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Scalar mesons and glueballs in D_p-D_q hard-wall models*

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Abstract We investigate the light scalar mesons and glueballs in the D_p-D_q hard-wall models, including D_3-D_q, D_4-D_q, and D_6-D_q systems. It is found that only in the D_4-D_6 and D_4-D_8 hard-wall models are the predicted masses of the $\bar{q}q$ scalar meson f_0 scalar glueball consistent with their experimental or lattice results. This indicates that D_4-D_6 and D_4-D_8 hard-wall models are the favorite candidates of the realistic holographic QCD model.

Key words scalar meson, scalar glueball, AdS/CFT

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1 Introduction

In recent years, there have been intense studies on scalar mesons and scalar glueballs and their mixing, e.g. see Refs. [1–4] and references therein.

The glueball spectrum has attracted much attention for the post three decades [5]. The study of particles like glueballs where the gauge field plays a more important dynamical role than in the standard hadrons, offers a good opportunity for understanding the nonperturbative aspects of QCD. The complexity of determining the glueball states lies in that gluonic bound states always mix with $\bar{q}q$ states. For example, one has to distinguish the lightest scalar glueball state among other scalar mesons observed in the energy range below 2 GeV. 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 $\bar{q}q$ nonet as in other sectors.

Despite the extensive study from both the experimental side and theoretical side, no conclusive answer has been obtained on scalar mesons and scalar glueballs. One possible scenario is: The lightest scalars σ, κ, f_0, a_0 below 1 GeV make a full $SU(3)$ flavor nonet. The inversion of the κ and f_0 or a_0 mass ordering, suggests that these mesons are not naive $\bar{q}q$ states, one natural explanation for this inverted mass spectrum is that these mesons are diquark and antidiquark bound states, or tetraquark states [6]. Above 1 GeV, the nonet $\bar{q}q$ mesons are made of an octet with largely unbroken $SU(3)$ symmetry and a fairly good singlet which is $f_0(1370)$. There are still a lot of controversies on identifying the glueball nature of $f_0(1500)$ and $f_0(1710)$, for review, see Ref. [4]. The experimental observation of the copious $f_0(1710)$ production in radiative J/ψ decays [7] suggests that $f_0(1710)$ is an almost pure scalar glueball with a $\sim 10\%$ mixture of $\bar{q}q$, which is supported by lattice calculation [8]. However, the scalar meson $f_0(1500)$ also shows non-$\bar{q}q$ features. The mixture of the glueball and the $\bar{q}q$ state in the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ has been widely discussed in literature [1].

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Recently, the discovery of the gravity/gauge duality, or anti-de Sitter/conformal field theory (AdS/CFT) correspondence [9, 10] provides a revolutionary method for tackling the problem of strongly coupled gauge theories, for reviews, see Ref. [11]. Many efforts have been invested in examining meson spectra, baryon spectra, see e.g. Ref. [12, 13], as well as in the glueball sector [14, 15]. 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 to be dual to a non-conformal D_p brane system, like the D_4-$\mathrm{D}_8/\bar{\mathrm{D}}_8$ system, i.e. the Sakai-Sugimoto model [16]. In Ref. [17], we have investigated the general embedding D_p-D_q systems, where the N_c background D_p-brane describes the effects of pure QCD theory, while the N_f probe D_q-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 D_p-D_q systems, and study which D_p-D_q system is closer to the dual theory of realistic QCD. Our finding is that in the D_4-D_6 and D_4-D_8 hard wall models, the predicted masses of the $\bar{\mathrm{q}}\mathrm{q}$ scalar meson f_0 and the scalar glueball are consistent with their experimental or lattice results, which indicates that D_4-D_6 and D_4-D_8 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 follows: After the introduction, we briefly introduce a 5-dimension metric structure of the D_p-D_q system in Type II superstring theory in Sec. 2. Then in Sec. 3, we give the equation of motion for mesons and glueballs, and we investigate the meson spectra and glueball spectra. At the end, we give discussions and conclusions in Sec. 4.

2 The D_p-D_q system

We have investigated the D_p-D_q systems in Ref. [17]. However, in order to keep this paper self-contained, in the following, we give a brief introduction to the D_p-D_q branes system in Type II superstring theory. In the D_p-D_q system, the N_c background D_p-brane describes the effects of pure gauge theory, while the N_f probe D_q-brane is to accommodate the fundamental flavor, which has been introduced by Karch and Katz [18].

The near horizon solution of the N_c background D_p-branes in Type II superstring theory in 10-dimension space-time is [19]

$$\mathrm{d}s^2 = h^{-\frac{1}{2}}\eta_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta + h^{\frac{1}{2}}\left(\mathrm{d}u^2 + u^2\mathrm{d}\Omega^2_{8-p}\right), \quad (1)$$

where $\alpha, \beta = 0, \cdots, p$, $\eta_{\alpha\beta} = \mathrm{diag}(-1, 1, 1, \cdots)$, and the warp factor $h(u) = (R/u)^{7-p}$ and R is a constant

$$R = \left[2^{5-p}\pi^{(5-p)/2}\Gamma\left(\frac{7-p}{2}\right)g_\mathrm{s}N_\mathrm{c}l_\mathrm{s}^{7-p}\right]^{\frac{1}{7-p}} .$$

The dilaton field in this background has the form of $\mathrm{e}^\Phi = g_\mathrm{s}\ h(u)^{\frac{(p-3)}{4}}$. The effective coupling of the Yang-Mills theory is $g_\mathrm{eff} \sim g_\mathrm{s}N_\mathrm{c}u^{p-3}$, 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 D_3-brane, $g_\mathrm{eff} \sim g_\mathrm{s}N_\mathrm{c}$ becomes a constant and the dual Yang-Mills theory is $\mathcal{N} = 4$ SYM theory which is a conformal field theory. The curvature of the background (1) is $\mathcal{R} \sim \dfrac{1}{l_\mathrm{s}^2 g_\mathrm{eff}}$, which reflects the string/gauge duality - the string on a background of curvature $\mathcal{R}$ 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 $\mathcal{R} \ll 1$, which means that the effective coupling in the dual gauge theory is large $g_\mathrm{eff} \gg 1/l_\mathrm{s}^2$. In the case of D_3-brane, the curvature $\mathcal{R}$ becomes a constant, and the background (1) reduces to a constant curvature spacetime - $\mathrm{AdS}_5 \times S^5$.

The coordinates transformation (for the cases of $p \neq 5$)

$$u = \left(\frac{5-p}{2}\right)^{\frac{2}{p-5}} R^{\frac{p-7}{p-5}} z^{\frac{2}{p-5}},$$

brings the above solution (1) to the following Poincaré form,

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

We then consider N_f probe D_q-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^α directions. The induced $q+1$ dimensions metric on the probe branes is given as

$$ds^2 = e^{2A(z)}\left[\eta_{\mu\nu}dx^\mu dx^\nu + dz^2 + \frac{z^2}{z_0^2}d\Omega_{q-4}^2\right], \quad (3)$$

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

$$A(z) = -a_0 \ln z, \quad \text{with} \quad a_0 = \frac{p-7}{2(p-5)}, \quad (4)$$

and the dilaton field part takes the form of

$$e^{\Phi(z)} = g_s\left(\frac{2}{5-p}\frac{R}{z}\right)^{\frac{(p-3)(p-7)}{2(p-5)}},$$

which gives

$$\Phi(z) \sim d_0 \ln z, \quad \text{with} \quad d_0 = -\frac{(p-3)(p-7)}{2(p-5)}. \quad (5)$$

The metric (3) is conformal to $AdS_5 \times S^{q-4}$.

A 5-dimension (5D) scalar field $X(x,z)$ can be described by the action in the gravitational background as

$$I_{S=0} = \frac{1}{2}\int d^5x\sqrt{g}\,e^{-\Phi(z)}\left[\partial_N X\partial^N X + m_{5,X}^2 X^2\right], \quad (6)$$

For higher spin fields, we can have the effective 5D action described by tensor fields as

$$I_{S>0} = \frac{1}{2}\int d^5x\sqrt{g}\,e^{-\Phi(z)}\Big\{\Delta_N\phi_{M_1\cdots M_S}\Delta^N\phi^{M_1\cdots M_S} + m_{5,\phi}^2\phi_{M_1\cdots M_S}\phi^{M_1\cdots M_S}\Big\}, \quad (7)$$

where $\phi_{M_1\cdots M_S}$ 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 (5). $m_{5,X}^2$ and $m_{5,\phi}^2$ are the 5D mass square of the bulk fields.

By assuming that the gauge fields are independent of the internal space S^{q-4}, after integrating out S^{q-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

$$\partial_z^2\psi_n - \partial_z B\cdot\partial_z\psi_n + \left(M_n^2 - m_5^2 e^{2A}\right)\psi_n = 0, \quad (8)$$

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

$$B = \Phi - k'kA = \Phi + k'c_0\ln z \quad (9)$$

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

$$c_0 = ka_0 = -\frac{(p-3)(q-5)+4}{2(p-5)}.$$

The parameter k is a parameter depending on the induced metric (3) of the D_q brane. After integrating out S^{q-4}, k is determined as

$$k = -\frac{(p-3)(q-5)+4}{p-7}.$$

It is obvious that k depends on both p and q.

The parameters c_0, d_0 and the curvature for any D_p-D_q system are listed in Table 1. We notice that $d_0 = 0$ for D_3 background branes, i.e. the dilaton field is constant in AdS_5 space. However, the dilaton field in a general D_p-D_q system can have a $\ln z$ term contribution, e.g. in the D_4-D_8 system $d_0 = -3/2$. We also want to point out that for the pure D_p-D_q system, the curvature is proportional to the inverse of the coupling strength g_{eff}. For D_3 background branes, the curvature is a constant. The curvature for D_4 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 D_6 background branes is large at IR, and small at UV, its dual gauge theory is weakly coulped at IR and strongly coupled at UV, which is opposite to QCD.

Table 1. Theoretical results for the D_p-D_q system.

p	3		4			6	
q	5	7	4	6	8	4	6
c_0	1		3/2	5/2	7/2	−1/2	−7/2
d_0	0		−3/2			3/2	
$\mathcal{R}$	$1/\sqrt{3}$		$z^{-2}/\sqrt{36\pi}$			$6\sqrt{2}z^6$	

3 Meson spectra and glueball spectra in the D_p-D_q hard-wall models

In the following, we are going to investigate the scalar mesons and glueballs in the 5D D_p-D_q model defined in Sec. 2. Because here we are only interested in the light excitations, we will use hard-wall models of the D_p-D_q system, i.e. we choose a slice of the 5D D_p-D_q metric in the region of $0 < z \leqslant z_m$. z_m will be fixed in each D_p-D_q model with the mass of vector meson ρ(770). We will use the scenario in the introduction as a 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 [7], and the mass of scalar glueball $G_0(0^{++})$ is in the range of 1500–1710 MeV [7, 8], while the nonet below 1 GeV is tetraquark state. We will also study several tensor glueballs for reference, the lattice result [8] shows that the masses for tensor glueball $G_2(2^{++})$ and $G_3(3^{++})$ are around 2400 MeV and 3600 MeV, respectively.

The key ingredient 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_5^2 of its dual field in the bulk as follows [10]:

$$m_5^2=(\Delta-f)(\Delta+f-4)\,. \tag{10}$$

For non-conformal D_p 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 D_p-D_q system in 5-dimension. In Table 2, we list the correspondent fields for mesons and glueballs considered, and their 5D mass square.

Table 2. 5D mass square of mesons and glueballs in D_p-D_q system.

	4D: $\mathcal{O}(x)$	Δ	f	m_5^2
f_0	$\bar{q}q$	3	0	−3
ρ	$\bar{q}\gamma_\mu q$	3	1	0
G_0	F^2	4	0	0
G_2	$FD_{\mu_1}D_{\mu_2}F$	6	2	16
G_3	$FD_{\mu_1}D_{\mu_2}D_{\mu_3}F$	7	3	24

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

$$-\psi_n''+V(z)\psi_n=M_n^2\psi_n\,, \tag{11}$$

where $V(z)$ takes the form of $V(z)=\dfrac{B'^2}{4}-\dfrac{B''}{2}+\mathrm{e}^{2A(z)}m_5^2$, with $B=(d_0+k'c_0)\ln z$. It is found that for any D_p-D_q system, $V(z)$ takes the general form of

$$V(z)=\frac{1}{z^2}\left(\frac{(d_0+k'c_0)^2}{4}+\frac{d_0+k'c_0}{2}+m_5^2\right). \tag{12}$$

In Table 3, we show the meson and glueball spectra by taking the boundary conditions as DN type, $\psi_n|_{z=0}=0$, $\partial_z\psi_n|_{z=z_m}=0$, i.e. the Dirichlet type at UV and Neumann type at IR. It is found that in the D_3-D_q system, the predicted $\bar{q}q$ scalar meson is below 1 GeV, 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 D_6-D_4 system and too heavy in the D_6-D_6 system, and both cases are far away from experimental/lattice results. The meson and glueball spectra in D_4-D_q brane systems are more reasonable comparing with the experimental/lattice results. Especially the spectra of scalar meson and scalar glueball in the D_4-D_6 and D_4-D_8 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.

In Table 4, we show the meson and glueball spectra by taking the boundary conditions as DD type, $\psi_n|_{z=0}=0$, $\psi_n|_{z=z_m}=0$, 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. [17]. Using DD type boundary conditions, the predicted meson and glueball spectra in D_4-D_8 system are still close to the experimental/lattice results, but the error is bigger. We thus conclude that the DN type boundary conditions are more appropriate for QCD hadron spectra.

Table 3. 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.

	Exp/Lat	D_3-D_q	D_4-D_4	D_4-D_6	D_4-D_8	D_6-D_4	D_6-D_6
z_m^M		3.852	2.04	3.852	5.268	3.85281	1.453
m_ρ	0.77	0.77*	0.77*	0.77*	0.77*	0.77*	0.77*
m_{f_0}	1.37–1.5	0.893	1.417	1.584	1.565	0.548	2.496
m_{G_0}	1.5–1.7	1.201	1.956	1.722	1.633	0.408	2.858
m_{G_2}	∼2.4	1.920	3.255	2.255	1.936	1.442	4.260
m_{G_3}	∼3.69	2.356	4.240	3.021	2.684	1.344	6.131

Table 4. Results of the meson/glueball spectra in the hard-wall D_p-D_q system with DD boudary condition. The unit for mass is in GeV.

	Exp/Lat	D_3-D_q	D_4-D_4	D_4-D_6	D_4-D_8	D_6-D_4	D_6-D_6
z_m^ρ		4.97624	4.07999	4.97624	5.8356	4.976	4.07999
m_ρ	0.77	0.77*	0.77*	0.77*	0.77*	0.77*	0.77*
m_{f_0}	$1.37-1.5$	0.77	0.939	1.292	1.441	0.795	1.744
m_{G_0}	$1.5-1.7$	1.032	1.259	1.404	1.503	0.631	1.860
m_{G_2}	~ 2.4	1.637	1.997	1.837	1.782	1.532	2.338
m_{G_3}	~ 3.69	1.937	2.441	2.400	2.444	1.739	3.726

4 Summary

We have investigated the light meson and glueball spectra in the D_p-D_q hard-wall models, with the IR cut-off fixed by the mass of vector meson mass ρ. 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 1500–1700 as references.

We find that the AdS_5 hard-wall model, i.e. our D_3-D_q hard-wall model is not the favored candidate of the holographic QCD model, because the predicted meson spectra and glueball spectra in this model do not agree well with the experimental/lattice results. The most favored candidates for the realistic holographic QCD model are the D_4-D_6 or D_4-D_8 hard-wall models. In these two models, the predicted meson and glueball spectra are close to the experimental and lattice results. This picture is consistent with the curvature analysis in Sec. 2. For D_3 background branes, the curvature is a constant, its dual gauge theory is a conformal field theory, which is not QCD-like. The curvature for D_4 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 D_6-D_4 system. However, as we pointed out in Sec. 2, the curvature for D_6 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 D_6-D_q system can be safely excluded for the candidates of the holographic QCD model.

These results agree with the main findings in the D_p-D_q soft-wall models [17], where we find that D_p 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 the experimental results in order to determine which D_p-D_q system is more favored as the candidate of the realistic holographic QCD model.

At the end, we want to emphasize that in this work, the mixing between the scalar $\bar{q}q$ meson and scalar glueball has been ignored. We leave this for a future project. We also 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 D_p-D_q systems. We need further studies in this direction.

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