ON THE BARYON, LEPTON-FLAVOUR AND RIGHT-HANDED ELECTRON ASYMMETRIES OF THE UNIVERSE

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Abstract

Non-perturbative electroweak effects, in thermal equilibrium in the early universe, have the potential to erase the baryon asymmetry of the universe, unless it is encoded in a B-L asymmetry, or in some “accidentally” conserved quantity. We first consider the possibility that the BAU may be regenerated from lepton flavour asymmetries even when initially $B - L = 0$. We show that provided some, but not all the lepton flavours are violated by $\Delta L \neq 0$ interactions in equilibrium, the BAU may be regenerated without lepton mass effects. We next examine the possibility of encoding the baryon asymmetry in a primordial asymmetry for the right-handed electron, which due to its weak Yukawa interaction only comes into chemical equilibrium as the sphalerons are falling out of equilibrium. This would also raise the possibility of preserving an initial baryon asymmetry when $B - L = 0$.

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The predominance of matter over antimatter throughout the observable Universe represents one of the old puzzles of Big Bang cosmology. It has become more acute in recent years, with the advent of inflationary models of the development of the early Universe. Any initial asymmetry would be inflated away, so we would be forced to rely on the microphysics of elementary particle interactions to regenerate the Baryon Asymmetry of the Universe (BAU). The basic requirements for the generation of the BAU were given by Sakharov in 1967. They are: non-conservation of baryon number, violation of C and CP symmetry, and out-of-equilibrium dynamics.

The first realizations of the Sakharov conditions were in the context of Grand Unified Theories (GUTs). In these theories, quarks and leptons were unified into multiplets of a larger simple gauge symmetry, which contained the Standard Model gauge group as a subgroup. Gauge and Higgs interactions of the larger simple group then violated baryon (B) and lepton (L) number at the high energy scales where grand unification occurred. During the thermal history of the Universe, heavy gauge and Higgs particles could, via their out-of-equilibrium decays, generate cosmological baryon and lepton asymmetries. In the simplest GUT models, these asymmetries were equal, and the net B-L of the Universe was zero. In standard inflationary cosmology, whilst reheating at the end of the inflationary epoch seems unlikely to have restored the GUT symmetry, one can still produce the BAU via the out-of-equilibrium decays of GUT Higgses, if they are in turn produced in decays of the quantum of the inflationary scalar field, the inflaton. In supersymmetric models, the GUT sector can also provide other indirect sources of the BAU, by inducing low-energy effective operators that introduce BAU-generating potential interactions into the coherent oscillations of squark and slepton v.e.v.'s along flat directions of the scalar potential.

The fact that simple GUT models tend to predict that B-L = 0 took on added importance with the realization that B- and L-violating, but B-L-conserving, non-perturbative electroweak effects, associated for example with sphalerons, should be in thermal equilibrium above the electroweak phase transition temperature $T_C$. These represent a double-edged source of new physics. First there is the possibility that the BAU is actually generated by out-of-equilibrium effects at the electroweak phase transition, as first analyzed by Kuzmin, Rubakov and Shaposhnikov (KRS1). Whether this is feasible depends sensitively on the nature of the electroweak phase transition and the sources of CP violation available in any given model. The possibility is also opened up of generating the BAU by electroweak reprocessing of an earlier lepton asymmetry, as proposed by Fukugita and Yanagida (FY) in the context of the neutrino mass see-saw. On the other hand, should BAU generation at the electroweak phase transition not occur, the disquieting prospect arises that any previously-produced BAU would be erased if it were not protected by a B-L asymmetry.

This danger of BAU erasure is pandemic in models with interactions beyond those of the Standard Model that violate B and/or L, and do not conserve B-L. This was first noticed by Fukugita and Yanagida (FY) in the context of the neutrino mass see-saw, where integrating out the heavy $N_R$ yields an effective $\nu_L \nu_L HH$ dimension-5 interaction. If this interaction were in thermal equilibrium
simultaneously with the sphaleron effects, then B and L would be relaxed separately to zero. In earlier papers, we and others [9]-[11] have extended this argument to constrain many extensions of the Standard Model, including supersymmetric theories and models yielding neutron-antineutron oscillations, assuming that the BAU could not be generated after the electroweak phase transition.

A possible way that the BAU might be protected, and our limits avoided, is if there is some other conserved quantum number with a primordial asymmetry, which cannot be erased by high temperature equilibrium interactions and can encode the BAU. The most trivial possibility in the absence of L-violating interactions is B-L, which is conserved even non-perturbatively in the Standard Model [12]. A more interesting possibility, which was first analyzed in another paper by Kuzmin, Rubakov and Shaposhnikov [14] (KRS2), is that individual lepton flavour asymmetries in a B-L=0 universe might regenerate a BAU at low temperatures when masses in the lepton sector become important. The criteria for a lepton flavour asymmetry to yield a BAU via sphaleron effects, set out in KRS2, are: 1) the generation of a lepton flavour asymmetry by the baryogenesis (or leptogenesis) mechanism responsible for the generation of the primordial BAU, 2) the absence from equilibrium of any lepton flavour violating interactions, for at least one of the lepton generations, 3) the presence of mass effects in the lepton sector while the non-perturbative electroweak processes are in equilibrium. In the Standard Model (SM), where the lepton mass effects are generated after the electroweak phase transition, this requirement translates into the necessity for the sphaleron processes to remain in equilibrium below $T_C$, and hence into a lower bound on the Higgs mass $m_H$.

If all three KRS2 conditions are satisfied, the equilibrium condition is one in which the BAU is (re)generated when the lepton sector masses switch on. The BAU is then proportional to mass differences in the lepton sector. In the case where the lepton sector masses are those of the leptons alone, KRS2 concluded that they are probably insufficient to regenerate enough BAU. The analysis of KRS2 has recently been elaborated by Dreiner and Ross [15], who reach the same conclusion and also note that in supersymmetric models slepton masses might provide mass effects that are more useful for BAU regeneration.

Following Nelson and Barr [16], we mentioned the KRS2 loophole in quoting our previous constraints [9]-[11] on B and L violating interactions, and noted that one must use lepton flavour asymmetries, since quark-flavour mixing is in thermal equilibrium. We also quoted two different sets of limits, considering sphaleron and new interactions either just above $T_C$ or at much higher temperatures. The latter bounds were much stronger for operator of dimension $d > 4$, but not for $d \leq 4$ operators. Recently, Ibáñez and Quevedo [17] have pointed out that chiral gaugino charges inhibit sphaleron erasure of baryon and lepton asymmetries in supersymmetric theories above the effective supersymmetry-breaking scale. The effects analyzed by Ibáñez and Quevedo [17] would appear at high temperature $T \geq M_{\text{susy}}^{2/3}M_F^{1/3}$, and hence could only affect the stronger versions of our bounds for $d > 4$ operators. They do not affect limits on $d \leq 4$ operators, nor the $T_C$ versions of our bounds for $d > 4$ operators.
In this paper we show that while lepton number violating effective interactions would wipe out a BAU if the interactions involving all lepton generations were in equilibrium\cite{9, 10, 11}, the BAU could actually be (re)generated from lepton flavour asymmetries if one or more (but not all) generations were out of equilibrium. We also examine the possibility that the BAU could be encoded in a primordial asymmetry for the right-handed electron field $e_R$, where the $e_R$ asymmetry arises to balance (part of) the baryon asymmetry generated by a B-L conserving interaction.

Let us first consider the (re)generation of a BAU from lepton flavour asymmetries when initially $B-L=0$. In particular we wish to ask if there is a way that this (re)generation can occur, without the produced BAU depending on the (small) lepton masses. What we will find is that provided lepton number violation occurs in equilibrium for some but not all lepton flavours, then a BAU can be generated depending on the initial lepton flavour asymmetries (not on lepton masses). A priori this is unexpected, as equilibrium lepton number violation for all lepton flavours would inexorably result in the erasure of all $B$ and all $L$, while no violation of lepton flavour would leave us with the situation analyzed in KRS2.

To illustrate our argument, let us consider the dimension-5 operator $\nu_L\nu_LHH$, which violates $L$ (and $B-L$) has been shown \cite{8}, \cite{13} to lead to the equilibrium condition $B=L=0$ in the presence of sphaleron interactions if interactions involving all three generations are in equilibrium. The requirement that the interactions be out of equilibrium led to a constraint on the Majorana mass term which characterizes the strength of the effective interaction. Let us write the additional lagrangian interaction terms as $h_{ij}\nu_L^i\nu_L^j + M_i\nu_R^i\nu_R^j$ where we work in a mass diagonal basis for the $\nu_R$, so that the effective interaction becomes

$$\sum h_{ik}h_{kj}M_k\nu_L^i\nu_L^j HH$$

(1)

and the light neutrino masses given by the see-saw are $m_{\nu_i} \simeq \sum h_{ik}h_{ki}v^2/M_k$ where $v$ is the electroweak Higgs expectation value. If the neutrino Yukawa couplings are not generation-dependent, one can set a limit on $M' = M/h^2 > 10^{10} - 10^{16}$ GeV depending on the scale the $B-L$ asymmetry was produced \cite{8}, \cite{13}.

Consider now however, the possibility that the neutrino Yukawas are generation-dependent. In this case, it is quite possible that only one or two generations satisfy the above bound on $M'$. In this case a baryon asymmetry could be (re)generated given an initial asymmetry in the neutrino generation for which $\bar{\nu}_i$ was out of equilibrium. To see this, let us assume that for the first two generations the $h_{1i}$ and $h_{2i}$ are all sufficiently small that $M'_1$ and $M'_2$ are large enough to satisfy the out-of-equilibrium bound. However we assume that some $h_{3i}$ is large and the rate of the effective interaction $\bar{\nu}_i$ is in equilibrium for the third generation. Using \cite{13}, one can easily work out the equilibrium conditions on the full set of chemical potentials. We find that the resulting baryon asymmetry can be expressed as
\[ B = \frac{84}{247} \mu \]  \hspace{1cm} (2)

where \( \mu \) is the chemical potentials for \((2/3)B - (L_1 + L_2)\). Thus the final asymmetry depends only on an initial asymmetry in the first two generations.

A posteriori this result is less surprising. If initially B-L=0 and the sphalerons are in equilibrium, then B=0=L, so we can take this as our initial condition. L=0 with a lepton flavour asymmetry means that the lepton asymmetry in one generation is cancelled by that in another lepton generation. If we then introduce a sufficiently large mass for the \( \nu_\tau \), we have an L-violating interaction in equilibrium that modifies the lepton asymmetry stored in the \( \nu_\tau \) and \( \tau_L \) (which was balancing the lepton number in the e and \( \mu \) generations to give L=0). So in equilibrium we will no longer have B-L=0 (since now L\( \neq 0 \)), and the nonperturbative electroweak effects will transform some of the lepton asymmetry into baryons.

What is surprising about the mechanism is that in the absence of lepton number violation (for primordial B-L=0) one would have obtained the lepton mass suppressed BAU calculated in KRS2; with violation of all lepton flavours the equilibrium condition one would have obtained B=0=L. So the efficient generation of a BAU from a lepton flavour asymmetry requires that some of the lepton flavours are violated by the lepton number violating operators, and others are not. Stated differently, for this mechanism of baryogenesis to occur we get a lower bound on the strength of the lepton violation in some generation, as well as an upper bound on the strength of the lepton violation in one of the other generations.

Clearly we may now extend our analysis to the consideration of general effective interactions violating lepton number, that we have analyzed previously for the case when there was no generation dependence \([9,11]\). In the new case where one tries to alter this analysis by baryogenesis from a lepton flavour asymmetry, and using generation dependence in the effective interaction to erase some lepton generations but not others, we see that our previous bounds take on an entirely new aspect. In the new case it is still true that our bounds on the operators must be satisfied for at least one of the lepton generations. But to use this baryogenesis mechanism then implies that the effective interaction must be in equilibrium for one of the other lepton generations, thus providing a lower bound for its strength in this generation. Clearly this new possibility only applies to operators involving leptons, where there is no standard model interaction mixing the generations. As such our previous generation independent analysis is generally valid for baryon number violating operators involving only quark fields.

We next turn to the possibility that an initial baryon asymmetry is preserved by being stored in \( e_R \). This could in principle occur even with no \( B - L \) nonconservation whatsoever. Of the 45 chiral states composing the three fermion generations of the Standard Model, the \( e_R \) is the most weakly coupled to the others. It is kept in thermal equilibrium via its coupling with the hypercharge gauge
boson, but this interaction does not change its quantum numbers or generation. The only interaction by which it connects to the other standard model states is its Yukawa coupling to the Higgs, which chirally flips it to $e_L$. The tiny electron mass tells us that this Yukawa coupling is particularly weak: $h_e \simeq \sqrt{2}m_e/v \simeq 2.1 \times 10^{-6}$. Comparing the interaction rate (say for $H \leftrightarrow e_R\bar{e}_L$) induced by such a coupling at high temperature in the early universe, with the expansion rate, we find that such the $e_R$ only comes into chemical equilibrium at temperatures $\simeq 1$ TeV. This means that any primordially-generated lepton number that occurred as $e_R$ would be decoupled from nonperturbative electroweak effects until this temperature. Since this is close to the temperature, at which the sphaleron effects fall out of equilibrium, it is possible that the $e_R$ may not be transformed into $e_L$ soon enough for the sphalerons to turn them into antiquarks, and thereby wipe out the remaining BAU.

We investigate this possibility numerically as a function of the Standard Model top quark and Higgs masses $m_t, m_H$. We find that the sphaleron suppression is exponentially sensitive to theoretical uncertainties. With the current best estimates of $T_C$ and the erasure rate for an $e_R$ asymmetry, it would wipe out a primordial baryon asymmetry for reasonable values of $m_t$ and $m_H$. However, an increase of $T_C$ by as little as 50%, or a decrease in the erasure rate by a factor of 3-4, could essentially preserve an initial $e_R$ asymmetry. This could occur either as our understanding of the Standard Model improves, or in some extension of the Standard Model. We also update the limits on B- and L-violating interactions that we derived previously for interactions involving the $e_R$, assuming the persistence of a primordial BAU.

We calculate the baryon erasure as the temperature drops towards the electroweak phase transition by integrating the rate equations. It is a two-step process, where first $e_R$ are chirally flipped to produce an $e_L$ asymmetry, and then these annihilate against the baryons via sphaleron interactions. However, the rate of sphaleron interaction is so large above threshold, even with any plausible guess for threshold turn-on, that effectively it is a one-step process, where the $e_R$ asymmetry is flipped and annihilates immediately. This means that we only need to consider the rate equation for chirality flip of the $e_R$ to determine the efficiency of erasure.

The time evolution for the number density of the $e_R$ asymmetry $\equiv n_R$ is determined by the difference in the rate equations for $e_R$ and $\bar{e}_R$. The rate of change of the $e_R$ number density includes terms due to Higgs decays and inverse decays, as well as reactions involving the hypercharge gauge boson. The gauge interactions always create or destroy an $e_R$ and an $e_R$ together, so will not change the $e_R$ asymmetry. However, this is not the case for the Higgs interactions which involve an $e_R\bar{e}_L$ or $e_L\bar{e}_R$ pair. We have checked that scattering processes make insignificant contributions to the rate equations, and we are justified within the Standard Model in neglecting CP-violating differences in $H \leftrightarrow e_R\bar{e}_L$ and $\bar{H} \leftrightarrow e_L\bar{e}_R$ rates. Thus the evolution of the difference $n_R \equiv n_{e_R} - n_{\bar{e}_R}$ is

$$\frac{dn_R}{dt} = -3Hn_R + 2(n_L - n_R)\Gamma_{ID} + 2n_H\Gamma_D$$

(3)
where \( n_L \) is the asymmetry in the left-handed electrons, \( n_H \) is the asymmetry in the Higgs, and \( \Gamma_D \) and \( \Gamma_{ID} \) are the thermally averaged decay and inverse Higgs decay rates. The factor of 2 in equation (3) is due to decays (and inverse decays) involving the charged and neutral Higgs fields.

We assume, for simplicity, that there is no \( H - \bar{H} \) or \( e_L - \bar{e}_L \) asymmetry. We also neglect final state phase space factors. This gives us:

\[
\ln \frac{n_R}{n_{Ri}} = -2 \int \Gamma_{ID} dt
\]

where we terminate the rate integration when the temperature falls to \( T_o \), where the sphaleron transitions drop out of equilibrium. The inverse decay rate \( \Gamma_{ID} \) is:

\[
\Gamma_{ID} = \frac{1}{n_e} \int \frac{d^3p}{(2\pi)^32E} \int \frac{d^3p'}{(2\pi)^32E'} \int \frac{d^3p^0}{(2\pi)^32E^0} (2\pi)^4 \delta^4(p + p' - p^0) |M|^2 ff' ,
\]

where \( p \) and \( p' \) are the \( e_R \) and \( \bar{e}_L \) momenta, \( p^0 \) is the \( H \) momentum, \( f \) and \( f' \) are the Fermi-Dirac thermal distributions for the \( e_R \) and \( \bar{e}_L \), and the matrix element is

\[
|M|^2 = 2p.p' h^2_e \]

The inverse decay, \( e_R \bar{e}_L \rightarrow H \) process is related to the \( H \rightarrow \bar{f}ff \) process we considered in [11], but has a different numerical coefficient, which we evaluate to be

\[
\Gamma_{ID} = \frac{m_o^2(T) h^2_e I}{12\pi\zeta(3) T^2} \approx \frac{(\ln(2))^2 m_o^2(T) h^2_e}{24\pi\zeta(3) T} \approx 5.3 \times 10^{-3} \frac{m_o^2(T) h^2_e}{T}
\]

where [13]:

\[
I = \int_1^\infty \ln \left( \frac{\cosh([u + (u^2 - 1)^{1/2}]m_o(T)/4T)}{\cosh([u - (u^2 - 1)^{1/2}]m_o(T)/4T)} \right) \frac{du}{[\exp(\frac{um_o(T)}{T}) - 1]}
\]

Note that \( (m_o(T)/T)I \) is only weakly dependent on temperature in the range that we are interested in. Furthermore, the approximation in equation (3) becomes exact for \( m_o(T) \ll T \). When evaluating \( \Gamma_{ID} \), we use the temperature-dependent effective Higgs mass at zero momentum and zero Higgs vev, which is known [19] to be

\[
m_o^2(T) = 2D(T^2 - T_o^2)
\]

where

\[
D = (2m_W^2 + m_Z^2 + 2m_t^2 + m_H^2/2)/8v^2
\]

and \( m_H \) is the zero-temperature Higgs mass. Calculations indicate that the sphaleron transitions drop out of equilibrium at:

\[
T_o^2 = T_C^2(1 - E^2/(\lambda_T^2 D))
\]
where
\[ T_C^2 = \frac{(m_H^2 - 8Bv^2)}{4D}, \]  
(12)

from the standard thermal one-loop calculation \[19\],
\[ B = \frac{3(2m_W^4 + m_Z^4 - 4m_t^4)}{64\pi^2v^4} \]  
(13)
\[ E = \frac{1}{4\pi v^2} (2m_W^2 + m_Z^2) \]  
(14)

and
\[ \lambda_{T_C} \simeq \frac{m_H^2}{2v^2} \]  
(15)

(for the full expression see \[19\]); \( T_o \) is only very slightly below \( T_C \) for the range of \( m_t \) and \( m_H \) chosen here. When combined with the expression for the expansion rate \( tT^2 = C \), with \( C = 3.65 \times 10^{21} \text{MeV}/\sqrt{N} \), and \( N = 427/4 \) for the Standard Model, the rate (7) gives:
\[ \ln \frac{n_R}{n_{R_i}} = -8.6 \times 10^4 \text{GeV} \frac{D}{T_o} \]  
(16)

We wish to emphasize that the erasure suppression factor (16) is exponentially sensitive to the chirality flip rate, so that this is one cosmological situation where even a factor of \( \sqrt{2} \) can be important! We also wish to remind the reader that we have performed our calculation in an approximation where we are dropping both \( n_{\bar{H}} - n_H \) and \( n_{\bar{e}_L} - n_{e_L} \). A full calculation retaining these terms would require the numerical integration of Boltzmann equations, and depend on other particle asymmetries, and will not be attempted here. We expect these effects to further suppress the final baryon asymmetry. Within the Standard Model, estimating the erasure rate \( \Gamma \) requires in particular precise knowledge of \( T_C \) and of \( m_0(T) \). One cannot yet be sure that the one-loop estimate (12) of \( T_C \) might not be significantly altered by higher-order effects. As for \( m_0(T) \), we find that the difference in the suppression factor \( n_R/n_{R_i} \) (16) is typically much less than a factor of 2 different from what would have been calculated using naively the zero-temperature value \( m_H \). However, in principle the rate should be calculated using the full dispersion relation for the Higgs boson as a function of its momentum \( p^0 \). More uncertainties enter once one goes beyond the Standard Model. The value of \( T_C \) is likely to change (Giudice \[20\] has calculated changes in \( T_C \) in the minimal and non-minimal supersymmetric extensions of the Standard Model), the Higgs-electron coupling will increase, e.g., in even the minimal supersymmetric extension of the Standard Model, the expansion rate of the Universe will change, and there may be other processes that flip the chirality of the \( e_R \).

Therefore, our estimate of the suppression factor \( n/n_i \) should be considered as only qualitative.

In the figure we plot the erasure suppression factor \( n_R/n_{R_i} \) (16) calculated as a function of \( m_t \) for various allowed values of the Higgs mass (as labelled on the curves). We can see that the suppression
factor is not small enough to preserve a useful fraction of a primordial asymmetry stored in the $e_R$. However, we emphasize again that, as we see from equation (16), the resulting suppression factor is exponentially sensitive to both the Higgs mass and the critical temperature for the electroweak phase transition.

Finally, we consider the implications of these considerations for cosmological limits on new interactions beyond the Standard Model. Previous analyses of the erasure of a primordial BAU, even with $B - L \neq 0$, depend on the number densities of all fields, in which baryon and lepton asymmetries are stored, being coupled to the thermal soup. That part of a baryon or lepton asymmetry which is stored in an uncoupled field will not be equilibrated, and one can only include the density it stores once it comes into thermal equilibrium. In the present context, the $e_R$ can, in principle, encode and protect the asymmetry for as long as it is out of equilibrium, though this requires the mechanism of primordial generation to produce at least part of the asymmetry in the form of the $e_R$. The non-equilibration limits on operators not involving the $e_R$ may not be inferred at temperatures above the $e_R$ equilibration temperature if there is a primordial $e_R$ asymmetry. This only affects operators of dimension greater than five - all others obtain their best limits at $T_C$ where the $e_R$ is in equilibrium, and only operators that do not involve the $e_R$ field - otherwise their equilibration would bring the $e_R$ into equilibrium. It also means that for these operators the best safe limit one can obtain would be from temperatures of order $T_C$. These limits are given in [11].

In conclusion: we have considered the possibility of (re)generating the BAU from a lepton flavour asymmetry for primordial $B-L=0$. We have found that if in addition to the lepton flavour asymmetry, there is a lepton number violating interaction that comes into equilibrium for at least one lepton generation, but not all lepton generations, then we may efficiently regenerate the BAU. This yields both upper limits on the strength of the interaction in at least one lepton generation, and lower limits on its strength in some other lepton generation. We have also examined the possibility of encoding the baryon asymmetry of the universe in a “balancing” $e_R$ asymmetry, whose incomplete thermal equilibration would protect the BAU from the depredations of non-perturbative electroweak baryon number violation. For the Standard Model, with the best current estimates of the parameters of the electroweak phase transition, the $e_R$ equilibration appears sufficient to erase a primordial BAU so encoded, at least for reasonable values of $m_t$ and $m_H$, but this conclusion is exponentially sensitive to the parameters of the model, and the dynamics of the electroweak phase transition. As such, it is an issue to be considered in discussions of baryogenesis, including in models which have different particle content near the electroweak scale.
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Figure Captions

Figure 1: The suppression factor $n_R/n_{R_i}$ for the $e_R$ number density is plotted as a function of $m_t$ for different values of the Higgs mass (labelled in GeV).