On the fate of quakonium in hot QCD medium

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Introduction: Charmonium suppression has long been proposed as a signature of the existence of QGP and has indeed been seen at CERN, SPS and RHIC[1]. However, a complete theoretical understanding is still missing. It is worthnoting that investigations on J/ψ suppression need understanding of the dissociation of $1S$ (J/ψ), $2S(\psi')$ as well as $1P$ (χ_c) states of $c\bar{c}$ in the hot QCD medium[2]. The main point of focus of the present article is to study the binding energies of the $1P$ states of charmonium and bottomonium (χ_c and χ_b respectively) by incorporating the non-perturbative effects such as non-zero value of the string tension between the quark-antiquark pair beyond T_c. The main motivation comes from the fact that the phase transition in full QCD appears as an crossover rather than a 'true' phase transition with related singularities in thermodynamic observables (in the high-temperature and low density regime)

The determination of binding energy of χ_c and χ_b is not so straight forward from the usual Bohr's theory. However, we need understanding of the dissociation of $1S$ and $2S$ states of charmonium and bottomomium which follow the Bohr's theory[3]. We address this very important issue by adopting a variational treatment of the relativistic two-fermion bound-state system in quantum electrodynamics [4]. In this approach, coupled integral equations for a relativistic two-fermion system are derived variationaly within the Hamiltonian formalism of quantum electrodynamics.

Dissociation of χ_c and χ_b: We shall employ the understanding of [3] to study the binding energies and dissociation of χ_c and χ_b in the QGP medium. The energy of the n-th $Q\bar{Q}$ bound state is given by employing the Bohr's famous formula:

$$E_n = -\frac{E_I}{n^2} \quad ; \quad E_I = \frac{m_Q \sigma^2}{m_D^4}, \qquad (1)$$

where m_Q is the mass of the heavy quark and E_I is the energy of the $Q\bar{Q}$ state in the first Bohr state. These energies are known as the ionization potentials/binding energies for the n-th bound state.

From charmonium and bottomonium spectroscopy with hydrogen like potential, the binding energies of $\chi_c(\chi_b)$ states can be obtained as

$$E(\chi_{c,b}) = E(\Psi', \Upsilon') + \Delta E, \qquad (2)$$

where $E(\Psi', \Upsilon') = m_{c/b}\sigma^2/(4m_D^4)$ and ΔE is the energy difference between the $\chi_{c,b}$ and $\Psi'(\Upsilon')$ states. It arises because of α^4 correction to the kinetic and potential energies [4]. Finally, we obtain the expression for ΔE for $\chi_{c,b}$'s as

$$\Delta E = \frac{m_{c/b}\alpha^4}{96}. \qquad (3)$$

Inserting this expression into Eq.(2), we obtain the following expression for the binding energy of $\chi_c(\chi_b)$,

$$E(\chi_{c,b}) = \frac{m_{c,b}\sigma^2}{4m_D^4}\left(1 + \frac{2}{3}\frac{\sigma^2}{m_D^4}\right). \qquad (4)$$

At this juncture, we employ a non-perturbative gauge invariant form of Debye mass in hot QCD computed by Kajantie having non-perturbative contributions of $O(g^2T)$ and $O(g^3T)$.

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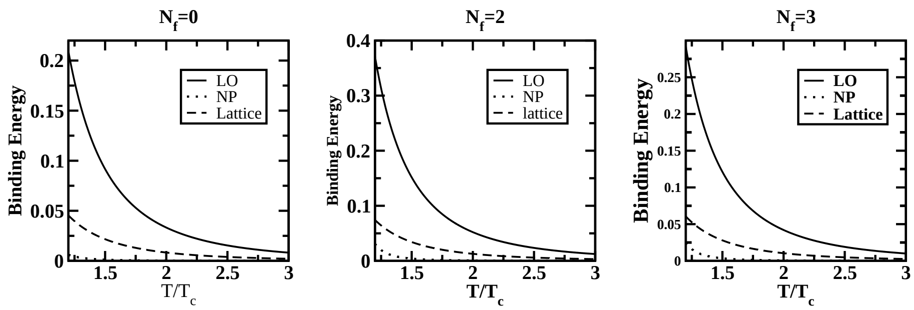

FIG. 1: Dependence of χ_c binding energy (in GeV) on temperature T/T_c.

The dissociation of a two-body bound state in a thermal medium can be explained as follows:

$$E(\chi_{c,b}) \equiv \frac{m_{c,b}\sigma^2}{4m_D^4}\left(1+\frac{2}{3}\frac{\sigma^2}{m_D^4}\right) = 3T_D. \quad (5)$$

This condition gives the lower bound on the dissociation temperatures after inserting the expression for the Debye mass. However, the choice $3T$ is not rigid because even at low temperatures $T < T_c$ (say) the Bose/Fermi distributions of partons will have a high energy tail with partons of mechanical energy $> |E_{\chi_{c,b}}|$. While determining the temperature dependence of the binding energy and dissociation temperatures, we have chosen the string tension, $\sigma = 0.184\text{GeV}^2$ and critical temperatures (T_c) $270MeV$, $203MeV$ and $197MeV$ for pure gluonic, 2-flavor and 3-flavor QCD medium respectively. We have shown the binding energy of χ_c as function of temperature for pure gauge theory, 2- and 3-flavour QCD for different choices of Debye mass in Fig.1. The binding energy χ_b shows the similar qualitative behaviour and approches to zero at relatively larger temperatures as compared to χ_c.

The dissociation temperatures for χ_c and χ_b of are listed in Table 1 with m_D^{LO}. The lattice parametrized form of the Debye mass, leads to much lower values (close to $\sim T_c$) for the dissociation temperature. However the qualitative features regarding the flavor dependence remains intact. The values in Table 1 agree quantitatively with the recent values reported by Mocsy and Petreczky [5].

TABLE I: Lower (upper) bound on the dissociation temperature(T_D) for the 1 P states of charmonium and bottomonium (in unit of T_c) using the leading-order term in the Debye mass m_D^{LO}.

Quarkonium state	Pure QCD	$N_f = 2$	$N_f = 3$
χ_c	0.9 (1.1)	1.1 (1.3)	1.0 (1.2)
χ_b	1.1 (1.4)	1.3 (1.6)	1.2 (1.5)

Conclusions: In conclusion, we have studied the dissociation of $1P$ states of charmonium and bottomonium spectra(χ_c and χ_b) in the hot QCD medium. To do so, we adopted a variational treatment of the relativistic two-fermion bound-state system in quantum electrodynamics [4] and combined it with the effective potential employed in [3]. We have studied the temperature as well as flavor dependence of their binding energies and dissociation temperatures.

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