AdS/QCD and Type 0 String Theory

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Abstract

We study gauge/string duality with flavor degrees of freedom in type 0B string theory. We construct a model by placing the $N_f$ probe $D9_-$/anti-$D9_-$ brane pairs in the background of the $N_c$ electric $D3$-branes. This model has some features in common with QCD, as in AdS/QCD model. By analyzing the effective action, we obtain the linear confinement behavior for the masses of the highly excited spin-1 mesons.

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1 Introduction

Gauge/string duality [1] has provided us with new tools for investigating strongly coupled gauge theories. Now, there are many attempts to use this duality to construct holographic dual of four-dimensional confining gauge theories, such as QCD. Basically, there are two approaches to construct holographic dual description of QCD, although the exact form has not yet been found.

One is the top-down approach in which one starts from string theory. A key point to obtain the holographic dual of QCD-like gauge theories in this approach is to add flavor degrees of freedom in non-supersymmetric backgrounds created by $N_c$ color branes. This can be done by introducing $N_f$ flavor branes in the probe approximation $N_f \ll N_c$, where the back reaction of the flavor branes can be neglected [2]. This has been applied to various supergravity models, for example [3] [4]. These models have been successful in capturing many qualitative features of low energy physics of QCD. For a recent review on this subject, see [5].

Another approach, the bottom up approach, is to start from QCD and attempt to find the holographic dual theory by matching it to some properties of QCD. This approach is often called AdS/QCD. In the simplest model [6] [7], the five-dimensional curved spacetime is taken to be $AdS_5$ with a hard IR cutoff, as first introduced in [8]. This IR cutoff can incorporate the quark confinement. Chiral symmetry breaking is modeled by a classical solution of scalar fields in a gravitational background. The UV conformal invariance is incorporated by the conformal isometry of $AdS$ space. A modification of this background has been considered in order to reproduce the linear confinement behavior for the masses squared of highly excited mesons, i.e. $m_{n,S}^2 \propto S + n$, where $S$ is spin and $n$ is radial excitation number [9].

In this paper, we would like to consider a string theory set up, keeping these nice properties of AdS/QCD model. High energy behavior of the known top down models is completely different from QCD since these models have been constructed by breaking conformal symmetry and supersymmetry. Therefore, we need to find a non-supersymmetric string theory set up.
Type 0 string theory [10] can be considered as a natural candidate because there is no supersymmetry but there exists fermionic degrees of freedom in the open string spectrum stretched between different types of $D$-branes [11].

Gauge/string duality has been considered in this theory [13]. The authors have considered a configuration of $N_c$ $D3_+$ branes in type 0B string theory. The dual field theory has been conjectured to be $U(N_c)$ four-dimensional Yang-Mills theory coupled to 6 adjoint scalar fields. The gravitational background corresponding to the $D3$ branes has been found in [14] [15]. This background has the properties that we need. IR cutoff is naturally introduced through the logarithmic behavior of the dilaton background. In the UV region, the background becomes AdS space asymptotically.

We wish to study the chiral symmetry breaking and the linear confinement behavior for meson masses by adding flavor degrees of freedom to this background. A general framework realizing chiral symmetry breaking has been formulated in [16]. The authors have considered a system of intersecting $D3$-$D9$-$D9$ branes. It has been argued that the open string tachyons stretched between $D9$ pairs can be used to describe the chiral symmetry breaking of a gauge theory. These fields correspond to the scalar fields modeling the chiral order parameter in AdS/QCD model. It has been also shown that the linear confinement behavior for highly excited spin-1 meson masses are automatic in the formalism if the IR background satisfy some appropriate conditions.

In this paper, we study a configuration of $D3_+$-brane and $D9_-$/$D9_-$ probe brane system in type 0B string theory using this framework. It will be shown that the low energy world volume theory of $D3_+$ branes is the $U(N_c)$ Yang-Mills gauge theory with 6 adjoint scalars coupled to $N_f$ fermions in the fundamental representation of $U(N_c)$. The fermions belong to the fundamental representation of the $U(N_f)_L \times U(N_f)_R$ flavor symmetry. Based

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2 As we will explain later, there is a doubled set of Ramond-Ramond fields. Therefore, there are two different types of $D$-branes, which are called $D_\pm$-branes.

3 A relevance between the spectrum of QCD and that of type 0 string theory has been discussed in [11] [12].

4 This method has been applied to the Sakai-Sugimoto model in [17] [18].

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on the framework, we discuss the chiral symmetry breaking and the linear confinement. We show that the type 0 IR background can be made to satisfy the conditions for linear confinement behavior by choosing the parameters associated with the IR background. Thus the background can be considered as a concrete example of the background discussed in [10].

The organization of this paper is as follows. In section 2, we briefly review some basic features of type 0 string theories. Then, we introduce the $D3{-}D9_{-}/D9_{-}$ brane configuration and explain the open string spectrum. In section 3, we present the gravitational background and effective action for mesons. We study the solution of tachyon equation of motion derived from the action in section 4. In section 5, we show that the mass spectra of highly excited vector and axial vector mesons have the behavior of the linear confinement. Section 6 is devoted to conclusions.

2 The set up in type 0 string theory

2.1 Type 0 string theory

Here we briefly review facts about type 0 string theories.

Let us first see that the closed string spectrum of type 0 string theories [10]. The GSO projection acts on the left and right-moving sectors together as $(1+(-1)^{F+F})/2$ in the NS-NS sectors and $(1\pm(-1)^{F+F})/2$ in the R-R sectors, where plus-minus sign corresponds to 0B and 0A theories, respectively. As a consequence of this GSO projection, type 0 string theories possess no spacetime supersymmetry. Following the notation of [19], the closed string spectrum of type 0A and 0B theories are summarized as follows:

\begin{align}
\text{type 0A} : & \quad (NS-, NS-) \oplus (NS+, NS+) \oplus (R+, R-) \oplus (R-, R+)
\text{type 0B} : & \quad (NS-, NS-) \oplus (NS+, NS+) \oplus (R+, R+) \oplus (R-, R-). \quad (1)
\end{align}

Both of these theories have no fermions in their spectra. The massless bosonic fields are same as these in the corresponding type II theory (A or B), but there are twice as many Ramond-Ramond fields. Type 0 theories also contain a tachyon coming from the $(NS-, NS-)$ sector.
The existence of a doubled set of R-R fields implies that of two different kinds of $D$-branes and corresponding anti $D$-branes. Let us denote the two kinds of $(p+1)$-form gauge potentials as $C_{p+1}$ and $\bar{C}_{p+1}$ corresponding to the R-R sectors in (1), for each $p$. ($p$ is even(odd) in 0A(0B) theory.) Then, we define the gauge potentials as

$$C_{p+1,\pm} \equiv \frac{1}{\sqrt{2}} (C_{p+1} + \bar{C}_{p+1}).$$

$D$-branes which are charged with respect to $C_{\pm}$ are called $D_{\pm}$ brane, respectively. In the case of $D3$ brane in 0B theory, the self-dual field strength $F_5 = dC_4$ and the anti-self-dual field strength $\bar{F}_5 = d\bar{C}_4$ can be combined to form an unconstrained 5-form field strength. $D3_{\pm}$ branes are called ”electric” and ”magnetic” branes, because of the Hodge duality transformation property $*F_5 = F_5^\pm$ [13].

2.2 The D-brane configuration

The $D$-brane configuration we consider consists of $N_c$ electric $D3$-branes and $N_f$ $D9_+/\bar{D}9_-$ brane pairs. The massless open string spectrum for this configuration is given in [11] [20] [21]. The results are summarized as follows:

- $(3^+, 3^\pm)$ strings: a gauge boson $A_{\mu}$ ($\mu = 0, 1, 2, 3$) and six adjoint scalar fields $\phi^i$ ($i = 1, \cdots, 6$) in the adjoint representation of $U(N_c)$ gauge group
- $(3^+, 9^-)$ strings: a Weyl fermion $q$ in the representation $(N_c, N_f)$ of $U(N_c) \times U(N_f)_L$
- $(3^+, \bar{9}^-)$ strings: a Weyl fermion $q$ in the representation $(N_c, N_f)$ of $U(N_c) \times U(N_f)_R$

$^5 U(N_c)$ is the gauge group associated with the $D3$-branes and $U(N_f)_L(U(N_f)_R)$ is the group associated with the $D9$-branes(anti $D9$-branes). We denote open strings with one end attached to the $D_{p\pm}$-brane and the other end to the $D_{q\pm}$-brane as $(p\pm, q\pm)$. We also denote the strings which belong to the bifundamental representation of $U(N) \otimes U(N')$ as $(N, N')$. 
• $(9_-,9_-)$ strings: a gauge boson $A^L_M$ ($M = 0, \cdots, 9$) in the adjoint representation of $U(N_f)_L$

• $(\bar{9}_-,\bar{9}_-)$ strings: a gauge boson $A^R_M$ in the adjoint representation of $U(N_f)_R$

• $(9_-,\bar{9}_-)$ strings: a tachyon $T$ in the representation $(N_f, N_f)$ of $U(N_f)_L \times U(N_f)_R$

The massless modes of $(3_+,3_-)$ strings consist of $A_\mu$ and $\phi^i$ which belong to the adjoint representation of the gauge group $U(N_c)$\footnote{The mass terms of the scalar fields $\phi^i$ are in general produced via loop-corrections. Thus, the low energy world volume theory of the $N_c$ electric $D3$-branes is expected to be pure Yang-Mills theory.}. From the $(3_+,9_-)$ and $(3_+,\bar{9}_-)$ strings, we obtain $N_f$ Weyl fermions $q$, which belong to the fundamental representation of the $U(N_c)$ gauge group. The chirality of $(3_+,9_-)$ fermions is opposite to that of $(3_+,\bar{9}_-)$ ones. Therefore, the $U(N_f)_L \times U(N_f)_R$ gauge symmetry of the $N_f$ $D9_-/\overline{D9}_-$ pairs can be interpreted as the $U(N_f)_L \times U(N_f)_R$ chiral symmetry.

In summary, the world volume effective theory on $N_c$ electric $D3$ branes of the above intersecting $D$-brane system is four-dimensional $U(N_c)$ Yang-Mills theory with $6$ adjoint scalars coupled to $N_f$ fermions with $U(N_f)_L \times U(N_f)_R$ chiral symmetry.

3 The Holographic dual model

Now let us describe the holographic dual of the above mentioned gauge theory. We first introduce the background which corresponds to the electric $D3$ brane solution of type 0B string theory. Then, we give the meson effective action. There exist KK modes coming from $S^5$. These degrees of freedom are generically present in a string theory set up. We are not interested in these KK modes because these modes do not appear in QCD. Thus, we ignore these modes as in other top-down approaches. For this, we assume that
meson fields are independent of the coordinate of $S^5$. We can obtain the 5D effective action for mesons by the dimensional reduction of the action.

### 3.1 The background

The low energy effective action of type 0B string theory is given in [13], as

$$S = \int d^{10}x \left[ e^{-2\phi} \left( R + 4(\partial_M \phi)^2 - \frac{1}{4}(\partial_M t)^2 - \frac{1}{4}g(t) \right) - \frac{f(t)}{4 \cdot 5!} F_5^2 \right]. \tag{3}$$

where

$$f(t) = 1 + t + \frac{1}{2}t^2, \tag{4}$$
$$g(t) = m^2 t^2 + \mathcal{O}(t^4). \tag{5}$$

Here we set $\alpha' = 1$. $f(t)$ describes the coupling of the tachyon to the 5-form field strength $F_5$. As noted in the previous subsection, $F_5$ is not constrained to be self-dual. $g(t)$ is the tachyon potential and $m^2 = -2/\alpha'$ is the tachyon mass squared.

Classical solution of $N_c$ stack of $D$-branes in this theory has been studied in [13] [15]. They have found the behaviors of the solution approximately in the UV and IR regions using the following ansatz,

$$ds^2 = e^{\frac{1}{2}\phi} \left( e^{\frac{1}{2}\xi - 5\eta} d\rho^2 + e^{-\frac{1}{2}\xi}\eta^{\mu\nu} dx_\mu dx_\nu + e^{\frac{1}{2}\xi - \eta} d\Omega_5^2 \right), \tag{6}$$
$$C_{4+\mu\nu\rho\sigma} = \epsilon_{\mu\nu\rho\sigma} C(\rho), \tag{7}$$

where $\rho$ is related to the radial direction transverse to the 3-brane. For the 4-form R-R potential $C_4$, $C_{0123}(\rho)$ has been taken to be the only non-vanishing component. Furthermore, all fields have been assumed to be functions of $\rho$. We give the forms of the solution in each region in order.
3.1.1 UV asymptotic solution

A solution valid in the UV region, $\rho \ll 1$, is given by \cite{15},

\begin{align}
\phi &= \ln(2^{15}Q^{-1}) - 2 \log y, \\
\xi &= \ln(2Q) - y + \frac{1}{y}, \\
\eta &= \ln 2 - \frac{1}{2} y + \frac{1}{y}, \\
t &= -1,
\end{align}

where $\rho/\rho_0 = e^{-y}$. $\rho_0$ is an integration constant. $Q$ is the total $D3$ brane charge which is proportional to $N_c$. An expansion which has higher order terms in $1/y$ is given in \cite{14}, but we focus on the above solution in this paper. In the Einstein frame, we can see that the metric is asymptotically $AdS_5 \times S^5$ in the limit $y \to \infty$. Furthermore, we can find that the gauge coupling dependence on $\rho$ as

\begin{equation}
\frac{1}{g_{YM}^2} = e^{-\phi} \propto Q \left( \ln \left( \frac{\rho}{\rho_0} \right) \right)^2.
\end{equation}

We can find a running coupling as the logarithmic behavior of the dilaton background. $\rho_0$ can be considered as the gauge theory length scale.

3.1.2 IR asymptotic solution

In the IR limit $\rho \to \infty$, it has been discussed in \cite{15} that the solution behaves as

\begin{align}
\phi &\simeq \phi_1 \rho + \phi_0, \\
\xi &\simeq \xi_1 \rho + \xi_0, \\
\eta &\simeq \eta_1 \rho + \eta_0, \\
t &\simeq t_1 \rho + t_0,.
\end{align}

\footnote{In \cite{22}, it has been shown that the UV solution can be connected to the IR solution.}
with the following conditions on integration constants $\phi_i$, $\xi_i$, $\eta_i$ and $t_i$ ($i = 0, 1$),

$$
\phi_1, \xi_1, \eta_1 > 0, \quad 5\eta_1 - \frac{1}{2}\phi_1 - \frac{1}{2}\xi_1 > 0,
$$

(17)

$$
\frac{1}{2}\phi_1^2 + \frac{1}{2}\xi_1^2 - 5\eta_1^2 + \frac{1}{4}t_1^2 = 0.
$$

(18)

These conditions are necessary for the solution to satisfy the equations of motion derived from the type 0B action (3).

In [15], it has been argued that this IR solution can lead to a linear quark potential by calculating the Wilson loop. The linear quark potential requires an additional condition on the constants:

$$
\phi_1 \geq \xi_1.
$$

(19)

As we will see later, the condition $\phi_1 = \xi_1$ is same as the one for the linear confinement behavior of highly excited spin-1 meson masses.

### 3.2 5D action

Let us present the low energy effective action on D9 brane pairs at quadratic order in gauge fields,

$$
S = -\int d^{10}x \text{Tr} \left[ e^{-\phi}V(\bar{T}T) \sqrt{-\det \tilde{g}_{MN}} \left( 1 + \frac{1}{4}g^{MN}_L g^{KL}_R \sum_{i=L,R} F^i_M F^i_N \right) \right],
$$

(20)

where

$$
\tilde{g}_{MN} = g_{MN} + \frac{1}{2} (D_M T)^\dagger (D_N T) + \frac{1}{2} (D_N T)^\dagger (D_M T),
$$

(21)

$$
F^L_{MN} = \partial_M A^L_N - \partial_N A^L_M, \quad F^R_{MN} = \partial_M A^L_N - \partial_N A^R_M+ \bar{T} A^L_M - iA^R_M T.
$$

(22)

(23)

$T$ is the open string tachyon and $V(\bar{T}T)$ is its potential. $A^L_M$ are the world-volume gauge fields. Note that $T$ transforms in the bifundamental representation of the $U(N_f)_L \times U(N_f)_R$ flavor symmetry group.

We only consider quadratic terms in the gauge fields because it is enough to find the mass spectrum. At this level, the action is just the sum of $N_f^2$ copies of the abelian action.
The form of the action coincides with that of the world volume DBI action on brane-antibrane pairs proposed in [23] [24] [25], expanded in terms of the gauge fields. In type 0 string theory, the DBI action on $D$-branes has the coupling of the closed string tachyon due to the existence of the tachyon tadpole on $D$-branes [14] [26]. However, it has been argued that the closed string tachyon may be stabilized due to the coupling of the tachyon and R-R field strength [13] [27]. This means that the tachyon reaches the minimum of its potential and has a fixed constant in the background introduced before. Thus, the coupling of the closed string tachyon may not affect the form of the effective action, at least in the low energy approximation.

In order to obtain the $5D$ effective action, we make the following assumptions: (1) $T$ depends only on $\rho$. (2) $T = \tau(\rho) \times 1$, where $1$ is the $N_f \times N_f$ identity matrix. (3) The tachyon potential has the form

$$V(\tau) = e^{-\frac{1}{2} \tau^2}. \quad (24)$$

(4) Gauge fields $A_{M}^{L,R}$ are functions of $x$ and $\rho$. (5) $A_{\alpha}^{R} = A_{\alpha}^{L} = 0$, where $\alpha$ denotes the coordinates of $S^5$.

The condition (2) means that the tachyon expectation values do not depend on the flavor degrees of freedom. (3) is necessary for the linear confinement behavior of highly excited meson masses. We impose (4) and (5) to make the gauge fields not to depend on the coordinate of $S^5$.

Assuming these, we can obtain the $5D$ effective action by the dimensional reduction. Choosing a gauge $A_{u}^{L} = A_{u}^{R} = 0$, we obtain

$$S = - \int d^4x du \left[ V(\tau) e^{\frac{i}{2} \phi + \frac{1}{2} \xi - \frac{1}{2} g_{xx}^2 \sqrt{g_{uu}} + (\partial_u \tau)^2} \right.$$

$$+ \frac{1}{4} F(u) \eta^{\mu\nu} \eta^{\rho\sigma} \left( V_{\mu\rho} V_{\nu\sigma} + A_{\mu\rho} A_{\nu\sigma} \right) + \frac{1}{2} G(u) \eta^{\mu\nu} \left( V_{\mu\nu} V_{\nu\mu} + A_{\mu\nu} A_{\nu\mu} \right)$$

$$+ H(u) \eta^{\mu\nu} A_{\mu\nu} \right], \quad (25)$$

where we define

$$V_{M} = \frac{A_{M}^{L} + A_{M}^{R}}{2}, \quad A_{M} = \frac{A_{M}^{L} - A_{M}^{R}}{2}. \quad (26)$$
The coefficients are given by

\begin{align*}
F(u) &= V(\tau)e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}(g_{uu} + (\partial_u \tau)^2)^{\frac{1}{2}}, \\
G(u) &= V(\tau)e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}g_{xx}(g_{uu} + (\partial_u \tau)^2)^{-\frac{1}{2}}, \\
H(u) &= V(\tau)e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}g_{xx}(g_{uu} + (\partial_u \tau)^2)^{\frac{1}{2}}\tau^2,
\end{align*}

(27) (28) (29)

4 Chiral symmetry breaking

The open string tachyons, in general, transform in the bifundamental representation of the flavor group, and couple on the boundary to scalar and pseudo-scalar bilinears of quark fields. It has been suggested in [16] that tachyon condensation on brane-antibrane system describes the physics of the chiral symmetry breaking. The tachyon expectation values, which is determined by the classical solution of the tachyon equation of motion derived from the above action, are related to the quark masses and the chiral condensate. In this section, we will see how these parameters appear in our model.

Let us set the \( A^L = A^R = 0 \), we obtain

\[
S = - \int d^4xd\tau \ V(\tau)e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}g_{xx}^2\sqrt{g_{uu} + (\partial_u \tau)^2}.
\]  

(30)

The equation of motion for the tachyon field \( \tau \) is given by

\[
\partial_u \left( V(\tau) \frac{e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}g_{xx}^2}{\sqrt{g_{uu} + (\partial_u \tau)^2}} \partial_u \tau \right) - V'(\tau)e^{\frac{1}{4}\phi + \frac{1}{2}\xi - \frac{5}{2}n}g_{xx}^2\sqrt{g_{uu} + (\partial_u \tau)^2} = 0,
\]  

(31)

where the prime denote differentiation with respect to \( \tau \).

Let us first consider the UV region. In the UV region, we expect that value of the tachyon becomes small. Thus, we assume that the tachyon equation is well described by linear terms of \( \tau \). In this assumption, we can approximate the equation as,

\[
\partial^2 \tau + \frac{y-2}{y}\partial_y \tau + \frac{4(2y-9)}{y^2} \tau = 0.
\]  

(32)

\[\text{[There are other attempts to incorporate the quark mass in holographic dual models] [28] [29]}\]
The solution of this equation in the limit $y \to \infty$ behaves as
\begin{equation}
\tau \sim m_q + \sigma e^{-y},
\end{equation}
where $m_q$ and $\sigma$ are integration constants. We now have two independent solutions and the constants associated with the solutions. Since $\tau$ is considered to be dual to the quark bilinear, these two integration constants can be related to the quark mass and the chiral condensate. This identification can be done by looking at the behavior of the solutions in the UV limit. In the UV limit $\rho \to \infty$, the tachyon solution behaves as $\tau(y) \sim m_q$. Thus, the constant $m_q$ may be related to quark mass, and the constant $\sigma$ may be related to the chiral condensate.

In the IR region, value of the open string tachyon is expected to be large\cite{16}. Thus, we should consider nonlinear equation. It seems to be difficult to find the general solution. However, we do not need to solve the equation of motion in order to find the behavior of linear confinement behavior. We only assume that the tachyon expectation value becomes large in the IR background.

5 Meson mass spectrum

Now let us turn to the meson sector. In particular, we focus on finding the linear confinement behavior for highly excited vector and axial meson masses. In\cite{16}, a framework for obtaining such a behavior has been formulated. The general conditions necessary for the behavior have been discussed. In this section, we show that one of the condition naturally comes from the linear potential behavior for quark confinement. We also show that other conditions can be imposed in the type 0 IR background.

\footnote{We can solve this equation as an asymptotic expansion,}
\begin{equation}
\tau(y) = m_q \left[ y^{-8} + \sum_{n=1}^{\infty} \frac{1}{n!} \prod_{m=1}^{n} [(m + 7)(m + 10) + 36] y^{-n-8} \right]
\end{equation}
\begin{equation}
+ \sigma e^{-y} \left[ y^{10} + \sum_{n=1}^{\infty} \frac{1}{n!} \prod_{m=1}^{n} [36 - (m - 8)(m - 11)] y^{10-n} \right].
\end{equation}
5.1 Vector fields

Let us consider the vector field \( V_\mu \). We assume that \( V_\mu \) can be expanded in terms of the complete sets \( \{ \psi_n(u) \} \) as

\[
V_\mu(x, u) = \sum_n V^m_\mu(x)\psi_n(u),
\]

with an appropriate normalization condition which will be specified below. The equations of motion for \( V_\mu(x, u) \) can be solved by choosing \( \psi_n \) as the eigenfunctions satisfying

\[
- \partial_u \left( G(u) \partial_u \psi_n \right) - F(u) m_n^2 \psi_n = 0,
\]

with the normalization condition of \( \psi_n \),

\[
\int du F(u) \psi_n \psi_m = \delta_{nm}.
\]

From these, we can obtain

\[
S = - \int d^4x \sum_n \left[ \frac{1}{4} Y^{(n)}_{\mu\nu} Y^{(m)\mu\nu} + \frac{1}{2} m_n^2 Y^{(n)}_\mu Y^{(n)\mu} \right].
\]

Let us study the vector meson mass spectrum. The spectrum of the highly excited meson masses depends on the background in the IR region. A general argument in [16] states that the conditions for linear confinement in the IR background are (1) \( g_{xx} \to \text{const} \), (2) \( \sqrt{g_{uu}} + (\partial_u \tau)^2 \sim \partial_u \tau \), (3) \( e^{-\tilde{\phi}} \sim V(\tau) \).

The condition (2) implies \( \tilde{g}_{uu} = g_{uu} + (\partial_u \tau)^2 \sim (\partial_u \tau)^2 \). Thus, the radial variable in the metric is proportional to \( \tau \). The Gaussian behavior of the tachyon potential is essential for the linear confinement behavior, as in [9].

Here, we would like to impose appropriate conditions on the IR background. In our case, it turns out that the conditions are (1) \( \phi_1 = \xi_1 \), (3) \( \frac{\phi_1}{4} + \frac{5\xi_1}{4} - \frac{5n}{2} = 0 \). (1) is a special case of the condition for the linear quark potential (19).

\[10\] \( e^{-\tilde{\phi}} \) is defined as,

\[
e^{-\tilde{\phi}} \tilde{g}_{xx} \sqrt{\tilde{g}_{uu}} = \int d\Omega_5 e^{-\phi} V(\tau) \sqrt{\det g},
\]

where \( \tilde{g}_{MN} = g_{MN} + \partial_M \tau \partial_N \tau \).
We can impose a constraint on the parameters to satisfy (3). From (1) and (3), we now have

\[ g_{\rho\rho} = e^{\left(\frac{1}{2}\phi_1 + \frac{1}{2}(1-5\eta)n\right)\rho} = e^{(\phi_1-5\eta)n\rho}, \]  

with \( \phi_1 < 5\eta_1 \). Therefore, in the IR limit \( \rho \to \infty \), we can see that (2) is automatically satisfied in our background. Therefore, we can reproduce the linear confinement behavior for highly excited vector meson masses.

5.2 Axial vector fields

The axial vector field fluctuation \( A_\mu \) can be split in a transverse and a longitudinal part, \( A_\mu = A_\mu^\perp + A_\mu^\parallel \), with \( \partial^\mu A_\mu^\perp = 0 \). Here, we consider the transverse part, corresponding to the axial vector meson excitation. We expand \( A_\mu^\perp \) as,

\[ A_\mu^\perp(x, u) = \sum_n A_{\mu}^{\perp(n)}(x)\phi_n(u). \]  

We choose \( \phi_n(x) \) as

\[ -\partial_u \left( G(u)\partial_u \phi_n \right) - F(u)\lambda_n\phi_n + H(u)\phi_n = 0, \]  

with the normalization conditions

\[ \int du F(u)\phi_n\phi_m = \delta_{nm}. \]  

We obtain,

\[ S = -\int d^4x \sum_n \left[ \frac{1}{4} A_{(n)\mu\nu} A^{\perp\mu\nu} + \frac{1}{2} H(u) A_{(n)\mu} A^{\perp\mu} \right]. \]  

We can find that the equation of motion has the same form as the vector case under the conditions discussed above. Therefore, in this case, we also have the linear confinement behavior, \( m_n^2 \propto n \), as in the vector case.

6 Conclusions

In this paper, we have studied a holographic dual model which has a type 0 string theory set up. The set up we have considered is a D-brane system
of the electric $D3$ and the probe $D9_-/D9_-$ branes. We have studied the $5D$ effective action on the $D3$ background. In particular, we have calculated the open string tachyon solution in the UV region. We have also shown that the vector and the axial vector meson mass spectrum have the behavior of linear confinement.

One interesting feature of type 0 string theory is that the Yang-Mills coupling has the logarithmic dependence on the coordinate transverse to $D3$-branes, \cite{12}. Since this behavior appears in the UV background, this is expected to be related to the high energy dynamics of the gauge theory. In QCD, there exist logarithmic scaling violations. These are due to the high energy processes. It is interesting to investigate high energy scatterings and how we can see the scaling violations in type 0 string theory.

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