Microphysics of Gauge Vortices and Baryogenesis∗

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Abstract

I give a brief overview of a novel mechanism for generating the baryon asymmetry of the universe at the electroweak scale. This scenario circumvents the need for a strongly first order electroweak phase transition by utilizing gauged topological solitons to realize the requisite departure from thermal equilibrium.

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I. INTRODUCTION

To a very good approximation, modern particle physics theories treat particles and their antiparticles in a symmetric manner. In particular this means that the physics describing the production, interactions and destruction of antimatter is the same as that describing the corresponding processes for matter. This fact is in stark contrast to terrestrial and cosmological observations which reveal that the universe appears to consist almost entirely of matter, with negligible antimatter on all scales up to the causal (Hubble) distance [1].

At a quantitative level, the outstanding success of the theory of primordial nucleosynthesis requires that

$$2 \times 10^{-10} < \eta \equiv \frac{n_b - n_{\bar{b}}}{s} < 7 \times 10^{-10},$$

where $n_b$ denotes the number density of baryons, $n_{\bar{b}}$ that of antibaryons and $s$ denotes the entropy density.

Electroweak baryogenesis is an attempt to understand how this number could have been dynamically generated at the electroweak scale, $\eta_{EW} \sim 10^2$ GeV, from baryon number symmetric initial conditions in the early universe (for a review and references see [2]). Here I present a brief overview of a variant of such a scenario in which a pivotal role is played by gauged topological solitons [4,5].

II. THE ELECTROWEAK THEORY AND SAKHAROV

Sakharov [3] identified the three necessary conditions for a particle physics model to produce a net baryon asymmetry. These are a violation of baryon number $(B)$ conservation, violations of charge conjugation $(C)$ and charge-parity $(CP)$ symmetries and a departure from thermal equilibrium. The electroweak theory includes all three ingredients. Baryon number is only violated nonperturbatively at the quantum level as a consequence of the anomaly [7]. The relevant process at zero temperature is an exponentially suppressed tunnelling under the energy barrier which separates inequivalent vacua in gauge and Higgs field configuration
space. However, at temperatures around or above the critical temperature of the electroweak phase transition (EWPT) thermal effects cause classical transitions over the barrier $\theta$. The standard electroweak theory is maximally $C$ violating due to the $V$-$A$ nature of the interactions. The only violation of $CP$ in the electroweak sector of the standard model occurs in the CKM matrix. Electroweak baryogenesis scenarios using this source of $CP$ violation are generally expected to produce a BAU which is far too small and so it is usual to consider extending the standard model to include new sources of $CP$ violation. Examples of extensions are the two-Higgs doublet model with explicit renormalizable $CP$ violating terms and effective theories of the standard model plus nonrenormalizable operators, some of which are $CP$ odd.

Finally, the departure from thermal equilibrium is typically achieved by assuming that the electroweak phase transition is strongly first order so that the violent conversion of the symmetric phase to the broken phase results in non-equilibrium conditions near the bubble walls separating the phases. In the minimal electroweak theory this assumption now appears unlikely to be true $\theta$ and here I present an alternative realization of the third Sakharov condition.

### III. ELECTROWEAK SYMMETRY RESTORATION AROUND VORTICES

The contents of this section can be extended to monopoles and domain walls. Here I restrict the discussion to cosmic strings and to a particular example $\theta$. Consider a local $U(1)$ cosmic string, formed at a scale $\eta > \eta_{EW}$, that couples to the electroweak model. Further, assume that the gauge fields corresponding to this higher symmetry scale acquire an extra mass at the electroweak scale. Let the string’s gauge field be $R_\mu$. The coupling between the string and the electroweak sector is through the covariant derivative

$$D_\mu \Phi = \left( \partial_\mu - \frac{1}{2} i g \tau^a W_\mu - \frac{1}{2} i g' B_\mu - \frac{1}{2} i g'' R_\mu \right) \Phi .$$

where $B_\mu$ is the hypercharge field and $W_\mu^a$ are the weak isospin fields. Since $\eta > \eta_{EW}$, we treat $R_\mu$ as a Nielsen-Olesen background. It can be shown the minimal energy is achieved when the electroweak symmetry is restored around the defect out to a radius
\[ R_s \sim \eta_{EW}^{-1}, \]  

up to couplings. A similar effect occurs around superconducting cosmic strings \[10,11\]. Within this symmetric electroweak region, \( B \) violating processes should not be exponentially suppressed.

**IV. DEFECT-MEDIATED ELECTROWEAK BARYOGENESIS**

The central idea is to compare the motion of the phase interfaces of an evolving network of cosmic strings with bubble walls at a first-order phase transition. Denote the baryon to entropy ratio produced by a bubble wall scenario by \( n_b^{(0)}/s \). This is generated when a wall passes points in space and false vacuum is converted to true. To compute the baryon asymmetry produced by strings, there are two principal effects to be taken into account.

First, there is an effect due to the geometry of the defects. Bubble walls sweep out the whole of space whereas a network of cosmic strings only sweeps out a volume \( V_{BG} \) in one Hubble time after the EWPT. This leads to a suppression factor \( \delta_1 \equiv V_{BG}/V \), where \( V \) is the total volume, compared to bubble wall baryogenesis. It turns out that only strings formed close to the electroweak scale yield a measurable asymmetry. In this case (\( \eta \) close to \( \eta_{EW} \)), the network is still in the friction-dominated epoch at the EWPT. For simplicity we focus on the contribution of long strings and assume one per correlation volume at the formation temperature, \( \eta \). Since the correlation length \( \xi \) obeys \[12\] \( \xi(\eta) \sim \eta^{-1} \) and \( \xi(T) \sim \xi(\eta)(\eta/T)^{5/2} \), we obtain

\[ \delta_1 \sim v \left( \frac{\eta_{EW}}{\eta} \right)^{3/2}, \]  

where \( v \) is the string velocity.

The second effect is due to cancellations between competing processes at the two faces of the string. The trailing edge of the defect behaves analogously to a bubble wall. In contrast, at the leading edge of the defect true vacuum is converted to false and in such a process \( CP \) violation works in the opposite way. Thus, at the leading edge antibaryons are produced.
However, cancellation is not complete. At the trailing edge the baryons remain “frozen” into the broken phase whereas at the leading edge the antibaryons spend the core passage time \( \tau = R_s/v \) in the symmetric phase where they can equilibrate to lower \( \mathcal{B} \) through anomalous processes. This leads to a further suppression factor

\[
\delta_2 \sim 1 - \exp(-\Gamma \tau) \sim \Gamma \tau ,
\]

(4.2)

where \( \Gamma \) is the rate of \( \mathcal{B} \) violating events.

Thus, the final baryon to entropy ratio produced by a network of cosmic strings produced not too far above the electroweak scale is

\[
\frac{n_b}{s} = \frac{n_b^{(0)}}{s} \delta_1 \delta_2 .
\]

(4.3)

Since bubble wall calculations can give \( n_b^{(0)}/s \sim 10^{-6} - 10^{-8} \), choosing \( \eta \sim 1\text{TeV} \) can yield a number consistent with the requirements of nucleosynthesis. It is interesting to note that particle physics models giving rise to such strings (and other solitons) at the TeV scale exist in a number of places in the literature [5].

\textbf{V. CONCLUSIONS}

If the electroweak phase transition is not strongly first order, traditional scenarios for electroweak baryogenesis seem unlikely to succeed. In that case, an alternative realization of the third Sakharov condition is necessary. Gauged topological solitons, in particular cosmic strings, can provide such a realization due to the restoration of the electroweak symmetry around their cores. The final baryon to entropy ratio generated in such models is suppressed relative to bubble scenarios but for strings formed at the TeV scale and optimistic parameter choices an acceptable asymmetry can still result. The group structure necessary to produce such TeV defects is present in some popular particle physics models and, if uncovered in accelerator experiments, would imply the cosmological existence of the required gauge solitons.
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