

CERN-TH-99-331
Imperial/TP/99-0/8
November, 1999

Type II Branes from Brane-Antibrane in M-theory

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Abstract

We discuss in a systematic way all the possible realisations of branes of M and type II theories as topological solitons of a brane-antibrane system. The classification of all the possibilities, consistent with the structure of the theory, is achieved by studying the Wess-Zumino terms in the worldvolume effective actions of the branes of M-theory and their reductions.

1 Introduction

During the past couple of years, significant progress has been made in our understanding of M-theory beyond the BPS configurations. These advances have already permitted to test the web of dualities relating the different phases of M-theory (the different superstring theories) on some of the non-BPS states of the spectrum, and a beautiful outlook on the interplays between BPS branes and non-BPS branes has been given in some cases (see [1]-[4] for reviews and references therein) along with an elegant mathematical formulation [5, 6]. For example, a BPS D p -brane of type II theory may be viewed as coming from a non-BPS system given by a D($p+2$), anti D($p+2$) pair [7], [8]. The instability of this non-BPS configuration manifests itself in a complex tachyonic mode of the open string stretched between the pair. When the pair coincides, the tachyon rolls down to a true vacuum and condenses leading to a stable vortex-like configuration, and the resulting object is a BPS D p -brane. Recently, it has been argued [9] that a similar mechanism could also produce fundamental strings. Namely, a fundamental string in the Type II theory could be described as a bound state of any pairs of stable D p , anti-D p branes where the tachyon of a D($p-2$)-brane stretched between them condenses. In [9], the author considers in some detail the case $p = 4$, i.e. the condensation of a D2-brane stretched between a D4, anti-D4 pair. Since the tachyonic condensing charged object is in this case extended (a tachyonic worldvolume string), there are no direct ways to describe quantitatively this type of mechanism. Nevertheless, the existence of this process can be deduced from the following three steps consideration [9]. One first notices that the usual process [8] of creation of a D2-brane in terms of the condensation of a fundamental string should have a description in M-theory in terms of creation of an M2-brane by condensation of a stretched M2 between a pair of M5, anti-M5 branes. Then one identifies in the worldvolume effective action of the brane anti-brane pair the Wess-Zumino term responsible for this process. Finally upon dimensional reduction one finds two Wess-Zumino terms, one describing the usual realisation of the D2 as a soliton, the other describing the fundamental string.

In this paper, we propose to extend in a systematic way this kind of consideration. We study all the possible realisations of branes of M and type II theories as topological solitons of a brane-antibrane system by looking at the Wess-Zumino terms of the worldvolume effective actions of the different brane anti-brane pairs in M-theory.

The paper is organised as follows. In section 2 we study the M5- $\overline{\text{M5}}$ system, reviewing the work of Yi [9]. Section 3 discusses the MKK- $\overline{\text{MKK}}$ system, and in section 4 we study the M9- $\overline{\text{M9}}$ case. Section 5 considers all

brane-antibrane systems in M-theory in which M-waves are involved, in particular the M2– $\overline{\text{M2}}$ case. Finally, section 6 analyses type IIB branes from the same kind of brane- antibrane systems. The last section contains a summary and some discussions.

2 The M5– $\overline{\text{M5}}$ system

In this section we briefly review the results of ref.[9]. We start with the M5– $\overline{\text{M5}}$ system and analyse the process of annihilation of a pair of M5, anti-M5 branes in terms of the tachyonic condensation of an M2-brane stretched between this pair. In particular, one can identify the following coupling [10] in the M5-brane, $\overline{\text{M5}}$ -brane worldvolume action:

$$\int_{R^{5+1}} \hat{C} \wedge d\hat{a}^{(2)}, \quad (2.1)$$

as the one describing the emergence of an M2-brane soliton when the stretched tachyonic M2-brane condenses [9]. Here \hat{C} is the 3-form of eleven dimensional supergravity and $\hat{a}^{(2)}$ the worldvolume 2-form present in the action of the M5-brane¹. This 2-form is self-dual for a single M5-brane, however for an M5, anti-M5 pair it is unrestricted [9], given that in the anti-M5 brane effective action it is anti-self-dual and both contributions are combined to describe the coinciding M5, anti-M5 pair². The topologically non-trivial tachyonic condensation of an M2 is though [9] to be accompanied by a localised magnetic flux $d\hat{a}^{(2)}$. Integrating over the flux on a transverse R^3 one finds:

$$\int_{R^{2+1}} \hat{C}, \quad (2.2)$$

which means that the condensation of the tachyonic mode of the M2 gives rise to the annihilation of the M5 anti-M5 pair into an M2-brane, since this is the way the M2-brane couples, minimally, to \hat{C} .

The dimensional reduction of the stretched M2-brane between the two M5-branes, along an M5-brane worldvolume direction, gives a fundamental string stretched between a D4 and an anti-D4 branes, if the reduction takes place along the M2-brane, or a D2-brane stretched between two D4, anti-D4 branes, if the reduction takes place along a direction transverse to the M2-brane. These two processes are described by the worldvolume reduction of (2.1)³:

¹Hats on target space fields indicate that they are 11-dimensional. We use hats as well for the worldvolume fields of branes in 11 dimensions.

²The complete WZ term including the coupling of the complex tachyonic field has been constructed in [11] for D brane anti-D brane systems.

³We ignore all numerical prefactors.

$$\int_{R^{5+1}} \hat{C} \wedge d\hat{a}^{(2)} \sim \int_{R^{4+1}} C^{(3)} \wedge db^{(1)} + \int_{R^{4+1}} B^{(2)} \wedge da^{(2)} \quad (2.3)$$

where:

$$\hat{a}_{\mu 5}^{(2)} = b_{\mu}^{(1)}, \quad \hat{a}_{\mu\nu}^{(2)} = a_{\mu\nu}^{(2)}, \quad \mu = 0, 1, \dots, 4, \quad (2.4)$$

and $C^{(3)}$ denotes the RR 3-form and $B^{(2)}$ the NS-NS 2-form of the Type IIA theory. The first term describes a stretched fundamental string, coupled to $b^{(1)}$, and the second a stretched D2-brane, coupled to $a^{(2)}$. Considering the first term, integration over the localised magnetic flux $db^{(1)}$, which accompanies the topologically non-trivial condensation of the tachyon of the string [8], along a transverse R^2 gives the coupling:

$$\int_{R^{2+1}} C^{(3)} \quad (2.5)$$

which is the way the RR 3-form couples to the D2-brane. Therefore, one recovers the fact [8] that the condensation of the stretched fundamental string, coupled to $b^{(1)}$, gives a solitonic D2-brane. Reversing the logic, the well-established process of creation of a D2-brane legitimates by oxidation the process of M2 creation described above.

On the other hand, a similar argument [9] on the second term of (2.3) shows that the mechanism of tachyonic condensation of the stretched D2-brane, coupled to $a^{(2)}$, upon integration over the localised flux $da^{(2)}$ on a transverse R^3 (flux which should accompany this topologically non-trivial process) gives:

$$\int_{R^{1+1}} B^{(2)}, \quad (2.6)$$

describing a solitonic fundamental string.

One can describe as well the process in which a D2-brane stretched between a NS5, anti-NS5 pair of branes condenses, giving rise to a D2-brane soliton. The corresponding coupling is given by the reduction of (2.1) along a direction perpendicular to the M5-branes worldvolume:

$$\int_{R^{5+1}} C^{(3)} \wedge da^{(2)}. \quad (2.7)$$

Here the integration over the localised flux $da^{(2)}$ on a transverse R^3 gives the minimal coupling of a D2-brane:

$$\int_{R^{2+1}} C^{(3)}. \quad (2.8)$$

3 The MKK– $\overline{\text{MKK}}$ system

Following the same reasoning as in the previous section we now analyse the different possible processes starting with the MKK– $\overline{\text{MKK}}$ system by looking at the relevant terms in the worldvolume effective action of the Kaluza-Klein monopole.

The worldvolume effective action of the M-theory Kaluza-Klein monopole was constructed in [12, 13]. The existence of the Taub-NUT direction in the space transverse to the monopole is implemented at the level of the effective action by introducing a Killing isometry which is gauged in the worldvolume. Then the target space fields must couple in the worldvolume with covariant derivatives of the embedding scalars, or through contraction with the Killing vector. The Kaluza-Klein monopole is charged with respect to an 8-form, which is the electric-magnetic dual of the Killing vector considered as a 1-form. This field is itself contracted with the Killing vector, giving a 7-form minimally coupled to the 7 dimensional worldvolume of the monopole.

The worldvolume effective action of the monopole contains the following term [13]:

$$\int_{R^{6+1}} i_{\hat{k}} \hat{C} \wedge d\hat{b}^{(1)}, \quad (3.1)$$

where \hat{C} denotes the 6-form of eleven dimensional supergravity, \hat{k} is the Killing vector, with $(i_{\hat{k}} \hat{C})_{\hat{\mu}_1 \dots \hat{\mu}_5} \equiv \hat{k}^{\hat{\mu}_6} \hat{C}_{\hat{\mu}_1 \dots \hat{\mu}_6}$, and $\hat{b}^{(1)}$ is a 1-form worldvolume field which describes the coupling to an M2-brane wrapped on the Taub-NUT direction. The same coupling appears in the effective action of the MKK– $\overline{\text{MKK}}$ pair, where now $\hat{b}^{(1)} = \hat{b}_1^{(1)} - \hat{b}_2^{(1)}$, with $\hat{b}_{1,2}^{(1)}$ the corresponding vector field in the worldvolume of each monopole. After condensation of the tachyonic mode of the M2-brane, the integration of the localised flux $d\hat{b}^{(1)}$ on a transverse R^2 gives

$$\int_{R^{4+1}} i_{\hat{k}} \hat{C} \quad (3.2)$$

i.e. an M5-brane soliton with one worldvolume direction wrapped around the Taub-NUT direction. Therefore we can describe a (wrapped) M5-brane soliton, as the condensation of an M2-brane stretched between the Kaluza-Klein anti Kaluza-Klein monopole pair.

We can now analyse the different possible processes in the type IIA theory to which this process gives rise. Dimensionally reducing along the Taub-NUT direction of the monopole we can describe a D4-brane through the condensation of an open string stretched between a D6, anti-D6 pair [8]. This is described by the coupling:

$$\int_{R^{6+1}} C^{(5)} \wedge db^{(1)} \quad (3.3)$$

which is straightforwardly obtained by reducing the coupling (3.1) describing the creation of the solitonic (wrapped) M5-brane.

The reduction along a worldvolume direction of the monopole gives as one of the possible configurations a solitonic NS5-brane, obtained after the condensation of an open string stretched between a Type IIA pair of Kaluza-Klein anti-Kaluza-Klein monopoles. The worldvolume reduction of (3.1) gives:

$$\int_{R^{5+1}} i_k C^{(5)} \wedge db^{(1)} + \int_{R^{5+1}} i_k B^{(6)} \wedge db^{(0)} \quad (3.4)$$

where $b^{(0)}$ arises as the component of $\hat{b}^{(1)}$ along the worldvolume direction that is being reduced. These terms describe two processes: One in which a (wrapped) D4-brane is created after condensation of a (wrapped) D2-brane stretched between two Type IIA monopoles, described by the first term, and one in which a (wrapped) NS5-brane is created after the condensation of a (wrapped) open string. This is, to our knowledge, the first example in which a NS5-brane has been described through a brane anti-brane pair annihilation.

There is another configuration giving rise to a solitonic NS5-brane, though it occurs after the annihilation of a pair of so-called exotic branes, i.e. branes not predicted by the analysis of the spacetime supersymmetry algebra. This process is obtained after the reduction of the M2-brane stretched between the KK, anti-KK pair along a direction transverse to the monopoles, but different from the Taub-NUT direction. This reduction of the M-theory Kaluza-Klein monopole gives rise to a Kaluza-Klein type of solution in ten dimensions whose transverse space is not a four dimensional euclidean Taub-NUT space, as for the conventional Kaluza-Klein monopole, but three dimensional. Therefore this solution is not asymptotically flat but logarithmically divergent. Moreover it is not predicted by the analysis of the Type IIA spacetime supersymmetry algebra (see [14] for a possible explanation of this fact). We will however discuss briefly this type of configurations because they give rise to interesting descriptions of NS-NS branes in terms of brane anti-brane annihilation. We will denote the brane obtained through this reduction of the M-theory KK-monopole as a KK6-brane⁴. The coupling in the KK6-brane worldvolume action reads:

$$\int_{R^{6+1}} i_k B^{(6)} \wedge db^{(1)}. \quad (3.5)$$

⁴The Type IIA Kaluza-Klein monopole would then be denoted as a KK5-brane.

This describes a (wrapped) NS5-brane after condensation of a (wrapped) D2-brane stretched between a KK6, anti-KK6 pair of branes.

We now turn to the “dual” process in the MKK– $\overline{\text{MKK}}$ system, i.e. obtaining an M2-brane soliton after the condensation of an M5-brane. A wrapped M5-brane is coupled in the worldvolume of a higher dimensional brane through a 4-form field, which in the 7 dimensional worldvolume of the monopole is dual to the vector field $\hat{b}^{(1)}$ describing the coupling of a wrapped M2-brane. Given a dual pair of worldvolume fields only one can couple at the same time in the worldvolume effective action, given that both of them carry the same number of degrees of freedom. Therefore we need to dualise the vector field $\hat{b}^{(1)}$ in the Kaluza-Klein monopole effective action. First, one adds a term

$$\int_{R^{6+1}} d\hat{b}^{(1)} \wedge d\hat{b}^{(4)} \quad (3.6)$$

to the action, and then integrates $\hat{b}^{(1)}$ from its equation of motion⁵. Since $\hat{b}^{(1)}$ couples through its gauge invariant field strength:

$$\hat{F}^{(2)} = d\hat{b}^{(1)} + (i_{\hat{k}}\hat{C}), \quad (3.7)$$

we can write (3.6) as

$$\int_{R^{6+1}} (\hat{F}^{(2)} - (i_{\hat{k}}\hat{C})) \wedge d\hat{b}^{(4)}, \quad (3.8)$$

from where a term

$$\int_{R^{6+1}} (i_{\hat{k}}\hat{C}) \wedge d\hat{b}^{(4)} \quad (3.9)$$

is already known to be coupled to the dual action without the need to eliminate explicitly $\hat{F}^{(2)}$ from its equation of motion. This term describes an M2-brane soliton. Indeed, the condensation of the wrapped M5-brane, accompanied by a localised $d\hat{b}^{(4)}$ -flux over a transverse R^5 , gives a coupling:

$$\int_{R^{1+1}} (i_{\hat{k}}\hat{C}), \quad (3.10)$$

which is the way the eleven dimensional 3-form couples to a wrapped M2-brane. Therefore, this is the soliton that is produced after the condensation.

The creation of a fundamental string in the Type IIA theory is now described as the reduction of the stretched M5-brane between the Kaluza-Klein anti Kaluza-Klein pair over the Taub-NUT direction of the monopole. This

⁵This step is normally quite involved due to the complicated form of the Born-Infeld part.

gives a D4-brane stretched between a D6, anti-D6 pair. The reduction of the coupling (3.9) gives:

$$\int_{R^{6+1}} B^{(2)} \wedge db^{(4)}. \quad (3.11)$$

Therefore, we find:

$$\int_{R^{1+1}} B^{(2)} \quad (3.12)$$

after the integration of the 4-form, describing a solitonic fundamental string [9].

Three other possible brane anti-brane annihilation processes can be deduced in Type IIA from the M-theory Kaluza-Klein anti-Kaluza-Klein annihilation that we have just discussed. If we reduce this process along a worldvolume direction of the Kaluza-Klein monopole we find the following couplings:

$$\int_{R^{5+1}} i_k B^{(2)} \wedge db^{(4)} + \int_{R^{5+1}} i_k C^{(3)} \wedge db^{(3)} \quad (3.13)$$

where:

$$\hat{b}_{\mu_1 \dots \mu_4}^{(4)} = b_{\mu_1 \dots \mu_4}^{(4)}, \quad \hat{b}_{\mu_1 \dots \mu_3 6}^{(4)} = b_{\mu_1 \dots \mu_3}^{(3)}, \quad \mu = 0, 1, \dots, 5. \quad (3.14)$$

The first term in (3.13) describes a fundamental string created after the condensation of a NS5-brane stretched between a pair of Type IIA Kaluza-Klein monopole anti-monopole. Both the fundamental string and the NS5-brane are wrapped on the Taub-NUT direction of the monopole. On the other hand, the second term represents a wrapped D2-brane arising after the condensation of a wrapped D4-brane stretched between the two monopoles. The third case is obtained reducing (3.9) along a direction transverse to the monopole but different from its Taub-NUT direction. We obtain the following coupling in the seven dimensional worldvolume of a KK6-brane:

$$\int_{R^{6+1}} i_k C^{(3)} \wedge db^{(4)}. \quad (3.15)$$

This describes a D2-brane wrapped around the NUT direction of the KK6-brane, and it is obtained after the condensation of a (wrapped) NS5-brane stretched between the brane anti-brane pair.

4 The M9– $\overline{\text{M9}}$ system

In this section we study the possible processes of creation of branes after tachyonic condensation in the M9– $\overline{\text{M9}}$ system. We identify the coupling in the M9-brane effective action responsible for this condensation and analyse the related processes of creation of branes in type IIA.

For this purpose it is important to recall that the M9-brane contains a gauged direction in its worldvolume [15], such that the field content is that of the nine dimensional vector multiplet. Reduction along this direction gives the D8-brane effective action, whereas the reduction along a different worldvolume direction gives the KK8-brane, another so-called exotic brane of the Type IIA theory, in the sense that it is not predicted by the analysis of the Type IIA spacetime supersymmetry algebra. This brane contains as well a gauged direction in its worldvolume, inherited from that of the M9-brane, and has been studied in connection with the 7-brane of the Type IIB theory in [14], where its worldvolume effective action has been derived. The Wess-Zumino term of the M9-brane effective action has not yet been constructed in the literature. However, from the effective action of the KK8-brane we can deduce the presence of the following term in the M9-brane worldvolume effective action:

$$\int_{R^{8+1}} i_{\hat{k}} \hat{N}^{(8)} \wedge d\hat{b}^{(1)}. \quad (4.1)$$

Let us stress that the M9-brane is effectively an 8-brane, given that it has one of its worldvolume directions gauged. Therefore the integration takes place over a nine dimensional space-time. The contraction of the 8-form potential $\hat{N}^{(8)}$ with the (worldvolume) Killing direction, denoted by \hat{k} , is the field to which the M-theory Kaluza-Klein monopole couples minimally⁶. $\hat{b}^{(1)}$ is a 1-form worldvolume field describing a wrapped M2-brane ending on the M9-brane [16]. The reduction of this term along a worldvolume direction different from the gauged direction gives the terms:

$$\int_{R^{7+1}} i_k N^{(8)} \wedge db^{(0)} + \int_{R^{7+1}} i_k N^{(7)} \wedge db^{(1)} \quad (4.2)$$

present in the effective action of the KK8-brane (expression (4.6) of reference [14]), and where:

$$\hat{b}_\mu^{(1)} = b_\mu^{(1)}, \quad \hat{b}_8^{(1)} = b^{(0)}, \mu = 0, 1, \dots, 7, \quad (4.3)$$

⁶As we mentioned in the previous section here $\hat{N}^{(8)}$ is the electric-magnetic dual of the Killing vector considered as a 1-form.

and $i_{\hat{k}}\hat{N}^{(8)}$ gives rise to the two fields $i_k N^{(8)}$, $i_k N^{(7)}$. $i_k N^{(8)}$ is the field that couples minimally to the KK6-brane that we considered in the previous section, whereas the ordinary Type IIA Kaluza-Klein monopole is charged with respect to $i_k N^{(7)}$.

The coupling (4.1) in the M9-brane worldvolume effective action describes the process in which a Kaluza-Klein monopole is created after the condensation of a, wrapped, M2-brane stretched between an M9, anti-M9 pair of branes. As in the previous sections the pair is described by choosing $\hat{b}^{(1)}$ as the difference of vector fields in each brane. Indeed, integration over the localised magnetic $\hat{b}^{(1)}$ -flux, associated to the wrapped M2-brane, on a transverse R^2 gives:

$$\int_{R^{6+1}} i_{\hat{k}}\hat{N}^{(8)} \quad (4.4)$$

i.e. the field minimally coupled to the Kaluza-Klein monopole.

Reducing (4.1) along the isometric worldvolume direction denoted by \hat{k} we can describe the process in which a D6-brane is created after the condensation of an open string stretched between a pair of D8, anti-D8 branes [8]. The resulting coupling in the worldvolume effective action of the D8 brane is given by:

$$\int_{R^{8+1}} C^{(7)} \wedge db^{(1)} \quad (4.5)$$

where $C^{(7)}$ is the RR 7-form potential of the Type IIA theory and is obtained through the reduction:

$$i_{\hat{k}}\hat{N}^{(8)} = C^{(7)} + \dots \quad (4.6)$$

(see [13] for the details of this reduction). Therefore the condensation of a fundamental string, accompanied by a localised $db^{(1)}$ flux over a transverse R^2 , gives a D6-brane soliton:

$$\int_{R^{6+1}} C^{(7)}. \quad (4.7)$$

Instead, we can reduce (4.1) along a worldvolume direction of the M9-brane, in which case we obtain a pair of KK8, anti-KK8 branes with the following couplings:

$$\int_{R^{7+1}} i_k N^{(7)} \wedge db^{(1)} + \int_{R^{7+1}} i_k N^{(8)} \wedge db^{(0)}, \quad (4.8)$$

derived already in (4.2). The first coupling describes a Type IIA Kaluza-Klein monopole, obtained after the condensation of a D2-brane. The Taub-NUT

direction of the monopole coincides with the gauged worldvolume direction of the KK8 branes, and the stretched D2-brane is also wrapped around this direction. The second coupling describes a KK6-brane, obtained after the condensation of a (wrapped) open string stretched between the two KK8, anti-KK8 branes. Again the Killing direction of the KK6 and KK8-branes coincide. A last reduction on (4.1) can be performed along the transverse direction. Such a reduction on the M9 gives rise to the NS9A-brane predicted by the Type IIA spacetime supersymmetry algebra [17]. We have thus the possibility of obtaining a KK6 after the condensation of a (wrapped) D2 stretched between a NS9A, anti-NS9A pair.

As in the previous section, the process in which a wrapped M2-brane is created through the condensation of a Kaluza-Klein monopole stretched between the pair of M9, anti-M9 branes is described by the coupling dual to (4.1). The Kaluza-Klein monopole must be coupled to the (9 dimensional) worldvolume of the M9-brane through a 6-form worldvolume field $\hat{b}^{(6)}$, which must be the worldvolume dual of the vector field $\hat{b}^{(1)}$. In the dualisation process we find:

$$\int_{R^{8+1}} d\hat{b}^{(1)} \wedge d\hat{b}^{(6)} = \int_{R^{8+1}} (\hat{F}^{(2)} - (i_{\hat{k}}\hat{C})) \wedge d\hat{b}^{(6)}, \quad (4.9)$$

from where we already identify a coupling:

$$\int_{R^{8+1}} i_{\hat{k}}\hat{C} \wedge d\hat{b}^{(6)} \quad (4.10)$$

in the dual effective action. Integration over a localised magnetic $\hat{b}^{(6)}$ -flux, associated to the Kaluza-Klein monopole, on a transverse R^7 gives:

$$\int_{R^{1+1}} i_{\hat{k}}\hat{C} \quad (4.11)$$

describing a wrapped M2-brane soliton.

The reduction of (4.10) along the \hat{k} -direction gives:

$$\int_{R^{8+1}} B^{(2)} \wedge db^{(6)}. \quad (4.12)$$

Here $b^{(6)}$ is associated to a D6-brane, and the integration of its localised magnetic flux on a transverse R^7 gives:

$$\int_{R^{1+1}} B^{(2)}, \quad (4.13)$$

describing a fundamental string soliton [9].

As before, we can also analyse the process obtained by reducing (4.10) along a worldvolume direction. We obtain:

$$\int_{R^{7+1}} i_k C^{(3)} \wedge db^{(5)} + \int_{R^{7+1}} i_k B^{(2)} \wedge db^{(6)}, \quad (4.14)$$

where $b^{(5)}$ arises from the reduction of $\hat{b}^{(6)}$ along the worldvolume direction. The first term describes a (wrapped) D2-brane, occuring after the condensation of a KK5 monopole whose Killing direction coincides with the Killing direction of the KK8, anti-KK8 branes obtained after the reduction. The second term describes a (wrapped) fundamental string, realised in this case after the condensation of a KK6-brane stretched between the pair of KK8, anti-KK8 branes. Finally, reducing (4.10) along the transverse direction leads to a process where a (wrapped) D2-brane is produced after the condensation of a KK6-brane stretched between a pair of NS9A, anti-NS9A branes.

5 Brane-antibrane systems in M-theory involving M-waves

In this section we analyse, among other processes, the brane-antibrane system in M-theory giving rise to the process in which a fundamental string stretched between a D2, anti-D2 pair condenses and a solitonic D0-brane is produced. This process is described in M-theory by a wrapped M2-brane stretched between a pair M2, anti-M2. When the tachyonic mode of the wrapped M2-brane condenses an M-wave soliton is produced. In order to identify the Wess-Zumino coupling in the worldvolume effective action of the M2, anti-M2 pair of branes that is responsible for this process let us first analyse its dual configuration, i.e. that in which an M-wave is “stretched” between the brane anti-brane pair and a wrapped M2-brane is created after its tachyonic mode condenses.

The so-called M-wave is a pp-wave in M-theory carrying momentum along a given direction, which we will denote by y . An M-wave ending on another M-brane is described in the worldvolume effective action of the latter by its coupling to the embedding scalar y . Therefore in order to have a non-trivial condensation of the tachyonic mode of the M-wave this direction must be topologically non-trivial. Indeed, the coupling in the worldvolume effective action of the M2, anti-M2 pair of branes that is responsible for the condensation of the tachyonic mode of the M-wave is given by:

$$\int_{R^{2+1}} i_{\hat{h}} \hat{C} \wedge dy, \quad (5.1)$$

where \hat{h} denotes a Killing vector in the y -direction. Integration over a localised magnetic dy -flux gives a coupling:

$$\int_{R^{1+1}} (i_{\hat{h}} \hat{C}), \quad (5.2)$$

describing an M2-brane wrapped on the y -direction. The dual process is now described by dualising this coupling. For this we need to recall that the field strength associated to the y -field, which appears in the worldvolume effective action of the M-theory pp-wave [18], is $\hat{F}^{(1)} = dy + \hat{h}^{-2} \hat{h}_{\mu} dx^{\mu}$, where μ runs over all directions but the y direction. Therefore, we find a coupling:

$$\int_{R^{2+1}} \hat{h}^{-2} \hat{h}_{\mu} dx^{\mu} \wedge d\hat{b}^{(1)}, \quad (5.3)$$

$\hat{b}^{(1)}$ being the worldvolume dual of the scalar y . Integrating now over a localised $\hat{b}^{(1)}$ -flux we end up with the coupling:

$$\int_R \hat{h}^{-2} \hat{h}_{\mu} dx^{\mu} \quad (5.4)$$

which is the field minimally coupled to the M-wave moving in the \hat{h} direction. Therefore condensation of the wrapped M2-brane coupled to $\hat{b}^{(1)}$ in the worldvolume of the pair produces an M-wave moving in the direction on which the stretched M2-brane is wrapped.

We can now analyse which are the Type IIA brane anti-brane annihilation processes to which these two systems give rise. It is particularly interesting to consider the reduction along the y -direction. The coupling (5.1) gives rise to:

$$\int_{R^{2+1}} B^{(2)} \wedge dy. \quad (5.5)$$

Therefore it describes a fundamental string, through the condensation of a D0-brane stretched between the D2, anti-D2 pair of branes obtained after the reduction. On the other hand, the coupling (5.3) gives:

$$\int_{R^{2+1}} C^{(1)} \wedge db^{(1)} \quad (5.6)$$

which in turn describes a solitonic D0-brane after condensation of a fundamental string. Therefore we can conclude that the M2, anti-M2 systems that we have discussed are the origin in M-theory of both the D0-brane creation studied by Sen [8] and the creation of a fundamental string in a D2, anti-D2 system after D0-brane condensation [9].

Reduction along a direction different from y gives rise to two interesting processes which, as we will see, generalise to all branes in Type II theories.

From worldvolume reduction we obtain a process in which a wrapped fundamental string stretched⁷ between a pair F1, anti-F1 gives rise to a pp-wave moving in the direction on which the stretched string is wrapped. Of course we also find the dual to this process, i.e. a solitonic wrapped fundamental string emerging after the condensation of a pp-wave in the same brane configuration. Similarly, after doing a direct dimensional reduction we obtain the same type of configurations but for D2-branes. A wrapped D2-brane is created after a pp-wave condenses in a D2, anti-D2 pair, and a pp-wave can also be created if instead a wrapped D2-brane condenses.

An M-wave, being coupled in the worldvolume of an M-brane through the worldvolume scalar labelling the direction in which it propagates, can end on any of the branes of M-theory. Therefore we can analyse the same two processes that we have studied in the M2- $\overline{\text{M2}}$ case on M5, MKK or M9 brane anti-brane systems. We are not going to repeat in detail the corresponding analysis of the Wess-Zumino terms responsible for these processes, since the reasoning goes straightforwardly as for the M2 system. Let us just mention that, together with the process in which any wrapped Type IIA p-brane⁸ stretched between a p-brane anti p-brane pair gives rise to a pp-wave soliton, and its dual (wrapped p-brane creation through condensation of a pp-wave), we find the following processes:

$$\begin{aligned}
&(\text{NS5}, \overline{\text{NS5}}; \text{D4} \rightarrow \text{D0}) \\
&(\text{NS5}, \overline{\text{NS5}}; \text{D0} \rightarrow \text{D4}) \\
&(\text{KK6}, \overline{\text{KK6}}; \text{KK5} \rightarrow \text{D0}) \\
&(\text{KK6}, \overline{\text{KK6}}; \text{D0} \rightarrow \text{KK5}) \\
&(\text{NS9}, \overline{\text{NS9}}; \text{KK8} \rightarrow \text{D0}) \\
&(\text{NS9}, \overline{\text{NS9}}; \text{D0} \rightarrow \text{KK8})
\end{aligned}$$

where we use a simplified notation to indicate that the condensation of a brane (third column) stretched between the brane-antibrane pair given by the first and second columns gives rise to a certain brane soliton, specified by the fourth column. Most of these processes involve exotic branes, but it is particularly interesting to see that a D0-brane can be realised as a solitonic configuration in an NS5, anti-NS5 annihilation process. This represents a novel way of realising this brane soliton other than through, the more conventional, D1, anti-D1 annihilation process [8].

⁷The string is in fact not really properly stretched between the pair being wrapped in the y -direction.

⁸Also NS-NS ones, like the fundamental string that we have just considered.

6 Type IIB branes from brane-antibrane systems

In the previous sections we have derived all the Type IIA branes that can possibly occur as solitons after the condensation of a tachyonic brane stretched between a pair brane-antibrane. This derivation was performed by direct reduction from M-theory, where the Wess-Zumino term in the worldvolume effective action of the brane-antibrane pair responsible for the process was identified. It is now straightforward to derive the T-dual couplings responsible for brane creation in a brane-antibrane system in the Type IIB theory.

Together with the realisation of Dp-branes as bound states of D(p+2), anti D(p+2) branes [8] we find the corresponding dual processes, in which a BPS fundamental string is described as a bound state of D(p+2), anti D(p+2) branes after the condensation of a tachyonic Dp-brane stretched between them. T-duality allows to identify explicitly the couplings in the D(p+2)-brane effective action that are responsible for these processes:

$$\int_{R^{p+3}} C^{(p+1)} \wedge db^{(1)} \quad (6.1)$$

describes Dp-brane creation after condensation of an F1, described by $b^{(1)}$, and:

$$\int_{R^{p+3}} B^{(2)} \wedge db^{(p)} \quad (6.2)$$

describes F1 creation after condensation of the p-brane described by $b^{(p)}$, worldvolume dual of $b^{(1)}$.

Type IIB branes are organised as singlets or doublets under the Type IIB $SL(2, Z)$ duality group. Therefore we expect to find a spectrum of brane solitons in brane-antibrane systems that respects this symmetry. The D5 brane forms an $SL(2, Z)$ doublet with the NS5 brane of the Type IIB theory. Therefore S-duality predicts the occurrence of a D3-brane soliton as a bound state in a NS5, anti-NS5 pair when the condensation of a D1-brane stretched between the two takes place. This process is indeed obtained after T-dualising two Type IIA configurations. Namely, that in which a D2 brane stretched between a pair of NS5, anti-NS5 branes condensed to give a BPS D2-brane, and that in which the same kind of brane was stretched between a pair of KK5 monopoles and condensed to give rise to a D4-brane soliton. Of course the process in which a D1-brane is created after the condensation of a D3-brane stretched between the two NS5, anti-NS5 branes is also predicted by T-duality from certain Type IIA configurations. For these and the following configurations we omit the explicit Wess-Zumino couplings, since

they can be straightforwardly derived from those in Type IIA found in the previous sections. The situation with the D9-brane is similar to that with the D5-brane, in the sense that it forms a doublet with an NS9-brane in the Type IIB theory. We have indeed obtained after T-duality the configurations describing a 7-brane as a bound state NS9, anti-NS9 after a stretched D1-brane condenses, and its dual, namely a D1-brane realised as a bound state NS9, anti-NS9 through the condensation of a tachyonic 7-brane.

For the Type IIB $\text{MKK}-\overline{\text{MKK}}$ system we find that a pair of Type IIB $\text{KK}, \overline{\text{KK}}$ monopoles can annihilate giving rise to the following solitonic branes:

$$(\text{KK5}, \overline{\text{KK5}}; \text{D3} \rightarrow \text{D3})$$

$$(\text{KK5}, \overline{\text{KK5}}; \text{D1} \rightarrow \text{D5})$$

$$(\text{KK5}, \overline{\text{KK5}}; \text{F1} \rightarrow \text{NS5})$$

$$(\text{KK5}, \overline{\text{KK5}}; \text{D5} \rightarrow \text{D1})$$

$$(\text{KK5}, \overline{\text{KK5}}; \text{NS5} \rightarrow \text{F1})$$

where we use the same simplified notation as in the previous section. We see from these configurations that the creation of both a brane and its S-dual is possible through annihilation of a pair of monopoles, which agrees with the fact that this brane is selfdual under S-duality, so all pairs of S-dual processes should be allowed.

Concerning 7-branes some remarks are in order. T-duality of the Type IIA KK6 and KK8 -branes predicts a 7-brane in the Type IIB theory which is connected by S-duality with the D7-brane, for what we will denote it as an NS7-brane. This is the 7-brane that appears for instance in the processes involving NS9, anti-NS9 annihilation. The existence of these two different effective actions describing 7-branes in the Type IIB theory, where the analysis of the spacetime supersymmetry algebra predicts a single 7-brane, was discussed in [14], where it was argued that the two worldvolume effective actions are indeed necessary in order to describe a single nonperturbative 7-brane in the weak and strong coupling regimes. Consistently with this picture, we find after T-duality one configuration in which an NS5-brane is created when a D1-brane stretched between a pair of NS7, anti-NS7 branes condenses, and the corresponding dual process, i.e. that in which a solitonic D1-brane emerges after condensation of an NS5-brane. These processes are S-dual to the more standard D5, F1 creation [8] [9] through D7, anti-D7 annihilation.

Finally, T-duality on the Type IIA configurations involving pp-waves predicts the analogous kind of configurations in the Type IIB theory. Namely,

solitonic wrapped p-branes after p-brane anti p-brane annihilation through condensation of a pp-wave, and solitonic pp-waves after condensation of a wrapped p-brane in the same system.

7 Discussion

In this paper, extending preceding considerations [9], we have classified the branes of the M and Type II theories which can be realised in a consistent way with respect to the structure of the theory as bound states of systems brane-antibrane, after condensation of the tachyon mode of open branes stretched between the pair. We have achieved this classification by studying the Wess-Zumino terms in the worldvolume effective actions of the branes of M-theory and their reductions.

We have shown that it is possible to give an eleven dimensional description to the creation of a fundamental string from the annihilation of a pair of Dp, anti-Dp branes with $p=2,6,8$. As for the case $p=4$ [9], the fundamental string is created by the condensation of a D(p-2)-brane stretched between the pair Dp, anti-Dp. We have identified the term in the Wess-Zumino action of the pair brane-antibrane in M-theory responsible for this creation. This term is obtained generically by finding the worldvolume dual of the coupling describing a stretched M2-brane between the brane anti-brane pair, which in turn describes an extended worldvolume soliton coming from the condensation of the M2-brane. The case $p=4$ is especially simple in this sense. Its description in M-theory is in terms of an M2-brane stretched between a pair of M5, anti-M5 branes, giving rise to a solitonic M2-brane. This process is self-dual, in the sense that the dual coupling in the six dimensional worldvolume of the M5-brane describes again a solitonic M2-brane, whereas this is not the case for the M-theory origin of the $p=2,6,8$ cases. Therefore, in these cases the reduction to the Type IIA theory gives many different realisations of BPS objects as bound states of brane anti-brane pairs, which by T-duality give in turn rise to many configurations in the Type IIB theory. As an interesting realisation we have found that the NS5-brane can originate from certain brane anti-brane annihilations, both in the Type IIA and Type IIB theories.

We can conclude in general that the BPS branes that can be realised as solitons in a given p-brane anti p-brane configuration are determined by the possible branes that can end on the p-brane, and whose tachyonic mode condenses giving rise to the soliton configuration. These branes are easily predicted by looking at the p-brane worldvolume effective action and identifying the different worldvolume q-forms that couple in it. For instance the

Type IIB Kaluza-Klein monopole anti-monopole pair gives rise to so many different solitonic configurations because there are two scalars and one 2-form coupled in the worldvolume effective action of the monopole [19], allowing for wrapped F1, D1 and D3-branes ending on it, together with the branes described by their worldvolume duals, i.e. D5 and NS5 branes.

Finally, it is worth emphasizing that a lot of progress remains to be done in order to reach a quantitative understanding of the dynamics of the possible processes discussed in this paper. One can furthermore hope that there exists a mathematical connection with some generalisation of K-theory [5, 6] where these processes could fit in.

Acknowledgements

L. H. would like to acknowledge the support of the European Commission TMR programme grant ERBFMBICT-98-2872.

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