D5-brane in Anti-de Sitter Space and Penrose Limit

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abstract

We consider the Penrose limit of the solution of D5-brane given in the Anti-de Sitter space and analyse the shape of the D5-brane in the pp-wave background. We find that the D5-brane leads to the branes and the throats connecting the branes. The branes spread on $\mathbb{R}^4$ with periodic values of the light-cone time $x^+$ and the throats lie along $x^+$. We also give some comments on holography.

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1. Introduction

In the last several years, a lot of works have been done on the AdS/CFT correspondence [1,2], by which supersymmetric Yang-Mills theories are associated with string theories in Anti-de Sitter spaces. When there are $N$ coincident D3-branes, we obtain an Anti-de Sitter space $AdS_5$ at the near-horizon limit.

Recently the string theory on a pp-wave background has been studied. The pp-wave background is known as one of maximally supersymmetric geometries. The Type IIB string theory on this background can be exactly solved by the Green-Schwarz formalism in light-cone gauge [3–6]. On the other hand, it has been pointed out that any space-time has a plane wave as a limit [7]. This limit is called the Penrose limit. Taking the Penrose limit for $AdS_5 \times S^5$, we obtain the pp-wave geometry. It has been found that the spectra of the string theory on the pp-wave background correspond to the operators of $\mathcal{N} = 4$ supersymmetric Yang-Mills theory [8,9]. A lot of related works have been done on orbifolds [10], D-branes [11], holography [12–15] and so on [16].

In the AdS/CFT correspondence the baryon vertex in the world-volume theory on the $N$ coincident D3-branes is constructed by the D5-brane wrapped on $S^5$ [17]. The D5-brane surrounds the D3-branes and $N$ open strings connect these D-branes. This configuration is analysed in terms of the Born-Infeld action of D5-brane [18,19]. The solution of the D5-brane has a spike sticking out toward the D3-branes and the tension of spike is equal to that of $N$ fundamental open strings. The direction of the spike can be identified with the holographic direction. On the other hand, the holography in the pp-wave background has been studied in [12–15], but it has not been clear yet. Though the dual gauge theory of the string theory in pp-wave background has been found, we do not know where the dual theory lives, in other words, we do not have D-brane configurations as in the AdS/CFT correspondence. In this paper we consider the Penrose limit of the solution of D5-brane given in the Anti-de Sitter space by the use of reasonable coordinate systems. We then analyse the shape of the D5-brane in the pp-wave background.

In Section 2 we introduce two types of coordinates of $AdS_5 \times S^5$ and confirm that the metrics written by such coordinates lead to the pp-wave metrics by the Penrose limit. In Section 3 the solution of D5-brane in $AdS_5 \times S^5$ is reviewed. We then calculate the Penrose limit of the solution and study the location of the D5-brane in the pp-wave background. We find the branes connected by throats with each other. Section 4 is devoted to conclusions and some comments on the holography.
2. Anti-de Sitter space and Penrose limit

The metric with $N$ coincident D3-branes has been known and it becomes $AdS_5 \times S^5$ at the near-horizon limit. In the AdS/CFT correspondence we have often used the metric,

$$ds^2 = \left(\frac{u}{R}\right)^2 \left(-dt^2 + \sum_{i=1}^{3} dx_i^2\right) + \left(\frac{R}{u}\right)^2 du^2 + R^2 d\Omega_5^2, \quad R^4 = 4\pi g_s N l_s^4, \quad (2.1)$$

for $AdS_5 \times S^5$. $g_s$ is a string coupling and $l_s$ is a string length. But for the convenience of later analyses we rescale the coordinates and describe the metric as

$$ds^2 = R^2 \left[l^2 \left(-dt^2 + \sum_{i=1}^{3} dx_i^2\right) + \frac{1}{l^2} d\tau^2\right] + R^2 \left(d\theta^2 + \cos^2 \theta d\psi^2 + \sin^2 \theta d\tilde{\Omega}_3^2\right). \quad (2.3)$$

In this coordinate system it is easy to find the descriptions of D-branes but it is hard to consider the Penrose limit. In order to make ready for taking the limit, we change the coordinates as

$$t = \frac{\cosh \rho \sin \tau}{\cosh \rho \cos \tau - n_4 \sinh \rho}, \quad (2.4)$$
$$x_i = \frac{n_i \sinh \rho}{\cosh \rho \cos \tau - n_4 \sinh \rho}, \quad (i = 1, 2, 3) \quad (2.5)$$
$$l = \cosh \rho \cos \tau - n_4 \sinh \rho, \quad (2.6)$$
$n_1^2 + n_2^2 + n_3^2 + n_4^2 = 1$.

Substituting (2.4), (2.5) and (2.6) into (2.3), we obtain the metric

$$ds^2 = R^2 (d\rho^2 - \cosh^2 \rho d\tau^2 + \sinh^2 \rho d\Omega_3^2) + R^2 (d\theta^2 + \cos^2 \theta d\psi^2 + \sin^2 \theta d\tilde{\Omega}_3^2). \quad (2.7)$$

Now let us consider the Penrose limit. We reparametrize the coordinates as

$$\rho = \frac{r}{R}, \quad \tau = \frac{x^+ + x^-}{R^2}, \quad \theta = \frac{y}{R}, \quad \psi = \frac{x^+ - x^-}{R^2}, \quad (2.8)$$

and take $R \to \infty$. The metric (2.7) then becomes

$$ds^2 = -4 dx^+ dx^- - (r^2 + y^2)(dx^+)^2 + dr^2 + r^2 d\Omega_3^2 + dy^2 + y^2 d\tilde{\Omega}_3^2. \quad (2.9)$$

$(r, \Omega_3)$ and $(y, \tilde{\Omega}_3)$ describe $\mathbb{R}^4 \times \mathbb{R}^4$. One of the two $\mathbb{R}^4$'s comes from $AdS_5$ and the other comes from $S^5$, but we can not distinguish between them at the Penrose limit. The radial
coordinate of $AdS_5$, which is associated with the holographic direction in the AdS/CFT correspondence, leads to $r$. But $r$ and $y$ play same roles in the Penrose limit [14]. So it is difficult to find the holographic direction in the limit. We will give some comments on this problem in the final section.

On the other hand, the metric (2.9) can be identified with the pp-wave metric which includes Ramond-Ramond flux,

$$F_{+1234} = F_{+5678} = 1,$$

where the suffices 1234 and 5678 denote the first and the second $\mathbb{R}^4$ respectively.

### 3. Penrose limit of D5-brane

Firstly we consider the D5-brane in $AdS_5 \times S^5$. In order to find a baryon vertex [17], we set the D5-brane to wrap $S^5$. The action of D5-brane is represented by Born-Infeld action and Chern-Simons action. The static solution of the action has been shown in [18,19]. Let $(\xi_\alpha)$ be coordinates on the world-volume of D5-brane. The action of D5-brane is described as

$$S = S_{BI} + S_{CS},$$

$$S_{BI} = T_5 \int d\xi^6 \sqrt{-\det(g + F)},$$

$$S_{CS} = -T_5 \int A \wedge C^{(5)},$$

where $T_5$ is the tension of D5-brane. $g$ is an induced metric, that is, $g^{\alpha\beta} = G^{ij} \frac{\partial X_i}{\partial \xi_\alpha} \frac{\partial X_j}{\partial \xi_\beta}$, where $G^{ij}$ is a space-time metric. $F (= \partial_\alpha A_\beta - \partial_\beta A_\alpha)$ is a gauge field strength on the D5-brane and $C^{(5)}$ is a five-form RR field strength. We suppose that the D5-brane is embedded in $(t, \theta, \Omega_4)$ directions of the metric (2.3). We also set only $l$ and the gauge field $A_t$ to depend on $\theta$ [18]. $l$ is one of the coordinates denoting the location of D5-brane. The action (3.1) is written down as

$$S = T_5 V_4 \int dt d\theta R^4 \sin^4 \theta \left[ -\sqrt{R^4(l^2 + l'^2)} - (\partial_\theta A_t)^2 + 4A_t \right],$$
where $V_4$ is the volume of unit four-sphere and $'$ denotes the derivative by $\theta$. By the Legendre transformation and partial integral of the above action, we obtain the energy of D5-brane \[18\],

$$
E = T_5 V_4 \int d\theta R^6 \sqrt{l'^2 + l^2} \sqrt{f(\theta)^2 + \sin^8 \theta},
$$

(3.4)

$$
f(\theta) \equiv \left[ \frac{3}{2} (\nu \pi - \theta) + \frac{3}{2} \sin \theta \cos \theta + \sin^3 \theta \cos \theta \right],
$$

(3.5)

where $\nu$ is an integral constant and satisfies $0 \leq \nu \leq 1$. From (3.4), we obtain the equation of motion for $l$,

$$
\frac{d}{d\theta} \left[ \frac{l'}{\sqrt{l'^2 + l^2}} \sqrt{f(\theta)^2 + \sin^8 \theta} \right] = \frac{l}{\sqrt{l'^2 + l^2}} \sqrt{f(\theta)^2 + \sin^8 \theta}.
$$

(3.6)

On the other hand, the BPS condition of the D5-brane has been discovered by \[20\] and is denoted by

$$
\frac{l'}{l} = \frac{\sin^5 \theta + f(\theta) \cos \theta}{\sin^4 \theta \cos \theta - f(\theta) \sin \theta}.
$$

(3.7)

Note that (3.7) is independent of $R$ because $f(\theta)$ does not include $R$. We can confirm that the solutions of the BPS condition satisfy the equation of motion (3.6). Since (3.7) is a first order differential equation, it is, in other words, the first integral of (3.6). Though (3.6) seems to be too difficult to be solved, (3.7) has been solved \[18,19\] and the solution is

$$
l = \frac{c}{\sin \theta} \left[ \frac{\theta - \pi \nu - \sin \theta \cos \theta}{\pi (1 - \nu)} \right]^{\frac{1}{3}},
$$

(3.8)

where $c$ is any constant. We should note that (3.6) and (3.7) have scale invariance for $l$, so we can introduce any scale parameter $c$.

Now let us consider the Penrose limits of the coordinates $l, t, x_i$ in (2.3) and make it clear the correspondences between the coordinates in (2.3) and in (2.9). Substituting (2.8) into (2.4), (2.5) and (2.6), we obtain

$$
t = \frac{\cosh \frac{r}{R} \sin \left( x^+ + \frac{x^-}{R^2} \right)}{\cosh \frac{r}{R} \cos \left( x^+ + \frac{x^-}{R^2} \right) - n_4 \sinh \frac{r}{R}},
$$

$$
x_i = \frac{n_i \sinh \frac{r}{R}}{\cosh \frac{r}{R} \cos \left( x^+ + \frac{x^-}{R^2} \right) - n_4 \sinh \frac{r}{R}},
$$

$$
l = \cosh \frac{r}{R} \cos \left( x^+ + \frac{x^-}{R^2} \right) - n_4 \sinh \frac{r}{R},
$$
We can then calculate the limit $R \to \infty$ as
\begin{align}
  t &\to \tan x^+, \\
  x_i &\to 0, \\
  l &\to \cos x^+.
\end{align}

In $AdS_5 \times S^5$ the D3-branes, on which the dual gauge theory exists, spread on the $(t, x_i)$ directions. (3.10) implies that the space directions of the D3-branes shrink to zero size, while from (3.9) we can read that the time direction of the D3-brane is included in the light-cone time $x^+$. So the location of D3-brane in the pp-wave background is not clear.

We consider the Penrose limit of the right hand side of (3.8). Substituting $\theta = \frac{y}{R}$ into (3.8), we obtain
\begin{equation}
  l(y) = \frac{c}{\sin \frac{y}{R}} \left[ \frac{\frac{y}{R} - \pi \nu - \sin \frac{y}{R} \cos \frac{y}{R}}{\pi(1 - \nu)} \right]^{\frac{1}{3}}.
\end{equation}

When we take the limit $R \to \infty$, the two cases which are $\nu = 0$ and $\nu \neq 0$ give us different results. Firstly we suppose that $\nu$ is equal to zero. If $c$ is independent of $R$, the right hand side of (3.12) then converges on
\begin{equation}
  c \left( \frac{2}{3\pi} \right)^{\frac{1}{3}}.
\end{equation}

We set that $c$ has a scale of $R^m$. If $m$ is negative, (3.12) goes to zero for that limit, while, if $m$ is positive, then (3.12) diverges. Note that the limit of (3.12) should take a value from $-1$ to $1$ on account of (3.11). So the solutions of D5-brane with the scale $R^m$ ($m > 0$) are not visible in the pp-wave background. For $m = 0$, that is, $c$ is independent of $R$, we should take $|c| \leq \left( \frac{3\pi}{2} \right)^{\frac{1}{3}}$. As a result the solutions of D5-brane in $x^+-y$ plane are
\begin{equation}
  x^+ = \pm \text{constant} + 2k\pi, \quad k \in \mathbb{Z}.
\end{equation}

Next we suppose that $\nu \neq 0$. (3.12) converges on a non-trivial function by $R \to \infty$ only if $c = \frac{a}{y}$, where $a$ is a constant independent of $R$. We then obtain
\begin{equation}
  l(y) \to \frac{a}{y} \left( \frac{\nu}{\nu - 1} \right)^{\frac{1}{3}}.
\end{equation}

Note that if $c$ has the scale of $R^m$ with $m < -1$, $l(y)$ shrinks to zero, and that if $m > -1$, $l(y)$ goes away to infinity. Let us analyse the case $c = \frac{a}{R}$ in detail. From (3.11) and (3.13), the solution of D5-brane at the Penrose limit is described as
\begin{equation}
  \cos x^+ = \frac{a}{y} \left( \frac{\nu}{\nu - 1} \right)^{\frac{1}{3}}.
\end{equation}
(3.14) is still naive. Since \( y \) is a radial direction, \( y \) should be positive. This condition can be satisfied by changing the sign of \( a \). Finally we obtain

\[
y = \left( \frac{\nu}{1 - \nu} \right)^{\frac{1}{3}} \left| \frac{a}{\cos x^+} \right|.
\]  

(3.15)

We should remember that \( \nu \) is the integral constant satisfying \( 0 \leq \nu \leq 1 \). Since \( y|\cos x^+| = |a| \left( \frac{\nu}{1 - \nu} \right)^{\frac{1}{3}} \) from (3.15), at the limit \( \nu \to 0 \) we obtain \( y = 0 \) or \( \cos x^+ = 0 \). These solutions can be rewritten by

\[
y = 0, \quad x^+ = \frac{\pi}{2} + k\pi \quad (k \in \mathbb{Z}).
\]

On the other hand, let us take the limit \( \nu \to 1 \). From the equation \( \frac{1}{y|\cos x^+|} = \frac{1}{a} \left( \frac{1 - \nu}{\nu} \right)^{\frac{1}{3}} \), we obtain \( y = \infty \) because \( -1 \leq \cos x^+ \leq 1 \).

\[\text{fig. 1 The Penrose limit of the D5-brane}\]

(a) The D5-branes with three values of \( \nu \) are described on \( y-\cos x^+ \) plane and they approach the axes when \( \nu \) becomes smaller.

(b) The D5-branes are depicted on \( y-x^+ \) plane.

The shape of the D5-brane is represented in fig. 1. When \( \nu \) goes to zero, the D5-brane approaches the axes in fig. 1 (a). The solution of D5-brane has periodicity for \( x^+ \) with
period $\pi$. From fig. 1 (b) we can see that the D5-brane has throats at $y = 0$. When $\nu$ goes to zero, the throats are sharpened. Since the D5-brane was wrapped on the three-sphere $\tilde{\Omega}_3$ in $AdS_5 \times S^5$, it is also wrapped on the three-sphere $\tilde{\Omega}_3$ in the pp-wave background. So at $x^+ = \frac{\pi}{2} + k\pi$ ($k \in \mathbb{Z}$) we obtain the branes spreading on $\mathbb{R}^4$ whose metric is given by $dy^2 + y^2d\tilde{\Omega}_3^2$ in (2.3).

In fig. 2 the branes lying on $\mathbb{R}^4$'s at $x^+ = \pm \frac{\pi}{2}$ are depicted. The throat connects these two branes.

In the Anti-de Sitter space $\psi$ is periodic with period $2\pi$. Since $x^+$ is denoted by $\frac{x^+ + \psi}{2}$, $x^+$ has $\pi$ periodicity. That is the reason why we have found that the D-branes appear at the periodic values of $x^+$ with period $\pi$ in the pp-wave background.

4. Conclusions and comments

We have introduced mainly two types of the metrics for $AdS_5 \times S^5$. One is (2.3), by which we can easily analyse the AdS/CFT correspondence. The solution of D5-brane in $AdS_5 \times S^5$ has been known [18,19]. The other is (2.7), which is convenient for us to consider the Penrose limit. But in this metric it is difficult to find the solution of D5-brane. We have shown the relations between the two metrics and obtained the pp-wave metric from the Penrose limit of (2.3). Using this limit, we have analysed branes in the pp-wave background. In $AdS_5 \times S^5$ the D5-brane has a spike sticking out along the radial direction.
of $AdS_5$, while in the pp-wave metric we have found throats around $y = 0$ and they lie along the light-cone time direction $x^+$. At $x^+ = \frac{x}{2} + k\pi$ ($k \in \mathbb{Z}$) the brane spreads on the $y$ direction and also wraps $S^3$ whose metric is $y^2d\tilde{\Omega}_3^2$ in (2.3). So we can say that the brane lies on $\mathbb{R}^4$. This $\mathbb{R}^4$ is derived from a part of $S^5$ in $AdS_5 \times S^5$. In the pp-wave metric there is the other $\mathbb{R}^4$ coming from a part of $AdS_5$. Since there is no difference between these two $\mathbb{R}^4$’s, we would be able to find the brane wrapped on the latter $\mathbb{R}^4$.

In the Penrose limit we have obtained the solution of D5-brane with $\pi$ periodicity for $x^+$ direction. It is better that the light-cone time $x^+$ is defined without a periodicity. In order to find non-periodic solutions of the branes, we should adopt other choice of coordinate transformations [15].

Though some proposals on the holography in the pp-wave background have been done, we have not clearly known where the holographic direction exists yet. In [21] it is shown that the spikes sticking out from D-branes can be identified with open strings. Let us remember fig. 2. The D5-brane in the Anti-de Sitter space leads to the branes wrapping $\mathbb{R}^4$’s with the fixed values of $x^+$ and the throats connecting the branes. The throats are sharpened as $\nu$ goes to zero. We can regard the throats as open strings and they are ending on the D3-branes lying on $\mathbb{R}^4$. So we may be able to suggest that the holographic direction is $x^+$, which is transverse to the D3-branes. But the correspondences between the gauge theory and the string theory in the pp-wave background may be essentially different from the AdS/CFT correspondence. In order to make clear the holography in the pp-wave background, we need to consider the Born-Infeld action directly in the pp-wave metric and to find the solutions of D-branes.

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