Odd-spin glueballs, AdS/QCD and information entropy

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Odd-spin glueballs in the dynamical AdS/QCD model are scrutinized, in the paradigm of the configurational entropy (CE). Configurational-entropic Regge trajectories, that relate the CE underlying odd-spin glueballs to their mass spectra and spin, are then engendered. They predict the mass spectra of odd-spin glueballs, besides pointing towards the configurational stability of odd-spin glueball resonances. The exponential modified dilaton with logarithmic anomalous dimensions comprises the most suitable choice to derive the mass spectra of odd-spin glueballs, compatible to lattice QCD. It is then used in a hybrid paradigm that takes both lattice QCD and the AdS/QCD correspondence into account.

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I. INTRODUCTION

The configurational entropy (CE) consists of the part of the entropy of a system that is related to representative correlations among its constituents. The CE measures the rate in which information can be compressed into any given system, in the lossless regime where one can recover the entire original message by decompression. Any compressed message presents the same amount of information as the original one, however, communicated along with fewer characters, being thus less redundant, complying with Shannon’s theory \[1, 2\]. The entropy of a message per bit, multiplied by the length of that message, is the measure of the information in the message.

For analyzing physical systems, the information compressed into physical modes has been providing prominent results that corroborate with experiments and observations. The CE recasts the shape complexity of a physical system in a coded form \[3\]. The CE can be calculated for any physical system, once a spatially-localized, Lebesgue-integrable, scalar field that describes the system is chosen. For general purposes, the $T_{00}$ component of the stress-energy-momentum tensor is a natural choice for the localized scalar field \[1\]. Nevertheless, scattering amplitudes and cross sections are also successful pickings for representing the localized scalar field in QCD \[5, 6\].

The CE is a precise tool for investigating and predicting relevant features of elementary particles and their resonances in AdS/QCD \[2, 7, 8\], supported by experimental data in the Particle Data Group (PDG) \[9\]. Besides, the CE has made important and precise predictions for current runnings in several experiments.

In the past five years, the CE has been repeatedly shown to be a prominent paradigm to examine complementary features of the AdS/QCD correspondence. In particular, the CE is a very suitable instrument for investigating QCD. In fact, several light-flavor meson families were scrutinized using the CE in AdS/QCD \[2, 7, 8\], whose mass spectra of their higher spin excitations have been also predicted and compared to lattice QCD. Scalar glueballs \[10\] and tensor mesons \[11\] were also studied in the CE paradigm. The stability of bottomonia and charmonia, at zero and finite temperatures and density with and without magnetic fields, was investigated in Refs. \[12–16\]. The CE has been also shown to play a relevant role in the study of baryons in AdS/QCD \[17, 18\]. Pomerons have been already investigated by the methods of CE, in the dynamical AdS/QCD setup \[19\].

The AdS/CFT correspondence consists of a successful scheme to report QCD as a theory that is dual to gravity in a codimension-one bulk. It emulates AdS/CFT in a special circumstance where QFT does not exactly represent a conformal field theory \[31–33\]. Since the bulk AdS space, where pure gravity lives, is invariant under conformal transformations, the associated string theory consists of a gauge theory that is conformally invariant, with features resembling QCD, in the large-$N_c$ regime. For establishing QCD from a dual gravity setup, conformal symmetry has to be broken on the boundary of AdS. It means that one must alter the AdS bulk, in such a way that the pure AdS bulk can be retrieved in the limit $z \to 0$, where $z$ denotes the bulk conformal coordinate, that also corresponds to an energy scale in the theory. This is justified by the fact that QCD is approximately conformal when the high-energy regime sets in. Introducing either a soft wall or a hard wall is a procedure that adjusts the AdS bulk. Each one of these choices is suitable for different purposes, yielding precise phenomenological aspects \[34–36\]. The broken conformal symmetry additionally emulates confinement, when the gauge theory effective range is restricted \[37–39\].

QCD conjectures the existence of bound states of glu-
ons, therefore encompassing glueball states [40]. QCD also encloses the odderon, consisting of a $C = -1 = P$ counterpart of the $C = 1 = P$ pomeron. Current works predict that the exchange of the odderon yields a phenomenological deviation between $pp$ and $p\bar{p}$ high-energy scattering. Besides, the central diffractive production of $f_0(980)$ and $f_2(1270)$ mesons at LHC has the odderon playing a relevant role in several production channels [41]. The photoproduction of $\eta^0$, $f_2(1270)$, and $a_2(1320)$ mesons allows a clear experimental signature of odderons. The odderon was initially announced in the 1970s, as some singularity in the complex $j$-plane, precisely at $j = 1$, supplying odd-undercrossing amplitudes. Experiments then showed that the odderon intercepts the Regge trajectory close to the unit, demonstrating then the existence of the odderon in perturbative QCD [42]. Among several odderons, the maximal odderon occupies a prominent role in QCD, yielding reasonable deviations between particle-antiparticle and particle-particle cross-sections. Experiments then showed that the odderon intercepts the Regge trajectory close to the unit, demonstrating then the existence of the odderon in perturbative QCD [42]. Among several odderons, the maximal odderon occupies a prominent role in QCD, yielding reasonable deviations between particle-antiparticle and particle-particle cross-sections. Besides, the maximal behavior introduced by Heisenberg [43], allowed for $pp$, was shown to have a close relationship to the odderon, whereas a colorless three-gluon swap at high-energy regime was proposed [44, 45]. The total elastic diffractive cross section measurement data was the first experimental signature of the maximal odderon [46–48].

Currently, the odderon is a pivotal tool in QCD, being studied in experiments at ATLAS – LHC and RHIC as well, when measuring hadronic scattering amplitudes [49]. The odderon can be thought of as being the leading exchange in the scattering of hadrons, at high energy regimes, wherein $C = -1 = P$ are carried into the $t$-channel, in the Regge theory [50, 51]. One can, therefore, assert that deeply studying the odderon is a current prominent test of QCD. In addition, the central exclusive production of the $\phi(1020)$ meson resonance was proposed to be a direct result of odderon-pomeron fusion [52]. The odderon solution, in perturbative QCD, can be also described from a three-gluon system point of view [53]. The so-called oddball [glueball] resonances can lie on odderon [pomeron] trajectories, whose parameters are usually fitted to the available experimental data on high-energy $pp$ and $p\bar{p}$ high-energy scattering. Extrapolating the trajectories to the resonance sector predicts the mass spectra of oddballs [glueballs] [54]. Soft high-energetic scattering models were also proposed, taking into account vertexes and propagators for pomerons, odderons, and reggeons [55].

The main goal in this work consists of employing the well-established CE approach, widely used in QCD, to study odd-spin glueballs in the AdS/QCD setup. CE Regge trajectories represent the leading apparatuses to derive odd-spin glueballs mass spectra, in a hybrid model that employs both lattice QCD and the AdS/QCD correspondence.

This paper is organized as follows: Sect. II sets up the holographic model for the background and for computing the odd-spin glueball spectra. Sect. III studies AdS/QCD and CE, applied to odd-spin glueball states. The mass spectra of odd-spin glueballs of higher spin are derived and compared with AdS/QCD predictions. Sect. IV comprises the main results and concluding remarks.

II. HOLOGRAPHIC SETUP AND GLUEBALL SPECTRA

The holographic setup to be considered consists of an Einstein-Hilbert action coupled to a dilaton on the AdS space in five dimensions,

$$S = \frac{1}{2\kappa^2} \int \sqrt{-g} \left( R - \frac{4}{3} g_{\mu\nu} \partial^\mu \Phi \partial^\nu \Phi + V(\Phi) \right) d^5x,$$  

where $2\kappa^2$ is the gravitational coupling constant, $g$ denotes the determinant of the $g_{\mu\nu}$ metric, $R$ is the (Ricci) scalar curvature, $\Phi$ stands for the dilaton profile and $V(\Phi)$ is the corresponding potential ruling the dilaton field. In this work we will use units such that the AdS radius $L = 1$.

For the background, we are going to consider an ansatz in Poincaré coordinates, whereas for the dilaton profile the exponential modified dilaton will be taken into account [56], which interpolates between the quadratic dilaton profile, $\Phi(z) \approx \phi_\infty z^2$, in the IR regime ($z \to \infty$), and a quartic dilaton profile, $\Phi(z) \approx \phi_\infty z^4$, in the UV regime ($z \to 0$), with $\phi_\infty$ being the dilaton constant. Thus the ansatze we are going to consider is given by:

$$ds^2 = \frac{1}{\zeta(z)^2} (dz^2 - dt^2 + dx_i dx^i),$$  

$$\Phi(z) = \phi_\infty z^2 \left( 1 - e^{-\phi_\infty z^2} \right).$$

Therefore, the equations of motion take the form$^1$

$$\frac{\zeta''(z)}{\zeta(z)} = \frac{4}{9} \Phi'(z)^2,$$  

$$V(\Phi) = 12 \zeta(z)^2 - \frac{4}{3} \zeta(z)^2 \Phi'(z)^2.$$  

Eqs. (4, 5) cannot be analytically solved, for the dilaton profile given by (3). Then one needs to solve them numerically, with the boundary condition $\zeta(z) \approx z$. In Figs. 1 and 2, the dilaton potential $V(\Phi)$, given by (5), and its first derivative as a function of $\Phi$, are respectively displayed, for a fixed value of $\phi_\infty$, which in this work will be set to $\phi_\infty = 0.335$ GeV$^2$. In fact, we have checked that for $\phi_\infty \geq 0.335$ GeV$^2$ the dilaton potential is a monotonically increasing function of $\Phi$ [57–59].

$^1$ For more details we refer the reader to Ref. [19] and references therein.
where one identifies $q^2 = -m_n^2$, with $m_n$ being the glueball masses, $n = 0, 1, 2, \ldots$ represents the radial excitations, whereas $V_{\text{Sch}}$ denotes the Schrödinger potential,

$$V_{\text{Sch}}(z) = \left( -\frac{B''}{2} + \frac{B'^2}{4} + M_5^2 \zeta^2 e^{\frac{2}{3} \Phi(z)} \right).$$

From the holographic dictionary and for higher spin fields in AdS, the subsequent mass relation can be regarded,

$$M_5^2 = \Delta(\Delta - 4) - J + \gamma(J),$$

where one assumes a contribution coming from the anomalous dimension $\gamma(J)$ for the glueball operator. For odd-spin glueballs [60–62], the operator that would describe the glueball state $1^{--}$ is given by $\mathcal{O}_\Delta \equiv \text{SymTr}(\tilde{F}_{\mu
u}F^2)$, which has conformal dimension $\Delta = 6$. In order to raise the spin, one has to insert the covariant derivatives, to end up with an operator with conformal dimension $\Delta = 6 + J$ given by $\mathcal{O}_{a+J} \equiv \text{SymTr}(FFD_{(\mu_1 \cdots D_{\mu_J}}F)$. Finally, concerning the anomalous dimensions, we are going to assume a logarithmic dependence on the spin $J$ as

$$\gamma(J) = \gamma_0 \log(1 + J),$$

where $\gamma_0$ is a fitting parameter.

With these ingredients, Eq. (8) can be now solved numerically, to obtain the odd-spin glueball mass spectra. The results for the mass spectra obtained are displayed in Table I, for $\phi_\infty = 0.335 \text{ GeV}^2$ fixed, and three values of the parameter $\gamma_0$. In Table II, we compare our results with Coulomb gauge QCD model of [63] and the DP Regge model [54].

| $J^{PC}$ | $1^{--}$ | $3^{--}$ | $5^{--}$ | $7^{--}$ | $9^{--}$ |
|----------|----------|----------|----------|----------|----------|
| $\gamma_0 = -24$ | 2.64 | 3.39 | 5.29 | 7.23 | 8.53 |
| $\gamma_0 = -25$ | 2.52 | 3.22 | 5.15 | 7.12 | 8.51 |
| $\gamma_0 = -26$ | 2.40 | 3.03 | 5.01 | 7.00 | 8.49 |
| $\gamma_0 = -27$ | 2.27 | 2.83 | 4.86 | 6.89 | 8.47 |
| $\gamma_0 = -28$ | 2.13 | 2.61 | 4.71 | 6.77 | 8.45 |

**TABLE I:** Mass spectra (GeV) of odd-spin glueballs for five values of $\gamma_0$ and $\phi_\infty = 0.335 \text{ GeV}^2$. 

Having dynamically constructed the background, we turn now to the holographic setup for computing the odd-spin glueball spectra, using the exponential dilaton profile given by Eq. (3).

In the string frame, the glueball action within the dynamical softwall model is given by

$$S = \int \sqrt{-g} e^{-\Phi} \left( g^{MN} \partial_M \Phi \partial_N \Phi + M_5^2 \Phi^2 \right) d^5x,$$

where $M_5$ is the mass of the scalar field $\Phi(z, x^\mu)$, and $\Phi(z)$ is given by Eq. (3).

The field equation coming from (6) can be put into a Schrödinger-like form, by using the following ansatz for the scalar field $\Phi(z, x^\mu)$:

$$\Phi(z, x^\mu) = e^{iq^\mu x^\mu + B(z)/2} \psi(z), \quad B(z) = 3 \log \zeta(z) + \Phi(z).$$

With this ansatz, one gets the Schrödinger-like equation

$$-\psi''(z) + V_{\text{Sch}}(z) \psi(z) = (-q^2) \psi(z),$$

where $\phi_\infty = 0.335 \text{ GeV}^2$. 

![FIG. 1: Dilaton potential $V(\Phi)$ for $\phi_\infty = 0.335 \text{ GeV}^2$.](image1.png)

![FIG. 2: First derivative of the dilaton potential $V(\Phi)$ for $\phi_\infty = 0.335 \text{ GeV}^2$.](image2.png)
TABLE II: Mass spectra (GeV) of odd-spin glueballs within the exponential dilaton AdS/QCD model with \( \gamma_0 = -26 \) and \( \phi_\infty = 0.335 \text{ GeV}^2 \) (second column), Coulomb gauge QCD model [63] (third column), and in DP Regge model [54] (fourth column).

| \( J^{PC} \) | Mass [this work] | Mass [Ref. [63]] | Mass [Ref. [54]] |
|----------|----------------|----------------|----------------|
| 1^{--}  | 2.40           | 3.95           |                 |
| 3^{--}  | 3.03           | 4.15           | 3.001          |
| 5^{--}  | 5.01           | 5.05           | 4.416          |
| 7^{--}  | 7.00           | 5.90           | 5.498          |
| 9^{--}  | 8.49           |                |                |

Finally, in Fig. 3, we show the Schrödinger potential (9), for several values of odd-spin spin \( J \) up to \( J = 9 \), for fixed values of \( \phi_\infty \) and \( \gamma_0 \).

One can reproduce the Regge trajectory of the odderon, illustrated by Fig. 4 in the dynamical AdS/QCD model with an exponential dilaton profile. Besides, using data in the fourth column of Table II, the Regge trajectory of the Odderon is depicted in Fig. 4 in DP Regge model [54].

III. CE REGGE TRAJECTORIES OF ODD-SPIN GLUEBALL RESONANCES AND MASS SPECTRA

When all the configurations of a physical system have equal weight, the CE is precisely given by the Boltzmann entropy \( S = k_B \log W \), in the discrete case, where \( k_B \) denotes the Boltzmann constant and \( W \) stands for the number of possible configurations. If the system is split into \( n \) states, with respective probabilities \( f_n \), the CE reads

\[
S = -k_B \sum_{n=1}^{W} f_n \log f_n. \tag{12}
\]

When disorder sets in, equivalently asserting that \( f_n = 1/W \), the standard Boltzmann formula is achieved. Contrarily, when there is a single mode configuration with unit probability, the entropy goes to zero. This formulation is the so-called Gibbs entropy formula, which is analogous to the Shannon information entropy [2]. For describing a physical system, the energy density \( T_{\mu\nu}(r) = \rho(r) \), for \( r \in \mathbb{R}^p \), plays an important role, where \( T_{\mu\nu} \) denotes the energy-momentum tensor that encodes the system. The 2-point correlation function \( F(r) = \int_{\mathbb{R}^p} \rho(r') \rho(r + r') \, d^p r' \) then yields the CE to correspond to the information entropy proposed by Shannon [13].

The first step in the calculation of the CE is to consider the Fourier transformation formula,

\[
\rho(k) = (2\pi)^{-n/2} \int_{\mathbb{R}^p} \rho(r) e^{-ik \cdot r} \, d^p r. \tag{13}
\]

In the CE protocol, the norm of Eq. (13) yields the square root of the power spectral density. Therefore, the modal fraction, that is equivalent to the correlations among modes in the system, reads [3]

\[
\hat{\rho}(k) = \frac{\vert \rho(k) \vert^2}{\int_{\mathbb{R}^p} \vert \rho(k) \vert^2 \, d^p k}. \tag{14}
\]
Since the power spectral density encrypts the way how the energy density fluctuates, then the modal fraction carries the input of all modes with momentum $k$ that contribute to the energy density profile. Accordingly, the CE for this continuum case is given by the following expression:

$$\text{CE}_\rho = -\int_{\mathbb{R}^4} \rho_i(k) \log \rho_i(k) \, dk,$$

where $\rho_i(k) = \bar{\rho}(k)/\bar{\rho}_{\text{max}}(k)$, for $\bar{\rho}_{\text{max}}$ denoting the supremum among all possible values of the modal fraction.

To start investigating odd-spin glueballs with the CE, let us consider $p = 1$, corresponding to the $z$ conformal coordinate along the bulk. Having the Lagrangian ($L$) associated with the glueball action (6) for odd-spins, and

$$T^{z\beta} = \frac{2}{\sqrt{-g}} \left[ \partial_{\alpha} \bar{\rho} \partial^\alpha (\sqrt{-g} L) - \partial_{\alpha} \partial^\alpha \bar{\rho} \right],$$

as the components of the energy-momentum tensor, hence

$$\rho(z) = T_{00}(z) = \frac{1}{(z^2)^2} \left[ \rho_0^2(z) + M_0^2 \Psi_0^2(z) \right].$$

The CE underlying the odd-spin glueballs can be immediately calculated by using Eqs. (13 – 15), for any odd value of $J$. Moreover, a first type of configurational-entropic (CE) Regge trajectory, that associates the CE of odd-spin glueballs to their $J$ spin, can be engendered. Table III compiles the resulting data. Hereon, for conciseness, we denote $\gamma_0, \equiv -26, \gamma_0, \equiv -27$, whereas $\gamma_0, \equiv -28$.

| $J$ | 1 | 3 | 5 | 7 | 9 | 11* | 13* | 15* |
|-----|---|---|---|---|---|-----|-----|-----|
| CE$_{\gamma_0}$ | 3.50 | 5.64 | 15.06 | 35.01 | 68.29 | 118.08 | 187.35 | 279.15 |
| CE$_{\gamma_0}$ | 3.73 | 5.91 | 16.94 | 37.21 | 71.66 | 121.58 | 190.09 | 279.79 |
| CE$_{\gamma_0}$ | 3.93 | 6.54 | 18.71 | 39.65 | 74.24 | 122.85 | 188.10 | 271.96 |

TABLE III: CE of odd-spin glueballs as a function of $J$. The CE of odd-spin glueball states with $J = 11, 13, 15$, indicated with an asterisk, are extrapolated from the CE Regge trajectories (18 – 20).

In Table III, the values of the CE for $J > 9$ can be extrapolated by interpolation of the previous values of the CE up to $J = 9$. It yields, respectively, the three CE Regge trajectories,

$$\text{CE}_{\gamma_0}(J) = 0.063 J^3 + 0.354 J^2 - 1.18 J + 4.272,$$

$$\text{CE}_{\gamma_0}(J) = 0.055 J^3 + 0.486 J^2 - 1.41 J + 4.540,$$

$$\text{CE}_{\gamma_0}(J) = 0.043 J^3 - 1.676 J^2 - 0.579 J + 4.831.$$  

Table III and the CE Regge trajectories (18 – 20) are illustrated in Fig. 5.

Now, to derive the odd-spin glueball mass spectra, we can take data in Table III and compute the CE as a function of the odd-spin glueball mass spectra for $J \leq 9$. Therefore, the mass spectra of odd-spin glueballs with $J = 11, 13, 15, \ldots$ can be obtained by interpolation methods. These second kinds of CE Regge trajectories are depicted in Fig. 6, whose interpolation formulas are shown in Eqs. (21 – 23).

Odd-spin glueball masses, for any value of $J$ can be obtained when one extrapolates the CE Regge trajectories,

$$\text{CE}_{\gamma_0}(m) = 0.0001 m^6 - 0.0037 m^4 + 0.6184 m^2 + 0.9999,$$

$$\text{CE}_{\gamma_0}(m) = 0.0001 m^6 - 0.0076 m^4 + 0.8055 m^2 - 0.2368,$$

$$\text{CE}_{\gamma_0}(m) = 0.0001 m^6 - 0.0064 m^4 + 0.9509 m^2 + 0.0390,$$

constructed upon interpolating the discrete points in Fig. 6, with accuracy within 0.1%. For $J = 11$, Eq. (18) yields $\text{CE}_{Ω_{11}} = 118.08$. When one substitutes it into (21) yields $m_{Ω_{11}} = 9.65 \text{ GeV}$, for the $J = 11 \, Ω_{11}$ odd-spin...
glueball mass. In a similar way, this procedure can be accomplished for higher odd-spin glueballs, for the three values of $\gamma_0$, respectively using the pairs of equations (19 – 22) and (20 – 23). The respective mass spectra are illustrated in Table IV. It is worth to mention that this method holds for any odd value of $J$. However we restrict ourselves to $J \leq 15$, since higher values of $J$ will be very unlikely to be detected even in future experiments. One can notice from Table IV that the three different values of the anomalous dimension parameter, $\gamma_0$, yield almost the same mass spectra.

One can still compare the odd-spin glueballs mass spectra in Table IV, to the mass spectra yielded by AdS/QCD in Table II. Denoting by $\Delta_J$ the difference between the mass spectra of odd-spin glueballs, $\Delta_{11} = 4.4\%$ and $\Delta_{13} = 5.9\%$, whereas $\Delta_{15} = 22.1\%$. The mass spectra in Table IV regards odd-spin glueballs that are more configurationally stable than their AdS/QCD counterparts.

### IV. CONCLUSIONS

Odd-spin glueballs were studied in the dynamical AdS/QCD model, with a modified exponential dilaton model having logarithmic anomalous dimension corrections. The CE that underlies the odd-spin glueballs was shown to engender two kinds of CE Regge trajectories. The first ones, associating the CE to the spin of the odd-spin glueballs, are represented by Eqs. (18 – 20), respectively for three different values of the anomalous dimension parameter, $\gamma_0$. These trajectories consist of interpolating the discrete data in Fig. 5. Therefore, odd-spin glueballs of higher $J$ can have the CE inferred from Eqs. (18 – 20). The second kind of CE Regge trajectories then associates odd-spin glueballs CE with the glueballs mass spectra, and are comprised in Eqs. (21 – 23), respectively for three different values of the anomalous dimension parameter. For spin $J = 11, 13, 15$, Table IV shows the mass spectra of odd-spin glueballs. These results and the second kind of trajectories are together shown in Fig. 6. The case $\gamma_0 = -28$ is more unstable, from the configurational entropy point of view. Thus, the odd-spin glueballs with $\gamma_0 = -26$ prevail, being eventually more likely to be detected [2, 7, 10]. It is worth to emphasize that PDG does not provide any data for odd-spin glueballs, up to our knowledge. Hence, the main relevance of this work consists of engendering an applicable database for future experiments and probing further aspects in AdS/QCD.

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| $J$ | 11 | 13 | 15 |
|-----|----|----|----|
| $\text{CE}_{\gamma_0}$ | 9.65 | 10.62 | 11.48 |
| $\text{CE}_{\gamma_1}$ | 9.64 | 10.61 | 11.44 |
| $\text{CE}_{\gamma_0}$ | 9.65 | 10.62 | 11.44 |

**Table IV:** Mass spectra (GeV) of odd-spin glueballs as a function of $J$. 

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