91-2-203

ALBERTA-THY-32-90
CERN-TH-5926/90
LAPP-TH-321/90
UMN-TH-915/90

Cosmological Baryon Asymmetry Constraints on Extensions of the Standard Model

Bruce A. CAMPBELL*

CERN, Theory Division, CH-1211, Geneva 23, SWITZERLAND

Sacha DAVIDSON

Physics Department, University of Alberta, Edmonton, Alberta, Canada T6G 2J1

John ELLIS

CERN, Theory Division, CH-1211, Geneva 23, SWITZERLAND

Keith A. OLIVE**

Laboratoire d'Annecy-le-Vieux de Physique des Particules,
IN2P3-CNRS, BP 110,
F-74941 Annecy-le-Vieux Cedex
FRANCE

ABSTRACT

The existence of the baryon asymmetry of the Universe puts strong constraints on extensions of the Standard Model which violate baryon and/or lepton number. Interactions violating baryon number but conserving lepton number in the early Universe could wash away any previously established baryon asymmetry. Interactions which violate lepton number separately (as first discussed by Fukugita and Yanagida), with or without associated violation of baryon number, could combine with non-perturbative baryon and lepton number violating electroweak effects to eradicate the cosmological baryon asymmetry. We derive the constraints on any such interaction of arbitrary dimension arising from the persistence of the cosmological baryon asymmetry. We find, in particular, severe constraints on $\Delta B \neq 0$ interactions that could mediate $n \leftrightarrow \bar{n}$ oscillations or $\Delta B \neq \Delta L$ proton decay, and on interactions that could violate R parity in supersymmetric models. These constraints severely limit the potential observability of $n\text{-}\bar{n}$ oscillations and R-parity violation in present laboratory experiments.

ALBERTA-THY-32-90
CERN-TH-5926/90
LAPP-TH-321/90
UMN-TH-915/90
November 1990

* On leave of absence from Department of Physics, University of Alberta, Edmonton, Alberta, Canada T6G 2J1.

** On leave of absence from School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA.

The possibility¹⁾ of generating the cosmological baryon asymmetry via non-equilibrium B-, C- and CP-violating interactions in the early Universe gave great impetus to astroparticle physics, and was a very attractive feature of grand unified theories (GUTs) going beyond the Standard Model. However, this idea is vulnerable to the effects of baryon-number violating interactions in the later Universe after the grand unified epoch. Possible examples of such interactions, which are perturbative, are those giving rise to neutron-antineutron oscillations, which should be characterized by scales $M \sim 10^4$ to 10^6 GeV $\ll M_{\text{GUT}}$ if such oscillations are to be observable in the laboratory^{2,3)}.

Another example is provided by non-perturbative Standard Model electroweak interactions⁴⁾ which violate B and L while conserving B-L, and are now believed likely to have been strong^{5,6)} in the early Universe at temperatures $T \gtrsim 100$ GeV. These non-perturbative Standard Model interactions would have wiped out, or at least diluted^{5,6)}, any previously-existing baryon asymmetry, unless it had been generated by interactions violating B-L, which are absent in minimal GUTs such as SU(5). It is in principle possible for these non-perturbative Standard Model interactions to have generated the baryon symmetry themselves⁷⁾, but initial scenarios of this type required a Higgs boson weighing $\lesssim 45$ GeV, which has since been excluded by experiments at LEP⁸⁾.

This cloudy picture would be even murkier if there were other perturbative interactions beyond the Standard Model that violated B-L. They and the non-perturbative electroweak interactions would between them wipe out any primordial combination of B and L. This potential disaster was first explored in the case of $\Delta L=2$ Majorana neutrino masses by Fukugita and Yanagida⁹⁾, who pointed out that it would be averted only if the Majorana neutrino masses were < 50 KeV. The purpose of this paper is to discuss the cosmological implications of perturbative interactions causing $n-\bar{n}$ oscillations, and to extend Fukugita and Yanagida's⁹⁾ line of argument to general B- and L-violating effective interactions, discussing in particular the dramatic implications for the types of $\Delta B \neq 0$ interactions that could mediate neutron-antineutron oscillations or $\Delta B \neq \Delta L$ proton decay, and interactions that could violate R-parity in supersymmetric theories.

We first consider generic effective interactions of dimension $2 \leq D \leq 10$ and discuss the condition that they not be in equilibrium during the expansion of the Universe, in particular not simultaneously with non-perturbative electroweak interactions at temperatures $100 \text{ GeV} \lesssim T \lesssim M_{\text{GUT}}$. We then apply this condition to the standard catalogue of SU(3) $\times$ SU(2) $\times$ U(1) -invariant B- and/or L-violating interaction operators made out of fields present in the Standard Model^{10,2)} and its extensions to include supersymmetry^{11,2)}. Similar results can be derived for models which also include a singlet neutrino (super) field. For each operator, we tabulate the best previous limit on its magnitude as well as the new limit we obtain from the persistence of

the cosmological baryon asymmetry. We then work out the applications of this general analysis to the specific cases of $n-\bar{n}$ oscillations and to R-parity-breaking, and the decay of the lightest supersymmetric particle (LSP). Our new limits suggest that $\tau_{n-\bar{n}} \gg 10^8 \text{ s}$ and $\tau_{\text{LSP}} \gg 10-10^5$ in most models, so that it seems very unlikely that neutron-antineutron oscillations or LSP decay will be observed in present laboratory experiments. It remains possible however that the LSP decays on a timescale relevant to cosmology.

Let us first consider the general case of an effective non-renormalizable interaction of dimension $D=4+n$

$$\mathcal{L}_D = \frac{O_D}{M^n} \quad (1)$$

where M is a mass scale parameter and $n \geq 1$. We assume that the generation structure of the interaction (not explicitly shown) is generic, and does not accidentally preserve one of the e , μ , or τ lepton flavors. Quark generations are not conserved in the Standard Model and hence cannot provide an accidental conserved quantity which might vitiate¹²⁾ our argument. The corresponding interaction rate

$$\Gamma_D(T) \sim \frac{T^{2n+1}}{M^{2n}} \quad (2)$$

for $T \lesssim M$, so that thermodynamic equilibrium is avoided if $\Gamma_D(T) \lesssim H$, where H is the Hubble expansion rate: $H \sim 20T^2/M_{\text{p}}$, giving

$$M^{2n} \gtrsim \frac{M_{\text{p}} T^{2n-1}}{20} \quad (3)$$

In the case of a $\Delta B = 2$ interaction that could cause $n-\bar{n}$ oscillations, persistence of the cosmological baryon asymmetry requires that the out-of-equilibrium condition (3) be imposed for all temperatures below that at which the asymmetry is generated. This would be $\sim 10^{14}$ GeV in the conventional GUT scenario, in which case we would require

$$M \gtrsim 10^{14+(2/n)} \text{ GeV} \quad (4)$$

for $\Delta B = 2$ interactions*.

* Note that to derive the bound (4) we use $T < M$, so that it is consistent to continue to use the effective non-renormalizable form of interaction (2).

In general, let us assume as a working hypothesis the existence of strong non-perturbative B- and L- violating but (B-L)-conserving electroweak interactions with an effective interaction rate^{5,6)} $\Gamma_{NP} \sim \alpha^2 T \theta(T-T_c)$, where $T_c \sim 100$ GeV is an effective threshold temperature whose precise value depends on details of the electroweak theory. Assuming again the conventional radiation-dominated Hubble expansion rate $H \sim 20 T^2/Mp$, we see that these non-perturbative electroweak interactions are in thermodynamic equilibrium for

$$T_c < T \leq T_M \equiv \frac{\alpha^2}{20} Mp \approx 10^{15} \text{ GeV} \quad (5)$$

These would wipe out any previously-existing baryon asymmetry that had $B = L^3$, and if any (B-L)-violating interactions were in thermodynamic equilibrium during the epoch (5), they would wipe out any previously-existing baryon asymmetry. Various scenarios exist for producing a baryon asymmetry by non-equilibrium interactions at temperatures from ~ 100 GeV to $\sim Mp$, so we will consider two extreme conditions for the preservation of the baryon asymmetry: absence of thermodynamic equilibrium for any beyond-the-standard-model (B-L)-violating interaction at temperatures (A) $T = T_c \approx 100 \text{ GeV}^{(9)}$, or (B) $T \leq T_M \approx 10^{14} \text{ GeV}^{(13)}$. Constraints from (A) are general, and apply to all effective interactions and mechanisms for baryogenesis at all temperatures down to the electroweak scale, whereas those from case (B) might be evaded if the baryon asymmetry was generated at a lower temperature than M_{GUT} , after the new $\Delta B \neq 0/\Delta L \neq 0$ interactions had fallen out of equilibrium. As one would expect for dimension $D > 4$ (non-renormalizable) operators, the baryon number relaxation is strongest at high temperature, and for these operators case (B) provides significantly better limits, subject to the above caveat.

Clearly, for a general $D > 4$ (B-L)-violating interaction the most stringent lower limit on M comes from considering the case (B) $T \sim T_M \sim 10^{14} \text{ GeV}$, namely

$$M \gtrsim 10^{14+(2/n)} \text{ GeV} \quad (6)$$

The corresponding lower limit on M in the case (A) $T \sim T_c \sim 10^2 \text{ GeV}$ is

$$M \gtrsim 10^{2+(8/n)} \text{ GeV}. \quad (7)$$

The parametrization (2) breaks down in the case of a renormalizable $D = 4$ interaction, which we instead parametrize by

$$\mathcal{L}_4 = \lambda O_4 \quad (8)$$

with a rate $\Gamma_4(T) \sim \lambda^2 T$. This is out of equilibrium if

$$\lambda^2 \lesssim \left(\frac{20}{Mp}\right) T \quad (9)$$

so that the most stringent upper bound on λ comes from considering case (A) $T = T_c \approx 100 \text{ GeV}$:

$$\lambda \lesssim 10^{-8} \quad (10)$$

We parametrize superrenormalizable $D = 3$ and 2 interactions by coefficients m and μ^2 respectively, yielding interaction rates

$$\Gamma_3(T) \sim m^2/T, \quad \Gamma_2 \sim \mu^4 T^3 \quad (11)$$

For these two types of interaction, the most stringent upper bounds on the parameters m and μ again come from considering the case (A) $T = T_c \approx 100 \text{ GeV}$:

$$m \lesssim 10^{-6} \text{ GeV}, \quad \mu \lesssim 10^{-2} \text{ GeV} \quad (12)$$

The constraints (4,6,7,9,12) have dramatic implications for models, as we now discuss.

The effective operators¹⁰⁾ describing new interactions beyond the Standard Model must be made out of light fields, and invariant under the symmetries which survive below the scale M , including Lorentz invariance and any surviving gauge and discrete symmetries, and perhaps supersymmetry. Often these residual symmetries suffice, by themselves, to rule out the appearance of operators of a given dimension which violate some quantum number. For example, with the Standard Model gauge group and field representation content it is impossible to construct gauge- and Lorentz-invariant renormalizable (dimension-four or less) baryon- (or lepton-) number-violating operators. This is no longer true in the supersymmetric version of the theory, where the addition of squarks and sleptons permits¹¹⁾ the construction of supersymmetric, Lorentz- and gauge-invariant, renormalizable superpotential interactions which violate baryon and/or lepton number. In most models these are removed by the imposition of an additional discrete symmetry, such as R-parity¹⁴⁾. If one removes the requirement of supersymmetry, as in the soft supersymmetry breaking terms induced via supergravity¹⁵⁾, then further soft ($D=2$ and 3) baryon- and lepton-number-violating interaction operators are possible. We now turn to the operators describing lepton- and baryon-number-violating

interactions, first those involving Standard Model fields, and then those involving their supersymmetric partners.

In Table 1 we display the types of operators that may appear at various dimensions involving Standard Model fields. Our notation is schematic; q, l represent quarks or leptons (and q^c, l^c their conjugates), h is the Higgs doublet scalar, and $\mathcal{O}$ is a gauge-covariant derivative. The chiral structure and gauge indices are suppressed. There are a variety of ways of producing gauge- and Lorentz-singlets, so, for example, $qqql$ in our table represents six independent operators formed from different combinations of chirality, color and weak isospin and hypercharge. Baryon- and lepton-number-violating interactions of Standard Model fields necessarily appear as operators of dimension five and higher.

The D=5 entry in the table is the effective low-energy lepton-number-violating operator arising from the "see-saw" neutrino mass generation mechanism¹⁶⁾, whose cosmological implications were first discussed by Fukugita and Yanagida⁹⁾. The remaining operators in our list involve baryon number violation, and laboratory limits on these operators involve an estimation of their hadronic matrix elements. We use the estimates given by Costa and Zwirner²⁾ for nucleon decay matrix elements to convert nucleon decay partial width limits into estimates of the operator mass scale listed in the column under "laboratory limit".

For the dimension-6 operator $qqql$, we quote no cosmological bound, since this operator conserves B-L, as do electroweak effects, so even together they would be unable to erase a B-L asymmetry produced at any temperature. For the D=7 operators which could induce $\Delta B = -\Delta L$ proton decay, we find that cosmological limits from the preservation of baryon asymmetry at the temperature scale T_M (case B) yield limits on M that are stronger than direct laboratory searches by four to five orders of magnitude. This is even more true for the baryon- and lepton-number-violating operators of dimension D=9, 10, or 11, where the cosmological limits exceed those of the laboratory by ten orders of magnitude.

The D=9 six-quark baryon-number-violating operator violates baryon number by two units without violating lepton number. Hence the laboratory limit arises from the bound on neutron-antineutron oscillations¹⁷⁾ ($\tau_{n \leftrightarrow \bar{n}} > 1.2 \times 10^8$ s) which we convert to a limit on M using an estimate for the matrix element from the reviews of Costa and Zwirner²⁾ and Mohapatra³⁾. Cosmologically, the violation of baryon number alone means that effects of this operator can relax the baryon number of the universe to zero without the aid of baryon-number-violating electroweak effects. In this case the limits in the columns in our table should be interpreted as the lower bound on M necessary to ensure the survival of baryon number generated at any $T \gtrsim 100$ GeV [case(A)] or $T \gtrsim M$ [case (B)]. In this case the cosmological survival of baryon number generated at (or above) the scale of physics inducing the baryon-number-violating

operator puts a limit on the scale of that operator nine orders of magnitude above that achieved in the laboratory, independent of nonperturbative electroweak effects.

The only way to avoid this condition would appear to be to generate the cosmological baryon asymmetry via out-of-equilibrium CP-violating $\Delta B = 2$ interactions themselves. This could in principle occur at a temperature seen from equation (3) to be

$$T \sim \left(\frac{20M_{\text{Pl}}^2 n}{M_{\text{Pl}}} \right)^{1/(2n-1)} \quad (13)$$

In the case of the popular $qqqqqq$ operator with $n = 5$, for which Table I tells us that $M \gtrsim 10^5$ GeV, in case (A) equation (13) indicates that $T \sim 10^{4.2}$ GeV. A similar conclusion applies to the $D = 7$ supersymmetric $\Delta B = 2$ operator in Table II ($M \gtrsim 10^8$ GeV, $T \sim 107.2$ GeV). Although it might appear that the cosmological baryon asymmetry could in fact be generated by $\Delta B = 2$ operators, this possibility requires further scrutiny.

We now take a general look at sources of baryon and/or lepton number violation in supersymmetric theories¹¹⁾. With the common definition of R-parity: $R = (-1)^{2S+L+3B}$, violation of B and/or L also signifies the breaking of R-parity*. R-parity violation may appear directly in exactly supersymmetric models, e.g. those with additional superpotential terms or D-terms beyond the minimal extension of the Standard Model. This can be described by the superpotential

$$F_{\text{MIN}} = h_u H U^c + h_d H Q D^c + h_e H L E^c + \epsilon H \bar{H} \quad (14)$$

where the chiral multiplets are denoted by $H, \bar{H}$ for the Higgs doublets, Q, L for the left-handed quark and lepton doublets and U^c, D^c, E^c for the right-handed singlets in the model. The couplings h_i are the standard Higgs Yukawa couplings and ϵ is a Higgs mixing mass parameter necessary to avoid a massless axion-like state. (Note that we have suppressed all generation indices.) R-parity violation could be introduced explicitly by adding to the superpotential

$$F_R = m_1 L H + \lambda_1 L L E^c + \lambda_2 L Q D^c + \lambda_3 U^c D^c E^c \\ + \frac{1}{M_1} Q Q Q L + \frac{1}{M_2} Q Q Q \bar{H} + \frac{1}{M_3} U^c U^c D^c E^c$$

* This is unless $\Delta L + 3\Delta B = 0 \pmod{2}$. Strictly speaking it is baryon number and lepton number violation which we constrain, even if the combination does not violate R-parity.

$$+ \frac{1}{M_4} \text{HHHL} + \frac{1}{M_5} \text{HHLL} + \frac{1}{M_6^3} \text{U}^c \text{D}^c \text{D}^c \text{U}^c \text{D}^c \text{D}^c + \dots \quad (15)$$

Alternatively, sources of R-parity breaking may be found in D-terms or soft supersymmetry-breaking terms, which take the form :

$$\begin{aligned} \mathcal{L} \ni & \mu_1^2 \tilde{t}_h + \mu_2^2 \tilde{t}_h^\dagger + m_2 \tilde{t}_h \tilde{t}_h^\dagger \\ & + m_3 \tilde{t}_h \tilde{q}^c + m_4 \tilde{q}^c \tilde{q}^c + m_5 \tilde{t}_h^\dagger + m_6 \tilde{t}_h^\dagger. \end{aligned} \quad (16)$$

The R-parity-breaking terms we consider are listed in Table II. In addition, the generation of a sneutrino ($\tilde{\nu}$) vev could break R-parity spontaneously¹⁸⁾. As in the case of the non-supersymmetric Standard Model described above, the dilution of the cosmological baryon asymmetry due to such terms will impose much tighter constraints than are available from laboratory cross-section measurements or the absence of rare processes.

As was discussed in detail by Hall and Suzuki¹⁹⁾, the $m_1 L H$ term is a source for Majorana neutrino masses, and the strongest constraint they derive is based on the neutrino mass limit from neutrinoless double-beta decay²⁰⁾ ($m_{\nu_e} \lesssim 1 \text{ eV}$) : $m_1 \lesssim 0.1 \left(\frac{\epsilon}{30 \text{ GeV}} \right) \text{ GeV}$. (We have rescaled their limit to account for this more recent constraint on the Majorana neutrino mass.) From eq.(12) we see that our limit is at least five orders of magnitude stronger : $m < 10^{-6} \text{ GeV}$. Furthermore, our bound is generation-independent whereas the bound from neutrino masses is much weaker for ν_μ and ν_τ . Analogous arguments place constraints on the soft masses: $\mu_{1e} \lesssim 0(1) \text{ GeV}$ from Majorana neutrino masses and $\mu_1 \lesssim 10^{-2} \text{ GeV}$ from the observed baryon asymmetry. Again the neutrino mass bound is weakened by going to higher generations e.g. to $\mu_1 \lesssim 100 \text{ GeV}$, whereas our bound is generation-independent. (Similar laboratory limits on μ_1 were derived in ref.21.)

The dimension-4 terms in (15) have been discussed extensively in the literature²²⁻²⁹⁾. The strongest constraints²⁵⁻²⁷⁾ on λ_1 and λ_2 are on the off-diagonal elements $\lambda_1^{113} \lesssim 2 \times 10^{-3}$

$\left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{1/2}$ and $\lambda_2^{113} \lesssim 10^{-3} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{1/2}$, due to their radiative contribution to the electron

neutrino Majorana mass. Charged current universality of quark and lepton couplings to W bosons have led to the limits $\lambda_1^{12k} < 0.04 \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)$ and $\lambda_2^{12k} < 0.03 \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)$ and the

absence of neutrinoless double-beta decay gives²⁵⁾ $\lambda_2^{111} < 3 \times 10^{-3} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2}$. The λ_3^{11k}

coupling is strongly constrained by the absence of $\bar{n}\bar{n}$ oscillations as was first pointed out by Zwirner²²⁾ who found $\lambda_3^{11k} < 2 \times 10^{-7} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2}$ (see also ref.24 where the limit $\lambda_3^{112} < 6 \times$

$10^{-9} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2}$ is derived from $NN \rightarrow KK + \dots$, but is subject to the enhanced nuclear uncertainties). The remaining bounds in ref.28 are typically $O(1) - O(4)$ from a variety of sources such as charged π -decay, τ -decay, ν_μ -e scattering etc. If two or more such couplings are non-zero, typical constraints^{23,26)} $\lambda < O(10^{-3})$ may be obtained from $\mu \rightarrow e\gamma$ or $\mu \rightarrow 3e$. From eq.(10), we find the surprisingly strong cosmological bound of $\lambda_{1,2,3} < 10^{-8}$, which is again generation-independent.

As was the case for the non-supersymmetric $D=6$ operator qqql, we cannot improve any existing bounds on the $D=5$ supersymmetric F-terms QQQL and $\text{UcU}^c \text{D}^c \text{D}^c$, as they both have $B-L=0$ and therefore parallel to the electroweak instanton operators. We are not aware of any previous bound on $\frac{1}{M_2} \text{QQQH}$, but here we find from eq.(6) that $M_2 > 10^{10} \text{ GeV}$. This is of course analogous to the bound on $\frac{1}{M_5} \text{HHLL}$ already derived by Fukugita and Yanagida⁹⁾. We are also not aware of any previous bounds on the soft terms $m_{2,3,4}$. As for the generic $D=3$ mass term m , we find $m_{2,3,4} \lesssim 10^{-6} \text{ GeV}$. Finally, for the $D=7$ term, we find $M_6 > 10^{4.7} (T/10^2 \text{ GeV})^{5/6}$, whereas the current limit from $n\bar{n}$ oscillations give^{2,3)} $M_6 > 1 \times 10^8 (100 \text{ GeV}/\tilde{m})^{2/3} \text{ GeV}$.

It is important to note that our bounds on λ_3 , m_4 , M_2 and M_6 do not depend on the presence of the electroweak instanton effects. As they are purely baryon-number-violating, the above limits on these operators apply independent of additional B-L violating interactions. That is, they alone are capable of diluting an existing baryon asymmetry.

Lastly, we come to limits on $\tilde{\nu}$ vevs which would break R-parity spontaneously¹⁸⁾. In the absence of any explicit R-parity-violating terms in the superpotential, spontaneous R-parity (lepton-number) breaking would lead to a massless Goldstone boson, the majoron. The emission of majorons in stars would require in turn the constraint³⁰⁾ on the sneutrino vev $v \lesssim 9 \text{ KeV}$. Explicit R-parity violation would relax this bound, but we will find limits on sneutrino vevs which are still orders of magnitude below typical weak scale vevs.

A sneutrino vev would induce mixing between the corresponding neutrino and gauginos leading to a non-vanishing neutrino mass³¹⁾. Upper limits²³⁾ on the $\tilde{\nu}$ vev from Majorana

neutrino masses range from $O(1)$ MeV for $\langle \tilde{\nu}_e \rangle \neq 0$ to $O(10)$ GeV for $\langle \tilde{\nu}_\tau \rangle \neq 0$. We will now see that the limits we derive, based on the presence of the baryon asymmetry if some $\langle \tilde{\nu} \rangle \neq 0$ is formed before non-perturbative electroweak interactions drop out of equilibrium, are complementary.

A sneutrino vev in the ordinary Yukawa term $h_e \bar{\psi}_L \psi_R$ leads to a $D = 3$ lepton number violating term $h_e \langle \tilde{\nu} \rangle > \bar{h}_e e$. From the limits described above, we require $h_e \langle \tilde{\nu}_e \rangle > \sim 10^{-6}$ GeV. Furthermore, h_e is the ordinary lepton Yukawa coupling and is therefore known. For $\langle \tilde{\nu}_e \rangle \neq 0$, we have our weakest constraint namely $\langle \tilde{\nu}_e \rangle > \sim 1/2$ GeV, and in this case the neutrino mass limit 10^{-3} GeV is stronger. For $\langle \tilde{\nu}_\mu \rangle$, we find $\langle \tilde{\nu}_\mu \rangle > \sim 3 \times 10^{-3}$ GeV and for $\langle \tilde{\nu}_\tau \rangle$, $\langle \tilde{\nu}_\tau \rangle > \sim 10^{-4}$ MeV. We do not address here the technical questions whether such a small vev can be generated in a realistic model^[32,26], and if so whether the vev forms before non-perturbative electroweak interactions drop out of equilibrium. The latter is of course a necessary condition for the above bounds on sneutrino vevs to be valid, and is what we would expect if the sneutrino were comparable in magnitude to the Higgs vev. Our bounds exclude this possibility. The maximum size of a sneutrino vev that does not cohabit with non-perturbative electroweak interactions is a dynamical question into which we do not enter here.

We comment finally on the observability of neutron-antineutron oscillations and R-parity breaking in the light of our results. In the case of the $D = 9$ qqqqqq operator, to tolerate $M \sim 10^5$ GeV close to the laboratory lower limit, we require baryogenesis to occur at some temperature found from equation (3) to be

$$T \lesssim \left(\frac{20}{M_P} M^{2n} \right)^{1/(2n-1)} \approx 10^{4.2} \text{ GeV} \quad (17)$$

The only candidate low-temperature mechanism in the Standard Model uses non-perturbative electroweak interactions^[7], and seems to be ruled out in its simplest form by the LEP lower limit^[8] on the Higgs boson mass. In the case of the $D = 7$ $(U^c D^c U^c D^c U^c)^F$ operator in the minimal supersymmetric extension of the Standard Model, the upper limit (18) is relaxed to $T \lesssim 10^{7.2}$ GeV. Also, one has a new candidate mechanism for baryogenesis, namely that due to Affleck and Dine^[33]. However, non-perturbative electroweak interactions are likely to be important after the $\tilde{q}$ and $\tilde{l}$ vacuum energy thermalizes in this scenario, and hence might wash out the Affleck-Dine baryon asymmetry.

R-parity breaking would have the laboratory signature of decays of the candidate for the lightest supersymmetric particle (LSP). However, this would be detectable only if the LSP decay path length were $\lesssim l_m$, corresponding to a lifetime $\tau_{LSP} \lesssim 10^{-8}$ s. There are two important

candidate decay modes for the LSP: $LSP \rightarrow \bar{\nu} f f$ and $LSP \rightarrow \nu \bar{\nu}$. One can easily estimate that the former has a partial lifetime^[24,26]

$$\tau_{\nu f f} \approx 10^{-21} \text{ s} \left(\frac{100 \text{ GeV}}{m_{LSP}} \right)^5 \left(\frac{m_{\tilde{f}}}{100 \text{ GeV}} \right)^4 \frac{1}{\lambda^2} \quad (18)$$

where λ is one of the trilinear superpotential couplings in equation (15). We found from our general analysis (10) that $\lambda \lesssim 10^{-8}$, corresponding via (19) to

$$\tau_{\nu f f} \gtrsim 10^{-5} \text{ s} \left(\frac{100 \text{ GeV}}{m_{LSP}} \right)^5 \left(\frac{m_{\tilde{f}}}{100 \text{ GeV}} \right)^4 \quad (19)$$

which is too long to be observable. An analogous estimate gives^[26]

$$\begin{aligned} \tau_{\nu \nu} &\approx 10^{-17} \text{ s} \left(\frac{100 \text{ GeV}}{m_{LSP}} \right)^3 \left(\frac{m_{\tilde{f}}}{100 \text{ GeV}} \right)^4 \frac{1}{\lambda^2} \\ &\geq 0.1 \text{ s} \left[\frac{100 \text{ GeV}}{m_{LSP}} \right]^3 \left[\frac{m_{\tilde{f}}}{100 \text{ GeV}} \right]^4 \end{aligned} \quad (20)$$

Similar estimates apply, as one can verify after making a basis change, if one breaks R-parity by an HL coupling or a sneutrino vev. We conclude that R-parity breaking will be unobservable in laboratory experiments if current ideas about strong non-perturbative electroweak interactions are correct.

We conclude that the survival of the cosmological baryon asymmetry imposes severe constraints on the B- and/or L- violating interactions beyond the Standard Model. These are in many cases far stronger than those derived from laboratory experiments. A corollary is that many interesting proposed non-Standard-Model phenomena appear to have little chance of being observed in the laboratory within the foreseeable future. Examples are neutron-antineutron oscillations and the violation of R-parity.

Acknowledgements

The work of BAC and SD was supported in part by the Natural Sciences and Engineering Research Council of Canada. The work of KAO was supported in part by

DOE grant DE-AC02-83ER-40105 and by a Presidential Young Investigator Award. We thank F. Zwirner for discussions.

REFERENCES

1. A.D. Sakharov, JETP Lett. **5** (1967) 24.
2. G. Costa and F. Zwirner, Riv. del Nuovo Cim. **9** (1986) 1.
3. R.N. Mohapatra, Nucl. Inst. Meth. **A284** (1989) 1.
4. G't Hooft, Phys. Rev. Lett. **37** (1976); Phys. Rev. **D14** (1976) 3432.
5. V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys. Lett. **B155** (1985) 36.
6. P. Arnold and L. Mc Lerran, Phys. Rev. **D36** (1987) 581; **D37** (1988) 1020.
7. M.E. Shaposhnikov, Nucl. Phys. **B287** (1987) 757; **B299** (1988) 797; L. Mc Lerran, Phys. Rev. Lett. **62** (1989) 1075.
8. ALEPH Collaboration, Phys. Lett. **B246** (1990) 306; DELPH Collaboration, CERN preprint PPE/90-44 (1990); L3 Collaboration, L3 preprint#010 (1990); OPAL Collaboration CERN preprint PPE/90-150 (1990).
9. M. Fukugita and T. Yanagida, Kyoto preprint, RIFP-847 (1990).
10. S. Weinberg, Phys. Rev. Lett. **43** (1979) 1566; F. Wilczek and A. Zee, Phys. Rev. Lett. **43** (1979) 1571; S. Weinberg, Phys. Rev. **D22** (1980) 1694.
11. N. Sakai and T. Yanagida, Nucl. Phys. **B197** (1982) 533; S. Weinberg, Phys. Rev. **D26** (1982) 287.
12. A.E. Nelson and S.M. Barr, Phys. Lett. **B246** (1990) 141.
13. J.A. Harvey and M.S. Turner, Fermilab preprint 90/49 (1990).
14. G. Farrar and P. Fayet, Phys. Lett. **B76** (1978) 575.
15. For a review see : H.P. Nilles, Phys. Rep. (1984) 2.
16. T. Yanagida, in Proceedings of the Workshop on the Unified Theory and the Baryon Number in the Universe (KEK, 1979) 95; M. Grell-Mann, P. Ramond and R. Slansky, in Proceedings of the Workshop on Supergravity (SUNY, 1979).
17. M. Takiya et al., Phys. Rev. **D34** (1986) 902.
18. C.S. Aulakh and R.N. Mohapatra, Phys. Lett. **B119** (1982) 136.

19. L.J. Hall and M. Suzuki, Nucle. Phys. **B231** (1984) 419.
20. For a review, D. O. Caldwell, Int. J. Mod. Phys. **A4** (1988) 185.
21. I.H. Lee, Phys. Lett. **B138** (1984) 121; Nucl. Phys. **B246** (1984) 120; G.G. Volkov, A.R. Kereselidze, A.G. Liparteli and F.G. Tkebuchava, Sov. J. Nucl. Phys. **47** (1988) 1117.
22. F. Zwirner, Phys. Lett. **B132** (1983) 103.
23. S. Dawson, Nucl. Phys. **B261** (1985) 297.
24. R. Barbieri and A. Masiero, Nucl. Phys. **B267** (1986) 679.
25. R.N. Mohapatra, Phys. Rev. **D34** (1986) 3457.
26. A. Bouquet and P. Salati, Nucl. Phys. **B284** (1987) 557.
27. S. Dimopoulos and L.J. Hall, Phys. Lett. **B207** (1987) 210.
28. V. Barger, G.F. Giudice and T. Han, Phys. Rev. **D40** (1989) 2987.
29. S. Dimopoulos, R. Esmailzadeh, L.J. Hall, J.P. Merlo and G.D. Starkman, Phys. Rev. **D41** (1990) 2099.
30. D. S. Dearborn, D. N. Schramm and G. Steigman, Phys. Rev. Lett. **56** (1985) 26.
31. J. Ellis, G. Gelmini, C. Jarlskog, G.G. Ross and J.W.F. Valle, Phys. Lett. **B151** (1985) 375.
32. B. Gato, J. Leon, J. Perez-Mercader and M. Quiros, Nucl. Phys. **B260** (1985) 203; M.S. Carena and C.E.M. Wagner, Phys. Lett. **B186** (1987) 361.
33. I. Affleck and M. Dine, Nucl. Phys. **B249** (1985) 361.

TABLE CAPTIONS

Table 1. Cosmological and laboratory limits on baryon/lepton number violating operators with standard model field content. *For 10^{-2} eV $< m_\nu < 10^2$ eV from the "see-saw" mass generation mechanism.

Table 2. Cosmological and laboratory limits on baryon/lepton number violating operators with supersymmetric standard model field content. *For 10^{-2} eV $< m_\nu < 10^2$ eV from the "see-saw" mass generation mechanism.

	Operator	D	ΔB	ΔL	Cosmological	Limit	Laboratory Limits
					Case (A)	Case (B)	
Standard Model	ll hh	5	0	2	$M > 10^{10}$ GeV	$M > 10^{16}$ GeV	$M > 10^{11}-10^{15}$ GeV*
	qqq l	6	1	1	None	None	$M > 10^{14}-10^{15}$ GeV
	qqq lch	7	1	-1	$M > 10^{4.7}$ GeV	$M > 10^{14.7}$ GeV	$M > 10^{10}-10^{11}$ GeV
	qqq l $\bar{c}$	7	1	-1	$M > 10^{4.7}$ GeV	$M > 10^{14.7}$ GeV	$M > 10^8-10^9$ GeV
	qqq qqq	9	2	0	$M > 10^{3.6}$ GeV	$M > 10^{14.4}$ GeV	$M > 10^5-10^6$ GeV
	qqq ll	9	1	3	$M > 10^{3.6}$ GeV	$M > 10^{14.4}$ GeV	No previous
	qqq l $\bar{c}$ l $\bar{c}$ ch	10	1	-3	$M > 10^{3.3}$ GeV	$M > 10^{14.3}$ GeV	$M > 10^4-10^5$ GeV
	qqq ll hh	11	1	3	$M > 10^{3.1}$ GeV	$M > 10^{14.3}$ GeV	$M > 10^4$ GeV

Table 1

	Operator	D	ΔB	ΔL	Cosmological	Limit	Laboratory Limits
					Case (A)	Case (B)	
Supersymmetric Interactions	$(LH)_F$	3	0	1	$m \leq 10^{-6} \text{ GeV}$	$m \leq 10^{-6} \text{ GeV}$	$m \leq O(1) \left(\frac{\epsilon}{30 \text{ GeV}} \right) \text{ GeV}$
	$(LLE^c)_F$	4	0	1	$\lambda \leq 10^{-8}$	$\lambda \leq 10^{-8}$	$\lambda_1^{113} < 2 \times 10^{-3} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{1/2}$
	$(QD^c L)_F$	4	0	1	$\lambda \leq 10^{-8}$	$\lambda \leq 10^{-8}$	$\lambda_2^{113} < 10^{-3} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{1/2}$
	$(U^c D^c D^c)_F$	4	1	0	$\lambda \leq 10^{-8}$	$\lambda \leq 10^{-8}$	$\lambda_3^{113} < 2 \times 10^{-7} \left(\frac{\tilde{m}}{100 \text{ GeV}} \right)^{5/2}$
	$(\bar{H} H H)_F$	5	0	2	$M > 10^{10} \text{ GeV}$	$M > 10^{16} \text{ GeV}$	$10^{11} - 10^{15} \text{ GeV}^*$
	$(\bar{H} \bar{H} H)_F$	5	0	1	$M \geq 10^{10} \text{ GeV}$	$M \geq 10^{16} \text{ GeV}$	No previous
	$(U^c D^c D^c E^c)_F$	5	1	1	None	None	
	$(QQQL)_F$	5	1	1	None	None	$M > 10^{15} \text{ GeV}$
	$(QQQL\bar{H})_F$	5	1	0	$M \geq 10^{10} \text{ GeV}$	$M \geq 10^{16} \text{ GeV}$	No previous
	$(D^c D^c D^c E^c)_D$	6	1	-1	$M \geq 10^6 \text{ GeV}$	$M \geq 10^{15} \text{ GeV}$	$M > 10^{11} \text{ GeV}$
	$(D^c D^c D^c Q L^*)_D$	6	1	-1	$M > 10^6 \text{ GeV}$	$M > 10^{15} \text{ GeV}$	$M > 10^{11} \text{ GeV}$
	$(D^c D^c D^c L^* \bar{H}^*)_F$	6	1	-1	$M > 10^6 \text{ GeV}$	$M > 10^{15} \text{ GeV}$	$M > 10^{11} \text{ GeV}$
	$(D^c D^c U^c L^* H^*)_F$	6	1	-1	$M > 10^6 \text{ GeV}$	$M > 10^{15} \text{ GeV}$	$M > 10^{11} \text{ GeV}$
	$(U^c D^c D^c U^c D^c)_F$	7	2	0	$M \geq 10^{4.7} \text{ GeV}$	$M \geq 10^{14.7} \text{ GeV}$	$> 1. \times 10^8 \left(\frac{100}{\tilde{m}} \right)^{2/3} \text{ GeV}$
Soft Supersymmetry -Breaking Interactions	$\bar{t} h (\bar{t} h^\dagger)$	2	0	1	$\mu \leq 10^{-2} \text{ GeV}$	$\mu \leq 10^{-2} \text{ GeV}$	$\mu < 1 - 100 \text{ GeV}$ generation dependent
	$\tilde{q} \tilde{q}^c \bar{t}$	3	0	1	$m \leq 10^{-6} \text{ GeV}$	$m \leq 10^{-6} \text{ GeV}$	No previous
	$\bar{t} \tilde{e} \bar{t}$	3	0	1	$m \leq 10^{-6} \text{ GeV}$	$m \leq 10^{-6} \text{ GeV}$	No previous
	$\tilde{u}^c \tilde{d}^c \tilde{d}^c$	3	1	0	$m \leq 10^{-6} \text{ GeV}$	$m \leq 10^{-6} \text{ GeV}$	No previous
	$\bar{t} \bar{h} (\bar{t} h^c)$	3	0	1	$m \leq 10^{-6} \text{ GeV}$	$m \leq 10^{-6} \text{ GeV}$	$m \leq 0.1 \left(\frac{\epsilon}{30 \text{ GeV}} \right)$

Table 2