TACHYONS IN STRING THEORY

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We give a non-technical review of some of the recent developments in our understanding of the tachyon in string theory. We also illustrate the conjecture that open string theory provides a complete description of the dynamics of unstable D-branes.

In this brief review I plan to give a general overview of tachyons and their significance in open string theory. I shall try to address the following questions:

(1) What are tachyons?
(2) How do we deal with tachyons in quantum field theory?
(3) How do tachyons appear in string theory?
(4) How do we make sense of tachyons in string theory?

I shall end the review by describing an open string completeness conjecture that arises out of the study of open string tachyons.

Let us begin with the question: What are tachyons? Historically tachyons were described as particles which travel faster than light. If we use the relativistic equation

$$v = \frac{pc}{\sqrt{p^2 + m^2c^2}}\,, \tag{1}$$

relating the velocity v of a particle to its momentum p, mass m and the velocity of light c, then we see that tachyons can also be regarded as particles with negative mass^2, i.e. imaginary mass. Both descriptions sound equally bizarre. On the other hand tachyons have been known to exist in string theory almost since its birth, and hence we need to make sense of them.

Actually tachyons do appear in conventional quantum field theories as well. Consider, for example, a classical scalar field ϕ with potential $V(\phi)$. To simplify notation I shall from now on set the Planck's constant $\hbar$ and the velocity of light c to 1. In p-space and 1-time dimension labelled by the time coordinate x^0 and space coordinates x^i $(1 \le i \le p)$ the lagrangian of the scalar field is

$$L = \frac{1}{2} \int d^p x [(\partial_0 \phi)^2 - \partial_i \phi \partial_i \phi - V(\phi)]\,. \tag{2}$$

Normally we choose the origin of ϕ so that the potential $V(\phi)$ has a minimum at $\phi = 0$. In this case quantization of ϕ gives a scalar particle of mass^2 $= V''(\phi)|_{\phi=0}$. This gives a positive mass^2 particle. But now suppose the potential has a maximum at $\phi = 0$. Then $V''(\phi)|_{\phi=0}$ is negative. Naive quantization will give a particle of negative mass^2. Thus we have a tachyon!

In this case however it is clear what we are doing wrong. When we identify $V''(0)$ as the mass^2 of the particle, we are making an approximation. We expand $V(\phi)$ in a Taylor series expansion in ϕ, and treat the cubic and higher order terms as small corrections to the quadratic term. This is true only if the quantum fluctuations of ϕ around $\phi = 0$ are small. But if $V(\phi)$

has a maximum at $\phi = 0$, then $\phi = 0$ is a classically unstable point. Hence we cannot expect the fluctuations of ϕ to be small. The remedy to this difficulty is to find the minimum ϕ_0 of the potential $V(\phi)$, and quantize the system around this point. More precisely this means that we can expand the potential around $\phi = \phi_0$, and treat the cubic and higher order terms in the expansion to be small. The mass^2 of the particle now can be identified as $V''(\phi_0)$. This is positive since $V(\phi)$ has a minimum at $\phi = \phi_0$. Hence the theory does not have tachyons.

Thus we see that the existence of a tachyon in a scalar field theory implies that the potential for the scalar field has a local maximum at the origin. In order for the theory to be sensible at least in perturbation theory, the potential must also have a (local) minimum. Typically whenever the potential in a scalar field theory has more than one extremum we can construct non-trivial (possibly unstable) classical solutions which depend on one or more spatial directions. For example consider a potential of the form $V(\phi) \propto (\phi^2 - \phi_0^2)^2$. In this case $V(\phi)$ has a maximum at $\phi = 0$ and a pair of minima at $\phi = \pm\phi_0$. In this theory we can construct a domain wall solution where 1) ϕ depends on one spatial coordinate x^1, 2) as $x^1 \to \infty$, $\phi \to \phi_0$, 3) as $x^1 \to -\infty$, $\phi \to -\phi_0$, and 4) the total energy is minimized subject to these constraints. For this configuration the energy density is concentrated around $x^1 \simeq 0$. This gives rise to a 'codimension 1 defect'. For more complicated cases we can have more complicated defects (of higher codimension). Examples of such defects are vortices which are codimension 2 defects, 't Hooft–Polyakov monopoles which are codimension 3 defects, etc. In general for a codimension k defect the energy density is localized around a subspace of dimension $(p - k)$.

The lessons learned from the field theory examples may be summarized as follows:

- Existence of tachyons in the spectrum tells us that we are expanding the potential around its maximum rather than its minimum.
- The correct procedure to deal with such a situation is to find the (global) minimum of the potential and expand the potential around the minimum. The resulting theory has a positive mass^2 scalar particle instead of a tachyon.
- Associated with the existence of tachyons we often have non-trivial space dependent classical solutions (defects).

We now turn to the discussion of tachyons in string theory. The conventional description of string theory is based on 'first quantized' formalism rather than a field theory. We take a string (closed or open) and quantize it maintaining Lorentz invariance. This gives infinite number of states characterized by momentum $\vec{p}$ and other discrete quantum numbers n. It turns out that the energy of the nth state carrying momentum $\vec{p}$ is given by $E_n = \sqrt{\vec{p}^2 + m_n^2}$, where m_n is some constant. This state clearly has the interpretation of being a particle of mass m_n. Thus string theory contains infinite number of single 'particle' states, as if it is a field theory with infinite number of fields.

Quantization of some closed or open strings gives rise to states with negative m_n^2 for some n. This corresponds to a tachyon! For example, the original bosonic string theory formulated in (25+1) dimensions has a tachyon in the spectrum of closed strings. This theory is thought to be inconsistent due to this reason.

Superstring theories are free from tachyons in the spectrum of closed string. But for certain boundary conditions, there can be tachyon in the spectrum of open strings even in superstring theories. Thus the question is: Does the existence of tachyons make the theory inconsistent? Or does it simply indicate that we are quantizing the theory around the wrong point? The problem in analyzing this question stems from the fact that unlike the example in a scalar field theory, the tachyon in string theory does not originally come from quantization of a scalar field. Thus in order to understand the tachyon, we have to reconstruct the scalar field and its potential from the known results in string theory, and then analyze if the potential has a minimum.

It turns out that for open string tachyons we now know the answer in many cases. On the other hand, closed string tachyons are only beginning to be explored. Hence we shall focus mainly on open string tachyons in this review.

There are five consistent, apparently different, superstring theories in 9-space and 1-time dimension. We shall focus on two of them, known as type IIA and type IIB string theories. Elementary excitations in this theory come from quantum states of the closed strings. But besides these elementary excitations these theories also contain 'composite' objects known as D-branes or more explicitly Dirichlet p-branes.

A Dp-brane is a p-dimensional object. Thus for example D0-brane corresponds to a particle like object, a D1-brane corresponds to a string-like object, a D2-brane corresponds to a membrane like object and so on. But unlike the kinks and other defects in field theory which are associated with classical solutions of the equations of motion of the fields, D-branes are defined by saying what happens in their presence rather than by saying what they are. Consider, for example, a static flat Dp-brane in flat space-time, lying along a p-dimensional subspace. The definition of a Dp-brane is simply that fundamental strings can end on the p-dimensional hypersurface along which the D-brane lies. This has been illustrated in Fig. 1.

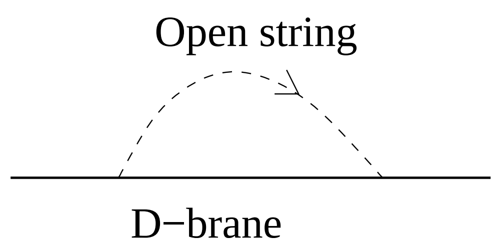

Figure 1. Fundamental strings (shown by dashed line) ending on a D-brane (shown by solid line).

Quantum states of a fundamental open string with ends on a D-brane represent quantum excitation modes of the D-brane. D-branes need to satisfy various consistency requirements, and as a result D-branes for different p have different properties. For type IIA string theory, these properties are summarized as follows:

(1) For even p, Dp-branes are oriented and are known as BPS D-branes due to some special properties which they possess. For these branes, the mass per unit p-volume, also known as the tension $\mathcal{T}_p$ of the brane, is given by

$$\mathcal{T}_p = \frac{1}{(2\pi)^p g_s}\,, \tag{3}$$

in a unit in which the tension of the fundamental string is $\frac{1}{2\pi}$. We shall use this unit throughout this review. g_s is a dimensionless constant known as the string coupling constant. We shall do most of our analysis to lowest order in the perturbation expansion in g_s.

It turns out that all open string states on a BPS D-brane have mass$^2 \geq 0$. Hence there are no tachyons in the spectrum.

(2) For odd p, the Dp-branes are unoriented (non-BPS). The tension $\widetilde{\mathcal{T}}_p$ of a non-BPS Dp-brane is given by

$$\widetilde{\mathcal{T}}_p = \frac{\sqrt{2}}{(2\pi)^p g_s}\,. \tag{4}$$

Each such D-brane has one open string mode with mass$^2 = -\frac{1}{2}$. In other words, there is a tachyonic mode on each of these non-BPS Dp-branes.

For type IIB string theory the situation is reversed. There are now oriented (BPS) Dp-branes for odd p and unoriented (non-BPS) Dp-branes for even p. The results that we shall discuss will be valid both for type IIA and type IIB string theory. Whether we are talking about type IIA theory or type IIB theory should be understood from the context. For example, if we are referring to a non-BPS Dp-brane, then it should be understood that we are talking about type IIA theory if p is odd, and type IIB theory if p is even.

For oriented D-branes we define an anti-D-brane ($\bar{\text{D}}$-brane) to be a D-brane with opposite orientation. It turns out that a coincident BPS Dp-brane $\bar{\text{D}}p$-brane pair has two tachyonic modes, each of mass$^2 = -\frac{1}{2}$, from the open strings with one end on the brane and one end on the antibrane (sectors (c) and (d) in Fig. 2).

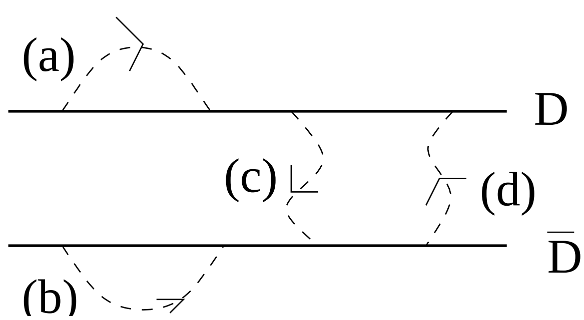

Figure 2. The tachyon on a Dp-$\bar{\text{D}}p$-brane pair comes from open strings whose two ends lie on two different branes.

Since string theory is formulated in a way that is different from a field theory, the method of analysis in string theory is very different from that in a field theory. Nevertheless it is useful to use the language of field theory to describe various situations in string theory. In particular, if we use the analogy with field theory origin of tachyons, then for a non-BPS Dp-brane, the dynamics of the single tachyonic mode should be described by a real scalar field T with negative mass^2 in p-space and one time dimensions. We shall refer to T as tachyon field. For the Dp-$\bar{\text{D}}p$ system, the dynamics of the pair of tachyonic modes should be described by a complex scalar field T with negative mass^2. Various results in string theory can be stated *as if* the dynamics of the tachyon T is described by an effective potential $V_{eff}(T)$ or more generally an effective action $S_{eff}(T)$. We shall first state the main results in this language and then briefly mention the various stringy techniques which are used to derive these results.

Let us begin by reviewing the properties of $S_{eff}(T)$ and $V_{eff}(T)$ which follow from simple considerations. First of all it is known that $S_{eff}(T)$ has simple symmetry properties. For example, for a non-BPS Dp-brane $S_{eff}(-T) = S_{eff}(T)$. On the other hand for a D-$\bar{\text{D}}$ system, $S_{eff}(e^{i\phi}T) = S_{eff}(T)$. The other property of that is obvious is that $V_{eff}(T)$ has a maximum at $T = 0$, since the field T is tachyonic.

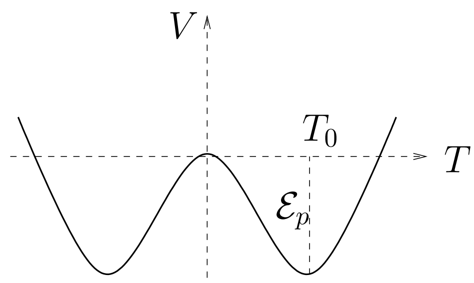

Figure 3. The tachyon potential on a non-BPS Dp-brane. The tachyon potential on a brane-antibrane system can be obtained by revolving this diagram around the vertical axis, so that we get a mexican hat potential.

The interesting questions the answers to which are not obvious are:

(1) Does $V_{eff}(T)$ have a minimum?
(2) If it does have a minimum, then what kind of mass spectrum do we get by quantizing the theory around the minimum?
(3) Do we get topological defects involving the tachyon?

etc. It turns out that the answers to many of these questions are now known. These results can be summarized as follows:

(1) $V_{eff}(T)$ does have a minimum at some value $|T| = T_0$. Furthermore, at this minimum [1,2]

$$V_{eff}(T_0) + \mathcal{E}_p = 0\,, \tag{5}$$

where $\mathcal{E}_p$ denotes the total energy density of the original system. Thus $\mathcal{E}_p = \widetilde{\mathcal{T}}_p$ for a non-BPS Dp brane, and $\mathcal{E}_p = 2\mathcal{T}_p$ for Dp − $\bar{\text{D}}p$ system. Thus at $|T| = T_0$ the total energy density vanishes identically. This situation has been illustrated in Fig. 3.

(2) $|T| = T_0$ configuration describes the closed string vacuum without any D-brane [1, 2]. Thus around this minimum there are no physical open string excitations. This is natural from the point of view of string theory, since the total energy vanishes at $T = T_0$, and hence we can identify this configuration as vacuum without any D-brane. Since there is no D-brane, there should be no open strings in the spectrum. However, this result is very surprising from the point of view of a normal field theory. Shifting the point around which we expand the potential can make a negative mass^2 state into a positive mass^2 state, but we do not normally eliminate the state altogether. On the other hand here expanding the action around the minimum of the potential not only gets rid of the original tachyon state, but also gets rid of the infinite number of other open string states which were present.

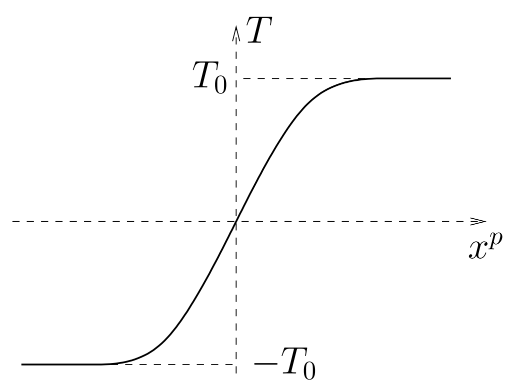

Figure 4. Tachyonic kink solution representing a BPS D$(p-1)$-brane.

(3) There are classical solutions of the equations of motion of T, representing lower dimensional D-branes [3–8]. For example, on a non-BPS Dp-brane a kink as shown in Fig. 4 represents a D$(p-1)$-brane. For this solution the energy density is localized around a codimension 1 subspace ($x^p = 0$) This looks like an ordinary kink solution in a field theory, but there is an important difference. In a conventional field theory, a defect lives on the space in which the field theory lives. Here, at the bottom of the potential, the object (original Dp-brane) whose dynamics the field theory describes disappears altogether. Nevertheless defects in the field can survive and describe non-trivial objects in the (9+1)-dimensional space-time in which full string theory lives.

There are also other more complicated examples of 'tachyonic defects'. For example, a vortex solution on a Dp-$\bar{\rm D}p$ pair describes a BPS D($p-2$)-brane [4]. On the other hand, a 't Hooft–Polyakov monopole on a pair of coincident non-BPS Dp-branes describes a non-BPS D($p-3$)-brane [7]. In this way all D-branes can be regarded as defects in the tachyon field living on D-branes of maximal dimension. This gives a more conventional description of D-branes as defects in the tachyon field. But more importantly this description gives a way to classify Dp-branes based on a branch of mathematics known as K-theory [5, 7]. Several new stable D-branes in various string theories have been discovered using this general scheme.

So far we have only described the properties of static solutions of the tachyon effective field theory. Let us now turn to dynamics, namely time dependent solutions of the equations of motion. In the case of a conventional scalar field, if we displace the field from its maximum and let it roll down the potential, the scalar field will oscillate about its minimum. Energy-momentum tensor $T_{\mu\nu}$ for this solution will have the form

$$T_{00} = \mathcal{E}\,, \qquad T_{ij} = -p(x^0)\delta_{ij}\,, \qquad T_{i0} = 0\,, \tag{6}$$

where i,j refer to the spatial directions. Here $\mathcal{E}$ denotes the energy density, and remains constant due to energy conservation. p denotes the pressure, and will typically oscillate about an average value (0 for a conventional scalar field) as the scalar field oscillates about its minimum. We can now ask: What happens if we displace the tachyon field on a D-$\bar{\rm D}$ pair (or a non-BPS D-brane) and let it roll down the hill? It turns out that in this case the energy density remains constant as usual by energy conservation, but the pressure goes to zero asymptotically instead of oscillating about 0. Thus the final state is a gas of non-zero energy density and zero pressure [9, 10]. Another important quantity that characterizes the system is the dilaton charge that measures the coupling of the dilaton to the system. It turns out that the final system also has zero dilaton charge.

Let me now say a few words about the various techniques which are used to derive the various results that we have mentioned so far. We begin by clarifying a point that may have been somewhat misleading. In stating the various results we have represented the tachyon by a single scalar field. But in reality it is inconsistent to deal only with the tachyon and not take into account its coupling with infinite number of other fields representing the massive string states. Thus in order to study the classical dynamics of the tachyon field, we actually have to solve infinite number of coupled equations involving infinite number of fields.

There are various approaches to this problem, but I shall discuss only two of them in some detail. We can use an indirect approach where we use the fact that there is a one to one correspondence between solutions of equations of motion in string theory and two dimensional conformal field theories. In this approach we directly try to get a solution of the equations of motion (describing the defect solutions or the time dependent rolling tachyon solution for example) by constructing the corresponding conformal field theory in two dimensions. This avoids the need to find the tachyon potential or its coupling to other fields. This procedure has been used to derive analytical results both for static and dynamical properties [4, 8–10]. In the direct approach (based on string field theory) [11–17] we take into account the coupling of the tachyon to all the other fields and try to solve the coupled equations for all the fields using some approximation scheme, known as level truncation. In this scheme, we include only fields below a certain fixed mass (say M). This gives a finite number of fields, and the corresponding equations can be solved (numerically). Then we include more fields, with mass below M' ($M' > M$) and repeat the procedure. If the procedure converges as we go to larger and larger cut-off on the mass, then we are on the right track. So far this procedure has been used to study only the static properties of the tachyon. In these applications the results converge rapidly to the conjectured answers.

There are various other approaches all of which has been successful to various extents in studying the properties of the tachyon. I shall only list them here without giving any details:

(1) Renormalization group flow [18]
(2) Non-commutative geometry [19, 20]
(3) Boundary string field theory [21–23]

etc.

Whatever be the method used, some of the results stated earlier (e.g. disappearance of open string states at the bottom of the tachyon potential, asymptotic vanishing of pressure for the rolling tachyon solution etc.) certainly seem very strange from the point of view of a conventional scalar field theory in which the action is given by the sum of a kinetic and a potential term. We can now ask if it is possible to write down an (unconventional) scalar field theory that can describe this apparently strange dynamics of the tachyon. It turns out that the qualitative aspects of the tachyon dynamics near the minimum of the potential is describable in terms of a non-standard action for the tachyon field T [24–26],

$$-\int d^{p+1}x\, V(T)\, \sqrt{1+\eta^{\mu\nu}\partial_\mu T\partial_\nu T}\,, \tag{7}$$

where η is the diagonal matrix with eigenvalues $(-1,1,1,\ldots 1)$, and $V(T)$ is the tachyon effective potential which in this parametrization has its minima at $T=\pm\infty$ and its maximum at $T=0$.

Various features of this theory makes this an attractive model for describing open string tachyon dynamics. First of all it has kink solutions with zero thickness but finite tension describing a BPS D$(p-1)$-brane, whose world-volume theory is given by the Dirac–Born–Infeld action [27–32]. This is the expected result in full string theory. The time dependent solutions describing the rolling of the tachyon is best described in the Hamiltonian formalism. The Hamiltonian for this system is given by [26, 33]

$$H=\int d^px\sqrt{\Pi^2+(V(T))^2}\,\sqrt{1+(\vec{\nabla}T)^2}\,, \tag{8}$$

where Π is the momentum conjugate to T. As the tachyon rolls down the potential hill, $V(T)\to 0$. Thus at late time we can ignore the $V(T)$ term in the Hamiltonian. It can be shown that in this limit the equations of motion derived from the Hamiltonian (8) are identical to the equations of motion of a pressureless non-interacting fluid (dust) with the identification that $|\Pi|\sqrt{1+(\vec{\nabla}T)^2}$ is interpreted as the energy density ρ of the dust, and $-\partial_\mu T$ is interpreted as the local $(p+1)$-velocity u_μ of the dust particle [26]. Thus at late time the classical solutions in this field theory are in one to one correspondence with the configurations of a system of non-interacting dust. Since dust particles at rest correspond to a pressureless fluid, this automatically explains the result as to why the solutions describing a homogeneous rolling tachyon evolve into a system of zero pressure. It is also easy to explain the vanishing of the dilaton charge. For a D-brane the dilaton charge is proportional to the lagrangian. At late time $V(T)\to 0$. Furthermore, equations of motion derived from the Hamiltonian (8) gives $\eta^{\mu\nu}\partial_\mu T\partial_\nu T=-1$. From (7) we see that for such a configuration the lagrangian and hence the dilaton charge vanishes. Finally, since a dust does not support propagating plane waves (a compressed dust remains compressed for example), we expect that quantization of this theory around the minimum of the potential does not lead to particle like excitations. This is what happens for the open string theory around the tachyon vacuum.

Although the qualitative features of the tachyon effective action given above do not depend on the specific choice of the potential $V(T)$ as long as it is even, has a maximum at $T = 0$ and approaches zero as $T \to \pm\infty$, it turns out that the choice $V(T) \propto \text{sech}(T/\sqrt{2})$ also reproduces some (but not all) of the quantitative aspects of tachyon dynamics on a non-BPS D-brane [34–36]. Although originally the action (8) was proposed in order to reproduce the results involving the open string tachyon without any first principle derivation, a partial justification of the validity of this action has been given in [37].

So far we have discussed the dynamics of the open string tachyon at the purely classical level, and have ignored the coupling of the D-brane to closed strings. Since D-branes act as source for various closed string fields, a time dependent open string field configuration such as the rolling tachyon solution acts as a time dependent source for closed string fields, and produces closed string radiation. This can be computed using the standard techniques. For unstable Dp-branes with all p directions wrapped on circles, we get the following result [35, 38]:

(1) Total amount of energy carried by any single closed string mode is a negligible fraction ($\sim g_s$) of the total energy of the D-brane.
(2) Total amount of energy carried by all the closed string modes is infinite.
(3) For an emitted closed string of mass M, the typical momentum carried by the string along directions transverse to the D-brane is of order $\sqrt{M}$, and the typical winding charge carried by the string along directions tangential to the D-brane is of order $\sqrt{M}$.

Clearly since the D-brane has finite mass, the total amount of energy radiated by the D-brane cannot be infinite. The most naive way to regularize the divergence is to put an explicit cut-off on the energy of the emitted closed string, the natural cut-off being of the order of the mass of the original D-brane. Since this is of order $1/g_s$, the conclusions 1-3 above get modified to:

(1) All the energy of the D-brane is radiated away into closed strings even though any single closed string mode carries a small ($\sim g_s$) fraction of the D-brane energy.
(2) Most of the energy is carried by closed strings of mass $\sim 1/g_s$.
(3) The typical momentum carried by these closed strings along directions transverse to the D-brane is of order $\sqrt{1/g_s}$, and the typical winding charge carried by these strings along directions tangential to the D-brane is also of order $\sqrt{1/g_s}$.

From this one would tend to conclude that the effect of closed string emission should invalidate the classical open string results on the rolling tachyon system discussed earlier. There are however some surprising coincidences:

(1) The classical open string results tell us that the final system associated with the rolling tachyon configuration has zero pressure. On the other hand closed string emission results tell us that the final closed strings have momentum/mass and winding/mass ratio of order $\sqrt{g_s}$ and hence pressure/ energy density ratio of order g_s. In the $g_s \to 0$ limit this vanishes. Thus it appears that the classical open string analysis correctly predicts the equation of state of the final system of closed strings into which the system decays.

(2) The open string analysis tells us that the final system has zero dilaton charge. By analyzing the properties of the closed string radiation produced by the decaying D-brane one finds that these closed strings also carry zero dilaton charge. Thus the classical open string analysis correctly captures the properties of the final state closed strings produced during the D-brane decay.

These results suggest that the classical open string theory already knows about the properties of the final state closed strings produced by the decay of the D-brane [39, 40]. This can be formally stated as an open string completeness conjecture according to which the complete dynamics of a D-brane is captured by the open string theory without any need to explicitly consider the coupling of the system to closed strings.[a] Closed strings provide a dual description of the system. This does not imply that any arbitrary state in string theory can be described in terms of open string theory on an unstable D-brane, but that all the quantum states required to describe the dynamics of a given D-brane are contained in this open string theory.

At the level of critical string theory one cannot prove this conjecture. However it turns out that this conjecture has a simple realization in a non-critical two dimensional string theory. This theory has two equivalent descriptions: 1) as a regular string theory in a somewhat complicated background [41, 42] in which the world-sheet dynamics of the fundamental string is described by the direct sum of a free scalar field theory and the Liouville theory with central charge 25, and 2) as a theory of free non-

[a] Previously this was called the open-closed string duality conjecture [40]. However since there are many different kinds of open-closed string duality conjecture, we find the name open string completeness conjecture more appropriate. In fact the proposed conjecture is not a statement of equivalence between the open and closed string description since the closed string theory could have many more states which are not accessible to the open string theory.

relativistic fermions moving under a shifted inverted harmonic oscillator potential $-\frac{1}{2}q^2 + \frac{1}{g_s}$ [43–45]. Although in the free fermion description the potential is unbounded from below, the ground state of the system has all the negative energy states filled, and hence the second quantized theory is well defined. The map between these two theories is also known. In particular the closed string states in the first description are related to the quanta of the scalar field obtained by bosonizing the second quantized fermion field in the second description [46–48].

In the regular string theory description the theory also has an unstable D0-brane with a tachyonic mode [49]. The classical properties of this tachyon are identical to those discussed earlier in this review in the context of critical string theory. In particular one can construct time dependent solution describing the rolling of the tachyon away from the maximum of the potential. Upon taking into account possible closed string emission effects one finds that as in the case of critical string theory, the D0-brane decays completely into closed strings [50].

By examining the coherent closed string field configuration produced in the D0-brane decay, and translating this into the fermionic description using the known relation between the closed string fields and the bosonized fermion, one discovers that the radiation produced by 'D0–brane decay' precisely corresponds to a single fermion excitation in the theory. This suggests that the D0-brane should be identified as the single fermion excitation in the matrix model [50–52]. Thus its dynamics is described by that of a single particle moving under the inverted harmonic oscillator potential with a lower-cutoff on the energy at the fermi level due to Pauli exclusion principle.

Given that the dynamics of a D0-brane is described by an open string theory, we see from this analysis that in this theory, the single particle mechanics with inverted harmonic oscillator potential corresponds to the open string theory describing the dynamics of the D0-brane. A consistency check of this proposal is that the second derivative of the inverted harmonic oscillator potential at the maximum precisely matches the negative mass^2 of the open string tachyon living on the D0-brane. This 'open string theory' clearly has the ability to describe the complete dynamics of a single D0-brane, which corresponds to single fermion excitations in the fermionic description. It is possible but not necessary to describe the system in terms of the scalar field obtained by bosonizing the second quantized fermion field. This corresponds to the closed string description of the system. This result is completely consistent with the open string completeness conjecture proposed earlier in the context of critical string theory.

We conclude by mentioning briefly the status of closed string tachyon condensation. Clearly we would like to know if we can make sense of closed string tachyon that appears in the original bosonic string theory. Existence of the tachyon is the only thing wrong with this theory, and hence by making sense of this tachyon we may make the theory consistent. For this we need to 1) establish the existence of the minimum of the potential, and 2) find an interpretation of the physics around this minimum. This is still an unsolved problem. However some progress has been made in understanding other kind of closed string tachyons which appear in superstring theories in non-trivial background [53, 54]. In each case that has been understood, the minimum of the tachyon potential always corresponds to some kind of stable background. Thus the tachyon reflects the instability of the original background to decay into the new background. Success of this analysis raises hope that perhaps the tachyon in (25+1) dimensional bosonic string theory may also be understood in a similar manner.

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