

Color Screening Melts Quarkonium

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We calculate quarkonium spectral functions in a quark-gluon plasma using a potential model based on full QCD lattice calculations of the free energy of a static quark-antiquark pair. We estimate the binding energy and the thermal width of different quarkonium states. The estimated upper limit for the dissociation temperatures is considerably lower than the ones suggested in the recent literature.

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One of the most important features of the quark-gluon plasma is the screening of static chromo-electric fields [1]. It has been argued that screening above the deconfinement temperature T_c is strong enough to lead to the dissolution of the J/ψ state, which can then signal quark-gluon plasma formation in heavy ion collisions [2]. The fact that the J/ψ -suppression pattern observed in SPS and RHIC experiments is still not understood [3], serves as a motivation for this work. In particular, our aim is to relate quarkonium suppression to deconfinement and color screening.

Because of the large quark mass $m = m_{c,b} \gg \Lambda_{\text{QCD}}$, the velocity v of heavy quarks in the bound state is small, and the binding effects in quarkonia at zero temperature can be understood in terms of nonrelativistic potential models [4]. More recently, the potential has been derived from QCD using a sequence of effective field theories: Nonrelativistic QCD (NRQCD), an effective theory where all modes above the scale m are integrated out, and potential NRQCD, an effective theory in which all modes above the scale mv are integrated out [5].

Based on the success of the potential model at zero temperature, and on the idea that color screening implies modification of the interquark forces, potential models have been used to try to understand quarkonium properties at finite T [2,6]. To discuss properties and dissolution of quarkonium states at finite temperature spectral functions have to be considered. Using lattice QCD, charmonium correlators have been calculated, and the corresponding spectral functions have been extracted using the maximum entropy method (MEM) [7–11]. The MEM at zero temperature can reconstruct the basic features of the spectral functions: the ground state, the excited states, and the continuum [11]. At finite temperature, however, the extraction of the spectral functions becomes difficult, because the length of the Euclidean time is limited by the inverse temperature.

In a recent paper [12] we calculated the spectral function using a potential model for the nonrelativistic Green's function. This detailed analysis shows that spectral func-

tions calculated in a potential model combined with perturbative QCD can describe the available lattice data on quarkonium correlators at zero and at finite temperature in QCD with no light quarks [12]. Charmonium states were found to dissolve at temperatures significantly lower than quoted in lattice QCD studies. In the present work we extend our analysis to the case of real QCD with one strange quark and two light quarks. Furthermore, using lattice results on color screening we derive upper bounds for the dissociation temperatures of various quarkonium states in the quark-gluon plasma which are considerably lower than previous estimates.

In the energy domain of the resonances and near the continuum threshold the spectral functions are calculated from the nonrelativistic Green's functions as [12]

$$\sigma(\omega) = \frac{2N_c}{\pi} \text{Im} G^{nr}(\vec{r}, \vec{r}', E)|_{\vec{r}=\vec{r}'=0}, \quad (1)$$

$$\sigma(\omega) = \frac{2N_c}{\pi} \frac{1}{m^2} \text{Im} \vec{\nabla} \cdot \vec{\nabla}' G^{nr}(\vec{r}, \vec{r}', E)|_{\vec{r}=\vec{r}'=0}, \quad (2)$$

for S -wave, and P -wave quarkonia, respectively. Here $E = \omega - 2m$, and the number of colors is $N_c = 3$. The nonrelativistic Green's function satisfies the Schrödinger equation $[-\frac{1}{m}\vec{\nabla}^2 + V(r) - E]G^{nr}(\vec{r}, \vec{r}', E) = \delta^3(r - r')$. The numerical method for solving this equation is presented in [12]. At large energies, away from the threshold, the nonrelativistic treatment is clearly not applicable. The spectral function in this domain, however, can be calculated using perturbation theory [12].

To calculate $G^{nr}(\vec{r}, \vec{r}', E)$ we need to specify the potential $V(r)$ in the Schrödinger equation. A Coulomb plus linear form, phenomenologically successful in describing quarkonia spectrum at $T = 0$, also gives a good parametrization of the lattice data on the static quark-antiquark potential for $0.1 \text{ fm} < r < 1 \text{ fm}$. Only at distances $r < 0.1 \text{ fm}$, not relevant for quarkonia studies, the effect of the running coupling is important [13]. At large distances, $r_{\text{med}} \approx 1.1 \text{ fm}$, the linear growth of the potential stops due to string break-

ing [14]. At high temperatures we expect that the effective range of the potential will be reduced and the interactions are exponentially screened at large distances. At sufficiently short distances, on the other hand, the interaction between the heavy quark and antiquark is temperature independent [13]. Motivated by the above, we use the following parametrization for the potential

$$V(r, T) = \begin{cases} -\frac{\alpha}{r} + \sigma r, & r < r_{\text{med}}(T), \\ V_{\infty}(T) - \frac{\alpha'(T)}{r} e^{-\mu(T)r}, & r > r_{\text{med}}(T). \end{cases} \quad (3)$$

Following the recent 2 + 1 flavor lattice QCD analysis [15], we fix $\alpha = 0.385$ and $\sigma = 1.263/r_0^2$, with $r_0 = 0.469$ fm being the Sommer-scale determined in [16]. At zero temperature we choose $r_{\text{med}} = 1.1$ fm and screening mass of $\mu = 0.4$ GeV. The later is motivated by the fact that the heavy-light meson pair is in the isosinglet channel. This choice then corresponds to $V_{\infty} \simeq 1.2$ GeV. The potential is shown in Fig. 1. For calculations of the charmonium spectral functions we have included in the potential also a relativistic spin-independent correction, estimated to be $-0.8\sigma/(m^2 r)$ [17]. The zero temperature potential with the above choice of the parameters gives a fairly good description of the quarkonium spectrum.

At finite temperature we fix the parameters in (3) utilizing the information available from lattice QCD on the free energy of a static heavy quark-antiquark pair. Free energy calculations are done in pure gluodynamics, 3-flavor and 2-flavor QCD [13,18,19], and preliminary results are also available in the physically relevant case of one heavy strange quark and two light quarks [15] (quark masses correspond to pion mass of about 200 MeV). These calculations show that the free energy is temperature independent for distances $r < 0.4$ fm/(T/T_c), while for distances $rT > 0.8$ it is exponentially screened, with a screening mass estimated to be $\mu(T) = 1.4(1)\sqrt{1 + N_f/6}g(T)T$ [13,19]. Here $g(T)$ is the 2-loop \overline{MS} gauge coupling at scale $2\pi T$. It was found also that at infinite separation of

the heavy quark and antiquark the free energy approaches a constant $F_{\infty}(T)$. At high temperatures perturbation theory tells us that $F_{\infty}(T)$ behaves like $-\alpha_s^{3/2}T$ [20] (lattice calculations confirm this behavior [13,15,18,19]). For $T > T_c$ we assume that $F_{\infty}(T) = a/T - bT$, where a and b are temperature-independent constants. The first term can be viewed as the contribution from a nonperturbative dimension two gluon-condensate [21], while the second term is the perturbative entropy contribution. This parametrization successfully describes the lattice data on $F_{\infty}(T)$ in pure gauge theory [21], and we checked that it works very well for $T > 1.1T_c$ also in 2 + 1 flavor QCD. In our numerical analysis we use the value $T_c = 0.192$ GeV determined in [22]. Although the 2 + 1 flavor lattice data on the free energy of static quark-antiquark used here were obtained on coarse lattices with temporal extent $N_{\tau} = 4$, discretization errors in this quantity are small [18].

It is important to note, that since it contains an entropy contribution, the free energy itself is not the potential. It can, nevertheless, provide some constraints on the parameters of (3). In particular, the discussion above implies $0.4 \text{ fm}/(T/T_c) < r_{\text{med}} < 0.8/T$, and due to the negative entropy contribution, $V_{\infty}(T) > F_{\infty}(T)$. We use $V_{\infty} = a/T$ and $\mu = 1.4\sqrt{1 + N_f/6}g(T)T$. The values of $\alpha'(T)$ are determined in [19]. The above described choice for V_{∞} , α' and μ , together with a requirement for the smoothness of the potential, predetermines the value of r_{med} . This turns out to be close to $0.4 \text{ fm}/(T/T_c)$, the value determined in lattice simulations. This physically motivated potential, labeled as set 1, is shown for different temperatures in Fig. 1. For comparison we display also the lattice data on the free energies. Denoted as set 2 in Fig. 1 an alternative choice, an upper bound on the finite temperature potential is shown: When fixing $r_{\text{med}} = 0.8/T$ the smoothness of the potential determines the value of $V_{\infty}(T)$. It turns out that this value is close to $U_{\infty}(T)$, the internal energy of the isolated static quark. We know that $U_{\infty}(T)$ provides an upper bound on the possible value of $V_{\infty}(T)$, because it contains all possible interactions of heavy quark with the medium. The values of $\mu(T)$ and $\alpha'(T)$ were fixed as in set 1. The numerical results on the spectral functions are mostly determined by the value of $V_{\infty}(T)$ and are insensitive to other details of the potential (see discussion in [12] also on the stability of the numerical solution).

In what follows we present numerical results for these two choices of the potential, and derive an upper bound for the dissociation temperatures. In Fig. 2 we show the spectral functions above the deconfinement temperature. The S -wave charmonium spectral function at $T = 1.1T_c$ exhibits a resonance peak with very small binding energy of about 0.014 GeV. Here, and in what follows, we define the binding energy as the distance between the peak position and the continuum threshold, $E_{\text{bin}} = 2m_{c,b} + V_{\infty} - M$, M being the resonance mass. Above $1.1T_c$ the charmonium spectral functions show no resonancelike structures, mean-

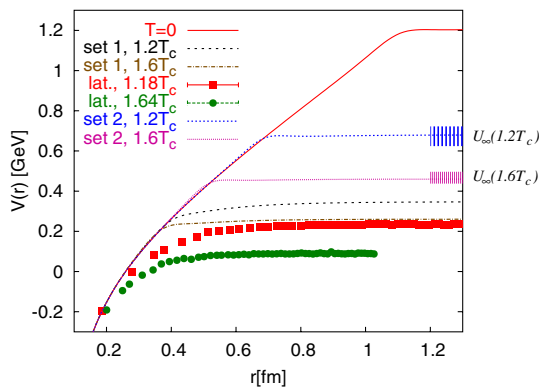


FIG. 1 (color online). The two choices of the potential (denoted as set 1 and set 2) used in our analysis for $1.2T_c$ and $1.6T_c$. We also show the free energy of static quark-antiquark pair calculated in 2 + 1 flavor QCD on the lattice [15].

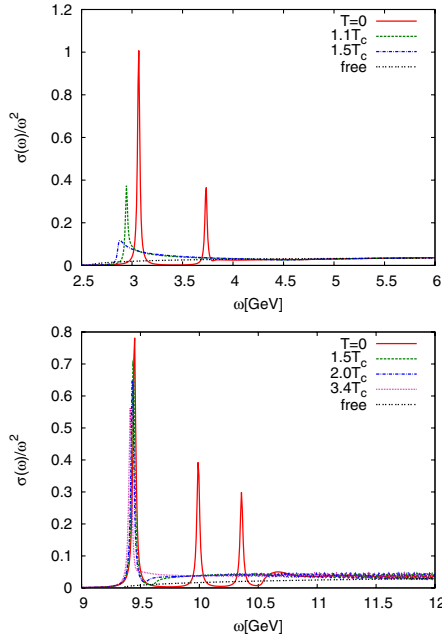


FIG. 2 (color online). S -wave charmonium (upper panel) and bottomonium (lower panel) spectral functions at different temperatures.

ing that all charmonium states are dissolved. Even though there are no resonances, the spectral function is strongly enhanced compared to the noninteracting case. This is also illustrated in Fig. 2. We would like to point out, that this threshold enhancement compensates for the dissociation of the states, and thus dramatic changes seen in the spectral function are not reflected in the correlation function (for a detailed discussion see [12]). Also, the strong enhancement in the threshold region is an indication that the heavy quark and antiquark remain correlated. In the case of bottomonium we see only the ground state above deconfinement, all other states are dissolved. Furthermore, as Fig. 2 shows, there is no significant change in the peak position of the ground state up to $2T_c$. Even though seemingly the resonance structure persists to temperatures even higher than this, the binding energy of the state is significantly reduced.

When the binding energy of a resonance drops below the temperature the state is weakly bound, and thermal fluctuations can destroy it by transferring energy and exciting the quark antiquark pair into the continuum. The rate of this excitation, or equivalently the width of the quarkonium states, is determined by the binding energy [23]. Therefore, in order to provide an upper bound on the dissociation temperature we need to estimate an upper bound for the binding energy. To do this, we calculate quarkonium spectral functions for the set 2 potential, providing the maximum possible binding still consistent with the lattice results on screening. We find that with this choice of the potential the S -wave charmonium spectral function has resonancelike structures up to $\sim 1.6T_c$. Furthermore, we also see resonancelike structures in the bottomonium spec-

tral functions corresponding to the $1P$ and $2S$ states. In the upper panel of Fig. 3 we show the corresponding binding energies of the different quarkonium states. Let us note, that in the past quarkonium widths at finite temperature have been calculated using perturbative QCD and the Boltzmann-approximation, assuming an ideal quark-gluon plasma. See [24] for a recent analysis. For quarkonium sizes realized in nature the validity of the perturbative calculations of the quarkonium-gluon cross section is doubtful. Furthermore, the Boltzmann-approximation breaks down if the binding energy is smaller than the temperature. In [23] the quarkonium dissociation rate due to thermal activation into the continuum has been estimated nonperturbatively, using a resonance plus a continuum model for the spectral function. The thermal dissociation rate $\Gamma(T)$ has a particularly simple form in two limits [23]: The limit of large and small binding, respectively:

$$\Gamma(T) = \frac{(LT)^2}{3\pi} M e^{-E_{\text{bin}}/T}, \quad E_{\text{bin}} \gg T, \quad (4)$$

$$\Gamma(T) = \frac{4}{L} \sqrt{\frac{T}{2\pi M}}, \quad E_{\text{bin}} \ll T. \quad (5)$$

Here L is the size of the spatial region of the potential, given by the distance from the average quarkonium radius to the top of the potential, i.e., $L = r_{\text{med}} - \langle r^2 \rangle^{1/2}$. From the top panel of Fig. 3 it is clear that for $T > 1.1T_c$ all

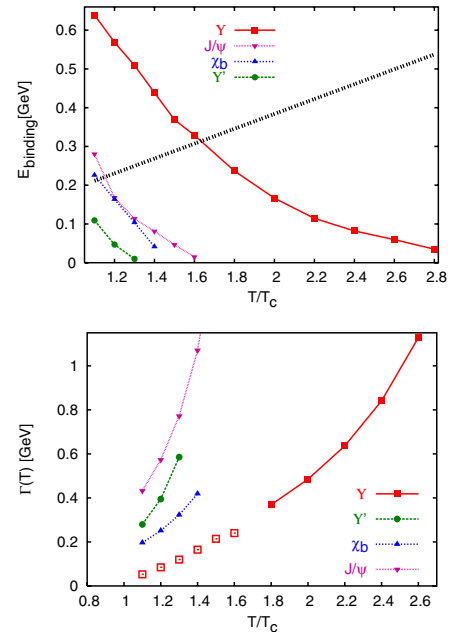


FIG. 3 (color online). An upper limit of the binding energy of different quarkonium states (top) and the quarkonium width (bottom). The open squares show the width of the $1S$ bottomonium state multiplied by six for better visibility, which has been calculated in the limit of small binding.

TABLE I. Upper bound on dissociation temperatures.

State	χ_c	ψ'	J/ψ	Y'	χ_b	Y
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

quarkonium states have binding energy smaller than the temperature, with the exception of the $Y(1S)$ state. Their width can thus be estimated using (5). The results are shown in the lower panel of Fig. 3. Note that all of these states have widths larger than 200 MeV, and are therefore likely to be dissociated in the plasma. In the case of the $Y(1S)$ for $T < 1.6T_c$ we use (4) to estimate the width, which is found to be smaller than 40 MeV. This is in fairly good agreement with the perturbative estimate of [24]. For temperatures $T > 1.6T_c$ even the $1S$ bottomonium is in the regime of small binding, and its width becomes very large by $2.6T_c$ (see Fig. 3). Note that uncertainty in the value of U_∞ in the lattice calculations, indicated as a band in Fig. 1, leads to uncertainty in the binding energy estimate of about 10%. When the thermal width is significantly larger than the binding energy the resonance structure seen in our calculation will not be observable in reality. We define the dissociation temperature as the smallest temperature where no resonance structure can be seen in the spectral function. The upper limit for the dissociation temperatures of the quarkonium states we determine by posing the conservative quantitative condition $\Gamma(T) \geq 2E_{\text{bin}}(T)$. The corresponding dissociation temperatures are summarized in Table I. A less conservative criterion $\Gamma(T) \geq E_{\text{bin}}(T)$ would reduce the dissociation temperature by roughly 10%.

In conclusion, we determined quarkonia spectral functions in the quark-gluon plasma using a potential model with two choices for the potential, both motivated by lattice QCD results on the free energy of a static quark-antiquark pair. We found that, due to color screening, for the first chosen potential most quarkonia states, except the Y , dissolve at temperatures close to that of deconfinement. For the most extreme potential which is still compatible with lattice data, resonance structure in the spectral functions exists up to higher temperatures. This potential provides an upper limit on the binding energy. Using the binding energy we calculate the width of various states, and give upper bounds on their dissociation temperatures which are significantly lower than previous estimates. As such, the model proposed in [25], where J/ψ suppression is due only to melting of the χ_c and ψ' states, cannot explain the nuclear modification factor R_{AA} measured in the experiments since color screening dissolves the J/ψ . On the other hand, the enhancement of the spectral function near the threshold shows that the heavy quarks and antiquarks remain strongly correlated in the plasma even though they do not form a bound state. This correlation could lead to the regeneration of some quarkonium states when the plasma converts to hadronic matter increasing R_{AA} values

above expectations from screening alone. The quark and antiquark may even reform into a higher excited state. For a quantitative description of R_{AA} , a model calculation of regeneration effects is needed. More precise calculations of the spectral function and detailed lattice calculations of the static quark-antiquark correlators will also be helpful.

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