Baryogenesis via lepton number violating scalar interactions

Patrick J. O'Donnell
Physics Department
University of Toronto
Toronto, Ontario M5S 1A7, Canada

and

Utpal Sarkar
Theory Group
Physical Research Laboratory
Ahmedabad - 380 009, India

UTPT-93-15

Abstract

We study baryogenesis through lepton number violation in left-right symmetric models. In these models the lepton number and CP violating interactions of the triplet higgs scalars can give rise to lepton number asymmetry through non-equilibrium decays of the $SU(2)_L$ triplet higgs and the right handed neutrinos. This in turn generates baryon asymmetry during the electroweak anomalous processes.

Cosmological baryon excess can be generated from the initial condition $B = 0$ if there is out-of-equilibrium baryon number violation along with CP violation [1]. However, the sphaleron induced, anomalous electroweak, process will wash out all the $(B-L)$ conserving baryon asymmetry [2] which is generated at the grand unified scale. The ratio

$$\frac{n_B}{n_\gamma} = (4-7) \times 10^{-10}$$

required by the standard big-bang model, can then be explained if there were primordial $(B-L)$ asymmetry. Since the lowest dimensional operators for the proton decay conserve $(B-L)$, it is unlikely that grand unified theories can generate enough $(B-L)$ asymmetry. Two interesting possibilities then remain open. In the first one the observed asymmetry is generated just after the electroweak phase transition [3]. In this case the electroweak phase transition has to be strongly first order so that after the transition the anomalous process is already too weak to erase the generated asymmetry. The second possibility is the one where $(B-L)$ asymmetry is generated during the anomalous electroweak process. If there are lepton number violating, out-of-equilibrium, interactions which violate CP, then during the epoch when the $(B+L)$ violating anomalous processes are in equilibrium in the universe, this lepton asymmetry can generate enough $(B-L)$ asymmetry. Some time back Fukugita and Yanagida [4, 5, 6] proposed this possibility, where the right handed neutrinos decay into light leptons and antileptons in different proportions when CP is violated [7]. This lepton asymmetry in turn generates baryon asymmetry. They considered an extension of the standard model which contains singlet right handed neutrinos and the lepton number is broken explicitly by the Majorana mass terms of the right handed neutrinos.

In this article we discuss the possibility of baryon asymmetry in models where $(B-L)$ is broken spontaneously rather than putting in an explicit $(B-L)$ violating interaction. This is natural in the left-right symmetric extension of the standard model [8]. The spontaneous breaking of $(B-L)$ give rise to lepton number violating interactions of the triplet higgs scalars. This can then generate lepton asymmetry if there is also CP violation through decays of the higgs and the heavy neutrinos. This generates enough baryon asymmetry during the electroweak anomalous process. We use the conventional choice of the higgs scalars for the breaking of the left-right symmetry, which also gives Majorana mass to the neutrinos. We also discuss an alternative, where the left-right parity is broken spontaneously [9].

In the left-right symmetric model [8], the standard electroweak theory $G_{std} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ emerges at low energy as a result of symmetry breaking of a larger group $G_{LR} \equiv SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$. The vacuum expectation value (*vev*) of the right handed triplet higgs field Δ_R (1,1,3,-2), breaks the gauge group $G_{LR} \rightarrow G_{std}$. Left-right symmetry implies the existence of another higgs field Δ_L which transforms as (1,3,1,-2) under G_{LR}. A higgs doublet field ϕ (1,2,2,0) breaks the electroweak symmetry and gives masses to the fermions. The Yukawa couplings are

$$\mathcal{L}_{Yuk} = f_{ij} \overline{\psi_{iL}} \psi_{jR} \phi + f_{Lij} \overline{\psi_{iL}}^c \psi_{jL} \Delta_L^\dagger + f_{Rij} \overline{\psi_{iR}}^c \psi_{jR} \Delta_R^\dagger. \tag{1}$$

The scalar interactions which are of importance for the generation of lepton number excess are

$$\mathcal{L}_{int} = g(\Delta_L^\dagger \Delta_R \phi\phi + \Delta_L \Delta_R^\dagger \phi\phi) + h.c. \tag{2}$$

The minimization of the complete scalar potential gives a relation between the *vev*s of these fields. Since right handed gauge bosons have not been observed, we are only interested in $v_L \neq v_R$, where $v_{L,R}$ and v are the *vev*s of the fields $\Delta_{L,R}$ and ϕ respectively. If the left-right parity ($D-$ parity) is not broken, then the masses of the fields Δ_L and Δ_R remains same even after the breaking of G_{LR}, *i.e.*, $m_{\Delta_L} = m_{\Delta_R} = m_\Delta \approx v_R$. The *vev*s of the fields $\Delta_{L,R}$ and ϕ are related by $v_L \approx v^2/v_R$. This allows a see-saw suppression of the *vev* of Δ_L compared to Δ_R.

In these models $(B-L)$ is a local symmetry. The breaking of the group G_{LR} gives spontaneous breaking of the $(B-L)$ symmetry. Thus *vev*s of the higgs scalars $\Delta_{L,R}$ give rise to baryon and lepton number violating interactions by two units, which can allow Majorana mass of the neutrinos and also neutron-antineutron oscillations. In the model considered by Fukugita and Yanagida [4], there was a Majorana mass term for the neutrinos which violated explicitly lepton number conservation. Such lepton number violating interactions gives rise to baryogenesis via leptogenesis through the decay of the heavy right handed neutrinos. In the left-right symmetric theories there exists other processes which arise from the lepton number violating interactions of the scalar fields. They can allow lepton asymmetry through the non-equilibrium decay of the left-handed higgs triplet and the right handed neutrinos, which then generates baryon asymmetry through sphaleron processes.

Following Eq. (1), $\Delta_{L,R}$ can decay into two neutrinos, $\Delta^\dagger_{L,R}$ into two antineutrinos

$$\Delta_{L,R} \rightarrow \nu_{L,R} + \nu_{L,R} \tag{3}$$

$$\Delta^\dagger_{L,R} \rightarrow \nu^c_{L,R} + \nu^c_{L,R} \tag{4}$$

Equation (2) gives lepton number violating scalar interactions of Δ_L and Δ_R, which is generated by the $(B-L)$ violating *vev*s of $\Delta_{R,L}$. Together with (3) and (4), these lepton number violating interactions then give

$$\Delta_{L,R} \rightarrow \phi + \phi$$

$$\rightarrow \phi^\dagger + \phi^\dagger .$$

To generate excess lepton number however, we need to violate CP and have an imaginary one-loop radiative correction. In principle, there can be a, rephasing invariant, complex phase in the Yukawa couplings, which can give CP violation. The interference of the tree level diagram and the one loop diagram of Fig.1 can then give rise to an asymmetry in the decay modes of (3) and (4) for the left-handed triplets Δ_L. For the right-handed triplet Δ_R the loop integral is real since the left-handed neutrinos, which enter in the loop, are light. This implies that the decay of the right-handed triplet higgs cannot generate any lepton asymmetry. The magnitude of the asymmetry generated by the left-handed triplet Δ_L decays is given by,

$$\epsilon_\Delta \approx \frac{1}{4\pi |f_{L,R}|^2} \mathrm{Im}[g^* f^*_{[L,R]ij} f_{ik} f_{jk}] \frac{g^*}{f_{[R,L]kk}} \tag{5}$$

In general, the quantity $[g^* f^*_{[L,R]ij} f_{ik} f_{jk}]$ can contain a, rephasing invariant, CP violating phase and so can be complex [7]. This generates the lepton number excess in the decays of the $SU(2)_L$ higgs triplets Δ_L. Note that in the loop integral the *vev* (v_R) of the triplet field Δ_R enters in the coupling of the Δ_L to ϕ and cancels with that in the propagator of the neutrinos. Hence the decays of Δ_L are not suppressed by any *vev*s.

Lepton number asymmetry is also generated by the heavy right handed neutrino decays. The *vev* of Δ_R spontaneously gives a Majorana mass to the right handed neutrinos. This in turn allows the decay of ν_R into a lepton *and* an antilepton,

$$\begin{aligned} \nu_{iR} &\rightarrow l_{jL} + \bar{\phi} && (6) \\ &\rightarrow {l_{jL}}^c + \phi. && (7) \end{aligned}$$

In the case of right-handed neutrinos there are two types of loop diagrams which can interfere with the tree level decays of (6) and (7) which are shown in Fig.2. The interference of the tree level diagram and the one loop diagram of Fig.2(a) generates lepton asymmetry of a magnitude similar to that of the triplet higgs decay. There is one additional contribution to the lepton asymmetry generated by the interference of the tree level diagram and that of

Fig.2(b). This second contribution is similar to the ones studied in the earlier papers on leptogenesis, where lepton number is broken explicitly through the Majorana mass term of the right handed-neutrinos [4, 5, 7, 6]. The magnitude of this lepton number excess is given by,

$$\epsilon_\nu \approx \frac{1}{4\pi |f_{ik}|^2} \mathrm{Im}[f_{ik} f_{il} f^*_{jk} f^*_{jl}] \frac{f_{Rii}}{f_{Rkk}}. \tag{8}$$

For the generation of the lepton number asymmetry we require another ingredient, namely, the decay rates should satisfy the out-of-equilibrium limit. The process (say, X-decay) which generates the lepton asymmetry should satisfy

$$\Gamma_X \leq 1.7 \sqrt{g} \frac{T^2}{M_{Pl}} \qquad\qquad \text{at} \quad T = M_X \tag{9}$$

and should decouple after the other particles whose decay violates lepton number have already decayed away and no other lepton number violating processes are in equilibrium. Otherwise after the X-decay has generated the asymmetry and already decayed, the other processes in equilibrium will again erase the asymmetry generated by the X-decay.

We now have to consider only the Δ_L, Δ_R and ν_{1R} decay processes (we assume ν_{1R} to be the lightest of the right handed neutrinos). The decay widths for $\Delta_{L,R}$ and ν_{1R} are,

$$\Gamma_{\Delta_{L,R}} = \frac{|f_{[L,R]ij}|^2}{16\pi} M_\Delta \qquad \text{and} \qquad \Gamma_{\nu_{1R}} = \frac{|f_{1j}|^2}{16\pi} M_\nu \tag{10}$$

where M_ν is the mass of ν_{1R}. Since the masses of all these fields are of the same order of magnitude $\sim v_R$, we have to consider all of them for the understanding of the lepton number generation.

If Δ_R is heavier than the other particles, then the lightest of Δ_L or ν_R (with mass m, say) should satisfy the out-of-equilibrium condition. Then, at $T = m$, all other fields have decayed away since the inverse reactions are not allowed by phase space. The lepton number is generated by the lightest of Δ_L or ν_R. However, if both Δ_L and ν_R satisfy (9) then the total lepton number generated is the sum of the contribution from Δ_L and ν_R.

On the other hand if Δ_R is lighter, then in addition to the Δ_L or ν_R (whichever is the lightest), Δ_R should also satisfy the out-of-equilibrium condition. Otherwise it will wash out the lepton number excess generated by the other particles. Although Δ_R can not generate lepton asymmetry since the loop integral is real, its equilibrium decay can make the number of leptons to be same as the number of antileptons.

If the Yukawa coupling for the first generation of neutrinos is of the order of $\sim 10^{-5}$, then the out-of-equilibrium condition requires $M > 10^6$ GeV. This constraint is satisfied by most of the left-right symmetric models. However, if left-right symmetry is observed at around a few TeV, then the baryon asymmetry has been generated through some other mechanism or else the Yukawa couplings for the triplet higgs should be $< 10^{-7}$. If the out-of-equilibrium condition is satisfied, then the next question will be whether the ϵs can be of the right order of magnitude to generate the observed baryon asymmetry. However, given the uncertainty in the Yukawa and the quartic scalar couplings, it is always possible to find a suitable choice of parameters which can produce the right amount of baryon asymmetry.

There is another variation of the left-right symmetric model in which the left-right D-parity is broken spontaneously. Under D-parity the scalar and the fermionic fields transform as $\Delta_{L,R} \rightarrow \Delta_{R,L}$ and $\psi_{L,R} \rightarrow \psi_{R,L}$, while ϕ stays the same. This D-symmetry can be broken by the *vev* of the singlet field η (1,1,1,0), which transforms under D as $\eta \rightarrow -\eta$. In the presence of the field η the lagrangian will now contain new terms,

$$\mathcal{L}_{\eta\Delta} = M_\eta \eta (\Delta_L^\dagger \Delta_L - \Delta_R^\dagger \Delta_R) + \lambda_\eta \eta^2 (\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R)$$

which can then allow a different scenario for the *vev*s and masses. One can find a solution of the form [9]

$$v_\eta = \langle \eta \rangle \gg v_R \gg v_L \qquad \text{and} \qquad v_L \approx \frac{v^2}{\langle \eta \rangle}$$

$$M_\eta \approx M_{\Delta_L} \approx v_\eta \gg M_{\Delta_R} = M_\Delta \approx v_R$$

Once this D-parity is broken, the gauge coupling constants g_L and g_R for the groups $SU(2)_L$ and $SU(2)_R$, respectively, will evolve in a different way (since $M_{\Delta_L} \gg M_{\Delta_R}$) and hence at low energy, even before G_{LR} is broken, $g_L \neq g_R$. Similarly, the Yukawa couplings f_L and f_R can also differ.

The Δ_L mass is very high. If Δ_R is now in equilibrium, then only out-of-equilibrium decays of ν_R can generate the asymmetry. Otherwise if $\Delta_{L,R}$ and ν_R satisfy the constraint (9) then both Δ_L and ν_R will contribute to the generation of lepton asymmetry.

In all the scenarios considered here, the higgs scalars Δ_L and Δ_R and their interactions introduce new processes at low energies such as

$$\nu_L + \nu_L \to \nu_L^c + \nu_L^c \qquad \text{and} \qquad \nu_L + \bar{\phi} \to \nu_L^c + \phi.$$

The rates for these processes are suppressed by M_Δ^{-4} and M_ν^{-2}. These again wash out the baryon asymmetry unless their rates are smaller than the expansion rate of the universe at the time of electroweak phase transition. These give further bounds on the mass scales [10, 11];

$$M_{\Delta_L} > f_L 10^6 \left(\frac{T_c}{100 \text{ GeV}}\right)^{3/4} \text{GeV}$$

$$M_\nu > f^2 10^9 \left(\frac{T_c}{100 \text{ GeV}}\right)^{1/2} \text{GeV},$$

which are much weaker than the bounds on the mass scales from the non-equilibrium condition (9).

In summary, we discussed the possibility of baryogenesis through lepton number violation in left-right symmetric theories. In this case the lepton number violating decays of the left-handed triplet higgs or the right handed neutrinos can generate the lepton asymmetry during the electroweak anomalous process which can then generate baryon asymmetry. On the other hand if these lepton number violating processes are in equilibrium then they can wash out any primordial $(B-L)$ asymmetry.

Acknowledgment We would like to thank the NSERC of Canada for an International Scientific Exchange Award.

References

[1] A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. **5** (1967) 32; E.W. Kolb and M.S. Turner, *The Early Universe* (Addison-Wesley, Reading, MA, 1989).

[2] V.A. Kuzmin, V.A Rubakov and M.E. Shaposhnikov, Phys. Lett. **B 155** (1985) 36.

[3] D. Brahm, in Proc. XXVI Int. Conf. High Energy Physics, Dallas, Texas, August 1992.

[4] M. Fukugita and T. Yanagida, Phys. Lett. **B 174** (1986) 45.

[5] M.A. Luty, Phys. Rev. **D 45** (1992) 445; P. Langacker, R.D. Peccei and T. Yanagida, Mod. Phys. Lett. **A1** (1986) 45.

[6] H. Murayama, H. Suzuki, T. Yanagida and J. Yokoyama, Phys. Rev. Lett. **70** (1993) 1912.

[7] A. Acker, H. Kikuchi, E. Ma and U. Sarkar, University of California at Riverside preprint no. UCRHEP-T109; P.J. O'Donnell and U. Sarkar, University of Toronto preprint no. UTPT-93-12.

[8] J.C. Pati and A. Salam, Phys. Rev. **D10** (1974) 275; R.N. Mohapatra and J.C. Pati, *ibid.* **D11** (1975) 566; R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44** (1980) 912; R.E. Marshak and R.N. Mohapatra, *ibid.* **44** (1980) 1316.

[9] D. Chang, R.N. Mohapatra and M.K. Parida, Phys. Rev. Lett. **52** (1984) 1072;

[10] M. Fukugita and T. Yanagida, Phys. Rev. **B 42** (1990) 1285.

[11] B.A. Campbell, S.Davidson, J. Ellis and K.A. Olive, Phys. Lett. **B 256** (1991) 457.

Figure Captions

Figure 1 Tree level and one loop diagrams for the decay of the left-handed triplet higgs scalars which generate lepton asymmetry

Figure 2 One loop diagrams for the decay of the right-handed neutrinos which generate lepton asymmetry