Meson Mass Modifications in Hot and Dense QCD Matter

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Introduction

In this work, we present a theoretical study of meson mass modifications in hot and dense QCD matter, where medium effects at finite temperature and density are incorporated by solving the radial Schrödinger equation with a complex heavy-quark potential [1–3] derived from the improved Gauss law model. The potential incorporates medium screening via a temperature- and density-dependent Debye mass, with its real part accounting for color screening and its imaginary part representing in-medium decay processes [2]. By extracting the binding energies from the numerical solutions and adding the constituent quark masses, we obtain temperature- and density-dependent meson masses. The approach successfully reproduces known vacuum meson masses at zero temperature and predicts consistent mass shifts under medium conditions, providing a reliable theoretical framework for investigating in-medium meson mass modifications [4–8].

Theoretical Framework

The ground-state pseudoscalar charmonium $\eta_c(1S)$ is modeled as a $c\bar{c}$ bound state in a medium [9], solved via the radial Schrödinger equation with an effective potential.

- **Vacuum potential ($T = 0$):** Cornell form with zero temperature:

$$V_{\rm vac}(r) = -\frac{\tilde{\alpha}_s}{r} + b\,r + c, \qquad (1)$$

where $\tilde{\alpha}_s$ is the four-loop corrected for better accuracy, $b = 0.412^2$ GeV^2, and $c = 0$. Values of these constants can be calculated from lattice QCD data.

- **Medium screening:** At finite T, interactions are screened via Debye mass:

$$m_D(T) = T\,g(\Lambda)\sqrt{\frac{N_c}{3}+\frac{N_f}{6}} + \frac{N_c\,T\,g(\Lambda)^2}{4\pi}\ln\left[\frac{1}{g(\Lambda)}\sqrt{\frac{N_c}{3}+\frac{N_f}{6}}\right]. \qquad (2)$$

with $N_c = 3,\ N_f = 3,\ \Lambda = 2\pi T$.

- **In-medium potential:** Improved Gauss Law model [1]: The real part of the potential consists of two terms. The first term is a screened Coulomb potential, which decreases with distance due to the medium effects. The second term is a screened string contribution, which also gets reduced at larger distances. Together, they describe the medium-modified potential governed by the Debye mass.

Reduces to Cornell form as $m_D \to 0$.

- **Schrödinger equation:** [14-16]

$$\Big[-\frac{1}{2\mu}\nabla^2 + \mathrm{Re}\,V(r,T)\Big]\psi_{1S}(r) = E_{1S}(T)\,\psi_{1S}(r), \quad \mu = \frac{m_c}{2}. \qquad (3)$$

with $m_c = 1.4692$ GeV.

- **In-medium mass:**

$$M_{\eta_c}(T) = 2m_c + E_{1S}(T). \qquad (4)$$

At $T = 0$: $M_{\eta_c} \approx 2.9207$ GeV; at $T > 0$: screening lowers binding and mass.

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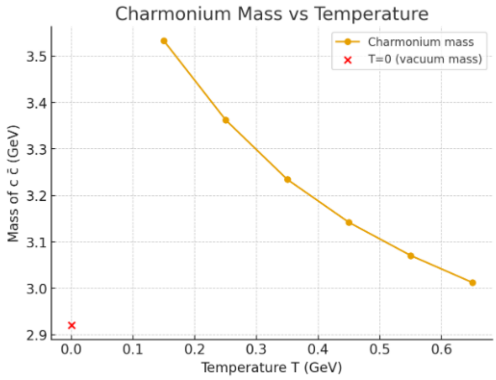

FIG. 1: Variation of Temperature Vs Mass.

TABLE I: Variation of masses with temperature using 2-loop running coupling constant.

Index	T (GeV)	Mass (GeV)	$\alpha_s(\mu)$ (2-loop)
1	0.15	3.5328	0.3350
2	0.25	3.3627	0.2545
3	0.35	3.2345	0.2216
4	0.45	3.1420	0.2026
5	0.55	3.0708	0.1899
6	0.65	3.0127	0.1805

Result and Discussion

The table shows how the $\eta_c(1S)$ mass changes with temperature in a quark–gluon plasma using the 2-loop running coupling. At $T = 0.15$ GeV, the in-medium mass is 3.533 GeV, slightly above the vacuum value from residual binding. With increasing temperature, the mass decreases to 3.013 GeV at 0.65 GeV, reflecting weaker charm–anticharm binding due to color screening. The coupling constant α_s also drops from 0.3350 to 0.1805, showing reduced QCD interaction strength. Together, these trends indicate thermal disruption of the bound state and signal the onset of charmonium melting in the QGP.

Acknowledgments

I thank to the Department of Physics(S.V.N.I.T) for their guidance and support.

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