Decimation and survival at baryon violating gantlet

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Abstract

We find that for second and weakly first order electroweak phase transition (EWPT) the mere presence of non-zero Majorana masses for left-handed neutrinos is sufficient to ensure the destruction of any existing baryon (lepton) asymmetry. Even if the EWPT is strongly first order, a baryon asymmetry generated before EWPT is seen to only barely survive, to the present, for cosmologically interesting values of neutrino masses and mixing angles; the scenario for survival being particularly bleak in the presence of an $SU(2)_R$ gauge symmetry at intermediate scales. Two sets of models, presented by us earlier, that can avert the destruction of baryon asymmetry for any value of neutrino masses and mixing angles and any order of EWPT are briefly discussed and their relevance, in the light of latest observations, is pointed out.
The neutrinos are massless in the Standard Model, but there exist observational indications that they may, after all, be massive. The solar electron-neutrino ($\nu_e$) and the atmospheric muon-neutrino ($\nu_\mu$) deficits, and the need for some hot dark matter are all looked upon as evidence for the existence of neutrino masses [1].

It is widely accepted that the solar $\nu_e$ deficit can be explained by the oscillation of $\nu_e$ to other neutrino species: the well known MSW effect [2]. The atmospheric $\nu_\mu$ deficit is most likely to be due to the oscillation of $\nu_\mu$ to $\nu_\tau$ [3]. The large amount of data available on the extent of structure in the universe on a wide range of distance scales is best fit by the Cold Hot Dark Matter (CHDM) models, and the most successful of these models requires the hot dark matter to account for 20% of the energy density of the universe [4]. For a flat universe and a value of the Hubble constant ($H$) around $50 \text{ km/s/Mpc}$, this puts a bound on the sum of stable neutrino masses $\sum m_{\nu_i} \sim 5 \text{ eV}$.

The neutrino oscillations do not constrain the neutrino masses directly but they impose restrictions on the mass squared difference, $\Delta m^2_{ij} = |m_i^2 - m_j^2|$, and the mixing angles $\theta_{ij}$.

Small neutrino masses (in the eV range or smaller) can be naturally generated by the see-saw mechanism [5]. All the left-handed neutrinos $\nu_i$ in the Standard Model can have right-handed companions $N_i$ that are Standard Model gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$, singlets. The $N_i$ can have Majorana mass terms of the form $M_i(N_i^C N_i + h.c.)$, where $C$ denotes charge conjugation. The mass $M_i$ can be much larger than the electroweak (EW) symmetry breaking scale, as it may arise when a right-handed symmetry is broken or it may just be present explicitly. When the EW symmetry is broken, Dirac mass terms of the type $m_{di}(\bar{\nu}_i N_i + h.c.)$ can arise. In the presence of both Majorana and Dirac masses, the mass eigenvalues are $O(m^2_{di}/M_i)$ and $O(M_i)$ corresponding to the self-conjugate mass eigenstates $(\nu^C_i + \nu_i) \equiv \omega_i$ and $(N^C_i + N_i) \equiv \chi_i$, respectively. Thus, a massive neutrino is essentially two self-conjugate Weyl states with distinct masses. Typically, $m_{di}$ is expected to be of the same order as the mass of the charged lepton and/or quarks of the $i^{th}$ generation. And if $m_{di} << M_i$, then we have a light Majorana neutrino $\omega_i$.

The Majorana mass terms for the neutrinos violate the lepton number ($L$) symmetry. At temperatures well above the electroweak phase transition (EWPT) temperature ($T_{EW}$) scale, lepton number may be violated due to the presence of Majorana mass for right-handed neutrinos ($N_i$). Two lepton number violating processes are:

(i) decay of massive right-handed neutrinos $N \rightarrow l_L \phi, l^C_L \phi^C$, where $l_L$ is a left-handed lepton doublet and $\phi$ is the standard electroweak Higgs doublet, and
(ii) $N$ mediated $2 \leftrightarrow 2$ scatterings with an effective interaction term $(l_L l_L \phi \phi + h.c.)$. If these processes are in thermal equilibrium at the same time as the sphaleron interactions, then the baryon number ($B$) and $L$ asymmetries will be wiped out even if initially $(B - L) \neq 0$.

The requirement that the rate of the lepton number violating interactions ($\Gamma_{\Delta L \neq 0}$) should be less than the expansion rate of the universe ($H$), so that these interactions are not in thermal equilibrium simultaneously with the sphaleron interactions, at $10^{12} GeV > T > T_{EW}$, has been extensively used to put restrictions on the values of Majorana masses ($m_{\nu_i}$) of the left-handed neutrinos [6]. The upper limits obtained range from $10^{-3} eV$ to $10^{5} eV$ depending on the specific lepton number violating process considered and other details of the mechanisms that may be effective in protecting the baryon number asymmetry. It should be noted that even though the analyses carried out at $T > T_{EW}$ can constrain the Majorana masses of the left-handed neutrinos, the left-handed neutrinos can acquire a mass only after the electroweak symmetry breaking at $T \sim T_{EW}$.

We find that if the sphaleron interactions are in thermal equilibrium after EWPT and if the left and the right handed neutrinos have non-zero Majorana masses, then $B$ and $L$ will be driven to zero regardless of the values of the Majorana masses.

And it appears that the sphaleron interactions may well be in thermal equilibrium after EWPT, at least in the models with just one Higgs doublet.

The sphaleron interactions will not be in thermal equilibrium below $T_{EW}$ if the EWPT is sufficiently strongly first-order such that $E_{sph}/T_{EW} \gtrsim 45$ where $E_{sph}$ is the energy of the sphaleron configuration [7]. This constrains the mass of the neutral Higgs boson ($m_H$) to be $m_H \lesssim (35 - 80)$ GeV [8]. The experimental lower limit $m_H > 58 GeV$ may be consistent with a strong first-order EWPT. But the one-loop quantum corrections to the electroweak scalar potential due to the heavy top quark ($m_{top} \sim 174 GeV$) will render the zero temperature effective potential for one Higgs doublet unbounded from below unless $m_H > 130 GeV$ [9]. Thus, in the one Higgs doublet models if the vacuum is to be stable then EWPT cannot be strongly first-order. In the presence of more than one Higgs doublet the constraints are different [10] but, still, there is no reason for the scalar potential parameters to forbid a second order or weakly first-order EWPT.

For a strongly first-order EWPT a non-zero $B$ may be generated through electroweak baryogenesis [11]. However, we should note that this mechanism is not very well understood and a debate on its viability is still on [12]. A baryon asymmetry, with $(B - L) \neq 0$, generated well above $T_{EW}$ may survive
the combined onslaught of sphaleron and $B$ and/or $L$ violating interactions, but only barely for cosmologically interesting values of neutrino masses and mixing angles, as we shall show. And thus, the need for viable and well understood mechanisms and models that can protect the baryon asymmetry generated well above $T_{EW}$ and/or generate it after the sphaleron interactions have gone out of equilibrium cannot be overstated.

First we shall perform an exercise in equilibrium thermodynamics along the lines of Harvey and Turner [13] to show that the presence of Majorana mass for neutrinos is sufficient to completely erase any baryon asymmetry if the sphaleron interactions are in thermal equilibrium after EWPT. Then we demonstrate that for the cosmologically interesting values of neutrino masses and mixing angles survival of a baryon asymmetry generated well above $T_{EW}$ is only barely possible even if the sphaleron interactions are not in thermal equilibrium after EWPT. And finally, we briefly discuss and stress the importance of two models, that we had constructed earlier [14,15], that allow the baryon asymmetry produced by the decay of heavy GUT scalars to be the baryon asymmetry that is observed today for any value of neutrino masses.

1. Particle asymmetries are most conveniently expressed in terms of chemical potentials. For ultrarelativistic particles the relation between the excess of particle over antiparticle and the particle’s chemical potential is given by [13,16]

$$n_+ - n_- = \frac{g T^3}{3} \left( \frac{\mu}{T} \right) F_b \left( \frac{m}{T} \right) \quad \text{(bosons),} \quad (1a)$$

$$n_+ - n_- = \frac{g T^3}{6} \left( \frac{\mu}{T} \right) F_f \left( \frac{m}{T} \right) \quad \text{(fermions),} \quad (1b)$$

$$F_b(x) = \frac{3}{\pi^2} \int_x^\infty dy \sqrt{y^2 - x^2} \frac{e^y}{(e^y - 1)^2}, \quad (1c)$$

$$F_f(x) = \frac{6}{\pi^2} \int_x^\infty dy \sqrt{y^2 - x^2} \frac{e^y}{(e^y + 1)^2}, \quad (1d)$$

where $n_+(n_-)$ is the equilibrium number density of the particle (CP conjugate) species and $\mu(m)$ is its chemical potential (mass) while $g$ counts the internal degrees of freedom. We have assumed that $|\mu/T|, m/T << 1$.

For $M_W << T < T_{EW}$ the particles expected to be in chemical equilibrium are $N$ standard model generations of fermions, the components of m Standard Higgs doublets that have not been eaten up by $W^\pm$ and $Z$, and the usual gauge
bosons of $SU(3)_C \times SU(2)_L \times U(1)_Y$. Rapid electroweak interactions enforce the following equilibrium relations among the chemical potentials:

\[ \mu_W = \mu_+ + \mu_0 \quad (W^- \leftrightarrow \phi^- + \phi^0), \quad (2a) \]

\[ \mu_{dL} = \mu_{uL} + \mu_W \quad (d_L \leftrightarrow u_L + W^-), \quad (2b) \]

\[ \mu_{iL} = \mu_i + \mu_W \quad (i_L \leftrightarrow \nu_{iL} + W^-), \quad (2c) \]

\[ \mu_{uR} = \mu_0 + \mu_{uL} \quad (u_R \leftrightarrow \phi^0 + u_L), \quad (2d) \]

\[ \mu_{dR} = -\mu_0 + \mu_{dL} \quad (d_R \leftrightarrow \bar{\phi}^0 + d_L), \quad (2e) \]

\[ \mu_{iR} = -\mu_0 + \mu_{iL} \quad (i_R \leftrightarrow \bar{\phi}^0 + i_L). \quad (2f) \]

In our notation the relationship between chemical potentials and the particles in brackets is one to one. $i$ denotes a lepton species ($e^-, \mu^-, \tau^-$). Cabibbo mixing should maintain the equality of chemical potentials of the up and down-quark states of different generations, and we assume that mixing between the components of $m$ Higgs doublets maintains the equality of their chemical potentials.

So long as sphaleron interactions are rapid, the following relation among the chemical potentials is enforced:

\[ N(\mu_{uL} + 2\mu_{dL}) + \sum_i \mu_i = 0. \quad (3) \]

The charge, baryon and lepton numbers carried by particles in chemical equilibrium can be expressed in terms of the chemical potentials as:

\[ B = N(\mu_{uL} + \mu_{uR}) + N(\mu_{dL} + \mu_{dR}) = 4N\mu_{uL} + 2N\mu_W, \quad (4) \]

\[ L = \sum_{i} (\mu_i + \mu_{iL} + \mu_{iR}), \quad (5) \]

\[ Q = 2N(\mu_{uL} + \mu_{uR}) - N(\mu_{dL} + \mu_{dR}) - \sum_{i} (\mu_{iL} + \mu_{iR}) - 6\mu_W - 2(m-1)\mu_-. \quad (6) \]
The eight gluon fields and $Z$ and photon fields have vanishing chemical potential and have been ignored for this exercise. Because of the vacuum condensate of $\phi^0$ Higgs bosons, $\mu_0$ must be equal to zero. And since the Dirac mass terms for fermions mix the left and right-handed states, their chemical potentials must be equal

$$\mu_{uL} = \mu_{uR}, \quad \mu_{dL} = \mu_{dR}, \quad \mu_{iL} = \mu_{iR}.$$  \hspace{1cm} (7)

The Majorana mass terms for the neutrinos mix the neutrinos and antineutrinos thereby making their chemical potential zero,

$$\mu_i = 0.$$  \hspace{1cm} (8)

Using (2), (3), (7) and (8) we have

$$Q = \left(\frac{-10}{3}N - 12 - 2(m - 1)\right)\mu_W,$$  \hspace{1cm} (9)

and if the mass effects are also taken into account then

$$Q = \left[-\frac{8}{3} \sum_u F_f(x_u) - \frac{2}{3} \sum_d F_f(x_d) - 2 \sum_i F_f(x_i) - 6 F_b(x_W) - 2(m - 1)F_b(x_{\phi^-})\right] \mu_W,$$  \hspace{1cm} (10)

where $x_j \equiv m_j/T$.

The electric charge carried by the particles in chemical equilibrium must be zero unless some special strategy has been adopted to ensure a non-zero value. For $Q = 0$, clearly $\mu_W = 0$; and all other chemical potentials are also zero. Thus, $B = 0(= L)$. This is our main point.

There is another way of easily seeing the physical basis of this result. In the presence of Majorana mass, the left-handed (and also right-handed) neutrinos cannot be assigned a definite lepton number. And consequently the charged weak interactions ($i_L \leftrightarrow \nu_i + W^-$) rapidly violate lepton number; even the sphaleron interactions can no longer preserve $B - L$. Hence, $B(L)$ is driven to zero.

While the sphaleron interactions are in thermal equilibrium for $M_W << T < T_{EW}$, the top-quark and the Higgs scalars (both neutral and charged) may become non-relativistic and disappear from the thermal soup due to annihilations and decay but $B$ will remain zero.
2. If the EWPT is strongly first order, the observed baryon asymmetry could have been produced by:

(i) the out-of-equilibrium decay of heavy GUT (type) scalars,

(ii) the baryogenesis via leptogenesis mechanism, involving the out of equilibrium decay of heavy right-handed Majorana neutrinos and the subsequent conversion of the lepton asymmetry thus generated into a comparable baryon asymmetry by the sphaleron interactions [18], and

(iii) the electroweak (EW) baryogenesis mechanism [11].

We have noted, earlier, that the EW baryogenesis mechanism is not well understood and its viability is, still, a contentious issue [12]. It is, more or less, ruled out in the one Higgs doublet model while with two Higgs doublets it may generate an adequately large baryon asymmetry, but only marginally [19].

Let us see how the cosmologically interesting values of neutrino masses and mixing angles affect the survival of baryon asymmetry generated by the out-of-equilibrium decay of heavy GUT (type) scalars and by the baryogenesis via leptogenesis mechanism.

If the solar $\nu_e$ and the atmospheric $\nu_\mu$ deficits can be accounted for by the $\nu_e \rightarrow \nu_\mu(\nu_\tau)$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations respectively, then the constraint on the sum of the left-handed Majorana neutrino masses due to dark matter requirements, $\sum m_{\nu_i} \sim 5$ eV, requires $m_{\nu_e} \sim m_{\nu_\mu} \sim m_{\nu_\tau} \sim 1.6$ eV [1]. And $\sin^2 2\theta_{ei} \sim (0.4 - 1.5) \times 10^{-2}$, $\sin^2 2\theta_{\mu\tau} \sim 1.0$.

A somewhat more successful model for the large scale structure formation in the universe [4] requires $m_{\nu_\mu} \sim m_{\nu_\tau} \sim 2.4$ eV, $\sin^2 2\theta_{\mu\tau} \sim 1.0$. In this case the solar $\nu_e$ deficit is accounted for by the oscillations of $\nu_e$ into a sterile neutrino species ($\nu_s$). Both $\nu_e$ and $\nu_s$ are required to be lighter than 2.4 eV, though the exact value of their masses is not determined. Even if $\nu_e$ is lighter than $\nu_\mu$ and $\nu_\tau$, we think it is safe to assume that the $e - \mu$ flavor mixing angle is not very small. It should be reasonable to suppose that it is of the same order as the mixing angle for the first and second generation quarks, $\sin \theta_{e\mu} \sim \sin \theta_{us} \sim 10^{-2} - 10^{-1}$.

Broadly, the cosmologically interesting values of the lepton flavor mixing angles can be taken to be of the same order as the quark mixing angles: $\sin \theta_{e\mu} \sim \sin \theta_{\mu\tau} \sim 10^{-2} - 10^{-1}$; and two of the left-handed neutrinos ($\nu_\mu$, $\nu_\tau$) should have mass in the $1 - 5$ eV range (with $\Delta m_{\mu\tau}$ small) while $\nu_e$ can be much lighter.

For $m_{\nu_i}$ in the range $1 - 5$ eV, the lepton number violating $2 \leftrightarrow 2$ scatterings mediated by the heavy right-handed Majorana neutrinos will be in thermal
equilibrium for $(10^{10} - 10^{11}) GeV < T < M_i$. If $\sin^2 \theta_{e\mu}$ and $\sin^2 \theta_{\mu\tau}$ are larger than $10^{-5} - 10^{-4}$, then the lepton flavor mixing due to charged weak (W mediated) interactions will also be in thermal equilibrium at $T \sim (10^{10} - 10^{11})$ GeV and all the lepton numbers will be violated.

If any of the right-handed neutrino Majorana masses ($M_i$) are smaller than $10^{10}$ GeV and the corresponding $m_{\nu_i}$ is larger than $10^{-3}$ eV, then for some temperature range around and above $M_i$ the lepton number violating decay of the right-handed neutrino will be in thermal equilibrium. And at $M_i < 10^{10}$ GeV the value of lepton flavor mixing angles $\sin^2 \theta_{ij}$ need only be larger than $(M_i GeV/10^{15} GeV)$ for W mediated lepton flavor mixing to be in thermal equilibrium: a constraint that should be easily satisfied for cosmologically interesting cases.

We, thus, see that the baryon asymmetry produced at $T \gtrsim 10^{10}$ GeV has to run through the gantlet of lepton number violating 2 ↔ 2 scatterings and decays of heavy right-handed Majorana neutrinos. These lepton number violating processes along with rapid lepton flavor mixing and sphaleron interactions can potentially destroy $B$ even if $(B - L) \neq 0$. For $B$ produced at $T < 10^{10}$ GeV, with $(B - L) \neq 0$, the dangerous processes are the in-equilibrium decays of right-handed neutrinos in case some of the $M_i$’s are less than $10^{10}$ GeV.

We, now, consider the survival of baryon asymmetry, generated well above $T_{EW}$, in the absence (and, then in the presence) of an intermediate $SU(2)_R$ gauge symmetry.

2.a. It is well known that without an $SU(2)_R$ gauge symmetry somewhere in the region $T_{EW} < T < T_{GUT}$, a unification of the gauge coupling constants is not possible [20] without invoking the existence of split multiplets of fermions [21,22] (or supersymmetry [21]). Still, heavy $GUT$ (type) scalars can exist and, surprisingly, the baryon asymmetry generated in their out-of-equilibrium decay has a better chance of surviving than when an $SU(2)_R$ gauge symmetry is present (as will be seen in sec.2.b.).

The heavy $GUT$ scalars present in the primeval soup must decay well before the temperature falls below $10^{10}$ GeV if they have regular strength Yukawa couplings with the fermions ($f_{\text{top}} \sim 1$, $f_{\text{up}} \sim 10^{-5} - 10^{-6}$). This is because the $GUT$ scalars with regular strength Yukawa coupling with the up and down quarks cannot be lighter than $(10^{10} - 10^{11})$ GeV without reducing the proton lifetime ($t_P$) below the current experimental lower limit, $t_P > 5.10^{32}$ years [23]; and their couplings to heavier fermions ensure that their decays are in thermal equilibrium for $T > 10^{10}$ GeV.

The baryon asymmetry generated at $T > 10^{10}$ GeV faces the double risk of being decimated by the lepton number violating scatterings and the in-
equilibrium decays of heavy right-handed Majorana neutrinos.

However, since the right-handed electrons ($e_R$) enter chemical equilibrium at $T \lesssim 10^4$ GeV it has been suggested that they may act as repositories of lepton number which is transformed into a comparable baryon number by the sphaleron interactions at $T < 10^4$ GeV [24] provided there are no lepton number violating processes below $10^4$ GeV ($M_i$’s $> 10^4$ GeV, or if an $M_i < 10^4$ GeV then $m_{\nu_i} < 10^{-3}$ eV). But producing an adequately large number of $e_R$’s in scalar decays is by no means easy. The ratio of partial decay rates of a heavy GUT (type) scalar into two distinct modes is roughly proportional to the square of the smaller of $(f_U^k/f_U^j, f_D^k/f_D^j)$, where $f_{U/D}^k$ is the Yukawa coupling for the up(down) sector fermions in the $k^{th}$ decay mode. The dominant decay mode is $(t_X^R \tau_R^L, t_Y^R b_R^L, t_Z^R Y_R^L)$ while the most relevant mode for producing $e_R$’s is $(t_X^R e_R^L, t_Y^R d_R^L, t_Z^R d_R^L)$, $X, Y, Z$ are color indices. Hence, the number density of $e_R$ can at most be $10^{-6}$ (total baryon/lepton number). For the baryon asymmetry produced via the sphaleron conversion of ($e_R$) lepton number to be the baryon asymmetry observed today, the total baryon number produced in the heavy GUT scalar decay should be $(n_B/s)_{\text{total}} \sim 10^{-5} - 10^{-4}$, $s$ is the entropy density. Such a large value of $(n_B/s)_{\text{total}}$ is just about the maximum that is attainable through heavy scalar decay and requires a large value of the CP-violation parameter ($\epsilon$) $\sim 10^{-2}$ (possible only in the Weinberg Three-Higgs model [25]) and the GUT scalars to be heavier than $(10^{15} - 10^{16})$ GeV so that they can decay completely out of equilibrium. Nevertheless, survival of an adequately large baryon asymmetry generated by the decay of heavy GUT scalars seems plausible.

For $m_{\nu_e} < 10^{-3}$ eV, the out-of-equilibrium decay of $N_e$ can produce a sufficiently large electron number [26] that can be converted into the observed baryon number by sphaleron interactions. And if $M_e < 10^{10}$ GeV and $M_e < (M_\mu, M_\tau)$, then the electron (baryon) number does not face threat of being erased.

2.b. In the presence of an $SU(2)_R \times SU(2)_L$ gauge symmetry C and CP are not violated and, hence, a baryon asymmetry cannot be generated [27]. Unification of gauge coupling constants is possible (in the absence of split multiplets of fermions and supersymmetry) if the scale at which $SU(2)_R$ breaks ($\Lambda_R$) is less than $10^{11}$ GeV [28]. So, the decay of only the lightest GUT scalars (mass $\sim 10^{10} - 10^{11}$ GeV) present in the primeval soup can generate baryon asymmetry.

But when $SU(2)_R$ breaks, Majorana masses for the right-handed neutrinos may be produced and lepton number violating scattering processes can be in thermal equilibrium for $T \sim (10^{10} - 10^{11})$ GeV. Further, interactions mediated by $W_R$ are expected to be in thermal equilibrium up to $T \sim (10^{-4} - 10^{-2})\Lambda_R$. #5
and in the presence of Majorana masses for the right-handed neutrinos they simply equate the chemical potentials of all the charged right-handed leptons, including $e_R$.

The combined effect of the rapid sphaleron interactions, the lepton number violating processes and the interactions mediated by $W_R$ is to completely erase any baryon (and lepton) asymmetry that may exist at $T \sim (10^{10} - 10^{11})$ GeV.

If $\Lambda_R \ll (10^{10} - 10^{11})$ GeV, then even the decay of the lightest GUT scalars present in the primeval soup cannot produce a baryon asymmetry. However, heavy GUT scalars can be produced around $T \approx \Lambda_R$ by the collapse or annihilation of topological defects. But if $M_\tau$ (or even $M_\mu$ and $M_e$) is not much smaller than $\Lambda_R$, its lepton number violating decay may be in thermal equilibrium at the same time as the $W_R$-mediated interactions and, again, the baryon asymmetry produced in the vicinity of $\Lambda_R$ will be completely erased. Anyway, if the baryon asymmetry produced by the monopoles and cosmic strings does, somehow, manage to survive to the present as the observed asymmetry then $\Lambda_R > 10^7$ GeV. This is because the monopoles can annihilate efficiently only for $T > 10^7$ GeV [29] and the annihilation of cusps on infinitely long cosmic strings (this being the dominant mechanism) can generate an adequately large baryon asymmetry only when $T > 10^7$ GeV [30].

As in the case without an $SU(2)_R$ gauge symmetry, the baryogenesis via leptogenesis mechanism is also viable for the case with an $SU(2)_R$ gauge symmetry. Only, now, $\Lambda_R$ should be larger than $10^6$ GeV ($M_{Z_R} > 10^5$ GeV) to sufficiently suppress the destruction of $N_e$ due to interactions mediated by $W_R, Z_R$.

But even here we do not have any compelling reason for $m_{\nu_e} < 10^{-3}$ eV, except that this favors an out of equilibrium decay of $N_e$. But even here we do not have any compelling reason for $m_{\nu_e} < 10^{-3}$ eV, except that this favors an out of equilibrium decay of $N_e$.

The lesson of the entire section 2 is that the baryon asymmetry generated by the out-of-equilibrium decay of heavy GUT (type) scalars can only barely survive to be the baryon asymmetry observed today, for cosmologically interesting values of neutrino masses and mixing angles: the likelihood of survival is really bleak in the presence of an $SU(2)_R$ gauge symmetry at intermediate scales. The baryon asymmetry produced via the out-of-equilibrium decay of $N_e$’s is more likely to survive, but this requires $m_{\nu_e} < 10^{-3}$ eV and we do not know if this inequality really holds.

Lastly, the analysis of section 2 is meaningful only if EWPT is strongly first order, and this requires an extended Higgs sector as for just one Higgs doublet EWPT cannot be strongly first order if the vacuum is to be stable.

3. Earlier, we had shown that working models can easily be constructed that can protect the baryon asymmetry generated above $T_{EW}$ from the effect of sphaleron interactions and other lepton number violating processes, and/or
generate an adequately large baryon asymmetry, below \( T_{EW} \), well after the
sphalerons have dropped out of thermal equilibrium [14,15].

In one set of these models the heavy GUT scalars are constrained to decay
out of equilibrium during a temporary phase of broken electromagnetic gauge
invariance \( U(1)_{em} \) [14]. The decay, thus, produces not just non-zero values
of \( B \) and \( L \) but also a non-zero electromagnetic charge \( Q \). Unless \( Q \) and
\( (B - L) \) satisfy a specific relationship that depends on the number of fermion
generations and Higgs doublets, the sphalerons cannot drive \( B(L) \) to zero [15].
The electric charge neutrality of the universe is restored, when \( U(1)_{em} \) gauge
invariance is restored somewhere above \( T_{EW} \), by the charge \(-Q\) carried by the
scalar field (\( \Phi \)) whose non-zero thermal expectation value is respon-
sible for breaking \( U(1)_{em} \). The \( \Phi \) stays out of chemical equilibrium till well below
\( T_{EW} \) and then decays into leptons.

The other set of models [15] consists of simply modified versions of the
Weinberg Three-Higgs model [25]. Here, a temporary phase of broken \( U(1)_{em} \)
is not required. An asymmetry in the numbers of two heavy GUT scalars
\( \phi_1 \) and \( \phi_2 \) is created by the CP-violating out-of-equilibrium decays of a third
heavy GUT scalar \( \phi_3 \). \( \phi_1 \) may have regular strength Yukawa couplings to the
fermions and may decay well above \( T_{EW} \) to produce non-zero \( B_1, L_1 \) and \( Q_1 \),
while \( \phi_2 \) may only be weakly coupled to the fermions so that it remains out
of chemical equilibrium and can decay only after the sphalerons have dropped
out of thermal equilibrium well below \( T_{EW} \). As before, the non-zero electro-
magnetic charge \( Q_1 \) can protect the \( B_1 \) from sphalerons and lepton number
violating processes. The charge \( Q_2 = -Q_1 \) carried by \( \phi_2 \), and eventually
transferred to the fermions it decays into, maintains the electric neutrality of
the universe throughout. The net baryon asymmetry is \( B'_1 + B_2 \), which is
generally non-zero and adequately large so that final \( n_B/s \approx (4 - 7) \times 10^{11} \).
\( B'_1 \) is the sphaleron-modified value of \( B_1 \), while \( B_2 \) is the baryon asymmetry
produced in the \( \phi_2 \) -decays.

Our models are fairly robust and capable of yielding an adequately large
baryon asymmetry, for any order of EWPT and any value of neutrino masses.

In section 2 we have noted that for a strongly first order EWPT, the me-
chanism of EW baryogenesis can, at best, only marginally yield an adequately
large value of baryon asymmetry. While \( B \) produced by the conventional out-
of-equilibrium decay of heavy GUT scalars at \( T > T_{EW} \) just barely survives
for cosmologically interesting values of neutrino masses and mixing angles; the
situation is particularly grim in the presence of an \( SU(2)_R \) gauge symmetry
at intermediate scales. Only \( B \) produced through the decay of right-handed
electron neutrinos seems to survive without any threat of destruction.

The exercise in equilibrium thermodynamics carried out in section 1 had
yielded our main result: for a second or weakly first order EWPT, $B(L)$ is made zero by the sphaleron interactions for non-zero values of Majorana masses of neutrinos. This result holds for $B$ generated by any of the well known mechanisms, including the baryogenesis via leptogenesis mechanism. Only our models are still viable.

Since our models are variations on the old theme of *out-of-equilibrium decays of heavy GUT (type) scalars can produce the observed baryon asymmetry*, we are tempted, like Kolb and Turner \[31\], to believe that the heavy GUT (type) scalars that link quarks and leptons, though out of reach of experiments planned for the near future, may have something to do with reality.
1. The Majorana mass eigenstates are actually $\omega(\chi)$ plus a small, $O(m_d/M_i)$, admixture of $\chi(\omega)$. We have chosen to neglect this small admixture.

2. The largest value of CP-violation parameter ($\epsilon$) attainable in the decay of heavy GUT gauge bosons is too small to yield the observed baryon asymmetry [17].

3. The $2 \leftrightarrow 2$ scatterings mediated by the right-handed Majorana neutrinos will be in thermal equilibrium at a temperature $T$ provided [13],

$$T \gtrsim (4\text{eV}/m_{\nu})^2(10^{10}\text{GeV}).$$

4. For the decay to be in thermal equilibrium at $T \sim M$, the decay rate ($\Gamma_D$) should be larger than the expansion rate of the universe $H(T = M)$:

$$\frac{1}{8\pi} \frac{m_d^2}{v^2} M > 17 \frac{M^2}{M_P};$$

using, $m_\nu = m_d^2/M$, $v = 175\text{GeV}$, we have $m_\nu \gtrsim 8 \times 10^{-4} \text{eV}$.

5. For $T < M_{W_R}$, the interactions mediated by $W_R$ are in thermal equilibrium upto $T_R \gtrsim (3.10^3 \Lambda_R^4 / M_P)^{1/3}$. It should be noted that $T_R$ is independent of the $SU(2)_R$ gauge coupling constant, $g_R$, as $M_{W_R} \sim g_R \Lambda_R$. With $\Lambda_R = 10^3 \text{GeV}$, $T_R \sim 10^{-13/3} \Lambda_R$ and with $\Lambda_R = 10^{11} \text{GeV}$, $T_R \sim 10^{-5/3} \Lambda_R$.

6. $N_e$ can annihilate via $Z_R$ mediated interactions and the number that ultimately decay will be very small unless the decay rate is larger than the annihilation rate at $T \sim M(< M_{Z_R})$, which requires

$$\Lambda_R^4 > \frac{M^4}{2\pi^2 f^2};$$

$f$ being the electron Yukawa coupling ($\sim 2 \times 10^{-6}$). If $M_i$ are to decay before the sphalerons go out of equilibrium, then $M_i > 10^2 \text{GeV}$ and hence $\Lambda_R > (10^5 - 10^6) \text{GeV}$.

7. At present, the double-beta decay experiments impose a limit: $m_{\nu_e} < 0.68 \text{eV}$. 

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