# Postsphaleron Baryogenesis

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We present a new mechanism for generating the baryon asymmetry of the Universe directly in the decay of a singlet scalar field $S_r$ with a weak scale mass and a high dimensional baryon number-violating coupling. Unlike most currently popular models, this mechanism, which becomes effective after the electroweak phase transition, does not rely on the sphalerons for inducing a nonzero baryon number. *CP* asymmetry in $S_r$ decay arises through loop diagrams involving the exchange of $W^{\pm}$ gauge bosons and is suppressed by light quark masses, leading naturally to a value of $\eta_B \sim 10^{-10}$. The simplest realization of this idea which uses a six quark $\Delta B = 2$ operator predicts colored scalars accessible to the CERN Large Hadron Collider and neutron-antineutron oscillation within reach of the next-generation experiments.

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Recent developments in particle physics have had a profound impact on cosmology. One of the most far-reaching consequences has been the possibility that new interactions beyond the standard model can explain the origin of matter-antimatter asymmetry of the Universe as a dynamical phenomenon. There are currently several attractive scenarios which achieve this, the two most widely discussed ones being (i) baryogenesis via leptogenesis [1], which is connected to the seesaw mechanism and neutrino masses, and (ii) weak scale baryogenesis [2], which involves supersymmetric or multi-Higgs extensions of the standard model. Both of these proposals depend crucially on the properties of the electroweak sphaleron [3], which serves as the source of $B$ violation. Since the nature of new physics beyond the standard model remains unknown presently, it is important to explore alternative mechanisms that can explain the matter-antimatter asymmetry while yielding testable consequences. In this Letter, we suggest and explore one such alternative.

The salient feature of our proposal is that baryogenesis occurs via the direct decay of a scalar boson $S_r$ having a weak scale mass and a high dimensional baryon-violating coupling. $S_r$ is the real part of a baryon number carrying complex scalar $S$, which acquires a vacuum expectation value (vev). The decays $S_r \to 6q$ and $S_r \to 6\bar{q}$ will then be allowed, providing the source for $B$ asymmetry. These decays occur when the temperature of the Universe is $T \sim 0.1$–$100$ GeV. By this time, the electroweak sphalerons have gone out of thermal equilibrium and, thus, play no role in the $B$ asymmetry generation. We call this mechanism "postsphaleron baryogenesis." The three Sakharov conditions for successful baryogenesis [4] are satisfied rather easily in our scheme. The high dimensionality of the $B$-violating coupling of $S_r$ to the quark fields allows the $\Delta B \neq 0$ decays to go out of equilibrium at weak scale temperatures. *CP* violation occurs in the decay via loop diagrams involving the exchange of the standard model $W^{\pm}$ gauge bosons. This amplitude has sufficient light quark mass suppression to explain naturally the observed (small) value of the baryon to photon ratio $\eta_B \sim 10^{-10}$. The simplest realization of our mechanism involves interactions that violate $B$ by two units and, therefore, gives rise to neutron-antineutron oscillations, bringing it to within the realm of observability. This connection provides a strong motivation for improved searches for $N \leftrightarrow \bar{N}$ oscillation [5].

To see the connection with $N \leftrightarrow \bar{N}$ oscillation, consider an interaction of the form $S\mathcal{O}_{\Delta B}$, with mass dimension $M^{-n}$, where $S$ is a standard model singlet complex scalar field, $\mathcal{O}_{\Delta B}$ is the baryon number-violating operator in question, and $n$ is a positive integer. This interaction will lead to baryon number violation if $\langle S \rangle \neq 0$. Since the rate of these $\Delta B \neq 0$ interactions in the early Universe goes like $M^{-2n}$, the out-of-equilibrium condition can be satisfied at a lower temperature (multi-GeV range) for $n \geq 3$. Clearly, the operator leading to the $B - L$ conserving proton decay mode cannot be useful for us, since present experimental limits on proton lifetime imply that this operator should go out of equilibrium at temperatures of the order of $10^{14}$–$10^{15}$ GeV. On the other hand, for a process such as $N \leftrightarrow \bar{N}$ oscillation [6–8], present experimental lower limits on the oscillation time $\tau_{N-\bar{N}} \geq 10^8$ sec [9,10] allow the mass $M$ appearing in the operator to be in the multi-TeV range. The out-of-equilibrium temperature for the processes $S_r \to 6q$ and $S_r \to 6\bar{q}$ is then allowed to be below the sphaleron decoupling temperature of about 100 GeV. While it might appear that postsphaleron baryogenesis would work with any $\Delta B = p$ operators with $p \geq 2$, it turns out that, for $p > 2$, the lifetime of $S_r$ will be too long, upsetting big bang nucleosynthesis. Thus, we focus on $\Delta B = 2$ operators. These are obtained by integrating out colored scalar fields, which are found to have masses within reach of the CERN Large Hadron Collider (LHC).

An attempt to generate baryon asymmetry at a temperature of the order of MeV via the decay of a heavy

 

($\sim$50 TeV) gravitino within supergravity was proposed in Ref. [11]. Such a large gravitino mass would, however, require fine-tuning to solve the hierarchy problem. Another suggested scenario [12] invokes the decay of the inflaton into squarks, with their subsequent decay producing baryon asymmetry. This mechanism requires that the reheating temperature be less than 1 GeV in order for the scattering and inverse decays not to wash out the asymmetry. The model presented here differs from these earlier attempts in three crucial ways: (i) There is a strong link between baryon asymmetry and $N \leftrightarrow \bar{N}$ oscillation, (ii) the mechanism of inducing $CP$ asymmetry via the standard model $W^{\pm}$ loops is entirely new, and (iii) the model predicts colored particles accessible to LHC.

To illustrate our mechanism for postsphaleron baryogenesis, we consider a generic TeV scale model that gives rise to the higher dimensional operator for $N \leftrightarrow \bar{N}$ oscillation. It consists of the following color sextet, $SU(2)_L$ singlet scalar bosons ($X$, $Y$, $Z$) with hypercharge $-\frac{4}{3}, +\frac{8}{3}, +\frac{2}{3}$, respectively, that couple to the right-handed quarks [13]. In addition, there is a complex scalar field $S$ which is a singlet of the standard model with mass in the 100 GeV range. With this field content, one has the following standard model invariant interaction:

$$\mathcal{L}_I = \frac{h_{ij}}{2} X d_i^c d_j^c + \frac{f_{ij}}{2} Y u_i^c u_j^c + g_{ij} Z u_i^c d_j^c + \frac{\lambda_1}{2} S X^2 Y + \frac{\lambda_2}{2} S X Z^2 + \text{H.c.} \quad (1)$$

If the scalar field $S$ which has $B = 2$ is given a vacuum expectation value, cubic scalar couplings of the type $X^2 Y$ that break the baryon number by two units will be induced. In turn, it will lead to $N \leftrightarrow \bar{N}$ oscillation via the diagram in Fig. 1 with $S_r$ replaced by $\langle S \rangle$ [8]. We note that not all of the ($X, Y, Z$) fields are needed for $B$ violation and $N \leftrightarrow \bar{N}$ oscillation; ($X, Y$) or ($X, Z$) fields will do.

To see the constraints on the parameters of the theory, we note that the present limits on $\tau_{N-\bar{N}} \geq 10^8$ sec imply that the strength $G_{N-\bar{N}}$ of the $\Delta B = 2$ transition is

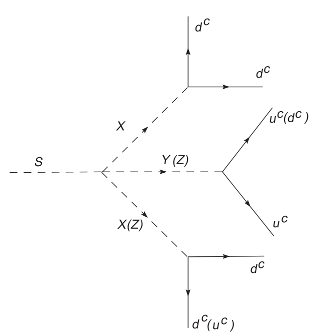


FIG. 1. Tree level diagrams contributing to $S_r$ decays into 6 antiquarks. There are other diagrams where $S_r$ decays into 6 quarks, obtained from the above by reversing the arrows of the quark fields.

$\leq 10^{-28}$ GeV$^{-5}$. From Fig. 1, we conclude that

$$G_{N-\bar{N}} \simeq \frac{\lambda_1 \langle S \rangle h_{11}^2 f_{11}}{M_Y^2 M_X^4} + \frac{\lambda_2 \langle S \rangle h_{11} g_{11}^2}{M_X^2 M_Z^4} \leq 10^{-28}\,\text{GeV}^{-5}. \quad (2)$$

For $\lambda_{1,2} \sim 1$, $h_{11} \sim f_{11} \sim g_{11} \sim 10^{-3}$–$10^{-4}$, and $\langle S \rangle \sim 10^2$ GeV, we find that $M_{X,Y,Z} \simeq 1$ TeV is allowed. In fact, we will see that the masses of $X$, $Y$, $Z$ cannot be much larger than 1 TeV for successful baryogenesis. Note that the couplings $(f, g, h)_{ij}$ to the second- and third-generation fermions could be larger.

Other constraints can come from low energy observations such as bounds on flavor changing hadronic processes such as $K - \bar{K}$, $D - \bar{D}$ transition, etc. If we make the simplest assumption dictated by the left-right symmetric theories that the left and the right-handed mixings are equal, then the strongest constraints come from the $K - \bar{K}$ transition, which implies that, for $h_{11} \sim 10^{-3}$, $M_X \geq$ 1 TeV, which is consistent with our choice of parameters dictated by observability of the $N \leftrightarrow \bar{N}$ transition.

The model of Eq. (1) is embeddable into an $SU(2)_L \times SU(2)_R \times SU(4)_c$ framework whence the $X$, $Y$, $Z$, $S$ fields will be part of the $\Delta^c(\mathbf{1}, \mathbf{3}, \mathbf{10})$ Higgs multiplet. In the supersymmetric version, it is natural, due to global symmetries present in this model, that the uneaten components of $\Delta^c$ which can be identified as $X$, $Y$, $Z$, $S$ remain light to the TeV scale. Unification of gauge couplings that occurs in the minimal supersymmetric standard model is no longer automatic in this case. While we take the baryon number as part of the gauge symmetry, the mechanism of $B$ asymmetry generation also works if $B$ is a spontaneously broken global symmetry [14]. The imaginary part of $S$ is a Goldstone boson in this case. (With gauged $B - L$, the imaginary part of $S$ has a mass of the order of TeV.)

Before proceeding to the discussion of how baryon asymmetry arises in this model, let us first consider the effect of the new interactions in Eq. (1) on any preexisting baryon asymmetry. For this purpose, we assume the following mass hierarchy between the $S$ field and the ($X, Y, Z$) fields: $M_S \sim 100$ GeV $\ll M_{X,Y,Z} \sim$ TeV. For $T \geq M_{X,Y,Z}$, the $\Delta B = 2$ interaction rates scale like $T$ (in the case where gauged $B - L$ symmetry is broken at a scale higher than $M_{X,Y,Z}$) and are in equilibrium at least down to $T \simeq M_{X,Y,Z}$. They will, therefore, erase any preexisting baryon asymmetry. They remain in equilibrium down to the temperature $T_*$ given by the inequality:

$$\frac{18}{(2\pi)^9} \frac{\lambda_2^2 h^2 g^4 T^{13}}{(6 M_{X,Z})^{12}} \leq \frac{g_*^{1/2} T^2}{M_{Pl}}. \quad (3)$$

Here $h$ and $g$ refer to the largest of $h_{ij}$ or $g_{ij}$ ($i$, $j$ are family indices). For $h$, $g$, $\lambda_2 \sim 1$, this leads to $T_* \simeq M_{X,Z}$.

The singlet field $S$ will play a key role in the generation of baryon asymmetry. We assume that $\langle S \rangle \sim M_{S_r} \sim 10^2$ GeV, where $S_r$ is the real part of the $S$ field after its vev is subtracted. $S_r$ can then decay into final states with

$B = \pm 2$, viz., $S_r \to 6q$ and $S_r \to 6\bar{q}$, inducing a net baryon asymmetry.

On the way to calculating the baryon asymmetry, let us first discuss the out-of-equilibrium condition. As the temperature of the Universe falls below the masses of the $X$, $Y$, $Z$ particles, the annihilation processes $X\bar{X} \to d^c \bar{d}^c$, etc., remain in equilibrium. As a result, the number density of $X$, $Y$, $Z$ particles gets depleted and only the $S$ particle survives along with the usual standard model particles. The primary decay modes of $S_r$ are $S_r \to u^c d^c d^c u^c d^c d^c$ and $S_r \to \bar{u}^c \bar{d}^c \bar{d}^c \bar{u}^c \bar{d}^c \bar{d}^c$. There could be other decay modes which can be made negligible by the choice of parameters without affecting our discussions of $N \leftrightarrow \bar{N}$ oscillation and baryogenesis (see later). For $T \geq M_{S_r}$, the decay rate of $S_r$ is given by the left-hand side of Eq. (3). This decay goes out of equilibrium around $T_* \sim M_X$. Below this temperature, the decay rate of $S_r$ falls very rapidly as the temperature cools. However, as soon as $T \leq M_{S_r}$, the decay rate becomes a constant while the expansion rate of the Universe slows down. So at a temperature $T_d$, $S_r$ will start to decay with

$$T_d \simeq \left[\frac{18 P \lambda_2^2 h^2 g^4 M_{P\ell} M_{S_r}^{13}}{(2\pi)^9 1.66 g_*^{1/2} (6M_X)^{12}}\right]^{1/2}. \qquad (4)$$

This is obtained by equating the decay rate of $S_r$ to the expansion rate of the Universe. In Eq. (4), the factor 18 is a color factor, $h^2 = \mathrm{Tr}(h^\dagger h)$, etc., while $P$ is a phase space factor, which we have computed for the six body decay via Monte Carlo methods and found $P \simeq 2.05$. The corresponding epoch must be above that of big bang nucleosynthesis. This puts a constraint on the parameters of the model. For instance, for $M_S \sim 200$ GeV and $M_X \sim$ TeV, we get $T_d \sim 40$ MeV (for $g \sim h \sim 1$). Note that $M_X$ cannot be much larger than about 1 TeV; otherwise, it will affect big bang nucleosynthesis significantly. Note also that at least some of the couplings in $h$ and $g$ should be of the order of 1. This would imply that the first family couplings should be of order ($10^{-3}$–$10^{-4}$) from naturalness ($h_{11} \sim V_{td}^2 h_{33}$, etc.), making $N \leftrightarrow \bar{N}$ oscillation accessible to next-generation experiments.

We now proceed to calculate the baryon asymmetry in this model. It is well known that baryon asymmetry can arise only via the interference of a tree diagram with a one-loop diagram which has an absorptive part. The tree diagrams are clearly the one where $S_r \to 6q$ and $S_r \to 6\bar{q}$. There are, however, two classes of loop diagrams that can contribute to baryon asymmetry: one where the loop involves the same fields $X$, $Y$, and $Z$ as in Fig. 2, and a second one involving $W^\pm$ gauge boson exchange as shown in Fig. 3. In the $(X, Z)$ model and in the $(X, Y)$ model, only the latter contribution exists (the former trace being real). So we focus on that latter and summarize our results. If one of the external up-type quarks is the top quark, the corresponding quark line receives a wave function correction via the $W^\pm$ gauge boson exchange. The asymmetry from this diagram is given by

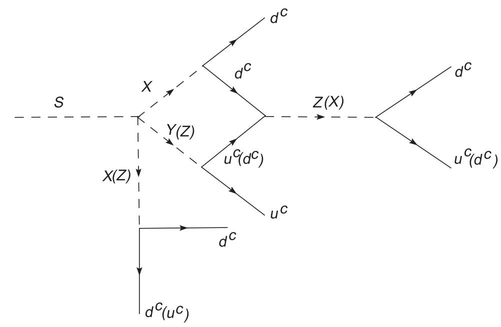


FIG. 2. Diamond loop diagram in the $(X, Y, Z)$ model.

$$\frac{\epsilon_B^{\mathrm{wave}}}{\mathrm{Br}} \simeq -\frac{3\alpha_2}{8}\left(1 + \frac{m_W^4}{m_t^4}\right)\frac{\mathrm{Im}[V^* \hat{M}_d^2 V^T \hat{M}_u g g^\dagger]_{33}}{m_t m_W^2 (g g^\dagger)_{33}}, \qquad (5)$$

where $\hat{M}_u = \mathrm{diag}(m_u, m_c, m_t)$, $\hat{M}_d = \mathrm{diag}(m_d, m_s, m_b)$, and $V$ is the Cabibbo-Kobayashi-Maskawa matrix. Br stands for the branching ratio of $S_r$ into $6q + 6\bar{q}$.

The vertex correction via the $W$ boson exchange gives

$$\frac{\epsilon_B^{\mathrm{vertex}}}{\mathrm{Br}} \simeq -\frac{\alpha_2}{4}\frac{\mathrm{Im\,Tr}[g^T \hat{M}_u V g^\dagger V^* \hat{M}_d]}{m_W^2 \mathrm{Tr}(g^\dagger g)}. \qquad (6)$$

Here we have assumed that $M_{S_r} \gg m_t$. In the limit where $m_{S_r} \ll m_W$, we have the same asymmetry as in Eq. (6) but with a factor of $(-1/4)$ multiplying it. Of course, in this case, decays involving the final state top quark are disallowed, which is to be implemented by removing the top quark contribution in the trace of Eq. (6) [15].

It is interesting to note that, in this mechanism, there is a natural explanation of the observed baryon asymmetry $\eta_B \sim 10^{-10}$. It follows from the light quark mass and mixing angle suppression. As an example, consider the following choice of parameters: $m_c(m_c) = 1.27$ GeV, $m_b(m_b) = 4.25$ GeV, $m_t = 174$ GeV, $V_{cb} \simeq 0.04$, $M_{S_r} = 200$ GeV, and $|g_{33}| \simeq |g_{23}| \sim 1$, with smaller values of $g_{1i}$. We find $\epsilon_B \sim 10^{-8}$ in this case from Eq. (5). The corresponding value from Eq. (6) is an order of magnitude larger, for the same input parameters.

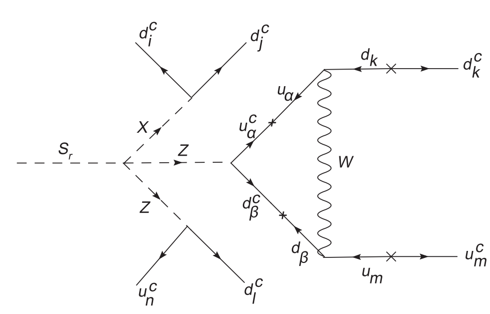


FIG. 3. One-loop vertex correction diagram for the $B$-violating decay $S_r \to 6q$. There are also wave function corrections involving the exchange of the $W^\pm$ gauge boson.

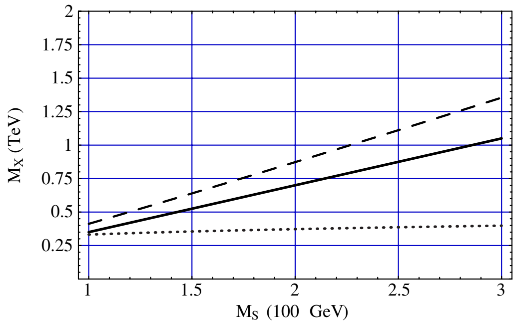


FIG. 4 (color online). The allowed range of $M_X$ and $M_S$ needed to generate the baryon asymmetry (along the black curve), decay temperature above 200 MeV (points below the dashed curve), and $\tau_{N\bar{N}} \geq 10^8$ sec with $\bar{\lambda} = 10^{-4}$ (points above the dotted curve).

There is a further dilution of the baryon asymmetry arising from the fact that $T_d \ll M_{S_r}$, since the decay of $S_r$ also releases entropy into the Universe. In this case, the baryon asymmetry is $\eta_B \simeq \epsilon_B(T_d/M_{S_r})$. In order that this dilution effect is not excessive, we require that $T_d/M_{S_r} \geq 0.01$. Since the decay rate of $S_r$ depends inversely as a high power of $M_{X,Y}$, heavier $X$, $Y$ bosons would imply that $\Gamma_S \sim H$ is satisfied at a lower temperature and, hence, give a lower $T_d/M_{S_r}$. In Fig. 4, we have plotted $M_{X,Y}$ vs $M_{S_r}$, which gives the right amount of baryon asymmetry consistent with the decay of $S_r$ before the QCD phase transition. Using the effective coupling $\bar{\lambda} \equiv (\lambda_1 h_{11}^2 f_{11})^{1/4} \sim (\lambda_2 h_{11} g_{11}^2)^{1/4} \sim 10^{-4}$ implies that $10^9$ sec $\leq \tau_{N-\bar{N}} \leq 10^{11}$ sec for $M_{S_r} \simeq$ 100–300 GeV.

We conclude with a few comments on some other aspects of the model:

(i) If the $(X, Y, Z)$ scalars are all present, the loop diagram in Fig. 2 will contribute to baryon asymmetry. Since there are two diagrams of the type shown in Fig. 2, the relevant trace has an imaginary piece. The asymmetry will have a suppression factor $M_{S_r}^2/M_X^2$, in addition to a loop factor and the Yukawa suppression.

(ii) $S_r$ can mix with the SM Higgs boson $H$ through the interaction $\lambda_S S^\dagger S H^\dagger H$, which will open new channels for the $S_r$ decays such as $S_r \to b\bar{b}$. The rate for this decay is $\Gamma(S_r \to b\bar{b}) \sim 3\beta^2 m_b^2 M_S/4\pi M_W^2$, where $\beta$ is the $S_r - h$ mixing angle. This decay could contribute dominantly to the $S_r$ width, thereby diluting the baryon asymmetry. Furthermore, this mode should be out of equilibrium at $T = M_{S_r}$. If the model is nonsupersymmetric, these two conditions are satisfied if $\lambda_S \leq 10^{-6}$. This coupling is automatically forbidden if the model is supersymmetric.

(iii) The present considerations could be easily extended to include supersymmetry. The $SX^2Y$ and $SXZZ$ interactions in this case are nonrenormalizable [16]. However, in this case we also expect mass terms in the superpotential of the form $M_S S\bar{S}$ so that the effective four scalar interaction responsible for baryogenesis is in the same form as discussed above.

(iv) Our theory is also testable in collider experiments such as the LHC since we have colored diquark scalar fields with masses in the TeV range. In a $p\bar{p}$ collision, one could produce the $X, Y, Z$ bosons either in pairs via the process $q\bar{q} \to X\bar{X}$ or singly via the process $q + g \to X + \bar{q}$. In the first case, the signal would be a four jet final state, whereas in the second case, it would be three jet final states. One distinguishing feature of these bosons is that they carry a baryon number, which may be testable in the decays of these bosons into top quark and bottom quarks.

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