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Avoiding the Domain Wall Problem in Models with a Discrete Symmetry Breaking at Low T_c

C. PANAGIOTAKOPOULOS

Theory Division
CERN, Geneva
Switzerland

Abstract

An inflationary mechanism for avoiding the cosmological domain wall problem associated with the breaking of a discrete symmetry at a phase transition with low ($\sim 1\text{TeV}$) critical temperature T_c in the early universe is proposed. Although the scenario is illustrated in the context of Calabi-Yau superstring inspired models it could be applicable to other models as well.

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One of the most promising ways of compactifying the ten-dimensional heterotic superstring [1] is the compactification on Ricci-flat spaces of $SU(3)$ holonomy, the well-known Calabi-Yau (C-Y) spaces [2]. The C-Y compactification gives rise to four-dimensional models with $N = 1$ supersymmetry and chiral fermions belonging to 27 (or $\overline{27}$) representations of the gauge group E_6 (or one of its proper subgroups containing the standard group). The net number of chiral fermion generations is also computable in terms of the Euler characteristic of the internal space. In addition to the gauge non-singlet superfields there exist, as a rule, many gauge singlets.

In spite of all the above rather positive features model building on C-Y spaces has to face many phenomenological disasters such as unacceptably fast proton decay, absence of light electroweak Higgs doublets, unacceptable light fermion spectrum etc. All attempts made so far to successfully address these problems rely heavily on the discrete symmetries of the internal space which survive as discrete symmetries of the corresponding four-dimensional model. In most cases, however, these discrete symmetries do not remain unbroken but suffer spontaneous breaking with the associated phase transition having a rather low ($\sim 17\text{eV}$) critical temperature [3,4]. A result of this breaking is the formation of domain walls in the early universe which are absolutely unacceptable in the context of the conventional standard cosmology.

Are there any ways out of this catastrophe? One possibility is that the discrete symmetry acts effectively like a continuous symmetry, for instance like an approximate Peccei-Quinn symmetry [3]. Although superstring inspired models exhibiting this phenomenon have been constructed none of them is based on the only concrete three-generation C-Y manifold known today. Another possibility is that the domain walls are inflated away. Implementation of this idea, however, seems to be obstructed by the fact that all phase transitions in superstring models of the C-Y type have a critical temperature T_c of the order of the supersymmetry breaking scale $M_s \sim 10^{2+1} \text{GeV}$ in the visible sector irrespectively of the vacuum expectation value of the field responsible for the phase transition. This phenomenon is a consequence of the mechanism of generation of intermediate scales in superstring models [5] which requires that, as a result of strong Yukawa couplings, the running mass squared terms $\sim M_s^2$ of certain boson

fields become negative. The presence of strong Yukawa couplings entails large (typically positive) temperature dependent mass terms for these fields which, in turn, force them to have a local minimum at the origin until the temperature T falls to $\sim T_c \sim M_s$. Such a low critical temperature makes it implausible that the phase transition will experience the primordial inflationary phase which is usually invoked in order to solve the homogeneity, isotropy and flatness problems of the standard conventional cosmological model.

The purpose of the present note is to point out a possible solution, in the context of the new inflationary universe scenario [6], of the domain wall problem associated with the spontaneous breaking of global discrete symmetries in models based on the C-Y compactification of the heterotic superstring. The mechanism, however, is general enough to be applicable to other models as well.

The idea behind our mechanism is actually very simple. Gauge singlet fields transforming non-trivially under a discrete symmetry and having at zero temperature positive mass squared terms could be coupled sufficiently weakly in order to have temperature dependent mass much smaller than the Hubble constant H_0 of a primordial inflation. After the end of inflation, due to the vacuum fluctuations during the exponential expansion [7], rather homogeneous configurations of such fields over the entire visible universe, with initial amplitude much larger than H_0 , are naturally expected [8]. The smallness of their temperature dependent mass allows them to remain large and rather homogeneous for much longer periods than other fields having strong couplings and consequently large temperature dependent mass. When the temperature T becomes comparable to the critical temperature T_c of the phase transition associated with the spontaneous breaking of the discrete symmetry the homogeneous gauge singlet fields, provided their amplitude is sufficiently larger than T_c and their mass smaller than the Hubble constant at T_c , could force the choice of only one of the possible discrete vacua over the whole region corresponding to the entire visible universe thereby solving the domain wall problem.

For a more concrete illustration of the mechanism let us consider a toy model involving two gauge singlet real boson fields ϕ and χ with a temperature dependent potential of the form

$$V \sim (-m_\chi^2 + T^2)\chi^2 + (m_\phi^2 + \lambda^2 T^2)\phi^2 + 1/4\chi^4 + \lambda\chi^3\phi + \lambda^4\phi^{2n}M_P^{4-2n},$$

where $m_\chi \sim 10^4 \text{ GeV}$, $m_\phi \sim 10 \text{ GeV}$, $\lambda \sim 10^{-9}$, $13 \geq n \geq 5$ and $M_P \sim 10^{19} \text{ GeV}$ is the Planck mass. The negative sign for the mass term $-m_\chi^2\chi^2$ of χ is a result of some large Yukawa couplings of the boson χ which are not displayed. Couplings of this type are also responsible for the large temperature dependent mass of χ . The absence of large Yukawa couplings for ϕ explains the positive sign for the term $m_\phi^2\phi^2$ and the small temperature correction $\sim \lambda^2 T^2$ to the mass squared term of ϕ . The potential V is invariant under the Z_2 symmetry generated by $\chi \rightarrow -\chi$ and $\phi \rightarrow -\phi$.

Let us assume a primordial inflation with Hubble constant $H_0 \sim 10^{14} \text{ GeV}$. In an exponentially expanding universe the wavelengths of all vacuum fluctuations of the low (compared to the Hubble constant) mass scalar field ϕ grow exponentially. When the wavelength of any particular fluctuation becomes greater than the inverse Hubble constant this fluctuation stops propagating and its amplitude freezes whereas its wavelength keeps growing exponentially. A consequence of the additive effect of frozen vacuum fluctuations with exponentially large wavelengths is the appearance of a nearly homogeneous, over distances corresponding to the size of the observable part of the universe, field ϕ with amplitude $\phi_0 \gg H_0$, as large as $H_0^2/m_\phi(T_H)$, where $m_\phi(T)$ is the temperature dependent mass of ϕ and $T_H = H_0/2\pi$ is the Hawking temperature of the de Sitter space. For the strongly interacting field χ the large temperature dependent mass $\sim T_H$ forbids any large classical field configuration. We will assume an inflaton field σ decaying according to the usual exponential decay law [9] with a decay width $\Gamma_\sigma \sim 10^2 \text{ GeV}$. The continuous decays of the inflaton determine the temperature T_0 immediately after inflation from the relation $\rho_{\sigma 0} \Gamma_\sigma H_0^{-1} \sim NT_0^4$, where $\rho_{\sigma 0}$ is the inflaton energy density immediately after inflation $\sim H_0^2 M_P^2$ and $N \sim 10^2 - 10^3$ is the number of massless (compared to the temperature) degrees of freedom of the (superstring) model. We find $T_0 \sim 10^{13} \text{ GeV}$ a value not much different from the Hawking temperature of

the de Sitter space. The large value of T_0 will force the strongly interacting (large temperature dependent mass) field χ to stay at zero while the weakly coupled field ϕ will keep its large amplitude $\phi_0 \gg H_0$. From the time $t_0 \sim H_0^{-1}$ till the time Γ_σ^{-1} the inflaton field σ (which we assume has a mass $\geq H_0$) keeps oscillating until it completely disappears. During this time interval there is a continuous entropy production, due to the continuous inflaton decays, and the temperature falls according to the law $T \sim t^{-1/4}$ (t is the cosmic time). The final temperature T_f (usually called 'reheat' temperature in the instantaneous decay approximation) is easily estimated to be $T_f \sim 10^{10} \text{ GeV}$ corresponding to cosmic time $t_f \sim \Gamma_\sigma^{-1}$. The value of $\lambda \sim 10^{-9}$ guarantees that the temperature dependent mass of ϕ remains smaller than the Hubble constant for the whole period between the end of inflation and the complete decay of the inflaton.

If we assume that radiation dominates the energy density of the universe for cosmic times $t \geq t_f \sim \Gamma_\sigma^{-1}$ corresponding to temperatures $T \leq T_f \sim 10^{10} \text{ GeV}$, then when the temperature falls to about $3 \times 10^9 \text{ GeV}$ the ϕ field starts oscillating coherently around the origin with frequency m_ϕ and amplitude decreasing like $R^{-3/2}$, R being the scale factor of the universe. However, in the models that we have in mind, namely C-Y superstring inspired models with large intermediate scales, we do not expect that the universe will be radiation dominated for the temperature range between a few orders of magnitude larger than $M, \sim 10^{11-1} \text{ GeV}$ and M_* . It will rather be dominated by the energy density corresponding to the difference between the true and the false vacuum associated with the largest scale in the theory [3,4]. For intermediate scales $M_f \geq 10^{16} \text{ GeV}$ this difference is $\sim M_*^2 M_f^2$ meaning that the universe experiences a mild inflation with Hubble constant $\sim M_* M_f M_P^{-1} \geq m_\phi$ and therefore the field ϕ has not had any time to oscillate before the temperature falls to $\sim T_c$.

For T just below $T_c \sim m_\chi$ the total mass squared term of χ becomes negative and the origin ceases being even a local minimum. In the background of the homogeneous field ϕ with amplitude ϕ_0 the term $\lambda\chi^3\phi_0$ breaks the symmetry $\chi \rightarrow -\chi$ and χ rolls towards large values with sign opposite to the sign of $\lambda\phi_0$ until the minimum value $\chi = -3\lambda\phi_0$ is reached. Assuming an amplitude $\phi_0 \sim M_P$ we can immediately check that for $|\chi| \sim T_c$ the term $\lambda\chi^3\phi_0$ is much more important than the energy density of

thermal fluctuations $\sim T_c^4$ as well as all other terms involving χ in the potential V . Also the presence of a local minimum for $\chi \sim m_\chi^2/\lambda\phi_0$ with $|\chi| \ll T_c$ and enormous energy difference compared to the true minimum $\chi = -3\lambda\phi_0$ is of no relevance. Eventually ϕ and χ will readjust their values such that they find themselves in the minimum which for $\lambda = (2/(27 - 2n))^{1/4}(m_\phi/M_P)^{1/2}$ is $|\phi| = M_P$ and $\chi = -3\lambda\phi \sim \lambda M_P$. We see that the so realized phase transition does not lead to any domain wall problem.

In realistic C-Y superstring models gauge non-singlet boson fields spontaneously break discrete symmetries through intermediate scale vacuum expectation values acquired at low temperatures. If a discrete symmetry has already been broken by the gauge singlet sector without domain wall formation, thanks to the mechanism just described, the subsequent phase transitions involving gauge non-singlet fields do not have to lead to any further domain wall production.

After the completion of the intermediate scale phase transitions we expect large entropy productions [3,4] from the decays of the various coherently oscillating fields around their minima which will dilute light gravitinos to acceptable levels [3]. The entropy produced will, however, also wash out any pre-existing baryon asymmetry. The observed baryon asymmetry will then have to be generated later, probably through a mechanism analogous to the one discussed in [10,11].

An important feature of the scenario for the avoidance of domain walls outlined above is its heavy dependence on the gauge singlet sector. This immediately guarantees that the formation of gauge cosmic strings [10] or harmless magnetic monopoles [12] at low temperatures through the breaking of gauge symmetries at intermediate scales will be left unaffected.

In conclusion, we propose a scenario for an inflationary solution of the domain wall problem of C-Y superstring models based on the gauge singlet sector of these models. The mechanism, however, could as well be applicable to other models in which a discrete symmetry breaks spontaneously at low temperatures.

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