are broken [10]. For CP violation this mechanism requires two heavy gauge or Higgs bosons, X and Y, each of which should have two decay modes,

$$X \to A + B^* \quad \text{and} \quad X \to C + D^*,$$

$$Y \to A + C^* \quad \text{and} \quad Y \to B + D^*,$$

so that there exist one-loop vertex corrections to these decays. The required CP violation occurs due to the interference between tree and loop diagrams. As required by the out-of-equilibrium condition, masses of these particles must satisfy

$$\Gamma_X < H = 1.7\sqrt{g_*}\,\frac{T^2}{M_P} \quad \text{at} \quad T = M_X, \tag{1}$$

where Γ_X is the decay rate of the heavy particle X; H is the Hubble constant; g_* is the effective number of massless degrees of freedom; and M_P is the Planck scale.

In specific GUT scenarios such as SU(5) and SO(10), $(B-L)$ is either a global or a local symmetry, respectively. Hence the asymmetry generated by the above mechanism is $(B-L)$ conserving [7]. When the scalar or vector bosons decay only into fermions, any attempt to generate a $(B-L)$ asymmetry leads to its large suppression in all these models. Only in models with a right-handed neutrino, such as SO(10), is it possible to generate a $(B-L)$ asymmetry after the $(B-L)$ symmetry is broken at some high scale, so that the right-handed neutrinos become massive and since they are Majorana fermions, their decays violate lepton number [11]. Since we are not concerned with any fermion beyond the SM, this scenario falls outside the scope of this paper.

The baryon asymmetry generated in the above scenarios by the interactions that conserve $(B-L)$ is washed out by sphaleron processes [3] effective at temperatures 10^2 GeV $\lesssim T \lesssim 10^{12}$ GeV. We shall now prove that if the decay products are SM fermions only, this is in fact a generic property of any baryon asymmetry generated by the above described mechanism. This follows from an operator analysis analogous to the one used to show that the minimal scenarios of proton decay conserve $(B-L)$ [12]. For definitness we consider scalars X and Y, but obviously the result generalizes also to vectors.

Let us start from the Lagrangian giving the decays of X and Y,

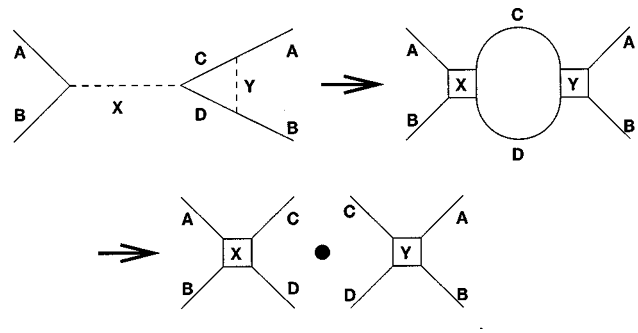

FIG. 1. Interference of effective four-fermion operators that generates baryon asymmetry.

$$\mathcal{L} = f_x^{ab}\bar{A}BX + f_x^{cd}\bar{C}DX + f_y^{ac}\bar{A}CY + f_y^{bd}\bar{B}DY, \tag{2}$$

where A,B,C,D denote any SM fermion. To obtain a nonzero CP violation from the interference between tree and vertex diagrams, we require X and Y to be distinct from each other and to have different decay modes. One can then write down all possible combinations of A, B, C, and D, with X and Y, and find out the decay modes of X and Y. Since the out-of-equilibrium condition and the nonvanishing of the absorptive part of the loop integral require these scalars X and Y to be much heavier than the fermions, we can integrate them out and write down the diagrams in terms of the four-fermion effective operators of the SM, as shown in Fig. 1 [13].

This simple but crucial step allows us to use existing knowledge on SM four-fermion operators for baryon number violation that have been studied extensively in the literature [12]. It was found that all these operators conserve $(B-L)$ to the lowest order. Any $(B-L)$ violating operator will be suppressed by $\langle\phi\rangle^2/M_{GUT}^2$ compared to the $(B+L)$ violating operators. In models with an intermediate symmetry-breaking scale or with new Higgs scalars at some intermediate scales, this suppression factor may be softened a little, but still strong enough to rule out any possibility of generating enough baryon asymmetry of the universe. On the other hand, any four-fermion operator that violates only lepton number requires all the fermions to be the same; hence it cannot generate the required CP asymmetry. Therefore a $(B-L)$ asymmetry, needed to survive the sphaleron processes, is impossible to generate with the SM four-fermion operators.

We now show how a $(B-L)$ asymmetry can be generated in GUTs if there are both heavy and light scalar bilinears. This is a generalization of a recently proposed scenario of leptogenesis [14]. Low-energy effective operators now contain two fermions and two scalar bilinears. The required CP violation for baryogenesis comes entirely from an interference between the tree-level decay and the self-energy corrections.

Consider the scalars $S_{1,2}$, each of which can decay into two fermions $\psi_1 + \psi_2$ and into two scalars $Z_1 + Z_2$. The Lagrangian describing these interactions is of the form

$$\mathcal{L} = M_a^2 S_a^\dagger S_a + (f_a \psi_1 \psi_2 S_a^\dagger + \mu_a Z_1 Z_2 S_a^\dagger + \text{H.c.}), \tag{3}$$

where the fermions $\psi_{1,2}$ and the scalars $Z_{1,2}$ are assumed to be much lighter than $S_{1,2}$. This is then analogous to Eq. (14) of Ref. [14] and we can simply use the formalism developed there to obtain the $(B-L)$ asymmetries generated by the tree-level decays of the physical states approximating $S_{1,2}$ and their interference with the one-loop self-energy diagrams [14], given by

$$\delta_a \simeq \Delta(B-L)\frac{\mathrm{Im}[\mu_1\mu_2^* f_1^* f_2]}{16\pi^2(M_1^2-M_2^2)}\left[\frac{M_a}{\Gamma_a}\right], \tag{4}$$

where $\Gamma_a=(|\mu_a|^2+M_a^2|f_a|^2)/(8\pi M_a)$ is the decay width.

Let $M_1>M_2$, then as the universe cooled down to below M_1, most of S_1 would decay away. However, the asymmetry so created would be erased by the $(B-L)$ nonconserving interactions of S_2. Hence only the subsequent decay of S_2 at $T<M_2$ would generate a $(B-L)$ asymmetry that would pass through the electroweak phase transition unscathed. If S_2 is heavy enough to satisfy the out-of-equilibrium condition $\Gamma_a<H$ of Eq. (1), then the final baryon asymmetry is approximately given by [10] $\delta_B\sim\delta_2/(3g_*)$. The desired value of $\delta_B\sim 10^{-10}$ may thus be obtained from Eq. (4) with a variety of scalar masses and couplings.

At energies below the heavy scalar $S_{1,2}$ masses, lower bounds of which can be obtained from Eq. (1), any $(B-L)$ violating dimension-five effective operator of the form

$$\mathcal{O}_{(B-L)}\equiv[\psi_1\psi_2 Z_1^\dagger Z_2^\dagger] \tag{5}$$

can generate a baryon asymmetry. In the SM there is only one Higgs doublet scalar ϕ; hence there can be only one $(B-L)$ violating effective operator of the required form, i.e., $l_i l_j\phi\phi$ [12]. This operator has been studied in the literature extensively. It contains all the scenarios of neutrino masses and leptogenesis [15]. For example, it can be induced by the triplet bilinear ξ in Table I generating a lepton asymmetry of the universe [14]. It may also originate from heavy Majorana neutrinos [11].

In GUTs where the scalar bilinears listed in Table I occur, there are many other possibilities to form dimension-five operators of the type given by Eq. (5) that violate lepton and baryon numbers. As all the scalar bilinears couple to ordinary fermions, the classification of the two-scalar–two-fermion baryon-asymmetry generating operators in GUTs reduces to that of all possible $(B-L)$ violating trilinear operators of the scalar bilinears, as shown in Table II. From this list, we see that the first two trilinear scalar operators, $\mathcal{O}_{1,2}$, give rise to the operator $l_i l_j\phi\phi$. The rest occur in GUTs such as SO(10) and E_6, as will be demonstrated below. Note the interesting fact that $|\Delta(B-L)|=2$ in all cases.

To exemplify the general discussion we shall now consider a large class of SUSY SO(10) GUTs. The SO(10) symmetry may be broken down to the SM symmetry through several intermediate steps that include the Pati-Salam $SU(4)_C\times SU(2)_L\times SU(2)_R$ and/or $SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ symmetries [16]. It has been shown [17,18] that at these intermediate stages, the requirement of stabilizing the charge-conserving vacuum after breaking the supersymmetry introduces higher-dimensional operators to the theory.

TABLE II. Trilinear scalar operators that can contribute to the baryon asymmetry of the universe.

Operators	$B-L$	Operators	$B-L$
$\mathcal{O}_1=\mu_1\phi\phi\chi^-$	-2	$\mathcal{O}_2=\mu_2\phi\phi\xi$	-2
$\mathcal{O}_3=\mu_3\chi^-\chi^-L^{++}$	-2	$\mathcal{O}_4=\mu_4\xi\xi L^{++}$	-2
$\mathcal{O}_5=\mu_5 Y_a Y_c^\dagger\chi^+$	2	$\mathcal{O}_6=\mu_6 Y_d Y_a Y_a$	2
$\mathcal{O}_7=\mu_7 Y_d Y_b Y_b$	2	$\mathcal{O}_8=\mu_8 Y_c Y_d Y_d$	2
$\mathcal{O}_9=\mu_9 Y_b Y_c^\dagger\xi^\dagger$	2	$\mathcal{O}_{10}=\mu_{10} Y_a Y_d^\dagger\chi^-$	-2
$\mathcal{O}_{11}=\mu_{11} Y_b Y_d^\dagger\xi$	-2	$\mathcal{O}_{12}=\mu_{12} Y_c Y_d^\dagger L^{--}$	-2
$\mathcal{O}_{13}=\mu_{13} X_b X_a^\dagger\chi^-$	-2	$\mathcal{O}_{14}=\mu_{14} X_b X_a^\dagger\xi$	-2
$\mathcal{O}_{15}=\mu_{15} X_a X_b Y_c^\dagger$	2	$\mathcal{O}_{16}=\mu_{16} X_a\phi Y_d$	2
$\mathcal{O}_{17}=\mu_{17} X_a\phi^\dagger Y_a$	2	$\mathcal{O}_{18}=\mu_{18} X_a\phi^\dagger Y_b$	2
$\mathcal{O}_{19}=\mu_{19} X_a X_a Y_a^\dagger$	2	$\mathcal{O}_{20}=\mu_{20} X_a X_a Y_b^\dagger$	2
$\mathcal{O}_{21}=\mu_{21} X_b Y_d\phi^\dagger$	2	$\mathcal{O}_{22}=\mu_{22}\Delta_a Y_a Y_a$	2
$\mathcal{O}_{23}=\mu_{23}\Delta_a Y_b Y_b$	2	$\mathcal{O}_{24}=\mu_{24}\Delta_a\Delta_b\Delta_b$	2
$\mathcal{O}_{25}=\mu_{25}\Delta_c\Delta_a\Delta_a$	2	$\mathcal{O}_{26}=\mu_{26}\Delta_c Y_d Y_d$	2
$\mathcal{O}_{27}=\mu_{27}\Delta_b X_a^\dagger X_a^\dagger$	-2	$\mathcal{O}_{28}=\mu_{28}\Delta_L Y_b Y_d$	2
$\mathcal{O}_{29}=\mu_{29}\Delta_b Y_a Y_d$	2	$\mathcal{O}_{30}=\mu_{30}\Delta_a Y_d Y_c$	2
$\mathcal{O}_{31}=\mu_{31}\Delta_c X_a^\dagger X_b^\dagger$	-2	$\mathcal{O}_{32}=\mu_{32}\Delta_L X_a^\dagger X_a^\dagger$	-2
$\mathcal{O}_{33}=\mu_{33}\Delta_L\Delta_L\Delta_a$	2	$\mathcal{O}_{34}=\mu_{34}\Delta_a^\dagger\Delta_b\chi^-$	-2
$\mathcal{O}_{35}=\mu_{35}\Delta_a^\dagger\Delta_L\xi$	-2	$\mathcal{O}_{36}=\mu_{36}\Delta_b^\dagger\Delta_c\chi^-$	-2
$\mathcal{O}_{37}=\mu_{37}\Delta_L^\dagger\Delta_c\xi$	-2	$\mathcal{O}_{38}=\mu_{38}\Delta_a^\dagger\Delta_c L^{--}$	-2

The resulting low-energy theory is the R-parity conserving minimal supersymmetric SM plus light diquark, leptoquark, and dilepton states, which obtain masses via seesaw-type relations.

In the supersymmetric limit and in the absence of the nonrenormalizable terms, the superpotential of a minimal SUSY Pati-Salam intermediate theory [19] has a complexified U(30) symmetry that operates on SU(2) triplet, SU(4) tenplet superfields. After the neutral components of the triplets acquire vacuum expectation values at the scale M_R, thus breaking the symmetry, a U(29) complexified symmetry remains, giving rise to 118 massless fields, 18 of which get masses from the D terms. Inclusion of the higher-dimensional effective terms necessary to conserve the electric charge leads thus to a total of 50 complex pseudo-Goldstone bosons with masses $m_{pG}\sim M_R^2/M_P$, where M_P is the Planck scale. For M_R as high as $\mathcal{O}(10^{10})$ GeV, the pseudo-Goldstone-type diquarks, leptoquarks, and dileptons may have masses $\mathcal{O}(1)$ TeV. More details can be found in Ref. [18].

Let us consider one of the choices that leaves one Y_b field as light as $\mathcal{O}(1)$ TeV. Then, for example, the operator $\mathcal{O}_{23}$ in Table II implies that some of the heavy Δ_a could generate a baryon asymmetry of the universe. Even though the left-right symmetry breaking scale M_R is around 10^{10} GeV, the Δ_a can be much heavier than this mass scale. The out-of-equilibrium condition implies that these fields are as heavy as 10^{13} GeV. Their decay modes into Y_b+Y_b and into d^c+d^c violate baryon number as well as $(B-L)$. Hence the $(B-L)$ asymmetry can be generated according to the mechanism discussed before. As the masses of ν_R are of order M_R in this model, their interactions may erase the generated asymmetry. We assume that this is not the case. The Yukawa couplings of ν_R should then be less than about 10^{-4}, which are now too small for realistic neutrino masses (for oscillations) via the canonical seesaw mechanism. However, there are also $SU(2)_L$ Higgs triplets in this model that can be used to generate the required neutrino masses [14].

An important feature of our new baryogenesis mechanism in general, and the discussed SUSY GUT scenario in particular, is that the light scalar bilinear fields can lead to detectable signatures at Fermilab Tevatron or CERN LHC. The most interesting among these are the *s*-channel resonance processes mediated by diquarks [9]. They may result in resonance production of light dijets or distinct final states such as tc or tt. The leptonic decays of two top quarks provide same-sign dilepton final states that have very little SM background. At the Tevatron, the *s*-channel production is seaquark suppressed and diquark masses up to only $\mathcal{O}(1)$ TeV are testable in the tc, tt channels, but at the LHC, diquark masses as high as $\mathcal{O}(10)$ TeV can be probed [9]. Therefore, any possible signal of this type detected at hadron colliders will lend support to the proposed baryogenesis mechanism.

To summarize, we have shown that a $(B-L)$ asymmetry cannot be generated in GUTs if the new heavy gauge bosons or scalar bilinears decay only into SM fermions. As a result, the baryon asymmetry of the universe generated by this type of mechanism cannot survive to the present day because it would have been washed out by the sphaleron processes. We then show that it is possible to generate a $(B-L)$ asymmetry in GUTs using heavy scalar bilinear decays into known fermions and into light scalars. We have classified all possible operators of the scalar bilinears that can contribute to this baryogenesis mechanism. As an example, we have demonstrated that the proposed baryogenesis mechanism occurs naturally in a wide class of SUSY GUTs based on the SO(10) gauge symmetry. The light scalar bilinears may lead to clear detectable experimental signatures at colliders, especially in the discussed SUSY GUTs where they are pesudo-Goldstone bosons with mass of $\mathcal{O}(1)$ TeV.

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