hep-th/9907038
LBNL-43634, SLAC-PUB-8187, SU-ITP-99/34

Orientifolds, RG Flows, and Closed String Tachyons

hep-th/9907038 v2 8 Jul 1999

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We discuss the fate of certain tachyonic closed string theories from two perspectives. In both cases our approach involves studying directly configurations with finite negative tree-level cosmological constant. Closed string analogues of orientifolds, which carry negative tension, are argued to represent the minima of the tachyon potential in some cases. In other cases, we make use of the fact, noted in the early string theory literature, that strings can propagate on spaces of subcritical dimension at the expense of introducing a tree-level cosmological constant. The form of the tachyon vertex operator in these cases makes it clear that a subcritical-dimension theory results from tachyon condensation. Using results of Kutasov, we argue that in some Scherk-Schwarz models, for finely-tuned tachyon condensates, a minimal model CFT times a subcritical dimension theory results. In some instances, these two sets of ideas may be related by duality.

July 1999

1. Introduction

Many closed string theories contain tachyons. In addition to the bosonic string, numerous orbifold models have tachyons appearing in a twisted sector. Although there are also many string backgrounds which do not contain tachyons in the perturbative spectrum, it is potentially of interest to understand the fate of those which do.

Some work that was done earlier involved attempting to study the tachyon potential directly through (off-shell) calculations of the tachyon effective potential [1]. In this paper we take a somewhat different approach to this question (using a combination of orientifold physics and the observations in [2]) and discuss some examples which realize it. A basic issue that arises is the following. A perturbative closed string compactification has vanishing tree-level vacuum energy (formally all one-point functions, including those of the dilaton and graviton, vanish in the closed-string sphere diagram). Therefore the tachyon potential, at fixed dilaton vacuum expectation value, looks like figure 1 in the regime accessible to the perturbative closed string description; in particular the tachyonic maximum of the potential is at $V(0) = 0$. Then tachyon condensation leads to configurations with negative energy. Our main question is whether (1) there is a minimum configuration with finite negative energy into which the system can roll (and then what the eventual solution of the dilaton equation of motion is) or whether (2) the tachyon rolls to negative infinity.

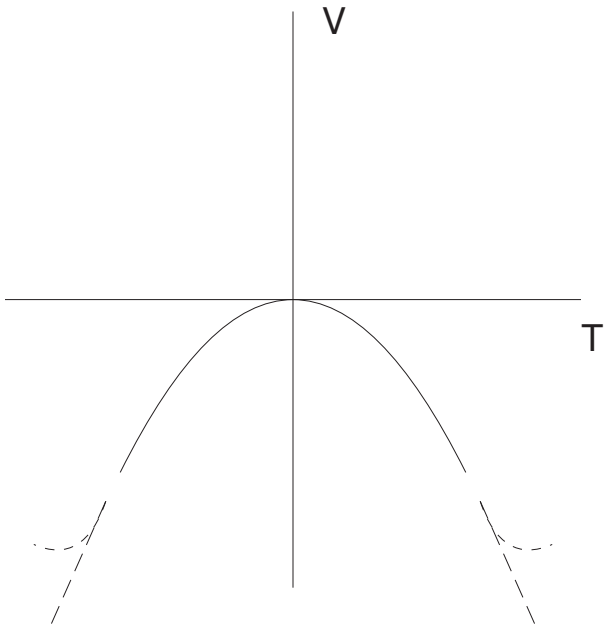

Figure 1: Tachyon on top of potential hill

We will here consider two different ways of obtaining configurations with finite negative tree-level cosmological constant. The first involves the physics of orientifolds (and

analogous configurations in closed string theories); the second involves strings propagating on spaces of subcritical dimension. As we will mention below, these two methods may in fact be related to each other by dualities.

In the context of open string theories orientifold backgrounds [3,4] have the feature one would need for possibility (1), namely a negative contribution to the tree-level vacuum energy, which is finite for fixed nonzero string coupling. In §2 we will set up an open string theory which involves orientifolds, anti-orientifolds, branes, and anti-branes in which the potential looks like figure 1. This model is similar to one discussed earlier in the context of string-string duality by Bergman and Gaberdiel [5]. Then using locally the mechanism of [6,7,8], we will see that the tachyons condense, leaving the system in a finite-negative-energy minimum involving only orientifolds and anti-orientifolds.

We find that in some closed string theories, non-perturbative configurations, analogous to orientifolds in the open string case, exist and can play a similar role. These configurations include the S-duals of orientifold planes [9,10] and non-level-matched but anomaly free orbifold backgrounds such as those of [11]. We will discuss these configurations, which look locally like figure 2, in §3. In this approach, problem is then to relate configurations of the type in figure 1 with those of the type in figure 2.

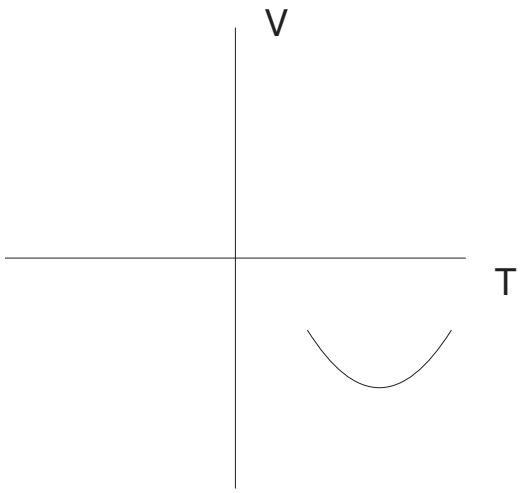

Figure 2: Tachyon at minimum of its potential

The simplest such examples are given by the S-dual of the open string theory of §2 (and various heterotic cousins of this S-dual model). We discuss these theories in §4. They involve orbifold fixed points whose degrees of freedom microscopically represent the collective coordinates of NS five-branes sitting at the singularities [9], as well as other orbifold fixed points, breaking a complementary half of the supersymmetries from the

first set, where NS anti-five-branes sit. Globally this system is unstable, and can undergo NS brane-anti-brane annihilation. Condensation of the unstable mode therefore leaves a vacuum with S-dual orientifolds and anti-orientifolds; the negative (S-dual) orientifold tensions account for the negative vacuum energy after tachyon condensation.

Our second approach, based on [2], is the following. An a priori different way of getting backgrounds with finite negative tree-level cosmological constant was explained in [2], in which corresponding solutions to the dilaton and graviton equations of motion (linear dilaton solutions) were obtained. (The latter step in particular eliminates the dilaton and graviton tadpoles which we ignored in the preceeding discussion.) These solutions involve strings propagating on spaces of sub-critical dimension, in which the worldsheet beta functions are cancelled by the contributions of dilaton gradients. In §5 we will argue that a large class of tachyonic theories can be seen to flow to such backgrounds upon tachyon condensation. This analysis uses simple features of the closed string tachyon vertex operators in this class of examples. In particular generically these vertex operators constitute (or generate) mass terms lifting some of the degrees of freedom on the worldsheet, and one is left after renormalization-group flow with a theory of sub-critical dimension of the type considered in [2]. For instance, we will see in §5 that by tuning the tachyon condensate in some Scherk-Schwarz models one can obtain minimal model CFTs times a sigma model on a subcritical dimension target space. We further find that this point of view is potentially related to the above point of view involving orientifolds if the type of duality conjectured in [5] is realized in string theory.

Before proceeding we should remark on the dilaton direction in the potential. Any Poincare-invariant configuration with negative tree-level vacuum energy is not a solution to the equations of motion. In string frame the vacuum energy is

$$\Lambda = \frac{1}{g_s^2}\Lambda_0 + \dots \tag{1.1}$$

So in order to solve the equations of motion the dilaton ϕ must vary over spacetime. Similar remarks apply to the spacetime metric $G_{\mu\nu}$. As we will discuss in §5, the full solution may be obtained through the conformal field theory techniques of [2]. However at some points in our analysis, particularly involving our first approach to the problem (in §2-§4), we will attempt to separate the dependence of the spacetime potential on the originally tachyonic mode from its dependence on the dilaton and metric by holding ϕ and $G_{\mu\nu} = \eta_{\mu\nu}$ fixed artificially. The true dynamics of the system will of course involve all of these fields, as discussed more thoroughly in §5.

Many interesting papers which discuss tachyons on branes in open string theories ("field theoretic" tachyons) have recently appeared; see e.g. [12]. There have also been interesting recent papers on other types of non-supersymmetric string backgrounds [13].

2. An illustrative open-string theory

Consider the type IIB string theory compactified on $T^d/I_d\Omega$, where I_d is a reflection on d coordinates and Ω is a reversal of orientation on the IIB worldsheet. The fixed planes of the $I_d\Omega$ action, the orientifold $(9-d)$-planes, have effectively negative tension [14]; that is, their graviton and dilaton one-point functions have the opposite sign to those of $D(9-d)$-branes. There being no degrees of freedom tied to the orientifold planes, this leads to a negative contribution to the tree-level vacuum energy without leading to any unphysical negative kinetic energy. These orientifold planes are also charged oppositely to the $D(9-d)$-branes under the $(10-d)$-form RR potential. Therefore in the compact T^d, in order for RR flux lines to end consistently, we must introduce 16 $D(9-d)$-branes. In addition to cancelling the RR charge, the positive tensions of the branes cancel the negative tree-level vacuum energy of the orientifolds. This example is very well known, as a T-dual of the type I string theory on T^d.

Now consider instead a $Z_2 \times Z_2$ orientifold of type IIB on T^d generated by

$$g_1 = I_d\Omega \tag{2.1}$$

$$g_2 = I_d\Omega(-1)^F\delta \tag{2.2}$$

where δ is a translation by halfway around one of the circles, with say coordinate x_1, of the T^d. The element g_2 preserves the opposite half of the supersymmetry from the half preserved by g_1; it introduces *anti*-orientifolds at positions halfway around the x_1 circle from the positions of the orientifold planes introduced by g_1. The element g_2 alone would require the introduction of 16 *anti*-D$(9-d)$ branes.

Given both the orientifolds and the anti-orientifolds, we now have many options. We could:

A) Add the 16 D$(9-d)$-branes and 16 anti-D$(9-d)$-branes corresponding to each orientifold action alone, and then project the resulting open string spectrum onto invariant states. This leads to a theory with RR charge conserved, zero tree-level vacuum energy, and gauge group $O(16) \times O(16)$ or a rank-16 subgroup depending on the positions of the

branes. There is also a tachyon multiplet in the $(\mathbf{16},\mathbf{16})$ of $O(16)\times O(16)$, for sufficiently small radius or sufficiently small separation of branes and anti-branes, and a closed string tachyon for sufficiently small radius.

Alternatively we could:

B) Add $k<16$ D$(9-d)$-branes and k anti-D$(9-d)$-branes. Again the RR charge is conserved, but the tree-level vacuum energy is negative (as there are too few branes to cancel the negative tension from the orientifolds). The gauge group is now $O(k)\times O(k)$ and there is a scalar in the bifundamental which becomes tachyonic in appropriate regimes of the classical moduli space where the branes and anti-branes are close enough to each other.

It is clear in this example that we can annihilate $16-k$ of the branes against $16-k$ of the antibranes, which proceeds via condensation of $(16-k)\times(16-k)$ components of the bifundamental tachyon along with condensation of the appropriate magnetic tachyon [8]. In particular when all the open string tachyons of A) condense, we are left with only orientifolds and antiorientifolds, no gauge group, and finite negative vacuum energy (for fixed nonzero dilaton). So in this open-string context, the zero-energy tachyonic theory A) rolls to a finite negative energy configuration B) (plus a gas of excitations, since energy is conserved in this process).

3. Negative-tension defects in closed string theory

Now, we turn to a discussion of closed string theories with tachyons. It is natural to ask if there are negative-tension configurations in closed string theory, analogous to the orientifolds of §2, to which such theories could roll.

3.1. S-duality and Orientifolds

One obvious place to look for such a configuration is from the S-dual of an orientifold plane in type IIB theory [9,15]. Consider for example an orientifold 5-plane. In the IIB theory on $\mathbb{R}^4/I_4\Omega$, cancelling the RR charge locally gives a D5-brane at an orientifold 5-plane. The S-dual of this orientifold is type IIB on the orbifold $\mathbb{R}^4/I_4(-1)^{F_L}$. The twisted sector of this orbifold constitutes precisely the worldvolume theory on an NS 5-brane at a Z_2 singularity. Giving vacuum expectation values to the twisted sector scalars corresponds to moving the NS 5-brane off of the fixed point. The Z_2 fixed point which is left (which has no degrees of freedom associated with it perturbatively – all of the "twisted sector

moduli" are accounted for by the translation modes of the NS 5-brane) is the S-dual of the orientifold. The full closed-string orbifold theory has zero vacuum energy, so since the NS 5-branes have positive tension (measured by an integral on a sphere surrounding the brane), the S-dual of the orientifold contributes negatively to the vacuum energy. So one expects, for instance, that a dilaton gradient should emerge as one turns on the marginal perturbations in the twisted sector of the orbifold (moving the NS brane away from the S-dual orientifold), in analogy with [16]. It would be very interesting to understand how this works out in detail.

3.2. More general examples from non-perturbative orbifolds

The S-dual orientifold is an example of a larger class of negative-tension backgrounds. In perturbative string theory, modular invariance imposes conditions which sometimes go beyond the physical condition of anomaly cancellation. Modular invariance in the context of orbifold models requires the inclusion of twisted sectors. In the S-dual orientifold example, after removing the NS 5-branes we are left with an orbifold fixed point with no twisted states. As we discussed above this object exists in the theory and has a negative contribution to Λ_{tree}.

More generally we can consider orbifold models in which the level-matching conditions, which ensure that physical perturbative string states exist in the twisted sectors, are violated [11]. For example, let us consider the heterotic theory compactified on a K3 surface realized as an orbifold $T^4/\mathbb{Z}_2$ (our comments generalize immediately to the $T^4/\mathbb{Z}_k$ orbifold realizations of K3 with $k \neq 2$ as well). Green-Schwarz anomaly cancellation requires only that

$$dH = trR \wedge R - trF \wedge F - n_5 \delta_5 \tag{3.1}$$

where δ_5 denotes delta functions localized at the positions of the n_5 fivebranes.

On the compact K3, $\int dH = 0$, so $\int trF \wedge F + n_5 = \int trR \wedge R$. This means that the number of instantons in the gauge bundle, n_{inst}, and the number of 5-branes n_5 are constrained by

$$n_{inst} + n_5 = 24. \tag{3.2}$$

The perturbative string orbifold level-matching conditions require the orbifold group to act nontrivially, according to one of a few discrete possibilities, on the gauge degrees of

freedom of the heterotic string. This enforces the introduction of 24 instantons. Non-perturbative orbifold backgrounds with fewer instantons and a compensating number of 5-branes involve non-modular-invariant choices of the action on the gauge degrees of freedom. These backgrounds fit into an intricate web of six-dimensional string dualities [11]. Again in these cases, the fact that the 5-branes have positive tension, and therefore contribute positively to Λ_{tree} in these backgrounds, means that the non-level-matched orbifold fixed points that are left over contribute negatively to Λ_{tree}.

In fact, even without invoking non-perturbative physics we can find configurations with effectively negative tension. Suppose for example that we start with an orbifold action with the standard embedding in the gauge degrees of freedom of the heterotic string. In this case, dH cancels locally. Now consider moving some large instantons off the orbifold fixed points. These instantons constitute gauge fivebranes [17] of the heterotic string, and have positive tension. Since the overall vacuum energy of the string vacuum is zero, the contribution of the remaining orbifold fixed points is negative. Clearly there is a whole zoo of possibilities of this sort. Furthermore as long as the instantons are large, the whole configuration is accessible perturbatively.[1]

3.3. S-dual O9-planes?

Hull and collaborators [10] have proposed formulating the $SO(32)$ heterotic string as an orbifold of type IIB by $(-1)^{F_L}$. In perturbative string theory, where we must add the twisted sectors dictated by modular invariance, orbifolding by $(-1)^{F_L}$ produces IIA from IIB and vice versa.

On the other hand, there are other solutions to the anomaly cancellation conditions. In particular, one could add an $SO(32)$ or $E_8 \times E_8$ gauge group, obtaining the heterotic string theory. In the $SO(32)$ case, it is argued in [10] that this background can be deconstructed into an S-dual O9-plane plus (in our way of counting) 16 NS 9-branes. In particular, by S-dualizing the Born-Infeld like action for the ordinary O9-plane plus 16 D9-branes, one obtains this formulation of the heterotic string. In this point of view, the S-dual O-9-plane has negative tension, $\Lambda_{S-O9} < 0$, which is cancelled by the tensions of the 16 NS 9-branes to give a vacuum with $\Lambda_{tree} = 0$. These branes, if they exist, may provide further possibilities for the endpoint of tachyon condensation in various backgrounds.

[1] We thank P. Aspinwall and R. Plesser for discussions on these points.

4. Examples of tachyon condensation

In the last section we saw that there exists a plethora of possible configurations of negative vacuum energy (a la figure 2), realized microscopically as S-duals of orientifolds and their generalizations. In this section we consider the problem, on which we will only make a start here, of understanding which tachyonic models (fig 1) roll to to which (if any) of these negative-energy configurations. In §5 we will consider another type of negative-energy configuration which can plausibly be the endpoint of tachyon condensation for a different class of theories. We have mostly been confined here to an analysis of orbifold backgrounds. One can hope that once more generic non-supersymmetric compactification geometries are understood, there will be more general examples of such backgrounds. Similarly many of the tachyonic theories (fig 1) that we are interested in explaining are perturbative string orbifolds. In general, as twisted sector tachyon condensation will break the quantum symmetry of the orbifold, we would expect orbifold models to roll to more generic geometrical backgrounds.

So we will here consider a non-supersymmetric theory whose tachyons arise at a more generic point on the CFT moduli point (away from an orbifold point). In particular, let us consider the non-supersymmetric model which is S-dual to the $d = 4$ (d is the number of compact dimensions) case of the orientifold model of §2. We begin with type IIB theory on T^4 and mod out by a $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry generated by

$$g_1 \;=\; I_4(-1)^{F_L}, \quad g_2 \;=\; I_4(-1)^{F_R}\delta_1. \tag{4.1}$$

Here δ_1 is say a shift halfway around one of the circles of the torus. This theory has 16 orbifold fixed points (8 fixed points each for the g_1 and g_2 actions). Based on the analysis of [9], we find that there are NS fivebranes sitting at the g_1 fixed points and NS anti-five-branes sitting at the g_2 fixed points. The vacuum energy is zero, and for large enough radius there is no tachyon in the $(-1)^F\delta_1$ twisted sector. At genus zero, this theory is consistently described by nonsingular orbifold conformal field theory.

Globally the set of fivebranes and anti-five-branes is topologically indistinguishable from the vacuum. This being true at the level of the classical field configuration, we expect to find an instability in this system at some order in conformal perturbation theory about the orbifold limit. The leading possibility is that moving some combination of fivebranes off the fixed point(s)–an exactly marginal perturbation–induces a tachyonic mass term for the collective coordinate describing the motion of the anti-five-branes off the orbifold

points. This corresponds to a force on the anti-five-branes linear in their displacement from the orbifold points. There is such a force in some regimes at the level of the low-energy gravity theory, valid when all distances are much larger than string scale. There is globally therefore a manifest instability in the system, though α' corrections may come in at substringy distances and lift the tachyonic mode from the point where the anti-fivebranes are at the orbifold points. In any case it is natural to postulate that the fivebranes and anti-fivebranes annihilate, leaving behind the S-dual orientifolds which are hidden at the orbifold fixed points.

Given this, this example gives us one case where the result of condensation of a negative mode, most probably a tachyon, is a configuration of finite negative tension of the type discussed in §3 (at fixed dilaton) . Many other similar models can be obtained by considering the heterotic theory on T^4 modded out by I_4 and $I_4(-1)^F$, with a level-matching action on the gauge bundle that introduces 24 instantons and 24 anti-instantons. These then can move off the fixed points and enlarge; there is a global instability in the moduli space which we would expect to see perturbatively. The global minimum of the potential for the non-dilatonic moduli is again a configuration of finite negative tension of the type discussed in §3. We leave detailed analysis of this class of examples for future work.

5. Tachyons and RG Flow

Another context in which backgrounds with finite negative tree-level cosmological constant arise is the following [2]. Consider bosonic strings propagating in a spacetime of dimension $D < D_{crit}$.[2] The Weyl anomaly cancellation conditions, which include

$$0 \equiv \beta^\Phi = \frac{D - D_{crit}}{6} - \frac{\alpha'}{2}\nabla^2\Phi + \alpha' \nabla_\mu \Phi \nabla^\mu \Phi - \frac{\alpha'}{24} H^2 + O(\alpha'^2) \tag{5.1}$$

can still be solved in such a situation by allowing the dilaton to vary over spacetime. For example one exact CFT solution is the linear dilaton background [2,18]. The Weyl anomaly conditions, regarded as equations of motion for the spacetime theory, follow from a Lagrangian

$$S \propto \int d^D x \sqrt{-G} e^{-2\Phi} \left(-\frac{2(D - D_{crit})}{3\alpha'} + R - \frac{1}{12} H^2 + 4\partial_\mu \Phi \partial^\mu \Phi + O(\alpha') \right) \tag{5.2}$$

[2] Our discussion applies with minor modifications to other strings as well.

The first term is a finite negative cosmological constant proportional to $D - D_{crit}$.

It was noted in [2] that such sub-critical-dimension theories could arise naturally as the result of tachyon condensation. Tachyon vertex operators are relevant operators of the internal worldsheet CFT (that is the part of the worldsheet CFT not involving the noncompact Poincare-invariant spacetime).

Let us consider a specific case. Take the bosonic string theory compactified on the $SO(32)$ lattice. In a fermionic description the $SO(32)^2$ current algebra arises from 32 real left-moving fermions $\lambda^I, I = 1, \ldots, 32$ and 32 real right-moving fermions $\tilde{\lambda}^{\tilde{I}}, \tilde{I} = 1, \ldots, 32$. There are in addition 10 scalar fields $X^\mu, \mu = 0, \ldots, 10$ making up the rest of the 26 units of central charge. This theory has in addition to the singlet tachyon (the universal tachyon of the bosonic string) a $(\mathbf{32}, \mathbf{32})$ tachyon. The vertex operator for the latter is

$$V_{(32,32)} = \lambda^I \tilde{\lambda}^{\tilde{J}} e^{ik \cdot X} \tag{5.3}$$

To describe tachyon condensation, at leading order we wish to add the integrated tachyon vertex operator to the worldsheet action. At zero momentum k this operator is relevant, and the covariant vertex operator which we would naively add,

$$\int d^2\sigma \sqrt{g} \lambda \tilde{\lambda} \tag{5.4}$$

has nontrivial dependence on the conformal factor ω in the worldsheet metric. (Here we use diffeomorphisms to fix $g = \eta e^{2\omega}$ where η is the flat metric on the worldsheet.) Heuristically, since (5.4) is a mass term for λ and $\tilde{\lambda}$, we expect this relevant deformation to lift these degrees of freedom from the worldsheet theory, giving us a string theory propagating effectively in $D = 26 - \frac{N}{2}$ where N is the number of worldsheet fermions that pair up and become massive.

However since this procedure involves going off shell, as formulated here it breaks the Weyl symmetry of the worldsheet theory classically. When we have a well-defined on-shell string theory, before condensing the tachyon, the formulation of the worldsheet theory involves dividing the worldsheet path integral out by the volume of the Weyl group, thereby eliminating the conformal factor ω from the theory. It is difficult to see how this degree of freedom could be introduced in a physically continuous deformation from that point.

Let us therefore consider adding instead[3]

$$\int d^2\sigma \sqrt{g} \lambda \tilde{\lambda} e^{ik\cdot X} \tag{5.5}$$

with $k^2 = m^2 < 0$. This operator is dimension (1,1) and the expression is Weyl invariant (due to the metric-dependence in the regulated operators [19]). In particular let us take $k = (\pm i\kappa, 0, \ldots, 0)$ with κ positive. This gives us a dimension (1,1) operator describing a time-dependent tachyon condensate. Then the terms we can add are of the form

$$\int d^2\sigma \sqrt{g} \lambda \tilde{\lambda} (a_+ e^{\kappa X_0} + a_- e^{-\kappa X_0}) \tag{5.6}$$

for some parameters $a_\pm$.

The addition (5.6) describes the initial time-dependence of the tachyon as it begins to roll down its potential hill. Let us take $a_- = 0$ so that the condensate vanishes at very early times $X_0 \to -\infty$. Though as the condensation proceeds we expect higher order corrections to (5.6), we do expect that the tachyon will continue to condense (rather than returning to its unstable maximum) and the coefficient of the $\lambda\tilde{\lambda}$ mass term in (5.6) will be nonzero for $X_0 > -\infty$. Therefore it seems quite plausible that the effect of tachyon condensation is to lift the degrees of freedom $\lambda, \tilde{\lambda}$ and correspondingly introduce a nonzero $D - 26$ term in the beta function equations (spacetime equations of motion). In order to preserve conformal invariance, therefore, the spacetime dilaton needs to begin varying so as to maintain $\beta^\Phi = 0$. (In other words we are adding a marginal perturbation (5.5) and therefore must maintain that the total central charge is constant.) One example of a solution to the modified equations of motion would, for instance, be the linear dilaton solution of [2,18], though it is not clear that the dynamics favors this solution.

5.1. Relation to orientifold picture?

This lifting of the $\lambda, \tilde{\lambda}$ degrees of freedom agrees with the picture one would obtain from the relation of this theory to a certain type I orientifold conjectured by Bergman and Gaberdiel [5]. The orientifold in question is simply an orientifold of type IIB by a $\mathbb{Z}_2 \times \mathbb{Z}_2$ action generated by $(-1)^F$ and Ω. This theory (which is extremely similar to the one we discussed in §4, differing by a shift and some duality transformations) has an orientifold 9-plane, an anti-orientifold 9-plane, 16 D9-branes and 16 anti-D9-branes. This

[3] We thank S. Shenker for a discussion on this approach.

gives a gauge group $SO(32)^2$ with tachyons in the $(\mathbf{32},\mathbf{32})$ representation. This theory contains in its spectrum of D1-branes one which has the worldvolume degrees of freedom of the bosonic string compactified on the $SO(32)$ lattice. These degrees of freedom consist of 10 bosonic collective coordinates from the 1-1 sector of open strings, and 32 left-moving fermions from the 1-9 sector and 32 right-moving fermions from the $1-\bar{9}$ sector.

In this theory it is relatively clear what happens when the $(\mathbf{32},\mathbf{32})$ tachyon condenses: the D9-branes annihilate with the anti-D9-branes. This leaves the spacetime theory with the O9 and anti-O9 planes, which contribute a finite negative amount to the tree-level cosmological constant as discussed in very similar circumstances above.

Now let us consider what happens on the D1-brane probe in the orientifold theory. Once the D9-branes and anti-D9-branes have annihilated, the contributions from the 1-9 and $1-\bar{9}$ sectors disappear. One is left with a low-energy worldvolume theory with 10 scalar collective coordinates $X^\mu, \mu = 1,\ldots,10$. This gives the same result as we found for the bosonic string in the RG flow analysis (in particular the absence of both the fermions λ and $\tilde{\lambda}$ and the decoupling of the Liouville mode classically on the worldsheet). Therefore if the duality between the two theories conjectured in [5] turns out to hold[4] there is a relation between the two approaches we are considering in this paper.

5.2. Other Models

There is a large set of models amenable to the analysis involving RG flow. For example, let us consider a (T-dual version of a) Scherk-Schwarz compactification. This consists of an orbifold of the toroidally compactified type II or heterotic theory by $(-1)^F\delta$ where δ is a level-matched shift symmetry of the Narain lattice. We choose δ so that the Scherk-Schwarz tachyon(s) are momentum modes which becomes tachyonic at sufficiently large radius. The integrated vertex operators for these tachyons take the form (in the type II case for specificity)

$$\int d^2z d^2\theta \sum_p \lambda_p cos[(p+\delta'+k)\cdot\mathbf{X}] + \rho_p sin[(p+\delta'+k)\cdot\mathbf{X}] \tag{5.7}$$

Here we take δ' to be half a momentum lattice vector, and we sum over those p in the momentum lattice such that the internal piece of the added operator is relevant–i.e. we

[4] The meaning of this duality proposal is not entirely clear, since the dilaton potential is not flat in the proposed duals.

only include tachyons. k is spacetime momentum in the noncompact directions. We work in $(1,1)$ superspace with $\mathbf{X} = X + \theta\psi + \bar{\theta}\tilde{\psi} + F$ a scalar superfield. In the $(0,0)$ picture, in components, the vertex operator is

$$V^{(0,0)} = (\delta'_L + k) \cdot \psi (\delta'_R + k) \cdot \tilde{\psi} e^{i\delta' \cdot X} e^{ik \cdot X} \tag{5.8}$$

The renormalization group flow for this type of potential has been studied by Kutasov [20]. He finds generically a mass gap for the degrees of freedom in $\mathbf{X} \cdot \delta'$. With some fine-tuning of the coefficients λ and ρ, one can obtain minima in the potential which locally take the form of $\mathbf{X}^n$ potentials for various $n > 2$. Thus minimal models arise as the result of tachyon condensation in these special directions. In such cases, although one does not lift all the central charge of the $\mathbf{X}$ multiplet, it decreases in the flow to the value of the appropriate minimal model, and the orthogonal spacetime part of the theory is still of sub-critical dimension.

A similar analysis can be done for heterotic compactifications of the form $T^d/(-1)^F\delta$. More generally, this set of ideas might be helpful in any situation where the closed string tachyon is charged under some spacetime gauge symmetry. Such theories with charged tachyons are natural candidates for admitting dual descriptions in terms of branes (as in [5]), where the tachyon condensation corresponds to some kind of brane annihilation process.

It would be interesting to see if these approaches to understanding closed string tachyons can teach one about string theory at the Hagedorn transition. A different approach to this problem was recently discussed in [21].

Acknowledgements

We would like to thank O. Aharony, P. Aspinwall, M. Berkooz, J. Harvey, I. Klebanov, E. Martinec, R. Plesser, and S. Shenker for discussions. We are also grateful to TASI-99 and the 1999 Amsterdam Summer Workshop on String Theory for hospitality during the course of this work. The research of S.K. is supported by NSF grant PHY-95-14797, by DOE contract DE-AC03-76SF00098, by an A.P. Sloan Foundation Fellowship and by a DOE OJI Award. The research of J.K. is supported by the Department of Defense NDSEG Fellowship Program and by NSF grant PHY-9870115. The research of E.S. is supported by the DOE under contract DE-AC03-76SF00515 and by an A.P. Sloan Foundation Fellowship.

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