Enhanced baryon number violation
due to cosmological defects
with localized fermions along extra dimension

Tomohiro Matsuda \footnote{matsuda@sit.ac.jp}

Laboratory of Physics, Saitama Institute of Technology,
Fusaiji, Okabe-machi, Saitama 369-0293, Japan

Abstract

We propose a new scenario of baryon number violation in models with extra
dimensions. In the true vacuum, baryon number is almost conserved due to the
localization mechanism of matter fields, which suppresses the interactions between
quarks and leptons. We consider several types of cosmological defects in four-
dimensional spacetime that shift the center of the localized matter fields, and show
that the magnitudes of the baryon number violating interactions are well enhanced.
Application to baryogenesis is also discussed.
1 Introduction

Although the quantum field theory made a great success, there is no consistent scenario in which the quantum gravity is included. The most promising scenario in this direction would be the string theory, where the consistency is maintained by the requirement of additional dimensions. At first the sizes of extra dimensions had been assumed to be as small as $M_p^{-1}$, however it has been observed later that there is no reason to expect such a tiny compactification radius\[1]. Denoting the volume of the $n$-dimensional compact space by $V_n$, the observed Planck mass is obtained by the relation $M_p^2 = M_*^{n+2} V_n$, where $M_*$ denotes the fundamental scale of gravity. If we assume more than two extra dimensions, $M_*$ can be assumed to be close to the electroweak scale without conflicting any observable bounds. Although such a low fundamental scale considerably improves the standard situation of the hierarchy problem, the scenario requires some degrees of fine-tuning. The largeness of the quantity $V_n$ is perhaps the most obvious example of such fine-tuning. There are of course other aspects of fine-tuning, which are common to conventional scenarios of grand unified theories(GUT). In particular, the compatibility between the stability of proton and baryogenesis may be the most problematic in models of such a low fundamental mass scale. In theories with low fundamental scale, the suppression can not be achieved by merely increasing the mass scale, and some non-trivial mechanism is needed. There is an interesting mechanism suggested in ref.\[2], where a dynamical mechanism for localization of fermions on the thick wall is adopted to solve the problem of the proton stability. In this scenario leptons and baryons are localized at displaced positions in the extra space, where the smallness of their interaction is insured by the smallness of the overlap of their wavefunctions along the extra dimension. On the other hand, the observed baryon number asymmetry of the Universe requires baryon number violating interactions to have been effective but non-equilibrium in the early Universe. In general the production of net baryon asymmetry requires baryon number violating interactions, C and CP violation and a departure from the thermal equilibrium\[3]. In the case that the fundamental mass scale is sufficiently high, the first two of these ingredients are naturally contained in conventional GUTs or other string-motivated scenarios, and the third can be realized in an expanding universe where it is not uncommon that interactions come in
and out of equilibrium, producing the stable heavy particles or cosmological defects. In the original and simplest model of baryogenesis\cite{4, 5}, a heavy GUT gauge or Higgs boson decays out of equilibrium producing a net baryon asymmetry. In our case, however, the situation is rather involved because of the low fundamental mass and the resulting low reheat temperature, which makes it much more difficult to produce the baryon asymmetry while achieving the proton stability in the present Universe\cite{6}. In this respect, it is very important to propose ideas to enhance the baryon number violating interactions that can appear even if the reheating temperature is low. In this letter we propose a mechanism where the enhancement of the baryon number violating interaction is realized by the several types of the cosmological defects that can survive well below the TeV scale. Our key idea is that the five-dimensional mass of the fermions, which determines the position of the wavefunctions of the fermions, can depend on the vacuum expectation value of some five-dimensional scalar field. We also assume that there are cosmological defect configurations of such scalar fields. In this case, depending on their effective couplings to the inflaton, cosmological defects can be formed at the (non-equilibrium) reheating period of the inflaton. The positions of the localized fermions vary in the defect configurations such as strings or monopoles, or in the quasi-degenerated false vacuum of the corresponding domain wall. Such a shift of the center of the wavefunction along the extra dimension can make the tiny baryon number violating interactions enhanced to produce the sufficient baryon number asymmetry. We consider the case where the fermionic mass in the five-dimensional theory, which had been assumed to be a constant in the original model, depends on the vacuum expectation value of the five-dimensional scalar field that is different from the one constitutes the fat kink configuration along the extra dimension. As we have discussed above, the most attractive effect is the enhancement of the baryon number violating interactions that can be a promising candidate to explain the baryogenesis with large extra dimensions.

2 Defects and domains

Localizing fields in the extra dimension necessitates breaking of higher dimensional translation invariance, which is accomplished by a spatially varying expectation value
of the five-dimensional scalar field $\phi_A$ of the thick wall along the extra dimension. If the scalar field $\phi_A$ couples to the five-dimensional fermionic field $\psi$ through the five-dimensional Yukawa interaction $g\phi_A \overline{\psi} \psi$, whose expectation value $< \phi_A >$ varies along the extra dimension but is constant on four-dimensional world, it is possible to show that the fermionic field localizes at the place where the total mass in the five-dimensional theory vanishes. For definiteness, we consider the Lagrangian

$$\mathcal{L} = \overline{\psi}_i \left( i \partial_5 + g_i \phi_A(y) + m_{5,i} \right) \psi_i$$

$$+ \frac{1}{2} \partial_\nu \phi_A \partial^\nu \phi_A$$

$$- V(\phi_A),$$

(2.1)

where $y$ is the fifth coordinate of the extra dimension. For the special choice $\phi_A(y) = 2\mu^2 y$, which corresponds to approximating the kink with a straight line interpolating two vacua, the wave function in the fifth coordinate becomes gaussian centered around the zeros of $g_i \phi_A(y) + m_{5,i}$. It is also shown\[1] that a left handed chiral fermionic field in the four-dimensional representation can result from the localization mechanism. The right handed part remains instead delocalized in the fifth dimension. The above idea can be utilized to certificate the proton stability. When leptons and baryons have the five-dimensional masses $m_{5,l}$ and $m_{5,q}$, the corresponding localizations are at $y_l = -\frac{m_{5,l}}{2g_i \mu^2}$ and $y_q = -\frac{m_{5,q}}{2g_i \mu^2}$, respectively. Even if the five-dimensional theory violates both baryon and lepton number maximally, the dangerous operator in the effective four-dimensional theory is safely suppressed. For example, we can expect the following dangerous operator in the five-dimensional theory,

$$O_5 \sim \int d^5 x \frac{QQQL}{M_*^2}$$

(2.2)

where $M_*$ denotes the fundamental mass scale and $Q, L$ are the five-dimensional representation of the fermionic field. The corresponding four-dimensional proton decay operator is obtained by simply replacing the five-dimensional fields by the zero mode fields and calculating the wave function overlap along the fifth dimension $y$. The result is

$$O_4 \sim \epsilon \times \int d^4 x \frac{qqq_l}{M_*^2},$$

(2.3)

\[2\]Here we limit ourselves to constructions with fermions localized within only one extra dimension\[2\]. Generalizations to higher dimensions are straightforward, which is already discussed in ref.[7].
where \( q, l \) denotes the four-dimensional representation of the chiral fermionic field. The overlap of the fermionic wavefunction along the fifth dimension is included in \( \epsilon \). For a separation \( r = |y_b - y_l| \) of \( \mu r = 10 \), one can obtain \( \epsilon \sim 10^{-33} \) which makes this operator safe even for \( M_* \sim \text{TeV} \).

Let us extend the above idea to include another scalar field \( \phi_B \) that determines the five-dimensional mass \( m_5 \) as well as the position of the center of the fermionic wavefunction along the fifth dimension.\(^3\) We assume that the additional scalar field does not make kink configuration along the fifth dimension, but does make a defect configuration in the conventional four-dimensional space. For definiteness, we consider the \( \phi_B \)-dependent five-dimensional mass \( m(\phi_B)_{5,i} \). \( \phi_A \) makes the kink configuration along the fifth dimension while \( \phi_B \) develops defect configuration in the four-dimensional spacetime. Here we consider the simplest case where \( m_{5,i} \) are given by \( m(\phi_B)_{5,i} = k_i \phi_B \), and the potential for \( \phi_B \) is given by the double-well potential of the form; \( V_B = -m_B \phi_B^2 + \lambda_B \phi_B^4 \). In our simplest example, because of the effective \( Z_2 \) symmetry of the scalar field \( \phi_B \), the resultant defect is the cosmological domain wall. Of course the effective \( Z_2 \) symmetry can be explicitly broken by the gravitational effect or the higher-dimensional operators suppressed by the cut-off scale\(^8, 9\). One can easily extend the model to include the string or monopole configuration in four-dimensional spacetime, if the appropriate symmetry is imposed on the scalar field \( \phi_B \). The most obvious example is the choices of the form,

\[
m(\phi_B)_{5,i} = k_i \frac{|\phi_B|^2}{M_*}
\]

\(^3\) We can utilize the idea of the orbifold boundary conditions that produce chiral fermion zero modes in compactified higher dimensional theories and provides a simple and explicit realization of the separation of quarks and leptons in the fifth dimension\(^8\). As is discussed in ref.\(^16\), one can obtain the localized fermions at the fixed points at \( y = 0 \) or \( y = L \). In this case one can obtain two degenerated solutions, one is the positive configuration for \( 0 < y < L \), and the other is the negative one\(^16\). If the sign is positive, the zero-mode is concentrated at \( y = 0 \). If it is negative, the zero mode is concentrated at \( y = L \). In general, two degenerated vacua generates the domain configuration, separated by the domain wall interpolating between them. If the splittings of the baryons and the leptons are induced by the above-mentioned mechanism of the orbifold, and if one of the scalar field develops domain wall structure, splitting can be dissolved in the quasi-degenerated false vacuum. Then the baryon number violation is maximally enhanced in the false vacuum, which helps the scenario of baryogenesis by the decaying heavy X bosons.
where $\phi_B$ is charged with $U(1)$. In any case, the position of the fermionic wavefunction along the fifth dimension can be modified by the defect configuration in the four-dimensional spacetime. The largest contribution is expected in the quasi-degenerated vacuum of the cosmological domain-wall that interpolates between $\phi_B = \pm v$. Let us assume that the wavefunctions of the quarks and the leptons are localized at the opposite side of the $\phi_A$ kink along the fifth dimension so that their wavefunctions are well separated. We also assume for simplicity that the five-dimensional masses $m_5$ for the leptons are constant. In the false vacuum domain of the $\phi_B$ wall, the centers of the quark wavefunctions move toward the opposite side of the $\phi_A$ wall. In this case the distances between quarks and leptons are changed by $O(1)$, which drastically modifies the magnitude of the baryon number violating interactions in the false vacuum.

Although it seems rather difficult to produce these defects merely by the thermal effect after inflation, nonthermal effect may create such defects during reheating period of inflation. Nonthermal creation of matter and defects has raised a remarkable interest in the last years. In particular, efficient production of such products during the period of coherent oscillations of the inflaton has been studied by many authors[10]. In this letter, however, we will not go into the details of such processes but simply assume the situation that the defects are efficiently produced after inflation by thermal or nonthermal effects.\footnote{4 There is a possibility that the defects are generated after the first brane inflation, while the reheat temperature after the second thermal brane inflation is kept much lower than the electroweak scale[11]. The cosmological constraint on the domain wall that is produced before thermal inflation is already discussed in ref.[9].}

Thermal effects may become more important when one considers the supersymmetric models where the positions of the localized matter fields may be parameterized by flat directions. In such cases, one can expect thermal symmetry restoration at the temperature much lower than the cut-off scale, which is accessible in realistic scenarios. During thermal symmetry restoration, if the five-dimensional mass terms $m_{5,i}$ are all determined by a field $\phi_B$ that parameterizes the flat direction, both leptons and baryons may be localized at $y = 0$. During this period the baryon number violation becomes maximal and the baryogenesis by the decaying heavy $X$ bosons can be promising. We will discuss this issue for supersymmetric grand unified theories in the forthcoming paper[12].
3 Enhanced baryon number violation and baryogenesis

In this section we explore the possibility of obtaining sufficient baryon number asymmetry of the Universe in models with localized fermions. Here we focus our attention to the baryogenesis by the decaying heavy particles.

First we consider a simplest model of baryogenesis\cite{5} with two species of heavy bosons $X_i$ which can decay into quarks and leptons, through the effective four-dimensional interactions of the form;

$$\mathcal{L}_{Xqq} = \lambda_1 X q\bar{q}$$
$$\mathcal{L}_{Xlq} = \lambda_2 X lq,$$

(3.1)

where $\lambda_2$ contains the tiny suppression factor $\epsilon_2$ of the form $\epsilon_2 \sim e^{-\mu^2 r^2}$. The baryogenesis with the enhanced baryon number violating interactions is already discussed in ref.\cite{13}, where they have expected that the thermal effect modifies the suppression factor, and concluded that the baryogenesis mediated by the heavy bosons becomes successful if the suppression factor $\epsilon_2$ is enhanced to be larger than $e^{-40}$. Unfortunately, the thermal effect is so weak in generic situations that the enhancement is not enough to produce the realistic baryon number of the Universe.

Now we consider the case that the five-dimensional mass depends on another scalar field $\phi_B$ and the vacuum expectation value of $\phi_B$ is determined by the effective $Z_2$-symmetric potential.\footnote{In general the effective $Z_2$ symmetry of the effective theory can be broken explicitly by the ultraviolet interactions. The explicit-breaking operators can appear in the effective Lagrangian suppressed by the cut-off scale, and destabilize the domain wall configuration. The condition for the safe decay is discussed in ref.\cite{8}} Expecting the generic double-well potential for $\phi_B$, there should be quasi-degenerated vacua where $\phi_B$ changes its sign. Let us imagine the situation that the quarks and leptons are placed at the opposite side of the $\phi_A$ kink, and their large distance certifies the proton stability in the true vacuum. On the other hand, when one of the five-dimensional mass changes its sign in the false vacuum, the distance can be modified by the factor of $O(1)$. For example, if the distance $r$ becomes $\frac{1}{2}r$ in the false vacuum, the
suppression factor $10^{-16}$ becomes $10^{-4}$, which is about $10^{12}$ times larger than the conventional value. This effect is obviously enough to explain the baryon number asymmetry in the scenario of ref. [13]. Although it seems easy to reduce the amount of the baryon number asymmetry in this scenario, it depends on the details of the reheating process of the inflation, which is beyond the scope of this letter.

Of course one can consider other cosmological defects, such as strings or monopoles. In generic situations, monopoles are not effective for baryogenesis, because of their small volume factor. However, in some realistic cases, strings can become effective source of baryon number violation that may either washout or produce the baryon asymmetry of the Universe [14]. It is easy to introduce string configurations in our model. The most promising way would be to consider the vortex solution along the extra dimensions in place of the wall-like kink configuration [15]. However, one can include the string configuration without modifying the simplest situation of the original idea. For example, we can consider the mass term: $m(\phi_B)_{5,i} = \lambda_i |\phi_B|^2 M_*$. In this case, the most interesting situation is that the position of both leptons and baryons are all determined by $\phi_B$, and their distance depends on their coupling constants. In the core of the string where $\phi_B$ vanishes, leptons and baryons are centered at the same point along the fifth dimension. The suppression disappears in the string, which is similar to the scenarios of the string-mediated baryon number violation in the conventional GUTs. In our model, however, we are not assuming the GUT-like symmetry restoration inside the string. Around the string, both the scattering and their decay by the loop can become the effective source of the baryon number violation. Although the idea of string-mediated baryogenesis is very attractive, it contains many kinds of models to be discussed. Detailed studies in this direction are given in the forthcoming paper [12] to avoid complexities.

4 Conclusions and Discussions

In this letter we have proposed a new scenario of baryon number violation in theories with localized fermion wavefunctions along the extra dimension. The baryon number can be almost conserved in the true vacuum by the localization mechanism, while it is well enhanced in the background of cosmological defect configurations. The baryon number
violating interactions are most effective for the cosmological domain walls, where the
domain of the false vacuum appears. It is convincing that this interesting idea opens new
possibilities for baryogenesis with extra dimensions, which is not discussed in the past.

5 Acknowledgment

We wish to thank K.Shima for encouragement, and our colleagues in Tokyo University
for their kind hospitality.

References

[1] I.Antoniadis, Phys.Lett.B246(1990)377;
   Ignatios Antoniadis, N.A-Hamed and S.Dimopoulos, Phys.Lett.B436(1998)257;
   N.A-Hamed, S.Dimopoulos, G.R.Dvali, Phys.Lett.B429(1998)263.

[2] N.Arkani-Hamed, M.Schmaltz, Phys.Rev.D61(2000)033005.

[3] A.D.Sakharov, JETP Lett.5(1967)24.

[4] S.Weinberg, Phys.Rev.Lett.42(1979)850
   D.Toussant, S.B.Treiman, F.Wilczek and A.Zee, Phys.Rev.D19(1979)1036.

[5] A.D.Dolgov, and A.D.Linde, Phys.Lett.B116(1982)329
   D.V.Nanopoulos, K.A.Olove and M.Srednicki, Phys.Lett.B127(1983)30.

[6] A.Mazumdar and A.Perez-Lorenzana, hep-ph/0103215;
   R.Allahverdi, K.Enqvist, A.Mazumdar and A.Perez-Lorenzana,
   Nucl.Phys.B618(2001)277;
   A.Mazumdar, Nucl.Phys.B597(2001)561, Phys.Rev.D64(2001)027304;
   D.J.H.Chung and Thomas Dent, hep-ph/0112360
   T.Matsuda, hep-ph/0202209.

[7] J.-M.Frere, M.V.Libanov, S.V.Troitsky, Phys.Lett. B512(2001)169.

[8] A.Vilenkin, Phys.Rev.D23(1981)852.
[9] T.Matsuda, Phys.Lett.B486(2000)300, Phys.Lett.B436(1998)264.

[10] E.J.Copeland, S.Pascoli, A.Rajantie, hep-ph/0202031;
A.D.Dolgov and A.D.Linde, Phys.Lett.116B(1982)329;
L.F.Abbott, E.Farhi and M.B.Wise, Phys.Lett.117B(1982)29;
J.H.Traschen and R.H.Brandenberger, Phys.Rev.D42(1990)2491;
L.Kofman, A.D.Linde and A.A.Starobinsky, Phys.Rev.Lett.73(1994)3195,
Phys.Rev.Lett.76(1996)1011; I.I.Tkachev, Phys.Lett.376B(1996)35;
I.Tkachev, S.Khlebnikov, L.Kofman and A.D.Linde, Phys.Lett.440B(1998)262;
L.M.Krauss and M.Trodden, Phys.Rev.Lett.83(1999)1502;
J.Garcia-Bellido, D.Y.Grigoriev, A.Kusenko and M.E.Shaposhnikov,
Phys.Rev.D60(1999)123504;
A.Rajantie, P.M.Saffin and E.J.Copeland, Phys.Rev.D63(2001)123512.

[11] G.R.Dvali, Phys.Lett.B459(1999)489.

[12] T.matsuda, in preparation.

[13] A.Masiero, M.Peloso, L.Sorbo and R.Tabbash, Phys.Rev.D62(2000)063515.

[14] M.B.Hindmarsh and T.W.B.Kibble, Rept.Prog.Phys.58(1995)477;
M.G.Alford, J.M-Russell and Frank Wilczek, Nucl.Phys.B328(1989)140;
W.B.Perkins, Nucl.Phys.B364(1991)451;
W.B.Perkins, L.Perivolaropoulos, A.C.Davis, R.H.Brandenberger and A.Matheson,
Nucl.Phys.B353(1991)237;
R.H.Brandenberger, A.C.Davis, A.M.Matheson, Phys.Lett.B218(1989)304;
R.H.Brandenberger, A.C.Davis and M.Hindmarsh, Phys.Lett.B263(1991)239;
R.H.Brandenberger, A.C.Davis and A.M.Matheson, Phys.Lett.B218(1989)304;
M.Kawasaki and K-i.Maeda, Phys.Lett.B208(1988)84.

[15] J.M.Frere, M.V.Libanov and S.V.Troitsky, Phys.Lett.B512(2001)169.

[16] H.Georgi, A.K.Grant and G.Hailu, Phys.Rev.D63(2001)064027.