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Glueball Decay in the Witten-Sakai-Sugimoto model and Finite Quark Masses

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We discuss recent results on the calculation of glueball decay rates in the Witten-Sakai-Sugimoto model, which favor the $f_0(1710)$ meson as a glueball candidate. The flavor asymmetric decay of $f_0(1710)$ is frequently attributed to a putative chiral suppression in glueball decays, which is however questionable in view of the large constituent quark masses induced by chiral symmetry breaking. We find that this can be explained by what we call nonchiral enhancement when finite quark masses are included in the holographic model, with good quantitative agreement with experimental data for $f_0(1710)$. Assuming the latter to indeed be a nearly pure glueball, the model makes essentially parameter-free and thus falsifiable predictions for its decay rates involving vector mesons and an upper limit on the $\eta\eta'$ decay rate.

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1. Introduction

The existence of glueballs, color-neutral bound states of gluons, is a particularly intriguing prediction of quantum chromodynamics (QCD) dating back to the early 1970's [1, 2, 3]. Lattice QCD [4] predicts the lightest glueball to be a scalar with mass in the range 1.5-1.8 GeV, but does not pin down sufficiently its potential mixing with scalar quark-antiquark states and its decay pattern. There exist a large number of phenomenological studies which model the three isoscalar mesons $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$ as being made up from mixtures of $u\bar{u}+d\bar{d}$, $s\bar{s}$, and a scalar glueball, alternatingly locating the glueball predominantly in $f_0(1500)$ or $f_0(1710)$ [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Models which identify $f_0(1500)$ as dominated by the glueball component typically have rather large mixing with $q\bar{q}$ states, while several of the models which favor $f_0(1710)$ as a glueball do so with comparatively little admixture of $q\bar{q}$.

The fact that $f_0(1710)$ decays preferentially into kaons and η mesons and less into pions, which goes contrary to the expectation of a flavor-blindness of glueball decays, has been attributed to a mechanism termed "chiral suppression" [18, 19, 20] according to which the decay amplitudes of a scalar glueball should be proportional to quark masses. At least the perturbative arguments in its favor appear questionable [17] in view of the large constituent quark masses brought about by chiral symmetry breaking.

In this paper we shall review our recent work on scalar glueball decay using the top-down holographic Witten-Sakai-Sugimoto model [21], which is flavor-symmetric, and its extension to finite quark masses which break SU(3)$_f$ [22, 23], where we have shown the possibility of what we called nonchiral enhancement in scalar glueball decay. The observed flavor asymmetries of the decays of $f_0(1710)$ into two pseudoscalars turn out to be reproduced well in coincidence with a very small branching ratio $G \to \eta\eta'$.

2. The Witten-Sakai-Sugimoto model and meson decay rates

The best studied string-theoretic realization of gauge/gravity duality relates ten-dimensional type IIB supergravity on $AdS_5 \times S^5$ to strongly coupled four-dimensional maximally supersymmetric Yang-Mills theory in the large-N_c limit. This has been widely used to study strongly coupled nonabelian gauge theories in the deconfined phase, where supersymmetry is broken by nonzero temperature. Due to its high amount of symmetries, this correspondence is however not suited to study low-energy QCD. Already in 1998 Witten [24] introduced a nonconformal version of the correspondence based on type IIA supergravity and five-dimensional super-Yang-Mills theory, compactified to give nonsupersymmetric four-dimensional Yang-Mills theory below a certain compatification scale $M_{\rm KK}$.

A D-brane construction which introduces $N_f \ll N_c$ chiral quarks was found by Sakai and Sugimoto [25, 26] and shown to reproduce various features of low-energy QCD. In particular, chiral symmetry breaking $\mathrm{U}(N_f)_L \times \mathrm{U}(N_f)_R \to \mathrm{U}(N_f)_V$ is realized purely geometrically, and an effective field theory involving the associated Nambu-Goldstone bosons, vector and axial vector mesons can be derived with all couplings fixed by just two parameters, the mass scale $M_{\rm KK}$ and the 't Hooft coupling λ at this scale. It also includes the correct Wess-Zumino-Witten term and a well-defined Witten-Veneziano mass term for the η'.

As reviewed in [27], this model works also remarkably well quantitatively. Fixing M_{KK} by the ρ meson mass and varying $\lambda = 16.63 \ldots 12.55$ such that either the pion decay constant or the string tension in large-N_c lattice simulations is matched, the decay rate of the ρ and the ω meson into pions is predicted to lie in the range [21]

$$\Gamma(\rho \to 2\pi)/m_\rho = 0.1535 \ldots 0.2034, \quad \Gamma(\omega \to 3\pi)/m_\omega = 0.0033 \ldots 0.0102, \tag{2.1}$$

which nicely include the experimental values, 0.191(1) and 0.0097(1), respectively.

One may therefore entertain the hope that the Witten-Sakai-Sugimoto model could also make useful predictions for the decay rates of glueballs. In fact, the spectrum of glueballs has been one of the first applications of the Witten model [28, 29, 30], and a first attempt to calculate the decay rate of the lightest glueball was made in [31]. However, the mass of the lowest-lying glueball comes out at only 855 MeV. In [21] we have revisited these calculations and argued that the lowest mode, which comes from a graviton mode with an "exotic" polarization along the compactification direction, should be discarded and instead the next-highest, predominantly dilatonic mode should be identified with the lowest-lying glueball of QCD. This turns out to have a mass closer to that expected from lattice QCD, to wit 1487 MeV, and also a significantly narrower width than the exotic mode.

Calculating the decay pattern of the holographic glueball with a mass that would fit to the $f_0(1500)$ meson however does not match the observed decays of the latter [32], which decays mostly into four pions (49.5%) and two pions (34.9%), with kaons and eta mesons suppressed significantly. The holographic result for four-pion decays is about an order of magnitude too small, the result for decay into two (massless) pseudoscalars less than 50% of the experimental value for two-pion decay, but more than twice as large as the actual decay into kaons.

However, the holographic result for the glueball mass is only 16% below the mass of the other glueball candidate, $f_0(1710)$. It thus seems reasonable to compare the results for the dimensionless quantities Γ/M with the experimental data for $f_0(1710)$. Now the holographic result [21]

$$\Gamma(G \to \pi\pi)/M = 0.009 \ldots 0.012 \quad \text{(vanishing quark masses)} \tag{2.2}$$

appears to much more compatible with experiment, while the larger rates into kaons and eta mesons would have to be attributed somehow to the nonnegligible strange quark mass.

3. Finite quark mass deformation of the Witten-Sakai-Sugimoto model

In the literature [33, 34, 35, 36, 37, 38], two ways of introducing finite quark masses in the Witten-Sakai-Sugimoto model have been discussed: either by world sheet instantons arising from additional D4 or D6 branes added to the geometry, or by taking into account a nonnormalizable mode in a bifundamental scalar corresponding to the open-string tachyon between D and anti-D branes. It was also suggested that the two approaches were actually two ways of viewing one and the same mechanism. While both approaches correctly reproduce the GOR relations, unfortunately neither has been developed to the point of fixing the interactions of glueball modes with the mass term, which has the following nonlocal form

$$\int d^4x \int_{u_{KK}}^{\infty} du\, h(u) \mathrm{Tr}\left(\mathscr{T}(u) \mathrm{P} e^{-i\int dz A_z(z,x)} + h.c.\right) = \int d^4x \mathrm{Tr}\left(U(x) \int_{u_{KK}}^{\infty} du\, h(u) \mathscr{T}(u) + h.c.\right). \tag{3.1}$$

	exp.[32]	WSS massive [22]
$\frac{4}{3}\cdot\Gamma(\pi\pi)/\Gamma(K\bar{K})$	$0.55^{+0.15}_{-0.23}$	0.463
$4\cdot\Gamma(\eta\eta)/\Gamma(K\bar{K})$	1.92±0.60	1.12

Table 1: Comparison between the flavor asymmetries observed in the decay rates of the glueball candidate $f_0(1710)$ and the prediction of the massive Witten-Sakai-Sugimoto model for a pure glueball of that mass.

Here u and z parametrize the holographic direction and are related by $(u/u_{\rm KK})^3 = 1+z^2$, with $u_{\rm KK}$ denoting the lower end of the cigar-shaped geometry. $\mathscr{T}(u)$ is a bifundamental field implementing the quark mass matrix according to

$$\int_{u_{KK}}^{\infty} du\, h(u)\mathscr{T}(u) \propto \mathscr{M} \equiv \mathrm{diag}(m_u, m_d, m_s) \tag{3.2}$$

and $h(u)$ contains metric and dilaton degrees of freedom, whose fluctuations contain the glueball modes.

A very similar nonlocal mass term arises already in the massless Witten-Sakai-Sugimoto model from the U(1)$_A$ anomaly, which can be calculated precisely [25]. The U(1)$_A$ anomaly requires the combination of a bulk Ramond-Ramond 2-form field and the boundary η_0 field,

$$\eta_0(x) = \frac{f_\pi}{\sqrt{2N_f}}\int dz\,\mathrm{Tr}A_z(z,x), \tag{3.3}$$

in the action

$$S \propto \int d^{10}x\,\sqrt{-g}|\tilde{F}_2|^2, \tag{3.4}$$

with

$$\tilde{F}_2 \propto \left(\theta + \frac{\sqrt{2N_f}}{f_\pi}\eta_0\right) du\wedge dx^4, \tag{3.5}$$

where θ is the QCD theta angle, x^4 the compactified coordinate of the cigar geometry, and f_π the pion decay constant. Integration over the bulk gives the four-dimensional effective action

$$S^{\rm eff.}_{\eta_0} = -\frac{1}{2}\int d^4x\, m_0^2\,\eta_0^2\,(1-3d_0G_D)+\ldots \tag{3.6}$$

where G_D is the scalar glueball mode,

$$d_0 \approx \frac{17.915}{\lambda^{1/2}N_c M_{\rm KK}}, \tag{3.7}$$

and

$$m_0^2 = \frac{N_f}{27\pi^2 N_c}\lambda^2 M_{\rm KK}^2 \tag{3.8}$$

the Witten-Veneziano mass. For $N_f = N_c = 3$, $M_{\rm KK} = 949$ MeV, and λ varied from 16.63 to 12.55 one finds $m_0 = 967\ldots730$ MeV.

Diagonalizing the mass terms for the entire nonet of pseudoscalar bosons in U gives, with $\mathscr{M} = \mathrm{diag}(\hat{m},\hat{m},m_s)$ fixed such that $m_\pi = 140$ MeV and $m_K = 497$ MeV:

$$m_\eta = 518\ldots476\text{ MeV},\quad m_{\eta'} = 1077\ldots894\text{ MeV}, \tag{3.9}$$

$$\theta_P = -14.4^\circ\ldots-24.2^\circ, \tag{3.10}$$

with θ_P the octet-singlet mixing angle. We thus find that the above holographic result for m_0 is in the right ballpark to approximate the pseudoscalars of the real world, in fact covering most of the values of θ_P that are being discussed in the phenomenological literature [39, 40, 41]. The central value of the above range of masses and the mixing angle happens to be very close to an optimal least-square choice of m_η and $m_{\eta'}$, with the interesting prediction $\theta_P \approx -19^\circ$ that is consistent with a determination from $\Gamma(\eta' \to 2\gamma)/\Gamma(\eta \to 2\gamma)$, which leads to [32] $\theta_P = (-18 \pm 2)^\circ$.

4. Nonchiral enhancement and $\eta\eta'$ decay rate

If we assume that the couplings of the glueball field to the mass terms of the pseudoscalar fields are universal, i.e. that they involve all the factor $(1-3d_0 G_D)$ obtained in (3.6), the glueball interactions do not mix η and η'. (In [22] we have made this case plausible by a simplistic calculation that gave a coupling which differed by a mere 4% from d_0.) In this most symmetric case, the chiral result for the decay rate $G \to PP$ for a given pseudoscalar of mass m_P turns out to be simply multiplied by the factor

$$\left(1-4\frac{m_P^2}{M^2}\right)^{1/2}\left(1+\alpha\frac{m_P^2}{M^2}\right)^2 \quad \text{with} \;\; \alpha = 4(3d_0/d_1 - 1) \approx 8.480, \tag{4.1}$$

where d_1 is the glueball coupling constant appearing in the chiral $G_D\pi\pi$ term [21]. Notice that this (leading-order) result is in fact independent of the two parameters λ and M_{KK} of the model.

Inserting physical values for m_K and m_η and setting M to the mass of the glueball candidate $f_0(1710)$ turns out to reproduce the experimental ratio $\Gamma(\pi\pi)/\Gamma(K\bar{K})$ within the experimental error bar, and the $\Gamma(\eta\eta)/\Gamma(K\bar{K})$ within 1.33 standard deviations (Table 1). This shows that the Witten-Sakai-Sugimoto model with finite quark masses naturally leads to an enhancement of decays into the heavier pseudoscalars that would be fully compatible with the interpretation of $f_0(1710)$ as a nearly unmixed glueball. We prefer to call the mechanism at work here as a "nonchiral enhancement" because the chiral limit worked out in [21] does not lead to a particular suppression of glueball decay into two Nambu-Goldstone bosons. Glueballs rather receive an additional coupling from the mass term induced by finite quark masses.

Since we have not been able to derive this coupling within a string-theoretic top-down construction but just assumed a particularly symmetric case, one should in fact also consider the consequences of a significantly different coupling $d_m \neq d_0$ in the GOR mass terms compared to the Witten-Veneziano mass term. This most general case leads to a nonzero decay rate $G \to \eta\eta'$ and modified nonchiral enhancements [23], such that the still to be determined $\eta\eta'$ decay is restricted by any bounds on the latter and vice versa. As shown in Fig. 1, the current upper limit from WA102 [42], $\Gamma(\eta\eta')/\Gamma(\pi\pi) < 0.18$ (red band in Fig. 1) is related to a range of $\Gamma(\pi\pi)/\Gamma(KK)$ that is significantly larger than the current experimental error reported in [32]. Under the assumption that the $f_0(1710)$ is a pure glueball, or very close to a pure glueball, and that the current data on $\Gamma(\pi\pi)/\Gamma(KK)$ hold up, the Witten-Sakai-Sugimoto model makes the prediction that $\Gamma(\eta\eta')/\Gamma(\pi\pi) \lesssim 0.04$, i.e. much smaller than the current upper bound. (Interestingly enough, the recent phenomenological study in [17] predicts $\eta\eta'$ rates for $f_0(1710)$ that are several times higher than the upper limit reported by WA102. Hopefully new data, e.g. from BESIII, will pin down this decay channel.)

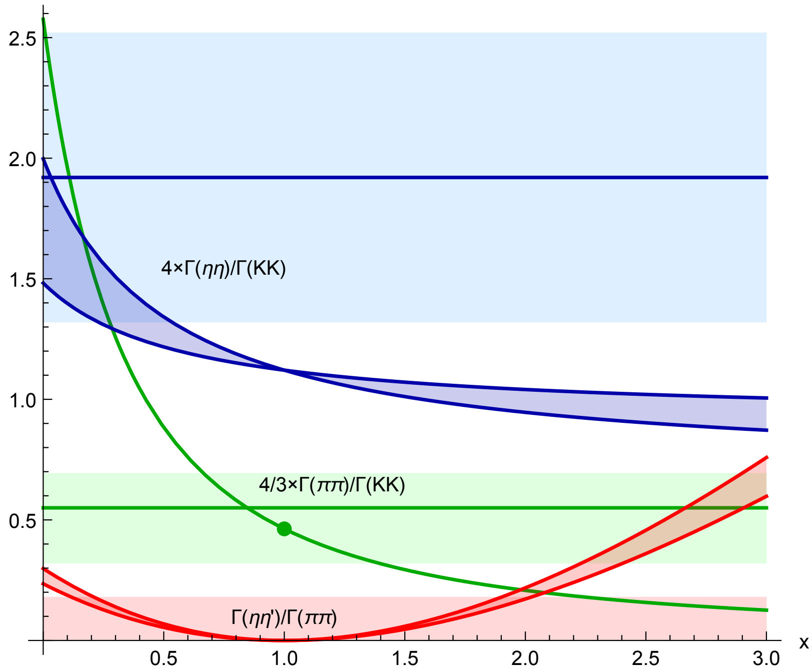

Figure 1: Results [23] of the massive Witten-Sakai-Sugimoto model on flavor asymmetries in the decay of a glueball of mass equal to that of $f_0(1710)$ into pairs of pseudoscalar mesons as a function of $x = d_m/d_0$ and with λ varied from 12.55 to 16.63. The case $x = 1$ studied in [22] and shown in Table 1 is marked by a dot. The light-green and light-blue bands give the current experimental results for $f_0(1710)$ reported in [32], the light-red band corresponds to the upper limit on the $\eta\eta'$ decay rate of WA102 [42].

Another prediction of the Witten-Sakai-Sugimoto model, which in fact does not change substantially when finite quark masses are introduced, is that a pure glueball with a mass of 1.7 GeV should have a substantial branching ratio into four pions [21]: $\Gamma(G \to 4\pi)/\Gamma(G \to 2\pi) \approx 2.5$, and also into two ω mesons: $\Gamma(G \to 2\omega)/\Gamma(G \to 2\pi) \approx 1.1$. While the latter process has been seen [32], the former will hopefully be measured in the near future, e.g. by CMS/TOTEM.

To conclude, the Witten-Sakai-Sugimoto model allows one to study flavor asymmetries in glueball decays, with quantitative results on decay rates that are remarkably close to experimental data on the glueball candidate $f_0(1710)$, and it does make a number of falsifiable predictions on still to be measured decays, if the scalar meson $f_0(1710)$ is indeed a nearly unmixed glueball.

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