Baryogenesis with four-fermion operators in low-scale models

Thomas Dent

Michigan Center for Theoretical Physics, Randall Lab.,
University of Michigan, Ann Arbor, MI 48109-1120

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Abstract

We describe a nonstandard proposal for baryogenesis in models with a low ($O(10 - 100) \text{ TeV}$) fundamental scale. The scenario has Standard Model field content and enhanced baryon number violating operators deriving from time-dependent fermion localization in an extra dimension. The CKM matrix provides sufficient CP violation. The major constraints are the low reheating temperature and rate of perturbative $B$-violating reactions compared to the total entropy created. A sufficient baryon fraction may arise, but the cosmological evolution required is likely to be somewhat contrived. Based on work in collaboration with D. J. H. Chung.

1 Introduction

The lower limit on the lifetime of the proton is a severe problem for models in which the fundamental scale of quantum gravity is low compared to the supersymmetric GUT scale $10^{16} \text{ GeV}$ [1, 2]. A baryon number $U(1)$ symmetry cannot be gauged in field theory, so like other accidental symmetries it is expected to be violated by effects at the string scale or by quantum wormholes.

*E-mail: tdent@umich.edu
and virtual black holes \[3\]. Such $B$ violation appears at low energies as nonrenormalizable operators, for example

$$\frac{\lambda_{ifgh}}{M_*^2} q_i q_f q_g q_h$$

(1)

where $M_*$ is the fundamental scale, $i, f, g, h$ are family labels and the $\lambda$ are expected to be $\mathcal{O}(1)$ in the absence of suppression mechanisms. Then for $M_*$ in the $\mathcal{O}(10 - 100)$ TeV range, for which collider signals of the fundamental degrees of freedom or of large extra dimensions may be observable, $\tau_p$ comes out to be under a second. Various solutions have been proposed \[4, 5, 6\] all of which have implications for the production of an excess of baryons over antibaryons in the early Universe, for which $B$ violation is a precondition.

The overproduction of gravitational Kaluza-Klein modes in such models, in which some compactified extra dimensions are orders of magnitude larger than the fundamental length, gives a severe upper bound on the temperatures that can be attained in the early Universe. Even for the maximum number (6) of large extra dimensions and the relatively large value $M_* = 100$ TeV, a reheating temperature of a few GeV is the maximum if overclosure of the Universe, disruption of the successful predictions of nucleosynthesis, and an observationally unacceptable level of background gamma-rays from K-K mode decay are to be avoided \[4, 8\]. Astrophysical production and decay of such modes also leads to an independent lower bound on the fundamental scale \[3\], which is also constrained by the non-observation of direct and loop effects in current experiments \[20\].

Any attempt at explaining proton longevity and baryogenesis should operate within these constraints. Exact (anomaly-free) discrete or horizontal symmetries can be imposed to forbid $B$-violating operators mediating proton decay \[10, 4\] while allowing others, through which baryogenesis occurs: this approach requires an “X-boson”, with couplings which appear unnaturally small (in contrast to the standard GUT scenario) \[1\]. Baryon number can be gauged if the anomaly is cancelled by a string theory mechanism, or $B$ violation may be forbidden to all orders in perturbation theory by string selection rules, in some “intersecting brane” models \[6\]. Note however that in a more general class of intersecting brane models \[4\], such selection rules do not prevent the four-fermion operators from appearing, as discussed above, in which case the fundamental scale cannot be low.

\[1\] Or a charged scalar with $B$-violating couplings which has a time-dependent v.e.v., in an Affleck-Dine-like model \[11\].
If baryon number is perturbatively exact, nonperturbative processes are the only option to create net baryon number. It is difficult to see how this proposal can be reconciled with cosmological constraints, since any such processes would operate at or above the electroweak scale and be enormously suppressed at low temperature.

We describe a scenario based on a geometrical mechanism for suppressing 4d $B$-violating operators, namely localization of fermions in extra dimensions. The simplest implementation is for the SU(2) $\times$ U(1) gauge fields to propagate in an extra dimension (cf. [13]), in which the quark and lepton wavefunctions are peaked about points separated by a distance $L \sim 30M^{-1}$. See Fig. 1. Then any strong $B$-violating operators in the effective 5d theory can only produce proton decay proportional to the overlap of the wavefunctions, which is exponentially small. Alternatively, proton decay by exchange of massive modes is suppressed by the Yukawa propagator over the distance $L$. Nonperturbative quantum effects which may lead to proton decay, for example virtual black holes [14], are also exponentially suppressed due to the integration over the fifth dimension.

Since the distance $L$ may vary over cosmological time, $B$ violation in the $D = 4$ field theory may have been unsuppressed ($\lambda \sim 1$) at some epoch. Then, if some Standard Model degrees of freedom have number densities out of equilibrium, nonzero $n_b$ may be created by the inelastic scattering or decay of fermions. A similar scenario was proposed in [16], but the authors concentrated on an “X-boson” model with somewhat arbitrary scalar mass and

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2It is unclear whether electroweak baryogenesis with low $T_{rh}$ [14, first reference] actually satisfies the bounds, since a hot plasma at temperature $T \gg T_{rh}$ is needed.

3Assuming that no light fermionic modes with $B$-violating interactions propagate over the bulk.

4$B$ violation by electroweak sphalerons [15], being an effect energetically suppressed at low temperatures, is not affected by the fermion localization.
couplings. We find that it may be unnecessary to introduce new particles with $B$-violating couplings, if the cosmological evolution of number densities and of the extra-dimensional geometry satisfy certain conditions. These appear somewhat special, in that a generic cosmology is unlikely to allow our proposal; however, they motivate further study of cosmology in low-scale models, since there is no standard picture and few general bounds exist on the behaviour before nucleosynthesis.

2 The model

The localization of fermions by scalar field profiles has been described in detail in [5, and references therein]: in essence, 5d fermions are coupled to a scalar field profile resulting in a position-dependent effective mass $m_5(y)$, where $y$ is the coordinate in the fifth dimension. Then the fermion wavefunctions $\psi_{L,R}(y)$ peak about the zeros of $m_5(y)$, with the 4d chirality of the localized state determined by the direction of crossing zero. Localized chiral fermions can also result from orbifold projection [17] and coupling to a scalar field odd under the orbifold action. Different localized positions can be produced by coupling to different scalar fields, or by allowing constant 5d fermion masses and factors of order 1 in the scalar coupling term. In the approximation that the scalar field profile is linear near the fermion position $y_f$ a Gaussian is obtained

$$\psi(y) \simeq \mu^{1/2}e^{-\mu^2(y-y_f)^2}, \quad (2)$$

where $\mu$ is a parameter of mass dimension 1 which describes the size of the scalar v.e.v.: $\Phi \sim \mu^2 y$ near $y = y_f$. Far away from $y_f$, if the scalar approaches a constant value $\Phi_0$ the wavefunction varies as $\psi \propto e^{-k\Phi_0|y-y_f|}$, with $k \sim 1$. Then given a 5d operator $\lambda^{(5)}M^{-3}_s(QQ)(QL)$, where ( ) denotes the Lorentz- and SU(2)-invariant sum, the resulting 4d interaction is

$$\delta S = \int d^4x \frac{\lambda}{M^2_s}(qq)(ql) \quad (3)$$

where $\lambda \sim \lambda^{(5)}\int dy \frac{\mu^2}{M^2}e^{-3\mu^2y^2-\mu^2(y-L)^2} \sim \lambda^{(5)}\frac{\mu}{M^2}e^{-3\mu^2L^2/4} \quad (4)$

in the approximation of a linear $\Phi(y)$. For a constant scalar v.e.v. the suppression goes as $\lambda \propto e^{-k\Phi_0L}$ with $k \sim 1$. 

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The presentday value of $L$ required for a sufficiently stable proton is estimated by comparing with dimension-6 operators induced at the SUSY-GUT scale: we require

$$\lambda^2 M^4 \approx M^4_{\text{GUT}} \approx (2 \times 10^{16} \text{GeV})^{-4}$$

thus $\lambda \sim e^{-50}$ for $M_\ast \sim 10 - 100 \text{TeV}$. Then assuming $\mu, \Phi_0$ to be of the order of $M_\ast$, up to small numerical factors we obtain $LM_\ast \geq 10$ for a linear scalar v.e.v. and $LM_\ast \geq 50$ for a constant v.e.v.. This order of magnitude is marginally compatible with perturbativity of the bulk SU(2) gauge dynamics, since the $D = 5$ gauge coupling satisfies $4\pi R_5 g_5^{-2} = \alpha_W^{-1} \simeq 31$ and 5d loop corrections at the fundamental scale are expected to be of order $M_\ast g_5^2/4\pi = \alpha_W M_\ast R_5$.

An independent bound on $M_\ast$ comes from experimental limits on neutron-antineutron oscillation, which is mediated by a dimension-9 operator of form $uddudd$. This operator is not suppressed by fermion localization, thus the coupling strength, of order $M_\ast^{-5}$, is bounded such that $M_\ast \gtrsim 10^5 \text{GeV}$ \cite{4}.

### 3 Creating $n_b$

The processes satisfying the Sakharov conditions of $B, C$ and $CP$ violation and out-of-equilibrium are fermion scattering and decay via the dimension-6 operators $\left[\right]$. $CP$ violation enters by the loop correction with $W$ exchange, in which CKM matrix elements appear (Fig. 2). The asymmetry in cross-section between a process and its $CP$ conjugate is proportional to the rephasing invariant combinations of couplings

$$\eta_{h,f,g,h} = \alpha_W \sum_{nm} \text{Im} \left( \lambda_{nm fh} \lambda_{gfh}^* \lambda_{im} \lambda_{ng}^* \right)$$

which are not necessarily correlated with the Jarlskog parameter of the SM, and may be of order $10^{-2} - 10^{-1}$.

Then our procedure is as follows: to place an upper bound on the baryon fraction $n_b/s$ we assume that the $\lambda$ are unsuppressed at the time of baryogenesis and that we have some fermion number densities $n_{f_i}$ well in excess of the thermal equilibrium density: technically, we assume kinetic equilibrium (distribution of energy) within each species but no chemical equilibrium between species. The upper limit on number densities is taken as the equilibrium density at $T = 30 \text{GeV}$ to avoid the possibility of restoring electroweak
symmetry. Then the evolution of $n_b$ and the entropy density $s$ can be found, given a reasonable time-dependence of $L(t)$, the 4d scale factor $a(t)$, temperature $T(t)$ and the extra-dimensional radii $R_i(t), i = 5, \ldots$ as inputs. The effect of scattering and decay reactions on the entropy density can be calculated directly using the Boltzmann equation [18], also taking into account out-of-equilibrium reactions which change number densities but do not change baryon number, for example weak decay and inelastic scattering, or annihilation of quarks into gluons. We find a surprisingly simple result, independent of the details of the cosmology: the baryon fraction is bounded above as

$$\frac{n_b}{s} < 2\eta \left( \frac{\Gamma_{BV}(t)}{\Gamma_{tot}(t)} \right)_{\text{max}}$$

where $\Gamma_{BV}(t)$ is the rate of $B$-violating reactions, $\Gamma_{tot}(t)$ is the total rate of reactions changing the number densities $n_{f_i}$ and the maximum is taken at a time when baryogenesis is occurring. The upper bound can be approached if sources of entropy apart from reactions of the $f_i$ during baryogenesis are small and the $B$-violating couplings turn off (i.e. $L$ becomes large) soon after baryogenesis. Since $B$-violating cross-sections are always suppressed as $\alpha_W M_\ast^{-4}$, compared to weak interactions suppressed as $\alpha_W^2 M_W^{-4}$ or strong scattering cross-sections varying as $\max(m_Q^2, T^4)^{-1} \alpha_S^2$, the bound is quite restrictive and rules out most possibilities for the $B$-violating reaction.

The remaining possibilities involve baryogenesis through scattering reactions of fermions $f_1, f_2$, where the competing $\Delta B = 0$ reactions are weak decay, annihilation and inelastic scattering. A more stringent entropy bound.
than (7) can be derived by considering $B$-conserving scattering of $f_1$ with $f_2$, from which we find

$$\frac{n_b}{s} \leq \frac{\eta}{\alpha_W |V_{\text{CKM}}|^2} \left( \frac{M_W}{M_*} \right)^2 \simeq 4 \cdot 10^{-14} (\alpha_W |V_{\text{CKM}}|^2)^{-1}$$

if the inelastic weak scattering is kinematically allowed, where $V_{\text{CKM}}$ is the relevant matrix element for this reaction. As noted above, the weak coupling may change if the radius of the 5th dimension varies, but even assuming $\alpha_W$ stays small one requires $|V_{\text{CKM}}|^2$ to be order $10^{-3}$ or smaller even for marginal viability. Then the $f_i$ must be such that the weak scattering is kinematically suppressed at temperatures above the QCD phase transition (we do not consider reactions below this temperature, since they are complicated by quark confinement).

There are two candidates for the reacting fermion species, $us$ (with $u$ out of equilibrium during baryogenesis) and $q\nu_\tau$ where $q = c, s, d, u$ (with either species out of equilibrium). For the first case, the entropy due to self-annihilation reactions can be estimated, with cosmology parameterised as $a(t) \propto t^n, T \propto a^{-\nu}$, with the result that $n_b/s$ is some orders of magnitude below what is required, for any reasonable value of $n$ and $\nu$ [18]. However, considering the self-annihilation reaction of $\nu_\tau$ one finds that if the effective temperature of the $\nu_\tau$ population is small enough (below approximately 0.4 GeV) then the annihilation cross-section can be arbitrarily small, vanishing (at tree level) in the limit of zero temperature and neutrino mass. Thus the rate of entropy creation through $B$-conserving reactions may be small enough to allow baryon creation to compete in this case.

### 4 Further discussion

Our assumptions about the mechanism of baryogenesis, in particular the restriction to the Standard Model degrees of freedom, lead to some definite conclusions ruling out many possibilities, regardless of the unknown details of cosmology. The amount of $CP$ violation, a major problem for baryogenesis in the Standard Model without $B$-violating operators and for supersymmetric electroweak baryogenesis if experimental bounds on soft breaking terms are to be respected, is not an important constraint for us, even if all $B$-violating couplings are real. The main problems for our proposal come from the fact that the species reacting to create baryon number almost always have strong
\( \Delta B = 0 \) reactions that compete overwhelmingly with operators suppressed by the fundamental scale.

We have still to address the questions of how the out-of-equilibrium number density of the particular species involved is to be obtained, and whether the late evolution of the “quark-lepton radion” \( L(t) \) can be consistent with cosmological and other bounds on scalars associated with the geometry of extra dimensions (recall that \( L \) should be order 1 at the time of baryogenesis). It should also be remembered that the estimates of entropy density that we presented are lower bounds, and any other significant sources might alter our conclusions (in a negative direction).

These issues should eventually be addressed within a low-scale cosmology which includes inflation, reheating, an effective potential driving the time-dependence of \( L(t) \), and a suitable evolution of the extra-dimensional scale factors. As noted above, there is no “standard model” for cosmology in low-scale theories, primarily because of the necessity to avoid overproducing light gravitational modes. However, extra-dimensional theories have possibilities which might give grounds for hope, for example if the radii \( R_{6-10} \) were smaller at the time of baryogenesis, the 4d Planck mass would be smaller and the out-of-equilibrium condition might be easier to satisfy. Also, the early stages of reheating are in general expected to produce a nonequilibrium distribution, with thermalization occurring later. The work described here shows only that if an appropriate cosmology can be constructed, baryogenesis through interaction of the SM degrees of freedom only is not a priori ruled out.

4.1 Experimental signals

Even in the absence of a complete model, one can ask whether the scenario we have described implies testable predictions. Certainly, since we use localized fermions, one would expect distinctive collider signatures [5, 19] in addition to those produced by Kaluza-Klein modes of gravity and gauge fields [20]. If baryon number is maximally violated in the underlying theory then we expect the unsuppressed \( n - \bar{n} \) oscillations to be detectable, at a rate close to the current experimental limit. However, this “signature” is rather indirect since it does not occur through the same operators as baryogenesis; it would, though, confirm in a dramatic fashion the existence of perturbative \( B \) violation. Given a low fundamental scale, the energy density during inflation must also be low, which will have definite consequences for cosmology [21].
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