Preprint BROWN-HET-1022, CLNS 95/1368, MIT-CTP-2485 (1995)

hep-ph/9511349, November 1995

Dynamical Breaking of CPT Symmetry in Defect Networks and Baryogenesis

Tomislav Prokopec[1]

Newman Laboratory for Nuclear Studies, Cornell University, Ithaca NY 14853, USA

Robert Brandenberger[2]

Physics Department, Brown University, Providence RI 02912, USA

Anne C. Davis[3]

D.A.M.T.P., Silver Street, Cambridge University, Cambridge CB3 9EW, UK

and

Mark Trodden[4]

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge MA 02139, USA

[1]e-mail: tomislav@hepth.cornell.edu
[2]e-mail: rhb@het.brown.edu
[3]e-mail: A.C.Davis@damtp.cam.ac.uk
[4]e-mail: trodden@ctpa04.mit.edu

Abstract

Based on a study of *charge,* (C), *parity* (P) and *time reversal* (T) symmetries we show how a CP violating network of defects in the early Universe may bias baryon number production. A static network, even though it violates CP, respects CPT and hence does not bias baryon number production. On the other hand, the *ordering dynamics* of defects in a network, governed by the interplay of string tension, friction, inertia and the expansion of the Universe, results in the dynamical breakdown of CPT symmetry and may lead to a net baryon number production.

1. Introduction

In Ref. [1] (see also Refs. [2] and [3]) we proposed an alternative electroweak scale baryogenesis mechanism which does not require the electroweak phase transition to be first order, but which instead makes essential use of the nontrivial dynamics of CP violating cosmological defect networks. The crucial third Sakharov condition for baryogenesis, the departure from thermal equilibrium, is achieved by the out-of-equilibrium motion of the defects through the plasma in the expanding Universe. Some of the issues related to CP and CPT violation were only touched on in Ref. [1]. The main goal of this letter is to clarify these issues.

In Ref. [1] we assumed that at the time of the electroweak phase transition there is a network of defects (e.g. cosmic strings) which were produced at an energy scale slightly higher than the electroweak scale and in the cores of which the electroweak symmetry is unbroken (for some concrete models see e.g. Ref. [4]). As the defects move through the primordial plasma, a nonvanishing net baryon number can be generated. As in many of the other electroweak baryogenesis mechanisms based on critical bubbles produced in a first order phase transition generating a net baryon number (see e.g. Refs. [5, 6]), we assume that there is extra CP violation in the Higgs sector (requiring us to consider extensions of the minimal standard model). In analogy to how the CP violating phase changes when a bubble wall passes over a point p in space, generating a net baryon number density at p, baryons will be generated when a wall of a topological defect! ! passes over p. More precisely, in the case of local baryogenesis, antibaryons will be generated when p enters the defect (because the CP violating phase changes in opposite direction to what happens when p changes from being in the false to being in the true vacuum), and an equal number of baryons are generated when p exits the defect. However, inside the defect the antibaryons are converted to leptons *via* sphaleron processes (since the latter are un-suppressed inside the defects as long as the defects are sufficiently thick), and therefore the net result of the dynamics is to produce a nonvanishing baryon number density. Obviously, both diffusion and the expansion of the Universe (without which there would be no defect network) play a crucial role in this mechanism. We have for simplicity described a local baryogenesis scenario in which CP violation and baryogenesis occur at the same spatial point. A similar description holds for non-local baryogenesis scenarios.

It will be seen that our mechanism is closely related (with notable differences which will become clear in the course of the letter) to the idea of *spontaneous baryogenesis* of Ref. [7] which asserts that if there is a field – named by the authors the *ilion* – in the early Universe which couples to the baryonic current, then either the expansion of the Universe alone or a potential for this field could cause it to evolve in a non-trivial manner, thus biasing baryon number production.

Dine *et al* [8] and Cohen, Kaplan and Nelson [9] realized that a CP violating relative Higgs phase θ of a two Higgs doublet model may 'play the role' of the ilion field. There are, however, notable differences: the phase θ couples *via* a derivative coupling to an axial current j_5^μ so that the effective Lagrangian containing a term $\propto (\partial_\mu \theta) j_5^\mu$ is CPT conserving. Nevertheless, CPT is violated *dynamically*. As the Universe super-cools in the false symmetric phase, critical bubbles of 'true' vacuum nucleate and grow driven by the release of latent heat. This bubble growth is the mechanism for dynamical violation of CPT symmetry and a net baryon number may be created. (The CPT transformed situation would comprise collapsing bubbles, which is clearly thermodynamically forbidden.)

In this letter we will show that the mechanism of Ref. [1] is an alternative way to obtain dynamical CPT violation, based on the ordering dynamics of defect networks and hence it is a realization of the original idea of spontaneous baryogenesis. Our case, however, is slightly more complicated than the original scenario in that the net change in θ vanishes.

2. Is there a CPT Paradox?

Let us review the mechanism of Ref. [1] in a bit more detail. The first assumption is that cosmic strings are produced at a phase transition above the electroweak scale, *i.e.* at an energy scale T_{CS} which satisfies $T_{CS} > T_{ew} \simeq 100\text{GeV}$, but which is not too high so that by the time of the electroweak phase transition the strings are not too diluted. Some particle physics models in which this mechanism can be implemented are discussed in Ref. [4]. Another candidate model is one in which the supersymmetric grand unified phase transition occurs (as a consequence of the presence of flat directions in the grand-unified Higgs potential) at around $T \sim 1\text{TeV}$ [10], [11]. We also need to assume that after the electroweak phase transition the electroweak symmetry $SU(2)_L \times U(1)_Y$ is preserved in the core of the strings, *i.e.* the electroweak Higgs expectation value vanishes. If there is extra CP violation in the theory, realized through *e.g.* explicit CP violation in the Higgs sector of a two Higgs doublet model, the CP violating relative Higgs phase θ will change across the string in a definite manner, just like in the case of bubble growth in a first order phase transition [12], [9], [13]. In this case strings are not CP invariant field configurations and the CP conjugate configurations are not solutions to the field equations. They would thus have a much higher energy. That is how the explicit CP violation in the Higgs sector is manifest in a string network. In this respect the 'ground state' is CP violating. Analogous investigations apply to domain walls and monopoles. However, monopoles lead to a large volume suppression factor for electroweak baryogenesis. Domain walls, although they would be more effective than cosmic strings from a geometric point of view (more volume in which baryogenesis can take place) suffer from the problem of energy dominance: unless one invokes as a remedy *e.g.* additional symmetry breaking that would destroy them, they would eventually dominate the energy density of the Universe. Cosmic strings, on the other hand, since they reach a scaling solution do not suffer from this problem. Note that the arguments we will present here concerning the basic baryogenesis mechanism are general in the sense that they apply to any defect network.

The CP violating relative Higgs phase θ changes across the core of the string (this is for example worked out for a spherical bubble in Ref. [13]). If we set it to *zero* outside the string it acquires a definite sign on the wall and in the core of the string, say $\theta \geq 0$ everywhere. The length over which θ varies, which specifies the thickness of the 'wall' and core size L of the defect, is given by the electroweak scale but is somewhat model dependent. Provided L is sufficiently large to accommodate the sphaleron of typical size $(g_w^2 T)^{-1}$, *i.e.* $L > (g_w^2 T)^{-1}$, it is plausible that the sphaleron rate is un-suppressed in the core of the string [14]. In this case, the rate of sphaleron transitions per unit volume is given by $\Gamma_{sph}/V = \kappa_{sph}(\alpha_w T)^4$, $\kappa_{sph} \sim 1$ [15], and the standard baryogenesis mechanism will apply [16, 17, 18, 19, 20].

A static string configuration is not CP invariant. The phase θ has the following transformation properties: it is even under parity (P), odd under charge conjugation (C) and odd under time reversal (T), so that under CP $\theta(x,t) \to -\theta(-x,t)$ and under T $\theta(x,t) \to -\theta(x,-t)$, and thus under CPT $\theta(x,t) \to \theta(-x,-t)$. Hence $\partial_\mu \theta$ is odd under CPT. (Note that $\partial_\mu \theta$ transforms as a vector field.)

How the string interacts with the plasma can be modeled by a term in Lagrangian of the form

$$\mathcal{L}_\theta \propto (\partial_\mu \theta) j_5^\mu \tag{1}$$

where $j_5^\mu = \bar{\Psi}\gamma^\mu\gamma_5\Psi$ is the axial current. This term can be obtained by a specific local rotation of fermions with rotation angle proportional to θ. (For the exact form of (1) in a two Higgs doublet model see [19].)

The axial current transforms under CPT as $j_5^\mu(x^\nu) \to -j_5^\mu(-x^\nu)$ so that the Lagrangian (1) is invariant under CPT as it should be. We conclude that a static string under CPT transformation transforms into itself, and hence can be considered to be its own 'anti-particle'.

We will now relate this conclusion to the CPT theorem. Recall that the CPT theorem states that any Lorentz invariant Lagrangian $\mathcal{L}(x)$ transforms under CPT into $\mathcal{L}^\dagger(-x)$ and hence, if hermitean, $\mathcal{L}$ is invariant under CPT [22]. A consequence of this theorem is that any stable configuration must be either its own 'anti-particle' or have an 'anti-particle' of exactly the same energy. Since defects are not CP eigenstates, the anti-defects have larger energy, hence they must be their own 'anti-particles'. Indeed, under CPT a static string transforms into itself. This is in agreement with the conclusion we have reached above. We have now established CPT invariance of a static defect network and its consistency with the CPT theorem.

How is it then possible that one gets any baryogenesis from defects? If a string moving in one direction produces a net number of baryons, then it seems that based on the CPT theorem the same string moving in the opposite direction should produce the same number of antibaryons. But our microphysical mechanism of baryogenesis is independent of the direction of motion of the string. In the rest of the paper we will argue that this apparent CPT paradox can be resolved taking into account the dynamics of the string network.

3. Resolution

For a static string there is no paradox: by the CPT theorem a static string as its own 'antiparticle' cannot generate a net baryon number. The same conclusion holds for a moving string in the absence of dissipation: the baryon density induced at the trailing edge of the defect exactly cancels the antibaryon density induced at the leading edge. As we will now see a net baryon number density results only if dissipation is effective.

As argued in [1], a moving string drives plasma out of equilibrium through coupling to the plasma *via* a term of the form (1). Thermal equilibrium is restored through dissipative processes in the plasma, an example being the biased sphaleron process

$$\dot{n}_B \propto -\Gamma_{sph}\mu_B, \tag{2}$$

where Γ_{sph} is the sphaleron rate, n_B, μ_B are baryon number density and the corresponding chemical potential. These processes all violate *time reversal* symmetry (T) and since they conserve CP, CPT is violated. This dynamical CPT violation should not surprise us too much: both when there is a surplus of particles over anti-particles and *vice versa* (CPT conjugate case), the out of equilibrium processes such as (2) will tend to restore a thermal equilibrium with equal numbers of particles and antiparticles. This out-of-equilibrium dissipative CPT violation makes the crucial difference between static and moving strings: *moving strings induce an effective CPT symmetry violation* analogous to the effective CPT violation induced by the dynamics of the *ilion* field of Ref. [7].

We will now describe a non-local baryogenesis scenario which, when compared with local baryogenesis scenarios, typically dominates baryon production. For *thick-walled* defects, for which particles scatter typically many times as they move across the phase boundary (wall), due to imperfect transport and finite decay time, the field $\partial_\mu\theta$ (sometimes called 'charged potential') will not be perfectly screened. In the case of *thin-walled* defects for which the scattering length exceeds the phase boundary thickness, a coherent quantum mechanical reflection will take place and source axial current in the vicinity of the defect; transport and decays will determine the destiny of this current, *e.g.* how it thermalises. One can show that under rather weak conditions (essentially sub-sonic velocity of the string is the necessary and sufficient condition), for both thin- and thick-walled defects, a diffusion tail of particle *minus* anti-particle excess forms in front of both the trailing and the front edges of a moving defect. The excess that overlaps the string core biases baryogenesis since in the core the sphaleron rate is un-suppressed, while the excess in front of the defect has no effect. We will now consider some of the aspects of this model related to symmetry conservation/violation.

Consider a segment of a string moving through the plasma which was set into motion by some initial kick. According to [1], the string leaves a trail of baryons in its wake. But also it slows down due to the friction force that plasma exerts and eventually stops. Hence, baryon production also stops. This process can be viewed as follows: a force that put the string in motion must be of non-equilibrium origin; the string then approaches equilibrium as it slows down. There is no contradiction since baryons are produced out of equilibrium. The key question now becomes: *What is the force that constantly kicks the strings in the early Universe?*

4. Out of Thermal Equilibrium

Strings are formed at a phase transition above the electroweak scale. The strings are a measure of the deviation of the field configuration from being in perfect thermal equilibrium. In the hypothetical limit of infinite transition time, no strings would remain. Immediately after the transition, the ordering dynamics is governed mostly by the string tension, inertia and friction; the expansion of the Universe is irrelevant. This initial stage is called friction-dominated regime. As the Universe expands, the friction decreases (since the plasma density is redshifted). Also, the long strings that typically traverse many horizons are stretched. Eventually, the expansion of the Universe becomes a more important 'damping force' for network dynamics than the friction, and the network enters the so called scaling regime in which the mean separation of strings remains proportional to the Hubble radius [23].

In both regimes strings are evolving out of equilibrium. Moving strings drive the surrounding plasma out of equilibrium. This ordering dynamics of string straightening never stops in an expanding Universe simply because the correlation length keeps growing. Correlations in the phases of the scalar field are established through dissipative processes like string intercommutation and string loop decay into gravitational radiation. The expansion of the Universe is hence crucial because *it keeps the network out of thermal equilibrium when it reaches a scaling regime.* In addition it cools down the Universe and hence provides the arrow of time.

Another way to demonstrate the out-of-equilibrium nature of the defect network dynamics is to consider what happens to a distribution of strings in the scaling regime if we suddenly let the Universe contract. On scales smaller than the Hubble radius at the time when the contraction starts, the phase coherence will be maintained. Hence, the final string configuration at the end of the contraction will be different from the initial configuration at the beginning of the expansion (assuming that the scale factor of the Universe at these two times is the same).

What about thermal fluctuations? Thermal excitations may generate string loops (that decay quickly). Since these loops are equilibrium configurations, there is no meaningful definition of time arrow and hence no dissipation and time reversal violation which are necessary for net baryon production. Indeed these thermal loops cannot excite net axial current and therefore no baryogenesis is possible.

5. Conclusions

We have argued that any network of defects dynamically breaks CPT symmetry. When these defects couple to the left handed fermion current or in fact any current that is not orthogonal to it (an example is the axial current in (1) which can be decomposed into the left-handed and right-handed fermion currents) in a CP violating manner (*via* a CP violating field as in (1)), and when in motion, they may bias baryon number production *via* the sphaleron processes in the core of defects.

We now compare this mechanism with the most popular model of electroweak baryogenesis in which baryon production occurs at a first order electroweak phase transition: on or around the phase boundary of a growing bubble axial currents are induced, driving fermions in the plasma out of equilibrium; and the bubbles expand due to release of latent heat. The motion of cosmic strings, on the other hand, is generated by the string tension and by the expansion of the Universe, both of which tend to straighten them. The dynamics is intrinsically out-of-equilibrium and does not approach an equilibrium configuration, at least on scales larger or equal to the string correlation length.

In conclusion, *when at a phase transition CP violating defects are produced,* ordering dynamics *drives the system out of equilibrium locally, leading to dynamical CPT violation. In conjunction with CP violation this biases* *baryon number production.*

Acknowledgments

The research of RB is funded in part by DOE Grant DE-FG02-91ER40688-Task A, that of AD by PPARC, TP acknowledges funding from PPARC and NSF, and MT is supported in part by funds provided by the US Department of Energy (D.O.E.) under cooperative research agreement #DF-FC02-94ER40818. We thank Michael Joyce, David Lyth and Neil Turok for useful discussions.

References

[1] R. Brandenberger, A. C. Davis, T. Prokopec, and M. Trodden, BROWN-HET-962, DAMTP 94-72, PUPT-94-1497 (Sep 1994), hep-ph/9409281.

[2] R. Brandenberger, A.-C. Davis and M. Trodden, *Phys. Lett.* **B335**, 123 (1994).

[3] R. Brandenberger and A. Davis, *Phys. Lett.* **B308**, 79 (1993).

[4] M. Trodden, A.-C. Davis and R. Brandenberger, *Phys. Lett.* **B349**, 131 (1995).

[5] N. Turok, in 'Perspectives on Higgs Physics', ed. G. Kane (World Scientific, Singapore, 1992).

[6] A. Cohen, D. Kaplan and A. Nelson, *Ann. Rev. Nucl. Part. Sci.* **43**, 27 (1993).

[7] A. Cohen and D. Kaplan, *Phys. Lett.* **B199**, 251 (1987); A. Cohen and D. Kaplan, *Nucl. Phys.* **B308**, 913 (1988).

[8] M. Dine, P. Huet, R. Singleton and L. Susskind, *Phys. Lett.* **B257**, 351 (1991).

[9] A. Cohen, D. Kaplan and A. Nelson, *Phys. Lett.* **B263**, 86 (1991).

[10] David H. Lyth, Ewan D. Stewart, LANCASTER-TH-9505, Sep 1995, hep-ph/9510204; *Phys. Rev. Lett.* **75** 201 (1995), hep-ph/9502417, and references therein.

[11] T. Barriero, E. J. Copeland, D. H. Lyth, T. Prokopec, work in progress

[12] N. Turok and T. Zadrozny, *Phys. Rev. Lett.* **65**, 2331 (1990); N. Turok and J. Zadrozny, *Nucl. Phys.* **B358**, 471 (1991); L. McLerran, M. Shaposhnikov, N. Turok and M. Voloshin, *Phys. Lett.* **B256**, 451 (1991)

[13] J. M. Cline, K. Kainulainen, and A. P. Vischer, Preprint McGill/95-16, CERN-TH-95/136, UMN-TH-1343-94, hep-ph/9506284 (1995)

[14] W. B. Perkins, *Nucl. Phys.* **B449**, 265 (1995), hep-ph/9506345.

[15] J. Ambjorn, A. Krasnitz, NBI-HE-95-23, Aug 1995, hep-ph/9508202, and references therein.

[16] A. Cohen, D. Kaplan and A. Nelson, *Phys. Lett.* **B245**, 561 (1990); A. Cohen, D. Kaplan and A. Nelson, *Nucl. Phys.* **B349**, 727 (1991); A. Nelson, D. Kaplan and A. Cohen, *Nucl. Phys.* **B373**, 453 (1992).

[17] M. Joyce, T. Prokopec and N. Turok, *Phys. Lett.* **B338**, 269-275 (1994), hep-ph/9401352.

[18] A. Cohen, D. Kaplan and A. Nelson, *Phys. Lett.* **B336**, 41 (1994), hep-ph/9406345.

[19] M. Joyce, T. Prokopec and N. Turok, Princeton preprint PUPT-94-1495 (1994), hep-ph/9410281, to be published in *Phys. Rev.* **D**

[20] M. Joyce, T. Prokopec and N. Turok, *Phys. Rev. Lett.* **75** 1695 (1995), hep-ph/9408339. M. Joyce, T. Prokopec and N. Turok, Princeton preprint PUPT-94-1496 (1994), hep-ph/9410282, to be published in *Phys. Rev.* **D**

[21] M. Joyce, T. Prokopec and N. Turok, *Phys. Lett.* **B 339**, 312 (1994), e-Print Archive: hep-ph/9401351.

[22] T.D. Lee, *Particle Physics and Introduction to Field Theory*, Published under license by Harwood Academic Press, Amsterdam (1988)

[23] A. Vilenkin and E.P.S. Shellard, "Cosmic Strings and Other Topological Defects" (Cambridge Univ. Press, Cambridge, 1994).