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Hidden Sector Baryogenesis

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Abstract

We introduce a novel mechanism for baryogenesis, in which mixed anomalies between the hidden sector and $U(1)_{baryon}$ drive the baryon asymmetry. We demonstrate that this mechanism occurs quite naturally in intersecting-brane constructions of the Standard Model, and show that it solves some of the theoretical difficulties faced in matching baryogenesis to experimental bounds. We illustrate with a specific example model. We also discuss the possible signals at the LHC.

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1 Introduction

One of the great puzzles facing theoretical physics is the question of why we observe so little anti-matter, as compared to matter [1]. The generation of the asymmetry is called baryogenesis, and Sakharov demonstrated [2] that the three conditions required for it to occur are

- Violation of baryon number, B
- C and CP violation
- Departure from thermal equilibrium

Several ideas have been proposed to satisfy these conditions, the most prominent of which are GUT baryogenesis, Affleck-Dine baryogenesis [3], baryogenesis via leptogenesis [4] and electroweak baryogenesis [5]. However all of these models have various theoretical or experimental constraints which make the fit to data problematic.

A parallel thread in model-building has been the construction, within the context of string theory, of intersecting brane models (IBMs) [6, 7, 8] which can perhaps provide a description of real-world low energy physics. These stringy constructions have provided new insights into the types of beyond-the-Standard-Model physics one might expect to find at colliders.

One of the ubiquitous features of these IBMs is the existence of hidden sectors, arising from the gauge theory living on extra branes (above and beyond the visible sector branes needed to generate the Standard Model). It is rather generic in this context for the hidden sector groups to have mixed anomalies with Standard Model $U(1)$'s. We suggest here a mechanism in which mixed anomalies between baryon number, $U(1)_B$, and hidden sector gauge groups can drive baryogenesis.

This provides a new mechanism for baryogenesis which not only provides a unique phenomenological signature, but also seems to appear rather generically in a large class of stringy constructions.

2 Motivation

In intersecting brane models, one obtains a Standard Model gauge theory as the low-energy limit of the theory of open strings which begin and end on a set of intersecting D-branes

(the “visible sector”). In such models, however, one generically can find additional D-branes, and the gauge theory living on those branes provides a hidden sector. The strings which stretch between those hidden sector branes, and between hidden and visible sector branes, form exotic matter¹.

In a construction with $N = 1$ supersymmetry (which arises in orientifold models), the strings stretching between branes yield degrees of freedom which are arranged into chiral multiplets. The net number of bifundamental chiral multiplets² stretched between two branes [9] is given by the topological intersection number I_{ab} :

$$I_{ab} \text{ multiplets} \rightarrow (\square_a, \bar{\square}_b) \quad (1)$$

Nontrivial topological intersections are somewhat generic in many constructions. One of the best understood IBMs arises from toroidal orientifolds (for example, $T^6/Z_2 \times Z_2 (\times \Omega R)$) of Type IIA string theory, on which D6-branes are wrapped. The branes in this example wrap 3-cycles on the compact dimensions, which can be represented by three coprime ordered-pairs of wrapping numbers: $(n_1, m_1)(n_2, m_2)(n_3, m_3)$, where (n_i, m_i) are the wrapping numbers on the a and b cycles of the i th torus. The topological intersection between branes a and b is then

$$I_{ab} = \prod_{i=1}^3 (n_i^a m_i^b - m_i^a n_i^b) \quad (2)$$

It is clear that $I_{ab} = 0$ only if D6-branes a and b have the same wrapping numbers on at least one torus. For a generic choice of wrapping numbers, this will not be the case, and $I_{ab} \neq 0$.

For a more general manifold, an orthogonal basis of 3-forms may be written as α_i, β^j , where $\int_{\Sigma} \alpha_i \wedge \beta^j = \delta_i^j$. Without loss of generality, assume brane a wraps the 3-cycle dual to α_1 . The form dual to the cycle wrapped by brane b is

$$\gamma = \sum_i a^i \alpha_i + b_i \beta^i. \quad (3)$$

In this case, $I_{ab} = 0$ only if $b_1 = 0$. For a generic choice of a_i, b^j , this will not be the case, and again $I_{ab} \neq 0$.

It is necessary to ensure that the gauge theory has canceled anomalies. The cancelation of cubic anomalies is automatically ensured by the RR-tadpole constraints (i.e, the constraint

¹Since there can be exotic matter charged under both the hidden and Standard Model gauge groups, our hidden sector is more precisely a pseudo-hidden sector.

²Other representations arise when the effects of the orientifold are accounted for, but we will not need them here.

that all space-filling charges cancel). There can also be mixed anomalies, however, which are canceled by a generalized Green-Schwarz mechanism. If a symmetry is broken by such an anomaly, then the associated gauge boson will receive mass through the Steuckelberg mechanism, and the symmetry will appear to be an anomalous global symmetry at low-energies. If two branes a and b have non-trivial intersection, then there will be chiral fermions transforming under the groups G_a and G_b , where $G_{a,b}$ are the gauge groups living on branes a and b respectively. It is clear from the field theory analysis that there will thus be a $U(1)_a - G_b^2$ mixed anomaly (where $U(1)_a$ is the diagonal $U(1)$ subgroup of G_a) given by

$$\partial_\mu j_a^\mu = \frac{I_{ab}}{32\pi^2} \text{Tr} F_b \wedge F_b \quad (4)$$

In a large class of intersecting brane world models, $SU(3)_{qcd}$ arises as a subgroup of a $U(3)$ gauge group living on a stack of 3 parallel D-branes (in certain cases where there is an orientifold plane, there will actually be 6 parallel D-branes in this stack). In such cases, the charge under the diagonal $U(1)_B$ is baryon number. As we have seen, $U(1)_B$ will generically have mixed anomalies with other gauge groups (both visible and hidden sector), provided that the $U(3)_{qcd}$ stack of branes and the other stack have non-trivial intersection.

We will consider the case where there is an anomaly between the hidden sector and $U(1)_B$. As a result, the divergence of the baryon current will be given by

$$\partial_\mu j_B^\mu \sim \text{Tr} F \wedge F \quad (5)$$

where F is the field strength of the hidden sector gauge theory. Instantons or sphalerons in the hidden sector will then violate baryon number, providing a source for the baryogenesis.

3 Baryogenesis driven by the hidden sector

Having motivated this mechanism from intersecting brane world constructions, we will develop this idea from the point of view of the low-energy effective field theory. In fact, motivation aside, this mechanism can appear just as readily in non-stringy constructions, and it will be easier to find specific models in low-energy effective field theory. We refer to Ref.[10] for other work on baryogenesis in related contexts.

We will consider a theory with $N = 1$ SUSY and Standard Model gauge group and matter content, as well as a non-trivial hidden sector including hidden group G . We will need four features:

- The cancelation of all cubic anomalies (in IBMs, this is ensured by the RR-tadpole constraints)
- A non-vanishing $U(1)_B - G^2$ mixed anomaly
- Vanishing $U(1)_Y$ mixed anomalies
- A Yukawa coupling which permits exotic baryons to decay to SM baryons

All multiplets charged under the fundamental of $SU(3)_{qcd}$ have charge $\frac{1}{3}$ under $U(1)_B$. In an intersecting brane model this will arise naturally, as $U(1)_B = \frac{1}{3}U(1)_{diag}$ is a gauged subgroup of $U(3)_{qcd}$. In a more general field theory model, $U(1)_B$ arises simply as a global symmetry.

The vanishing of $U(1)_Y$ mixed anomalies is easy to arrange in intersecting brane models. In that case, $U(1)_Y$ arises as a linear combination of $U(1)$'s, and in many constructions it is easy to arrange for the existence of such a non-anomalous symmetry. In such constructions, the vanishing of the hypercharge anomaly naturally leads to the existence of the appropriate Yukawa coupling. For example, one might arrange for the $U(1)_Y - G^2$ anomaly to vanish by ensuring a non-trivial intersection between the G branes and a $U(1)_{T_{3R}}$ brane. But as we will see, this permits a Yukawa coupling which allows exotic quarks to decay to right-handed quarks, plus an exotic scalar. From the effective field theory point of view, we merely need to choose our exotic with matter with appropriate hypercharge couplings to ensure vanishing anomalies and the appropriate Yukawa couplings.

3.1 A specific model

We will now look at a specific model with a hidden gauge group G contained in a larger hidden sector. In our model, we have $U(1)_Y = \frac{1}{2}(U(1)_B - U(1)_L + U(1)_{T_{3R}} - U(1)_G + \dots)$, where $U(1)_G$ is the diagonal $U(1)$ subgroup of G . We have 2 chiral multiplets q_i transforming in the bifundamental of $(U(3)_B, G)$ and with hypercharge $Q_Y = \frac{2}{3}$; four multiplets λ_j transforming in the fundamental of G with charge $Q_{T_{3R}} = -1$ and hypercharge $Q_Y = -1$; one chiral multiplet η transforming in the fundamental of G with charge $Q_{T_{3R}} = 1$ and hypercharge $Q_Y = 0$; and one chiral multiplet ξ transforming in the anti-fundamental of G with charge $Q_L = 1$ and hypercharge $Q_Y = 0$. The charges for this specific model are described in Table 1. This could arise in a brane model (assuming we label the branes as follows: $a = U(3)_B$, $b = U(1)_{T_{3R}}$, $c = U(1)_L$ and $g = G$) with intersection numbers $I_{ag} = 2$, $I_{gb} = 4$, $I_{gb'} = 1$, and $I_{cg} = 1$, where b' is the orientifold image of the b brane.

Table 1: Particle spectrum for the example model.

particle	Q_B	Q_G	$Q_{T_{3R}}$	Q_L	Q_Y
q_i	$\frac{1}{3}$	-1	0	0	$\frac{2}{3}$
λ_j	0	1	-1	0	-1
η	0	1	1	0	0
ξ	0	-1	0	1	0

We see that all of this matter is charged under the (anti)fundamental of G , and the net hypercharge of this matter content is zero. As a result, we induce no $U(1)_Y - G^2$ mixed anomaly. Note however, that $U(1)_B$ and $U(1)_{B-L}$ have mixed anomalies with G . We assume that the rest of the hidden sector cancels the RR-tadpoles. This ensures the cancelation of all cubic anomalies. Assuming that there are no symmetric or antisymmetric representations of $SU(3)_{qcd}$ (which is easy to arrange by a judicious choice of the QCD branes), this also ensures that there are no net chiral exotics.

The divergence of the baryon current will contain a hidden-sector contribution given by

$$\partial_\mu j_B^\mu \propto \frac{1}{32\pi^2} (g_G^2 \text{Tr} F_G \wedge F_G + \dots) \quad (6)$$

At low energies $U(1)_B$ will appear to be an anomalous global symmetry. We will assume that G and other hidden sector gauge groups break at some scale (breaking or confinement will be necessary in order to avoid exotic massless fermions which are charged under the Standard Model). The breaking of G can involve complicated hidden sector dynamics such as brane recombination [11, 8] in which other hidden sector groups simultaneously break. For a phenomenologically viable model, however, the $U(1)$ hypercharge must remain unbroken.

3.2 Phase transitions and baryogenesis

Having discussed the basic setup, one can now address the way baryogenesis actually occurs. As the universe expands and cools, we assume that there is a phase transition (such as the spontaneous symmetry breaking of G) at some temperature T_C . If this G phase transition is strongly first-order, then it will result the nucleation of expanding bubbles of a broken symmetry vacuum.

At the bubble walls, there will be a departure from equilibrium. During this process, CP can generically be violated in the G -sector. G -sphalerons correspond to transitions from one vacuum of the hidden sector theory to another, and the mixed $U(1)_B - G^2$ anomaly implies that these transitions are accompanied by a discrete violation of baryon number [12].

All of the Sakharov conditions are thus satisfied, and a baryon asymmetry can be produced during the phase transition. G -sphalerons will be unsuppressed above the phase transition, but will generally be suppressed at low temperatures [13]. Thus, to avoid washout of the produced asymmetry by G -sphalerons after the phase transition, one must demand the usual condition [14]

$$\frac{v(T_c)}{T_c} \geq 1, \quad (7)$$

where $v(T_c) = \langle \phi \rangle$ is the order parameter of the first order phase transition. This mechanism is reminiscent of electroweak baryogenesis [15], but does not suffer from the tunings required to fit electroweak baryogenesis into the parameter space allowed by LEP-II data and EDM bounds [16, 17, 18].

It is interesting to note that the amount of chiral matter charged under G and $U(1)_L$ need not be the same as the amount charged under G and $U(1)_B$. As a result, there may be a $U(1)_{B-L} - G^2$ anomaly (indeed, $U(1)_L$ may have no anomaly). In IBMs, one expects a $U(1)_{B-L} - G^2$ anomaly unless $U(1)_L$ lives on a lepton brane which is parallel to the QCD branes, as in a Pati-Salam model. One thus expects that these G sphalerons can violate both B and $B - L$. As a result, even if G breaks at a scale significantly larger than TeV, electroweak sphalerons will not wash out the baryon asymmetry. This naturally avoids one of the difficulties of GUT baryogenesis.

Of course, one can choose models where the G -sphaleron does preserve $B - L$. This will occur if the $U(1)_L - G^2$ anomaly has the same magnitude as the $U(1)_B - G^2$ anomaly, as is the case in Pati-Salam constructions of the SM sector (where $U(1)_{B-L}$ is a non-diagonal subgroup of $U(4)$). In this case, the hidden sector drives baryogenesis only if the scale of G breaking is approximately at or below the electroweak scale. This would be natural in a scenario where supersymmetry breaking is communicated to both the G and SM sectors by gravity/moduli.

In our specific example, the exotic particles generated by the G sphalerons will be the exotic baryons schematically represented by $q_i q_i q_i$, as well as λ_i , η and ξ . We will use a tilde to represent the scalar of the appropriate chiral multiplet, while the fermion will be represented without a tilde where no confusion is caused. In order to provide realistic baryogenesis, there must be a process whereby the qqq baryons decay to Standard Model baryons and the λ fermions decay to Standard Model particles. Generically, there will be Yukawa coupling

terms of the form³

$$W_{yuk.} = c_{ik} q_i u_k^c \eta + d_{jm} \lambda_j e_m^c \xi + \dots \quad (8)$$

which allow an exotic q_i quark to decay to u^c and $\tilde{\eta}$ and allow λ_i to decay to e^c and $\tilde{\xi}$; we assume that these decays are kinematically allowed (if this is not the case, then we would instead find exotic baryons which do not decay to SM baryons). These decays conserve R -parity if we assign the following charges: $Q_\eta = Q_\lambda = -1$, $Q_q = Q_\xi = 1$. Indeed, we must be sure that λ_i can decay to only charged SM and neutral exotics before nucleosynthesis, in order to avoid Li^6 production bounds [19].

The fields η and ξ can play the role of dark matter particles. These fields can get Majorana masses once the $U(1)_{T_{3R}} \times U(1)_L$ symmetry is broken (leaving only $U(1)_Y$). The fermionic parts of the fields (assuming they are lighter) can take part in constituting the dark matter of the universe. The annihilation of these new particles can happen via a t -channel exchange of exotic quarks.

But in a more general scenario where $U(1)_L$ is unbroken, ξ cannot obtain a Majorana mass. As ξ is produced by the same G -sphalerons, one expects the ξ number density to be related to the baryon number density (the precise ratio depends on the specifics of a model). In a simple scenario the mass of ξ could be $10m_{proton}$ which would provide a nice mechanism for relating the baryon and dark matter densities, along the lines of [20].

As we have not specified the precise nature of the hidden sector, it is not clear whether baryogenesis is dominated by local or nonlocal processes. If nonlocal baryogenesis dominates, and if G -sphalerons do not violate L , then one might face a variety of effects which suppress baryogenesis [21].

3.3 Different transitions

In many known intersecting braneworld models, the hidden sector gauge groups are known to confine (the β -function for the USp groups are negative) [7], rather than break at low energies. It is interesting to consider how this impacts baryogenesis. The role of the first-order transition in the Sakharov conditions is to drive the system away from thermal equilibrium. From that point of view, a first-order confining phase transition will do just as well as a symmetry breaking transition. The fundamental question is the suppression of G -sphalerons after the transition. In a Higgsing transition, it is clear that G -sphalerons

³The subscripts on u^c and e^c denote flavors of right-handed up-type quarks and electron-type leptons.

will be suppressed below the transition, and thus would be unable to wash out the baryon asymmetry. But after a confining transition, it is not entirely clear if sphaleron-like processes are suppressed. This is analogous to the question of whether or not strong sphalerons are suppressed at temperatures below Λ_{QCD} . It is of course difficult to make any concrete calculations, due to the inherent difficulties in computing in a strongly coupled gauge theory near confinement. But we expect that there should be a mass-gap on the confining side of the phase transition. Thus, we expect that there will be an upper limit on the size of instantons after confinement. As such, the energy barrier which the sphaleron-like process must cross should have a non-zero minimum size, which in turn implies Boltzmann suppression at low temperatures. So although it is not clear, it seems quite plausible that a first-order confining transition in the G sector can also produce a departure from equilibrium and seed baryogenesis, while shutting off sphalerons to prevent washout.

4 Signatures at the LHC

It is of prime interest to determine the signatures for this type of hidden sector baryogenesis (HSB) at LHC. As mentioned, HSB can occur even if G breaks at a relatively high-scale, provided that $B - L$ is also broken. In this case, however, there will not necessarily be any clear signature visible at LHC. However, if supersymmetry breaking is mediated to both the visible and hidden sectors by gravity, then one might expect G to in any case break at a scale \sim TeV. One might expect that G -sphaleron processes can then be accessed at LHC. Unfortunately, this is likely not the case. As shown in [22] in the context of electroweak theory, sphalerons can be accessed efficiently at high temperature, but not in high-energy scattering. On the other hand, if G sector particles have masses set by the TeV scale, then they can be produced directly at LHC.

At the LHC, the exotic quark (q) can be pair-produced and the production process in this case would be $gg \rightarrow q\bar{q}$ via a t -channel exchange of the exotic quark. The exotic quark q would then decay into q_{SM} and missing energy (η). The q_{SM} could be one of the up type quarks. The Yukawa couplings between the exotic quarks and the SM quarks are controlled by the structure of intersections between the G -branes and SM branes. In general, the signal will be multiple jets +leptons(arising from the decay of top quarks) +missing energy. The exotic quark can also be singly produced via $gq \rightarrow q_{exotic}\eta$. The exotic quark then decays into a SM quark and η . The jet E_T depends on the mass difference between the exotic quark and η . If the E_T is large the signal becomes more easily accessible. So the final state can have a high E_T jet plus missing energy. We can also have leptonic signals once the λ s are

produced (via Z interaction) which will then decay into lepton plus missing energy (ξ). So the signal is similar as in R-parity conserving SUSY scenarios.

Interestingly, if the exotic quarks do not have the same hypercharge as Standard Model quarks, then the scalars λ and η would have fractional charge. This would provide a unique signature of new physics. But due to the difficulty in decaying fractionally charged particles into SM particles, such models would be tightly bound by cosmology data and direct tests, requiring the fractionally charged particles to recombine or annihilate almost entirely.

5 Conclusions

We have discussed a novel mechanism for baryogenesis which avoids many of the tight constraints arising from electroweak and GUT baryogenesis. This model utilizes a first-order transition in a hidden sector which has a mixed anomaly with $U(1)_B$ to drive baryogenesis. As such, this mechanism naturally provides a way to break $B-L$, allowing the hidden sector group to break at any scale without washout from electroweak sphalerons (a major concern for GUT baryogenesis). Furthermore, this mechanism does not face the same challenge as electroweak baryogenesis in fitting the precision data from LEP-II and other experiments.

Perhaps most notable, however, is that this mechanism seems natural in IBM's. Hidden sectors appear generically, and it is quite natural for them to have mixed anomalies with $U(1)_B$. For an IBM model to be viable, such hidden sector groups (those with matter also charged under $SU(3)$) must break, and if the breaking is a first-order transition then one would expect baryogenesis. This mechanism can be expected to occur quite naturally, regardless of any other sources of baryon asymmetry. If the exotic baryons produced at the hidden sector transition can decay to SM baryons, then HSB can provide a substantial component of the asymmetry. If not, then it will provide exotic baryons which become a challenge in reconciling the IBM with observation. The signal of this scenario at the LHC will be consistent with multiple jets plus missing energy and jets plus leptons plus missing energy.

This is a fascinating example of how string theoretic input can provide intuition for low-energy phenomenology and cosmology. It will be interesting to see how this mechanism works in specific models, particularly those IBMs for which flux vacua can be counted. It would be quite interesting to determine, for example, brane models with large amounts of flux vacua which exhibit HSB. An analysis of the open string hidden-sector landscape [23] would be quite useful for this purpose.

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