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A holographic approach to heavy non $q\bar{q}$-states using configurational entropy

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Abstract. This work uses the connection between hadronic stability and configurational entropy to explore hadronic structures written in terms of non-quadratic dilaton $(\kappa z)^{2-\alpha}$. These hadronic structures are described using the relation between the parameters κ and α with the constituent mass. We test Z_c, Z_b, and ψ as non-$q\bar{q}$ states defined as hybrid meson, hadroquarkonium, hadronic molecule, or diquark-antidiquark pair. We find that, holographically speaking, Z_c and Z_B are better described as a hybrid meson and ψ as hadrocharmonium.

1 Introduction

One of the most famous and successful bottom-up models is the so-called *softwall* (SWM) [1]. In this model, confinement is induced by slightly breaking the AdS conformal symmetry by adding a dilaton field $\Phi(z) = (\kappa z)^2$ that sets the masses of hadrons living at the boundary. This set of masses is organized in linear Regge trajectories. However, the quadratic nature of the SWM dilaton is tied up to the constituent mass inside hadrons. We will use this idea to describe non-$q\bar{q}$ states based on the constituents and their structures inside hadrons.

Non-$q\bar{q}$ states or exotic hadrons are all the hadronic states with quantum numbers not allowed by the usual constituent quark model. They have been observed in hadronic facilities since the early 2000s. However, much discussion remains about their inner structure and constituent (or cluster) interaction. On the holographic description, we have works written in the context of dilaton-based models [2–4].

2 Hadrons in AdS/QCD

In AdS/CFT correspondence, hadrons are non-perturbative boundary operators dual to bulk fields. For a given hadronic boundary operator defined as $O = f(q, \bar{q}, G_{\mu\nu}, D_\mu)$, the scaling dimension $\dim O = \Delta + L + \gamma$ establishes the hadronic identity in the bulk AdS through the bulk mass M_5 [5], where Δ is the energy dimension of the pure constituent operator, L is the angular momentum and γ is an anomalous dimension. This relation is a consequence of the so-called field/operator duality, which tells you how the bulk fields match the boundary information [6]. For massive bulk p-forms in AdS$_5$ written as $A_p(z,q) = A_p(q)\,\psi(z,q)$, this duality ensures that $\psi(z,q)|_{z\to 0} = C\,z^{\Delta-p}$.

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Notice that in the most general case for the bulk mass, we have $M_5 = M_5(\Delta, L, \gamma)$. This fact implies that *a hadron in holographic models is a bag of constituents characterized by the bulk mass* M_5. However, this picture has no information about the inner hadronic structure.

Along with this definition, there is the emergence of confinement in these models. In pure AdS space, bulk modes are not normalizable because of field/operator duality: localized normalizable states at the boundary become diffuse (non-localized) and non-normalizable. However, we can avoid this problem by introducing energy scales that fix hadronic masses. One of the possible scenarios to do this is the so-called *bottom-up perspective.*

3 Bottom-up approach in the static dilaton context

The emergence of bounded states of hadrons is a consequence of color confinement. This observation is realized when we break the conformal symmetry slightly in the bulk by introducing an energy scale that will fix the hadron mass [1, 7]. This is the idea behind the so-called bottom-up models. From a wider perspective, *bottom-up holography describes boundary physics with adequate bulk fields inspired by boundary phenomenology*.

Concerning the hadronic spectrum, we will consider the *softwall model prescription*, where confinement is achieved by placing a dilaton field $\Phi(z)$ in the AdS bulk. In pure AdS, free modes are not normalizable (in the sense of the Breitenlohner-Freedman bound [8]) and non-localizable. By placing a dilaton with an energy scale, the states become normalizable, i.e., the spectrum is now bounded.

For the sake of clarity, let us focus on bulk vector fields dual to vector non-$q\bar{q}$. Keep in mind that these ideas can be extended to higher $p-$forms. For this bulk vector field, minimally coupled to a static dilaton $\Phi(z)$, we will define the following action density:

$$I_{\text{hadrons}} = -\frac{1}{2}\int d^5x\,\sqrt{-g}\,e^{-\Phi(z)}\left[\frac{1}{2\,g_5^2}F_{mn}\,F^{mn} + M_5^2\,A_m\,A^m\right], \tag{1}$$

where g_5 is a coupling constant that fixes action units. It is defined from the OPE of the large N QCD two-point function [9], and $M_5^2\,R^2 = (\Delta + L - 1)(\Delta + L - 3)$. Notice that we are considering a massive vector field since for multiquark states, the bulk mass is different from zero. Also, the presence of the bulk mass does not affect the boundary gauge invariance since we can always choose the gauge $A_z = 0$ that preserves the boundary structure [10]. This action will be living in the Poincare Patch defined as:

$$dS^2 = \frac{R^2}{z^2}\left[dz^2 + \eta_{\mu\nu}\,dx^\mu\,dx^\nu\right], \tag{2}$$

with R the AdS radius, z the holographic coordinate, and $\eta_{\mu\nu}$ the Minkowski metric with negative signature.

Once we set the framework, we perform the Fourier transformation of the bulk field A_m and split it into the boundary source and the bulk mode: $A_m(z, q) = \psi(z, q)\,A_m(q)$. Then, we impose the static gauge $A_z = 0$. These definitions allow us to write down the equations of motion for the bulk mode in the Sturm-Liouville form, whose equation is given by:

$$\partial_z\left[e^{-B(z)}\,\partial_z\,\psi(z, q)\right] + (-q^2)\,e^{-B(z)}\,\psi(z, q) - \frac{M_5^2\,R^2}{z^2}\,e^{-B(z)}\,\psi(z, q) = 0. \tag{3}$$

The function B is written regarding the warp factor and the dilaton. In the most general case, it is written as $B(z) = \Phi(z) + \beta\,\log(R/z)$, where $\beta = -(3 - 2\,p)$ represents the spin of the hadron. For vector hadrons ($p = 1$), we have $\beta = -1$. This function B is useful to define the effective holographic potential. To do so, we perform a *Bogoliubov transformation* $\psi(z, q) =$

$e^{\Phi(z)/2}\phi(z,q)$ which allows us to write the bulk equations of motion into a Schrödinger-like one for the field $\phi(z,q)$:

$$-\phi''(z,q) + V(z)\,\phi(z) = (-q^2)\,\phi(z,q), \tag{4}$$

with the following definition:

$$V(z) = \frac{B'(z)^2}{4} - \frac{B''(z)}{2} + \frac{M_5^2\,R^2}{z^2}. \tag{5}$$

If we impose the on-shell mass condition on the equations above, i.e. $-q^2 = M_n^2$, the Regge trajectories emerge as the holographic potential $V(z)$ eigenvalues. We will consider the static dilaton exposed in [11], where the authors proposed a new dilaton to address the isovector mesons spectra. This dilaton is defined as a deformation of the standard softwall model:

$$\Phi(z) = (\kappa\,z)^{2-\alpha}\,, \tag{6}$$

where κ is an energy scale that fixes the hadron masses, and α is a deformation that accounts for quark content. Both parameters are flavor-dependent. However, if we have a fit for different states ranging from light to heavy quarks, we can define a set of calibration curves. These curves allow us to infer, from phenomenological bounds, the contribution of the structure to the holographic model. For further details, see [4, 11]. The next section will apply this machinery to the non-$q\bar{q}$ states.

4 Non-$q\bar{q}$ states

The relation between bulk mass and hadronic identity is not univocally determined in this context of hadrons considered as a bag of constituents. For example, for 1-form bulk fields, dual to vector hadrons on the boundary, we observe that $\Delta = 6$ could be associated with multiquark states with four constituent quarks or hybrid structures with three constituent gluons. The very same picture emerges for other bulk fields as scalar or fermionic.

A possible form to circumvent this issue was exposed in [4, 11] in the context of non-linear Regge trajectories and models based on dilaton fields. The parameter set (κ, α) for the isovector meson family (ρ, ω, ϕ, j/ψ, Υ) establishes a running with a constituent mass *threshold* $\bar{m}$:

$$\alpha(\bar{m}) = a_\alpha - b_\alpha e^{-c_\alpha \bar{m}^2} \tag{7}$$

$$\kappa(\bar{m}) = a_\kappa - b_\kappa e^{-c_\kappa \bar{m}^2}, \tag{8}$$

where $\{a_i,\, b_i,\, c_i\}$ with $i = \kappa,\, \alpha$, are fitting constants determined from isovector meson spectrum modeling [11]. This threshold mass is understood as a *stoichiometric* relation describing what kind of constituents there are in the hadron and in what proportion they contribute to the hadron structure. For example, for a $q\bar{q}$ state, it is straightforward to infer that the mass threshold should be the arithmetic mean between the masses, that is, $\bar{m} = \frac{m_1+m_2}{2}$.

For other more general and exotic structures, we can extend the arithmetic mean idea to the general stoichiometric relation given by the following expressions:

$$\bar{m}_{eh} = \sum_{i=1}^{N} (P_i^{\text{quark}}\,\bar{m}_{q_i} + P_i^{\text{Gluon}}\,m_{G_i} + P_i^{\text{meson}}\,m_{\text{meson}_i}), \tag{9}$$

Table 1. Constituent masses (in GeV) used in the numerical fit. See [12, 13].

Const	Mass	Const	Mass	Const	Mass	Const	Mass
q_u	0.360	q_d	0.340	q_c	1.550	q_b	4.730
Gluon	0.700	J/ψ	3.097	$\rho(770)$	0.77526	Υ	9.460

along with the constraint condition:

$$\sum_{i=1}^{N}(P_i^{\text{quark}} + P_i^{\text{Gluon}} + P_i^{\text{meson}}) = 1. \tag{10}$$

In the expressions above, we model an exotic hadron, with mass m_{eh}, having a structure given by N constituents (quarks, gluons, or mesons). The contribution to the exotic structure is measured by the normalized weights $P_i^{\text{constituent}}$. Thus, the problem of describing exotic mesons in dilaton-based models is reduced to how we determine the set of weights $P_i^{\text{constituents}}$. We will consider heavy exotic states that can be described as diquark clusters, hadroquarkonium, and hadronic molecules. The constituent weights are defined by phenomenological bounds read from the exotic hadron theory [14, 15], which encloses the parameter space in the numerical fitting of exotic states. We will test these ideas with the spectrum of exotic hadrons composed of Z_c, ψ, and Z_b states.

Table 2. Calibration curves and threshold masses for exotic hadrons in the non-quadratic softwall model.

Calibration Curves for $\bar{m}$		
$\kappa(\bar{m}) = 15.2085 - 14.808\, e^{-0.0524\,\bar{m}^2}$		
$\alpha(\bar{m}) = 0.8454 - 0.8455\, e^{-0.4233\,\bar{m}^2}$		
Stoichiometric relations for exotic hadrons		
Structure	**$\bar{m}$ (GeV)**	Δ
Diquark for Z_c	$m_{4q} = m_c = 1.55$	6
Diquark for Z_b	$m_{4q} = m_b = 4.730$	6
Hadroquarkonium for ψ	$\bar{m}_{HQc} = \frac{1}{2} m_{J/\psi} + \frac{1}{4}(\bar{m}_u + \bar{m}_d) = 1.717$	6
Hadronic Molecule for ψ	$\bar{m}_{HM,\psi} = \frac{1}{3} m_{J/\psi} + \frac{2}{3} m_\rho = 1.549$	6
Hadronic Molecule for Z_c	$\bar{m}_{HM,Z_c} = 0.283\, m_{J/\psi} + 0.717\, m_\rho = 1.4323$	6
Hadronic Molecule for Z_b	$\bar{m}_{HM,Z_B} = 0.458\, m_{\Upsilon(1S)} + 0.542\, m_\rho = 4.753$	6
Hybrid meson for Z_c	$\bar{m}_{Z_c} = 0.98\, m_c + 0.2\, m_G = 1.533$	5 (One gluon)
Hybrid meson for Z_b	$\bar{m}_{Z_b} = 0.99\, m_b + 0.01\, m_G = 4.6897$	7 (Two gluons)

Holographically, the exotic spectrum depends entirely on the dilaton field and geometry. The hadronic identity is defined by the bulk mass $M_5(\Delta)$. All of this information is condensed into the holographic potential for vector hadronic states, defined as:

$$V_{\text{non-}q\bar{q}}(z, \kappa,\, \Delta) = V_{q\,\bar{q}}(z, \kappa, \alpha) + \frac{M_5^2(\Delta)\, R^2}{z^2}, \tag{11}$$

where $V_{q\,\bar{q}}(z, \kappa, \alpha)$ is the holographic potential used to describe isovector meson states in the context of holographic nonlinear Regge trajectories [11]. The parameter set is summarized in table 1. The calibration curves and the threshold mass for each exotic structure is written in table 2. Table 3 exposes the non-$q\bar{q}$ spectrum fit results. Experimental masses are read from PDG [12].

Table 3. Holographic mass spectrum for the non-$q\bar{q}$ states candidates according to their threshold mass $\bar{m}$. The parameters κ and α are read from the calibration curves, and the stoichiometric relations are exposed in table 2. Experimental data come from [12].

Z_c **states with** $I^G(J^{CP}) = 1^+(1^{+-})$			
Non-$q\bar{q}$ state	$Z_c(3900)$	$Z_c(4200))$	$Z_c(4430)$
Exp. Masses (MeV)	3887.1 ± 3.6	4296^{+35}_{-32}	4478^{+13}_{-18}
Diquark-Antidiquark (MeV) $\bar{m}_{4Q} = 1550$ MeV $\kappa = 2151$ MeV and $\alpha = 0.5387$	4004.8 (3.0%)	4384.9 (2.1%)	4706.6 (5.1%)
Hadronic Molecule (MeV) $\bar{m}_{HM} = 1432.3$ MeV $\kappa = 1907$ MeV and $\alpha = 0.4887$	3817.1 (1.8%)	4214.7 (1.9%)	4552.1 (1.6%)
Hybrid Meson (MeV) $\bar{m}_{Z_c} = 1533$ MeV $\kappa = 2114.8$ MeV and $\alpha = 0.5317$	3721.9 (4.2%)	4156.4 (3.2%)	4513.2 (0.8%)
ψ **states with** $0^+(1^{--})$			
Non-$q\bar{q}$ state	$\psi(4230)$	$\psi(4360))$	$\psi(4660)$
Exp. Masses (MeV)	4222.5 ± 2.4	4374 ± 7	4630 ± 6
Hadrocharmonium (MeV) $\bar{m}_{HQc} = 1717$ MeV $\kappa = 2522.6$ MeV and $\alpha = 0.6036$	4222.5 (0.2%)	4577.4 (4.6%)	4871.8 (5.2%)
Hadronic Molecule (MeV) $\bar{m}_{HM} = 1549.1$ MeV $\kappa = 2149.2$ MeV and $\alpha = 0.5384$	4003.5 (5.2%)	4383.7 (0.2%)	4705.6 (1.6%)
Z_b **states with** $I^G(J^{CP}) = 1^+(1^{+-})$			
Non-$q\bar{q}$ state	$Z_b(10610)$	$Z_b(10650))$	**—**
Exp. Masses (MeV)	10609 ± 6	10652.2 ± 1.5	—
Diquark-Antidiquark (MeV) $\bar{m}_{HM} = 4753$ MeV $\kappa = 11269.5$ MeV and $\alpha = 0.8633$	10224.5 (3.6%)	10517.6 (1.3%)	—
Hybrid Meson (MeV) $\bar{m}_{Zb} = 4689.7$ MeV $\kappa = 11102.3$ MeV and $\alpha = 0.8633$	10257.9 (3.3%)	10512.5 (1.3%)	—

5 Configurational entropy and stability

Configurational entropy [16] is associated with the information content in solutions to a given set of equations of motion and accounts for the microstate configurations emerging in a given macrostate at a fixed temperature. Thus, higher possible microstate configurations imply a higher values of configurational entropy (CE), inferring that the system could be unstable. In information theory, CE is connected to the information content in such EOM solutions. The information content is measured in terms of *complexity and localization*. In other words, highly localized solutions in space will lead to lower values of CE. Thus, ground states should be more stable than excited ones [17].

In the case of AdS/QCD, CE can be used to test hadronic stability [4]. The key point is how locality is a synonym of confinement. From the NRQCD potential model, a hadron should have a *well-localized* wave function. A particular set of constituents living inside hadrons, with defined structures, will have an associated CE. Preferred structures would be those with smaller CE. This localized information is encoded into the bulk dual modes. Thus, studying the CE of bulk modes will give us an insight into which structure is more stable.

Mesons in bottom-up models appear from the field/operator duality. The key point is the dimension of boundary hadronic operators, accounting for constituents nor the hadron inner structure. This constituent information is encoded in the bulk mass. Any information about the hadronic inner structure is not present *ab initio*. This map between boundary and bulk physics also implies that normalizable bulk modes are dual to mesons at the boundary. From the AdS/CFT point of view, this claim clashes with field/operator duality since *spatially localized wave functions at the boundary should be delocalized at the bulk*. This is the case for $\mathcal{N} = 4$ SYM theory dual to a Type IIB supergravity, where bulk states are unbounded [18]. However, long ago, we learned that one of the consequences of releasing the bulk conformal invariance is precisely this reinterpretation of the operator/field duality where extended and localized objects at the boundary are dual to localized objects at the bulk [19]. This locality in the bulk objects seems natural in non-conformal theories [20]. This idea supports computing hadronic properties (mass spectrum, form factors, decay constants, thermal densities, etc.) in bottom-up models. Therefore, in models where non-conformality exists, *boundary local operators have local dual bulk objects*. This claim directly connects to the configurational entropy. Therefore, we can say *locality at the bulk (involving lower configurational entropy) implies stability at the boundary*.

Let us move to the holographic calculation of the configurational entropy. We will follow the prescription exposed in [21, 22]. The CE algorithm can be summarized as follows. Start by defining the on-shell energy-momentum tensor as

$$T_{mn} = \frac{2}{\sqrt{-g}} \frac{\partial \left[\sqrt{-g}\, \mathcal{L}_{\text{Hadron}} \right]}{\partial\, g^{mn}}. \tag{12}$$

Then, extract the T_{00} component that defines the energy density for the bulk modes. In our particular case of dilaton-base models, the energy density $\rho(z)$ acquires the form:

$$\rho(z) \equiv T_{00} = \frac{e^{-B(z)}}{2} \left(\frac{z}{R}\right)^3 \left\{ \left[\frac{1}{g_5^2} \left(M_n^2\, \psi_n^2 + \psi_n'^2 \right) - \frac{M_5^2\, R^2}{z^2} \psi_n^2 \right] \right\} \Omega. \tag{13}$$

Then, Fourier-transform the density to compute the *modal fraction* as:

$$f(k) = \frac{|\bar{\rho}(k)|^2}{\int dk |\bar{\rho}(k)|^2}. \tag{14}$$

The next step is to normalize this modal fraction with the its maximum value, i.e., $\tilde{f}(k) = f(k) / f(k)_{\text{Max}}$. Now, compute *differential configurational entropy* using the Shannon-like expression:

$$S_{DCE} = -\int dk\, \tilde{f}(k) \log\, \tilde{f}(k). \tag{15}$$

We computed the DCE for each non-$q\bar{q}$ possible structure proposed in this work. The numerical results are depicted in figure 1. According to the claim that less CE implies a more stable structure, we can conclude that Z_c and Z_b could be better described as *hybrid mesons*, and ψ (or Y) states fit better with *hadroquarkonium proposal*.

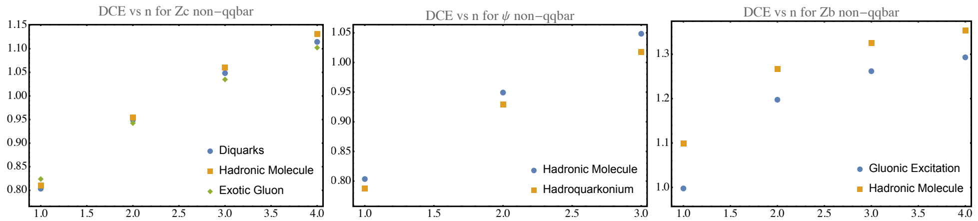

Figure 1. Differential configurational entropy (DCE), in natural entropy units, as a function of excitation number for non-$q\bar{q}$ candidates. From DCE grounds, those structures with less entropy are the most stable and, therefore, preferred.

6 Conclusions

This manuscript has discussed two main ideas: configurational entropy to measure stability and the implication that this measure can predict the constituent arrangement in nature from holographic grounds. These ideas are the cornerstone of our research and are crucial in advancing our understanding of theoretical physics. Recalling to hadronic stability is equivalent to addressing the wave function locality. This discussion stretches the hypothesis that normalizable modes living in the AdS bulk are dual to meson modes. This claim is supported by slightly breaking the bulk conformal invariance, inducing bounded KK-towers dual to hadronic Regge trajectories. In bottom-up models, we achieve this by introducing a dilaton field. Thus, well-localized (bounded) bulk modes imply localized and confined objects at the boundary. In this holographic context, we found that for the heavy non-$q\bar{q}$ states analyzed, the Z_c and Z_b states should be cataloged as *hybrid mesons*, and the ψ states as *hadrocharmonium*.

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