Postprint of Holographic Model Studies on QCD Phase Structure

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Abstract

Exploring the phase structure of Quantum Chromodynamics (QCD) has always been a major objective in high-energy heavy-ion collision physics. In recent years, QCD phase transitions in rotating backgrounds have attracted considerable attention from researchers. Based on the AdS/QCD correspondence, this work investigates the influence of chemical potential and angular velocity on the QCD critical point. The study reveals that chemical potential reduces the critical angular velocity ωc, while angular velocity decreases µc and the phase transition temperature. By calculating several probes that can characterize QCD phase transitions, such as drag force, diffusion coefficient, jet quenching parameter, and the spectral function of J/ , we find that both the jet quenching parameter and drag force exhibit enhancement near the phase transition temperature, with the peak temperature decreasing as chemical potential increases, which is consistent with the phase diagram where the phase transition temperature decreases with chemical potential. The spectral function results indicate that magnetic fields facilitate the dissolution of heavy mesons, leading to more pronounced suppression of final-state J/ yields. We also examine the gravitational waves generated by QCD holographic phase transitions in the early universe, discovering that gluon condensation suppresses the energy density of gravitational waves, and that the peak frequency shifts to lower values as gluon condensation increases.

Full Text

Preamble

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Study of QCD Phase Structure from Holographic Models

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Abstract

Exploring the phase structure of Quantum Chromodynamics (QCD) has long been a central goal in high-energy heavy-ion collision physics. In recent years, the QCD phase transition under rotation has attracted considerable attention from researchers. Based on the AdS/QCD correspondence, this work investigates the influence of chemical potential and angular velocity on the QCD critical endpoint. Our findings reveal that chemical potential reduces the critical angular velocity ωc, while angular velocity decreases µc and the phase transition temperature. By calculating several probes that characterize the QCD phase transition—such as drag force, diffusion coefficient, jet quenching parameter, and J/ spectral function—we observe enhancements in the jet quenching parameter and drag force near the phase transition temperature. The temperature corresponding to the peak decreases with increasing chemical potential, consistent with the phase diagram where the transition temperature decreases with chemical potential. The spectral function results demonstrate that magnetic fields promote heavy meson dissociation, leading to more pronounced suppression of final-state J/ yields. We also examine gravitational waves produced by the holographic QCD phase transition in the early universe, finding that gluon condensation suppresses the energy density of gravitational waves, with the peak frequency shifting downward as gluon condensation increases.

Keywords: Phase transition, Energy loss, Spectral function, Gravitational waves

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Quantum Chromodynamics (QCD) is a non-Abelian theory describing the strong interaction—the dynamics of quarks and gluons. Quarks are considered the fundamental constituents of matter, yet free quarks are not observed in nature. Current QCD theory posits that free quarks are confined within hadrons. At high energies or short distances, the interaction between gluons and quarks becomes weak, a phenomenon known as "asymptotic freedom," while at low energies or long distances, the interaction becomes strong, leading to "quark confinement." Research indicates that QCD primarily exists in the hadronic phase at low temperatures and densities, while under extreme high temperature and density conditions, QCD undergoes a phase transition from the confinement phase to the deconfinement phase, producing quark-gluon plasma (QGP) [1]. Scientists believe QGP was a product of the early universe; approximately 4 seconds after the Big Bang, the universe may have experienced a QCD phase transition at temperatures of 150–200 MeV, during which the universe was filled with QGP. As the universe continued to expand and cool, quarks and gluons combined to form hadrons, eventually evolving into the world we observe today. Studying the properties of QGP not only helps us investigate the fundamental composition of matter but also aids in understanding the origin and evolution of the universe.

The QCD phase transition and its properties have long been focal points in high-energy physics. Scientists have observed angular velocity production [2,3] in relativistic heavy-ion collisions at RHIC (Relativistic Heavy Ion Collider) and LHC (Large Hadron Collider). Angular velocity not only induces anomalous transport properties but also influences the QCD phase structure. Investigating the QCD phase diagram under rotation may more closely approximate the actual conditions of heavy-ion collisions. Since QGP exists for an extremely short duration in experiments, direct detection is challenging. Therefore, we can use hard probes such as jet quenching [4,5] and heavy quarkonia suppression [6] to investigate QGP properties. High-transverse-momentum jets traversing the QGP medium lose energy through gluon radiation and develop momentum broadening in directions perpendicular to their initial momentum. The mean square of transverse momentum broadening per unit distance defines the jet quenching parameter, and studying jet quenching can indirectly provide information about the temperature and density of the QGP medium. Additionally, heavy quarks can maintain flavor conservation while traversing the QGP. Previous studies have investigated energy loss, and here we discuss the jet quenching parameter, heavy quark energy loss (i.e., drag force) [7], and J/ spectral function [8] near the phase transition temperature. Finally, we examine the effect of gluon condensation—a non-perturbative effect—on the first-order phase transition, and subsequently calculate the impact of gluon condensation on gravitational waves [9] using holographic methods, comparing our results with detections from the International Pulsar Timing Array, Square Kilometre Array, and Taiji.

In 1997, Maldacena proposed a duality between gravitational theory in (d+1)-dimensional spacetime and d-dimensional N=4 supersymmetric Yang-Mills theory, known as AdS/CFT (Anti-de Sitter/Conformal Field Theory), or holography [10]. This provided a novel non-perturbative method for studying the strong-coupling limit of non-Abelian quantum field theories. Subsequently, Witten [11] and Gubser [12] derived the specific mathematical formulation of holography. Holography has been widely applied to study strong-coupling problems in QCD, collectively referred to as holographic QCD or AdS/QCD. Compared to the vacua of the two theories, QCD theory and N=4 supersymmetric Yang-Mills theory show even smaller differences near the phase transition temperature.

Holographic QCD methods are broadly divided into two categories: top-down and bottom-up. As the names suggest, the top-down approach starts from superstring theory itself and introduces symmetry-breaking mechanisms to break supersymmetry. The bottom-up approach begins with the QCD Lagrangian, focusing on QCD properties such as linear confinement, Regge trajectories, the QCD equation of state, and spontaneous chiral symmetry breaking. The earliest bottom-up holographic models were the hard-wall [13] and soft-wall [14] models. The hard-wall model artificially truncates the radial coordinate in the fifth dimension of AdS space, thereby breaking conformal symmetry, but this model fails to properly reproduce Regge trajectories. The soft-wall model manually introduces a dilaton term but does not consider the effect of the dilaton field on the spacetime metric. In recent bottom-up holographic Einstein-Maxwell-Dilaton (EMD) models, the effect of the dilaton field is considered, the gravitational metric is solved exactly, and these models can effectively characterize several physical properties of QCD [15].

We know that the QCD phase transition and its properties depend on quark mass and flavor number. In the heavy quark limit, the phase transition of pure SU(3) gauge theory is a first-order confinement-deconfinement transition; for light quark masses or for our physical world—the physical point—the transition is a rapid crossover. Holographic QCD models can effectively describe phase diagrams under different conditions. When constructing EMD models, model parameters can be made to quantitatively or qualitatively match lattice QCD equation-of-state results. The quantitative approach fixes the dilaton potential and gauge kinetic function, thereby fixing the form of the gravitational action. While this EMD model can fit lattice results well, it is difficult to obtain analytical solutions for the metric expressions. The qualitative approach employs so-called potential reconstruction, where the dilaton potential is related to the form of the warp factor in the metric. This method can also incorporate QCD properties into the model and yields analytical solutions for the metric expressions. However, the gravitational action may depend on temperature, chemical potential, or magnetic field, requiring further verification when constructing such models.

In recent years, researchers have discussed QCD phase diagrams under various conditions using different holographic models. Reference [15] constructed an EMD model containing both chemical potential and magnetic field, fitting the confinement-deconfinement transition temperature in the pure gluon background. The study found that both chemical potential and magnetic field reduce the critical temperature, though chemical potential does not significantly affect the critical point Bc. Reference [16] constructed a holographic model under anisotropic backgrounds and discussed T- diagrams under different anisotropies, finding that anisotropy reduces the critical temperature of the phase transition.

The EMD models in references [17,18] can quantitatively match lattice results, predicting critical points (c, Tc) at large chemical potentials of (724, 89) MeV and (555, 105) MeV, respectively. Reference [19] discussed chiral phase transitions under rotation, finding that angular velocity reduces the transition temperature. Reference [20] studied rotating Hawking-Page phase transitions, showing that angular velocity decreases the deconfinement transition temperature. Reference [21] examined the effect of rotation on deconfinement phase transitions in pure gluon and two-flavor systems. In pure gluon systems, angular velocity reduces both c and Tc at the critical point; in two-flavor systems, angular velocity reduces Tc, but the transition remains a crossover. This paper presents the effects of rotational angular velocity on deconfinement transition temperature and critical points in (2+1)-flavor systems.

Holographic Phase Structure

In early holographic dictionaries, the first-order confinement-deconfinement phase transition is dual to the first-order Hawking-Page phase transition [22]. Herzog later applied this concept to discuss QCD phase transitions in hard-wall and soft-wall models [23]. In holographic EMD models, the confinement-deconfinement phase transition is dual to the phase transition between large and small black hole phases. Furthermore, magnetic fields and chemical potential can be introduced by adding gauge fields to the EMD model action. In holography, chemical potential is dual to the time component of the gauge field, while angular velocity corresponds to the boundary value of the metric' s angular component. Rotation can be introduced by considering local Lorentz boosts [24,25]:

$$t \to t + L^2\omega\phi, \quad \phi \to \phi + \omega t$$

where L is the AdS radius and ω is the angular velocity.

Next, we discuss the phase transition between large and small black hole phases by studying black hole thermodynamic properties (the relationship between black hole free energy and temperature). The black hole free energy F is related to entropy s and temperature T by:

$$F = -T \int s \, dT$$

where z_h is the black hole horizon.

[Figure 1: see original paper] illustrates the effects of angular velocity on black hole temperature and free energy. From Fig. 1(a), we observe that at small angular velocities, the temperature-horizon relationship is monotonic; when the angular velocity exceeds the critical value ω_c, three black hole phases appear: the large black hole phase ( ), the unstable phase ( ), and the small black hole phase ( ). This suggests a possible phase transition between large and small black hole phases. Fig. 1(b) shows the effect of angular velocity on black hole free energy. When the angular velocity exceeds ω_c, a swallowtail shape emerges, representing the unstable phase. This indicates a first-order phase transition, with the critical point located at the intersection of the swallowtail shape. Angular velocity thus promotes the occurrence of a first-order phase transition and reduces the critical transition temperature.

By analyzing the effect of angular velocity on black hole free energy as shown in Fig. 1, we can determine the phase transition points. Applying the same method, we obtain the T-ωL phase diagram at different chemical potentials and angular velocities. Figure 2: see original paper and (b) display the phase diagrams in the T-μ and T-ωL planes, respectively. From Fig. 2(a), we see that the transition is a crossover at small chemical potentials. As chemical potential increases, the transition gradually changes from crossover to first-order, with the transition temperature decreasing as chemical potential increases. As angular velocity increases, the critical point moves downward and leftward, indicating that angular velocity reduces μ_c and decreases T_c. Fig. 2(b) shows that at very small chemical potentials, the transition remains a crossover. At larger chemical potentials, the transition is initially a crossover; as angular velocity increases, it changes from crossover to first-order, with the transition temperature decreasing as angular velocity increases. Additionally, as chemical potential increases, the critical point moves upward and leftward, suggesting that chemical potential reduces ω_c while increasing T_c. Besides holographic approaches, researchers have extensively studied the QCD phase diagram under rotation using the Nambu-Jona-Lasinio (NJL) model [26,27], lattice QCD [28,29], and other phenomenological models [30,31].

Energy Loss and Spectral Functions Near Phase Transition Temperature

Investigating the QCD phase transition and searching for signatures of QGP production have been central concerns in high-energy heavy-ion collision experiments. Since QGP exists for extremely short durations, various probes can indirectly confirm its production. This section introduces three powerful probes for investigating QGP properties.

First, heavy quarks produced in hard processes during heavy-ion collisions can maintain flavor conservation while traversing the strongly coupled medium, allowing us to extract spatiotemporal and transport properties of the medium by studying heavy quark behavior. We calculate heavy quark energy loss and diffusion coefficients in the medium, the jet quenching parameter describing energy loss of high-energy partons in the medium, and the J/ spectral function. J/ represents a bound state of charm and anti-charm quarks, and its existence can be confirmed by detecting resonance peaks in final-state lepton pairs, serving as a signature of QGP production.

Heavy quarks lose energy through drag force (dp/dt) in the medium, which can be holographically studied by calculating the energy flow from the string endpoint to the worldsheet horizon. Heavy quark motion in the medium can be described by the Langevin equation:

$$\frac{dp}{dt} = -\eta_D p + f_1$$

where the drag force f equals $\eta_D p$, and η_D is the drag coefficient. When the heavy quark moves at constant velocity, $dp/dt = 0$, and the drag force f balances the driving force f_1. The diffusion coefficient D can be calculated from the drag coefficient:

$$D = \frac{T}{m\eta_D}$$

where $t = 1/\eta_D$ is the relaxation time, m is the quark mass, and T is the medium temperature.

[Figure 3: see original paper] shows the relationship between drag force and temperature at different dimensions and chemical potentials [7]. In four dimensions and for slowly moving heavy quarks, energy loss exhibits enhancement near $1.09T_{HP}$; in four dimensions and at high velocities, drag force shows enhancement near $1.2T_{HP}$. In five dimensions, enhancement only appears at high velocities. This demonstrates that heavy quark energy loss has a non-monotonic temperature dependence. Furthermore, the peak increases with chemical potential, indicating that chemical potential enhances energy loss, possibly due to reduced QGP viscosity. Numerically, as chemical potential increases, the energy loss peak shifts slightly toward lower temperatures, corresponding to the decrease in transition temperature with increasing chemical potential. The diffusion coefficient describes the coupling strength between heavy quarks and the strongly coupled medium. [Figure 4: see original paper] displays the diffusion coefficient in four and five dimensions for different velocities and chemical potentials [7]. The diffusion coefficient is temperature-dependent and reaches a minimum near the phase transition temperature. Additionally, chemical potential suppresses the diffusion coefficient, again suggesting reduced QGP viscosity.

The jet quenching parameter describes the energy loss of high-energy partons in the medium. In holographic description, the expectation value of the Wilson loop in the adjoint representation relates to the jet quenching parameter as [32]:

$$\langle W(C)\rangle \approx \exp\left(-\frac{1}{4\sqrt{2}}\hat{q}L^-L^2\right)$$

where C is a rectangular contour of size $L \times L^-$, L is the separation distance between quark pairs, and L^- is the light-like distance.

[Figure 5: see original paper] presents $\hat{q}/T^3$ as a function of temperature. When the jet moves parallel to the magnetic field direction with transverse momentum broadening perpendicular to the field, we denote this as $\hat{q}(\parallel, \perp)$. When the jet moves perpendicular to the magnetic field with transverse momentum broadening either perpendicular or parallel to the field, we denote these as $\hat{q}(\perp, \perp)$ and $\hat{q}(\perp, \parallel)$, respectively. The figure shows that the jet quenching parameter exhibits enhancement near 1.3-1.4T_c, consistent with lattice results [33]. Additionally, $\hat{q}(\perp, \perp) > \hat{q}(\perp, \parallel) > \hat{q}(\parallel, \perp)$, indicating that jets lose more energy when moving perpendicular to the magnetic field direction. The results for jet quenching parameter, drag force, and diffusion coefficient collectively show that heavy quarks or jets lose the most energy near the phase transition temperature, suggesting QGP production and serving as a signature of its existence.

The spectral function of vector mesons can be defined as:

$$\rho_{\alpha\alpha}(\omega) = -\frac{1}{\pi}\mathrm{Im}[G^R_{\alpha\alpha}(\omega)]$$

[Figure 6: see original paper] illustrates the effect of varying magnetic fields on the spectral function, showing cases where the magnetic field is parallel and perpendicular to the polarization. In spectral function plots, the bell shape indicates resonance states, with the peak position corresponding to the resonance mass and the full width at half maximum representing the decay width. For both configurations in Fig. 6, increasing magnetic field reduces the peak height and broadens the width, indicating that magnetic fields accelerate resonance dissociation and cause more pronounced suppression of final-state J/ yields.

Gravitational Waves from Holographic Models

Studying gravitational waves from QCD phase transitions via holographic methods may provide a new approach for investigating gravitational wave source information and exploring early universe evolution. Gluon condensation is a non-perturbative QCD effect corresponding to a non-vanishing vacuum expectation value of the gluon field operator. Lattice QCD results show that the gluon condensation value drops sharply near the phase transition temperature, which can be regarded as an order parameter for the confinement-deconfinement transition. We first derive the relationship between gluon condensation and the confinement-deconfinement transition temperature, then substitute phenomenological estimates of gluon condensation from QCD sum rules to determine the transition temperature [8].

Consider a holographic model containing gluon condensation. The gravitational action is:

$$S = \frac{1}{2\kappa^2}\int d^{5x}\sqrt{-g}\left[R - \frac{1}{2}(\partial_\mu\phi)^2 - V(\phi)\right]$$

where the dilaton field ϕ couples to the gluon operator. The gravitational action has two solutions corresponding to zero temperature (thermal phase) [34] and finite temperature (black hole phase) [35]. The metric expressions for zero and finite temperature are respectively:

$$ds^2 = \frac{1}{z^2}\left[-f(z)dt^2 + \frac{dz^2}{f(z)} + dx_i^2\right]$$

where c represents gluon condensation and relates to the gluon operator $G^2_{\mu\nu}$ as:

$$c = \frac{8\pi^2}{3(N_c^2-1)}\frac{\langle G^2_{\mu\nu}\rangle}{(\pi T)^4}$$

and $f^2 = a^2 + c^2$, $a = (\pi T)^4$.

By calculating the free energy difference between the thermal and black hole phases, we can obtain the relationship between transition temperature and gluon condensation value:

$$\Delta F(T) = F_{\mathrm{BH}}(T) - F_{\mathrm{thermal}}(T)$$

The total gravitational wave spectrum ($h^2\Omega(f)$) comprises three sources: bubble wall collisions and shocks ($h^2\Omega_{\mathrm{env}}$), sound waves ($h^2\Omega_{\mathrm{sw}}$), and magnetohydrodynamic turbulence ($h^2\Omega_{\mathrm{turb}}$) [36]:

$$h^2\Omega(f) = h^2\Omega_{\mathrm{env}}(f) + h^2\Omega_{\mathrm{sw}}(f) + h^2\Omega_{\mathrm{turb}}(f)$$

where:

$$h^2\Omega_{\mathrm{env}}(f) = 1.67\times10^{-5}\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\left(\frac{\kappa_{\mathrm{env}}\alpha}{1+\alpha}\right)^2 S_{\mathrm{env}}(f)$$

$$h^2\Omega_{\mathrm{sw}}(f) = 2.65\times10^{-6}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{v_b}{S_{\mathrm{sw}}(f)}\right)$$

$$h^2\Omega_{\mathrm{turb}}(f) = 3.35\times10^{-4}\left(\frac{\kappa_{\mathrm{turb}}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{v_b}{S_{\mathrm{turb}}(f)}\right)$$

Here, κ represents the fraction of vacuum energy converted to bubble kinetic energy; κ_v is the fraction converted to bulk fluid motion; and κ_{turb} is the fraction of latent heat converted to magnetohydrodynamic turbulence, expressed as:

$$\kappa = \frac{1}{1+0.73\alpha+0.083\alpha^{3/2}+\alpha^3}$$

$$\kappa_{\text{turb}} = \epsilon \kappa_v$$

where ϵ represents the turbulent fraction of bulk motion, with values between 0.05 and 0.1. α is the ratio of vacuum energy density to thermal energy density, and α_∞ is the minimum value for bubble nucleation:

$$\alpha_\infty = \frac{\epsilon_*}{g_* T_*^4}$$

where T_* is the transition temperature, assumed to be $T_* \approx T_c$; g_* is the number of effective relativistic degrees of freedom; and ϵ_* is the vacuum energy.

$$\Delta F(T) = F_{\text{confined}}(T) - F_{\text{deconfined}}(T)$$

[Figure 7: see original paper] shows the gravitational wave spectrum from first-order QCD phase transition with gluon condensation [8], where the total spectrum is represented by the solid line. Ω_{env}, Ω_{sw}, and Ω_{turb} represent contributions from bubble collisions, sound waves, and magnetohydrodynamic turbulence, respectively. The spectrum may be detectable by the Big-Bang Observer (BBO), Square Kilometre Array (SKA), and International Pulsar Timing Array (IPTA). Bubble collisions dominate the total gravitational wave contribution for frequencies $f < 4 \times 10^{-6}$ Hz; sound waves primarily determine the peak position, located near 2×10^{-6} Hz; and magnetohydrodynamic turbulence contributions are negligible. [Figure 8: see original paper] illustrates the effect of gluon condensation on the gravitational wave spectrum, where lines with larger peak frequencies correspond to smaller gluon condensation values. The results show that gluon condensation suppresses the energy density of gravitational waves, and the peak frequency shifts leftward as gluon condensation increases.

Conclusion

This work investigates QCD structure under different dimensions and rotating backgrounds using holographic QCD models, then studies heavy quark energy loss, jet quenching parameter, and spectral functions near the phase transition temperature, and finally calculates gravitational waves from holographic QCD phase transitions. We find that chemical potential reduces the critical angular velocity ω_c and increases the critical temperature T_c, while rotational angular velocity decreases μ_c and the phase transition temperature T_c. Near the phase transition temperature, jets and heavy quarks exhibit enhanced energy loss, with peak temperatures decreasing as chemical potential increases. Chemical potential enhances energy loss, and jets lose more energy when moving perpendicular to the magnetic field direction. Spectral function studies reveal that magnetic fields accelerate resonance dissociation, causing more pronounced suppression of final-state J/ yields. Gluon condensation suppresses the energy density of gravitational waves, and the peak frequency decreases with increasing gluon condensation. These results demonstrate that holographic QCD methods provide another effective non-perturbative approach for studying QCD matter phase structure and properties under various extreme conditions.

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Note: Figure translations are in progress. See original paper for figures.