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Baryon Asymmetry of the Universe and Large Lepton Asymmetries

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Abstract

It is shown how a large lepton asymmetry of the universe $L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma} \geq 1$ can lead to a small baryon asymmetry $B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-9}$ via sphaleron mediated transitions.

There are many specific models for generating the baryon asymmetry of the universe [1], but it is generally accepted that baryon number violating interactions become rapid as T approaches the temperature of the electroweak phase transition [2].

The conventional picture assumes that sphaleron [3] mediated processes dominate in the temperature range $M_W/\alpha_W > T > M_W$.

Many authors have discussed the possibility of generating the baryon asymmetry by making use of the anomaly free $B - L$ symmetry in the standard model. These models incorporate an initially present or, preferably, a dynamically generated $B - L$. Some [4] start by generating at high temperatures, e.g. $T \geq 10^{10}$ GeV a lepton asymmetry of order

$$L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma} \sim 10^{-9} \quad (1)$$

(n_γ is the photon density of the universe) which then leads to a baryon asymmetry because of $B - L$ preserving, but $B + L$ violating interactions.

In this note we will present a somewhat paradoxical picture, which can lead quite naturally to a baryon asymmetry $B = \frac{n_B}{n_\gamma} \sim 10^{-9}$. We begin by assuming that at some large temperature, e.g. $T \geq 10^{10}$ GeV, the lepton asymmetry L is greater than one, $L \geq 1$. Present experimental limits [5] restrict L weakly to $L \leq 3 \times 10^3$. We furthermore assume that lepton number erasure mechanisms are ineffective so that L remains ≥ 1 (we will return to this point shortly).

Almost twenty years ago, Linde [6] pointed out that a large enough L could prevent restoration of $SU(2)$ symmetry at high temperatures. The underlying reason is that a non zero $n_0 = n_\nu - n_{\bar{\nu}}$ breaks Lorentz invariance explicitly as well as $SU(2)$; this allows the $SU(2)$ gauge fields to acquire non vanishing v.e.v.'s (vacuum expectation values). For a Higgs doublet ϕ with quartic self coupling λ and v.e.v. $\langle \phi \rangle = v$, the equation for v , with non-zero n_0 , is

$$v \left[\lambda v^2 - \mu^2 - \frac{n_0^2}{v^4} \right] = 0. \quad (2)$$

At finite temperatures, for $SU(2) \times U(1)$, the equation for $v(T)$ is [6]

$$\lambda v(T) \left[v^2(T) - v^2(0) - \frac{16a_1 n_0^2}{[v^2(T) + a_2 T^2]} + a_3 T^2 \right] = 0 \quad (3)$$

where $a_{1,2,3}$, are model dependent constants, typically $0(1)$. We see that a large enough n_0 blocks symmetry restoration at high T . In particular, setting $n_\gamma = 2\zeta(3)T^2/\pi^2 \simeq T^2/4$, we see that $v(T) \neq 0$ for

$$L = \frac{n_0}{n_\gamma} \geq a_2 \sqrt{a_3/a_1} = L_c \quad (4)$$

(for $SU(2) \times U(1)$, L_c ranges between two and thirteen as we vary λ). For $L \geq L_c$, $v(T)$ is proportional to T

$$\left[\frac{v(T)}{T}\right]^2 = \beta \left[\frac{L^2}{L_c^2} - 1\right] \theta\left[\frac{L^2}{L_c^2} - 1\right] \quad (5)$$

where $\beta \equiv \frac{a_3 a_2}{a_2 + a_3}$ is also $0(1)$.

The fact that symmetry is not restored as T increases has many dramatic effects: one of these is presumably that sphaleron dominance of $B + L$ violating transitions persists as we increase T , since we never reach the regime where $T \geq v(T)$.

Let us briefly recapitulate the situation in the more conventional picture. The rate for $B + L$ violation is there shown to be [1] [2][3]

$$\Gamma_{B+L} \sim AT e^{-F_{sph.}/T} \quad (6)$$

where $A \sim 0(1)$. $F_{sph.}$ is the sphaleron free energy [3]

$$F_{sph.} \sim \frac{4\pi v}{g} \quad (7)$$

where g is the $SU(2)$ coupling constant. For $T \ll T_c$ (critical temperature for the phase transition), Γ_{B+L} is exponentially suppressed, but as $T \rightarrow T_c$, $v(T) \rightarrow 0$ and hence $\Gamma_{B+L} \rightarrow AT_c$. By contrast the expansion rate of the universe

$$H \sim \frac{KT^2}{M_{PL.}} \quad (8)$$

with $K \sim 0(1)$, so that, as $T \rightarrow T_c$

$$\frac{\Gamma_{B+L}}{H} \rightarrow \frac{AM_{PL.}}{KT_c} \sim 10^{17} \quad (9)$$

We see that any initial $B + L$ is erased. Incidentally, this is also the conventional argument against a surviving large L ; since Γ_{B+L} is so rapid, a large L would lead to a baryon asymmetry differing from L only by the initial $B - L$. Small B suggests small L . By contrast, for $L \geq L_c$, we see that $F_{sph.}$ in equations (6),(7), does not go to zero since the phase transition in which $v(T) \rightarrow 0$ does not occur. A rough evaluation of the exponential gives

$$e^{-F_{sph.}/T} \sim e^{-4\pi v(T)/gT} \sim e^{-4\pi/g} \sim e^{-40} \quad (10)$$

by, as we saw earlier, setting $\frac{v(T)}{T} \sim 1$. Since $e^{-40} \sim 10^{-17}$, we see that the expansion rate of the universe is in fact greater than Γ_{B+L} i.e. $\frac{\Gamma_{B+L}}{H} \leq 0(1)$ until we reach temperatures $T \sim 100\text{Gev.}$ where they finally become comparable. At this point our approximations are breaking down in any case.

A detailed prediction for the baryon asymmetry is unwarranted. It would depend on details of the sphaleron model and of course on the value of L . It appears clear however that a small baryon asymmetry, $B \sim 10^{-9}$ can be generated by $B + L$ violating sphaleron violating processes occurring all along during the era when $\frac{\Gamma_{B+L}}{H} \leq 1$. The smaller this ratio, the smaller is the baryon asymmetry we generate. Let us once again re-emphasize that this is only true provided initially $L/L_c \geq 1$.

The model has one clear prediction, namely that the present lepton asymmetry of the universe, $L_{PRESENT} \geq 1$. This is presently not testable, but hopefully will be in the not too distant future.

Let us turn to our assumptions. We already saw that $L \geq 1$ was consistent with experiment[5]. A detailed analysis of lepton number erasure in models where L is initially large was given ten years ago by Langacker et.al. [7]; it was shown there, that for initial $L \geq L_c$, it followed that $L \rightarrow L_c$ at temperatures larger than 100Gev. and that $v(T)$ then went to zero. The erasure mechanism depended quadratically on the neutrino zero temperature masses and the assumption was made there of a 10ev. mass. If one takes the much lower value of 10^{-3}ev. , as motivated by present solar neutrino experiments the erasure does not occur.

A second, and perhaps amusing, consequence of large L leading to large $v(T)$ can occur

if we assume that the Higgs self coupling constant, λ , is $O(1)$ and hence that the Higgs boson mass $M_H \sim \lambda v(T) \geq T$. The two most commonly discussed mechanisms for lepton number erasure [4] [7][10] are 1) $\nu + \nu \rightarrow \phi + \phi$ and 2) $\nu + \phi \rightarrow \bar{\nu} + \phi$, where ϕ is of course a Higgs boson. In this situation, neither of these reactions occurs appreciably. The first one is suppressed by a Boltzmann weighting factor because the Higgs boson masses $M_H \geq T$. As for the second mechanism, we have already seen that ϕ 's are not copiously produced in the early universe; even if they were produced, they would be very massive and hence decay to e.g. massive quark-anti-quark pairs, so they would not be present in the early universe to scatter off of neutrinos.

A second caveat is of a field theoretic nature. We have assumed that the sphaleron analysis[3] holds, even for non zero B and L ; this is conventionally assumed, but is of course a considerable extrapolation for the case when $L \geq 1$. It is probably true however[11]. We are also tacitly assuming that $L/L_c \geq 1$, but not $\gg 1$, so that even the neutrinos at the top of the Fermi sea have energies less than the top of the potential barrier. In fact, for $L/L_c \gg 1$, $v(T)/T \simeq [L/L_c]^{\frac{1}{3}}$ [7], we see that the neutrinos at the top of the Fermi sea are now above the barrier. In this case erasure presumably occurs rapidly until one reaches $L/L_c \geq 1$ and we return to the earlier scenario.

In conclusion, we have shown that a small baryon asymmetry, $B \sim 10^{-9}$, can be generated straightforwardly if we have an initial lepton asymmetry, $L \simeq 1$. Models in which this asymmetry could be generated at $T \gg 10^{10}$ GeV. by decays of heavy Majorana leptons have been considered in the literature [9] , [7] , but we choose here to simply assume that initially L is greater than one.

We have discussed in this note one example of a model in which erasure becomes incomplete because the symmetry is not restored, but it is obvious that the phenomenon is more general.

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