# SO(10) GUT Baryogenesis

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Baryogenesis, through the decays of heavy bosons, was considered to be one of the major successes of the grand unified theories (GUTs). It was then realized that the sphaleron processes erased any baryon asymmetry from the GUT-baryogenesis at a later stage. In this paper, we discuss the idea of resurrecting GUT-baryogenesis [1] in a large class of SO(10) GUTs. Our analysis shows that fast lepton number violating but baryon number conserving processes can partially wash out the GUT-baryogenesis produced lepton and/or baryon asymmetry associated with or without the sphaleron and/or Yukawa interactions.



One of the major triumphs of the GUTs is to *naturally* explain the observed matter-antimatter asymmetry [2] in the universe. In the GUT-baryogenesis [3] scenario, the quark-lepton unification provides the required baryon number violation, the gauge and Yukawa couplings contain the required CP phases and also satisfy the out-of-equilibrium condition near the scale of grand unification. Thus the three conditions [4] for baryogenesis are all satisfied and a baryon asymmetry could be produced.

It was then pointed out [5] that there is a $\mathrm{SU}(2)_L$ global anomaly in the standard model (SM), where the baryon number ($B$) and the lepton number ($L$) are violated by equal amount, so that their difference $B-L$ is still conserved. Since anomalies are quantum processes that destroys classical symmetries of any theory, this anomaly induced anomalous $B+L$ violating process will be suppressed by quantum tunneling probability at zero temperature. But at finite temperature this process becomes fast in the presence of an instanton-like solution, the sphaleron [6]. During the period [7],

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

this sphaleron induced $B+L$ violating process will be too fast, and hence, it will wash out any primordial $B+L$ asymmetry. However, it will not affect any primordial $B-L$ asymmetry and will partially transfer a $B-L$ asymmetry to a baryon asymmetry.

Note that $B-L$ is a global symmetry in the SU(5) GUTs, while it is a local symmetry in the SO(10) or $\mathrm{E}_6$ GUTs. Thus the baryon and lepton asymmetry generated in these theories at the GUT scale (before the $B-L$ symmetry breaking) conserves $B-L$ and, in fact, only a $B+L$ asymmetry is generated in all the GUTs. This $B+L$ asymmetry would then be depleted exponentially by the sphaleron transitions before the electroweak symmetry breaking, and hence, the GUT-baryogenesis fails to explain why there are more matter compared to antimatter in the universe.

To solve this problem of GUT-baryogenesis, many newer mechanisms have been proposed. The most popular one is called leptogenesis [8], in which the lepton number violation required for the neutrino masses generates a lepton asymmetry at some intermediate symmetry breaking scale, which is then converted to a baryon asymmetry in the presence of the sphalerons before the electroweak phase transition. In this case the $B+L$ asymmetry generated by the GUT-baryogenesis is washed out by the sphaleron transitions before the leptogenesis begins. Recently, the resurrecting GUT-baryogenesis [1] was proposed. In this scenario, the lepton number violation starts before the sphaleron transitions begin, so that the produced $B+L$ asymmetry in the GUT-baryogenesis is converted to a $B-L$ asymmetry, which then generates the required baryon asymmetry in the presence of the sphalerons.

In this paper, we discuss the idea of resurrecting GUT-baryogenesis in the SO(10) GUTs. Our general analysis shows that in several versions of SO(10) GUTs, it is possible to generate the matter-antimatter asymmetry of the universe from GUT-baryogenesis. Unlike the leptogenesis scenarios there is no necessity for the lepton number violating interactions to generate a lepton asymmetry. We start with the trivial case, when the SO(10) GUTs breaks down to $SU(3)_c \times SU(2)_L \times U(1)_Y$ at the GUT scale. In this case $B-L$ is broken at the GUT scale and hence the asymmetry generated by the decays of the heavy bosons is a $B-L$ asymmetry, and hence the sphaleron transitions will not deplete it. However, such single stage symmetry breaking SO(10) GUT scenario will have all the problems of the SU(5) GUTs, like the gauge coupling unification, fermion mass relations, strong CP problem and neutrino masses. So, we shall exclude this possibility from the rest of our discussions. We shall now present a popular version of the SO(10) GUTs with conventional Higgs scalars and point out how the GUT-baryogenesis in this model can explain the matter-antimatter asymmetry of the universe without any added ingredients. This mechanism can be applied to other versions of SO(10) GUTs, but we shall not include them in our present discussion.

We start with an SO(10) GUT with the following sym-

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metry breaking pattern:

$$\begin{aligned} SO(10) &\xrightarrow{M_G} SU(4)_c \times SU(2)_L \times SU(2)_R \\ &\xrightarrow{M_X} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\xrightarrow{M_{B-L}} SU(3)_c \times SU(2)_L \times U(1)_Y \\ &\xrightarrow{m_W} SU(3)_c \times U(1)_{em} \,. \end{aligned} \quad (2)$$

The unification of the gauge coupling constants constrains the left-right symmetry breaking scale to be greater than $10^{13}$ GeV.

In the present case we shall consider the following Higgs scalars for the left-right and electroweak symmetry breaking:

$$\Delta_L \equiv (\mathbf{1},\mathbf{3},\mathbf{1},-2), \Delta_R \equiv (\mathbf{1},\mathbf{1},\mathbf{3},-2), \Phi \equiv (\mathbf{1},\mathbf{2},\mathbf{2},0). \quad (3)$$

The left-right symmetry will be broken at the scale $M_{B-L}$ by the vacuum expectation value (*vev*) $\langle\Delta_R\rangle$. The left-right symmetry will ensure $M_{\Delta_L} = M_{\Delta_R} \equiv M_\Delta \sim \langle\Delta_R\rangle$. The bi-doublet Higgs can be looked on as a combination of two $SU(2)_L$ doublets in the SM, one denoted by $\phi$ corresponding to the SM Higgs doublet having *vev* $\langle\phi\rangle \simeq 174$ GeV, while the other denoted by $\phi'$ having zero *vev*. The *vev* $\langle\Delta_L\rangle$ is determined by the minimization of the scalar potential and it is highly suppressed,

$$\langle\Delta_L\rangle = \alpha \frac{\langle\phi\rangle^2}{\langle\Delta_R\rangle} \,, \quad (4)$$

where $\alpha$ is some combination of couplings entering in the scalar potential.

For simplicity, we only write down the following Yukawa couplings and scalar interaction that are relevant for the rest of our discussions:

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{2} f_{L_{ij}} \overline{\ell_{L_i}} \, i\tau_2 \, \Delta_L \, \ell^c_{L_j} - \frac{1}{2} f_{R_{ij}} \overline{\ell_{R_i}} \, i\tau_2 \, \Delta_R \, \ell^c_{R_j} \\ & - y_{1_{ij}} \overline{\ell_{L_i}} \, \Phi_1 \, \ell_{R_j} - y_{2_{ij}} \overline{\ell_{L_i}} \, \Phi_2 \, \ell_{R_j} \\ & - \gamma_{ij} \, \mathrm{Tr} \left( \Delta_R^\dagger \, \Phi_j \, \Delta_L \, \Phi_i^\dagger \right) + \text{h.c.} \,, \end{aligned} \quad (5)$$

where $\ell_L \equiv (\mathbf{1},\mathbf{2},\mathbf{1},-1)$ and $\ell_R \equiv (\mathbf{1},\mathbf{1},\mathbf{2},-1)$ are the leptons, $\Phi_1 \equiv \Phi$ and $\Phi_2 \equiv \tau_2 \Phi^* \tau_2$. After the left-right symmetry is broken by $\langle\Delta_R\rangle$, we deduce

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{2} f_{L_{ij}} \overline{\ell_{L_i}} \, i\tau_2 \, \Delta_L \, \ell^c_{L_j} - \mu \, \phi^T \, i\tau_2 \, \Delta_L \, \phi \\ & - y_{ij} \overline{\ell_{L_i}} \, \phi \, \nu_{R_j} - \frac{1}{2} M_{R_i} \overline{\nu_{R_i}} \, \nu^c_{R_i} + \text{h.c.} \,, \end{aligned} \quad (6)$$

with $\mu \sim \langle\Delta_R\rangle$, $M_R = f_R\langle\Delta_R\rangle$. Here we have conveniently chosen the basis, under which the Majorana mass matrix $M_R$ is diagonal and real. It is straightforward to see the second term violates the *left-handed lepton number* and the last term violates the *right-handed lepton number* by two units.

We now mention the general conditions that allows the GUT-baryogenesis to explain the matter-antimatter asymmetry of the universe:

*Condition 1*: Without going into the details of symmetry breaking at the GUT scale, we assume that a baryon asymmetry is generated at this scale $M_G \sim 10^{16}$ GeV through the decays of some heavy bosons. Since $B-L$ is a local symmetry below the GUT scale, the generated asymmetry is an $B+L$ asymmetry, which is expected in any GUT-baryogenesis.

*Condition 2*: We demand that after the left-right symmetry is broken, there will be fast lepton number violating interactions, but there are no fast baryon number violating interactions. This is true for most of the models. As discussed previously, the *vev* $\langle\Delta_R\rangle$ that breaks $U(1)_{B-L}$ will lead to the breaking of the lepton and baryon number. But since the baryon number violation by two units requires higher dimensional operators, these processes are never fast. For example, the simplest dimension-9 operator is of the form $qqqqqq$, which corresponds to three quarks going into three antiquarks. But this process can never be in equilibrium since the probability of three quarks coming at a point is strongly phase space suppressed and then this dimension-9 process is also suppressed by five powers of the heavy left-right symmetry breaking mass scale. Thus, although $\langle\Delta_R\rangle$ breaks both baryon and lepton numbers, only lepton number violation can be fast.

*Condition 3*: Before the baryon and lepton asymmetry is completely erased, the lepton number violating interactions will go out of equilibrium. The sphaleron process directly affects the left-handed fermions, but can also act on the right-handed fermions if it is associated with the fast Yukawa interactions. In other words we need to consider both left-handed and right-handed fermions for the decoupling of the lepton number violating interactions, so that the existing asymmetry is not washed out by the sphaleron process.

We then give a general analysis in a class of SO(10) GUTs, in which the GUT-baryogenesis continues to work and the produced $B+L$ asymmetry is not completely wiped out by the sphaleron process. The different cases can be classified by the decoupling temperatures for the left-handed lepton number ($L_L$) and right-handed lepton number ($L_R$) violating interactions $T_L$ and $T_R$.

- For $T_L > M_{B-L}$ and $T_R > T_{sph}$, the $L_R$ asymmetry is washed out before the sphaleron transitions, leaving the $B+L_L$ asymmetry from the GUT-baryogenesis. This $B+L_L$ asymmetry gives a non-zero $B-L$, which then survives the sphaleron process.
- Similarly, when $T_R > M_{B-L}$ and $T_L > T_{sph}$, the $B+L_R$ asymmetry remains unaffected and contribute to a $B-L$ asymmetry.
- When the $L_L$ and $L_R$ violating interactions are both in equilibrium before the sphaleron process becomes operational, only the $B$ asymmetry from the GUT-baryogenesis survives and contributes to a $B-L$ asymmetry, which then get converted to a baryon asymmetry.
- If the $L_R$ violating interactions remain out of equilibrium, the $L_R$ asymmetry may survive even after the $B+L_L$ asymmetry is erased by the joint sphaleron and

Yukawa interactions as long as the Yukawa interactions are not fast enough to relate the number densities of the left- and right-handed leptons at this stage. This $L_R$ asymmetry can be related to the $L_L$ asymmetry after the Yukawa interactions become effective and then can be converted to a baryon asymmetry.

For the purpose of demonstration, we consider a hierarchal case, where $M_{\Delta,R} > M_{B-L} \sim M_{W_R}$. Here $M_{W_R} = g\langle\Delta_R\rangle$ is the mass of the charged right-handed gauge boson with $g$ being the $SU(2)$ gauge coupling. Therefore, $\Delta_L$ and $\nu_R$ have decoupled as the $B-L$ symmetry is broken. We thus integrate out the heavy left-handed triplet Higgs and right-handed neutrinos from Eq. (6) and then obtain a dimension-5 operator,

$$\mathcal{O}_L \;=\; -\frac{1}{2}\,h_{ij}\,\overline{\ell_{L_i}}\,\phi\,\phi^T\,\ell^c_{L_j} \;+\;\text{h.c.} \qquad (7)$$

with $h = -y\dfrac{1}{M_R}y^T - \dfrac{\mu^*}{M_\Delta^2}f_L$. Obviously, this operator will give the neutrinos a small Majorana mass matrix, $m_\nu = h\langle\phi\rangle^2$ [9] after the electroweak symmetry breaking. Note that the interaction (7) only breaks the left-handed lepton number. We can also obtain a $L_R$ violating operator by integrating out the right-handed neutrinos from the kinetic terms of the right-handed leptons, for example,

$$\mathcal{O}_R \;=\; -\,g_{ij}\,\overline{e_{R_i}}\,W_R^-\,W_R^-\,e^c_{R_j} \;+\;\text{h.c.} \qquad (8)$$

with

$$g_{ij} \;=\; \frac{1}{2}\,g^2\,V_{ik}\frac{1}{M_{R_k}}V^T_{kj} \;=\; \frac{1}{2}\,g^2\,\frac{1}{\widetilde{M}_{R_{ij}}}\,, \qquad (9)$$

where $V$ is the orthogonal matrix diagonalizing the Majorana mass matrix of the right-handed neutrinos. Since $M_{W_R} \sim M_{B-L}$, the induced $L_R$ violating processes whose details depend on the specific models will only remain effective for very short interval of time and hence will not have a significant effect on the GUT-baryogenesis produced baryon and lepton asymmetry.

For the left-handed lepton number violating processes, $\ell_{L_i}\phi^* \leftrightarrow \ell^c_{L_j}\phi$ and $\ell_{L_i}\ell_{L_j} \leftrightarrow \phi\phi$, the reaction rate should be [10]

$$\Gamma_{\not{L}_L} \;=\; \frac{1}{\pi^3}\,T^3\,\left|h_{ij}\right|^2 \;=\; \frac{1}{\pi^3}\,\frac{T^3\,\left|m_{\nu_{ij}}\right|^2}{\langle\phi\rangle^4}\,. \qquad (10)$$

Comparing this reaction rate to the expansion rate of the universe,

$$H \;=\; \left(\frac{8\,\pi^3\,g_*}{90}\right)^{\frac{1}{2}}\,\frac{T^2}{M_{\rm Pl}} \qquad (11)$$

with $g_* = \mathcal{O}(100)$ and $M_{\rm Pl} \simeq 1.22\times10^{19}\,\text{GeV}$, we obtain,

$$T_L \;\gtrsim\; \left(\frac{2^2\,\pi^9\,g_*}{45}\right)^{\frac{1}{2}}\,\frac{\langle\phi\rangle^4}{M_{\rm Pl}\,\left|m_{\nu_{ij}}\right|^2}$$
$$\sim\; \left(\frac{0.1\,\text{eV}}{m_\nu}\right)^2 \times\, 3.9\,\times\,10^{12}\,\text{GeV}\,. \qquad (12)$$

The right-handed leptons will be related to the left-handed ones when their Yukawa interactions are in equilibrium. The rate of a scattering process between the SM left- and right-handed fermions, Higgs and $W$ bosons, $\psi_L\phi \leftrightarrow \psi_R W^-$, is

$$\Gamma_Y \sim \alpha_W \lambda^2 T \qquad (13)$$

with $\alpha_W = g^2/(4\pi)$ being the weak coupling constant and $\lambda$ being the Yukawa couplings. Hence the Yukawa interactions of electron, muon and tau leptons will keep in equilibrium below the temperatures,

$$T_e \lesssim 10^4\,\text{GeV}\,,\; T_\mu \lesssim 10^{10}\,\text{GeV}\,,\; T_\tau \lesssim 10^{12}\,\text{GeV}\,. \qquad (14)$$

For illustration, let us consider a representative set of values for the mass scales: $M_{B-L} \sim \mathcal{O}(10^{14}\,\text{GeV})$ and $m_\nu = \mathcal{O}(0.1\,\text{eV})$. The $L_L$ violating interactions will decouple at $T_L \gtrsim 10^{12}\,\text{GeV}$. In this case the GUT-baryogenesis generated a $B+L$ asymmetry at the GUT scale $M_G$. Below the $B-L$ breaking scale $M_{B-L}$, the $L_L$ violating interactions are in equilibrium, but the sphaleron and Yukawa processes have not yet started. So, although the $L_L$ asymmetry is depleted, the $B$ and $L_R$ asymmetry are not altered. But since $T_L > T_{sph} \sim T_\tau$, when the sphaleron process starts, the $L_L$ violating interactions will no longer be effective. Thus the $B+L_R$ asymmetry generated by the GUT-baryogenesis will survive. In consequence, a non-zero $B-L$ asymmetry will get converted to a baryon asymmetry before the electroweak phase transition and then give us the required matter-antimatter asymmetry.

We now discuss the possibility that the GUT-baryogenesis and leptogenesis both contribute to the generation of the matter-antimatter asymmetry of the universe. We consider two types of $L_L$ violating interactions: (a) the $L_L$ violating processes (7) mediated by the left-handed triplet Higgs $\Delta_L$; (b) the $L_L$ violating decays of $N = \nu_R + \nu_R^c$ to the left-handed leptons. For the proper parameter choice, we have the flexibility to keep the (a) processes in equilibrium before the sphaleron action becomes effective. Thus, the GUT-baryogenesis produced $B+L_R$ asymmetry will survive. Subsequently, the $N$ can decay to generate a $L_L$ asymmetry above the temperature $T_{sph} \sim T_\tau$. When the sphaleron interactions become effective, there will be no other lepton number violating interactions, so the residual $B+L_R+L_L$ asymmetry, where $B$ and $L_R$ both come from the GUT-baryogenesis while $L_L$ comes from the leptogenesis, will get converted to a $B-L$ asymmetry. This $B-L$ asymmetry can give us a desired baryon asymmetry through the sphaleron process.

In this paper, we discuss the resurrecting GUT-baryogenesis in the SO(10) GUTs. We did not attempt to present any specific model, instead we restrict ourselves to making general statements comparing the amplitudes of different processes with the expansion rate of the universe. Since the parameter range for the different possibilities are not too flexible, in a realistic model one should solve the Boltzmann equation to get the exact numerical estimates of the asymmetry. Our analysis shows that in a class of SO(10) GUTs, after the $B+L$ asymmetry is produced by the decays of heavy bosons, there are fast lepton number violating but baryon number conserving interactions, which can partially wash out the existing lepton and/or baryon asymmetry associated with or without the sphaleron action and/or Yukawa interactions. Thus a $B-L$ asymmetry can be generated from the GUT $B+L$ asymmetry. Subsequently, this $B-L$ asymmetry gets converted to a baryon asymmetry in the presence of the sphalerons before the electroweak symmetry breaking, which is consistent with the observed matter-antimatter asymmetry of the universe.


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