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Abstract: An (m, n)-string bound state (with m, n relatively prime integers) in type IIB string theory can be interpreted from the D-string worldsheet point of view as n D-strings carrying m units of quantized electric flux or quantized electric field. We argue, from the D-brane worldvolume point of view, that similar Dp-brane bound states should also exist for $2 \leq p \leq 8$ in both type IIA (when p is even) and type IIB (when p is odd) string theories. As in $p = 1$ case, these bound states can each be interpreted as n Dp-branes carrying m units of quantized constant electric field. In particular, they all preserve one half of the spacetime supersymmetries.

Keywords: Superstrings and Heterotic Strings, String Duality, p-branes, D-branes.

Contents

1. Introduction

Polchinski's seminal work [1] on D-brane has dramatically changed our view on perturbative superstrings. Yet, we can use many tools developed in the perturbative framework of superstrings to do D-brane calculations. These help us, at least in certain cases, to attack some hard problems in physics such as the information loss puzzle and the entropy problem in black hole physics. The D-brane picture is also the basis for the recent AdS/CFT conjectures of Maldacena [2]. By definition, a D-brane is a hypersurface carrying a RR charge in type II string theory on which an open string can end. From the D-brane worldvolume point of view, such an ending of a fundamental string (for short, F-string) is characterized by the non-vanishing U(1) gauge field strength on the brane at least in the low energy limit. A configuration of an F-string ending on a Dp-brane for every allowable p can actually be BPS saturated, preserving a quarter of the spacetime supersymmetries. At the linearized approximation, this has been demonstrated by Callan and Maldacena [3] for $p \geq 2$ cases and by Dasgupta and Mukhi [4] for $p = 1$ case. The interpretations for $p \geq 2$ and $p = 1$ cases are, however, quite different. In the former case, the excitation of a worldvolume scalar field along a transverse direction is interpreted as the F-string attached to the Dp-brane. Whereas, for the latter one, the excitation of this scalar field due to the introduction of an F-string ending indicates that one half of the original D-string must bend rigidly to form a 3-string junction.

In spite of our reasonably well understanding of an F-string ending on a Dp-brane from the worldvolume point of view, our understanding of this same ending from the spacetime point of view is still unsatisfactory.[1] The well-known p-brane solitonic solutions of type II supergravity theories [6, 7], nowadays called Dp-branes, are merely hypersurfaces carrying RR charges each of which preserves one half of

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[1] For some very recent efforts in this direction see [5].

the spacetime supersymmetries of type II string theories. The mass per unit p-brane volume for such a configuration carrying unit RR charge is just the Dp-brane tension. This BPS configuration can also be described by its worldvolume Born-Infeld action in its simplest form with flat background and vanishing worldvolume gauge field strength which clearly indicates that each of the spacetime Dp-brane solitonic solutions does not have an F-string ending on it (this also explains why they preserve 1/2 rather than 1/4 of the spacetime supersymmetries). Instead of finding a spacetime stable BPS configuration of an F-string ending on a Dp brane from the corresponding supergravity directly, we pose the following simpler question. Can we find a spacetime stable BPS configuration carrying information about an F-string ending on a Dp brane and yet preserving *one half* of the spacetime supersymmetries from the corresponding supergravity?

As just pointed out, a non-vanishing worldvolume gauge field strength is an indication of a string ending on the corresponding Dp-brane. In general we expect that such a configuration preserves *a quarter* of the spacetime supersymmetries. The above question can therefore be rephrased as: does there exist a stable BPS state for each Dp-brane that has a non-vanishing worldvolume gauge field strength and yet preserves *one half* of the spacetime supersymmetries? We will argue from the worldvolume view in this paper that the answer is yes based on known Dp-brane results and the 3-string junction. Each of these BPS states is actually a non-threshold bound state of a Dp brane carrying certain units of quantized constant electric field strength or a non-threshold (F, Dp) bound state with F representing the F-strings. There actually exist more general non-threshold bound states. For example, by the type IIB S-duality, we should have D3 branes carrying both quantized constant electric and magnetic fields. We will discuss the $p = 3$ case in this paper and others in the subsequent publications. In the following section, we will review relevant Dp-brane results for the purpose of this paper. In section 3, we will present our arguments for the existence of such BPS states and conclude this paper.

2. Review of some D-brane results

This section is largely based on the discussion of BPS states of a fundamental string (F-string) ending on a Dp-brane by Callan and Maldacena [3] for $p \geq 2$ and by Dasgupta and Mukhi [4] for $p = 1$ in the linearized approximation. The linear arguments should be trusted since we are here interested only in BPS states. As in [3], we assume that the massless excitations of a Dp-brane are described by the dimensional reduction of the 10-dimensional supersymmetric Maxwell theory. The supersymmetry variation of the gaugino is

$$\delta\chi = \Gamma^{MN} F_{MN} \epsilon\,, \tag{2.1}$$

where M, N are the 10-dimensional indices. A BPS configuration is the one in which $\delta\chi = 0$ for some non-vanishing killing spinor. The ending of an F-string on a Dp-brane is equivalent to placing a point charge on the brane. The Coulomb potential due to such a point charge will give rise to a non-vanishing F_{0r} with r the radial coordinate of the p spatial dimensions of the worldvolume. With a non-vanishing F_{0r}, it is obvious from eq. (2.1) and $\delta\chi = 0$ that the existence of non-vanishing Killing spinors (i.e., the preservation of some unbroken supersymmetries), requires the excitation of one of the scalar fields, say X^9, such that $F_{9r} = -\partial_r X^9 = F_{0r}$. Then $\delta\chi = 0$ can be expressed in a familiar form as

$$\left(1 - \Gamma^0\Gamma^9\right)\epsilon = 0\,, \tag{2.2}$$

which says that one half of the worldvolume supersymmetries are broken by this configuration. In other words, this configuration of an F-string ending on a Dp-brane is still a BPS state which preserves one half of the worldvolume supersymmetries or a quarter of the spacetime supersymmetries. It is easy to check that $F_{0r} = F_{9r} = c_p(p-2)/r^{p-1}$ for $p > 2$, $F_{0r} = F_{9r} = c_2/r$ for $p = 2$, and $F_{01} = F_{91} = c_1$ for $x^1 > 0$ and $F_{01} = F_{91} = 0$ for $x^1 < 0$[2] for $p = 1$ satisfy the corresponding linearized equations of motion, respectively. This has to be true to guarantee the existence of the corresponding BPS states. In the above, the constant c_p is related to the point charge and can be fixed by some charge quantization which will be discussed later.

To have a clear picture about an F-string ending on a Dp-brane, we need to examine the above BPS configuration closely. The cases for $p \geq 2$ and $p = 1$ are quite different. So we discuss them separately. Let us discuss $p > 2$ first. Here we can solve X^9 from $F_{9r} = c_p(p-2)/r^{p-1} = -\partial_r X^9$ as $X^9 = c_p/r^{p-2}$. As explained in [3], the excitation of X^9 amounts to giving the brane a transverse 'spike' protruding in the 9 direction and running off to infinity. This spike must be interpreted as an F-string attached to the Dp-brane. Callan and Maldacena have shown that the energy change due to the introduction of a point charge to the Dp-brane worldvolume equals precisely to the F-string tension times X^9 which is the energy of an F-string if the spike is interpreted as the F-string. This also says that attaching an F-string to a Dp-brane does not cost any energy which is not true in the case of $p = 1$.

The $p = 2$ case is not much different from $p > 2$ cases apart from the fact that X^9 now behaves according to $X^9 = c_2 \ln r/\delta$ with δ a small-distance cutoff rather than like a 'spike'. This X^9, a sort of inverse 'spike', should also be interpreted as an F-string because of the underlying D-brane picture and the similar energy relation.[3]

So far, we have considered only the single-center Coulomb solution in the above BPS states describing an F-string ending on a Dp-brane for $p \geq 2$. The BPS nature

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[2] For concreteness, we assume that the original D-string is placed along the x^1-axis.

[3] The energy change of D2 due to the introduction of a point charge to the worldvolume can also be expressed as the F-string tension times X^9. Here a large-distance cutoff needs to be introduced to make the calculation meaningful.

of these configurations allows multi-center solutions. For example, for $p > 2$, X^9 is now

$$X^9 = \sum_i \frac{c_p^i}{|\vec{r} - \vec{r}_i|^{p-2}} \,, \tag{2.3}$$

where c_p^i can be positive or negative, depending on to which side of the Dp-brane an F-string is attached. This solution represents multiple strings along X^9 direction ending at arbitrary locations on the brane. This solution is still BPS, preserving also a quarter of the spacetime supersymmetries. The energy change of Dp-brane due to the endings of multiple strings is again equal to the summation of the F-string tension times individual F-string length and is independent of the locations of the end points. Therefore, no attachment energy is spent for such endings. These multi-center solutions are one of the important properties which we need in section 3.

The story for $p = 1$ case is quite different. As discussed in [4], the excitation of X^9 is no longer interpreted as an F-string ending on a D-string but as an indication that one side of the original infinitely long and straight D-string or (0,1)-string must be bent rigidly (with vanishing axion) with respect to the point on the D-string where a point charge is inserted. Let us look at it in some detail since the physics picture for this case consists of the starting point of our arguments for the existence of the Dp-brane bound states in the next section. In the presence of this point charge, Gauss' law in one spatial dimension states, in the case of vanishing axion, that $F_{01} = c_1$ for $x^1 > 0$ and $F_{01} = 0$ for $x^1 < 0$[4] when the original D-string or (0,1)-string is along x^1 axis. Unbroken susy condition $F_{91} = -\partial_1 X^9 = F_{01}$ says

$$\begin{aligned} X^9 &= -c_1 x^1 \,, \quad && x^1 > 0 \,, \\ &= 0 \,, && x^1 < 0 \,. \end{aligned} \tag{2.4}$$

Because of the special properties of $1+1$ dimensional electrodynamics, the above solution is linearly increasing away from the inserted charge, in contrast to $p \geq 2$ cases. Before the work of Dasgupta and Mukhi, Aharony et al. [8] concluded that three strings are allowed to meet at one point provided there exist the corresponding couplings and the charges at the junction point are conserved. Schwarz [9] then went one step further to conjecture, based on his (m,n)-string [10] in type IIB theory, that there exists a BPS state for such 3-string junction provided the three strings are semi-infinite and the angles are chosen such that tensions, treated as vectors, add up to zero. With this, one should not be surprised about the above solution and the natural interpretation, as indicated already in [9] for an F-string ending on a D-string, that the insertion of the point charge at the origin of the D-string causes one half of the string to bend rigidly. The solution itself does not spell out the ending of F-string or (1,0)-string. But a consistent picture requires that the point

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[4] One can also have an alternative solution of $F_{01} = 0$ for $x^1 > 0$ and $F_{01} = -c_1$ for $x^1 < 0$.

charge represents the ending of a semi-infinitely long F-string or (1,0)-string (chosen here along positive x^9 direction) coming in perpendicular to the original D-string or (0,1)-string along x^1 direction. The bent segment described by eq. (2.4) that goes out from the junction is a D-string carrying one unit of quantized electric flux or Schwarz's (1,1)-string (or (−1,−1)-string depending on the orientation) in type IIB theory which follows from the charge conservation. The 3-string junction has also been studied by Sen [11] from spacetime point of view based on Schwarz's (m,n)-strings in type IIB theory. He showed that a 3-string junction indeed preserves 1/4 of the spacetime supersymmetries and a string network which also preserves 1/4 of the spacetime supersymmetries can actually be constructed using 3-string junctions as building blocks. Such a string network may, to our understanding, correspond to the multi-center solutions in $p \geq 2$ cases. The energy change of the D-string due to the ending of an F-string, unlike the $p \geq 2$ cases, is no longer equal to the F-string tension times the attached F-string length, primarily due to the formation of the (1,1)-string bound state.

In summary, the 3-string junction, as the BPS state of an F-string ending on a D-string, is just the consequence of D-brane picture, 1 + 1 dimensional electrodynamics and the non-perturbative $\mathrm{SL}(2,\mathbb{Z})$ strong-weak duality symmetry in type IIB string theory. One important point to notice, which is well known nowadays and will be useful in our later discussion, is that m F-strings in the (m,n)-string bound state in type IIB theory are just m units of the quantized electric flux.

Therefore an (m,1)-string can be viewed as a D-string carrying m units of quantized electric flux. The (m,1)-string tension is $\sqrt{1/g^2 + m^2}\, T_f$ with $T_f = 1/2\pi\alpha'$ the F-string tension. For small string coupling g and small m, the (m,1)-string tension can be approximated as $(1/g + gm^2/2)T_f$. Therefore, $(gm^2/2)T_f$ should correspond to the linearized energy per unit length of the worldsheet constant gauge field strength F_{01}, i.e., $((2\pi\alpha' F_{01})^2/2g)T_f$. So we have $F_{01} = gmT_f$ which fixes $c_1 = gT_f$ for a single F-string. By T-dualities, the electric field F due to the ending of F-strings on a Dp-brane is quantized according to

$$\frac{1}{(2\pi)^{p-2}\,\alpha'^{(p-3)/2}} \int_{S_{p-1}} *F = gm\,, \tag{2.5}$$

where $*$ denotes the Hodge dual in the worldvolume. This is precisely the condition used in [3] to fix the constant c_p.

3. Dp-brane bound states

As discussed in the previous section, there are two pictures in describing the 3-string junction. The worldsheet picture says that an F-string ending on a D-string causes one half of the original D-string to bend rigidly to form a 3-string junction. The bent semi-infinite segment is now a D-string carrying one unit of quantized electric field or flux. In terms of Schwarz's (m, n)-strings, the spacetime picture of the same 3-string junction is that a (1,0)-string meeting a (0,1)-string gives rise to a (1,1)-string by charge conservation and no-force condition to form such a junction.

Let us focus first on the worldsheet picture of this 3-string junction. Recall that a 3-string junction is a stable BPS configuration and each string in the junction is semi-infinitely long. Now let us push the junction point to spatial infinity in such a way that the D-string carrying one unit of quantized electric flux is along one of the axes while the F-string and the D-string are all at spatial infinity. To a local observer, this D-string carrying one unit of quantized electric flux must appear to be a stable BPS configuration. This is confirmed by the fact that the D-string carrying one unit of quantized electric flux is nothing but Schwarz's (1,1)-string. This also tells us that the D-string carrying one unit of quantized electric flux preserves one half of the spacetime supersymmetries. So we answer the question raised in the introduction for $p = 1$ case.

Can we generalize this to $p > 1$ cases? Before we provide the answer, let us discuss first what we expect from the spacetime point of view. As we know, the obvious reason for the existence of Schwarz's (m,n)-strings in non-perturbative type IIB string theory is the $\mathrm{SL}(2, \mathbb{Z})$ strong-weak duality symmetry under which the NSNS and RR 2-form potentials transform as a doublet. From this, it is not obvious that we can combine D3-branes with F-strings to form a similar non-threshold bound state since the 4-from potential associated with the D3-branes is inert under the $\mathrm{SL}(2, \mathbb{Z})$. By similar token, we do not expect a non-threshold bound state of D5-branes and F-strings since the RR 3-form field strength cannot be combined with the magnetic dual of the NSNS 3-form field strength to form a doublet under the $\mathrm{SL}(2, \mathbb{Z})$. In type IIA, we do not expect similar bound states of Dp branes and F-strings (for $p =$ even) since we do not have an $\mathrm{SL}(2, \mathbb{Z})$ to begin with. This spacetime point of view seems to indicate that Schwarz's (m, n)-strings are special. However, as we will explain below, an (m,n)-string bound state is not special at all if it is interpreted as n D-strings carrying m units of quantized electric flux or field strength as discussed in the previous section. Such a kind of bound states, i.e., a Dp-brane carrying certain units of quantized constant electric field, actually exist for all Dp branes with $1 \leq p \leq 8$. All these bound states are BPS saturated and preserve *one half* of the spacetime supersymmetries.[5]

If we take the worldsheet point of view, the only thing special for the bound state of n D-strings carrying m units of quantized electric flux is the $1 + 1$ dimensional electrodynamics which states that the gauge field strength is *constant* on one side

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[5] This implicitly indicates that we might have a 'hidden' $\mathrm{SL}(2, \mathbb{Z})$ symmetry which may or may not be identified with the type IIB $\mathrm{SL}(2, \mathbb{Z})$. For $p \neq 1$, this symmetry may only be a symmetry of BPS spectrum and cannot manifest itself in the low energy supergravity. The existence of these bound states can also be inferred [16] by T-dualities acting on a Schwarz's (m, n)-string along its transverse directions which will be discussed later in this section.

of a point charge. So, if we can *consistently* have a *constant* electric field in a Dp-brane worldvolume, we find no reason that a Dp-brane carrying certain units of quantized constant electric field should not exist from the above discussion. In what follows, we will show how a constant electric field can be realized consistently in a Dp-brane worldvolume.

To make our arguments for the existence of such Dp-brane bound states clear, let us first consider a specific $p = 3$ case. We take $p = 3$ partially because of the current fashion of AdS_5/CFT_4 correspondence and partially because of the familiarity of the $1 + 3$ dimensional electrodynamics. We will discuss the general cases for $1 \leq p \leq 8$ afterwards.

In the case of D3-brane, we do not have the property of $1 + 1$ dimensional electrodynamics. In general, when an F-string ends on a D3-brane, the F-string will be spike-like, not rigid, near the end point. But this will not prevent us from doing the same as we did above for $p = 1$ case. As we will see, insisting a constant electric field in any finite spatial region of worldvolume in a consistent fashion will automatically push the endings of F-strings to spatial infinity. Therefore, the 'spike' will appear to be a rigid F-string to any finite region of space.

The first question is what kind of electric charge distribution in $1 + 3$ dimensions gives rise to a constant electric field.[6] We know that a uniform 2-d surface charge distribution will do the job. The next question is where this surface should be placed. When we say a constant electric field, we mean that the field is constant not only in magnitude but also in direction in any finite region of space. So we have to place this charge surface at spatial infinity. Otherwise, the direction of the electric field will be opposite on the two sides of the surface. For concreteness, let us say that we label x^1, x^2 and x^3 as the 3-space of D3 brane and take the charge surface as x^2x^3-plane and place it at $x^1 = -\infty$. Now where does the surface charge come from? It all comes from the endings of parallel NSNS-strings, say along x^9 direction, on the x^2x^3-plane such that the resulting surface charge density is a constant. This is possible because of the existence of the multi-center solution discussed in the previous section. Since these NSNS-strings are parallel to each other, the whole system is still a BPS one, preserving a quarter of the spacetime supersymmetries. Note that these endings of F-strings are now at spatial infinity. Therefore the 'spikes' describing the endings of these F-strings have no influence on the electric field in any finite region of space. So everything fits together nicely. In any finite region, we can detect only the D3-brane carrying a constant electric field in it. The D3-brane carrying constant electric

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[6] It happens in this case that we can also have a bound state of a D3 brane carrying certain units of quantized constant magnetic field by the type IIB S-duality. There actually exist such bound states for $2 \leq p \leq 8$ [12]. For $p = 3$, we can have a bound state of a D3 brane carrying both quantized constant electric and magnetic fields. We will discuss the $p = 3$ bound states later in this section. There actually exist similar and more general bound states which will be discussed in forthcoming papers [13, 14].

field preserves also one half of the spacetime supersymmetries since it is related to the D-string carrying a constant electric field by T-duality and T-duality preserves supersymmetries.[7]

Because the charge at the end of each of these NSNS-strings is quantized, we expect that the electric field should also be quantized. If each of these NSNS-strings is m F-strings, we should have here $F_{01} = gmT_f$ with g the corresponding string coupling constant. This can be obtained by T-dualities from the $F_{01} = gmT_f$ in $p = 1$ case.[8]

The discussion for a general p for $2 \leq p \leq 8$ is not much different from the $p = 3$ case. To be concrete, let us take the spatial dimensions of a Dp-brane along $x^1, \ldots, x^p$. The $(p-1)$ dimensional surface with uniform charge distribution resulting from the endings of parallel NSNS-strings, say, along x^9-direction is taken as a $(p-1)$-plane along $x^2, \ldots, x^p$ directions and is placed at $x^1 = -\infty$. Then the electric field resulting from this charge surface will be constant and along x^1-direction in any finite region of space. It is also quantized as $F_{01} = gmT_f$ for an NSNS-string (to be thought of as m F-strings). The rest will be the same as in the case of $p = 3$. Since $F_{01} = gmT_f$, we can use the corresponding Dp-brane action to determine the corresponding tension $T_p(m, n)$ describing n Dp-branes carrying m units of quantized constant electric field which is

$$T_p(m,n) = \frac{T_0^p}{g} \sqrt{n^2 + g^2 m^2}\,, \tag{3.1}$$

where $T_0^p = 1/(2\pi)^p \alpha'^{(p+1)/2}$. This expression clearly indicates that the configuration of n Dp-branes carrying m units of quantized constant electric field with m and n relatively prime integers is a non-threshold bound state. So we conclude that n Dp-branes carrying m units of quantized constant electric field consist of a BPS non-threshold bound state which preserves one half of the spacetime supersymmetries.

Since the quantized electric flux or field lines can be interpreted as F-strings, these bound states should be identified with the (F, Dp) bound states which are also related to the (m,n)-string or (F, D1) by T-dualities along the transverse directions. But here we must be careful about the notation 'F' in (F, Dp). This F actually represents an infinite number of parallel NS-strings along, say, x^1 direction, which are distributed evenly over a $(p-1)$-dimensional plane perpendicular to the x^1-axis (or the strings). As indicated above, each of these NS-strings is m F-strings

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[7] The existence of such stable BPS states preserving one half of the spacetime supersymmetries can also be inferred by T-dualities on the D-string carrying a constant electric field along directions transverse to the D-string.

[8] To be more precise, we T-dualize the D3 brane Born-Infeld action with flat background and non-vanishing constant worldvolume field F_{01} along x^2 and x^3 directions. We then end up with a D-string Born-Infeld action. Therefore we can read $F_{01} = gmT_f$. Noticing the relationship between the exact tension and linearized tension for $p = 1$ case, we must have the tension for the D3 brane bound state as given in eq. (3.1) since the two cases are related to each other by T-dualities.

if $F_{01} = gmT_f$. The tension formula eq. (3.1) implies that we should have one NS-string (or m F-strings) per $(2\pi)^{p-1}\alpha'^{(p-1)/2}$ area over the above $(p-1)$-plane. Since T-dualities preserve supersymmetries, we can see in a different way that these bound states preserve one half of the spacetime supersymmetries since the original (F,D1) preserves one half of the spacetime supersymmetries. We will use this identification and perform T-dualities to construct explicitly the spacetime configurations for these bound states in a forthcoming paper [15]. We will show there that the tension formula eq. (3.1) holds and there are indeed m F-strings per $(2\pi)^{p-1}\alpha'^{(p-1)/2}$ area of $(p-1)$-dimensions. The spacetime configurations for (F, Dp) for $p = 3, 4, 6$ have been given in [16, 18, 17], respectively.

Once we have the above, it should not be difficult to have a non-threshold bound state of n D3 branes carrying q units of quantized constant magnetic field with n, q relatively prime. All we need is to replace the F-strings in the above for $p = 3$ case by D-strings. If we also choose the quantized constant magnetic field along the x^1-axis, we must have $F_{23} = qT_f$ from the discussion in [3] about a D-string ending on a D3 brane. The corresponding tension is

$$T_3(q,n) = \frac{T_0^3}{g}\sqrt{n^2+q^2}\,. \tag{3.2}$$

This tension formula implies that the linearized approximation on the D3 brane worldvolume is good only if $n \gg q$. This bound state should correspond to the so-called (D1, D3) bound state. Again, we should have an infinite number of D-strings in this bound state and there should be q D-strings per $(2\pi)^2\alpha'$ area over the x^2x^3-plane.

Similarly, if we replace the F-strings or D-strings by (m,q)-strings in the above, we should end up with a non-threshold bound state of n D3 branes carrying m units of quantized electric flux lines and q units of quantized magnetic flux lines with any two of the three integers relatively prime. The tension for this bound state is

$$T_3(m,q,n) = \frac{T_0^3}{g}\sqrt{n^2+q^2+g^2m^2}\,. \tag{3.3}$$

The linearized approximation on the worldvolume is good if either $n \gg q, n \gg m$ for fixed and finite g or $n \gg q$ for small g and finite m. We denote this bound state as ((F, D1),D3). We should also have an infinite number of (m,q)-strings in this bound state and there is one (m,q)-string per $(2\pi)^2\alpha'$ area over the x^2x^3-plane.

In [13], we will construct explicit configuration or ((F,D1),D3) bound state which gives the (D1, D3) bound state as a special case. We will confirm all the above mentioned properties for them. The spacetime configurations for (Dp, D$(p+2)$) for $0 \le p \le 4$ have been given in [12, 17, 18].

Note added: After the submission of this paper to hep-th, we were informed that the existence of the bound states of Dp branes carrying constant electric fields was also discussed in [19] but in a completely different approach of the mixed boundary conditions.

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