Fate of Quarkonia in hot QCD medium

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Outline

- Some Intrduction and Motivation
- Potential models for Quarkonia dissociation – Our approach
  Phys.Rev.D 94 (2016) 9, 094006, Phys .Rev.D **97** (2018) 9, 094033 (with Yousuf Jamal, Vineet Agotiya, I Nilima)
- Momentum dependent relaxation time and quarkonia phenomenology
  Phys.Rev.D 110 (2024) 1, 014004, (with Manu Kurian and Sunny Singh), Singh et al Phys.Rev.D 112 (2025) 9, 094056
- Heavy quark potential in magnetic field and heavy quark dynamics (brief mention)
  Phys.Rev.D 112 (2025) 1, 016011 (with Santosh Das, D. Day, A Bandopadhyay, S. Dash)
- Summary and outlook

Physics is much too hard for physicists–David Hilbert

Motivation

- Heavy quarkonia (e.g., charmonium, bottomonium) are bound states of a heavy quark and antiquark. These Heavy quarkonium states such are sensitive probes of the quark–gluon plasma (QGP) created in relativistic heavy-ion collisions.
- Their in-medium properties are governed by the interaction between a heavy quark and antiquark in a thermal environment.
- Their fate in hot QCD medium/QGP help in understanding the nature of strong interaction physics in heavy-ion collisions
- Quarkonia dissociation in the QGP medium: Not simply a melting process but a dynamical one including screening, collisions, recombination in a rapidly evolving medium
- Some of our past work focused on the modeling of heavy quark potential and its application on understanding the dissociation phenomenon of quakonium states

QCD phase diargram and QGP

- QCD predicts a crossover from hadronic matter to the "effectively deconfined" hot QCD matter/Quark-gluon plasma

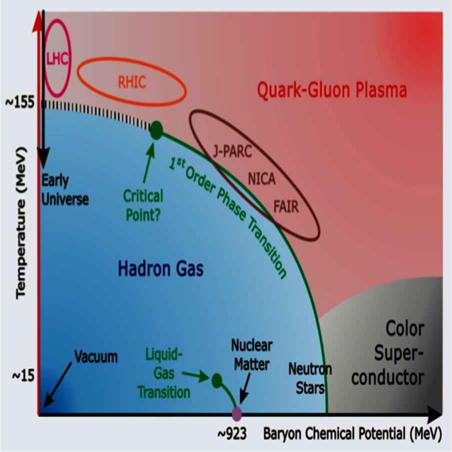

Diagram taken from GSI website

- The QGP can be modelled through relativistic dissipative hydrodynamics+magnetic field+spin

Our motivation to study quarkonia in QGP medium

- Hardonic state to QGP at T_c is crossover (Aoki, Endrodi, Fodor, Katz, and Szabo, Nature 443, 675 (2006)). Therefore, the non-perturbative effects can also be present beyond T_c

- QGP is a strongly coupled medium: QCD EOS from lattice QCD, 3-loop HTL effective theory
  HTL EOS: Arnold and Zhai Phys. Rev. D 51, 1906 (1995), Kajantie et al, Phys. Rev. D 67, 105008 (2003), Haque et. al JHEP 05 (2014) 027.
  Latiice EOS: A. Bazavov et. al, Phys. Rev. D 90, 094503 (2014).

- QGP can be modeled as a dissipative fluid derived from appropriate hydrodynamics from relativistic kinetic theory that requires approximation beyond RTA

- Magnetic fields may create observable effects too (see talk of Manu Kurian)

- All the above need to be incorporated while studying static/dynamical aspects of heavy quark-antiquark potential and thereby the in-medium properties of the quarkonia

Heavy quark static potential in the QGP medium within a quasi-particle model

- The vacuum form of the potential is considered to be Cornell form

$$V(r, T = 0) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma\ r$$

- In the case of finite-temperature QCD we here employ the ansatz that the medium modification enters in the Fourier transform of heavy quark potential, $V(k)$:

$$\tilde{V}(k) = \frac{V(k)}{\epsilon(k)} \quad , \tag{1}$$

where $\epsilon(k)$ is the dielectric permittivity which is obtained from the static limit of the longitudinal part of gluon self-energy, $\Pi^{\mu\nu}$ as:

$$\Delta^{\mu\nu}(\omega, \mathbf{k}) = k^2 g^{\mu\nu} - k^\mu k^\nu + \Pi^{\mu\nu}(\omega, \mathbf{k}). \tag{2}$$

$$\epsilon^{-1}(\mathbf{k}) = -\lim_{\omega\to 0} k^2 \Delta^{00}(\omega, \mathbf{k}). \tag{3}$$

$$\epsilon(k) = \left(1 + \frac{\Pi_L(0, k, T)}{k^2}\right) \equiv \left(1 + \frac{m_D^2}{k^2}\right). \tag{4}$$

In our case, $V(k)$ in Eq.(1) is the Fourier transform (FT) of the Cornell potential (to compute the FT we need to introduce a modulator of the form $\exp(-\gamma r)$ and finally let the γ tends to zero), which is obtained as

$$\mathbf{V}(k) = -\sqrt{(2/\pi)}\frac{\alpha}{k^2} - \frac{4\sigma}{\sqrt{2\pi}k^4}. \tag{5}$$

Next, substituting Eq.(4) and Eq. (5) into Eq. (1) and evaluating the inverse FT, we obtain r-dependence of the medium modified potential:

$$\begin{aligned} \mathbf{V}(r,T) &= \left(\frac{2\sigma}{m_D^2} - \alpha\right)\frac{\exp\left(-m_D r\right)}{r} \\ &- \frac{2\sigma}{m_D^2 r} + \frac{2\sigma}{m_D} - \alpha m_D \end{aligned} \tag{6}$$

- Interestingly, this potential has a long range Coulombic tail in addition to the standard Yukawa term. In the limiting case $r >> 1/m_D$, the dominant terms in the potential are the long range Coulombic tail and αm_D. The potential will look as,

$$V(r,T) \sim -\frac{2\sigma}{m_D^2 r} - \alpha m_D \tag{7}$$

, this form will decide the fate of quakonium states in the medium

Debye mass and effective coupling constant

- Let us consider the kinetic theory definition of Debye mass in the medium (that agrees with 1-loop result from HTL)

$$m_D^2 \equiv -g^2 \int \frac{\mathrm{d}^3\bar{\vec{p}}}{(2\pi)^3} \frac{\mathrm{d}f_{eq}(\bar{p})}{\mathrm{d}\bar{p}}. \tag{8}$$

$$f_{eq} = 2N_c f_g(\vec{p}) + 2N_f(f_q(\vec{p}) + f_{\bar{q}}(\vec{p}))$$

- To model the effective distribution functions in hot QCD medium we employ a quasi-particle model that interprets hot QCD equations of states (Lattice or 3 loop HTL) as:

$$f_{g,q} = \frac{z_{g,q}\exp(-\beta p)}{\Big(1 \mp z_{g,q}\exp(-\beta p)\Big)}. \tag{9}$$

where g stands for quasi-gluons, and q stands for quasi-quarks. z_g/q are the quasi-gluon/quark effective fugacities. VC, Ravishankar, Physical Review D 84, 074013 (2011)

- The Physical meaning of the fugacities could be understood from the non-trivial energy dispersions:

$$\omega_{g,q}(p) = E_p + T^2\partial_T \ln(z_{g/q})$$

VC, Mitra, Phys.Rev.D 97 (2018) 3, 034032

Effective model for hot QCD equation of state

- The debye from Eq. 6, can be obtained as:

$$m_D^2 = g^2(T)T^2\Bigg[\left(\frac{N_c}{3}\times\frac{6PolyLog[2,z_g]}{\pi^2}\right) + \left(\frac{N_f}{6}\times\frac{-12PolyLog[2,-z_q]}{\pi^2}\right)\Bigg]. \quad (10)$$

- The medium modified m_D in terms of effective fugacities can be understood by relating it with the charge renormalization in the medium. This could be done by defining the effective charges for the quasi-gluons and quarks as Q_g and Q_q. These effective charges are given by the equations:

$$Q_g^2 = g^2(T)\frac{6PolyLog[2,z_g]}{\pi^2}$$
$$Q_q^2 = g^2(T)\frac{-12PolyLog[2,-z_q]}{\pi^2}. \quad (11)$$

Now the expressions for the Debye mass can be rewritten as,

$$m_D^2 = \begin{cases} Q_g^2 T^2 \frac{N_c}{3} & \text{for pure gauge,} \\ T^2(\frac{N_c}{3}Q_g^2) + (\frac{N_f}{6}Q_q^2) & \text{for full QCD} \end{cases} \quad (12)$$

Here, $\{Q_g^2, Q_q^2\} \leq g^2(T)$ since it acquire the ideal value $g^2(T)$ asymptotically.

Dissociation mechanism for the heavy quarkonia

- Dissociation is purely governed by the Debye screening: Whenever binding energy is overcomed by the thermal effects the particular quarkonia will melt. In otherwords, whenever the distance between the quark-antiquark pair is greater then the Debye radium $(1/m_D)$ quakonium will dissociate **Chu and Matsui**: Phys. Lett. B (1986).

- Thermal effects can dissovciate the quaokonia: wheneveer temperature $(\sim \mathrm{K}_B T)$ over comes the binidng energy of a quarkoniun state, the state will dissociate

- Complex heavy quark potential in the medium: whenever binding energy is overcomed by the thermal width of the a particulay quarkonium state it will melt.
  Laine et. al, JHEP 03 (2007) 054.

Complex Heavy Quark Potential

- We have utilized the real part of $1/\epsilon$ to obtain the real part of the potential. The imaginary part of the potential is obtained by employing the imaginary part of $1/\epsilon$ (both real and imaginary parts are obtained from gluon self-energy)(Burnier et. al, PLB 678, 86 (2009)):

$$\frac{1}{\epsilon(k)} = -\pi T m_D^2 \frac{k^2}{k(k^2+m_D^2)^2}. \tag{13}$$

We can obtain the imaginary part of the potential by correcting the Cornell potential with Imaginary part of $1/\epsilon$ and then taking the inverse Fourier transport to get the spatial dependence:

$$\begin{aligned} ImV(r,T) &= -\int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}(e^{i\mathbf{k}\cdot\mathbf{r}}-1) \\ &\quad \times \left(-\sqrt{\frac{2}{\pi}}\frac{\alpha}{k^2} - \frac{4\sigma}{\sqrt{2\pi k^4}}\right)\frac{-\pi T m_D^2\ k}{(k^2+m_D^2)^2} \\ &\equiv ImV_1(r,T) + ImV_2(r,T)\ , \end{aligned} \tag{14}$$

where $ImV_1(r,T)$ and $ImV_2(r,T)$ are the imaginary parts of the potential due to the medium modification to the short-distance and long-distance terms, respectively.

Complex heavy quark potential

- The short and long distance parts are:

$$ImV_1(r,T) = -\frac{\alpha}{2\pi^2}\int d^3\mathbf{k}(e^{i\mathbf{k}\cdot\mathbf{r}}-1)\left[\frac{\pi T m_D^2}{k(k^2+m_D^2)^2}\right]$$

$$ImV_2(r,T) = -\frac{4\sigma}{(2\pi)^2}\int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}(e^{i\mathbf{k}\cdot\mathbf{r}}-1)\frac{1}{k^2}\left[\frac{\pi T m_D^2}{k(k^2+m_D^2)^2}\right].$$

- This can further be simplified in the small ($rm_D = \hat{r}$ limit) as follows

$$ImV(r,T) = T\left(\frac{\alpha\hat{r}^2}{3} - \frac{\sigma\hat{r}^4}{30m_D^2}\right)\log(\frac{1}{\hat{r}}).` \quad (15)$$

- We can have rough estimate of the width of the resonances/quarkonia by folding the imaginary part with the Columbic form of the wave functions (1S), we obtain:

$$\Gamma = \left(1+\frac{3\sigma}{\alpha m_Q^2}\right)\frac{4T}{\alpha}\frac{m_D^2}{m_Q^2}\log\frac{\alpha m_Q}{2m_D}. \quad (16)$$

Dissociation temperatures

- We employed the following three equation of states, and extracted effective fugacities in different cases: EOS1: $O(g^5)$ HTL QCD equation of state EOS2: $O(g^6(\ln(1/g)+\delta))$ equation of state, LEOS: 2+1: Flavor lattice QCD equation state: Bazabov (Hot QCD collaboration), 2014.

Table: Lower(upper) bound on the dissociation temperature(T_D) for the quarkonia states (in units of T_c)for using fugacity parameters of EOS 1

State	Pure QCD	$N_f = 2$	$N_f = 3$
J/ψ	1.6(1.9)	1.6(2.1)	1.5(2.0)
ψ'	1.3(1.5)	1.3(1.6)	1.3(1.5)
Υ	1.9(2.4)	2.1(2.6)	2.0(2.5)
Υ'	1.5(1.8)	1.6(1.9)	1.5(1.9)

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Table: Lower(upper) bound on the dissociation temperature(T_D) for the quarkonia states (in units of T_c)for using fugacity parameters of EOS 2

State	Pure QCD	$N_f = 2$	$N_f = 3$
J/ψ	1.5(1.8)	1.7(2.0)	1.6(1.9)
ψ'	1.2(1.4)	1.3(1.6)	1.3(1.6)

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Table: The dissociation temperature(T_D) for the quarkonia states (in units of T_c)for using fugacity parameters of EoS 1, when thermal width =2 BE

State	Pure QCD	$N_f = 2$	$N_f = 3$
$J\psi$	1.8	2.0	1.9
ψ'	1.6	1.8	1.8
Υ	2.6	2.8	2.2
Υ'	2.1	2.2	2.1

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Table: The dissociation temperature(T_D) for the quarkonia states (in units of T_c)for using fugacity parameters of EoS 2, when thermal width =2 BE

State	Pure QCD	$N_f = 2$	$N_f = 3$
J/ψ	1.7	1.9	1.9
ψ'	1.5	1.7	1.7
Υ	2.5	2.7	2.6
Υ'	2.0	2.2	2.1

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Results for LEOS

Table: Lower(upper) bound on the dissociation temperature(T_D) for the quarkonia states for 2+1 flavour (in units of T_c) case while using the fugacity parameters of the LEoS (second row). The third row records the estimates with second criterion of the dissociation (2 BE $\equiv$ thermal width)

State	J/ψ	ψ'	Υ	Υ'
LEoS	1.9(2.3)	1.5(1.8)	2.3(2.8)	1.8(2.1)
LEoS	2.1	1.8	3.1	2.6

- We could distinguish among various equations of states
- Medium effects are included through the effective models
- Inclusion of spin/rotation, magnetic field effects might change the results.

- Momentum anisotropy could be there during entire space-time evolution of QGP and may effect the HQ/quarkonia dissociation

- our approach we include it through the anisotropic momentum distribution functions along with the EOS effects:

$$f(\mathbf{p}) \to f_\xi(\mathbf{p}) = C_\xi \; f(\sqrt{\mathbf{p}^2 + \xi(\mathbf{p}\cdot\hat{\mathbf{n}})^2})$$

- We work in the small anisotropy limit ($\xi << 1$). Note that θ_n is the angle between the particle momentum and the direction of the anisotropy.

- The real part of the potential will be modified by the real part of $1/\epsilon$

$$\epsilon^{-1}(\mathbf{k}) = \frac{k^2}{k^2+m_D^2} + k^2\xi\Big(\frac{1}{3(k^2+m_D^2)} - \frac{m_D^2(3\cos 2\theta_n - 1)}{6(k^2+m_D^2)^2}\Big). \tag{17}$$

- Similarly, the imaginary part of the potential can be modified by using, $\epsilon(\mathbf{k})$

$$\epsilon^{-1}(\mathbf{k}) = \pi \; T \; m_D^2\Big(\frac{k^2}{k(k^2+m_D^2)^2} - \xi k^2\Big(\frac{-1}{3k(k^2+m_D^2)^2}$$

Complex potential in the presence of anisotropy

$$
\begin{aligned}
Re[V(\mathbf{r},\xi,T)] &= \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}(e^{i\mathbf{k}\cdot\mathbf{r}}-1)\Big(-\sqrt{\frac{2}{\pi}}\frac{\alpha}{k^2} \\
&- \frac{4\sigma}{\sqrt{2\pi}k^4}\Big)\Big(\frac{k^2}{k^2+m_D^2}+k^2\xi\Big(\frac{1}{3(k^2+m_D^2)} \\
&- \frac{m_D^2(3\cos 2\theta_n-1)}{6(k^2+m_D^2)^2}\Big)\Big).
\end{aligned}
\tag{19}
$$

$$
\begin{aligned}
\mathrm{Im}[V(\mathbf{r},\xi,T)] &= \pi\ T\ m_D^2 \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}(e^{i\mathbf{k}\cdot\mathbf{r}}-1)\Big(-\sqrt{\frac{2}{\pi}}\frac{\alpha}{k^2} \\
&- \frac{4\sigma}{\sqrt{2\pi}k^4}\Big)\Big(\frac{k}{(k^2+m_D^2)^2}-\xi\Big(\frac{-k}{3(k^2+m_D^2)^2} \\
&+ \frac{3k\sin^2\theta_n}{4(k^2+m_D^2)^2}-\frac{2m_D^2k\big(3\sin^2(\theta_n)-1\big)}{3(k^2+m_D^2)^3}\Big)\Big).
\end{aligned}
\tag{20}
$$

- The real and the imaginary parts in the limit: $s < 1$ ($s = rm_D$) are obtained as:

$$Re[V(\mathbf{r},\xi,T)] = \frac{s\ \sigma}{m_D}\left(1+\frac{\xi}{3}\right) - \frac{\alpha\ m_D}{s}\left(1+\frac{s^2}{2} + \xi\left(\frac{1}{3}+\frac{s^2}{16}\left(\frac{1}{3}+\cos\left(2\theta_r\right)\right)\right)\right). \tag{21}$$

- The imaginary part of the modified potential in the anisotropic medium is given as,

$$\mathrm{Im}[V(r,\theta_r,T)] = \frac{\alpha\ s^2\ T}{3}\left\{\frac{\xi}{60}(7-9\cos 2\theta_r)-1\right\}\log\left(\frac{1}{s}\right) + \frac{s^4\ \sigma\ T}{m_D^2}\left\{\frac{\xi}{35}\left(\frac{1}{9}-\frac{1}{4}\cos 2\theta_r\right) - \frac{1}{30}\right\}\log\left(\frac{1}{s}\right). \tag{22}$$

- θ_r is the angle between $\vec{r}$ and direction of anisotropy.

Results on Dissociation temperatures

Table: HTL perturbative results for all three prolate, isotropic and oblate cases

3-loop HTLpt			
Temperatures are in the unit of T_c			
States $\downarrow$	$\xi = -0.3$	$\xi = 0.0$	$\xi = 0.3$
Υ	2.427	2.540	2.639
Υ'	1.008	1.067	1.118
J/ψ	1.054	1.119	1.172

Table: Lattice simulation results for all three prolate, isotropic and oblate cases

Lattice Bazabov(2014)			
Temperatures are in the unit of T_c			
States $\downarrow$	$\xi = -0.3$	$\xi = 0.0$	$\xi = 0.3$
Υ	2.451	2.564	2.665
Υ'	1.023	1.074	1.120
J/ψ	1.063	1.121	1.172

- The anisotropy affects results within 10-25 percent.

A digression: Momentum dependent RTA

- We can connect kinetic theory with hydrodynamics through the matching of the energy momentum tensor and conserved currents (baryon number charge etc.)

$$T^{\mu\nu} = \varepsilon U^\mu U^\nu - \mathcal{P}\Delta^{\mu\nu} + \pi^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3 p} P^\mu P^\nu f(X, P), \tag{23}$$

$$N^\mu = nU^\mu + V^\mu = \int \frac{d^3p}{(2\pi)^3 p} P^\mu f(X, P) \tag{24}$$

- Hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$, $\partial_\mu N^\mu = 0$
- To do that you choose an appropriate form for the near distribution functions with RTA (Anderson and H. R. Witting, Physica 74, 466 (1974)) (usually)

$$P^\mu \partial_\mu f = -\frac{(U \cdot P)}{\tau_{\mathrm{R}}} (f - f_0), \tag{25}$$

- Decompose the distribution in equilibrium and non-equilibrium part (Chapman-Enskog)

$$f(X, P) = f_0(X, P) + \delta f(X, P), \tag{26}$$

- To realize the conservation laws, you need to be in the landau frame and relaxation times are momentum independent
- But in practice, theories like QCD, scalar field theories support momentum dependent relaxation times: Dusling, Moore, Teaney, Phys.Rev.C81:034907,2010.

Momentum dependent RTA

- We just generalize the transport equation as:

$$P^{\mu}\partial_{\mu}f = -\frac{(U \cdot P)}{\tau_{\mathrm{R}}}\left(f - f_0^*\right), \tag{27}$$

where f_0^* is given by,

$$f_0^*(X,P) = \frac{1}{\exp\left[\beta^*\left(U^* \cdot P\right) + \alpha^*\right] + a}, \tag{28}$$

- with $\beta^* = 1/T^*$, $\alpha^* = \mu^*/T^*$. Here, T^*, μ^*, and U_{μ}^* correspond to the temperature, chemical potential, and the fluid four velocity of the system at equilibrium. The starred quantities are called the *thermodynamic variables*, and consequently, f_0^* represents the true thermodynamic local equilibrium of the system toward which the out-of-equilibrium system relaxes as $t \to \infty$.

- It should be noted that in general, the variables, β^*, U_{μ}^* and μ^* are functions of spacetime.
Dash, Bhadury, Jaiswal, and Jaiswal, Phys. Lett. B 831, 137202 (2022).

- The thermodynamic variables and hydrodynamic variables are related to each other through the relation,

$$U^*_\mu = U_\mu + \delta U_\mu, \qquad T^* = T + \delta T, \qquad \mu^* = \mu + \delta\mu, \tag{29}$$

The form of the relaxation time could be taken to be:

$$\tau_{\rm R}(X, P) = t_{\rm R}(X) \left(\frac{U \cdot P}{T} \right)^\ell . \tag{30}$$

- By solving the relativistic Boltzmann equation as described, we obtain the non-equilibrium correction as:,

$$\delta f_{(1)} = \frac{\beta \tau_{\rm R}(X, P)}{(U \cdot P)} P^\mu P^\nu \sigma_{\mu\nu} f_0 \tilde{f}_0 = \frac{\beta^{1+\ell} t_{\rm R}(X)}{(U \cdot P)^{1-\ell}} P^\mu P^\nu \sigma_{\mu\nu} f_0 \tilde{f}_0, \tag{31}$$

where the subscript '(1)' in $\delta f_{(1)}$ denotes that only the first-order corrections have been considered, and we have defined $\tilde{f}_0 = 1 - a f_0$ $(a = \pm)$

ERTA framework

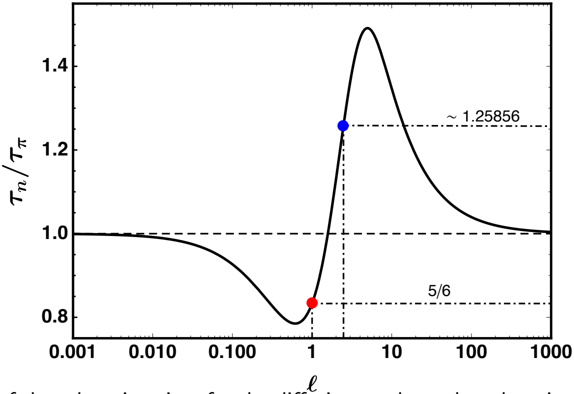


Figure: The ratio of the relaxation time for the diffusion mode to the relaxation time for the shear mode as a function of the momentum dependence parameter ℓ. The red dot corresponds to the prediction for $\lambda\phi^4$ theory and the blue dot corresponds to this ratio for hard sphere scattering.

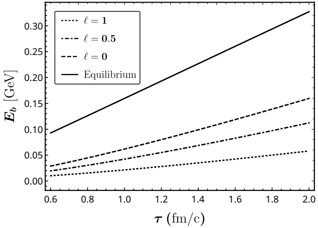
Ref: Phys.Rev.D 110 (2024) 1, 014004, (with Manu Kurian and Sunny Singh), Phys.Rev.D 111 (2025) 11, 114007 (with Sunny, Manu and Samapan)

ERTA and Debye mass

We then compute the corrections to Gluon-self energy and obtain the following expression of the Debye mass:

$$m_D^2 = \frac{g_s^2 T^2}{6}(N_f + 2N_c) + \frac{4g_s^2 t_{\mathrm{R}} T^2}{3\pi^2 \tau}\left[N_c + N_f(1 - 2^{-(\ell+1)})\right]\Gamma(\ell+3)\zeta(\ell+2), \qquad \ell > -1. \tag{32}$$

- The modification of the screening mass can affect the real and imaginary part of quarkonia potential (through ϵ)which in turn can modify the in-medium properties of heavy quarkonia
- We consider 1+1-dimensional boost invariant expansion



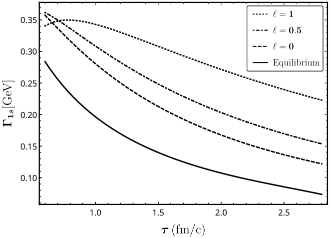


Figure: The binding energy of the J/Ψ ground state as a function of proper time, τ at various values of ℓ (left panel). The line width at various values of the momentum dependence parameter ℓ (right panel).

- This study requires further extensions and refinement to connect it with complex physics of quarkonia in the medium
  Ref. : Sunny Singh et. al Phys.Rev.D 112 (2025) 9, 094056.

Heavy quark potential and non-perturbative heavy quark diffusion

- Modelled the HQ potential in the medium in the presence of magnetic field (static and dynamic cases)
- For $T \neq 0$, $B = 0$), the HQ potential can be written as [?]

$$V(r) = V_Y(r) + V_S(r) = -\frac{4}{3}\alpha_s \frac{e^{-m_D r}}{r} - \sigma \frac{e^{-m_s r}}{m_s}, \tag{33}$$

m_d and m_s screening masses are not independent as originates from the the same interactions.

- $B \neq 0$

$$V_Y(q) = -\frac{4}{3}g^2 \left(\frac{1}{q^2 + m_D^2 + \delta m_D^2} + i\,\frac{\pi T \left[m_D^2 - \sum_f \frac{g^2 (q_f B)^2}{2\pi^2} \left\{ F_1(1+\cos^2\theta) + F_2(7/3 + \cos^2\theta) \right\} \right]}{q(q^2 + m_D^2 + \delta m_D^2)^2} \right)$$

$$V_S(q) = -\frac{4}{3}g^2 \left(\frac{m_G^2}{(q^2 + m_D^2 + \delta m_D^2)^2} + i\,\frac{\pi T m_G^2 \left[m_D^2 - \sum_f \frac{g^2 (q_f B)^2}{\pi^2} \left\{ F_1(1+\cos^2\theta) + F_2(7/3 + \cos^2\theta) \right\} \right]}{q(q^2 + m_D^2 + \delta m_D^2)^3} \right), \tag{34}$$

Heavy quark diffusion:NP effects in the presence of strong magnetic field

- The spatial diffusion coefficient D_s can be defined via the zero-momentum value of κ

$$D_s = \frac{2T^2}{\kappa(p=0)} \tag{35}$$

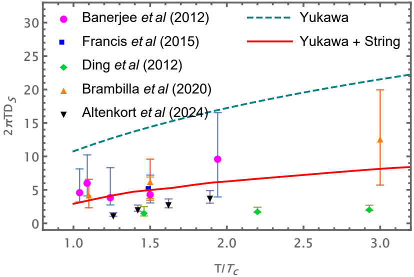


Figure: Scaled spatial diffusion coefficient as a function of T.

Phys.Rev.D 112 (2025) 1, 016011 (with Santosh Das, D. Day, A Bandopadhyay, S. Dash)

Future directions/outlook

- We aim to develop refined potential models for quarkonia and study their medium-modified forms, which can capture both perturbative and non-perturbative aspects of heavy-quark diffusion.
- The T-matrix approach (Cabrera and Rapp, Phys. Rev. D 76, 114506 (2007)) incorporates key features of quarkonia (Tang et al., Phys. Rev. Lett. 135, 142302 (2025)) in the hot QCD medium and motivates our recent work on heavy-quark dynamics
- Treating quarkonia within an open quantum system framework may further reveal important dynamical effects (Nora's talk yesterday).

IIT Gandhinagar: Conference Annocement

Heavy Flavor Meet 2026: 5th Edition at IIT Gandhinagar, India: October 1-3, 2026

First Announcement: by February 2026 Last Week

I would like to sincerely thank all of my past and current collaborators for their support and help.

Special Mention to Santosh, Yousuf, Manu and Sunny

THANK YOU FOR YOUR ATTENTION!

You can not swim for new horizons until you have courage to loose sight of the shore
-William Faulkner
To live without hope is to cease to live." — Fyodor Dostoevsky