Stable non-BPS D-particles

Oren Bergman

Lyman Laboratory of Physics
Harvard University
Cambridge, MA 02138

Matthias R. Gaberdiel

Department of Applied Mathematics and Theoretical Physics
University of Cambridge, Silver Street,
Cambridge CB3 9EW, U.K.

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Abstract

It is shown that the orbifold of type IIB string theory by \((-1)^{F_L} \mathbb{Z}_4\) admits a stable non-BPS Dirichlet particle that is stuck on the orbifold fixed plane. It is charged under the \(SO(2)\) gauge group coming from the twisted sector, and transforms as a long multiplet of the \(D = 6\) supersymmetry algebra. This suggests that it is the strong coupling dual of the perturbative stable non-BPS state that appears in the orientifold of type IIB by \(\Omega \mathbb{Z}_4\).

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*E-mail address: bergman@string.harvard.edu
†E-mail address: M.R.Gaberdiel@damtp.cam.ac.uk
1 Introduction

Recently, it was observed by Sen [1] that duality symmetries in string theory sometimes predict the existence of solitonic states which are not BPS, but are stable due to the fact that they are the lightest states carrying a given set of charge quantum numbers. The most familiar example of this kind arises in the $\text{Spin}(32)/\mathbb{Z}_2$ heterotic string, where the states in the spinor representation of the gauge group are stable because of charge conservation, but are not BPS as the right-movers are not in their ground states. Consequently, the dual type I string theory should have a corresponding stable non-BPS soliton. Other examples involve the open string state stretching between a pair of Dirichlet $p$-branes of type II string theory on top of an orientifold $p$-plane with $SO$ projection. In some of these cases, (namely for $p = 4, 6$ and $7$), Sen gave an interpretation of the corresponding dual solitonic state and determined its mass in the appropriate limit [1].

In this paper we shall consider the case corresponding to $p = 5$ where one of the theories in the dual pair is the orientifold of type IIB string theory by $\Omega I_4$. Under S-duality of type IIB, $\Omega$ is converted to $(-1)^{F_L}$ (where $F_L$ is the left-moving spacetime fermion number), and the corresponding dual theory is the orbifold of type IIB by $(-1)^{F_L}I_4$. As we shall explain below, the spectrum of the orbifold contains in the twisted sector a massless vector multiplet of $\mathcal{N} = (1,1)$ supersymmetry in $D = 6$, and this implies that the orbifold fixed-plane corresponds to a (mirror) pair of D5-branes on top of an orientifold 5-plane [1]. Because of the orientifold projection, the massless states of the string stretching between the two D5-branes is removed, and the gauge group is reduced from $U(2)$ to $SO(2)$. The lightest state that is charged under the $SO(2)$ is then the first excited open string state of the string stretching between the two D5-branes: it forms a long multiplet of the $\mathcal{N} = (1,1) D = 6$ supersymmetry, containing 128 bosons and 128 fermions. Since these states are stable, one should therefore expect that the dual (orbifold) theory also contains a stable multiplet of states that is charged under this $SO(2)$. It is the purpose of this paper to construct the corresponding state (which shall turn out to be an unconventional D-particle), and to show that it satisfies all the required properties. A somewhat different proposal for this state has recently been made by Sen [1], who argued that it should be described as a bound state of a D-string and an anti-D-string. It is tempting to believe that the D-particle state we find corresponds precisely to this bound state.

The paper is organised as follows. In section 2 we shall review briefly the boundary state approach to D-branes that we employ in the following. In section 3 we describe in detail the spectrum of the orbifold theory and construct the D-particle state. We also analyse its properties and show that it satisfies all the requirements. We close with some open problems in section 4.
2 Boundary states

Let us briefly review the boundary state approach to Dirichlet branes \([3, 4, 5, 6]\). For simplicity we shall work in light-cone gauge with \(x^\pm = x^0 \pm x^9\) and transverse coordinates \(x^1, \ldots, x^8\). In this framework, a Dirichlet \(p\)-brane that is parallel to the coordinate axes satisfies Neumann boundary conditions for \(x^i\) with \(i = 1, \ldots, p + 1\), and Dirichlet boundary conditions for \(x^\pm\) and \(x^I\) with \(I = p + 2, \ldots, 8\). The corresponding boundary state is then of the form

\[
|B_p, \eta \rangle = \exp \left\{ \sum_{n>0} \frac{1}{n} \left[ \alpha_n^I \tilde{\alpha}_n^I - \alpha_n^i \tilde{\alpha}_n^i \right] + i \eta \sum_{r>0} \left[ \psi_r^I \tilde{\psi}_r^I - \psi_r^i \tilde{\psi}_r^i \right] \right\} |B_p, \eta \rangle^{(0)}. \tag{2.1}
\]

The parameter \(\eta = \pm\) labels the different spin structures, and depending on the different sectors (untwisted or twisted, NS or R), the modings of the oscillators are either half-integral or integral. The ground state is usually taken to be an eigenstate of the momenta in the Dirichlet directions for which bosonic zero modes exist \(|B_p, \eta, k^\mu \rangle^{(0)}\). In the untwisted sectors, \(\mu\) runs over all \(9 - p\) Dirichlet directions, whereas in the twisted sectors some of these directions may not have a zero mode. Position eigenstates are obtained by integrating over these momenta, and in the untwisted sectors we have for example

\[
|B_p, \eta, x^I = x^\pm = 0 \rangle^{(0)} = \int d^{9-p}k \ |B_p, \eta, k^I, x^\pm \rangle^{(0)}. \tag{2.2}
\]

In the following, when we write \(|B_p, \eta \rangle^{(0)}\), we shall always refer to the position eigenstate with \(x^I = x^\pm = 0\).

A physical boundary state is invariant under the GSO-projection and the various discrete symmetries, and is usually a linear combination of states of the form \(|B_p, \eta \rangle^{(0)}\). In some situations, the state should also be invariant under some of the supersymmetry transformations. In order to identify a physical boundary state with a D-brane, i.e. an object on which open strings can end, one must further demand that the open string spectrum resulting from the presence of this state is consistent with that of the closed sector of the theory, since open strings that begin and end on the D-brane can close to give a closed string state. The relevant open string spectrum can be determined by computing a tree-level two-point function (cylinder) of the boundary state (with itself), and expressing the result as a trace over open string states (annulus),

\[
\int dl \langle B_p, \eta | e^{-2lH_o} | B_p, \eta \rangle = 2V \int \frac{dt}{2t} \text{Tr}_{\text{open}} e^{-2tH_o}, \tag{2.3}
\]

where \(V\) is the (infinite) volume of the Neumann directions, and the factor of 2 is due to the fact that there are two orientations for the open string. The open string sectors that appear on the right hand side of \((2.3)\) depend both on the closed string sector and on the spin structures \(\eta, \eta'\). The relation is summarised in table 1.

\footnote{Strictly speaking these states are related by a double Wick rotation to Dirichlet branes \([3, 5]\).}
As an example, consider type IIA/B string theory. The GSO projection is given by
\[ P_{GSO} = \frac{1}{4} \left\{ \begin{array}{ll} (1 + (-1)F)(1 + (-1)\tilde{F}) & \text{NSNS} \\
(1 \mp (-1)\tilde{F})(1 + (-1)F) & \text{RR} \end{array} \right. \]
where the tilde denotes left-movers. The NSNS sector has a non-degenerate ground state \(|Bp, \eta\rangle_{NSNS}^{(0)} = |0\rangle_{NSNS}\), which is taken to be odd under both \((-1)F\) and \((-1)\tilde{F}\). The bosonic oscillators \(\alpha_\mu^n, \tilde{\alpha}_\mu^n\) are integrally moded, \(n \in \mathbb{Z}\), and the fermionic oscillators \(\psi_\mu^r, \tilde{\psi}_\mu^r\) are half-integrally moded, \(r \in \mathbb{Z} + 1/2\). The action of \((-1)F\) and \((-1)\tilde{F}\) on the boundary states is given by
\[ (-1)^F|Bp, \eta\rangle_{NSNS} = (-1)^{\tilde{F}}|Bp, \eta\rangle_{NSNS} = -|Bp, -\eta\rangle_{NSNS}, \]
and therefore the combination \((|Bp, +\rangle_{NSNS} - |Bp, -\rangle_{NSNS})\) is GSO invariant and corresponds to a physical boundary state. In the RR sector the fermionic oscillators are integrally moded, \(r \in \mathbb{Z}\), and there are therefore sixteen fermionic zero modes given by \(\psi_\mu^0, \tilde{\psi}_\mu^0\) with \(\mu = 1, \ldots, 8\). If we introduce
\[ \psi_\pm^\mu = \frac{1}{\sqrt{2}}(\psi_0^\mu \pm i\tilde{\psi}_0^\mu), \]
the ground state in the RR sector corresponding to the spin-structure \(\eta\), \(|Bp, \eta\rangle_{RR}^{(0)}\), satisfies
\[ \psi^I_\eta |Bp, \eta\rangle_{RR}^{(0)} = 0 \]
\[ \psi^I_{-\eta} |Bp, \eta\rangle_{RR}^{(0)} = 0. \]
We choose the relative normalisation between the states corresponding to \(\eta = \pm\) by defining
\[ |Bp, +\rangle_{RR}^{(0)} = \prod_{i=1}^{p+1} \psi^i_+ \prod_{i=p+2}^{8} \psi^I_- |Bp, -\rangle_{RR}^{(0)}. \]
It then follows that
\[ |B_p, -\rangle^{(0)}_{RR} = \prod_{i=1}^{p+1} \psi_i \prod_{I=p+2}^{8} \psi^I_+ |B_p, +\rangle^{(0)}_{RR}. \] (2.9)

As in [2], the GSO operators \((-1)^F\) and \((-1)^{\tilde{F}}\) act on the RR ground states as
\[ (-1)^F = \prod_{\mu=1}^{8} (\sqrt{2} \psi^\mu_0), \quad (-1)^{\tilde{F}} = \prod_{\mu=1}^{8} (\sqrt{2} \tilde{\psi}^\mu_0), \] (2.10)
and consequently,
\[ (-1)^F |B_p, \eta\rangle_{RR} = |B_p, -\eta\rangle_{RR} \]
\[ (-1)^{\tilde{F}} |B_p, \eta\rangle_{RR} = (-1)^{p+1} |B_p, -\eta\rangle_{RR}. \] (2.11)

We therefore find that the combinations \((|B_p, +\rangle_{RR} + |B_p, -\rangle_{RR})\) are physical provided that \(p\) is even in IIA, and \(p\) is odd in IIB. By combining NSNS and RR boundary states we get states which preserve 1/2 of the supersymmetry, i.e. BPS states. These are the D-branes (or anti-D-branes)
\[ |D_p\rangle = (|B_p, +\rangle_{NSNS} - |B_p, -\rangle_{NSNS}) \pm (|B_p, +\rangle_{RR} + |B_p, -\rangle_{RR}), \] (2.12)
where the relative sign between the NSNS and the RR component distinguishes branes from anti-branes. Due to the above restriction on \(p\) in the RR component, there are only even \(p\) D-branes in type IIA, and only odd \(p\) D-branes in IIB. The necessity of combining the NSNS and RR boundary states can also be understood from the open-closed consistency condition (see table 1): in order to get the GSO-projected NS open string spectrum (without a tachyon), we need both a contribution from NSNS and RR. Since the NSNS and RR components are linear combinations of \(\eta = \pm\), the entire open string spectrum consists of NS\((1 + (-1)^F) / 2\) and R\((1 + (-1)^{\tilde{F}}) / 2\), which is indeed supersymmetric.

3 A D-particle in type IIB/\((-1)^{F_L} I_4\)

Let us now consider the orbifold of type IIB theory on \(R^{9,1}/(-1)^{F_L} I_4\), where \(F_L\) is the left-moving space-time fermion number, and \(I_4\) denotes inversion of four spatial coordinates, \(x^5, \ldots, x^8\), say. The fixed points under \(I_4\) form a 5-plane at \(x^5 = x^6 = x^7 = x^8 = 0\), which extends along the coordinates \(x^1, \ldots, x^4\), as well as the light-cone coordinates \(x^9, x^9\). In light-cone gauge, type IIB string theory has 16 dynamical supersymmetries and 16 kinematical supersymmetries. The former transform under the transverse \(SO(8)\) as
\[ Q \sim 8_s, \quad \tilde{Q} \sim \overline{8}_s. \] (3.1)
The orbifold breaks the transverse $SO(8)$ into $SO(4)_S \times SO(4)_R$, where the $SO(4)_S$ factor corresponds to rotations of $(x^1, \ldots, x^4)$, and the $SO(4)_R$ factor to rotations of $(x^5, \ldots, x^8)$. The above supercharges therefore decompose as
\[ 8_s \rightarrow ((2, 1), (2, 1)) + ((1, 2), (1, 2)) . \]

(3.2)

The operator $I_4$ reverses the sign of the vector representation of $SO(4)_R$ (the $(2, 2)$), and we therefore choose its action on the $SO(4)_R$ spinors as
\[ I_4 : \begin{cases} (2, 1) \rightarrow (2, 1) \\ (1, 2) \rightarrow -(1, 2) \end{cases} . \]

(3.3)

The action of $(-1)^F_L$ is simply
\[ (-1)^F_L : \begin{cases} Q \rightarrow Q , \\ \tilde{Q} \rightarrow -\tilde{Q} , \end{cases} \]

(3.4)

and the surviving supersymmetries thus transform as
\[ Q \sim ((2, 1), (2, 1)) , \quad \tilde{Q} \sim ((1, 2), (1, 2)) . \]

(3.5)

From the point of view of the 5-plane world-volume this is (dynamical, light-cone) $N = (1, 1)$ supersymmetry.

The closed string spectrum consists of an untwisted sector containing type IIB states which are even under $(-1)^F_L I_4$, and a twisted sector which is localised at the 5-plane. In the twisted sector the various oscillators are moded as
\[ \text{twisted NS} : \quad n \in \begin{cases} \mathbb{Z} & \mu = 1, \ldots, 4 \\ \mathbb{Z} + 1/2 & \mu = 5, \ldots, 8 \end{cases} , \quad r \in \begin{cases} \mathbb{Z} + 1/2 & \mu = 1, \ldots, 4 \\ \mathbb{Z} & \mu = 5, \ldots, 8 \end{cases} , \]
\[ \text{twisted R} : \quad n \in \begin{cases} \mathbb{Z} & \mu = 1, \ldots, 4 \\ \mathbb{Z} + 1/2 & \mu = 5, \ldots, 8 \end{cases} , \quad r \in \begin{cases} \mathbb{Z} & \mu = 1, \ldots, 4 \\ \mathbb{Z} + 1/2 & \mu = 5, \ldots, 8 . \end{cases} \]

(3.6)

The ground state energy vanishes in both the R and NS sectors, and they both contain four fermionic zero modes that transform in the vector representation of $SO(4)_S$ and $SO(4)_R$, respectively. Consequently the twisted NSNS and RR ground states transform as
\[ ((2, 1) + (1, 2)) \otimes ((2, 1) + (1, 2)) , \]

(3.7)

where the charges correspond to $SO(4)_S (SO(4)_R)$ in the RR (NSNS) sector. The unique massless representation of $D = 6 \ N = (1, 1)$ supersymmetry (other than the gravity multiplet) is the vector multiplet
\[ ((2, 2), (1, 1)) + ((1, 1), (2, 2)) + \text{fermions} . \]

(3.8)

\[ ^3 \text{The same orbifold of type IIA would yield } N = (2, 0) \text{ supersymmetry.} \]
In order to preserve supersymmetry, we therefore have to choose the GSO-projections in all twisted sectors to be of the form

\[ P_{GSO,T} = \frac{1}{4} (1 - (-1)^F) \left( 1 + (-1)^F \right). \]  

(3.9)

This agrees with what we would have expected from standard orbifold techniques, namely that the effect of \((-1)^F_L\) is to change the left-GSO projection in the twisted sector. In addition, the spectrum of the twisted sector must be projected onto a subspace with either \((-1)^F_L I_4 = +1\) or \((-1)^F_L I_4 = -1\) (in the untwisted sector only +1 is allowed). Since twisted NSNS (RR) states are even (odd) under \((-1)^F_L\), and \(I_4\) reverses the sign of the vector of \(SO(4)_R\) (and leaves the vector of \(SO(4)_S\) invariant), we conclude that in the present case the twisted sector states are odd under \((-1)^F_L I_4\).

Having described the spectrum and the GSO projections of the various sectors in some detail, we can now analyse whether a D-particle boundary state is permitted. In the (untwisted) NSNS sector \((-1)^F_L\) acts trivially, and all boundary states of the form (2.1) are invariant under \(I_4\), since \(I_4\) acts in the same way on left- and right-movers. We therefore have a physical \(p = 0\) NSNS boundary state

\[ |U0\rangle = (|B0, +\rangle_{NSNS} - |B0, -\rangle_{NSNS}). \]  

(3.10)

On the other hand the \(p = 0\) RR boundary state is not physical because of (2.11). In the twisted sector, the boundary state is of the same form (with the appropriate modings). Since there are only bosonic zero modes for \(\mu = 0, 1, 2, 3, 4, 9\), and since \(x^1\) is a Neumann direction, the momentum integral is over the 5-dimensional space corresponding to \(\mu = 0, 2, 3, 4, 9\). The ground states satisfy

\[ \psi_\pm^\nu |B0, \pm\rangle_{NSNS,T}^{(0)} = 0 \quad \text{for } \nu = 5, 6, 7, 8, \]  

(3.11)

in the twisted NSNS sector, and

\[ \psi_\pm^\mu |B0, \pm\rangle_{RR,T}^{(0)} = 0 \quad \text{for } \mu = 2, 3, 4, \]  

(3.12)

in the twisted RR sector. On the ground states, the GSO operators act as

\[ \begin{align*}
\text{twisted NSNS:} & \quad (-1)^F = \Pi_{\mu=2}^8 (\sqrt{2}\psi_\mu^\mu), \quad (-1)^\bar{F} = \Pi_{\mu=5}^8 (\sqrt{2}\bar{\psi}_\mu^\mu) \\
\text{twisted RR:} & \quad \bar{(-1)}^F = \Pi_{\mu=1}^4 (\sqrt{2}\bar{\psi}_\mu^\mu), \quad (-1)^\bar{F} = \Pi_{\mu=1}^4 (\sqrt{2}\psi_\mu^\mu).
\end{align*} \]  

(3.13)

\(^4\text{This boundary state is also not invariant under } (-1)^{F_L} I_4, \text{ as follows from the analysis of } \mathbb{Z}_2.\)
Using the same arguments as before in the untwisted sector we find
\[ (-1)^F |B0, \pm\rangle_{NSNS,T} = |B0, \mp\rangle_{NSNS,T}, \quad (-1)^\tilde{F} |B0, \pm\rangle_{NSNS,T} = +|B0, \mp\rangle_{NSNS,T} \quad (3.14) \]
and
\[ (-1)^F |B0, \pm\rangle_{RR,T} = |B0, \mp\rangle_{RR,T}, \quad (-1)^\tilde{F} |B0, \pm\rangle_{RR,T} = -|B0, \mp\rangle_{RR,T}. \quad (3.15) \]
Because of (3.9) it then follows that only the combination \(|B0, +\rangle_{RR,T} + |B0, -\rangle_{RR,T}\) in the twisted RR sector survives the GSO-projection, and that no combination of twisted NSNS sector boundary states is GSO invariant. In addition, the ground states of the twisted RR sector boundary state are odd under \((-1)^F I_4\), as they are precisely the vector states of \(SO(4)_{S}\) that arise in the twisted sector. We therefore have one further physical boundary state
\[ |T0\rangle = (|B0, +\rangle_{RR,T} + |B0, -\rangle_{RR,T}), \quad (3.16) \]
and the total D-particle state is of the form
\[ |D0\rangle = N_U |U0\rangle + N_T |T0\rangle. \quad (3.17) \]
We can then determine the cylinder diagram for a closed string that begins and ends on the D-particle, and we find that
\[ \int_0^\infty dl \langle D0 | e^{-lH_c} | D0 \rangle = \int_0^\infty \frac{dt}{t^{3/2}} \left\{ \frac{2^{9/2}N_U^2 f_3^8(e^{-\pi t}) - f_2^8(e^{-\pi t})}{f_3^8(e^{-\pi t})} + 2^{5/2}N_T^2 \frac{f_3^4(e^{-\pi t}) f_4^4(e^{-\pi t})}{f_1^4(e^{-\pi t}) f_2^4(e^{-\pi t})} \right\}, \quad (3.18) \]
where \(f_i\) are the standard \(f\)-functions [4, 5]. For \(N_T^2 = 2^4 N_U^2 = L/(\pi 2^3)\) we then obtain (compare [2])
\[ \int dl \langle D0 | e^{-lH_c} | D0 \rangle = 2L \int \frac{dt}{2t} \text{Tr}_{NS-R} \left[ \frac{1}{2} (1 + (-1)^F I_4) e^{-2tH_0} \right], \quad (3.19) \]
where \(L\) is the (infinite) size of the \(x^0\) direction. The open string spectrum thus consists of NS and R sectors, both projected by \(1/2 (1 + (-1)^F I_4)\). The tachyon of the NS sector is even under \(I_4\) but odd under \((-1)^F\), and is therefore removed from the spectrum. This indicates that the D-particle is stable.

In addition, 4 massless states are removed from the NS sector, leaving 4 massless bosons, and the R sector contains 8 massless fermions. Including the zero modes in the light-cone directions this gives the D-particle 5 bosonic zero modes and 16 fermionic zero modes. The 5When counting the zero modes of a D-brane one must include the light-cone directions as well as the physical (transverse) massless states of the open string. See for example [6] for a discussion of the type IIB D-string.

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former reflect the fact that the D-particle is restricted to moving within the 5-plane, and
the latter give rise to a long ($2^8 = 256$-dimensional) representation of the six-dimensional
$\mathcal{N} = (1,1)$ supersymmetry. Finally, the D-particle is charged under the vector field in the
twisted RR sector. We have therefore managed to construct a boundary state that possesses
all the properties that we expected to find from the S-dual description.

It seems quite plausible that this D-particle is the elusive ground state of the D-string
anti-D-string system sought by Sen [2]. In particular, the analysis of Sen suggests that
the bound state should correspond to a superposition of an untwisted NSNS state and a
twisted RR state, but should not have any other components, and this is indeed what we
find. On the other hand, the mass of our D-particle does not seem to agree with the mass
predicted by Sen: the D-particle has the same mass as a conventional D-particle in type IIA,
$M_{D0} = 1/(\sqrt{\alpha'} g_5)$, and this differs by a factor of $\sqrt{2}$ from the formula given in [2].

4 Conclusions

In this paper we have constructed a Dirichlet particle boundary state in the orbifold of type
IIB by $(-1)^{F_L} I_4$. The D-particle is stuck on the orbifold plane, and satisfies the properties
that are expected from the S-dual description. In particular, it is stable (as the open string
beginning and ending on the D-particle is tachyon-free), it gives rise to a long multiplet of
the six-dimensional $\mathcal{N} = (1,1)$ supersymmetry, and it is charged under the relevant $SO(2)$
 gauge group.

On the other hand some open problems remain. In particular, since the open string
that begins and ends on the D-particle has the projection $1/2(1 + (-1)^F I_4)$, rather than
$1/4(1 + (-1)^F)(1 + I_4)$, the open string spectrum admits states that are $I_4$ odd as well as
states that are $I_4$ even. It is therefore not obvious that such a spectrum is consistent with
the closed string spectrum, given that open and closed strings couple. On the other hand,
it is quite plausible that the open-closed consistency condition is indeed satisfied, since the
closed string spectrum also contains $I_4$ even and $I_4$ odd states. (Indeed, it is not clear either
whether the other projection would in fact give rise to a consistent open-closed spectrum.)
It would be interesting to check this in detail.

It would also be interesting to see whether a similar analysis can be given for the case of
the spinorial representation of the $Spin(32)/\mathbb{Z}_2$ heterotic string, whose corresponding dual
should be a non-BPS particle in type I. It is again possible to have the NSNS component of
the boundary state, but in this case it is not clear what should play the role of the twisted
RR component, or how to get rid of the open string tachyon. The situation is therefore much
less clear.

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6If we take the superpositions of the states in section 3 of [2] literally, then the other components cancel.
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