

Electroweak baryogenesis and hierarchy

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Abstract

We consider the scenario of electroweak baryogenesis mediated by cosmological defects in a model of extra dimension. We consider the domain wall on the brane in higher-dimensional theories. The electroweak breaking scale is suppressed and the sphaleron interaction is activated in the false vacuum.

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1 Introduction

Contrary to a naive cosmological expectation, all evidences suggest that the Universe contains an abundance of matter over antimatter. Electroweak baryogenesis is an attractive idea in which testable physics, present in the standard model of electroweak interactions and its modest extensions, is responsible for this fundamental cosmological datum. One may take the previous negative results as indication that the asymmetry in the baryon number was not created at the electroweak epoch, but rather related to the physics of $B - L$ violation and neutrino masses. To stick to electroweak baryogenesis one can consider extensions of the particle content of the model to get stronger electroweak phase transition. In general scenario for electroweak baryogenesis requires the co-existence of regions of large and small $\langle H/T \rangle$, where H denotes the Higgs field in the standard model. At small $\langle H/T \rangle$, sphalerons are unsuppressed and mediate baryon number violation while large $\langle H/T \rangle$ is needed to store the created baryon number. Below the critical temperature T_c^{EW} of the electroweak phase transition, $\langle H/T \rangle$ grows until sphalerons are shut-off. For electroweak baryogenesis to be possible, one needs some specific regions where $\langle H \rangle$ is displaced from the equilibrium value.

The idea we point out in this letter is that this can happen along topological defects left over from some other cosmological phase transitions that took place before the electroweak phase transition[1]. If the electroweak symmetry breaking scale is suppressed in some regions around cosmological defects, sphalerons could be activated in such regions while they would be suppressed in the other part of space. The motion of the defect network, in a similar way as the motion of string surface in the usual defect-mediate scenario[1], will leave a net baryon number behind the moving surface and then the baryon asymmetry will be kept in the sphaleron-suppressed true vacuum. We find that a new type of defect-mediated electroweak baryogenesis is possible when the radion is stabilized by the Goldberger-Wise mechanism[2]. The mechanism for baryon number production at the phase boundary is the same as the conventional defect-mediated electroweak baryogenesis. The electroweak phase transition itself is not required to be first order, which is the same characteristic of the conventional defect-mediated electroweak baryogenesis. The strings-mediated electroweak baryogenesis is critically analyzed in ref.[3] and the baryon number

production by strings is proved to be too small. The critical point in ref.[3] is that the baryon number violation in the string core is too slow since the region where electroweak symmetry is restored is never wide enough to allow sufficient sphaleron events. Such suppression does not appear in our case, which makes it possible to expect the generation of the observed baryon number by defect-mediated electroweak baryogenesis.

2 Defect-mediated electroweak baryogenesis in GW model

When the hierarchy is determined by the typical length scales of the extra dimensions, there must be some mechanisms that ensure the stability of such scales. If the mechanism for the stability is affected by the defects on the brane or in the bulk, the defects may induce the displacement of the electroweak scale in the defect core or in the false vacuum, resulting in the same mechanism discussed in ref.[1].

Here we examine an attractive model proposed by Goldberger and Wise[2] for giving the radion a potential energy to stabilize the length scale. They introduced a bulk scalar field with different VEV's, v_0 and v_1 , on two branes. If the mass m of the scalar is small compared to the scale k which appears in the warp factor e^{-ky} , then it is possible to obtain the desired interbrane separation and one finds the relation $e^{-ky} \simeq (v_1/v_0)^{4k^2/m^2}$. They added to the model a scalar field Φ with the following bulk action

$$S_b = \frac{1}{2} \int d^4x \int_{-\pi}^{\pi} d\phi \sqrt{G} \left(G^{AB} \partial_A \Phi \partial_B \Phi - m^2 \Phi^2 \right), \quad (2.1)$$

where G_{AB} with $A, B = \mu, \phi$ is given by[4]

$$d^2s = e^{2kr_c|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2. \quad (2.2)$$

They also included interaction terms on the hidden and visible branes (at $\phi = 0$ and $\phi = \pi$ respectively) given by

$$S_h = - \int d^4x \sqrt{-g_h} \lambda_h \left(\Phi^2 - v_h^2 \right)^2, \quad (2.3)$$

and

$$S_v = - \int d^4x \sqrt{-g_v} \lambda_v \left(\Phi^2 - v_v^2 \right)^2, \quad (2.4)$$

where g_h and g_v are the determinants of the induced metric on the hidden and visible branes respectively. The terms on the branes cause Φ to develop a ϕ -dependent vacuum expectation value $\Phi(\phi)$ which is determined classically by solving the differential equation

$$0 = -\frac{1}{r_c^2} \partial_\phi \left(e^{-4\sigma} \partial_\phi \Phi \right) + m^2 e^{-4\sigma} \Phi + 4e^{-4\sigma} \lambda_v \Phi \left(\Phi^2 - v_v^2 \right) \frac{\delta(\phi - \pi)}{r_c} + 4e^{-4\sigma} \lambda_h \Phi \left(\Phi^2 - v_h^2 \right) \frac{\delta(\phi)}{r_c}, \quad (2.5)$$

where $\sigma(\phi) = kr_c|\phi|$. Away from the boundaries at $\phi = 0, \pi$, this equation has the general solution

$$\Phi(\phi) = e^{2\sigma} [Ae^{\nu\sigma} + Be^{-\nu\sigma}], \quad (2.6)$$

with $\nu = \sqrt{4 + m^2/k^2}$. Putting this solution back into the scalar field action and integrating over ϕ yields an effective four-dimensional potential for r_c . Then the unknown coefficients A and B are determined by imposing appropriate boundary conditions on the 3-branes. They considered the simplified case in which the parameters λ_h and λ_v are large, and supposing that $m/k \ll 1$, and neglecting the subleading powers of $\exp(-kr_c\phi)$, then obtained the potential as

$$V_\Phi(r_c) = k\epsilon v_h^2 + 4ke^{-4kr_c\pi} (v_v - v_h e^{-\epsilon kr_c\pi})^2 \left(1 + \frac{\epsilon}{4} \right) - k\epsilon v_h e^{-(4+\epsilon)kr_c\pi} (2v_v - v_h e^{-\epsilon kr_c\pi}) \quad (2.7)$$

where terms of order ϵ^2 are neglected. If one ignores the terms proportional to ϵ , this potential has a minimum at

$$kr_c = \left(\frac{4}{\pi} \right) \frac{k^2}{m^2} \ln \left[\frac{v_h}{v_v} \right]. \quad (2.8)$$

With $\ln(v_h/v_v)$ of order unity, one only needs m^2/k^2 of order 1/10 to get $kr_c \sim 10$.

In this limit, it is energetically favorable to have $\Phi(0) = v_h$ and $\Phi(\pi) = v_v$. The configuration that has both VEVs of the same sign has lower energy than the one with alternating signs, and therefore corresponds to the ground state.

Then a question arises: “*What happens if the vacuum with alternating signs is also produced at an early stage of the Universe?*” Then from eq.(2.7), one can easily find that each term in the effective potential has the same positive sign and it looks like a runaway potential for such an unstable configuration. From eq.(2.3) and eq.(2.4), one may think that there are discrete symmetries $Z_2^h \times Z_2^v$. ($Z_2^h: \Phi(0) = v_h \leftrightarrow \Phi(0) = -v_h$ (Z_2^h) and $Z_2^v: \Phi(\pi) = v_v \leftrightarrow \Phi(\pi) = -v_v$ (Z_2^v)). This symmetry is, however, explicitly broken by the

interaction terms and only a discrete symmetry Z'_2 , which corresponds to the simultaneous flip is left. (See also eq.(2.7) and ref.[2].) In the conventional case, the potential in the hidden brane is so high that one can assume $\Phi(0) = v_h$. In this case the domain wall is induced by v_v . The explicit breaking term is explicitly given in eq.(2.7). Substituting v_v by $-v_v$, one can find the false vacuum potential for r_c . In general, an instability of the vacuum is a problem if the vacuum is the true vacuum or it dominates the whole universe. However, in our paper the unstable vacuum is a false vacuum which appears in the universe as the bubble surrounded by the true vacuum. In this case, the unstable false vacua disappears before they become harmful. What we should be concerned about is the local behaviour of the effective theory around the phase boundary. In the true vacuum the positioning of the brane is not altered. In the false vacuum, the positioning of the brane is altered to make the brane distance larger than the true vacuum. At the temperature near the electroweak phase transition, the symmetry restoration can be induced by the small shift of the effective electroweak scale. In this respect, the phase boundary becomes much thinner than the background wall configuration because of its exponential dependence on the brane distance. What we should be concerned about is the higgs profile which induces the flux in front of the phase boundary, since it controls the electroweak baryogenesis. The domain wall that interpolates the vacuum with $\Phi(\pi) = v_v$ and $\Phi(\pi) = -v_v$ at the visible brane (or possibly $\Phi(0) = v_h$ and $\Phi(0) = -v_h$ at the hidden brane) is nothing but the commonly known Z_2 domain wall with explicit breaking of Z_2 symmetry in the effective four dimensional theory.

For electroweak baryogenesis to be possible, as we have noted, one needs some specific region where Higgs vacuum expectation value $\langle H \rangle$ is displaced from the equilibrium value. Here the difference of the warp factor is expected to induce the difference of the electroweak scale in the local region. Now we consider the case where the electroweak symmetry breaking scale is suppressed in the false vacuum. Then sphaleron interactions are activated in this restricted area while they are suppressed in the bulk of space when $T < T_{EW}$. The motion of the defect network, in a similar way as the motion of bubble walls in the usual strongly first order phase transition scenario, will leave a net baryon number behind the moving surface and then the baryon asymmetry will be kept in the sphaleron-suppressed regions. Although the defect should have a long tail toward the runaway

direction, the typical length scale that is relevant for the electroweak baryogenesis is determined by the radion mass at the phase boundary, which is larger than the Higgs mass. In this sense, the changes in the effective electroweak scale induced by the background defect configuration is steep so that the thin wall approximation is possible when one considers the electroweak baryogenesis. The mechanism for baryon number production is the same as the conventional defect-mediated electroweak baryogenesis. The electroweak phase transition itself is not required to be first order, which is the same characteristic of the conventional defect-mediated electroweak baryogenesis. Thus we conclude that the scenario is a possible candidate for generating sufficient BAU.

Here we also mention the collapsing mechanism for the cosmological domain wall. When the collapse is induced by the energy difference ϵ which is induced by the explicit breaking of Z_2 symmetry, one can add extra components in the bulk to adjust ϵ to a suitable value. Another mechanism is the biased domain wall[7], whose decaying process is determined by cosmology, and may (or may not) be adjusted to produce the suitable domain wall structure.

What we are considering is the electroweak baryogenesis, in which the the flux is injected by the phase boundary into the unbroken phase and it induces the baryon asymmetry near the phase boundary in the unbroken phase. Then the produced baryons are trapped in the broken phase. In this respect, the mechanism of our model is similar to the conventional mechanism for electroweak baryogenesis. The efficiency of the mechanism is determined by the higgs profile in the phase boundary. In our case the phase boundary is thin and the magnitude of the injected flux is determined by the CP phase and the vacuum expectation value of the Higgs field in the broken phase[9]. The electroweak baryogenesis in the effective theory of the brane universe does not utilize the bulk dynamics to produce the baryon asymmetry, since the sphalerons are activated in the unbroken phase.

We should note that the radion stabilization is generally affected by the potentials on the brane and in the bulk[5]. In this respect, the defects in the bulk or on the brane can act to displace the radion even if no specific mechanism is implicated, and there is a chance for our mechanism to work in any models for radion stabilization.

3 Conclusions and Discussions

In this letter we have proposed a novel possibility for electroweak baryogenesis mediated by cosmological defects.

We considered an interesting aspect of the Goldberger-Wise mechanism for the stabilization of the radion in the RS model. We expect that this mechanism works in other models for extra dimensions in which the radion is stabilized by the configurations in the bulk or on the brane[6].

The electroweak phase transition itself is not required to be first order, which is the same characteristic of the conventional defect-mediated electroweak baryogenesis. Although the problem of the first order phase transition is solved in our model, the problem of small CP breaking parameter remains. To obtain large CP parameter, one should extend the low energy effective theory.

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Figure 1: The cosmological domain wall that appears at the temperature $T_c > T > T'_c$ is given. Here the structure of interest is the domain wall on the visible brane, which interpolates between $\Phi(\pi) = +v_v$ and $\Phi(\pi) = -v_v$. The left hand side (true vacuum) is already in the broken phase, but the right hand side (false vacuum) is still in the symmetric phase because the effective scale of the electroweak symmetry breaking has a gap. H_0 denotes the Higgs expectation value in the true vacuum. Our mechanism works at the temperature $T_c > T > T'_c$, where T_c and T'_c denote the critical temperature in the true vacuum and the one in the false vacuum. The Higgs vacuum expectation value is 0 in the false vacuum because of the gap in the effective critical temperature which we have assumed to be induced by the shift of the hierarchy factor. Note that the walls does not necessarily sweep the whole Universe, which is the similar situation as the conventional defect-mediated electroweak baryogenesis.

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