Kaluza-Klein dipoles, brane/anti-brane pairs
and instabilities

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ABSTRACT

We review the method of constructing dipole and string loop solutions from the higher-dimensional (Euclidean) Kerr black hole. We analyse the results in various dimensions, finding solutions earlier given in the literature. Then we construct a new heterotic dipole with non-trivial dilaton and gauge fields. This can, in turn, be describes as a brane/anti-brane pair which interpolates between the KK-dipole and the $H$-dipole. Finally an argument is presented on the tachyonic instability by analysing the string fluctuations on the dipole background.

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1. Introduction

Brane/anti-brane pairs have recently played very important role in our understanding of stable non-BPS states in string theory [1]. As a classical vacuum, brane/anti-brane pair leads to unstable configuration. First of all, they attract each other as they are oppositely charged. Moreover, when the separation between them is of the order of the string length, there appears tachyon in the configuration [2]. However, it has been argued in the recent past that, in certain cases, this tachyon leads the system to a stable fixed point in the renormalisation group sense [3].

Since the classical force between brane/anti-brane system never vanishes, search for a configuration describing the pair as a classical solution looses its meaning. However, if we introduce a non-zero background electromagnetic field which triggers repulsion between brane and the anti-brane in such a way that it cancels the attractive force between them, then one would expect to find a classical configuration describing the pair in equilibrium [3]. In [4], such a solution was constructed in string theory and various instabilities were analysed. It has been argued that the Kaluza-Klein (KK) dipole of 5-dimensional gravity [5] has the property of describing brane/anti-brane pair when we add required flat direction [4]. An asymptotic magnetic field appears naturally which, in turn, keeps the system in equilibrium. To our knowledge, this is the only classical configuration known for the brane/anti-brane system till now.

Before we go into the detail of our analysis of brane/anti-brane pair let us first summarise what we do in this letter. In section 2.1, we review, in brief, the $D = 5$ dipole following [4]. This dipole is constructed by starting with Euclidean Kerr metric and adding a time direction. The dipole configuration is made out of monopole, anti-monopole pair. While lifted up in eleven dimensions, it describes a Dirichlet six and anti-six brane pair upon dimensional reduction over the Taub-NUT direction. In section 2.2, we analyse the situation in higher dimensions [5]. Following [5] closely, we argue that similar construction in $D = 6$ gives an oriented string loop. The opposite

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3 It may not be a stable equilibrium though. Instabilities due to the tachyon is expected to be absent if the distance between the pair is large enough.

4 On the other hand, some of the dipole like solutions with magnetic flux tubes have directly been constructed in [4, 5]. However, most of them do not have KK interpretation.

5 This corrects a crucial interpretational error that was made in an earlier version of this paper.
points on the loop behaves as monopole or anti-monopole if we look close enough. We discuss this in a very explicit manner. We further use these results in section 2.3 to excite gauge field along the world-sheet direction of the string loop. Noticing the importance of brane/anti-brane configurations in understanding the physics of non-BPS states, in section 3, we construct a very general five-dimensional dipole which can be embedded in heterotic string theory. This solution is characterized by an angular parameter. This parameter allows the solution to interpolate between the usual KK dipole and the $H$-dipole. We also, as before, analyse the system critically to isolate each of the constituents of the dipole system. In the last section, we try to understand if these brane/anti-brane configurations (in the presence of background electromagnetic field) can be realised as stable string or super-string background at least when the distance between constituents is large. Unfortunately, we find that they likely lead to unstable string backgrounds. A string or superstring propagating in these background contains tachyon in their spectrum.

2. Dipoles and Loops

We start with the $(D-1)$-dimensional Kerr metric [9]:

$$dS^2_{(D-1)} = -\frac{r^2 + a^2\cos^2\theta - 2Mr^{6-D}}{r^2 + a^2\cos^2\theta} \ d\tau^2 - \frac{4Mr^{6-D}\sin^2\theta}{r^2 + a^2\cos^2\theta} \ d\tau d\phi \ (1)$$

$$+ \frac{\sin^2\theta}{r^2 + a^2\cos^2\theta} \left[ (r^2 + a^2)(r^2 + a^2\cos^2\theta) + 2Mr^{6-D}a^2\sin^2\theta \right] d\phi^2$$

$$+ (r^2 + a^2\cos^2\theta) \left[ \frac{d\tau^2}{r^2 + a^2 - 2Mr^{6-D}} + \ d\theta^2 \right] + r^2\cos^2\theta \ d\Omega^{D-5}.$$

Note that this metric has horizon(s) when

$$r^2 + a^2 - 2Mr^{6-D} = 0. \ (2)$$

For $D \leq 6$, there is a critical value of $a$ beyond which the horizon does not exists. However, in case of $D > 6$, for any $a$ and $M$, there exists one horizon.

We then perform an Euclidean rotation

$$\tau \to -iX, \quad a \to ia, \quad (3)$$
and add a new time direction $t$. The solution thus obtained has the following form:

$$
\begin{align*}
    dS^2 &= -dt^2 + (r^2 - a^2 \cos^2 \theta) \left( \frac{dr^2}{\Delta} + d\theta^2 \right) + \Delta \sin^2 \theta \, \mathcal{H} \, d\phi^2 \\
    &\quad + \mathcal{H}^{-1} \left( dX - A_\phi d\phi \right)^2 + r^2 \cos^2 \theta \, d\Omega^{D-5},
\end{align*}
$$

(4)

where the gauge field $A_\phi$ and the functions $\mathcal{H}$ are given by:

$$
\begin{align*}
    \mathcal{H} &= \frac{r^2 - a^2 \cos^2 \theta}{\Delta + a^2 \sin^2 \theta}, \\
    A_\phi &= \frac{2Mr^{6-D}a \sin^2 \theta}{\Delta + a^2 \sin^2 \theta},
\end{align*}
$$

(5)

and

$$
\Delta = r^2 - a^2 - 2Mr^{6-D},
$$

(6)

Since the solutions (1) and (4) are time independent, the above construction is guaranteed to give a solution of the Einstein equations and can be embedded in any theory containing gravity.

2.1. Brane/anti-brane pair

In $D = 5$, (4) corresponds to monopole/anti-monopole pair as has been discussed in [4]. This can be seen explicitly by looking at the metric on $\Delta = 0$. At $\Delta = 0$, and $\theta = 0$, the above metric reduces to an anti-monopole configuration, and, on the other hand, at $\Delta = 0$ and $\theta = \pi$, we get a monopole configuration. Notice that, in order to avoid singularities, the coordinates appearing in (4) have to lie within certain period. For $D = 5$, they are given by

$$
\begin{align*}
    M + \sqrt{M^2 + a^2} \leq r \leq \infty, \\
    0 \leq X \leq \frac{4\pi M(M + \sqrt{M^2 + a^2})}{\sqrt{M^2 + a^2}}, \\
    0 \leq \phi - \frac{aX}{2M(M + \sqrt{M^2 + a^2})} \leq 2\pi.
\end{align*}
$$

(7)

The non-trivial periodicity of $\phi$ shows, in fact, the existence of an external magnetic field, causing a repulsive magnetic force which cancels the attractive electric and gravitational forces and keeps the monopole and anti-monopole in equilibrium [4]. The distance between the pair can be calculated easily by integrating the metric along $\theta$. For large $a$, the distance turns out to be $2a$. This associates a physical meaning to the parameter $a$. 
The above configuration can be lifted up to \( D = 10 \) or \( D = 11 \) in a straightforward way by adding extra flat directions. Upon dimensional reduction over \( X \), the eleven dimensional metric reduces to a Dirichlet six/anti-six brane pair in type IIA string theory. Since under \( T \)-duality along \( X \), the constituent monopole goes to an \( H \)-monopole, we expect for \( D = 5 \), the \( T \)-dual metric that follows from (4) will describe an \( H \)-dipole.

### 2.2. Oriented string loop

One might wonder as to what happens if we generalize the dipole configuration of the sub-section 2.1 for higher dimensions without just adding flat directions. In other words, analysing Eqn. (4) for \( D \geq 5 \) in the same line as above. In that case, one gets a loop of KK-brane \( \mathbb{S} \) rather than a monopole/anti-monopole. In this sub-section, we discuss the configuration in some detail for \( D = 6 \). We will see that indeed for \( D = 6 \), Eqn. (4) is nothing but a KK-string loop lying along the transverse direction \( d\chi \). In the last sub-section, we will use this result to excite gauge fields along the world-sheet direction of the loop.

As mentioned above, we start with Eqn. (4) for \( D = 6 \). The metric in six dimensions takes the form:

\[
\begin{align*}
\text{d}S^2 &= -\text{d}t^2 + (r^2 - a^2 \cos^2 \theta) \left( \frac{\text{d}r^2}{\Delta} + \text{d}\theta^2 \right) + \Delta \sin^2 \theta \, H \, \text{d}\phi^2 \\
&\quad + H^{-1} (\text{d}X - A_\phi \text{d}\phi)^2 + r^2 \cos^2 \theta \, \text{d}\chi^2.
\end{align*}
\]

(8)

where

\[
\Delta = r^2 - a^2 - 2M, \quad A_\phi = \frac{2M \sin^2 \theta}{\Delta + a^2 \sin^2 \theta}.
\]

(9)

To avoid the conical singularity at \( r = \sqrt{a^2 + 2M} \), one must have

\[
0 \leq X \leq \frac{4\pi M}{\sqrt{a^2 + 2M}}, \quad 0 \leq \phi - \frac{aX}{2M} \leq 2\pi.
\]

(10)

Notice that in the limit of large \( a \), the radius in the \( X \) direction depends on the ratio \( \frac{M}{a} \). This is unlike the dipoles in \( D = 5 \), where the radius along \( X \) at large \( a \) is independent of \( a \). Due to this twisted boundary condition \( \mathbb{I} \)

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\( ^6 \)We thank R. Emparan for pointing out a misinterpretation of this result in the previous version of this paper.
on $\phi$, there is an asymptotic magnetic field $[8]$. If we use $\psi = \phi - aX/2M$ as independent coordinate, the magnetic field is given by $B = a/2M$.  

To have further insights of the configuration, we will now analyse the metric at $\theta = 0, \pi$ when $\Delta$ vanishes. From the structure it is clear that the zero of $\Delta$ occurs at $r = r_0 = \sqrt{a^2 + 2M}$. To analyse the metric near $r = r_0$, $\theta = 0$, we define coordinates

$$\sqrt{a^2 + 2M} \sin^2 \theta = \tilde{\rho} \left( 1 - \cos \tilde{\theta} \right), \quad (11)$$

$$2(r - r_0) = \tilde{\rho} \left( 1 + \cos \tilde{\theta} \right), \quad (12)$$

and look at the limit

$$a \to \infty, \quad M \to 0, \quad \theta \to 0, \quad r \to r_0 \quad (13)$$

with $a \sin^2 \theta$ fixed and $r - r_0$ finite. In this limit, the metric takes the following form

$$dS^2 = -dt^2 + d\tilde{\chi}^2 + H^{-1} \left( dX - A_\phi d\phi \right)^2 + H \left( d\tilde{\rho}^2 + \tilde{\rho}^2 d\tilde{\theta}^2 + \tilde{\rho}^2 \sin^2 \tilde{\theta} d\phi^2 \right) \quad (14)$$

with

$$H = 1 + \frac{\tilde{M}}{\tilde{\rho}} \quad A_\phi = \tilde{M} (1 - \cos \tilde{\theta}) \quad \tilde{M} = \frac{M}{\sqrt{a^2 + 2M}} \quad (15)$$

In (14), $\tilde{\chi} = \sqrt{a^2 + 2M} \chi$ with period $0 \leq \tilde{\chi} \leq 2\pi \sqrt{a^2 + 2M}$. Thus we see that near $r = r_0$, $\theta = 0$, there is a six-dimensional KK anti-monopole structure, a string-like object with world-sheet coordinates $(t, \tilde{\chi})$. Similarly, one can analyse at $r = r_0$, $\theta = \pi$. This gives a metric of a monopole configuration which has the same metric as (14) with a change of sign in the gauge field.

However, we must notice that the $\chi$-direction is an isometry direction with period $2\pi r_0$. Hence the limit (13) is true for every value of $\chi$ and what we are seeing is actually an oriented string loop along $\chi$ (see Figure [1]). The (anti)-monopole structure (14) in the limit (13) is just a limit artifact, the different signs of the gauge fields at $\theta = 0$ and $\theta = \pi$ is due to the opposite orientation of the loop.

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7 A different choice of coordinate will however change the magnetic field, see [8].

8 This coordinate system turns out to be the analogous one that was used in [4] for the five-dimensional dipole.
2.3. Exciting gauge field on the loop

In general, a $D$-dimensional Kerr black hole is characterized by $[\frac{D-1}{2}]$ angular momentum parameters $[9]$, where the square brackets indicate the integer part. In order to obtain a string loop configuration with more than one non-trivial gauge field, we need to start with the general $D$-dimensional Kerr metric. We illustrate this by starting with the Kerr metric in five dimensions with two non-zero angular momenta proportional to $a_1$ and $a_2$ $[9]$. We then follow the same procedure as described in (3). The resulting metric has the form:

$$
\begin{align*}
\text{d}S^2 &= -\text{d}t^2 + (r^2 - a_1^2\cos^2\theta - a_2^2\sin^2\theta)\left[\frac{dr^2}{\Delta + a_1^2a_2^2r^{-2}} + d\theta^2\right] \\
&\quad+ \frac{\sin^2\theta[(r^2 - a_1^2)(\Delta + a_1^2\sin^2\theta + a_2^2\cos^2\theta) - 2Ma_1^2\sin^2\theta]}{\Delta + a_1^2\sin^2\theta + a_2^2\cos^2\theta} \text{d}\phi^2 \\
&\quad+ \frac{\cos^2\theta[(r^2 - a_2^2)(\Delta + a_1^2\sin^2\theta + a_2^2\cos^2\theta) - 2Ma_2^2\cos^2\theta]}{\Delta + a_1^2\sin^2\theta + a_2^2\cos^2\theta} \text{d}\chi^2 \\
&\quad- \frac{4a_1a_2M\sin^2\theta\cos^2\theta}{\Delta + a_1^2\sin^2\theta + a_2^2\cos^2\theta} \text{d}\phi \text{d}\chi
\end{align*}
$$
\[ \Delta = r^2 - a_1^2 - a_2^2 - 2M \quad \text{and} \quad \Delta + a_1^2 \sin^2 \theta + a_2^2 \cos^2 \theta. \]
the above metric describes a string loop with gauge field $A_\chi$ excited on the world-sheet direction $\chi$.

In exactly similar manner, we can study the limit $a_2 \gg a_1$. In this case, the poles change the position, now located at $\theta = \pi/2$ and $3\pi/2$ and the gauge fields interchange their roles.

3. Heterotic Dipole

A more general dipole solution can be found, starting from the general rotating charged black hole solution of $D = 4$ heterotic string theory. Such a solution with one $U(1)$ gauge field $V_\mu$ (all other $U(1)$ vectors, moduli and vectors coming from compactification set equal to zero) was given in [10]. The metric is characterized by three parameters, namely $M, a$ and $\alpha$, where $\alpha$ parametrizes an $O(1, 1)$ T-duality rotation between the Kerr-solution and the heterotic charged rotating black hole. After an Euclidean rotation

$$\tau \to -iX, \quad a \to ia, \quad \alpha \to i\alpha,$$

and adding a new time direction $t$, we get the following solution of $D = 5$ heterotic string theory (in the string frame, following the notation of [11]):

$$dS^2 = -dt^2 + \left( r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2} \right) \left( \frac{dr^2}{\Delta} + d\theta^2 \right) + \Delta \sin^2 \theta \mathcal{H}_{(\alpha=0)} \, d\phi^2 + \mathcal{H}^{-1}_{(\alpha)} \left[ dX - A_\phi^{(\alpha)} d\phi \right]^2,$$

$$e^{-2\Phi^{(\alpha)}} = \frac{r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2}}{r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2}}, \quad B^{(\alpha)}_{X\phi} = \frac{2Mra \sin^2 \theta \sin^2 \frac{\alpha}{2}}{r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2}},$$

$$V^{(\alpha)}_X = \frac{-2Mr \sin \alpha}{r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2}}, \quad V^{(\alpha)}_\phi = \frac{-2Mra \sin^2 \theta \sin \alpha}{r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2}}$$

where the functions $\mathcal{H}_{(\alpha)}$ and $A_\phi^{(\alpha)}$ are given by

$$\mathcal{H}_{(\alpha)} = \frac{(r^2 - a^2 \cos^2 \theta - 2Mr \sin^2 \frac{\alpha}{2})^2}{(\Delta + a^2 \sin^2 \theta)(r^2 - a^2 \cos^2 \theta)},$$

$$A_\phi^{(\alpha)} = \frac{2Mra \sin^2 \theta \cos^2 \frac{\alpha}{2}}{\Delta + a^2 \sin^2 \theta}.$$

9
Note that for $\alpha = 0$ we recover the five-dimensional dipole (4), and for $\alpha = \pi$, the solution takes the form of a $S0/\text{anti-}S0$-brane ($H$-dipole) which is $T$-dual to (3). The dipole nature of the interpolating solution can be easily seen from the asymptotic behaviour of the vector fields $A_{\phi}^{(\alpha)}$ and $B^{(\alpha)}_{X\phi}$. The total dipole moment of the solution is $2Ma$, to which the above gauge fields contribute with a factor $\cos^2 \frac{\alpha}{2}$ and $\sin^2 \frac{\alpha}{2}$ respectively. Furthermore, to avoid singularities associated with the above metric, one must have

$$M + \sqrt{M^2 + a^2} \leq r \leq \infty,$$

$$0 \leq X \leq \frac{2\pi M(1 + \cos \alpha)(M + \sqrt{M^2 + a^2})}{\sqrt{M^2 + a^2}},$$

$$0 \leq \phi - \frac{aX}{M(1 + \cos \alpha)(M + \sqrt{M^2 + a^2})} \leq 2\pi.$$

(25)

Note that for $\alpha = 0$ we find the periodicity of the previous case (7), but however we do not understand the limit $\alpha \to \pi$, where the period of $X$ goes to zero. As before, due to the non-trivial periodicity of $\phi$, we see an appearance of background magnetic field. In the near pole limit (13), the solution (23) is of the form

$$dS^2 = -dt^2 + \frac{H(0)}{H(\alpha)}[dX + A_{\phi}^{(\alpha)}d\phi]^2 + H(0)[d\bar{\rho}^2 + \bar{\rho}^2d\bar{\theta}^2 + \bar{\rho}^2 \sin^2 \bar{\theta}d\phi^2],$$

$$e^{-2\Phi(\alpha)} = \frac{H(0)}{H(\alpha)},$$

$$B^{(\alpha)}_{X\phi} = -H^{-1}(\alpha)(A_{\phi}^{(\alpha)} - A_{\phi}^{(0)}),$$

$$V^{(\alpha)}_{\phi} = H^{-1}(\alpha) A_{\phi}^{(0)} \sin \alpha, \quad V^{(\alpha)}_{X} = -H^{-1}(\alpha) \frac{M}{\bar{\rho}} \sin \alpha,$$

(26)

where

$$H(\alpha) = 1 + \frac{M}{\bar{\rho}} \cos^2 \frac{\alpha}{2}, \quad A_{\phi}^{(\alpha)} = M(1 - \cos \tilde{\theta}) \cos^2 \frac{\alpha}{2}.$$

(27)

The geodesic distance among the constituents of the dipole can be calculated from the metric by integrating along $\theta$. For large $a$, the distance turns out to be $2a$ in the string-frame.
4. Tachyonic Instability

All the solutions that are discussed in (4) can be embedded obviously in any string or superstring theories since they are the solutions of Einstein gravity. As a consequence, they can be considered as various string backgrounds. A natural question thus is to ask if these backgrounds are stable. First thing in this direction will be to check if string/superstring propagating in these backgrounds contain tachyons in their fluctuation spectrum. The aim of this section is to carry out an analysis of this issue. In general, string fluctuations in a non-trivial background is hard to analyse. This is because one needs to have a description of the background in terms of world-sheet conformal field theory (CFT). The dipole backgrounds that we have discussed earlier have very complicated field configurations. However, at very large radial distance the the structure simplifies. Fortunately for us, in this regime, the two dimensional CFT is known and has been analysed in the literature [12]. We will thus make use of his results.

As an illustrative example, we will work with the solution (4) for $D = 5$. The solution can be read off from (4). Various parameters are

$$\Delta = r^2 - 2Mr - a^2, \quad r_0 = M + \sqrt{M^2 + a^2}. \quad (28)$$

Here as before $r_0$ corresponds to the zero of $\Delta$. For our present purpose, we will also need the periods of $X$ and $\phi$. Their ranges are

$$0 \leq X \leq \frac{4\pi M(M + \sqrt{M^2 + a^2})}{\sqrt{M^2 + a^2}}, \quad 0 \leq \phi \leq \frac{2\pi a}{\sqrt{M^2 + a^2}}. \quad (29)$$

In order to proceed, we first notice that for $r \to \infty$, the metric reduces to

$$dS^2 = -dt^2 + d\rho^2 + dz^2 + \rho^2 d\phi^2 + dX^2. \quad (30)$$

Here we have defined $\rho = r \sin \theta, z = r \cos \theta$. Thus the metric is flat. However, due to nontrivial periods of various coordinates (29), there is an asymptotic magnetic field $B$ given by

$$B = \frac{a}{2M(M + \sqrt{M^2 + a^2})}. \quad (31)$$

Upon reduction over $X$, we would thus get four dimensional Melvin solution (see [13] for detail).
Fortunately, Melvin background is one of the very few backgrounds where string world-sheet has a description in terms of CFT \[^{12}\]. If we denote the radius of \(X\) by \(R\) (which follows from (29)), then for integer \(\frac{1}{\pi R}\), one has an orbifold CFT. The non-trivial part of the CFT is a \(Z_N\) orbifold of 2-dimensional plane times a circle, where \(N\) is related to the magnetic field of the Melvin solution. However, it is known that this CFT description for string or superstring, contains tachyon in the spectrum and the mass formula is given by \(\alpha' m^2 = -4 + \frac{4}{N}\) \[^{14}\]. From this observation, we thus conclude that the dipole solution for \(D = 5\) at large radial distance leads to unstable string or superstring background due to the presence of tachyon.

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\[^9\] Of course, to have the right central charge, one needs to add to this background an internal CFT or SCFT. Since this internal CFT will be completely decoupled from space-time physics, we will not pay attention to this sector.
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