ANOMALOUS ELECTROWEAK BARYON NUMBER NON-CONSERVATION AND GUT MECHANISM FOR BARYOGENESIS

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We formulate the necessary conditions for the survival of the baryon asymmetry generated in the $B-L$ conserving leptoquark decays. We find that equilibrium anomalous electroweak B-non-conserving interactions do not wash out all the baryon asymmetry if (i) there is no mixing in the leptonic sector, (ii) there is large flavour asymmetry in the leptoquark decays, (iii) the mass of the Higgs boson is larger than 56 GeV.

The existence of the rapid anomalous electroweak baryon number non-conserving processes at sufficiently small temperatures ($T>100$ GeV) [1] changes the standard scenario [2] of the baryon asymmetry of the Universe (BAU) generation in grand unified theories (GUTs). In fact, the BAU production may take place already in the standard electroweak theory during the first-order phase transition with the breaking of the SU(2) group [3]. This happens if the ground state of gauge theories at high temperatures has non-trivial degeneracy with respect to the Chern–Simons number [3] [‡1]. The other necessary condition for BAU to be generated by electroweak interactions is the relatively low magnitude of the Higgs boson mass, $M_H<56$ GeV. If $M_H>56$ GeV then all the BAU generated during the electroweak phase transition was washed out by equilibrium B-non-conserving interactions [3].

The aim of the present note is the investigation of the contribution of GUTs with $B-L$ conservation to the value of BAU. This question is important because of the following reason. At present one cannot be absolutely sure that the BAU generation indeed takes place in the electroweak interactions. This is because up to now there was no investigation of the ground state of high-temperature gauge theories from the point of view of Chern–Simons number. In addition, the Higgs mass is unknown and it may turn out to be larger than 56 GeV. What to do in the latter case? Does it mean that GUTs with $B-L$ conservation [‡2] are excluded?

In ref. [1] we have shown that the $B+L$ part of the asymmetry totally disappears to the moment of electroweak phase transition. However, this can be true if there are no other conservation laws in addition to $B-L$.

At the tree level in standard electroweak theory $N+1$ different fermionic numbers are conserved. These are $l_1, l_2, \ldots, l_N$ and B where l_1 is the electronic number, l_2 is the muonic number, etc., N being the number of fermionic generations. Selection rules for

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[‡1] This point can be tested numerically by the investigation of three-dimensional lattice pure gauge theories.

[‡2] Note that $B-L$ conservation is characteristic for popular GUTs originated from superstring models.

B and L non-conserving processes are [1] $\Delta B = N$, $\Delta l_1 = \Delta l_2 = ... = \Delta l_N = 1$, so we get N independently conserved quantum numbers:

$$L_1 = l_1 - N^{-1}B, \quad ...,$$

$$L_N = l_N - N^{-1}B . \tag{1}$$

Suppose now that these numbers are effectively conserved during and after the BAU generation in the decays of leptoquarks at the GUT stage of the expansion of the Universe. This is indeed the case if the only source of L_i violation is the interaction of leptoquarks giving rise to the baryon asymmetry. So, the leptoquark decays generally produce the non-zero values for L_i ($\sum_i L = 0$ due to $B-L$ conservation and initial condition $B-L=0$).

Now, let us find the BAU. Let T_* be the freezing temperature of anomalous electroweak B violating reactions. Then, at $T > T_*$ there is thermal equilibrium, so the baryon number can be found by minimization of the free energy F,

$$F = \sum_{i=1}^{N} [2F(m_{l_i}, \mu_i) + F(0, \mu_i)] + 6 \sum_{i=1}^{2N} F(m_{q_i}, \mu) . \tag{2}$$

Here

$$F = -T \int \frac{d^3k}{(2\pi)^3} \ln\{1 + \exp[-(\varepsilon + \mu)/T]\}$$

$$+ (\mu \to -\mu) , \quad \varepsilon = \sqrt{k^2 + m^2} , \tag{3}$$

μ_i are leptonic chemical potentials for each doublet, μ is the quark chemical potential. Note that one should not attribute different chemical potentials for different quark doublets because flavour changing interactions are in thermal equilibrium. The chemical potential for the leptons in the same doublet are equal to each other due to the equilibrium with respect to the SU(2) interactions. This is not so for the different leptonic doublets because of the absence of mixing in the standard electroweak theory with massless neutrinos [‡3].

‡3 The mixing is negligible from the cosmological point of view even if neutrinos have small Dirac masses, because the characteristic time is large compared with the age of the Universe at temperature T_*.

The expressions for leptonic and baryonic densities are

$$l_i = \frac{d}{d\mu_i} [2F(m_{l_i}, \mu_i) + F(0, \mu_i)] ,$$

$$B = 2 \frac{d}{d\mu} \sum_{i=1}^{2N} F(m_{q_i}, \mu) . \tag{4}$$

In the high-temperature approximation $m^2/T^2 \ll 1$ we get

$$F(m, \mu) \sim \mu^2 T^2 \left(1 - \frac{3}{2\pi^2} \frac{m^2}{T^2}\right) . \tag{5}$$

The minimization of F with respect to B taking into account eq. (1) gives

$$B = -\frac{4}{13} \sum_{i=1}^{N} L_i \left(1 + \frac{1}{\pi^2} \frac{m_{l_i}^2}{T^2}\right) . \tag{6}$$

Hence, the final baryon asymmetry is equal to [note that $\sum_{i=1}^{N} L_i = (L-B) = 0$]

$$\frac{n_B}{n_\gamma} \equiv \Delta = -\frac{4}{13\pi^2} \sum_{i=1}^{N} \frac{m_{l_i}^2(T_*)}{T_*^2} \Delta_i^{\mathrm{GUT}} , \tag{7}$$

where Δ_i^{GUT} are just the GUT asymmetries for the quantum numbers L_i. Fortunately, the leptoquark decays are non-symmetric with respect to fermionic flavours. (In the symmetric case we get $\Delta_1^{\mathrm{GUT}} = ... = \Delta_N^{\mathrm{GUT}} = 0$. The same is true if the processes which mix different leptonic flavours are in thermal equilibrium.) Namely, the BAU is usually proportional to the largest Yukawa couplings. Therefore, the baryon and lepton asymmetries are concentrated in the heaviest fermionic generation. So, the most natural choice of Δ_i^{GUT} is

$$\Delta_1^{\mathrm{GUT}} \approx ... \approx \Delta_{N-1}^{\mathrm{GUT}} \approx 0 , \quad \Delta_N^{\mathrm{GUT}} \approx \frac{N-1}{N} \Delta_B ,$$

where Δ_B is the baryon asymmetry in grand unified theory.

Some comments are now in order. If the mass of the Higgs boson is smaller than 56 GeV then after the electroweak phase transition baryon number non-conserving processes are out of equilibrium. Therefore, $m(T_*) = 0$ because T_* coincides with the critical temperature. This means that the BAU production during SU(2) phase transition does not intersect with the BAU generation at the GUT temperature scale.

In the case of three fermionic generations and $M_H > 56$ GeV we obtain ($T_* \sim O(200$ GeV) [1,3])

$$\Delta \simeq 3\times 10^{-6}\,\Delta_3^{\mathrm{GUT}}\,. \tag{8}$$

Hence, to get a reasonable number $\Delta \sim O(10^{-9})$ we should demand that the microscopic asymmetry in the leptoquark decays is of the order of one,

$$\delta_{\mathrm{ms}} \sim \frac{\Gamma(\mathrm{x}\to\mathrm{out}) - \Gamma(\bar{\mathrm{x}}\to\overline{\mathrm{out}})}{\Gamma(\mathrm{x}\to\mathrm{out}) + \Gamma(\bar{\mathrm{x}}\to\overline{\mathrm{out}})}\,, \tag{9}$$

which seems to be unnatural. Recall that the expression for the BAU originated from out of equilibrium decays is [2]

$$\Delta \sim \frac{45\zeta(3)}{4\pi N_{\mathrm{eff}}}\,\delta_{\mathrm{ms}} \sim 10^{-3}\,\delta_{\mathrm{ms}}\,, \tag{10}$$

N_{eff} being the effective number of massless degrees of freedom. In the SU(5) model with two quintets of Higgs fields with equal vacuum expectation values the characteristic magnitude of δ_{ms} is [4]

$$\delta_{\mathrm{ms}} \sim \alpha_{\mathrm{GUT}}\,\frac{m_t m_b}{m_W^2} \sim O(10^{-3}), \quad \Delta \sim 10^{-12}\,. \tag{11}$$

Note that we somewhat overestimated Δ because we did not take into account partial equilibrium of baryon number non-conserving processes during the leptoquark decays [2,4]. Therefore we conclude that the BAU generated in the model with three fermionic generations is small compared with observations. The possible way of BAU amplification is the introduction of the fourth generation. This increases δ_{ms} and the $m^2(T_*)/T_*^2$ ratio simultaneously. Thus, for

$$m_{t'}\, m_{b'}\, m_{\tau'}^2 \sim O(10^4)\, m_t m_b m_\tau^2\,, \tag{12}$$

we obtain $\Delta \sim 10^{-8}$.

To summarize, the necessary conditions for BAU survival in the theories with $B-L$ conservation are (i) the absence of mixing in the leptonic sector after the leptoquark decay, (ii) large flavour asymmetry in the leptoquark decays, (iii) a large mass of the Higgs boson, $M_H > 56$ GeV. The existence of a fourth generation is also very useful.

If these conditions are not fulfilled, the BAU must originate in the SU(2) phase transition [3], or one should invoke some other mechanism such as decay of squark and slepton fields [5]. Here BAU occurs at a relatively low temperature which has to be smaller than the temperature of decoupling of anomalous electroweak B-violating processes. A different way out is the construction of theories with $B-L$ non-conservation. In this case $B = \frac{4}{13}(B-L)_{\mathrm{in}}$. The consequences of that for particle physics may be non-zero Majorana masses for neutrinos, neutron–antineutron oscillations, $B-L$ non-conservation in the proton decay (modes $\mathrm{n}\to\mathrm{e}^-\mathrm{K}^+$, $\mathrm{p}\to\nu\mathrm{K}^0$, etc.).

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