The Decay of The Five Brane

in $AdS_5 \times \mathbb{R}P^5$*

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ABSTRACT: The baryon vertex of IIB superstring theory on $AdS_5 \times \mathbb{R}P^5$, for the case of orthogonal groups, is studied. The energy of the three brane decayed from an original five brane is calculated explicitly. The radius of this decayed three brane, for a BPS configuration, is also given and interpreted.

KEYWORDS: Type IIB superstring, AdS/CFT correspondence, String theory on orientifolds.

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1. Introduction

The conjecture of Maldacena [1] says that the four-dimensional $\mathcal{N} = 4$ super Yang Mills theory with gauge group $SU(N)$ is equivalent to Type IIB superstring theory on $AdS_5 \times S^5$ where $AdS_5$ is the five-dimensional Anti de Sitter space and $N$ the five-form flux on the five sphere representing the number of the parallel D3 branes on which the theory lives. Soon after this important discovery, several applications to systems with reduced supersymmetry, that are obtained by an orbifolding operation in which $S^5$ was replaced by $R\mathbb{P}^5 = S^5/\mathbb{Z}_2$ and where the gauge group $SU(N)$ is now replaced by an orthogonal $SO(N)$ or symplectic $Sp(N)$ gauge groups. Moreover, the author has discussed the possibility of wrapping branes depending in the discrete torsion and has given interpretations to known examples of the gauge theory in terms of branes in $R\mathbb{P}^5$ as pfaffian, domain walls and baryon vertex.

In particular interest, Witten in [7] has studied the case of the orientifolding operation in which $S^5$ is replaced by $R\mathbb{P}^5 = S^5/\mathbb{Z}_2$ and where the gauge group $SU(N)$ is now replaced by an orthogonal $SO(N)$ or symplectic $Sp(N)$ gauge groups. Moreover, the author has discussed the possibility of wrapping branes depending in the discrete torsion and has given interpretations to known examples of the gauge theory in terms of branes in $R\mathbb{P}^5$ as pfaffian, domain walls and baryon vertex.

In $AdS_5 \times S^5$, the baryon configuration consists of five brane wrapped around $S^5$ and joined to the boundary by $N$ fundamental strings with the same orientation [11, 12, 13]. The wrapped five brane feels two forces: the gravitational force caused by the $N$ D3 branes and the tension of $N$ fundamental strings attached on it. On the other hand, in
a supersymmetric configuration, there is an effect of the electric field living on the brane to be not neglected and that can deform the brane. Therefore, the correct energy of the configuration is obtained by using the Born-Infeld action of D-branes [8, 9]. Based on the previous works, authors in [10] were able to compute the bending energy and the radius of this baryon vertex starting from its BI action in $AdS_5 \times S^5$, see also [14, 15].

In the present paper, we generalize this analysis by studying the decay of the five brane in $AdS_5 \times \mathbb{R}P^5$ in the case of the orthogonal group leading to a three brane configuration attached by a string or a three brane configuration alone. We compute explicitly the energy of this configurations and give the expression of the decayed three brane energy and radius in terms of the collatitude angle. We also give an interpretation of the result based on diagram ullistrations.

This paper is organized as follows. In section 2, we give a brief review on baryon vertex in terms of branes. In section 3, we discuss the possibility of wrapping branes of type IIB superstring on $AdS_5 \times \mathbb{R}P^5$ for symplectic and orthogonal groups. In section 4, we focus on five brane and its decay to three brane in the case of orthogonal group. In section 5, we compute the energy of the decayed three brane configuration and give the expression of its radius. The final section is devoted to the conclusion.

2. Baryonic D5-Brane

Let us here summarize in few lines what does a baryonic D5-Brane mean. Following the correspondence between IIB on $AdS_5 \times S^5$ space and conformal field theory on its boundary, one would like to find, in terms of string theory, the equivalent of a static baryon vertex of the $SU(N)$ gauge theory namely a static gauge invariant antisymmetric combination of $N$ external electric quarks. In fact, it consists of a static wrapped D5-brane of type IIB superstring theory centered in the bulk and joined to the boundary by $N$ elementary strings. In this configuration, the static external quarks in the SYM theory, that is static external electric charges transforming in the fundamental representation of $SU(N)$, are described by the endpoints of the fundamental strings (see figure 1). What plays the role of the “glue” for this vertex is the coupling

$$\int_{S^5 \times \mathbb{R}} A \wedge \frac{G_5}{2\pi}$$

(2.1)

between the self-dual five form field strength $G_5$, contributing with $N$ units of five form flux on $S^5$, and the $U(N)$ gauge field $A$ living on the world volume of the D5-brane.

Moreover, the deformation of the shape of the D5-brane caused by the tension of the strings is given by the radial position $r$ of the D5-brane in $AdS$ space as a function of the collatitude angle $\theta$ as

$$r(\theta) \sim \left(\frac{\pi - \theta + \sin \theta \cos \theta}{\sin \theta}\right)^{1/3}$$

(2.2)
Figure 1: Baryon vertex of IIB superstring on $AdS_5 \times S^5$ representing by a wrapped five brane on $S^5$ and attached to the boundary by $N$ strings.

we see from eq (2.2) that $r(\theta)$ diverges for small $\theta$'s representing the $N$ fundamental strings connecting the D5 brane to the boundary at $r \to \infty$.

3. Branes on $\mathbb{R}P^5$

In this section we select the whole possibilities of wrapping branes on $\mathbb{R}P^5$. But before going ahead, recall that the $SO(N)$ (for even $N$) and $Sp(N)$ gauge symmetries can be obtained by considering $N$ parallel threebrane at an orientifold threeplane. In contrast to the $SU(N)$ gauge theory case, where the near horizon geometry of $N$ parallel threebranes in $\mathbb{R}^{10}$ lead to $AdS_5 \times S^5$ description, here and under $\mathbb{Z}_2$ action on $\mathbb{R}^6$ part of $\mathbb{R}^{10}$, one gets in the near horizon geometry $AdS_5 \times \mathbb{R}P^5$.

Thus, the $\mathcal{N} = 4$ super Yang-Mills theory with orthogonal or symplectic gauge group can be described by Type IIB superstring theory on an $AdS_5 \times \mathbb{R}P^5$ orientifold [3, 4, 5, 6]. The spectra of the $SO(N)$ and $Sp(N)$ gauge theory can be obtained from those of the $SU(N)$ theory by extracting the part invariant under an orientifold projection.

Homology and Cohomology of $\mathbb{R}P^5$

In type IIB superstring theory, there exist a supersymmetric orientifold threeplane that is invariant under the $SL(2, \mathbb{Z})$ S-duality symmetry group leading to an $SL(2, \mathbb{Z})$ invariant
configuration of three branes on $AdS_5 \times S^5/\mathbb{Z}_2$ (after taking the near horizon geometry of $\mathbb{R}^4 \times \mathbb{R}^6/\mathbb{Z}_2$). In addition to this, the two two-form fields: the Neveu Schwarz $B$ field $B_{NS}$ and Ramond-Ramond $B$ field $B_{RR}$ define four other models determined by the values of their discrete torsions.

The different homology groups that will play a central role in the wrapping branes are summarized hereafter. For odd $i$, $\mathbb{R}P^i$ determines an element of $H^i(\mathbb{R}P^5, \mathbb{Z})$ and if $i$ is even it determines an element of $H^i(\mathbb{R}P^5, \mathbb{Z})$, where $\mathbb{R}P^i$ is a subspace of $\mathbb{R}P^5$ defined by a linear embedding $(x_1, x_2, \ldots, x_{i+1}) \rightarrow (x_1, x_2, \ldots, x_{i+1}, 0, \ldots, 0)$. The homology groups generated by the two torsion element defined by these subspaces are

\begin{align*}
H_1(\mathbb{R}P^5, \mathbb{Z}) &= H_3(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2 \\
H_0(\mathbb{R}P^5, \mathbb{Z}) &= H_5(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2 \\
H_2(\mathbb{R}P^5, \mathbb{Z}) &= H_4(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2 \\
H_0(\mathbb{R}P^5, \mathbb{Z}) &= \mathbb{Z}_2,
\end{align*}

where $\mathbb{Z}$ is the twisted sheaf of integers. The Poincaré duality permit us to get cohomology groups from homology ones, thus we have

\begin{align*}
H_i(\mathbb{R}P^5, \mathbb{Z}) &= H^{5-i}(\mathbb{R}P^5, \mathbb{Z}) \\
H_i(\mathbb{R}P^5, \mathbb{Z}) &= H^{5-i}(\mathbb{R}P^5, \mathbb{Z})
\end{align*}

\textit{Wrapping Branes in $\mathbb{R}P^5$}

Return now to the possibilities of wrapping branes. At first site, a five brane can be wrapped on a tow-cycle to give, in $AdS_5$, a threebrane or on a four-cycle to give a string as $H_2(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2$ for the former and $H_4(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2$ for the later.

Similarly for the three brane, it can be wrapped on a one-cycle to give a two brane or on three-cycle to give a particle on $AdS_5$ as here also $H_1(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2$ and $H_3(\mathbb{R}P^5, \mathbb{Z}) = \mathbb{Z}_2$

But this is not the end of the story as there is some topological restriction based on discrete torsion. In fact, and as was explained in [7], a D5-brane (NS5-brane) can be wrapped on an $\mathbb{R}P^4 \subset \mathbb{R}P^5$, to make a string, only if $\theta_{NS} = 0$ ($\theta_{RR} = 0$). And the three brane can be wrapped on an $\mathbb{R}P^3 \subset \mathbb{R}P^5$, to make a particle, only if $\theta_{NS} = \theta_{RR} = 0$.

In the other hand, the existing four models of gauge theories, depending on whether the discrete torsion vanishes or not, are classified in the following way as:

\begin{align*}
(\theta_{NS} = 0, \quad \theta_{RR} = 0) &\quad \rightarrow \quad SO(N) \quad \text{for even } N \\
(\theta_{NS} = 0, \quad \theta_{RR} \neq 0) &\quad \rightarrow \quad SO(N) \quad \text{for odd } N \\
(\theta_{NS} \neq 0, \quad \theta_{RR} = 0) &\quad \rightarrow \quad Sp(N) \\
(\theta_{NS} \neq 0, \quad \theta_{RR} \neq 0) &\quad \rightarrow \quad Sp(N).
\end{align*}
Finally, a wrapping D5-brane on $\mathbb{R}P^4$ gives rise to orthogonal gauge group, likewise an so wrapped NS5-brane gives rise to either $SO(N)$ for $N = 2k$ or symplectic gauge group. While only the orthogonal group for $N = 2k$ is permitted in the case of wrapping threebrane on $\mathbb{R}P^3$.

We conclude this section by saying that a five brane can be wrapped around a two cycle in $\mathbb{R}P^5$ to give a three brane with orthogonal gauge group.

4. Baryon Vertex for Orthogonal and Symplectic Groups

Let us summarize here the stability of the baryonic D5-brane in $\mathbb{R}P^5$ depending on the nature of the gauge groups [7]. For the case of the symplectic gauge group i.e. $\theta_{NS} \neq 0$, there exist always mesons $M = \frac{1}{2} \gamma_{ij} \psi^i \psi^j$ to which a baryon $B = \frac{1}{N!} \varepsilon_{i_1 i_2 ... i_N} \psi^{i_1} \psi^{i_2} ... \psi^{i_N}$ can decay as

$$B = \frac{1}{(N/2)!} M^{N/2}$$

where $\gamma_{ij}$ is an invariant second rank antisymmetric tensor and $\psi$ a fermion in the fundamental representation of the gauge group. Therefore, an initial state with a fivebrane wrapped twice on $\mathbb{R}P^5$ and connected by $N$ elementary strings to charges on the boundary is able to decay to a state with no fivebrane and with $N/2$ strings that join the external quarks pairwise.

In the case of the orthogonal gauge group that is for $\theta_{NS} = 0$, we have to distinguish between $N$ even and odd. In the former case, the final state is a Pfaffian combination of $N/2$ gauge bosons interpreted as a wrapped threebrane plus strings making pairwise connections between external charges (see figure 2). While in the later, it contains in addition an odd number of strings connecting the wrapped threebrane to the boundary (see figure 3).

5. Decay of D5-Brane

In this section we concentrate our attention to the decay of the D5-brane to three brane i.e. the case of orthogonal gauge group corresponding to the vanishing value of $\theta_{NS}$. We will give the equivalent, in our case, of the eq (2.2), expressing the behavior of the radius of the D5-brane in terms of the collatitude angle $\theta$, and discuss its behavior at extreme limits. To do so, one may start directly from the metric of a D3 brane but this will be not interesting in our study as we plan to describe the decay of the baryonic D5-brane in $AdS_5 \times \mathbb{R}P^5$ to a three brane of type IIB super string theory. Our philosophy is to start from the action of the D5-brane and then we arrange to express it in terms of three brane one. Indeed, one way to write a D5-brane metric in the background geometry of a stack
Figure 2: The final state of the decay of a five brane in $AdS_5 \times \mathbb{R}P^5$ for $SO(N)$ gauge group with $N$ even. It is a three brane wrapped on a three cycle in $\mathbb{R}P^5$ and strings joined to the boundary pairwise.

of $N$ D3-branes is the following

$$ds^2 = \frac{r^2}{R^2} \left[-dt^2 + dx_{||}^2\right] + \frac{R^2}{r^2} \left[dr^2 + r^2 d\Omega_5^2\right]$$

(5.1)

where $x_{||}$ are the three dimensional Euclidean $\mathbb{E}^3$ coordinates and $d\Omega_5^2$ is the line element on the five sphere $S^5$. Then the world volume action of this D5-brane is the Born-Infeld action given by

$$S = -T_5 \int d^6\zeta \sqrt{-\det(g^{ind})} + T_5 \int d^6\zeta A_{\alpha} \partial_{\beta} X^{M_1} \wedge ... \wedge \partial_{\delta} X^{M_5} G_{M_1...M_5}$$

(5.2)

with

$$g^{ind}_{\alpha\beta} = g_{MN} \partial_{\alpha} X^M \partial_{\beta} X^N + F_{\alpha\beta}$$

and where $T_5$ is the D5 brane tension and the second term in eq (5.2) is the explicit WZW coupling of the world volume gauge field $A$ to the background five form field strength $G$.

Now, given this metric at hand, eq (5.1), we can decompose its last term as

$$ds^2 = \frac{r^2}{R^2} \left[-dt^2 + dx_{||}^2\right] + \frac{R^2}{r^2} \left[dr^2 + r^2 \left(d\theta^2 + \cos^2 \theta d\psi^2 + \sin^2 \theta d\Omega_3^2\right)\right]$$

with

$$d\Omega_3^2 = d\theta'^2 + \cos^2 \theta' d\psi'^2 + \sin^2 \theta' d\phi$$
Figure 3: This final states represents the decay of a five brane in $AdS_5 \times \mathbb{R}P^5$ for $SO(N)$ gauge group with $N$ odd. It is a three brane wrapped on a three cycle in $\mathbb{R}P^5$ and a string attached on it in addition to strings joined to the boundary pairwise.

Describing a line element of the three sphere $S^3$.

Now our strategy is to choose the world volume coordinates for the D5-brane as

$$\zeta_\alpha = (t, \theta, \psi, \theta', \psi', \phi)$$

where $t$ is the target space time, and then set the space time coordinates as

$$X^M = (t, x_\parallel, r, \theta, \psi, \theta', \psi', \phi)$$

Furthermore, we suppose that the radius of the decayed threebrane is described by $r$ such that

$$r = r \sin \theta.$$ (5.3)

The key idea is to fix $\theta$ and look for a static solutions of the form $r (\theta')$ and $A_0 (\theta')$, with the $\theta'$ is interpreted as representing an angle from the opposite point to the string endpoint. The other four parameters $\theta, \psi, \psi'$ and $\phi$ are angular variables parameterizing $\mathbb{R}P^4 \subset \mathbb{R}P^5$ with fixed $\theta'$. Thus, the only two independent variables are $r$ and $\theta'$, so

$$r' = \frac{\partial r}{\partial \theta'} = \frac{\partial }{\partial \theta'} (r \sin \theta) = r' \sin \theta,$$

and

$$\dot{r} = \frac{\partial r}{\partial t} = \frac{\partial }{\partial t} (r \sin \theta) = \dot{r} \sin \theta.$$
6. Three brane energy

All materials at hand, we can now compute the binding energy of the decayed three brane and its radius. But before going ahead let us rewrite the metric following the assumption of the previous section as a metric on $AdS_2 \times \mathbb{R}P^3$

$$ds^2 = \frac{-r^2}{\sin^2 \theta R^2} dt^2 + \frac{\sin^2 \theta R^2}{r^2} \left[dr^2 + r^2 d\theta'^2 + r^2 \sin^2 \theta d\phi + r^2 \cos^2 \theta d\psi'^2\right]$$

Then the induced metric on the three brane is given by

$$h_{\alpha \beta} = \begin{bmatrix} -\frac{r^2}{\sin^2 \theta R^2} & F_{0\theta'} \\ -F_{0\theta'} & \frac{R^2}{r^2} \left[r^2 + r^2 \sin^2 \theta\right] \end{bmatrix}$$

whose determinant is

$$\det h_{\alpha \beta} = -\left(\frac{r^2}{\sin^2 \theta} + r^2\right) + F_{0\theta'}^2.$$ 

Finally, one can derive the three brane energy starting from D5-brane one as

$$\mathcal{E} = T \int d\theta d\theta' \sin^4 \theta \left\{-R^4 \sqrt{\frac{r^2}{\sin^2 \theta} + r^2 - F_{0\theta'}^2} + 4A_0 R^4\right\} \tag{6.1}$$

with $T = T_5 \Omega_3$, where $\Omega_3$ denote the unit three sphere.

Then, the gauge field equation of motion following from this energy reads as

$$\partial_{\theta'} \left[ \frac{E'}{\sqrt{\frac{r^2}{\sin^2 \theta} + r^2 - E'}} \right] = -4, \tag{6.2}$$

with $F_{0\theta'} = E'$ and if we interpret the term between parenthesis as the three brane displacement

$$D (\theta, \theta') = \frac{E'}{\sqrt{\frac{r^2}{\sin^2 \theta} + r^2 - E'}} \tag{6.3}$$

then eq(6.2) becomes

$$\partial_{\theta'} D (\theta, \theta') = -4. \tag{6.4}$$

To resolve eq (6.4), we come back to our starting assumption, that a D5 brane decay to a three brane, so we argue that this differential equation should be treated in taking in the account this previous detail. Thus, we propose that its solution should be given by

$$D (\theta, \theta') = -4\theta' + D (\theta) \tag{6.5}$$
where \( D(\theta) \) is the displacement of the original D5 brane given by

\[
D(\theta) = -\frac{3}{2}\theta + \frac{3}{2}\sin\theta \cos\theta + \sin^3\theta \cos\theta.
\] (6.6)

It is more useful to express the energy eq (6.1) in terms of \( D \) so

\[
\mathcal{E} = T \int d\theta d\theta' \sin^4 \theta R^4 \left\{ \frac{r'^2}{\sin^2 \theta} + r^2 - E'^2 + D E' \right\}
\]

The final form of the energy is given after the elimination of \( E' \) in terms of \( D \) using eq (6.3) and

\[
\sqrt{\frac{r'^2}{\sin^2 \theta} + r^2 - E'^2} = \frac{\sqrt{\frac{r'^2}{\sin^2 \theta} + r^2}}{\sqrt{D^2 + 1}}.
\]

so we get by the end the expression of decayed three energy brane as a function of its displacement and radius

\[
\mathcal{E} = T \int d\theta d\theta' \sin^4 \theta R^4 \sqrt{D^2 + 1} \sqrt{\frac{r'^2}{\sin^2 \theta} + r^2}.
\] (6.7)
Now we are ready to compute the Euler Lagrange equations and deduce the differential equation of the radius. Indeed a straightforward calculation lead to

$$\frac{d}{d\theta'} \left\{ \frac{r'}{\sqrt{\frac{r'^2}{\sin^2 \theta} + r^2}} \sqrt{D^2 + 1} \right\} = \frac{r \sin^2 \theta}{\sqrt{\frac{r'^2}{\sin^2 \theta} + r^2}} \sqrt{D^2 + 1},$$

(6.8)

from which one can extract the desired expression of the radius. But as we are looking for a BPS solution, we argue that a the equation (6.8) is reduces to

$$\frac{r'}{r} = \frac{\sin \theta + D \cos \theta}{\cos \theta - D \sin \theta}$$

(6.9)

whose solution can be given as

$$r = ([\cos \theta - D \sin \theta] + 4 \theta' \sin \theta)^{\frac{1}{2}(1+\alpha^2)} \cdot \exp (-\alpha \theta')$$

(6.10)

where $\alpha = \frac{1}{\sin \theta}$ and $D$ is given by eq (6.6).

**Discussion**

Let us now interpret the solution of the radius eq (6.10) in terms of $\theta'$ and $\theta$. It is clear, due to the exponential term, that the expression eq(6.10) approaches zero. For a special value of $\theta = \frac{\pi}{4}$, we see that the radius rich a maximum than decrease rapidly (see figure 4) the same behavior can be remarked for small values of $\theta$ (figure 5). One can comment this by saying that the three brane radius rich its maximum for values of $\theta'$ very close to zero then once $\theta'$ is distant from the origin $r$ approaches zero. This means that the three brane becomes bigger for $\theta'_{\text{max}}$ corresponding to the maximum values of $r_{\text{max}}$ and shrinks to zero size otherwise. This result agree perfectly with the fact that the shape of the wrapped brane depend in the strings attached on it and exercising forces to keep it inflated. In our cases, there is at the maximum one string attached on the three brane and thus this brane finishes by shrinking to zero size (as found in figures 4 and 5).

**7. Conclusion**

In this paper, we have discussed the decay of the D5 brane wrapped twice around $\mathbb{R}P^2$ giving a three brane in the frame work of the AdS/CFT correspondence with an orthogonal gauge group. We have shown that, in the case of the super Yang-Mills theory with $SU(N)$ gauge group, the baryon vertex is represented by a D5 brane wrapped around $S^5$ and linked to the boundary by $N$ fundamental strings. For the case of $SO(N)$ gauge theory, This D5-brane becomes unstable and transforms to a state of wrapped three brane around a three cycle in $\mathbb{R}P^5$ permitted by the topological restriction on the discrete torsion. We have studied this decay qualitatively by computing the energy of the three brane final
state and discuss the behavior of its radius in terms of the angle $\theta'$. During this analysis we have made some assumptions like that all the variables are independent apart the trial $(t, r, \theta')$ and the fact that $r$ and $A_0$ depend only in $\theta'$ meaning that we are looking for static solutions. The result we have gotten agrees with the responsibility of the strings attached on branes on the form of this later.

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