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Tachyon condensation in unstable type-I D-brane systems

Oren Bergman

California Institute of Technology
Pasadena, CA 91125, USA, and
CIT/USC Center for Theoretical Physics
Univ. of Southern California, Los Angeles CA
E-mail: `bergman@theory.caltech.edu`

Abstract: Type-I string theory provides eight classes of unstable D-brane systems. We determine the gauge group and tachyon spectrum for each one, and thereby describe the gauge symmetry breaking pattern in the low-energy world-volume field theory. The topologies of the resulting coset vacuum manifolds are related to the real K-theory groups KO^{-n}, extending the known relations between the type-II classifying spaces BU and U and the complex K-theory groups K^0 and K^{-1}. We also comment on the role of the background D9-branes.

Keywords: D-branes, Brane Dynamics in Gauge Theories.

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Contents

1. Introduction

An unstable system of D-branes is characterized by the existence of tachyonic modes in the open string spectrum. Examples of such systems include brane-antibrane configurations in type-II string theory, and unstable D-branes in type-II and bosonic string theory. Since tachyons have a negative mass-squared they are expected to condense to a non-vanishing expectation value corresponding to the true vacuum of the open string theory, provided the complete potential is bounded from below.[1] On the other hand, since D-branes can also be thought of as states in a closed string theory, one expects an unstable system of such states to decay into a stable closed string state carrying the same charges. In particular, a system carrying no net charge should decay into the closed string vacuum.

Sen has conjectured that this decay is described by tachyon condensation [1]. This conjecture makes three important predictions. First, the tachyon vacuum should be identified with the closed string vacuum, and therefore its negative energy density should precisely cancel the positive energy density of the unstable D-brane system. Second, soliton configurations of the tachyon field should be identified with lower-dimensional D-branes, and finally, all open string states should be removed from the spectrum in the tachyon vacuum. A complete proof of the conjecture presumably requires solving the full open string field theory associated with the unstable D-brane

[1] In the bosonic case the potential is unbounded from below, and the condensate is at most meta-stable.

system, and there are recent indications that this may indeed be possible [2, 3]. Notwithstanding, a considerable amount of evidence for the correctness of the conjecture has accumulated from various sources, including low-energy world-volume field theory [4]–[7], conformal field theory [8], and level-truncated open string field theory [9]. The latter in particular has been extremely successful in testing the first prediction, and all three have been useful in verifying the second. The last prediction of Sen's conjecture, and probably the most significant, is less well established. Whereas the first two are essentially classical results, understanding how the open string states are removed from the spectrum appears to require taking quantum effects into account [6].

At the most basic level, an unstable D-brane system is described by a gauge field theory, where the tachyon plays the role of an ordinary Higgs field. The process of tachyon condensation then reduces to the Higgs mechanism. This simple description, while clearly not complete, already incorporates some of the features described above. In particular, the Higgs mechanism creates a mass gap for some of the fields, which can be seen as a low-energy manifestation of the removal of (some) open string states from the spectrum. In addition, spontaneously broken gauge theories exhibit stable soliton configurations, whose topological charges are classified by the homotopy groups of the vacuum manifold. These can in turn be identified with the topological charges of lower-dimensional D-branes via K-theory [10, 11].

The systems studied most extensively are brane-antibrane configurations in type-II string theory, and unstable D-branes in type-II and bosonic string theory. The gauge group for N brane-antibrane pairs is $\mathrm{U}(N)\times\mathrm{U}(N)$, and the tachyon transforms in the bi-fundamental representation. Tachyon condensation therefore breaks the group to the diagonal $\mathrm{U}(N)$, and the vacuum manifold is equivalent to $\mathrm{U}(N)$. The corresponding spectrum of stable solitons consists (for large enough N) of all even co-dimension configurations, in agreement with the spectrum of stable (BPS) D-branes. The gauge group on a system of N unstable D-branes is $\mathrm{U}(N)$, and the tachyon transforms in the adjoint representation. In this case the unbroken gauge group (for even N) is given by $\mathrm{U}(N/2)\times\mathrm{U}(N/2)$ [12, 11]. The resulting vacuum manifold is $\mathrm{U}(N)/(\mathrm{U}(N/2)\times\mathrm{U}(N/2))$, which for large N is equivalent to the universal classifying space BU. This time the spectrum of stable solitons consists of odd co-dimension configurations, which again agrees with the stable D-brane spectrum.[2]

The aim of this paper is to extend the above picture to unstable D-brane systems in type-I string theory. Here we find eight classes of systems, with different gauge groups and different tachyon spectra. In section 2 we describe how to obtain the gauge group and tachyon representation in each case. In section 3 we make contact

[2]This is true for the type-II unstable D-branes, but not for the bosonic D-branes. Due to the cubic term in the tachyon potential for the latter, the gauge group $\mathrm{U}(N)$ is actually unbroken in the bosonic case (see [13] for a discussion of the closely related $\mathrm{SU}(N)$ case). The vacuum manifold is therefore trivial, which is consistent with the fact that all bosonic D-branes are unstable.

type-I system	$\mathcal{G}$	tachyon	$\mathcal{H}$	$\mathcal{G}/\mathcal{H}$
$N(\mathrm{D9}+\overline{\mathrm{D9}})$	$\mathrm{O}(N)\times\mathrm{O}(N)$	$(\Box,\Box)$	$\mathrm{O}(N)$	O
N D8	$\mathrm{O}(N)$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathrm{U}(N/2)$	O/U
N D7	$\mathrm{U}(N)$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathrm{Sp}(N)$	U / Sp
N D6	$\mathrm{Sp}(N)$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathrm{Sp}(N/2)\times\mathrm{Sp}(N/2)$	BSp
$N(\mathrm{D5}+\overline{\mathrm{D5}})$	$\mathrm{Sp}(N)\times\mathrm{Sp}(N)$	$(\Box,\Box)$	$\mathrm{Sp}(N)$	Sp
N D4	$\mathrm{Sp}(N)$	$\Box\Box$	$\mathrm{U}(N/2)$	Sp / U
N D3	$\mathrm{U}(N)$	$\Box\Box$	$\mathrm{O}(N)$	U / O
N D2	$\mathrm{O}(N)$	$\Box\Box$	$\mathrm{O}(N/2)\times\mathrm{O}(N/2)$	BO
$N(\mathrm{D1}+\overline{\mathrm{D1}})$	$\mathrm{O}(N)\times\mathrm{O}(N)$	$(\Box,\Box)$	$\mathrm{O}(N)$	O
N D0	$\mathrm{O}(N)$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathrm{U}(N/2)$	O / U
N D(-1)	$\mathrm{U}(N)$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathrm{Sp}(N)$	U / Sp

Table 1: Tachyon condensation and classifying spaces in type-I unstable D-brane systems. N is assumed to be even for the $p = 8, 7, 5, 4, 2, 0$ and -1 systems, and a multiple of 4 for $p = 6$.

with real K-theory, generalizing the known relations between complex K-theory and unstable D-brane systems in type-II. In section 4 we discuss a couple of subtleties associated with the background D9-branes of type-I, and we end with some conclusions and open questions in section 5. For convenience, the main results of the paper are summarized in table 1.

2. Unstable type-I D-brane systems

In this section we shall determine the gauge group and tachyon representation for each of the unstable D-brane systems in type-I string theory. Some of this information, such as the gauge group for $p = 1, 5$ and 9, and the tachyon spectrum for $p = -1, 3$ and 7, can be obtained using the consistency conditions of [14]. The rest, such as the gauge group and tachyon spectrum for even p, will be obtained by other means. We will ignore the background D9-branes for now, and consider their effect in section 4.

2.1 p odd

The odd-dimensional systems correspond to Dp-$\overline{\mathrm{D}p}$ systems in type-IIB string theory projected by Ω. The type-IIB system has a gauge group $\mathrm{U}(N)\times\mathrm{U}(N)$ from the diagonal $p-p$ and $\overline{p}-\overline{p}$ sectors, and a tachyon transforming in the bi-fundamental representation $(\mathbf{N},\overline{\mathbf{N}})\oplus(\overline{\mathbf{N}},\mathbf{N})$ from the off-diagonal $p-\overline{p}$ and $\overline{p}-p$ sectors.

For $p = 1, 5$ and 9 the RR component of the boundary state is invariant under Ω [15], so both the Dp-brane and the $\overline{\mathrm{D}p}$-brane are invariant. Since $p-p$ (and $\overline{p}-\overline{p}$) strings are therefore mapped to themselves, one can use the consistency conditions of [14] to determine the gauge group. One simply gets twice the result of [14], i.e. $\mathcal{G} = \mathrm{O}(N) \times \mathrm{O}(N)$ for $p = 1$ and 9, and $\mathrm{Sp}(N) \times \mathrm{Sp}(N)$ for $p = 5$. On the other hand, since $p - \overline{p}$ strings are mapped to $\overline{p} - p$ strings, these conditions do not restrict the tachyon spectrum. The projection simply picks out one linear combination of the two sectors with an arbitrary phase. This leaves precisely the *bi-fundamental* representation regardless of the phase. The unbroken group $\mathcal{H}$ is therefore the diagonal combination of the two factors in $\mathcal{G}$.

For $p = -1, 3$ and 7 the RR component of the boundary state is odd, so the brane and antibrane are interchanged. In this case $p - \overline{p}$ strings are mapped to themselves, so the Gimon-Polchinski conditions fix the action of Ω on the tachyons. One finds

$$T_{a\overline{b}} \longrightarrow \omega_p T_{b\overline{a}} \ , \tag{2.1}$$

where $\omega_p = (-i)^{1+(9-p)/2}$ [16, 10]. The gauge group is not fixed by these conditions, but, as with the tachyons in the previous case, the projection simply keeps one linear combination of the two $\mathrm{U}(N)$'s with an arbitrary phase [10]. It then follows from (2.1) that the tachyons transform in the *symmetric* representation of $\mathrm{U}(N)$ for $p = 3$, and in the *antisymmetric* representation for $p = -1$ and 7. The unbroken gauge groups in these cases were determined in [12]. One gets $\mathrm{O}(N)$ in the first case, and $\mathrm{Sp}(N)$ in the second case.

2.2 p even

For the even-dimensional branes we start with the corresponding non-BPS Dp-brane in type-IIB string theory, which has a gauge group $\mathrm{U}(N)$ and a tachyon in the adjoint representation. The world-sheet arguments of [14] fail in this case, since the Dp-D9 strings have an odd number of mixed (ND) boundary conditions, and therefore an odd number of fermionic zero modes in both the R and NS sectors. Instead we will determine $\mathcal{G}$ by demanding that the Dp-D9 strings are real. Since these strings transform in the spinor representation of the Clifford algebra formed by the fermionic zero modes, and at the same time in the fundamental representation of the gauge group, demanding reality will restrict the form of $\mathcal{G}$.

In the R sector there are $p+1$ fermionic zero modes (one of which is time-like), so the ground state transforms as a spinor of $\mathrm{SO}(p,1)$. In the NS sector there are $9-p$ zero modes, and the ground state is a spinor of $\mathrm{SO}(9-p)$. For odd p there are two irreducible representations in both sectors corresponding to the two Weyl spinors. The zero-mode part of the GSO projection $(-1)^f = \prod \Gamma_i$ removes one and keeps the other. For even p there is only one irreducible spinor and no GSO projection.[3] The resulting spinors are *real* for $p = 0, 1, 2 \pmod 8$, *pseudoreal* for $p = 4, 5, 6 \pmod 8$, and *complex* for $p = 3, 7 \pmod 8$. Consequently $\mathcal{G}$ is *orthogonal*

[3] The odd-dimensional Clifford algebras associated with the fermionic zero modes for even p actually have *two* irreducible representations (related by $\Gamma_i \to -\Gamma_i$), which are equivalent as representations of the corresponding groups. This subtlety can be overlooked in determining the spectrum, but becomes important in the path integral, where one is required to sum over spin structures [10].

in the first case, *symplectic* in the second case, and *unitary* in the third case. This is consistent with what we found in the previous section for odd p. Note however that the above argument does not determine how many factors of these groups $\mathcal{G}$ contains. In particular, for $p = 1, 5$ and 9 there are two factors, whereas for $p = 3$ and 7 there is only one. This is of course a consequence of the fact that in the former case the type-I system consists of BPS branes and BPS antibranes, and in the latter only of non-BPS branes. By analogy, we conclude that the gauge groups for even p must be $\mathrm{O}(N)$ for $p = 0, 2 \pmod 8$, and $\mathrm{Sp}(N)$ for $p = 4, 6$.

In order to determine the representation of the tachyon we need to know how Ω acts on the tachyon wavefunction, and how it acts on the CP factors of the $p - p$ string. The latter can be determined from the above results, together with the fact that the vector is odd under Ω [17]. We find

$$\Lambda \longrightarrow \gamma_\Omega \Lambda^T \gamma_\Omega^{-1}\,, \qquad \gamma_\Omega = \begin{cases} \mathbf{1} & p = 0, 2 \pmod 8 \\ \mathbf{J} & p = 4, 6\,, \end{cases} \tag{2.2}$$

where

$$\mathbf{J} = \begin{pmatrix} 0 & i\mathbf{1} \\ -i\mathbf{1} & 0 \end{pmatrix}, \tag{2.3}$$

The action on the tachyon wavefunction[4] can be determined using Sen's approach, by considering a disc amplitude in type-IIB string theory involving a tachyon vertex operator at the boundary and a RR p-form vertex operator in the bulk [18]. Both vertex operators contribute a σ_1 factor in the trace, so the amplitude is non-zero, and gives rise to the interaction

$$\int C^{(p)} \wedge dT\,. \tag{2.4}$$

Since $C^{(p)}$ is odd under Ω for $p = 0 \pmod 4$, and even for $p = 2 \pmod 4$, it follows that T is odd for $p = 0 \pmod 4$ and even for $p = 2 \pmod 4$. Combining this with the action on the CP factors gives *antisymmetric* representations for $p = 0, 6$ (mod 8), and *symmetric* representations for $p = 2, 4$.

The unbroken gauge groups for $\mathrm{O}(N)$ with a Higgs field in the symmetric and antisymmetric representations were determined in [12], and are given by $\mathrm{O}(N/2) \times \mathrm{O}(N/2)$ and $\mathrm{U}(N/2)$, respectively. The unbroken gauge groups for $\mathrm{Sp}(N)$ can be determined in a similar way, and turn out to be $\mathrm{U}(N/2)$ for a symmetric Higgs, and $\mathrm{Sp}(N/2) \times \mathrm{Sp}(N/2)$ for an antisymmetric Higgs.

To facilitate this sum, Witten proposed to include an additional world-sheet fermion $\eta(\tau)$ at each boundary of the open string ending on a Dp-brane [10]. The GSO operator $(-1)^f = \eta \prod \Gamma_i$ then provides the required prescription. The signature of η must be chosen such that the Weyl spinor one gets after GSO-projection has the same properties as the original spinor. The R sector Clifford algebra is therefore increased to that of $\mathrm{SO}(p+1, 1)$ for $p = 0 \pmod 4$, and $\mathrm{SO}(p, 2)$ for $p = 2$ (mod 4). In the NS sector one effectively gets $\mathrm{SO}(9-p, 1)$ in the first case, and $\mathrm{SO}(10-p)$ in the second.

[4]This is not fixed by action on the vector since the two states belong to different CP sectors [18].

3. Relation to real K-theory

The topology of the tachyon vacuum manifold, i.e. the classifying space, determines the soliton spectrum, and therefore the spectrum of lower-dimensional D-branes. On the other hand, since D-branes carry gauge fields they are classified in K-theory. In particular, D-branes in type-II brane-antibrane systems are elements of $\widetilde{K}^0(X)$, and D-branes in type-II unstable D-branes are elements of $K^{-1}(X)$. It is therefore not surprising that there exists a relation between the the mapping class groups, i.e. homotopy groups, of the vacuum manifold and the isomorphism class groups, i.e. K-theory groups, of the gauge bundles. In the complex case the relevant relations are [19, 20]

$$\begin{aligned} \widetilde{K}^0(X) &\approx [X, \mathrm{BU}] \\ K^{-1}(X) &\approx [X, U]\,, \end{aligned} \tag{3.1}$$

where BU is the $N \to \infty$ limit of $\mathrm{U}(N)/(\mathrm{U}(N/2) \times \mathrm{U}(N/2))$, and U is the $N \to \infty$ limit of $\mathrm{U}(N)$.[5] One usually assumes that the space X is compact, but an extension to non-compact X is possible by defining K-theory with compact support.

Note that the classifying spaces on the right hand side appear to be in the wrong place; the vacuum manifold is U for the brane-antibrane system and BU for the unstable D-brane. On the other hand, non-trivial tachyon configurations cannot be in the vacuum everywhere in X, and are therefore not classified by maps from X to the vacuum manifold. Consider for example $X = \mathbb{R}^k$ (or its compactification S^k). Finite energy tachyon field configurations must approach the vacuum at infinity, and are therefore associated with maps from S^{k-1} to the vacuum manifold. These are in turn classified by $\pi_{k-1}(U)$ for the brane-antibrane system, and by $\pi_{k-1}(\mathrm{BU})$ for the unstable D-branes. From the relations[6]

$$\begin{aligned} \pi_{k-1}(U) &= \pi_k(\mathrm{BU}) \\ \pi_{k-1}(\mathrm{BU}) &= \pi_k(U)\,, \end{aligned} \tag{3.2}$$

it then follows that the tachyon vacuum manifolds appearing in (3.1) should indeed be shifted by one relative to the corresponding K-theory.

In the real case the story is similar. The analogous relations between the higher KO-groups and the classifying spaces are given by [21]

$$KO^{-n}(X) \approx [X, \mathcal{M}_n]\,, \tag{3.3}$$

[5]More generally, $\widetilde{K}^{-n}(X) = [X, \Omega^n \,\mathrm{BU}]$, where $\Omega^n Y$ is the n-th iterated loop space of Y. One can prove that $\Omega\,\mathrm{BU}$ is homotopically equivalent to U, and $\Omega^2\,\mathrm{BU}$ is homotopically equivalent to BU. In conjunction with (3.1), this fact leads to Bott periodicity, $K^{-n-2}(X) = K^{-n}(X)$.

[6]These follow from $\pi_k(X) = \pi_{k-1}(\Omega X)$ [20], and the homotopic equivalences $\Omega\,\mathrm{BU} \sim U$, $\Omega^2\,\mathrm{BU} \sim \mathrm{BU}$.

where, in order,

$$\mathcal{M}_n = \mathrm{BO},\ \mathrm{O},\ \mathrm{O}\,/\,\mathrm{U},\ \mathrm{U}\,/\,\mathrm{Sp},\ \mathrm{BSp},\ \mathrm{Sp},\ \mathrm{Sp}\,/\,\mathrm{U},\ \mathrm{U}\,/\,\mathrm{O} \tag{3.4}$$

for $n = 0, \ldots, 7 \pmod 8$. Since type-I D-branes in the D9-$\overline{\mathrm{D9}}$ system (ignoring the background D9-branes) are classified by $\widetilde{KO}^0(X)$, it is apparent from table 1 that the vacuum manifolds are again shifted by one relative to the corresponding KO-groups. In analogy with the complex case, for $X = S^k$ this follows from the identities[7]

$$\pi_{k-1}(\mathcal{M}_{n+1}) = \pi_k(\mathcal{M}_n)\,. \tag{3.5}$$

For example, the D5-brane can be obtained as a stable defect in the D7-brane system, corresponding to the generator of

$$\pi_1(\mathrm{U}\,/\,\mathrm{Sp}) = \pi_2(\mathrm{O}\,/\,\mathrm{U}) = KO^{-2}(S^2) = \mathbb{Z}\,. \tag{3.6}$$

4. Including the background D9-branes

Two important subtleties arise when one includes the 32 background D9-branes. First, since the zero-point energy of the NS sector of a Dp-D9 string is given by [17]

$$m^2 = \frac{5-p}{8}\,, \tag{4.1}$$

the $p = 8, 7$ and 6 systems have 32 additional tachyons, which transform in the fundamental representation of the corresponding gauge group $\mathcal{G}$. From the world-volume gauge theory perspective, their only effect is to reduce the rank of $\mathcal{G}$, keeping its form fixed. The results in table 1 are therefore qualitatively unchanged. On the other hand, as was first pointed out in [16], their presence has a dramatic effect on the single D7 and D8-brane in spacetime, which are found to be unstable despite being tachyon-free in the $p-p$ sector. A natural question is what these branes decay into, given that they carry non-trivial topological ($\mathbb{Z}_2$) charges in K-theory.

The discussion of [10] seems to suggest that the decay products are O(32) gauge field configurations on the background D9-branes, which are classified respectively by $\pi_1(\mathrm{O}(32))$ and $\pi_0(\mathrm{O}(32))$ (both of which are $\mathbb{Z}_2$). In particular, the latter corresponds to a non-trivial $\mathbb{Z}_2 \subset \mathrm{O}(32)$ holonomy. The D8-brane therefore decays into a gauge field configuration that is pure gauge at $x = \pm\infty$, such that $A(\infty)$ and $A(-\infty)$ are related by the reflection element in O(32) [22].[8] Despite being topologically

[7] These follow from the homotopic equivalence of the n-th iterated loop space of $\mathcal{M}_0 = \mathrm{BO}$ and $\mathcal{M}_n$, e.g. $\Omega\,\mathrm{BO} \sim \mathrm{O}$, $\Omega^2\,\mathrm{BO} \sim \mathrm{O}\,/\,\mathrm{U}$, etc.

[8] The type-I gauge group is actually spin(32)/$\mathbb{Z}_2$, which does not contain this element [10]. However, there are two choices for the $\mathbb{Z}_2$ projection, corresponding to which spinor chirality is kept. These are exchanged by the reflection element of O(32), so the D8-brane corresponds to a domain wall separating regions of type-I vacuum which differ in the chirality of the spinor state.

stable however, these gauge field configurations are not solutions of the Yang-Mills equations. A simple scaling argument shows that (for $p > 6$) they will expand indefinitely to minimize the action [10], leaving behind a dilute gauge field.

There exist also other topologically stable gauge field configurations corresponding to non-trivial elements in $\pi_{8-p}(\mathrm{O}(32))$, with $p = 5, 1, 0$ and -1. In contrast to the previous two, these will tend to shrink, which suggests the existence of p-dimensional stringy objects [10]. Indeed, Dp-branes with the above values of p exist and are stable, even in the presence of the background D9-branes. Given that these D-branes are stable, what is the role of the gauge field configurations in this case?

The answer is related to the second subtlety associated with the background D9-branes. Namely, the gauge group of the unstable $p = 9$ system is $\mathrm{O}(32+N) \times \mathrm{O}(N)$ rather than $\mathrm{O}(N) \times \mathrm{O}(N)$. The tachyon is still bi-fundamental, so the unbroken subgroup is now $\mathrm{O}(32) \times \mathrm{O}(N)$. Consequently the vacuum manifold is topologically equivalent to $\mathrm{O}(32+N)/\,\mathrm{O}(32)$, rather than $\mathrm{O}(N)$. For $N = 1$ this is simply the 32-sphere S^{32}. More generally it is known as the real Stiefel manifold $V_{32+N,N}$. A common property of this space for all N is that $\pi_k(V_{32+N,N}) = 0$ for $k < 32$. Therefore there are *no topologically stable tachyon configurations* (of relevance in ten dimensions). The D-brane charges are instead encoded in the above gauge field configurations. The configurations which tend to shrink ($p = -1, 0, 1, 5$) correspond to stable D-branes, and those which tend to expand ($p = 7, 8$) correspond to topologically stable, but dynamically unstable, D-branes.

In light of this one wonders why $\widetilde{KO}^0(X)$ is the appropriate classifying group for D-branes in type-I string theory. The relation to homotopy theory is

$$\widetilde{KO}^0(S^n) = \pi_{n-1}(O)\,, \tag{4.2}$$

but the vacuum manifold is actually $\mathrm{O}(32+N)/\,\mathrm{O}(32)$, not O. On the other hand, as argued above, the D-brane charges are encoded in the topology of $\mathrm{O}(32)$, rather than the topology of the vacuum manifold. Since $n \leq 10$, one is well within the stability regime for the homotopy groups of $\mathrm{O}(32)$, which are therefore the same as those of O. This is why $\widetilde{KO}^0(X)$ gives the correct answers.

5. Conclusions

Tachyons appear in many forms when supersymmetry is broken in string theory. Since it is difficult to make general statements about the consequence of their condensation, it is useful to have many examples. Unstable D-brane systems provide a relatively simple arena for studying this phenomenon for the case of open string tachyons. In this paper we analyzed the unstable D-branes systems of type-I string theory in the most basic approach, namely the world-volume gauge theory coupled to a Higgs field. It would be interesting to apply some of the other approaches mentioned in the introduction to these systems.

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Another interesting question is how the physics of unstable D-brane systems in string theory is lifted to M-theory. The two brane-antibrane systems are M2-$\overline{\text{M2}}$ and M5-$\overline{\text{M5}}$. The former is difficult to study, since it corresponds to a non-trivial conformal field theory. The situation is somewhat analogous to a string-antistring system, since the M2-brane really serves as the fundamental object in M-theory. The M5-$\overline{\text{M5}}$ system is, at least qualitatively, more tractable [5]. For a single pair, it corresponds to a rank two antisymmetric tensor theory (without the restriction of self-duality). The tachyon presumably comes from an open M2-brane, and therefore corresponds to a string-field. While the complete dynamics of the M2-brane are not understood, it is straightforward to generalize the Higgs mechanism to a rank two antisymmetric tensor field [23]. In particular, there exists a stable co-dimension three defect, which can be identified with the M2-brane [5].

Another unstable system in M-theory is the non-chiral $S^1/\mathbb{Z}_2$ compactification, also known as the $E_8 \times \overline{E_8}$ system [24]. In this case the two "ends of the world" support ordinary gauge theories, and one might expect their annihilation to be described, in part, by an ordinary Higgs mechanism. In particular, since the only non-trivial configuration of E_8 (of relevance in ten dimensions) is the instanton associated with $\pi_3(E_8) = \mathbb{Z}$, which is furthermore identified with the M5-brane, one expects the symmetry breaking pattern to be $E_8 \times E_8 \to E_8$. The question is whether there is a tachyon field that achieves this.

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References

[1] A. Sen, *Tachyon condensation on the brane antibrane system*, *J. High Energy Phys.* **08** (1998) 012 [hep-th/9805170].

[2] V.A. Kostelecky and R. Potting, *Analytical construction of a nonperturbative vacuum for the open bosonic string*, hep-th/0008252.

[3] A.A. Gerasimov and S.L. Shatashvili, *On exact tachyon potential in open string field theory*, *J. High Energy Phys.* **10** (2000) 034 [hep-th/0009103];
D. Kutasov, M. Marino and G. Moore, *Some exact results on tachyon condensation in string field theory*, *J. High Energy Phys.* **10** (2000) 045 [hep-th/0009148].

[4] A. Sen, *Supersymmetric world-volume action for non-BPS D-branes*, *J. High Energy Phys.* **10** (1999) 008 [hep-th/9909062].

[5] P. Yi, *Membranes from five-branes and fundamental strings from Dp-branes*, *Nucl. Phys.* **B 550** (1999) 214 [hep-th/9901159].

[6] O. Bergman, K. Hori and P. Yi, *Confinement on the brane*, *Nucl. Phys.* **B 580** (2000) 289 [hep-th/0002223];
G. Gibbons, K. Hori and P. Yi, *String fluid from unstable D-branes*, hep-th/0009061.

[7] K. Dasgupta, S. Mukhi and G. Rajesh, *Noncommutative tachyons*, *J. High Energy Phys.* **06** (2000) 022 [hep-th/0005006];
J.A. Harvey, P. Kraus, F. Larsen and E.J. Martinec, *D-branes and strings as non-commutative solitons*, *J. High Energy Phys.* **07** (2000) 042 [hep-th/0005031];
C. Sochichiu, *Noncommutative tachyonic solitons: interaction with gauge field*, *J. High Energy Phys.* **08** (2000) 026 [hep-th/0007217];
R. Gopakumar, S. Minwalla and A. Strominger, *Symmetry restoration and tachyon condensation in open string theory*, hep-th/0007226;
G. Mandal and S.-J. Rey, *A note on D-branes of odd codimensions from noncommutative tachyons*, hep-th/0008214;
Y. Matsuo, *Topological charges of noncommutative soliton*, hep-th/0009002;
J.A. Harvey and G. Moore, *Noncommutative tachyons and k-theory*, hep-th/0009030.

[8] A. Sen, SO(32) *spinors of type-I and other solitons on brane-antibrane pair*, *J. High Energy Phys.* **09** (1998) 023 [hep-th/9808141];
J.A. Harvey, D. Kutasov and E.J. Martinec, *On the relevance of tachyons*, hep-th/0003101;
P. Fendley, H. Saleur and N.P. Warner, *Exact solution of a massless scalar field with a relevant boundary interaction*, *Nucl. Phys.* **B 430** (1994) 577 [hep-th/9406125];
J. Majumder and A. Sen, *Vortex pair creation on brane-antibrane pair via marginal deformation*, *J. High Energy Phys.* **06** (2000) 010 [hep-th/0003124].

[9] V.A. Kostelecky and S. Samuel, *The static tachyon potential in the open bosonic string theory*, *Phys. Lett.* **B 207** (1988) 169;
A. Sen and B. Zwiebach, *Tachyon condensation in string field theory*, *J. High Energy Phys.* **03** (2000) 002 [hep-th/9912249];
N. Berkovits, *The tachyon potential in open Neveu-Schwarz string field theory*, *J. High Energy Phys.* **04** (2000) 022 [hep-th/0001084];
W. Taylor, *D-brane effective field theory from string field theory*, *Nucl. Phys.* **B 585** (2000) 171 [hep-th/0001201];
N. Moeller and W. Taylor, *Level truncation and the tachyon in open bosonic string field theory*, *Nucl. Phys.* **B 583** (2000) 105 [hep-th/0002237];
J.A. Harvey and P. Kraus, *D-branes as unstable lumps in bosonic open string field theory*, *J. High Energy Phys.* **04** (2000) 012 [hep-th/0002117];

N. Berkovits, A. Sen and B. Zwiebach, *Tachyon condensation in superstring field theory*, *Nucl. Phys.* **B 587** (2000) 147 [hep-th/0002211];
R. de Mello Koch, A. Jevicki, M. Mihailescu and R. Tatar, *Lumps and p-branes in open string field theory*, *Phys. Lett.* **B 482** (2000) 249 [hep-th/0003031];
P.-J.D. Smet and J. Raeymaekers, *Level four approximation to the tachyon potential in superstring field theory*, *J. High Energy Phys.* **05** (2000) 051 [hep-th/0003220];
A. Iqbal and A. Naqvi, *Tachyon condensation on a non-BPS D-brane*, hep-th/0004015;
N. Moeller, A. Sen and B. Zwiebach, *D-branes as tachyon lumps in string field theory*, *J. High Energy Phys.* **08** (2000) 039 [hep-th/0005036];
L. Rastelli and B. Zwiebach, *Tachyon potentials, star products and universality*, hep-th/0006240;
J.R. David, *Tachyon condensation in the D0/D4 system*, *J. High Energy Phys.* **10** (2000) 004 [hep-th/0007235];
W. Taylor, *Mass generation from tachyon condensation for vector fields on D-branes*, *J. High Energy Phys.* **08** (2000) 038 [hep-th/0008033];
R. de Mello Koch and J.P. Rodrigues, *Lumps in level truncated open string field theory*, hep-th/0008053;
N. Moeller, *Codimension two lump solutions in string field theory and tachyonic theories*, hep-th/0008101;
A. Iqbal and A. Naqvi, *On marginal deformations in superstring field theory*, hep-th/0008127.

[10] E. Witten, *D-branes and K-theory*, *J. High Energy Phys.* **12** (1998) 019 [hep-th/9810188].

[11] P. Hořava, *Type-IIA D-branes, K-theory and matrix theory*, *Adv. Theor. Math. Phys.* **2** (1999) 1373 [hep-th/9812135].

[12] L.-F. Li, *Group theory of the spontaneously broken gauge symmetries*, *Phys. Rev.* **D 9** (1974) 1723.

[13] H. Ruegg, *Extremas of* SU(N) *Higgs potentials and symmetry breaking pattern*, *Phys. Rev.* **D 22** (1980) 2040.

[14] E.G. Gimon and J. Polchinski, *Consistency conditions for orientifolds and d-manifolds*, *Phys. Rev.* **D 54** (1996) 1667 [hep-th/9601038].

[15] O. Bergman and M.R. Gaberdiel, *A non-supersymmetric open-string theory and S-duality*, *Nucl. Phys.* **B 499** (1997) 183 [hep-th/9701137].

[16] M. Frau, L. Gallot, A. Lerda and P. Strigazzi, *Stable non-BPS D-branes in type-I string theory*, *Nucl. Phys.* **B 564** (2000) 60 [hep-th/9903123];
M. Frau, L. Gallot, A. Lerda and P. Strigazzi, *Stable non-BPS D-branes of type-I*, hep-th/0003022.

[17] J. Polchinski, *String theory*, vol. 2, Cambridge, 1998.

[18] A. Sen, *Non-BPS states and branes in string theory*, hep-th/9904207.

[19] M.F. Atiyah, *K-theory*, Benjamin, 1964.

[20] R. Bott and L.W. Tu, *Differential forms in algebraic topology*, Springer, 1982,

[21] M. Karoubi, *K-theory. An introduction*, Springer, 1978.

[22] J.H. Schwarz, *Remarks on non-BPS D-branes*, *Class. and Quant. Grav.* **17** (2000) 1245 [hep-th/9908091].

[23] S.-J. Rey, *The Higgs mechanism for Kalb-Ramond gauge field*, *Phys. Rev.* **D 40** (1989) 3396.

[24] M. Fabinger and P. Hořava, *Casimir effect between world-branes in heterotic M-theory*, *Nucl. Phys.* **B 580** (2000) 243 [hep-th/0002073].