UCLA-92-TEP-33
Fermilab Library
0 1160 0148412 1

UCLA/92/TEP/33

Baryogenesis and Neutrino Masses*

R. D. Peccei

Department of Physics, UCLA, Los Angeles, California 90024

ABSTRACT

The erasure of any preexisting $B+L$ asymmetry in the universe in its late stages suggests that the B asymmetry observed today either originated at the electroweak scale or it arose from an original L asymmetry. For the latter case to be viable either neutrino masses are much below the eV scale or the L asymmetry itself is generated at an intermediate scale. Several features of the generation of a B asymmetry via an L asymmetry are discussed, including the interesting possibility that the present baryon asymmetry in the universe originates as a result of CP violating phases in the neutrino mass matrix.

* Talk given at the XXVI International Conference on High Energy Physics, Dallas, Texas, August. 1992. To appear in the Proceedings.

BARYOGENESIS AND NEUTRINO MASSES

R. D. Peccei
Department of Physics
Univ. of California at Los Angeles,
Los Angeles, CA. 90024

Abstract

The erasure of any preexisting $B+L$ asymmetry in the universe in its late stages suggests that the B asymmetry observed today either originated at the electroweak scale or it arose from an original L asymmetry. For the latter case to be viable either neutrino masses are much below the eV scale or the L asymmety itself is generated at an intermediate scale. Several features of the generation of a B asymmetry via an L asymmetry are discussed, including the interesting possibility that the present baryon asymmetry in the universe originates as a result of CP violating phases in the neutrino mass matrix.

THE KRS MECHANISM

The sum of baryon plus lepton number, $B+L$, in the standard model is classically conserved but violated at the quantum level [1] by chiral anomalies [2].

$$\partial_\mu J^\mu_{B+L} = 2N_g[\frac{\alpha_2}{8\pi}W^{\mu\nu}_a\tilde{W}_{a\mu\nu} + \frac{\alpha_1}{8\pi}Y^{\mu\nu}\tilde{Y}_{\mu\nu}] \quad . \tag{1}$$

Of particular relevance is the $SU(2)$ anomaly since it implies that changes of $B+L$ in any process are necessarily associated with gauge field configurations of non trivial index ν:

$$\Delta(B+L) = 2N_g\nu \tag{2}$$

where N_g is the number of generations and

$$\nu = \frac{\alpha_2}{2\pi}\int d^4x W^{\mu\nu}_a\tilde{W}_{a\mu\nu} \quad . \tag{3}$$

As was shown by 't Hooft [1], this circumstance, at least semiclassically, leads to a strong suppression of $B+L$ violating processes at zero temperature. This is, however, no longer the case at temperatures T of the order of the electroweak phase transition [3], so that standard model $B+L$ violating processes become of cosmological significance.

't Hooft [1] showed that one can estimate the $B+L$ violating amplitudes in the standard model by focusing on the changes in the gauge vacuum needed to have $\nu \neq 0$. In essence, a transition with $\nu \neq 0$ can be viewed as occuring by tunneling between two vacuum states and is thus suppressed by a tunneling factor

$$A(\nu) \sim e^{-\frac{2\pi}{\alpha_2}\nu} \quad . \tag{4}$$

This factor is irrelevantly small for the standard model. However, the situation is different at finite temperatures, since the transition between different vacuum states can occur by thermal fluctuations, rather than by tunneling. This important point was realized a few years ago by Kuzmin, Rubakov and Shaposhnikov [3] who suggested that the rate of $B+L$ violation at finite temperature is determined,

instead than by a tunneling factor, by a Boltzman factor

$$A(\nu) \sim e^{-\frac{V_0}{T}\nu} \quad , \tag{5}$$

with V_0 being the height of the barrier separating the vacuum states. Kuzmin, Rubakov and Shaposhnikov estimated V_0 by semiclassical methods, associating V_0 with the energy of a static field configuration with $\nu = 1/2$ of the standard model - known as a sphaleron - discovered earlier by Klinkhamer and Manton [4]. Because the sphaleron energy decreases with temperatures as one approaches the electroweak phase transition, Kuzmin, Rubakov and Shaposhnikov made the seminal observation that near this transition $B+L$ violating processes are sufficiently rapid compared to the expansion of the universe, so that they are in equilibrium. As a consequence, one should then expect that any preexisting asymmetry in $B+L$ in the universe would get washed out at these temperatures.

The early estimates of Kuzmin, Rubakov and Shaposhnikov [3] of the rate for $B+L$ violation in the universe due to standard model processes have been verified by more complete calculations and extended to temperatures T above that of the electroweak phase transition T_c [5]. The transition probability for $\nu = 1$ $B+L$ violating processes, per unit volume per unit time, $\gamma_{\text{B+L viol}} = \frac{\Gamma_{\text{B+L viol}}}{V}$ for T both below and above T_c is found to be

$$\begin{aligned} \gamma_{B+L \text{ viol}} &= C\left[\frac{\pi^6 M_W^7(T)}{\alpha_2^3 T^3}\right] e^{-E_{\text{sph}}(t)/T}, T < T_c \\ \gamma_{\text{B+L viol}} &= C'(\alpha_2 T)^4 \quad , \quad T > T_c \end{aligned} \tag{6}$$

where C and C' are constants of 0(1) and

$$E_{\text{sph}}(T) = \frac{\pi M_W(T)}{\alpha_2} K(\lambda/g_2) \tag{7}$$

with K, being a function of 0(1) calculated by Klinkhamer and Manton [4].

Using the above formulas, it is easy to check that the rate for $B+L$ violation $\Gamma_{B+L \text{ viol}}$ is faster than the expansion rate of the universe

$$H = \frac{5}{3}(g^*)^{1/2}\frac{T^2}{M_P} \equiv \frac{T^2}{M_0} \quad , \tag{8}$$

with $M_0 \simeq 10^{18}\ GeV$, for large periods of the Universe's lifetime:

$$\Gamma_{\text{B+L viol}} > H$$

$$T_{\text{min}} \sim 10^2 GeV < T < T_{\text{max}} \sim 10^{12}\ GeV \quad .$$

It is easy to see that if the above obtains, so that $B+L$ violating processes are in equilibrium in the universe, then any $B+L$ asymmetry produced before T_{max} is erased. In equilibrium one can write for the rate of change of the $B+L$ and $\overline{B+L}$ densities (n and $\bar{n}$, respectively) the formula

$$\begin{aligned} \frac{d}{dt}\left[n - \bar{n}\right] &= \gamma_{\text{B+L viol}}\, e^{-\mu/T} - \gamma_{B+L \text{ viol}} e^{+\mu/T} \\ &\simeq -\frac{2\mu}{T}\gamma_{\text{B+L viol}} \quad , \end{aligned} \tag{9}$$

where μ is the chemical potential. In the high temperture limit, μ is simply related to the densities themselves

$$n - \bar{n} = \frac{4\mu}{\pi^2}T^2 \quad , \tag{10}$$

so that one is lead to an exponential dilution of any preexisting asymmetry

$$n - \bar{n} = (\Delta n)_0 \ e^{-\frac{\pi}{2}t\Gamma_{B+L \text{ viol}}} \quad . \tag{11}$$

OPTIONS FOR THE BARYON ASYMMETRY

Given the presence of $B+L$ erasing processes in the temperature range $10^2\ GeV < T < 10^{12}\ GeV$, two possibilities appear open to explain the present observed B asymmetry of the universe [$N_B \equiv n_B/s$

$$\simeq n_B/7n_\gamma \simeq (0.6-1)\times 10^{-10}[6]\ ]:$$

i) The observed asymmetry is generated at the electroweak phase transition. Furthermore, this transition is sufficiently strongly first order so that after the transition the rate of $B+L$ violating processes is already so small that the generated asymmetry is not erased [7].

ii) The observed B asymmetry is a result of some primordial $B+L$ asymmetry or an L asymmetry. In either case, since $B-L$ is not affected by the weak interaction anomalies, any asymmetry in this number density survives to present times, so that the observed B asymmetry is simply related to this primordial asymmetry.

If the observed baryon asymmetry is indeed generated at the electroweak scale, one has the exciting possibility that N_B is computable from "low energy" physics, i.e. from the standard model or simple extensions thereof. This is an extremely active research area, which has been reviewed by D. Brahm[8] in this conference. A number of interesting ideas have been suggested which in principle could lead to $N_B \sim 10^{-10}$ but, to my mind, a really convincing scenario is still lacking. For this reason, it appears sensible to concentrate also on the second option above and I shall try to detail here some of its consequences.

If the B asymmetry is not generated at the electroweak scale, the observed baryon asymmetry is related to some primordial $B-L$ violation. It turns out that the final B asymmetry is not just simply $N_B = \frac{1}{2}(N_{B-L})$, as the trivial equation $B = \frac{1}{2}(B+L) + \frac{1}{2}(B-L)$ would suggest, but has a slightly more complicated form [9]:

$$N_B = \left(\frac{8N_g + 4N_H}{22N_g + 13N_H}\right)(N_{B-L})_{\text{prim}} \qquad (12)$$

where N_H is the number of Higgs doublets. At any rate, for the above equation to hold one has to assume that in the epoch between $T_{\text{max}} \simeq 10^{12} GeV$ and $T_{\text{min}} \simeq 10^2 GeV$, where $B+L$ violating processes are in equilibrium in the universe, $B-L$ violating processes must be out of equilibrium

$$\Gamma_{B-L\ \text{viol}} < H \qquad (13)$$

$$T_{\text{min}} \sim 10^2 GeV < T < \quad T_{\text{max}} \sim 10^{12}\ GeV,$$

otherwise also $(N_{B-L})_{\text{prim}}$ would be erased. In this temperature range, effectively, any purely lepton number violating processes is also $B-L$ violating. Hence, one must also require that $\Gamma_{L\ \text{viol}} < H$ in this temperature range. As noted originally by Fukugita and Yanagida [10], and as will be seen in more detail below, this requirement leads to constraints on neutrino masses.

If the rates for $B-L$ violating (or L violating) processes are **faster** than the universe's expansion rate below T_{max}, it is actually still possible to generate the present day B asymmetry, provided that somewhere above T_{min} one can generate a new $B-L$ (or L) asymmetry of sufficient magnitude. This asymmetry is then transformed as before into a B asymmetry by the KRS mechanism. Although the conditions for producing a significant $B-L$, or L, asymmetry at intermediate scales are somewhat more challenging, this scenario allows eV neutrino masses and relates in an interesting way the universe's baryon asymmetry to CP violating phases in the neutrino mass matrix. I will return to this option shortly.

BOUNDS ON L VIOLATING INTERACTIONS

If the B asymmetry of the universe is due to some primordial $B-L$ asymmetry generated at a temperature $T > T_{\text{max}}$, it is neces-

sary that no $B-L$ violating processes be fast enough so as to erase this primordial asymmetry below $T_{\max} \simeq 10^{12}\ GeV$. However, in theories where $B-L$ is violated at very high scales (GUT or Planck), one expects at lower energies the appearance of $B-L$ violating interactions of dimension $d > 4$. These interactions, if they are not weak enough, could bring $B-L$ violating processes into equilibrium below $T_{\max}$. Thus the condition $\Gamma_{B-L\ \mathrm{viol}} < H$ for $T < T_{\max}$ imposes, in general, some constraints on the parameters of the theory.

As pointed out by Fukugita and Yanagida [10], a particularly interesting L-violating interaction term, which is generic to theories where $B-L$ is violated at high scales, is characterized by the effective Lagrangian

$$\mathcal{L}_{\Delta L=2} = \frac{m_\nu}{v^2} L L \Phi \Phi \tag{14}$$

where v is the vacuum expectation value of the standard model Higgs doublet Φ. Thus m_ν above is the neutrino Majorana mass matrix associated with the left-handed neutrinos in the lepton doublets L. The above interaction can lead to rapid $B-L$ violating processes, like $\nu\nu \to \Phi\Phi$, below $T_{\max}$. If ν_H is the largest eigenvalue of m_ν, requiring that

$$\Gamma_{\Delta L=2} =< n\sigma(\nu_H \nu_H \to \Phi\Phi) >\simeq \frac{m_{\nu_H}^3}{\pi v^4} T^3 \tag{15}$$

be slow compared to $H = T^2/M_0$ implies a bound on m_{ν_H}[10][11].

$$m_{\nu_H} < \frac{4eV}{[T_{\max}/10^{10} GeV]^{1/2}} \tag{16}$$

Thus for $T_{\max} = 10^{12}\ GeV$ one has that $m_{\nu_H} < 0.4\ eV$.

The above bound can be considerably strengthened in models where one can directly compute the $B-L$, or L violating decays of heavy states [12]. For example, consider the decay of a heavy Majorana neutrino N_R which has a standard Yukawa coupling to the doublet Higgs and the lepton doublets L. Since

$$\mathcal{L}_{\mathrm{Yukawa}} = \lambda \bar{N}_R \Phi L + h \cdot c \cdot \tag{17}$$

can lead to both the decays $N_R \to \nu_L H$ and $N_R \to \bar{\nu}_L H$ it is necessary that the decay rate of N_R at a temperature $T < T_{\max}$ be less than H. Since λ^2 is related to the left-handed neutrino mass matrix m_ν by the see saw mechanism, requiring that $\Gamma_D/H < 1$ for $T \sim M_N$ implies a strong constraint on m_ν. Focusing again on the largest eigenvalue, one has

$$\frac{\Gamma_D}{H}|_{T\simeq M_H} \simeq \frac{5}{24\sqrt{2}\pi^2} m_{\nu_H} \frac{M_0}{v^2} < 1 \tag{18}$$

which yields the bound [12]

$$m_{\nu_H} \lesssim 10^{-3} eV \tag{19}$$

Similar considerations, and quite analogous analyses, can be used to bound a variety of other $B-L$ violating interactions in various extensions of the standard model. A very thorough discussion of the restrictions on all possible B violating and L violating operators 0_i^d of high dimension $(d = 4+n)$

$$\mathcal{L}_{\mathrm{viol}} = \sum_i \frac{0_i^d}{M^n} \ , \tag{20}$$

both in the standard model and its supersymmetric extension, has been carried out recently by Campbell, Davidson, Ellis and Olive [13]. In general, these authors find that the requirement that these operators should not lead to rapid $B-L$ violating processes in the temperature range between $T_{\max}$ and $T_{\min}$ provides stronger limits on the scales M associated with the various operators 0_i^d than can be provided purely by laboratory experiments. In particular, these considerations lead to very strong limits on the strenth of the $d = 4$ R symmetry violating operators in supersymmetric extensions of the standard model [13].

L ASYMMETRY AT INTERMEDIATE SCALES

If the universe's baryon asymmetry originates from a primordial $B-L$ asymmetry, the above discussion makes it difficult to contemplate the possibility that at least one neutrino has a mass in the eV range - a range which is of interest for the dark matter problem. There appears, however, to be three interesting ways to obviate this conclusion. The first way is simply to believe that the B asymmetry is generated at the electroweak scale, rendering our preceeding discussion moot. The second way, is a somewhat wild, but perfectly consistent, recent speculation of Gelmini and Yanagida [14]. They arrive at eV neutrino masses, not from effective interactions originating from a high scale, but as a result of having vacuum expectation values in the KeV range. In this way they avoid altogether the $B-L$ constraints, but the price they pay is a new hierarchy of VEV's. The third way obtains the B asymmetry through a $B-L$ (or L) asymmetry generated at an intermediate scale. By so doing one avoids the direct constraints on neutrino masses of the preceeding section and one is left with other interesting features which are related to neutrinos. This type of scenario was advocated sometime ago by Fukugita and Yanagida [10] and Langacker, Yanagida and I [16], and has been analyzed recently in a much more thorough manner by Luty [17].

The general idea of the above scenario is to generate an L asymmetry at an intermediate scale ($M_N < 10^{12}\ GeV$) from out of equilibrium processes involving a heavy Majorana right handed neutrino N_R. If the light neutrino to which N_R decays has a mass of $0(eV)$, then our earlier computation indicates that at $T \simeq M_N$, $\Gamma_D >> H$, so that any primordial L (or $B-L$) asymmetry would be erased. However, eventually for $T < M_N$ a new L asymmetry can be established when the inverse decays $\nu H \to N_R$, $\bar{\nu} H \to N_R$ go out of equilibrium. The amount of lepton asymmetry that one can generate in these circumstances is considerably reduced from what one would expect in the standard "delayed decay" scenario, but the reduction may be tolerable. Roughly [6], one expects

$$N_L \simeq 0.3\left(\frac{H}{\Gamma_D}\right)_{T=M_N} \cdot (N_L)_{\text{standard}} \ , \qquad (21)$$

which in our case would amount to a reduction of around a factor of order 10^{-3}.

Apart from the above thermodynamic reduction factor, the asymmetry N_L is diluted by the number of degrees of freedom at $T \simeq M_N$ ($g^* \sim 100$) and is proportional to the amount of microscopic L violation produced by the decays of N_R into νH and $\bar{\nu} H$. That is,

$$\begin{aligned}(N_L)_{\text{standard}} &\simeq \frac{1}{g^*}\left[\frac{\Gamma(N_R \to \nu H) - \Gamma(N_R \to \bar{\nu} H)}{\Gamma(N_R \to \nu H) + \Gamma(N_R \to \bar{\nu} H)}\right] \\ &= \frac{\epsilon_L}{g^*} \qquad (22\end{aligned}$$

The calculation of ϵ_L requires detailed assumptions on the structure of the neutrino mass matrix, both for the Yukawa couplings λ between N_R, L and Φ and for the masses of the heavy Majorana neutrinos. In particular, ϵ_L depends explictly on CP violating phases in the neutrino sector and it would vanish if CP were conserved. Note also that the first non vanishing contribution for ϵ_L is of $0(\lambda^4)$, since the rates for $N_R \to \nu H$ and $N_R \to \bar{\nu} H$ are identical in lowest order.

Fukugita and Yanagida [10], and more recently Luty [17], have estimated ϵ_L by retaining the leading Yukawa coupling and assuming a simple hierarchical structure for the heavy Majorana states. With these approximations one obtain

$$\epsilon_L \simeq \frac{m_{D_3}^2}{\pi v^2} \cdot \frac{M_{N_2}}{M_{N_3}} \cdot \sin\delta \ , \qquad (23)$$

where the three terms above represent, respectively, the leading Yukawa coupling contribution, some structure in the Majorana mass matrix and a typical CP violating phase. With this formula in hand, it is not impossible to imagine that one could obtain values for ϵ_L in the range of $10^{-4} - 10^{-6}$. Such values would allow a value of $N_L \sim 10^{-10}$ to be generated at an intermediate temperature $T_{\min} < M_N < T_{\max}$. By the KRS mechanism such a leptonic asymmetry would then generate a baryonic asymmetry N_B of the desired order of magnitude. These rough estimates are confirmed by the results of the recent detailed calculations of Luty [17], in which he uses the Boltzman equation to study the evolution of N_B and includes the effects of 2 to 2 processes. From his calculations it appears that, without stretching parameters to much, one can produce both a baryon asymmetry $N_B \sim 10^{-10}$ today and a 3rd generation neutrino with an eV mass.

CONCLUDING REMARKS

Let me reiterate the main points discussed. First and foremost, as discovered by Kuzmin, Rubakov and Shaposhnikov, in the standard model there exist rapid $B + L$ violating processes which are in equilibrium in the early universe. This circumstance has important implications for baryogenesis. Because of the KRS mechanism, either one must suppose that the universe's baryon asymmetry is generated at the electroweak scale, or that this asymmetry arises via the transmutation of some $B - L$ or L asymmetry into a B asymmetry. In this latter case, either neutrinos are very light ($m_{\nu_H} < 10^{-3} eV$) allowing some primordial $(B - L)$ asymmetry to survive to become the observed B asymmetry, or an L or $(B - L)$ asymmetry is generated at some intermediate scale ($M_N \sim 10^{10} GeV$), eventually transmuting itself into the observed B asymmetry. In the last scenario, eV neutrinos are permissible and one has the amusing result that the universe's baryon asymmetry is related to CP phases in the neutrino sector. However, it does not appear that all these CP phases are observable, even in principle, in neutrino oscillations. They should, however, enter in CP violating phenomena involving neutrino - antineutrino oscillations. Unfortunately, neutrino-antineutrino oscillations are suppressed by chirality factors, which renders them only an academic curiosity [18].

ACKNOWLEDGEMENTS

I am grateful to Graciela Gelmini for numerous helpful conversations on this subject matter. I would also like to thank Marcela Carena, Boris Kayser and Sandip Pakvasa for illuminating remarks on CP violating phases in the neutrino sector. I am thankful to V. Zakharov for his hospitality at the Max Planck Institute, where this note was written up. This work was partially supported by the Department of Energy under the contract DE-FG03-91ER40662, TASK C.

REFERENCES

1. G. 't Hooft, *Phy. Rev. Lett*, 37, (1976) 8
2. S. L. Adler, *Phys. Rev.* 177, (1969) 2426; J. S. Bell and R. Jackiw, *Nuovo Cimento* 60A (1969) 49; W. A. Bardeen, *Phys. Rev* 184 (1969) 1841
3. V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, *Phys. Lett* 166B (1985) 36
4. R. F. Klinkhamer and N. S. Manton, *Phys. Rev.* D30 (1984) 3212
5. P. Arnold and L. McLerran, *Phys.*

Rev. D36 (1987) 581; *Phys. Rev.* D37, (1988) 1020; S. Yu Khlebnikov and M. E. Shaposhnikov, *Nucl. Phys.* B308 (1938) 885; M. Dine, O. Lechtenfeld, B. Sakita, W. Fischler and J. Polchinski, *Nucl. Phys.* B342 (1990) 381

6. See for example, E. W. Kolb and M. S. Turner, *The Early Universe.* (Addison, Wesley, Reading, Mass. 1989)

7. M. E. Shaposhnikov, *Nucl. Phys.* B287 (1987) 757; B299 (1988) 797

8. D. Brahm, these Proceedings

9. S. Yu. Khlebnikov and M. E. Shaposhnikov, *Nucl. Phys* B308 (1988) 835; J. Harvey and M. Turner, *Phys. Rev.* D42 (1990) 3344; A. Nelson and S. Barr, *Phys. Lett.* B246 (1990) 141

10. M. Fukugita and T. Yanagida, *Phys. Rev.* D42 (1990) 1285

11. J. Harvey and M. S. Turner, *Phys. Rev.* D42 (1990) 3344; A. Nelson and S. Barr, *Phys. Lett.* B246 (1990) 141

12. W. Fischler, G. F. Giudice, R. G. Leigh and S. Paban, *Phys. Lett.* B258 (1991) 45

13. B. Campbell, S. Davidson, J. Ellis and K. Olive, *Phys. Lett.* B256 (1991) 457

14. G. Gelmini and T. Yanagida, UCLA preprint UCLA/92/TEP/24

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

16. P. Langacker, R. D. Peccei and T. Yanagida, *Mod. Phys. Lett. A1* (1986) 541

17. M. Luty, *Phys. Rev.* D45 (1992) 455

18. B. Kayser, in *CP Violation*, ed. by C. Jarlskog (World Scientific, Singapore, 1988)