Baryogenesis by Heavy Quarks: Q-genesis

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Abstract. In this talk, I present a new mechanism for baryogenesis the Q-genesis in which the heavy quarks are the source of baryon number $\Delta B$. There exists a narrow allowed region for the Q-genesis.  

INTRODUCTION

From the observed facts in the heaven, astrophysics and cosmology deal with cosmic microwave background radiation (CMBR), abundant light elements, galaxies and intergalactic molecules, and dark matter (DM) and dark energy (DE) in the universe. In this talk, I present a recent work [1] regarding the light elements in this list whose source can be baryon number ($B$) from heavy quark decay.

Sakharov’s three conditions for generating $\Delta B \neq 0$ from a baryon symmetric universe are

- Existence of $\Delta B \neq 0$ interaction,
- C and CP violation, and
- Evolution in a nonequilibrium state.

GUTs seemed to provide the basic theoretical framework for baryogenesis, because in most GUTs $\Delta B \neq 0$ interaction is present. Introduction of C and CP violation is always possible if not forbidden by some symmetry. The third condition on the non-equilibrium state evolution can be possible in the evolving universe but it has to be checked with specific interactions.

Thus, a cosmological evolution with $\Delta B \neq 0$ and C and CP violating particle physics model can produce a nonvanishing $\Delta B$. The problem is “How big is the generated $\Delta B$". Here, for nucleosynthesis, we need

$$\Delta B \simeq 0.6 \times 10^9 n_\gamma.$$  \hspace{1cm} (1)

For example, the SU(5) GUT with X and Y gauge boson interactions are not generating the needed magnitude when applied in the evolving universe. In the SU(5) GUT, two quintet Higgs are needed for the required magnitude. With this scenario, GUTs with colored scalars seemed to be the theory for baryogenesis for some time.

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1 Talk presented at CICHEP-II, Cairo, Egypt, Jan. 15, 2006.
But high temperature QFT aspects changed this view completely. The spontaneously broken electroweak sector of the standard model (SM) does not allow instanton solutions. When the SU(2)_W is not broken, there are electroweak SU(2) instanton solutions. Tunneling via these electroweak instantons is extremely suppressed, \( \sim \exp\left(-\frac{2\pi}{\alpha_w}\right) \). This tunneling amplitude is the zero temperature estimate. At high temperature where the electroweak phase transition occurs, the transition rate can be huge, and in cosmology this effect must be considered \[2\]. The tunneling amplitude due to sphaleron effect is large at high and small at low temperatures as shown in Fig. 1. This sphaleron effect transforms SU(2) doublets. The 't Hooft vertex for this process must be a SM singlet, which is shown in Fig. 2.

![Figure 1. Vacuum tunneling at high (dashed arrow) and low (solid arrow) temperatures.](image)

The baryon number violating interaction washes out the baryon asymmetry produced during the GUT era. Since the above sphaleron interaction violates \( B + L \) but conserves \( B - L \), if there were a net \( B - L \), there results a baryon asymmetry below the weak scale. The partition of \( (B - L) \) into \( B \) and \( L \) below the electroweak scale is the following if the complete washout of \( B + L \) is achieved,

\[
\Delta B = \frac{1}{2}(B - L)_{\text{orig}}, \quad \Delta L = \frac{1}{2}(B - L)_{\text{orig}}.
\]  

(2)

\( B - L \) must be present in the beginning. If so, the leptogenesis uses this transformation of the \( (B - L) \) number (obtained from heavy \( N \) decays) to baryon number. The \( \nu \)-genesis also uses this transformation.

Thus, in some \( L \) to \( B \) transformation models, we need to generate a net \( (B - L) \) number at the GUT scale (\( Q \)-genesis does not need this). The SU(5) GUT conserves \( B - L \) and hence cannot generate a net \( B - L \).
So, for the baryon number generation one has to go beyond the SU(5) GUT. There exist three examples of baryon number generation from fermion sources: (1) Leptogenesis [3], (2) Neutrino genesis [4], and (3) Q-genesis [1].

INTRODUCTION OF HEAVY QUARKS

We note that SU(2) singlets avoid the sphaleron process and hence singlet quarks survive the electroweak era. With this idea, we must pursue along the line of heavy quarks that achieves

- Heavy quarks must mix with light quarks so that after the electroweak phase transition they can generate the quark number \( \frac{B}{3} \).
- They must be sufficiently long lived.
- Of course, a correct order of \( \Delta B \neq 0 \) should be generated.

The SU(2) singlet quarks were considered before in connection with (i) flavor changing neutral currents (FCNC) [5], and recently for the BELLE data [6].

For the absence of FCNC at tree level, the electroweak isospin \( T_3 \) eigenvalues must be the same. Thus, introducing L-hand quark singlets will potentially introduce the FCNC problem. But in most discussions, the smallness of mixing angles with singlet quarks has been overlooked. Since the quark singlets can be superheavy compared to 100 GeV, the small mixing angles are natural, rather than being unnatural.

For definiteness, let us consider \( Q_{em} = -\frac{1}{3} \) heavy quark \( D \) for which we must satisfy

1. \( \Delta D \) generation mechanism is possible,
2. \( 10^{-10} \text{s} < \tau_D < 1 \text{ s} \),
3. Sphaleron should not wash out all \( \Delta D \), and
4. The FCNC bound is satisfied.

Theoretically, is it natural to introduce such a heavy quark(s)? It is so. For example, in E6 GUT there exist \( Ds \) in \( 27_F \). Trinification GUT also has particle \( D \), viz.

\[
27 \rightarrow 16 + 10 + 1 \rightarrow 10 + 5^* + 1 + 5 + 5^* + 1 \\
\rightarrow (q + u^c + d^c) + N_5 + (l + d^c) + (D + L_2) + (D^c + L_1) + N_{10} \quad (3)
\]

When we consider this kind of vector-like quarks \( (D + D^c) \), there are three immediate related physical problems to deal with: heavy quark axion, the Nelson-Barr type, and FCNC. But here, we will consider the FCNC problem only.

We will consider one family first for \( d \)-type, \( \langle t, b \rangle_L^T, b_R \). It gives all the needed features. The mass matrix is

\[
M_{-1/3} = \begin{pmatrix}
m & J \\0 & M
\end{pmatrix} \quad (4)
\]

The entry \( 0 \) in the above is a natural choice, since it can be achieved by redefinition of R-handed singlets. The above mass matrix can be diagonalized by considering \( MM^\dagger \), to
\[
\left( \begin{array}{c}
|m_b|^2 \\
|m_D|^2
\end{array} \right) = \frac{1}{2} \left( |M|^2 + |m|^2 + |J|^2 \right) \mp \sqrt{\left( |M| + |m| \right)^2 + |J|^2} \cdot \left( |M| - |m| \right)^2 + |J|^2
\]

(5)

which tends to \( m_b \to m \) and \( m_D \to M \) in the limit of \( M^2 \gg |m|^2, |mJ| \). So, with vanishing phases, we have the following eigenstates,

\[
|b\rangle \simeq \left( \begin{array}{c}
1 \\
-J/M
\end{array} \right), \quad |D\rangle \simeq \left( \begin{array}{c}
J/M \\
1
\end{array} \right).
\]

(6)

Since \( J \) is the doublet VEV and \( M \) is a parameter or a singlet VEV, the mixing angle can be sufficiently small. This is the well-known decoupling of vectorlike quarks. It can be generalized to three ordinary quarks and \( n \) heavy quarks. The \((3+n)\times(3+n)\) matrix

\[
M_{-1/3} = \begin{pmatrix} M_d & J \\ J' & M_D \end{pmatrix}
\]

can take the following form by redefining R-handed \( b \) and \( D \) fields,

\[
M_{-1/3} = \begin{pmatrix} M_d & J \\ 0 & M_D \end{pmatrix}
\]

(7)

For an easy estimate, below we express \( J \) as

\[
J = fm_b.
\]

**Q-GENESIS BY HEAVY QUARKS**

Here, we generate the \( D \) number as usual in GUTs cosmology through the Sakharov mechanism, and in the end we will identify the \( D \) number as the \( 3B \) number. The relevant interaction we introduce is

\[
g_{Di} X_i u^c D^c + g_{ei} X_i u^c e^c + \text{h.c.}
\]

(8)

which can introduce \( \Delta D \) through the interference term from Fig. 3 plus self energy diagrams.

The interference is needed to generate a nonvanishing \( D \) number. The cross term contributes as \( g_{e1} g_{e2} g_{D1} g_{D2} \). If we allow arbitrary phases in the Yukawa couplings, the relative phases of \( g_{D1} \) and \( g_{D2} \) can be cancelled only by the relative phase redefinition of \( X_2 \) and \( X_1 \). The same applies to \( g_{e1} \) and \( g_{e2} \). Thus, the phase \( \eta \) appearing in \( g_{e1} g_{e2} g_{D1} g_{D2} \) is physical. The \( D \) number generated in this way is

\[
\frac{n_D}{n_\gamma} \simeq 0.5 \times 10^{-2} \varepsilon
\]

(9)

\[
\varepsilon \sim 10^{-2} \frac{\eta}{8\pi} \left[ F(x) - F(1/x) \right], \quad x = \frac{M_{X_1}}{M_{X_2}}
\]

(10)

where \( F(x) = 1 - x \ln(1 + (1/x)) \).
FIGURE 3. Diagrams contributing to $X \rightarrow u^c + D^c$.

**LIFETIME ESTIMATE**

The dominant decay of $D$ proceeds via

$$D \rightarrow tW, bZ, bH^0$$

from which we obtain

$$\Gamma_D = \frac{\sqrt{2}G_F}{8\pi} |J|^2 m_D, \quad \epsilon = \frac{f m_b}{m_D}$$

The lifetime of $D$ must be made longer than $2 \times 10^{-11} \text{ s}$ (beginning of electroweak phase transition), and it should be made shorter than $1 \text{ s}$ (beginning of nucleosynthesis), i.e. $2 \times 10^{-11} \text{ s} < \tau_D < 1 \text{ s}$, which gives

$$\frac{1}{(10^6 m_{D, \text{GeV}})^{3/2}} < |\epsilon| < \frac{1}{(2.7 \times 10^2 m_{D, \text{GeV}})^{3/2}}, \quad m_{D, \text{GeV}} = \frac{m_D}{\text{GeV}}.$$  

The mixing of $D$ with $b$ is of order $\epsilon$. For one period of oscillation, we expect that a fraction $|\epsilon|^2$ of $D$ is expected to transform to $b$. Since the period keeping the electroweak phase in cosmology is of order,

$$\frac{1}{H} = \sqrt{\frac{3 M_P^2}{\rho}} \approx \sqrt{\frac{3}{g^* M_W^2}},$$

Thus, the following fraction is expected to be washed out via $D$ oscillation into $b$,

$$\sim \frac{M_p m_b^2}{M_W m_D} f^2 \simeq 10^{16} \frac{f^2}{m_{D, \text{GeV}}^2}.$$  

For $m_D$ of order $> 10^6 \text{ GeV}$, we need $f < 10^{-5}$. In this range, some heavy quarks are left and the sphaleron does not erase the remaining $D$ number.
FIGURE 4. Allowed parameter space in terms of mixing angle and $D$ quark mass.

**FCNC**

For the FCNC, we consider the following processes which are compared with the existing experimental bounds

$$Z \rightarrow b\bar{b}, \quad |z_{bb}| = 0.996 \pm 0.005 \quad \rightarrow \quad |\epsilon| \leq 0.009$$

$$B \rightarrow X_s l^+ l^-, \quad \text{from tree} \quad |z_{sb}| = \frac{f \lambda_s}{m_D^2} < 1.4 \times 10^{-3}$$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}, \quad |z_{sd}| \leq 7.3 \times 10^{-6}$$ (14)

where the last bound comes from

$$\frac{\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{FCNC}}}{\text{Br}(K^+ \rightarrow \pi^0 e^+ \nu)} = \frac{3|z_{sd}|^2}{2\lambda^2} \leq 2 \times 10^{-9}.$$

Therefore, from the FCNC processes, we obtain the bound on the coupling $f$,

$$\frac{1}{(4.8 \times 10^9 \sqrt{m_{D,\text{GeV}}})} < |f| < \frac{1}{(2.1 \times 10^4 \sqrt{m_{D,\text{GeV}}})}.$$ (15)

Fig. 4 summarizes the allowed parameter space in terms of mixing angle and $D$ quark mass. The remarkable fact is that there exist a band allowed by the current data.
Z₂ SYMMETRY

To implement a small $f$ naturally, we can impose a discrete symmetry such as a parity symmetry $Z₂$,

$$Z₂ : \begin{cases} b_{L,R} \rightarrow b_{L,R}, \quad D_{L,R} \rightarrow D_{L,R} \\ \phi \rightarrow \phi, \quad \varphi \rightarrow -\varphi \end{cases} \quad (16)$$

where $\phi$ and $\varphi$ are Higgs doublets giving mass and mixing, respectively. The discrete symmetry forbids a mixing between doublets. We introduce a soft term, violating the discrete symmetry, which can mix them. Consistently with the discrete symmetry except the soft term, the potential is given by

$$V = (m_ϕ^2 \phi^* \phi + \text{h.c.}) - \mu^2 \phi^* \phi + M_ϕ^2 \phi^* \varphi + \lambda_1 (\phi^* \varphi)^2 + \lambda_2 (\varphi^* \phi)^2 + \cdots \quad (17)$$

The soft term violates the $Z₂$ symmetry. If the $Z₂$ is exact, there is no mixing between $D$ and $b$ and then $D$ is absolutely stable: $\langle \phi \rangle = v \neq 0$, and $\langle \varphi \rangle = 0$. But the existence of the soft term violates the $Z₂$ and a tiny VEV, $\langle \varphi \rangle$, is generated. The estimate of mixing is

$$\langle \varphi \rangle = \frac{m_ϕ^2 v}{M_ϕ^2}, \quad f_{\text{off}} \langle q_L \varphi D_R \rangle \quad \rightarrow \quad J = f_{\text{off}} \frac{m_ϕ^2 v}{M_ϕ^2}$$

from which we estimate

$$f = \frac{\sqrt{2} f_{\text{off}} m_ϕ^2}{f_b M_ϕ^2} \quad (18)$$

which can lead to naturally small values of $|J| = f m_b$ and $\epsilon = J/M_D$. Typical value for $m_D$ is given by constraints. The mass $M_ϕ^2$ can be superheavy.

Another point to be stressed, but unrelated to $Q$-genesis, is that we can construct a DM model of $D$ with an exact $Z₂$ symmetry.

A related idea in the effective theory, but not the same at the renormalizable level, can be found in [7], where $R$-parity violating SUSY is used with $B$ carrying singlet scalars $S$,

$$W_{NR} \sim \frac{1}{M_T} u^c d^c c^c S + \text{h.c.}$$

where $T$ is our heavy quark $D$. But here $T$ is much heavier than $S$. It has the similar idea of evading the electroweak phase transition era.

CONCLUSION

We presented a new mechanism for baryogenesis: the $Q$-genesis. We obtained the constraints on the parameter space. With a $Z₂$ discrete symmetry, the smallness of the parameter is naturally implemented.
TABLE 1. Comparison of a few baryogenesis mechanisms.

| Mechanism     | $B - L = 0$ | $B - L \neq 0$ | Sphaleron          |
|---------------|------------|----------------|-------------------|
| leptogenesis   | Yes        | $\nu_L$ converts to $B$ |
| $\nu$-genesis | Possible   | Possible       | $\nu_L$ converts to $B$ |
| $Q$-genesis    | Possible   | Possible       | $Q$ decay produces $B$ |

Finally, in Table 1, this $Q$-genesis mechanism is compared with other baryogenesis mechanisms. Leptogenesis and $\nu$-genesis seem to be the plausible ones since the observed neutrino masses need R-handed neutrinos. Survival hypothesis sides with leptogenesis. $Q$-genesis depends on the unobserved $Q$, but this may be needed in solutions of the strong CP problem. Also, it appears in $E_6$ and trinification GUTs. One should consider all kinds of SM singlet particles and vector-like representations for the baryon asymmetry in the universe:

\[ N, \nu_R : \text{fermion singlets} \]
\[ Q_L + Q_R : \text{vectorlike fermion} \]
\[ N_L + N_R : \text{vectorlike fermion with Dirac mass} \]
\[ S : \text{singlet scalar carrying } B \text{ number} \]

In Table 1, the $B - L$ number is that of light fermions. So, in the neutrino-genesis, one counts the R-handed light neutrino($\nu_R$) number also in the $B - L$ number. In the $Q$-genesis, whatever sphaleron does on the light lepton number, still there exists baryon number generation from the $Q$ decay, which occurs independently from the light fermion number.

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\[2\] Note colored scalars can appear in the Affleck-Dine mechanism [8].