GAUGE/GRAVITY DUALITY, HOLOGRAPHY and MESONS

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We give a brief review of a new scheme to compute strong coupling and large N limit of QCD. which is called "holographic QCD." This is an application of so-called "gauge/gravity duality (AdS/CFT correspondence)" which has been found in string theory. After the review, we give our predictions on identification of the lightest scalar glueball in hadronic spectrum, based on our computations in the holographic QCD.

1 A prediction from string theory

Some of the readers may be surprised if we announce the following prediction *from string theory*: The decay $f_0(1500) \rightarrow 4\pi^0$ is highly suppressed. This conjecture is based on a concrete computation in string theory.

String theory, which is known as a candidate for theory of everything, is quite fertile and now it is at a stage where one can actually apply the string theory to various hard problems in field theories. One of the obvious last-standing problems is low-energy QCD. Because of its strong coupling nature, no analytic approach which is effective for analyzing the low-energy QCD has been found, except for renowned chiral perturbation. String theory provides us with a quite effective and new way to attack the problem of the low energy QCD. This is called "holographic QCD." Some of the holographic models are strong enough not only to reproduce results in the chiral perturbation theory but also explicitly to give coefficients of the chiral lagrangians.

The gauge/gravity correspondence, which we will review in the next section briefly, is a correspondence (equivalence) between 4 dimensional gauge theory (such as QCD) and a higher dimensional classical gravity on a curved background. The gauge theory side should be at large N limit and also with a large 'tHooft coupling limit. This equivalence is still a conjecture, but there are numerous supporting evidence for the most popular case of maximally supersymmetric Yang-Mills theory at the gauge theory side. So one can naively expect that even when the supersymmetries are broken, this equivalence would hold. When this is applied to QCD, one can use a "gravity-dual" to analyze the QCD — this is called "holographic QCD," actually classical gravity theory is equivalent to low energy QCD with strong coupling, at large N. In particular, hadronic spectra and interactions can be computed in classical gravity theory (string theory) in this way.

We apply this holographic QCD to a specific problem in QCD: identification of glueballs in hadronic spectra. The glueballs are just gauge-invariant composite operators purely made of gluon fields in QCD. It is expected that confinement of the gluonic degrees of freedom will generate a massgap in bosonic Yang-Mills theory, and the massive states are called glueball states. They should exist somewhere in the hadronic data, but so far its identification has not been successful.

The reason for that is: First, lattice study predicts that the lightest scalar glueball should have mass around 1700 MeV. Unfortunately, there are several candidates around that mass scale: $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. These three have very different decay branches, so in order to distinguish these states one needs to compute the branching ratios theoretically in QCD. Unfortunately, lattice calculations are not strong enough to compute the branching ratios precisely.

Secondly, one may hope to ask a help to chiral perturbation theory; unfortunately, the mass scale of our concern with the scalar glueball state is too high for the chiral perturbation theory to be applied. The chiral perturbation theory is used in derivative expansion, so basically if the energy of interest is higher than the pion decay constant, it is not trustable.

Thirdly, it is possible that the scalar glueball state is mixed with other states such as scalar mesons with the same charges (which are flavor-blind). Therefore, to clarify the question of the identification of the glueball state, this mixing is required to be computed on theoretical ground. So far, lattice calculation is again not enough to fix this problem.

For these reasons, we find that string theory — holographic QCD — is the best (at present) to give a trustable computation for identifying the lightest scalar glueball in these three hadronic states. Our conclusion, based on the publication [1] which was done in collaboration with Chung-I Tan and Seiji Terashima, is that the state $f_0(1500)$ is most likely to be the lightest scalar glueball, and furthermore, we can give a prediction that its decay to $4\pi^0$ is suppressed, according to our computation in the gravity-dual theory.

In the following, we give a brief review of the holographic QCD in string theory, and then will present our result on the identification of the glueball and also the computation of the branching ratios of the glueball.

2 Holographic QCD in nutshell

The gauge/gravity correspondence came from two ways to look at D-branes in string theory. The D-branes are objects on which open strings can end, and from this simple fact they can be regarded as sources for closed strings. D-branes can take various worldvolume dimensions. From oscillating fluctuations of the open string give rise to gauge field which can propagate on the D-branes, while those of the closed string give rise to a graviton propagating in the bulk 10 dimensional spacetime. So, D-branes are sources for gravity, and thus they are identified as blackholes. On the other hand, they are at the same time described by gauge theories which are typically Yang-Mills theories. This is the gauge/gravity correspondence, first stated by J.Maldacena [2].

Precise statement between physical observables on both sides is as follows: correlators of gauge invariant composite operators in the gauge theory can be computed by fluctuation analysis of the gravitational theory in the curved background [3]. This curved background is nothing but the blackhole mentioned earlier. One needs to take a near horizon geometry of the blackhole since one is looking at physics near the source D-brane.

By putting another D-brane which intersects with the original D-branes, one can introduce quarks to the gauge theory. On the intersection, strings connecting different D-branes can exist, and with a suitable choice of the D-branes and their dimensions, those strings can fluctuate to give chiral fermions in dour dimensional spacetime. Furthermore, one can break supersymmetries in superstring theory in such a way that only the gluonic degrees of freedom remain at low energy while gluinos get heavy. This is a realization of QCD in terms of string theory: this is called brane-engineering.

Now QCD is constructed by a set of D-branes, then let us apply the gauge/gravity duality to this system. One replaces the gluonic D-branes by their blackhole geometry. The additional D-branes which were introduced to get the chiral quarks are just living there as they are. These "flavor D-branes" are treated as probes (meaning that they are assumed not to modify the background geometry, as the number of the flavors (= number of the flavor D=branes) kept to be much smaller than the number of the color (=number of the gluonic D-branes), $N_f \ll N_c$). In order for the gravity theory to be weakly coupled and can be analyzed classically, one need to take a large N_c limit and $N_c \to \infty$ and also a large 'tHooft coupling limit $\lambda = g_{\rm YM}^2 N_c \to \infty$ limit.

In the gravity side of the duality, there are two fluctuation excitations: one is a fluctuation of supergravity fields such as the graviton and dilaton, and another is a fluctuation of gauge fields living on the flavor D-branes. Now the shape of the flavor D-brane is curved, so the gauge fluctuation is a Yang-Mills theory on a curved background. The fluctuation eigenmodes of the supergravity fields correspond to glueball states in Yang-Mills theory, and the eigenmodes of the curved Yang-Mills theory are identified as meson fields in QCD.

One of the most popular model of the holographic QCD is Sakai-Sugimoto model[4] in which N_c D4-branes are used for the gluonic D-branes and N_f D8-branes and N_f anti-D8-branes are for the flavor D-branes. Computation of the Yang-Mills spectra on the D8-branes give the meson spectra, and in fact the low energy effective theory on the D8-branes in the curved background reproduces a standard chiral lagrangian, but now with definite explicit coefficients which cannot be computed in the chiral perturbation theory.

Our target is the glueball decay. So we focus on the interaction between the glueball and the mesons, that is translated to the language of the gravity side as interaction between the supergravity fields and the gauge fields on the curved D8-branes. We compute the interaction lagrangian explicitly, and compute the decay width for each decay mode of the lightest scalar glueball state, in the dual gravity theory. The interaction lagrangian is basically the low energy effective theory of the D8-branes. D8-brane Yang-Mills fields can couple to the background supergravity fluctuation, and this coupling is identified as the glueball-meson coupling which we want for the issue of the identification of the glueball in the hadronic spectrum.

3 Our results

Here we do not present our complicated lagrangian for the glueball/meson interaction. Readers who are interested in its explicit form are advised to look at our published paper[1].

We present our final results for the decay widths and the decay branching ratios. Our results are summarized in the following table, with data in Particle Data Group for the $f_0(1500)$ excitation to be compared. In the experimental data (taken from Particle Data Group publication), the decay to 4π branching ($4\pi^0$ or $2\pi^+ + 2\pi^-$) is not specified, but the total width for the decay to 4π is given as 0.035.

The experimental data for the decay of $f_0(1370)$ includes 2γ, while that for $f_0(1710)$ has too much decay to K mesons, thus we can identify the $f_0(1500)$ to be the lightest scalar glueball. Since at the leading order the $4\pi^0$ decay is not possible in our results, we can give a prediction:

Branch	Our results	Experiments
2π	0.040	0.025
$2\pi^+ 2\pi^-$	0.059	
$4\pi^0$	suppressed	
2γ	suppressed	not seen

Table 1: Our results for the decay width $\Gamma/M_{\rm glueball}$ of the lightest scalar glueball, and experimental data in Particle Data Group

$f_0(1500) \to 4\pi^0$ decay is highly suppressed. This is a prediction from string theory, based on concrete computation at low energy QCD. Note that the holographic QCD is valid only for large N_c expansion and the large 'tHooft coupling expansion, thus the result obtained above is at the leading order of these expansions. Since the real QCD is with $N_c = 3$, there may be large corrections.

Furthermore, our analysis shows that there is no mixing between the meson states and the lightest scalar glueball, at the leading order. So it is meaningful to discuss the identification of the glueball state.

It is very important that new string theory technique, the holographic QCD, can give at least qualitative results for low energy QCD directly related to hadronic data in experiments. This is regarded not only as a new and powerful tool for low energy QCD and hadron physics but also a new way to check theoretical correctness of string theory via direct comparison with experimental data. Without doubt we can say that this new holographic QCD will be one of the major subjects for analyzing hadronic QCD.

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