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Exotic hadron holography from anomalous dimensions

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The anomalous dimensions of hadronic interpolators contain dynamical information on the properties of the associated hadron states. We point out that they provide, in particular, a link by which gauge-invariant information on exotic contributions to hadronic wavefunctionals can be obtained from approximate gravity duals for QCD. This is demonstrated by the holographic description of a dominant tetraquark component in the lightest scalar mesons.

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While the anomalous dimensions of color-singlet operators play a central role in the original, conformal versions of the gauge/string correspondence [1], they have only recently begun to enter holographic approaches to QCD. In particular, anomalous dimensions of hadronic interpolators were implemented to provide an AdS/QCD [2] description of quark correlations inside hadrons [3, 4] which can have a significant and in exotic cases even striking impact on the hadron properties. Although multiquark components in hadronic wave functionals are typically gauge dependent, a holographic description is still possible because the five-dimensional bulk modes are dual to the interpolators of the corresponding hadrons. Hence the anomalous dimensions of these interpolators import gauge-invariant information on their quark content and couplings, and thus on the multiquark correlations in the corresponding hadron, as bulk-mode mass corrections into the gravity dual.

This AdS/QCD representation of multiquark effects was originally introduced to describe diquark correlations in baryons [3]. It changes the resulting light-quark baryon excitation spectrum into

$$M_{n,L}^2 = 4\lambda^2\left(n+L+\frac{3}{2}\right) - 2\left(M_\Delta^2 - M_N^2\right)\kappa \tag{1}$$

(where λ is the IR scale of the "metric soft-wall" gravity dual [5] while n (L) denotes the radial (angular momentum) excitation level). The second term, proportional to the baryon's "good-diquark fraction" κ, is generated by suitable anomalous dimensions for the QCD nucleon interpolators. Equation (1) describes the linear square-mass trajectories of the over 40 measured nucleon and delta (with $\kappa = 0$) resonances with unprecendented accuracy. The dual mode solutions further reveal that baryons with larger κ have a smaller size.

Encouraged by these results, the anomalous-dimension-induced representation of multiquark correlations was then applied to the more challenging holographic description of exotic hadrons with a non-standard (valence) quark content. The light scalar meson sector [6] with its expected tetraquark component [7] was examined in Ref. [4]. The radial bulk equation for the modes dual to the scalars can be written as the Sturm-Liouville problem $\left[-\partial_z^2 + V(z)\right]\phi(q,z) = q^2\phi(q,z)$. In the dilaton soft-wall gravity dual [8] without anomalous-dimension contributions, the potential V has the form

$$V(z) = \left(\frac{15}{4} + m_5^2 R^2\right)\frac{1}{z^2} + \lambda^2\left(\lambda^2 z^2 + 2\right). \tag{2}$$

The anomalous dimension $\gamma(z)$ of the tetraquark interpolator $J_{\bar{q}^2 q^2}$ (i.e. the local four-quark operator which most strongly couples to the tetraquark state) with scaling dimension $\Delta_{\bar{q}^2 q^2} = 6 + \gamma(z)$ adds the universal contribution

$$\Delta V(z) = \gamma(z)\left[\gamma(z) + 8\right]\frac{1}{z^2} \tag{3}$$

to the potential (2) with $m_5^2 R^2 = 12$. Eq. (3) implies the crucial lower bound $\Delta V(z) \geq -16/z^2$ which holds for any γ and prevents the collapse of the dual modes into the AdS_5 boundary. This bound is saturated by $\gamma \equiv -4$ and therefore determines the lightest tetraquark mass

$$M_{\bar{q}^2 q^2, 0} \geq M_{\Delta=2,0} = 2\lambda \tag{4}$$

which the anomalous-dimension-induced holographic binding mechanism can produce. Moreover, for constant values $-4 < \gamma < -3$ the tetraquark ground state is lighter than its $\bar{q}q$ counterpart. Since

γ only enters through the mass term of the bulk mode which is model-independently prescribed by the AdS/CFT dictionary, the correction (3) and the associated binding mechanism will arise in other AdS/QCD duals as well.

To estimate the quantitative impact of the anomalous-dimension contribution ΔV (until direct QCD information on the RG flow of γ will eventually become available and fix ΔV uniquely), a typical power ansatz $\gamma(z) = -az^{\eta} + bz^{\kappa}$ can be adopted. Its coefficients turn out to be tightly constrained by consistency and stability requirements but can still produce almost maximal ground-state binding [4]. The latter drives the mass $M_{\bar{q}^2q^2,0}$ of the lightest tetraquark from $\sim 40\%$ above (for $\gamma \equiv 0$) down to $\sim 20\%$ below the $\bar{q}q$ ground-state mass $M_{q\bar{q},0} = \sqrt{6}\lambda$. The resulting masses $M_{\bar{q}^2q^2,n}$ of the tetraquark excitations get pushed beyond the corresponding $M_{\bar{q}q,n}$ from around $n \gtrsim 2$. The higher-lying radial tetraquark excitations will therefore likely be broad enough to prevent the appearance of supernumeral states in the scalar meson spectrum.

It should be interesting to extend the anomalous-dimension-based holographic description of non-valence quark components to other exotics, including heavy tetraquarks, pentaquarks and hybrids. Moreover, anomalous-dimension-induced corrections also encode other aspects of hadronic structure which largely remain to be explored.

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