Reheating the D-brane universe via instant preheating

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We investigate a possibility of reheating in a scenario of D-brane inflation in a warped deformed conifold background which includes perturbative corrections to throat geometry sourced by chiral operator of dimension 3/2 in the CFT. The effective D-brane potential, in this case, belongs to the class of non-oscillatory models of inflation for which the conventional reheating mechanism does not work. We find that gravitational particle production is inefficient and leads to reheating temperature of the order of $10^8 GeV$. We show that instant preheating is quite suitable to the present scenario and can easily reheat universe to a temperature which is higher by about three orders of magnitudes than its counterpart associated with gravitational particle production. The reheating temperature is shown to be insensitive to a particular choice of inflationary parameters suitable to observations.

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I. INTRODUCTION

Inflatonary scenario in cosmology is known to solve a number of problems associated with the big bang model and is well supported by observation. It is believed that universe, at the end of the inflationary epoch, consisted almost entirely of the homogeneous inflaton field which decayed into inhomogeneous fluctuations and other particles. This decay period, known as reheating, is fairly understood and has provided crucial links between the inflationary epoch and the subsequent thermalized era. In the early days of the reheating proposal, it was believed that the inflaton field decayed perturbatively as a collection of particles and during the decay it went through a large number of oscillations around the minimum of its potential. A different hypothesis is that the decay could have been initiated by coherent field effects such as parametric resonance. For such a decay process the field undergoes only a few oscillations. This rapid non-perturbative decay has been termed as preheating. Subsequently a new proposal for reheating, dubbed instant preheating was made in Refs. which does not require oscillation of the inflaton field.

In this paper we investigate the instant preheating mechanism in a recently studied brane inflation model using the leading corrections to the brane potential obtained in Ref. The model used a single throat, containing the D3-brane moving towards the D3-brane located at the tip of the throat. The position of the D3-brane with respect to the localized D3-brane is interpreted as an inflaton field following the method outlined in the original proposal of Ref. Earlier attempts to study reheating in brane inflation model using multi-throat configurations were made in Refs.

We recall that the proposal in Ref. is based on type IIB string compactification, with background fluxes that stabilize all the complex structure moduli fields using a Klebanov-Strassler (KS) throat. It also made use of the proposal in Ref. for the stabilization of Kähler moduli fields due to non-perturbative effects that arise via the the gauge dynamics of either an Euclidean D3-brane or a stack of D7-branes wrapping a four cycle in the warped throat. The AdS vacuum is lifted to a de-Sitter vacuum by placing D3-brane at the tip of the throat since the warped tension of the anti-brane adds to the energy density of the system. Inflation, in this scenario, is realized by the motion of a D3-brane towards the anti-brane due to their mutual Coulomb attraction and the radial separation between them serves as the inflaton field. However, the moduli stabilization, in presence of the mobile D3-brane affects the potential for the inflaton field yielding a mass term for the inflaton which, unfortunately, turns out to be of the order of the Hubble parameter and hence effectively spoils the inflation. To bring out new features of the inflaton potential, it was proposed to restrict the motion of D3-brane deep inside the throat assuming certain embeddings of the stack of D7-branes. An inflationary dynamics was studied in Ref. using the potential obtained in the above model, which involves two scalar fields, namely, the volume modulus field and the field representing the radial distance between the brane and the anti-brane. The result turned out to be unrealistic since not only it needed severe fine tunings but also it was found that in case of the scale invariant spectrum of scalar perturbations, their amplitude becomes much larger than the COBE normalized value (see, Ref. on the related theme).

A proposal, using the holographic point of view, to account for the ultraviolet physics arising from gluing the warped throat to the compact Calabi-Yau manifold is made in Ref. The authors employed gauge/string correspondence for the warped deformed conifold. In this framework, the position of the mobile D3 brane is identified with the Coulomb branch vacuum expectation value of the dual gauge theory. In such a holographic formulation, the bulk effects are encoded in the coupling of a gauge invariant operator $O_{\Delta}$ of scaling dimension $\Delta$ to its dual bulk mode in the gauge theory which modifies the inflaton potential with an additional term given by
where $c$ is a positive constant and $a_0$ is the warp factor at the tip of the deformed conifold which depends upon the background fluxes. The potential above is obtained after the minimization over the angular location and written in terms of the canonically normalized inflaton field $\phi = \sqrt{T_3}r$, where $r$ is the radial distance of the D3-brane from the tip of the throat, $T_3$ being the tension of the D3-brane and $\phi_{UV}$ is the value of the field $\phi$ corresponding to a cut off scale $M_{UV}$ of the conformal field theory. Moreover, it was found that the leading corrections to the inflaton potential comes either from modes corresponding to $\Delta = 3/2$ related to the scaling dimension of a chiral operator in the gauge theory or $\Delta = 2$ corresponding to the same of a non-chiral operator. If the former is not forbidden by a certain discrete symmetry of the string compactification then this operator provides the dominant correction to the potential. We consider this situation and include the other known contribution to the inflaton potential after which the full potential is found to be

$$V(\phi) = D \left[ 1 + \frac{1}{3} \left( \frac{\phi}{M_{pl}} \right)^2 - C_{3/2} \left( \frac{\phi}{M_{UV}} \right)^{3/2} - \frac{3D}{16\pi^2\phi^4} \right],$$

(2)

where $C_{3/2}$ is a positive constant and $D = 2a_0^2T_3$. Remarkably, this potential is same as that obtained in [17–19] after the volume modulus is stabilized at the instantaneous minimum by making use of the adiabatic approximation. However the interpretation and the constraint on $C_{3/2}$ are different. The fact that the generic form of the potential is same, it tells us that the holographic point of view is another approach to compute the inflation potential. In the next section, we discuss the constraints on allowed values of the model parameters which can give rise to an inflationary dynamics consistent with observation.

II. INFLATIONARY POTENTIAL AND FINE TUNED PARAMETERS

The possibility of a viable D-brane inflation based upon the effective potential (2) was examined in Ref. [3]. In what follows, we shall briefly review the analysis for the dynamics of inflation presented there. For convenience, we use the following dimensionless form of the potential,

$$V = D \left( 1 + \frac{\alpha^2}{3} x^2 - C_{3/2} x^{3/2} - \frac{3D}{16\pi^2 x^4} \right),$$

(3)

$$x = \phi/M_{UV}, \quad \mathcal{V} = V/M_{UV}^4,$$

$$D = D/M_{UV}^4, \quad \alpha = M_{UV}/M_P.$$

In this scenario, $0 < x < 1$ as $\phi < \phi_{UV} = M_{UV}$ and the mobile D3-brane moves towards the $\bar{D}3$ brane located at the tip of the throat corresponding to $x = 0$. The slow roll parameters for the generic field range are given by

$$\epsilon = \frac{1}{2\alpha^2} \left( \frac{\mathcal{V}_x}{\mathcal{V}(x)} \right)^2 \approx \frac{\alpha^2}{3} - \frac{3C_{3/2}^2}{2},$$

$$\eta = \frac{1}{\alpha^2} \left( \frac{\mathcal{V}_{xx}}{\mathcal{V}(x)} \right) \approx \frac{2}{3} - \frac{3C_{3/2}}{4\alpha^2} x^{-1/2} - \frac{15D}{4\pi^2\alpha^4 x^6},$$

(4)

(5)

Since in the present case $|\epsilon| < |\eta|$, it is sufficient to consider $\eta$ for discussing the slow roll conditions. It follows from Eq. (4) that $\eta$ is always less than one; it decreases as $x$ moves towards the origin. At a particular value of $x$, the slow roll parameter $\eta = -1$ marks the end of inflation and thereafter it takes large negative values as $x \to 0$.

Note that in the present set up, the field $x$ rolls from $x = 1$ towards $x = 0$ where $D3$ brane is located. This implies that the field potential should be monotonously increasing function of $x$. However, depending upon the numerical values of the model parameters ($D, C_{3/2}, \alpha$), the effective potential may acquire a minimum with large value of $\eta_{\text{min}}$ giving rise to spectral index inconsistent with observation. It is observed that the region where $\eta$ is small lies below $\phi_{\text{min}}$, in this case, and is not accessible dynamically. The choice of parameters should also be consistent with the constraints coming from the compactification as well as other considerations necessary for the validity of the effective potential (2). Monotonicity of $\mathcal{V}(x)$ is ensured provided that $\mathcal{V}_{xx} > 0$,

$$C_{3/2} \leq \frac{2}{3} \left( \frac{2\alpha^2 \sqrt{x}}{3} + \frac{3D}{4\pi^2 x^{11/2}} \right).$$

(6)

In Eq. (6), the right hand side as a function of $x$ has minimum at $x = x_{\text{min}} = (9D/16\pi^2 \alpha^2)^{1/6}$ which imposes a constraint on the coefficient, $C_{3/2}$,

$$C_{3/2} \leq \frac{8}{3\beta^{1/4}} \left( \frac{\alpha^{2D}}{\pi^2} \right)^{1/12},$$

(7)

The potential (3) is plotted in (4) for $0 < x < 1$ keeping in mind the aforementioned constraints. The parameters should therefore be chosen such that the potential has the right behavior. It turns out that for $D^{1/4} \lesssim 10^{-4}$ and $\alpha < 1$, the observational constraints can be satisfied by pushing $C_{3/2}$ towards numerical values much smaller than one, (see Table 1). Since the field range viable for inflation is narrow, the potential should be made sufficiently flat to obtain required number of e-foldings. In particular, it means that the slow roll parameter $\epsilon$ is very small leading to low value of tensor to scalar ratio of perturbations. This feature, however, becomes problematic for scalar perturbations. Indeed, since $\delta_H^2 \propto \mathcal{V}/\epsilon$ and $\mathcal{V} \sim D$, smaller values of $\epsilon$ lead to larger values of density perturbations. We also emphasize a peculiarity of the potential associated with the last term in (3). The constant
$\mathcal{D}$ not only appears as an overall scale in the expression of the effective potential, it also affects the behavior of $V(x)$ in a crucial manner, for instance it changes the slow roll parameters, which makes it tedious to set the COBE normalization.

Our numerical investigations, considering the allowed values of $\mathcal{D}$, $\alpha$ and $C_{3/2}$ coming from the validity of the model considered here, confirm that there exist regions in parameter space which allows us to satisfy all the observational constraints including the COBE normalization. For instance, one of the choices is given in Table I. We note that $\mathcal{D}$, which is the scaled value of $D$ as defined in (3) is related to the warped tension of the D3-brane. The warp factor at the tip of the throat, in turn, is an exponential function of the integer used in the compactification scheme. It is, thus, permitted to tune them to obtain the quoted values of $\mathcal{D}$ in Table I. Similarly, $C_{3/2}$ which is a parameter corresponding to the strength of the perturbation in dual CFT is also very small.

However, it is also possible to allow small changes in the quoted values of these parameters and still satisfy the observational constraints. We should remark here that the model parameters should be suitably fine tuned to satisfy the observational constraints. For instance, $C_{3/2}$ is required to be fine tuned to the level of one part in $10^{-7}$. The changes at the seventh decimal puts physical quantities out side their observational bounds otherwise the potential can develop a local minimum and hence can spoil all the nice features of the model. Similarly other parameters are also needed to be fine tuned. For example, if we take $\mathcal{D} = 1.210 \times 10^{-17}$ instead of $\mathcal{D} = 1.211 \times 10^{-17}$, the field gets into the fast roll regime before we could meet the requirements of having 60 e-folds as well as being consistent with COBE normalization. The parameter $\alpha^{-1}$ also requires fine tuning of the order of one part in $10^{-5}$. It is quite possible that the systematic search of these parameters based on Monte-Carlo method discussed in Ref.[21] might help to alleviate the fine tuning problem. It is, nevertheless, remarkable that the correction to the inflaton potential without changing the throat geometry, as being discussed here but originally reported in Ref.9, allows not only to solve the well know $\eta$ problem but also helps in satisfying all the observational constraints given by the WMAP5.

Let us note that in a viable inflationary scenario, inflation should be followed by a successful reheating. In the model under investigation, the D-brane effective potential, with parameters appropriately chosen, does not possess a minimum and therefore, the conventional reheating mechanism does not work in this case. The instant preheating mechanism might be helpful in such a case. At the end of inflation, the effective potential becomes steep and assumes large negative values as the field approaches the origin. The perturbative string theory calculations used to obtain the effective potential become unreliable near the tip of the throat. The non-perturbative result might give rise to an effective potential with a minimum or the brane-brane collision might lead to particle production. However, if the true D-brane potential is run away type, the instant preheating mechanism might give rise to a viable thermal history of universe. In the next section, we shall investigate the said possibility.
TABLE I: A possible choice of parameters which can give rise to a viable inflation.

| $\alpha$ | $C_{3/2}$ | $D$ | $n_s$ | $\delta^2_g$ |
|----------|------------|-----|-------|------------|
| 0.50     | $4.50272 \times 10^{-3}$ | $1.3820 \times 10^{-12}$ | 0.96 | $2.4 \times 10^{-9}$ |
| 0.25     | $1.58407 \times 10^{-3}$ | $2.0829 \times 10^{-17}$ | 0.96 | $2.4 \times 10^{-9}$ |
| 0.10     | $4.00285 \times 10^{-4}$ | $8.0254 \times 10^{-16}$ | 0.96 | $2.4 \times 10^{-9}$ |

III. D-BRANE INFLATION FOLLOWED BY INSTANT PREHEATING

Before getting into instant preheating, let us estimate the reheating temperature due to gravitational particle production. The space time geometry undergoes a crucial transition at the end of inflation involving essentially a non-adiabatic process which leads to particle production. The energy density of radiation produced in this process is given by\(^2\)

$$\rho_r \simeq 0.01 \times g_p H^4_{\text{end}},$$

(8)

where $g_p$ is the number of different species produced at the end of inflation and varies typically between 10 and 100. For a possible choice of inflationary parameters given by: ($\alpha = 0.1$, $C_{3/2} = 4.00285 \times 10^{-4}$, $D = 8.0254 \times 10^{-16}$), we find that

$$H_{\text{end}} = 1.636 \times 10^{-10} M_p \Rightarrow T \simeq \rho^1_\gamma \simeq 4 \times 10^8 \text{GeV}.$$

(9)

The low reheating temperature signifies that the gravitational particle production is an inefficient process. We have verified that temperature does not improve significantly for other possible choices of inflationary parameters. The instant preheating generally gives rise to much higher reheating temperature than the gravitational particle production. In this scenario, in order to achieve reheating after inflation, one assumes that the inflaton $\phi$ interacts with another scalar field $\chi$ which has a Yukawa-type interaction with a Fermi field $\psi$. The interaction Lagrangian has the following form\(^6, 7, 25-27\)

$$L_{\text{int}} = -\frac{1}{2} g^2 (\phi - v)^2 \chi^2 - \hbar \psi \bar{\psi} \chi,$$

(10)

where $v$ is chosen corresponding to the vanishing of $m_\chi$ at the end of inflation ($v = \phi_{\text{end}}$). This is done keeping in mind that the field $\chi$ has to be extremely light so that it does not participate in the dynamics during the inflationary epoch, which is one of the requirements of the proposal of instant reheating. In the present context, where all the moduli are stabilized and we are considering the scenario of large volume compactification, the scalar field $\chi$ appearing in the Lagrangian \(10\) could be thought of as a low lying Kaluza-Klein excitation so that it is automatically light. ¹

¹ We thank Ashoke Sen for a discussion clarifying this point.

The region of the violation of the adiabaticity is bounded by the intersection point of two curves, $|\phi| \& g(\phi - v)^2$. Larger $g$ means smaller time duration of particle production and the corresponding larger value of $|\phi_{\text{pro}}|$. In Fig.2 we have displayed the post inflationary evolution of $|\phi|$ and $g(\phi - v)^2$. We find that for any generic value of the parameter $g$, the preheating takes place instantaneously. The lower limit of $g$ is fixed such that the non-adiabatic process stops before singularity is reached. For instance, the variation of $g$ is given by, $0.006 \lesssim g \lesssim 1$ in case of $\alpha = 0.5$. We can estimate the momentum of the produced particles using the uncertainty relation

$$k_p \sim \delta t^{-1} \sim \frac{|\phi|}{|\phi|} = \alpha \left| \frac{\nabla}{x} \right| M_p,$$

(13)

FIG. 3: Plot shows the region in parameter space ($g, h$) corresponding to $\alpha = 0.5$ allowed by post inflationary non-adiabatic process and the consideration of back reaction. The upper limit on $\hbar \kappa g$ is dictated by the validity of perturbation theory. The shaded region $0.006 \lesssim g \lesssim 1$ and $0.053 \lesssim h \lesssim 1$ leads to successful instant reheating.
Using Eq. (15), we can finally compute the energy density

\[ \rho \approx \frac{\alpha}{2} \left( \frac{N}{2} \right)^3 \left( \frac{M_{\text{UV}}}{8\pi^3} \right)^{3}, \]

which allows us to estimate the \( \chi \) particle number density,

\[ n_\chi = \frac{1}{2\pi^2} \int_0^{\infty} k^2 N_k k \approx \frac{k_p^3}{8\pi^3}. \]

Using Eq. (14), we can finally compute the energy density of the \( \chi \) particles,

\[ \rho_\chi = m_\chi n_\chi \left( \frac{a_{\text{end}}}{a} \right)^3 g |(\phi - v)| \left( \frac{k_p^3}{8\pi^3} \right) \left( \frac{a_{\text{end}}}{a} \right)^3 , \]

where \( \phi \) is \( \phi_{\text{prod}} \) which is obtained from the intersection of two curves \( g(\phi - v)^2 \) and \( |\phi| \). It would be convenient to express the \( \rho_\chi \) through the dimensionless variables \( x, y \) making use of (13) & (16) as

\[ \rho_\chi = \frac{g}{8\pi^3} |x - \tilde{v}| a^4 \left[ \frac{y^2}{x^3} \right] M_p^4 \left( \frac{a_{\text{end}}}{a} \right)^3 , \]

where \( \tilde{v} = v/M_{\text{UV}} \). We assume that the energy of \( \chi \) particles which are produced after inflation, is thermalized instantaneously giving rise to the radiation energy density,

\[ \rho_r = n_\chi m_\chi = \frac{g a^4}{8\pi^3} \left| \frac{y^2(x - \tilde{v})}{x^3} \right| M_p^4 , \]

where we have dropped the cosmic dilution factor due to instant character of reheating process. Our numerical calculations show that the reheating temperature, \( 10^{10} \text{GeV} \lesssim T \lesssim 10^{11} \text{GeV} \) (for permissible values of the parameter \( g \)) which is higher by about three orders of magnitudes compared to its counter part associated with gravitational particle production.

The decay rate of \( \chi \) particles to \( \psi \) and \( \bar{\psi} \) is given by,

\[ \Gamma_{\chi \psi} = h^2 m_\chi / 8\pi \]

which must be larger than the expansion rate of universe for the back reaction of \( \chi \) particles, on the background post inflationary evolution of \( \phi \), to be negligible. This gives the lower bound on the parameter \( h \),

\[ \Gamma_{\chi \psi} > H \Rightarrow h^2 > 8\pi \frac{H_{\text{end}}}{g|\phi_{\text{prod}} - v|} . \]

where we have made use of the fact that the Hubble parameter, \( H \approx H_{\text{end}} \) in the non-adiabatic region. Relation (19) along with generic values of parameter \( g \) leads to the region in parameter space \((h, g)\) which may give rise to viable instant preheating.

IV. CONCLUSIONS

In this paper we have investigated a possibility for reheating followed by D-brane inflation described by the effective potential (3). The D-brane effective potential belongs to the category of non-oscillatory models for which the conventional reheating mechanism does not work. The gravitational particle production is generally inefficient and leads to reheating temperature around \( 10^{8} \text{GeV} \) in the present model. The instant preheating is demonstrated to be more efficient than gravitational particle production. The mechanism involves interaction of inflaton with a scalar degree of freedom \( \chi \) with zero bare mass \( m_\chi^2 = g^2 (\phi - v)^2 \chi^2 \). The effective mass of \( \chi \) linearly depends on the inflaton field which is identically zero at the end of inflation but increases thereafter. The scalar degree of freedom interacts with fermion and anti-fermion pair \((h \chi \bar{\psi} \psi)\). We found a viable range of parameters for preheating demanding the fulfillment of non-adiabaticity condition during post inflationary evolution and at the same time keeping the back reaction under control. This requirement leads to the range of parameters specified by: \( 0.006 \lesssim g \lesssim 1 \) and \( 0.053 \lesssim h \lesssim 1 \). The corresponding preheating temperature \( T \) is shown to be in the range : \( 10^{10} \text{GeV} \lesssim T \lesssim 10^{11} \text{GeV} \). We find that, for the permissible values of parameters \((h, g)\), the process of preheating is almost instantaneous. Interestingly, the allowed range of parameters \( h \) and \( g \) and the corresponding preheating temperature turn out to be weakly dependent on the choice of numerical values of inflationary parameters suitable to observations.

To be rigorous, we should note that the number of e-folds \( N \), in general, depends upon the reheating temperature. In our analysis, we have assumed horizon exit corresponding to 60 e-folds which is a popular choice. However, the general constraints do not allow \( N \) to take appreciably larger values than the one quoted here. We have observed that generic variations of \( N \) does not lead significant improvement of the preheating temperature.
We, therefore, conclude that instant reheating is a viable mechanism for a single throat model.

Let us point out here an important issue related to the energy transfer from inflaton to the standard model particles. Though concrete proposal for such mechanism does not exist at present, one possibility could be to embed the flux compactification of Type IIB theory in F-theory compactification with fluxes. One could then consider the scenario of intersecting branes to obtain the spectrum of particles with standard model gauge group. The fermion field that we have considered in this paper could very well be one of the fields in the standard model living on the world volume of the intersecting branes. Another possibility is related to the assumption that the standard model particles are localized in one of the D7-branes wrapping the four cycle of the compact internal manifold used to generate the non-perturbative potential. Such a possibility is recently analyzed in [28] (see also Ref. [29] on the related theme). It should be noted that in a realistic scenario, the energy transfer to standard model degrees of freedom may not be that efficient as assumed in the present analysis while comparing the instant preheating with gravitational particle production. In our opinion, this is an important issue which deserves further investigations.

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