Scalar Mesons and glueballs in $Dp - Dq$ hard-wall models

Chao Wang¹, Song He³, Mei Huang¹,², Qi-Shu Yan³, and Yi Yang⁴,⁵

¹ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
² Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing, China
³ Department of Physics, University of Toronto, Toronto, Canada
⁴ Department of Electrophysics, National Chiao-Tung University, Hsinchu, Taiwan
⁵ Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan

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We investigate light scalar mesons and glueballs in the $Dp - Dq$ hard-wall models, including $D3 - Dq$, $D4 - Dq$, and $D6 - Dq$ systems. It is found that only in the $D4 - D6$ and $D4 - D8$ hard wall models, the predicted masses of the $qq$ scalar meson $f_0$, scalar glueball are consistent with their experimental or lattice results. This indicates that $D4 - D6$ and $D4 - D8$ hard-wall models are favorite candidates of the realistic holographic QCD model.

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I. INTRODUCTION

In recent years, there have been intense studies on scalar mesons and scalar glueballs and their mixing, e.g. see Refs. [1, 2, 3] and references therein.

The glueball spectrum has attracted much attention more than three decades [4]. Study particles like glueballs where the gauge field plays a more important dynamical role than in the standard hadrons, offers a good opportunity of understanding the nonperturbative aspects of QCD. The complexity of determining the glueball states lies in that gluonic bound states always mix with $qq$ states. For example, one has to distinguish the lightest scalar glueball state among other scalar mesons observed in the energy range below 2GeV. Though the pseudoscalar, vector and axial-vector, and tensor mesons with light quarks have been reasonably well known in terms of their $SU(3)$ classification and quark content, the scalar meson sector, on the other hand, is much less understood in this regard. There are 19 states which are more than twice the usual $qq$ nonet as in other sectors.

Despite of extensive study from both experimental side and theoretical side, no conclusive answer has been obtained on scalar mesons and scalar glueballs. One possible scenario is: The lightest scalars $\sigma, \kappa, f_0, a_0$ below 1GeV make a full $SU(3)$ flavor nonet. The inversion of the $\kappa$ and $f_0$ or $a_0$ mass ordering, suggests that these mesons are not naive $qq$ states, one natural explanation for this inverted mass spectrum is that these mesons are diquark and antidiquark bound states, or tetraquark states [5]. Above 1GeV, the nonet $\bar{q}q$ mesons are made of an octet with largely unbroken $SU(3)$ symmetry and a fairly good singlet which is $f_0(1370)$. The other left scalar meson $f_0(1710)$ is identified as an almost pure scalar glueball with a $\sim 10\%$ mixture of $\bar{q}q$, which is supported from lattice calculation [6] and experimental observation of the copious $f_0(1710)$ production in radiative $J/\psi$ decays [7].

Recently, the discovery of the gravity/gauge duality, or anti-de Sitter/conformal field theory (AdS/CFT) correspondence [8, 9] provides a revolutionary method to tackle the problem of strongly coupled gauge theories, for reviews see Ref. [10]. Many efforts have been invested in examining meson spectra, baryon spectra, see e.g. Refs. [11, 12], as well as in the glueball sector [13, 14]. It is widely expected that this new analytical approach can shed some light on our understanding of the nonperturbative aspects of QCD.

The string description of realistic QCD has not been successfully formulated yet. By using AdS/CFT correspondence to study non-conformal field theory like QCD, the usual way of breaking conformal symmetry is by introducing a hard infrared (IR) cut-off, i.e. the hard-wall $AdS_5$ model or introducing a smooth cut-off through a dilaton background field, i.e. the soft-wall $AdS_5$ model. One can extend the AdS/CFT correspondence to a more general case, and expect the realistic QCD is dual to a non-conformal $Dp$ brane system, like the $D4 - D8/D8$ system, i.e. the Sakai-Sugimoto model [15]. In Ref. [10], we have investigated the general embedding $Dp - Dq$ systems, where the $N_f$ background $Dp$-brane describes the effects of pure QCD theory, while the $N_f$ probe $Dq$-brane is to accommodate the fundamental flavors.

The motivation of this paper is to investigate the scalar meson and glueball spectra in the general embedding $Dp - Dq$ systems, and study which $Dp - Dq$ system is more close to the dual theory of realistic QCD. Our finding is that in the $D4 - D6$ and $D4 - D8$ hard wall models, the predicted masses of the $qq$ scalar meson $f_0$ and the scalar glueball are consistent with their experimental or lattice results, which indicates that $D4 - D6$ and $D4 - D8$ hard-wall models are favorite candidates of the realistic holographic QCD model. Because this paper is an attempt to describe light mesons and glueballs in one holographic model, we will leave the mixing between scalar mesons, tetraquark states and glueballs for future studies.

The paper is organized as following: After the introduction, we briefly introduce 5-dimension metric structure of the $Dp - Dq$ system in type II superstring theory in Sec. [11]. Then in Sec. [11] we give the equation of motion for
II. THE $D_p - D_q$ SYSTEM

We have investigated the $D_p - D_q$ systems in Ref. \[16\], however, in order to keep this paper self-contained, in the following, we give a brief introduce on the $D_p - D_q$ branes system in type II superstring theory. In the $D_p - D_q$ system, the $N_c$ background $Dp$-brane describes the effects of pure gauge theory, while the $N_f$ probe $Dq$-brane is to accommodate the fundamental flavors which has been introduced by Karch and Katz \[17\].

The near horizon solution of the $N_c$ background $Dp$-branes in type II superstring theory in 10-dimension spacetime is \[18\]

$$ds^2 = h^{-\frac{p}{2}}\eta_{\alpha\beta}dx^\alpha dx^\beta + h^{\frac{p}{2}}(du^2 + u^2d\Omega^2_{8-p}) ,$$

where $\alpha, \beta = 0, \cdots, p$, $\eta_{\alpha\beta} = \text{diag}(-1,1,1,\ldots)$, and the warp factor $h(u) = (R/u)^{\frac{p}{2}}$ and $R$ is a constant $R = [2^{p-5}\pi^{(5-p)/2}\Gamma(\frac{p-7}{2})]^{-\frac{1}{p-2}}$. The dilaton field in this background has the form of $e^\Phi = g_s h(u)^{\frac{p-7}{p-2}}$. The effective coupling of the Yang-Mills theory is $g_{eff} \sim g_s N_c u^{p-3}$, which is $u$ dependent. This $u$ dependence corresponds to the RG flow in the Yang-Mills theory, i.e. the effective $g_{eff}$ coupling constant depends on the energy scale $u$. In the case of $D3$-brane, $g_{eff} \sim g_s N_c$ becomes a constant and the dual Yang-Mills theory is $N = 4$ SYM theory which is a conformal field theory. The curvature of the background \(1\) is $R \sim \frac{1}{g_{eff}}$, which reflects the string/gauge duality - the string on a background of curvature $R$ is dual to a gauge theory with the effective coupling $g_{eff}$. To make the perturbation valid in the string side, we require that the curvature is small $R \ll 1$, which means that the effective coupling in the dual gauge theory is large $g_{eff} \gg 1/l_s^2$. In the case of $D3$-brane, the curvature $R$ becomes a constant, and the background \(1\) reduces to a constant curvature spacetime - $AdS_5 \times S^5$.

The coordinates transformation (for the cases of $p \neq 5$) $u = \left(\frac{5-p}{2}\right)\frac{z^{-\frac{p-7}{2}}}{R^{p-5}z^{p-5}}$, brings the above solution \(1\) to the following Poincaré form,

$$ds^2 = e^{2A(z)}\left[\eta_{\alpha\beta}dx^\alpha dx^\beta + dz^2 + \frac{(p-5)^2}{4}z^2d\Omega^2_{8-4}\right].$$

We then consider $N_f$ probe $Dq$-branes with $q - 4$ of their dimensions in the $S^{q-4}$ part of $S^{8-p}$, with the other dimensions in $z$ and $x^\alpha$ directions. The induced $q + 1$ dimensions metric on the probe branes is given as

$$ds^2 = e^{2A(z)}\left[\eta_{\mu\nu}dx^\mu dx^\nu + dz^2 + \frac{z^2}{z_0^2}d\Omega^2_{q-4}\right],$$

where $\mu, \nu = 0, \cdots, 3$, $\eta_{\mu\nu} = \text{diag}(-1,1,1,1)$, and the metric function of the warp factor only includes the logarithmic term

$$A(z) = -a_0 \ln z, \text{ with } a_0 = \frac{p-7}{2(p-5)},$$

and the dilaton field part takes the form of $e^{\Phi(z)} = g_s \left(\frac{z}{z_0}\right)^{\frac{(p-3)(p-7)}{2(p-5)}}$, which gives

$$\Phi(z) \sim d_0 \ln z, \text{ with } d_0 = -\frac{(p-3)(p-7)}{2(p-5)}.$$
where $\phi M_1, \ldots M_p$ is the tensor field and $M_i$ is the tensor index. The value of $S$ is equal to the spin of the field. The parameters $g$ and $\Phi(z)$ are the induced $q + 1$ dimension metric and dilaton field as shown in Eq. \(3\) and \(15\). $m_{3,X}^2$ and $m_{3,\phi}^2$ are the 5D mass square of the bulk fields.

By assuming that the gauge fields are independent of the internal space $S^{n-4}$, after integrating out $S^{n-4}$, up to the quadratic terms and following the standard procedure of dimensional reduction, we can decompose the bulk field into its 4D components $\phi^n(x)$ and their fifth profiles $\psi_n(z)$. The equation of motion (EOM) of the fifth profile wavefunctions $\psi_n(z)$ for the general spin field including $S = 0$ and $S > 1$ can be derived as

$$\frac{d^2 \psi_n}{dz^2} - \frac{\partial z B \cdot \partial z \psi_n + (M_n^2 - m_2^2 \epsilon^{2A}) \psi_n = 0,}$$

where $M_n$ is the mass of the 4-dimension field $\phi^n(x)$, and

$$B = \Phi - k' k A = \Phi + k c_0 \ln z$$

is the linear combination of the metric background function and the dilaton field, with $k' = 3$ for scalar field, and $k' = 2S - 1$ for higher spin fields. For simplicity, we have defined $c_0 = ka_0 = -\frac{(p-3)(q-5)+4}{2(p-4)}$. The parameter $k$ is a parameter depending on the induced metric of the $Dq$ brane. After integrating out $S^{n-4}$, $k$ is determined as

$$k = -\frac{(p-3)(q-5)+4}{p-4}.\right)$$

It is obviously that $k$ depends on both $p$ and $q$.

The parameters $c_0, d_0$ and the curvature for any $Dp – Dq$ system are listed in Table I. We notice that $d_0 = 0$

| $p$ | 3  | 4  | 6  |
|-----|----|----|----|
| $q$ | 5  | 7  | 4  |
| $c_0$ | 31/2 | 7/2 | 17/2 |
| $d_0$ | 0  | -3/2 | 3/2 |
| $k$ | $\frac{1}{\sqrt{3}} z^{-2/\sqrt{36\pi}}$ | $6\sqrt{2}z^b$ |

TABLE I: Theoretical results for the $Dp – Dq$ system.

for $D3$ background branes, *i.e.* dilaton field is constant in AdS$_5$ space. However, the dilaton field in a general $Dp – Dq$ system can have a $\ln z$ term contribution, e.g. in the $D4 – D8$ system $d_0 = -3/2$. We also want to point out that for pure $Dp – Dq$ system, the curvature is proportional to the inverse of the coupling strength $g_{eff}$. For $D3$ background branes, the curvature is a constant. The curvature for $D4$ background branes is small at IR, and large at UV, its dual gauge theory is strongly coupled at IR and weakly coupled at UV, which is similar to QCD. However, the curvature for $D6$ background branes is large at IR, and small at UV, its dual gauge theory is weakly coupled at IR and strongly coupled at UV, which is opposite to QCD.

### III. MESON SPECTRA AND GLUEBALL SPECTRA IN THE $Dp – Dq$ HARD-WALL MODELS

In the following, we are going to investigate the scalar mesons and glueballs in the 5D $Dp – Dq$ model defined in Sec. \[1\]. Because here we are only interested in the light excitations, we will use hard-wall models of $Dp – Dq$ system, *i.e.* we choose a slice of the 5D $Dp – Dq$ metric in the region of $0 < z < z_m$. $z_m$ will be fixed in each $Dp – Dq$ model with the mass of vector meson $\rho(770)$. We will use the scenario in the introduction as reference for the scalar mesons and glueballs: the mass of $\bar{q}q$ scalar meson $f_0$ is in the range of $1370 – 1500$ MeV \[2\], and the mass of scalar glueball $G_0(0^{++})$ is around $1710$ MeV \[3\], \[4\], while the nonet below $1$GeV are tetraquark states. We will also study several tensor glueballs for reference, the lattice result \[4\] shows that the masses for tensor glueball $G_2(2^{++})$ and $G_3(3^{++})$ are around $2400$ MeV and $3600$ MeV, respectively.

The key ingredients of the AdS/CFT correspondence is that it establishes a one-to-one correspondence between a certain class of local operators in the 4D $\mathcal{N} = 4$ superconformal gauge theory and supergravity fields representing the holographic correspondents in the $AdS_5 \times S^5$ bulk theory. In the bottom-up approach, we can expect a more general correspondence, *i.e.* each operator $\mathcal{O}(x)$ in the 4D field theory corresponds to a field $\phi(x, z)$ in the 5D bulk theory. To investigate the meson and glueball spectra, we consider the lowest dimension operators with the corresponding quantum numbers and defined in the field theory living on the 4D boundary. According to AdS/CFT correspondence, the conformal dimension of a $(f$-form) operator on the boundary is related to the $m_2^2$ of its dual field in the bulk as follows \[4\] :

$$m_2^2 = (\Delta - f)(\Delta + f - 4).$$

(10)
For non-conformal $Dp$ branes, the induced metric (3) is still conformal to an AdS metric as we mentioned before. We thus assume the above correspondence can be extended to any $Dp - Dq$ system in 5-dimension. In Table III, we list the correspondent fields for mesons and glueballs considered, and their 5D mass square.

The equation of motion Eq. (8) can be simplified as

$$ - \psi''_n + V(z)\psi_n = M_n^2 \psi_n, $$

where $V(z)$ takes the form of $V(z) = \frac{B^2}{4} - \frac{\beta_n^2}{2} + e^{2A(z)}n_5^2$, with $B = (d_0 + k'c_0) \ln z$. It is found that for any $Dp - Dq$ system, $V(z)$ takes the general form of

$$ V(z) = \frac{1}{z^2} \left( \frac{(d_0 + k'c_0)^2}{4} + \frac{d_0 + k'c_0}{2} + m_5^2 \right). $$

In Table III, we show the meson and glueball spectra by taking the boundary conditions as DN type, $\psi_{n|z=0} = 0, \partial_z \psi_{n|z=0} = 0$, i.e. the Dirichlet type at UV and Neumann type at IR. It is found that in the $D3 - Dq$ system, the predicted $\bar{q}q$ scalar meson is below 1GeV, and the scalar and tensor glueball masses are much lighter than the lattice results. The predicted meson and glueball masses are too light in the $D6 - D4$ system and too heavy in the $D6 - D6$ system, and both cases are far away from experimental/lattice results. The meson and glueball spectra in $D4 - Dq$ systems are more reasonable comparing with the experimental/lattice results. Especially the spectra of scalar meson and scalar glueball in the $D4 - D6$ and $D4 - D8$ systems are very close to the experimental/lattice results. The tensor glueball spectra in these two systems are 80% - 90% in agreement with the lattice results.

$$ E_{exp/Lat} | D_3 - D_q | D_3 - D_3 | D_4 - D_6 | D_4 - D_8 | D_6 - D_8 | D_6 - D_6 $$

| $\rho$ | $\bar{q}q$ | $D_0$ | $D_2$ | $D_4$ | $D_6$ | $D_8$ |
|-------|-------|------|------|------|------|------|
| 3.852 | 2.04  | 3.852| 5.268| 3.85281| 1.453|      |
| $m_{\rho}$ | 0.77 | 0.77 | 0.77 | 0.77 | 0.77 |      |
| $m_{D_0}$ | 1.37 | 1.5 | 0.893| 1.417| 1.584| 1.565| 0.548| 2.496|
| $m_{D_2}$ | 1.6 | 1.7 | 1.201| 1.956| 1.722| 1.633| 0.408| 2.858|
| $m_{D_4}$ | 2.4 | 2.4 | 3.255| 2.255| 1.936| 1.442| 4.269|      |
| $m_{D_6}$ | 3.69| 2.356| 4.240| 3.021| 2.884| 1.344| 6.131|      |

| $z_m^M$ | $z_m^\rho$ | $z_m^{D_0}$ | $z_m^{D_2}$ | $z_m^{D_4}$ | $z_m^{D_6}$ | $z_m^{D_8}$ |
|---------|------------|-------------|-------------|-------------|-------------|-------------|
| 3.852   | 2.04       | 3.852       | 5.268       | 3.85281     | 1.453       |            |
| 0.77    | 0.77       | 0.77        | 0.77        | 0.77        | 0.77        |            |
| 1.37    | 1.5        | 0.893       | 1.417       | 1.584       | 1.565       | 0.548      | 2.496     |
| 1.6     | 1.7        | 1.201       | 1.956       | 1.722       | 1.633       | 0.408      | 2.858     |
| 2.4     | 2.4        | 3.255       | 2.255       | 1.936       | 1.442       | 4.269      |            |
| 3.69    | 2.356      | 4.240       | 3.021       | 2.884       | 1.344       | 6.131      |            |

TABLE III: Results of the meson/glueball spectra in the hard-wall $D_p - D_q$ system with the DN boundary condition. The unit for mass is in GeV.

In Table IV, we show the meson and glueball spectra by taking the boundary conditions as DD type, $\psi_{n|z=0} = 0, \partial_z \psi_{n|z=0} = 0$, i.e. the Dirichlet type both at UV and at IR. It is found that the results in hard-wall models are sensitive to the boundary conditions, which is unlike the case in the soft-wall models as we have shown in Ref. [16].

Using DD type boundary conditions, the predicted meson and glueball spectra in $D4 - D8$ system is still close to the experimental/lattice results, but the error is bigger. We thus conclude that DN type boundary conditions are more appropriate for QCD hadron spectra.

IV. SUMMARY

We have investigated the light meson and glueball spectra in the $Dp - Dq$ hard-wall models, with the IR cut-off fixed by the mass of vector meson mass $\rho$. We have used the experimental/lattice results for the scalar meson mass in the range of 1370 - 1500 and the scalar glueball mass in the range of 1600 - 1700 as references.

We find that the AdS$_5$ hard-wall model, i.e. our $D3 - Dq$ hard-wall model is not the favored candidate of the holographic QCD model, because the predicted meson spectra and glueball spectra in this model does not agree well with experimental/lattice results. The most favored candidates for the realistic holographic QCD model are...
the $D4-D6$ or $D4-D8$ hard wall models. In these two models, the predicted meson and glueball spectra are close to the experimental and lattice results. This picture is in consistent with the curvature analysis in Sec. \[ \] For $D3$ background branes, the curvature is a constant, its dual gauge theory is a conformal field theory, which is not QCD-like. The curvature for $D4$ background branes is small at IR, and large at UV, its dual gauge theory is strongly coupled at IR and weakly coupled at UV, which is similar to QCD.

It is noticed that there is another scenario where the $\sigma(600)$ is identified as the scalar glueball \[2\]. This scenario can be realized in our $D6-D4$ system. However, as we pointed out in Sec. \[3\] the curvature for $D6$ background branes is large at IR, and small at UV, its dual gauge theory is weakly coupled at IR and strongly coupled at UV, which is opposite to QCD. Therefore, the $D6-Dq$ system can be safely excluded for the candidates of holographic QCD model.

These results agree with the main findings in the $Dp-Dq$ soft-wall models \[10\], where we find that $Dp$ for $p = 3, 4$ systems are consistent with the Regge behavior of the vector and axial-vector mesons. More physical quantities need to be evaluated and compared with experimental results in order to determine which $Dp-Dq$ system is more favored as the candidate of the realistic holographic QCD model.

At the end, we want to point out that our results are based on the assumption that the 5D mass square of the dual field follows the relation Eq. \[10\] in the AdS/CFT dictionary. This relation might be modified in the non-conformal $Dp-Dq$ systems. We need further studies along this direction.

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| $z_m^p$ | $Exp/Lat$ | $D_3-D_6$ | $D_4-D_6$ | $D_4-D_8$ | $D_4-D_6$ | $D_6-D_4$ | $D_6-D_8$ |
|--------|------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $m_p$  | 0.77       | 0.77        | 0.77        | 0.77        | 0.77        | 0.77        | 0.77        |
| $m_{q_1}$ | 1.37       | 0.77       | 0.939       | 1.292       | 1.441       | 0.795       | 1.744       |
| $m_{G_2}$ | 1.6 - 1.7  | 1.632      | 1.259       | 1.404       | 1.503       | 0.631       | 1.860       |
| $m_{G_3}$ | ~ 2.4     | 1.637      | 1.997       | 1.837       | 1.782       | 1.532       | 2.338       |

For $D3$ background branes, the curvature is a constant, its dual gauge theory is a conformal field theory, which is not QCD-like. The curvature for $D4$ background branes is small at IR, and large at UV, its dual gauge theory is strongly coupled at IR and weakly coupled at UV, which is similar to QCD.

| TABLE IV: Results of the meson/glueball spectra in the hard-wall $D_p-D_q$ system with DD boundary condition. The unit for mass is in GeV. |
|--------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| $z_m^p$ | $Exp/Lat$   | $D_3-D_6$  | $D_4-D_6$  | $D_4-D_8$  | $D_6-D_4$  | $D_6-D_8$  |
| $m_p$  | 0.77        | 0.77        | 0.77        | 0.77        | 0.77        | 0.77        |
| $m_{q_1}$ | 1.37       | 0.77        | 0.939       | 1.292       | 1.441       | 0.795       | 1.744       |
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The $D4-D6$ or $D4-D8$ hard wall models. In these two models, the predicted meson and glueball spectra are close to the experimental and lattice results. This picture is in consistent with the curvature analysis in Sec. \[ \] For $D3$ background branes, the curvature is a constant, its dual gauge theory is a conformal field theory, which is not QCD-like. The curvature for $D4$ background branes is small at IR, and large at UV, its dual gauge theory is strongly coupled at IR and weakly coupled at UV, which is similar to QCD.

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