$B-L$ Conserved Baryogenesis

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In the presence of anomaly induced sphaleron process, only a $B-L$ asymmetry can be partially converted to the baryon asymmetry while any $B+L$ asymmetry would be completely erased. Thus in any successful baryogenesis theories, $B-L$ is usually violated above the electroweak scale to explain the observed matter-antimatter asymmetry of the universe. However, if any lepton asymmetry is not affected by the sphaleron processes, a $B-L$ conserved theory can still realize the baryogenesis. We present here an SU(5) GUT realization of this scenario, which naturally accommodates small masses of Dirac neutrinos.

It is well known [1] that there is a $SU(2)_L$ global anomaly in the standard model (SM), where the baryon number and the lepton number are both violated, but their difference $B-L$ is still conserved. This anomaly induced anomalous $B+L$ violating process will be suppressed by quantum tunneling probability at zero temperature, but at finite temperature this process could become fast in the presence of a instanton-like solution, the sphaleron [2]. During the period [3],

$$100\,\mathrm{GeV} \sim T_{EW} < T < T_{sph} \sim 10^{12}\,\mathrm{GeV}\,, \qquad (1)$$

this sphaleron process will be so fast as to wash out any primordial $B+L$ asymmetry, although it will not affect any primordial $B-L$ asymmetry and will partially transfer the existing $B-L$ asymmetry to a baryon asymmetry. Thus any successful baryogenesis theories above the electroweak scale have to satisfy the requirement of $B-L$ violation in addition to the CP violation and the out-of-equilibrium conditions as required by the Sakharov's conditions [4]. However, any lepton asymmetry in some exotic particles or the right-handed fermions may be immune to the sphaleron effects, which may allow a baryon asymmetry even in a $B-L$ conserved theory. In general, the right-handed fermions interact with the left-handed fermions through the Yukawa couplings, and hence any asymmetry in the right-handed fermions will be transferred to the left-handed fermions before the electroweak phase transition and they cannot be immune to the sphaleron processes. But if some Yukawa couplings could be very small, then the asymmetry in the right-handed fermions will not be affected by the sphalerons and it may be possible to have a baryon asymmetry of the universe in a $B-L$ conserved theory [5].

In this note we construct grand unified theories (GUTs) where this possibility could be realized. In GUTs based on the gauge group SO(10) or some larger groups, in which $B-L$ is a local symmetry, it is not possible to embed this scenario. So, we shall demonstrate this in an SU(5) GUT, in which, $B-L$ is a global symmetry. We shall demonstrate how this scenario could be embedded in an SU(5) GUT.

In the usual SU(5) GUT baryogenesis scenario, we have the following Yukawa couplings,

$$\mathcal{L} \supset -f^{(1)}_{aij}\,\chi_i\,\chi_j\,H_a - f^{(2)}_{aij}\,\psi_i\,\chi_j\,H_a^\dagger + \mathrm{h.c.}\,, \qquad (2)$$

where ψ_i, χ_i $(i=1,2,3)$ are the $\mathbf{5}^*$ and $\mathbf{10}$ fermions, respectively while H_a $(a=1,2)$ is the $\mathbf{5}$ Higgs scalar composed of a $SU(3)_c$ triplet Higgs h_a and a SM $SU(2)_L$ doublet Higgs ϕ_a. The pair decays of (h_a, h_a^*) can produce a baryon and lepton asymmetry [6]. Although the sphaleron process has no direct impact on the right-handed fermions, the baryon and lepton asymmetry stored in the right-handed fermions will be eventually affected because the Yukawa interactions are sufficiently strong to rapidly convert the right-handed quantum numbers to the left-handed ones. Thus the baryon asymmetry and the equal lepton asymmetry will be completely washed out by the sphaleron action.

To generate the neutrino mass, we assume the presence of singlet right-handed neutrinos in addition to the standard $\mathbf{5}^*$ and $\mathbf{10}$ fermions and then obtain the new Yukawa couplings,

$$\mathcal{L} \supset -y_{aij}\,\overline{\nu_{R_i}}\,\psi_j\,H_a + \mathrm{h.c.} \qquad (3)$$

with ν_{R_j} $(j=1,2,3)$ being the right-handed neutrinos. Since the right-handed neutrinos are singlets, they can have a Majorana mass, but a natural scale for this mass is around the scale of grand unification. This will then induce too small a Majorana mass of the left-handed neutrinos, which is unacceptable. Moreover this will break $B-L$ symmetry and will not allow us to embed the proposed scenario. We shall thus forbid the Majorana masses of right-handed neutrinos by the requirement of conserving the $B-L$ number. Thus the neutrinos will obtain their Dirac masses, $m_\nu = \sum_a y_a \langle H_a\rangle$, once the Higgs fields $H_{1,2}$ develop their vacuum expectation values (*vevs*). For consistency, the *vevs* of the Higgs doublets or the effective Yukawa couplings have to be very small.

The pair decays of (h_a, h_a^*) cannot generate any $B-L$ asymmetry. If there is CP violation, then a $B-L$ asymmetry in ψ_i can be generated, but an equal and opposite

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amount of $B-L$ asymmetry in ν_{R_j} will compensate this, resulting in zero $B-L$ asymmetry. However, since the effective Yukawa coupling is very small, the $B-L$ asymmetry in ν_{R_j} will not be affected by the sphaleron processes and hence remain intact, whereas the $B-L$ asymmetry stored in ψ_i will get converted to a baryon asymmetry of the universe in the presence of the sphalerons. Thus, the Yukawa interactions (2) and (3) will allow the $B-L$ asymmetry stored in the SM particles to generate a baryon asymmetry of the universe, produced by the pair decays of (h_a, h_a^*) by the interference of tree-level and one-loop diagrams since the Sakharov's conditions [4] are available to satisfy in these processes. This $B-L$ asymmetry should be proportional to the branching ratio of the colored Higgs scalar h_a decaying into the multiplets and the singlet right-handed neutrinos. But the constraint from the experimental data [7] requires the Yukawa couplings to be extremely small for Dirac neutrinos unless we highly fine tune the cancellation between $y_1\langle H_1\rangle$ and $y_2\langle H_2\rangle$. Under the circumstances, the magnitude of the essential branch ratio is so small that we can not obtain the desired amount of $B-L$ asymmetry stored in the SM particles to explain the observed matter-antimatter asymmetry of the universe.

We shall now extend the SU(5) GUT with additional singlet fields and a discrete Z_2 symmetry. All the SM particles are even under the Z_2 symmetry, while the right-handed neutrinos are odd and hence the Yukawa couplings (3) are forbidden. We further introduce some new fields including singlet fermions ξ_{L_i,R_i} $(i=1,...)$, **5** Higgs scalars H'_a $(a=1,...)$, and a real singlet scalar η, in addition to the right-handed neutrinos. The right-handed neutrinos and the singlet fermions are assigned $B-L=-1$, while the new scalars are assigned $B-L=0$. The Yukawa couplings of the usual SU(5) baryogenesis model (2) will have several new terms, but we shall restrict some of these interactions by invoking the Z_2 symmetry. We shall assume that only the singlet fermions are even under the Z_2 symmetry, while all other particles including the right-handed neutrinos are odd. We can then write down the $B-L$ and Z_2 invariant Lagrangian with all the fields. We shall present here only the terms that are directly related to the rest of our discussions:

$$\begin{aligned}\mathcal{L} \supset & -f^{(1)}_{aij}\,\chi_i\,\chi_j\,H_a - f^{(2)}_{aij}\,\psi_i\,\chi_j\,H_a^\dagger \\ & -y^{(1)}_{aij}\,\overline{\xi_{R_i}}\,\psi_j\,H_a - z_{ij}\,\overline{\nu_{R_i}}\,\xi_{L_j}\,\eta \\ & -y^{(2)}_{aij}\,\overline{\nu_{R_i}}\,\psi_j\,H'_a - \mu_{ab}\,\eta H'^\dagger_a\,H_b \\ & -M_{\xi_{ij}}\,\overline{\xi_{R_i}}\,\xi_{L_j} + \text{h.c.}\,. \end{aligned} \tag{4}$$

The charged fermion masses come from the *vevs* of H_a's. But the neutrinos remain massless, since the $B-L$ symmetry prevents any Majorana mass while the Z_2 symmetry prevents any Dirac mass. Only after the real scalar field η develops a *vev*, it induces a *vev* to the fields H'_a, which in turn generate a small Dirac mass of the neutrinos [9]. Thus after the breaking of both the Z_2 and electroweak symmetry, we will obtain an effective neutrino Dirac mass term,

$$\mathcal{L} \supset -m_{\nu_{ij}}\,\overline{\nu_{R_i}}\,\nu_{L_j} + \text{h.c.} \tag{5}$$

with $m_\nu \equiv \sum_a y^{eff}_a \langle H_a\rangle$, where the effective Yukawa couplings,

$$y^{eff} = -y^{(1)}\,\frac{\langle\eta\rangle}{M_\xi}\,z - y^{(2)}\,\frac{\langle\eta\rangle}{M^2_{H'}}\,\mu\,, \tag{6}$$

can be highly suppressed by the ratio of the *vev* of real scalar over the heavy mass scales [8, 9]. In the first term, the singlet fermion gives a see-saw contribution, while the second term is generated by the effective *vev* of the Higgs H'_a. Since both these terms are of the same order of magnitude, any one of these terms could generate the required neutrino masses. Thus we could include any one of the singlet fermions or the Higgs field H'_a for the neutrino masses. However, for baryogenesis we require all these fields.

We now explain how to predict the observed matter-antimatter asymmetry in the present $B-L$ conserved model. Depending on the values of masses and couplings, either the pair decays of (h_a, h_a^*) or the pair decays of (ξ_i, ξ_i^c) and (H'_a, H'^*_a) can contribute to the final baryon and lepton asymmetry. For simplicity and illustration, we consider two limiting cases. In the first one, we take $M_{\xi,H'} \gg M_h$, thus the pair decays of (ξ_i, ξ_i^c) and (H'_a, H'^*_a) can produce a $B-L$ asymmetry stored in the SM particles. An equal and opposite amount of $B-L$ asymmetry will be stored in the right-handed neutrinos. These $B-L$ asymmetries will emerge through the tree-level diagrams interfering with the self-energy corrections [9, 10] and/or vertex corrections [11] once they go out of equilibrium. Since there are no other processes violating the SM $B-L$ number, these produced $B-L$ asymmetry stored in the SM particles can be partially converted to the baryon asymmetry through the sphaleron process. However, the right-handed neutrinos interact with the left-handed fields only through the effective Yukawa couplings y^{eff}, which is very small and hence the $B-L$ asymmetry stored in the right-handed neutrinos are not transferred to the SM particles, and hence, cannot take part in sphaleron process.

We now consider another limiting case, where $M_{\xi,H'} \ll M_h$. The pair decays of (h_a, h_a^*) will produce a baryon asymmetry stored in the SM quarks with an equal lepton asymmetry stored in the pairs of (ξ_i, ξ_i^c), if (ξ_i, ξ_i^c) satisfies departure from equilibrium, or produce a pure baryon asymmetry if (ξ_i, ξ_i^c) keeps in equilibrium. Anyway we can eventually obtain a net $B-L$ asymmetry stored in the SM particles since even the lepton asymmetry stored in the pairs of (ξ_i, ξ_i^c) will be transferred to the SM leptons and the right-handed neutrinos, proportional to their branching ratios in the decays of the singlet fermions. Note, in this case, we have not considered the contribution from the out-of-equilibrium and CP-violation decays of (ξ_i, ξ_i^c) and (H'_a, H'^*_a) to the final

SM lepton asymmetry for simplicity, since we are flexible to keep the CP conservation in these pair decays by choosing the proper CP phases.

In this note we propose a new scenario for baryogenesis before the electroweak phase transition. Since a lepton asymmetry is immune from the sphaleron action in our scenario, a net $B-L$ asymmetry can be converted to the baryon asymmetry through the sphaleron process and then explain the observed matter-antimatter asymmetry of the universe although the total $B-L$ number is still conserved.

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