PARTICLE PHYSICS MODELS, TOPOLOGICAL DEFECTS
AND
ELECTROWEAK BARYOGENESIS

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Abstract

We demonstrate the viability of electroweak baryogenesis scenarios in which the necessary departure from equilibrium is realized by the evolution of a network of topological defects. We consider several effective models of TeV physics, each addressing a fundamental particle physics problem, and in which the conditions necessary for defect-mediated electroweak baryogenesis are naturally satisfied. In each case we compare the strength of the model with that expected from scenarios in which baryogenesis proceeds with the propagation of critical bubbles.

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1 Introduction

The past few years have seen a great deal of effort devoted to attempts to explain the generation of the baryon asymmetry of the universe (BAU) at the electroweak scale\cite{1,2} (for reviews see \cite{3,4}).

Within the context of the Weinberg-Salam theory of electroweak interactions it is possible to satisfy all three of the Sakharov\cite{7} criteria necessary for a particle physics model to generate a net baryonic excess. These criteria are

1. the existence of baryon number violating processes,
2. C and CP violation,
3. departure from thermal equilibrium.

Common to all scenarios is the use of finite temperature sphaleron transitions to achieve the first of these\cite{8,9,10}. Also, most authors invoke an extended Higgs sector to obtain sufficient CP violation (C is violated maximally) in the model (see \cite{11} and \cite{12} for attempts to relax this). Recent attention has focussed on two alternative ways to achieve the departure from equilibrium which is also required.

The most common scenario for weak scale baryogenesis involves a strongly first order electroweak phase transition which is assumed to proceed by the nucleation and propagation of critical bubbles of the true vacuum in the false. It is in the walls of these bubbles that the changing Higgs fields communicate the departure from equilibrium to the other particle species\cite{1,2}.

However, there exists an alternative realization of the third Sakharov criterion in the context of the electroweak phase transition in the presence of topological defects remaining after a previous symmetry breaking\cite{13}. This is made possible by the fact that the electroweak symmetry may be restored out to some distance around
these defects and thus the evolution of the defect network provides a departure from equilibrium in an analogous manner to that produced by bubble walls.

In previous papers\[13\] we have analyzed the details of this mechanism in a general context without reference to a specific particle physics implementation. We have examined general symmetry breaking schemes

\[
G \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{em}
\]

such that the first stage produces topological defects of a given type determined by the non-triviality of the appropriate homotopy group of the vacuum manifold \( M \equiv G/SU(3) \times SU(2) \times U(1) \). If \( \pi_1(M) \neq 1 \) we obtain cosmic strings and if \( \pi_0(M) \neq 1 \) we have domain walls. In each case we have examined the baryon to entropy ratio expected to be produced by the evolution of the defect network.

In this letter our aim is to outline examples of existing effective TeV theories in which the criteria set forth in our earlier work are satisfied. Thus we shall demonstrate the viability of defect-mediated electroweak baryogenesis in the context of existing particle physics models.

It is interesting to note that the original motivations for studying the models we describe are the resolution of particular particle physics problems. It is therefore satisfying that the structure we require is an existing feature of the models.

The outline of this letter is as follows. In section 2 we shall give a brief summary of defect-mediated baryogenesis and define the relevant model-dependent quantities. In section 3 we consider baryogenesis in the Aspon model \[14\] and a supersymmetric (SUSY) model with an extra \( U(1) \) symmetry\[15\]. Section four describes how the scenario is realized in a model with a discrete family symmetry\[16\] and in section 5 we conclude.
2 Defect-Mediated Electroweak Baryogenesis

It has recently been shown that topological defects produced at scales above the weak scale may restore the electroweak symmetry out to some distance $R_s$ around their core\cite{17}-\cite{19}. Since the electroweak Higgs vacuum expectation value (VEV) is zero in this region we expect that just after the weak phase transition baryon number violating processes will be unsuppressed in the symmetric phase.

Shortly after the electroweak phase transition the evolution of the defect network leads to a departure from thermal equilibrium in the walls of the defects in the same manner as the motion of phase boundaries in other mechanisms. Sufficient CP violation also occurs in the walls. This is assumed, as in other models to come from an extended Higgs sector. Thus all three Sakharov conditions are satisfied.

The final baryon to entropy ratio produced by such a scenario may be written as

$$\frac{n_b}{s} = \frac{n_b^{(0)}}{s}(1 - e^{-Q})(SF)$$

(2)

where $n_b^{(0)}/s$ is the baryon to entropy ratio produced by a comparable bubble wall mechanism, $Q$ is a factor connected with the competing effects from different sides of the defect and $(SF)$ given by

$$(SF) = \left(\frac{V_{BG}}{V}\right)$$

(3)

is the volume suppression factor. This is the fraction of space swept out by the defect network.

The factor $Q$ is dependent only on the type of baryogenesis considered: local, where baryon number violation and CP violation take place at the same spacetime point or nonlocal, where the two act in different regions; CP violation leads to asymmetries in quantum numbers other than baryon number on the wall and these are then converted into baryon number in the larger region of symmetry restoration. We
shall comment briefly on this later. However, (SF) is dependent on the geometry of
the defects formed and their evolution. This must be evaluated separately in each
model.

3 Models with TeV Scale Cosmic Strings

The particle physics literature contains many examples which admit linear topological
defects - cosmic strings - some occurring at or around the TeV scale. Here we shall
give two examples and an estimate of the baryon to entropy ratio which they may
produce.

3.1 The Aspon Model

The Aspon model\[14\] is intended as a resolution of the strong CP problem of the stan-
dard strong and electroweak theory. In Quantum Chromodynamics (QCD) instanton
effects induce CP violating interactions. These effects contribute to the electric dipole
moment of the neutron by an amount which disagrees with experiment unless the di-

dimensionless parameter $\theta$ which measures their strength is kept small or zero.

The Aspon model achieves this by extending the gauge group of the standard
model by a new $U(1)$ symmetry. This leads to CP being a symmetry of the La-
grangian. The $U(1)_{\text{new}}$ symmetry is then required to be broken at a scale $\eta$. Thus
the symmetry breaking scheme is

\[
SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{\text{new}} \xrightarrow{n} SU(3)_c \times SU(2)_L \times U(1)_Y \xrightarrow{\text{new}} SU(3)_c \times U(1)_{\text{em}}
\]

(4)

(c.f. equation 1).

In addition to the particle content of the standard model (with a two-Higgs struc-
ture for extra CP violation in the Higgs sector) the simplest example contains two
vectorlike quarks and two Higgs scalars $\chi_1, \chi_2$, singlets under the standard model
gauge group, which break the $U(1)_{\text{new}}$. Two such fields are required so that the phase
$\theta$ which is adjusted to solve the strong CP problem cannot be rotated away by a
gauge transformation.

It is assumed that these scalars get VEV’s

$$
\langle \chi_1 \rangle = \frac{1}{\sqrt{2}} \kappa_1 e^{i\theta} \quad \langle \chi_2 \rangle = \frac{1}{\sqrt{2}} \kappa_2
$$

(5)

In order to obtain a simultaneous fit to weak and strong CP phenomenology it is
required that

$$
\kappa < 2 \text{ TeV}
$$

(6)

where $\kappa^2 \equiv \kappa_1^2 + \kappa_2^2$. Thus the extra symmetry $U(1)_{\text{new}}$ is broken at a scale $\eta \sim \text{1 TeV}$
and cosmic strings are produced. After the electroweak phase transition the electroweak symmetry remains restored around these objects. Note that since the extra
sector is fitted to weak CP data we expect to need an additional source of CP violation
in the standard model Higgs sector to implement baryogenesis.

3.2 Supersymmetry with an Extra $U(1)$

The particular supersymmetric model we consider[15] is proposed as a solution to the
$\mu$-problem of the minimal supersymmetric standard model (MSSM) and the cosmological solar neutrino problem.

In the MSSM there exists a supersymmetric Higgs mixing term of the form

$$
\mathcal{L}_\mu = \mu \tilde{H}H
$$

(7)
In order to obtain radiative SUSY breaking at the weak scale it is necessary that 
\( \mu \sim \mathcal{O}(G_F^{-1/2}) \) where \( G_F \) is the Fermi constant. However, there is no natural scale in 
the MSSM to ensure that this is the case.

In the model under consideration the MSSM is supplemented by two \( U(1) \) sym-
metries. One of the extra \( U(1) \)’s breaks at a high scale (\( \sim 10^{15}\)GeV) and is concerned 
with the implementation of the MSW\([20] \) solution of the solar neutrino problem via 
the seesaw mechanism. We shall not discuss this further. The \( \mu \)-term in this model 
is given in terms of a Yukawa coupling \( \lambda' \) and a scalar \( S \) which is a singlet under the 
standard model gauge group but charged under the low energy extra \( U(1) \). Thus the 
term (7) is forbidden and in its place we have a term

\[
\mathcal{L}_\mu = \lambda' S \bar{H} H
\]

Therefore if the low energy \( U(1) \) breaks at a scale \( \eta \) of the order of 1TeV then \( S \) gets 
a VEV of this order and the \( \mu \)-problem is resolved.

Thus the symmetry breaking scheme of the model is

\[
SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1) \times U(1) \quad \rightarrow \quad SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1) \\
\quad \xrightarrow{\eta} \quad SU(3)_c \times SU(2)_L \times U(1)_Y \\
\quad \xrightarrow{\eta_{EW}} \quad SU(3)_c \times U(1)_{em}
\]

Clearly we obtain TeV scale cosmic strings from this final \( U(1) \) breaking.

3.3 Cosmic Strings and Electroweak Baryogenesis

Both models described above give rise to cosmic strings with a mass per unit length 
of \( \mathcal{O}(1TeV^2) \). Now, a string with mass per unit length \( \mu \) remains in the friction 
dominated epoch until\([21] \) a time
\[ t^* = (G\mu)^{-1}t_c \]  

(10)

where \( t_c \) is the time of the defect-forming phase transition. For our strings the corresponding temperature is \( T^* = 10^{-3}\text{TeV} = 1\text{GeV} < \eta_{EW} \). Therefore the string network is still in the friction dominated era at the electroweak phase transition.

The contribution to the baryon asymmetry comes from both string loops and “infinite” strings. Let us focus on long strings, since in the friction dominated era most of the energy of the network is in this form. The suppression factor for long strings can easily be shown to be (see [13] for details)

\[ (SF) = \lambda v_D \left( \frac{\eta_{EW}}{\eta} \right)^{3/2} \]  

(11)

where \( \lambda \) is the standard model Higgs self-coupling and \( v_D \) is the velocity of the defect. If we assume one “infinite” string per correlation volume this yields

\[ (SF) \sim \frac{\lambda v_D}{30} \]  

(12)

for \( \eta \sim 1\text{TeV} \).

If we consider nonlocal baryogenesis then the final baryon to entropy ratio is given by (2) with \( n_b^{(0)}/s \) given by (see [22])

\[ \frac{n_b^{(0)}}{s} \sim 10^{-6}\kappa \Delta \theta y_\tau^2 v_D \]  

(13)

where \( 0.1 \leq \kappa \leq 1 \) is defined by \( \Gamma_B = \kappa(\alpha_W T)^4 \) with \( \Gamma_B \) the rate per unit volume of baryon number violating processes in the region of unbroken electroweak symmetry[23, 24]. Here \( \Delta \theta \) is a measure of the CP violation and \( y_\tau \) is the Yukawa coupling of the \( \tau \)-lepton, the scattering of which we have focussed on.

Thus this scenario can be compatible with the required nucleosynthesis value of \( n_b/s \sim 10^{-10} \).
4 Domain Walls from Family Symmetries

We shall consider particle physics models which attempt to explain the mass hierarchy in the standard model, in particular the large top quark mass, using discrete family symmetries\[16\].

In general the symmetry breaking scheme of such a model is

\[
SU(3)_c \times SU(2)_L \times U(1)_Y \times G \quad \rightarrow \quad SU(3)_c \times SU(2)_L \times U(1)_Y \times G^1 \\
\rightarrow \quad SU(3)_c \times SU(2)_L \times U(1)_Y \times G^2 \\
\vdots \\
\rightarrow \quad SU(3)_c \times SU(2)_L \times U(1)_Y \times G^n \\
\xrightarrow{\eta} \quad SU(3)_c \times SU(2)_L \times U(1)_Y \\
\xrightarrow{\eta_{EW}} \quad SU(3)_c \times U(1)_{em}
\]

(14)

where \( G \supset G^1 \supset G^2 \supset \cdots \supset G^n \) are nested discrete groups, the symmetry breakings between which lead to the generation of the mass hierarchy.

It is commonly assumed that these finite groups are gauged in the sense that \( G \) arises from the spontaneous breaking of a continuous group \( H \). This is necessary to protect the theory from the wormhole effects thought to plague global symmetries.

For definiteness let us concentrate on a specific example

\[
H = SU(2), \quad G = Q_6, \quad G^n = Z_6
\]

(15)

where \( Q_6 \) is the double dihedral group of order 12. We shall be interested only in the final discrete breaking in which \( Z_6 \) is broken completely giving tree level masses to the strange quark and the \( \mu \)-meson. This breaking occurs at the ubiquitous scale \( \eta \sim \mathcal{O}(1\text{TeV}) \) and produces cosmological domain walls. It is an important caveat that
we require that there be a mechanism to dispose of these walls after the electroweak phase transition so that they do not dominate the energy density of the universe.

Since we expect the electroweak symmetry to be restored around the TeV domain walls produced by the above theory it is simple to estimate the final baryon asymmetry expected to be produced by their evolution.

Consider the effect of "infinite" domain walls. Then the suppression factor \((SF)\) is given by (see [13])

\[
(SF) \sim \mathcal{O}(1)v_D
\]  \hspace{1cm} (16)

Thus, using (2) and estimates for \(n_b^{(0)}/s\) which may be \(10^{-8}\) or even smaller, the final baryon to entropy ratio can be compatible with observations.

5 Conclusions

We have discussed several specific particle physics models in which the criteria for defect-mediated electroweak baryogenesis are satisfied. Each model is an effective TeV theory with its own particle physics virtues.

Clearly there are more models which fulfill the requirements and the above are a small sample which we believe demonstrate the viability of the scenario.

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