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Thermal modification of quarkonium spectral functions from QCD sum rules with the maximum entropy method

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The quarkonium spectral functions at finite temperature are analyzed by employing QCD sum rules with the maximum entropy method. This approach enables us to extract the spectral functions without any phenomenological parametrization, and thus to visualize deformation of the spectral functions due to temperature effects driven by change of gluon condensates, which can be estimated in lattice QCD. As a result, it is found that the charmonium ground states of both S-wave and P-wave channels disappear at temperatures around or slightly above the critical temperature T_c, while the bottomonium states survive up to well above T_c, at least $2.5T_c$ for S-wave states and around $2.0T_c$ for P-wave states. Furthermore, a detailed analysis of Υ state shows that the obtained lowest peak at T=0 contains contribution not only from the ground state but also from the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$. Our results at finite T are consistent with the picture that the excited states of bottomonia dissociate at lower temperature than that of the ground state. Assuming this picture, we find that $\Upsilon(2S)$ and $\Upsilon(3S)$ disappear at $T = 1.5-2.0T_c$.

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1. Introduction

Quantum chromodynamics (QCD) predicts matter composed of deconfined quarks and gluons, called quark-gluon plasma (QGP). In such a state of matter, spectral property of quarkonium, a bound state of a heavy (charm or bottom) quark and a heavy antiquark, is expected to be modified and resultant yields will be suppressed, as being well-known as "quarkonium suppression" [1]. Recent experimental measurements have suggested significant modification of the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra in hot matter. Especially, for the bottomonium vector channel (Υ), a comparison between the p-p and Pb-Pb collisions at the Large Hadron Collider (LHC) indicates larger suppression of the excited states than the ground state [2, 3]. Our purpose of this work is to study these phenomena from a theoretical viewpoint.

QCD sum rules [4] are traditionally known as a powerful tool to investigate the properties of the hadrons from QCD. Recently, it has become possible to apply the maximum entropy method (MEM) technique to QCD sum rules [5], which allows to extract the most probable form of the spectral function from the operator product expansion (OPE) without assuming some specific functional form. This approach was successfully performed for the ρ meson [5], the nucleon with positive [6] or negative [7] parity and the quarkonia channels [8, 9].

In this work, we have investigated the behavior of charmonium [8] and bottomonium [9] spectral functions at finite temperature. Our approach [5] based on QCD sum rules and the MEM, enables us to extract directly the shape of the spectral functions. Therefore, this is a suitable tool to study the deformation of the spectral functions with respect to the change of the temperature. We then point out that bottomonium spectral functions are crucially different from those of charmonium in the sense that there are several excited states below the continuum threshold. Because of this, we have obtained a single peak of the spectral function as a mixture of the ground and excited states, i.e. our approach for the bottomonium cannot separate the ground state as an individual peak. We can, however, extract the behavior of the excited states at finite temperature by studying the temperature dependence of the residue of the peak.

In these proceedings, we show only the most important results of our investigations, while more details can be found in [8, 9].

2. Method

In analyses of QCD sum rules, we start with defining the hadronic current correlation function

$$\Pi^J(q) = i\int d^4x e^{iq\cdot x}\langle T[j^J(x)j^{J\dagger}(0)]\rangle, \tag{2.1}$$

where J stands for the pseudoscalar (P), vector(V), scalar (S), and axial-vector (A) channel. Each current is defined as $j^P = \bar{h}\gamma_5 h$, $j^V_\mu = \bar{h}\gamma_\mu h$, $j^S = \bar{h}h$, and $j^A_\mu = (q_\mu q_\nu/q^2 - g_{\mu\nu})\bar{h}\gamma_5\gamma^\nu h$ with h being the heavy quark operator.

Using the OPE, one can expand the operator $j^J(x)j^{J\dagger}(0)$ of Eq.(2.1) as a series of local operators O_n with mass dimension n in deep Euclidean region. Then, the dimensionless correlation functions, $\tilde{\Pi}^{P,S}(q^2) = \Pi^{P,S}(q)/q^2$ and $\tilde{\Pi}^{V,A}(q^2) = \Pi^{\mu V,A}_\mu(q)/(-3q^2)$, for $q^2 \ll 0$ are given as

$$\tilde{\Pi}^J(q^2) = \sum_n C^J_n(q^2)\langle O_n\rangle. \tag{2.2}$$

If the scale of the gluon condensates is smaller than the separation scale: $4m_h^2 - q^2 \gg \langle G\rangle \sim (\Lambda_{QCD} + aT + b\mu)^2$, one can assume that all the temperature effects are included in the expectation values of the local operators $\langle O_n\rangle$ [10, 11]. Thus the Wilson coefficients $C_n^J(q^2)$ can be considered to be independent of T, as long as the temperature is not too high. The details of the Wilson coefficients can be found in Ref. [11].

QCD sum rules are constructed from a dispersion relation derived from the analytic properties of hadronic current correlation functions. For the spectral function of the given channel J, $\rho^J(\omega)$, after the application of the Borel transform, one obtains

$$\mathscr{M}^J(\nu) = \int_0^\infty d\omega^2 e^{-\nu\omega^2/4m_h^2} \rho^J(\omega). \tag{2.3}$$

The left-hand side can be calculated through the OPE, Eq.(2.2), in the deep Euclidean region now given by $\nu \gg 1$, and then given by perturbative contributions and non-perturbative condensate terms where we include scalar gluon condensate $G_0(T) = \langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu}\rangle_T$ and twist-2 gluon condensate $\langle \frac{\alpha_s}{\pi} G^{a\mu\sigma} G^{a\nu}_{\sigma}\rangle_T = (u^\mu u^\nu - \frac{1}{4} g^{\mu\nu}) G_2(T)$. The temperature dependences of the gluon condensates are obtained using the approach proposed in Ref. [12], where the dimension-4 gluon condensates are related to the energy-momentum tensor, which can be expressed in terms of the energy density ε, the pressure p and the strong coupling constant α_s. In concrete, $G_0(T) = G_0^{vac} - \frac{8}{11}[\varepsilon(T) - 3p(T)]$ and $G_2(T) = -\frac{\alpha_s(T)}{\pi}[\varepsilon(T) + p(T)]$. We then utilize the results of quenched lattice QCD [13, 14] to obtain the temperature dependence of $\varepsilon(T)$, $p(T)$ and $\alpha_s(T)$.

In order to extract physical quantities which relate to the spectral function in Eq.(2.3), the conventional methods of analyzing QCD sum rules assume a particular form for the spectral function. One of the most popular ansatz is the “pole + continuum” form. By contrast, such an assumption is not necessary in our method [5] since the shape of spectral functions is directly extracted from the MEM.

3. Results

The results of the charmonium and bottomonium spectral functions at zero and finite temperatures are shown in Fig. 1 and Fig. 2. In the case of charmonium, all the peaks are suppressed at a temperature around or slightly above the critical temperature T_c. On the other hand, the bottomonium peaks survive at higher temperatures than the charmonium peaks. This difference of the melting temperatures is caused by the Wilson coefficients of the gluon condensate terms which are inversely proportional to the fourth power of the heavy quark mass.

	$m_{J/\psi}$	m_{η_c}	$m_{\chi_{c0}}$	$m_{\chi_{c1}}$	m_{Υ}	m_{η_b}	$m_{\chi_{b0}}$	$m_{\chi_{b1}}$
Results [GeV]	3.06	3.02	3.36	3.50	9.56	9.51	10.15	10.42
Exp. [GeV]	3.097	2.980	3.414	3.510	9.460	9.389	9.859	9.893

Table 1: Peak positions of the spectral functions at zero temperature from MEM and the experimental values for each ground state.

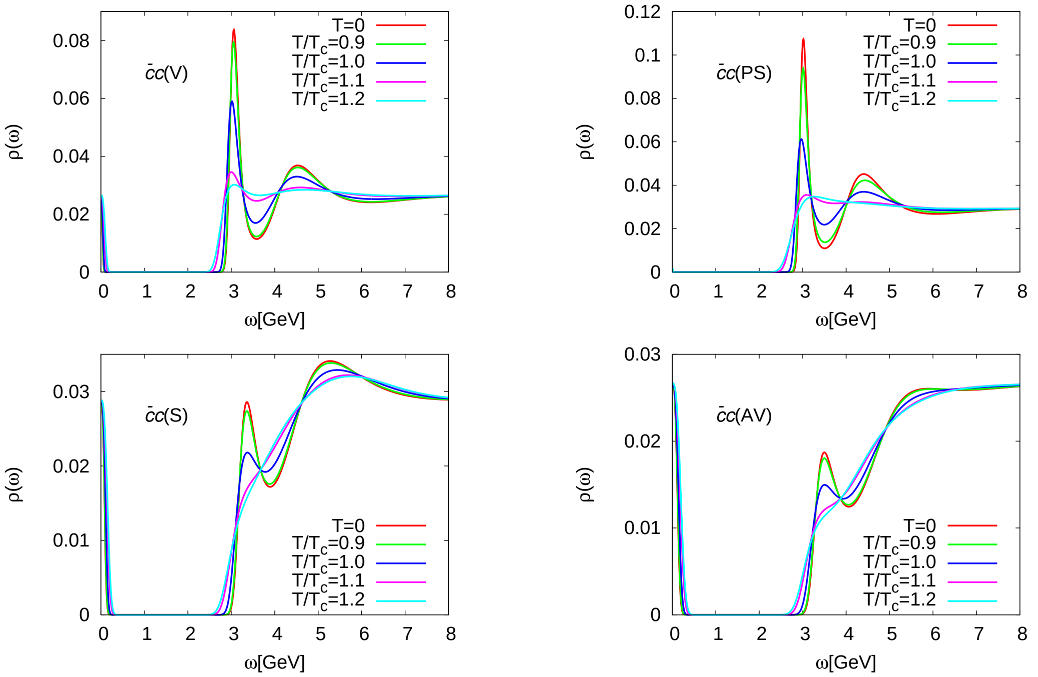

Figure 1: Spectral functions of charmonia at finite temperature from MEM. Upper left : vector (J/ψ), upper right : pseudoscalar (η_c), lower left : scalar (χ_{c0}), lower right : axial-vector (χ_{c1})[8].

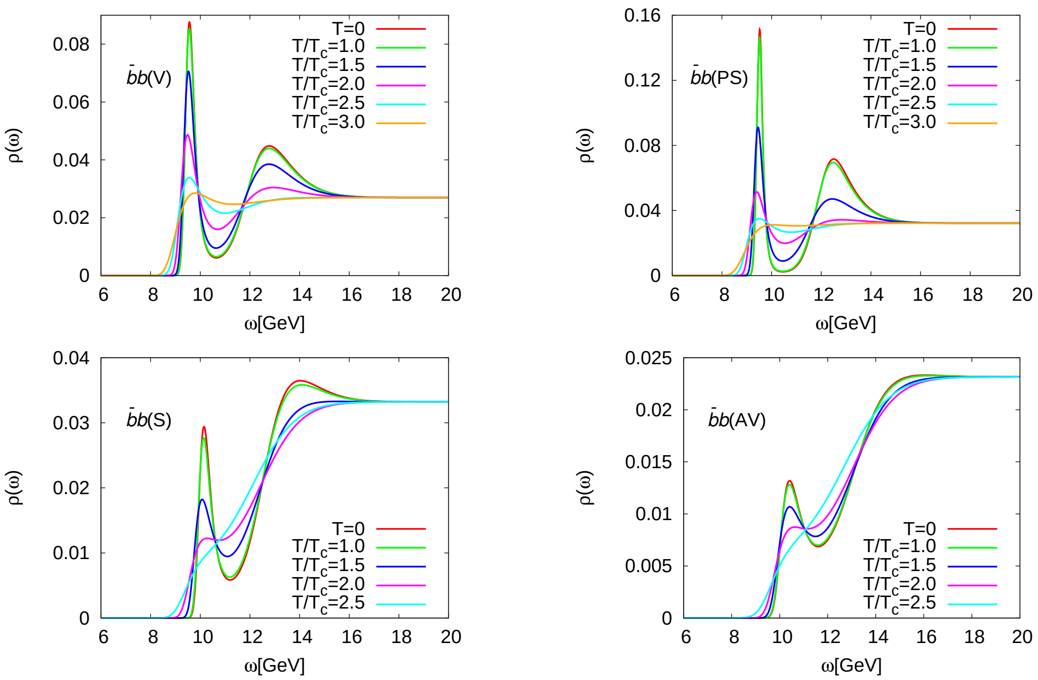

Figure 2: Spectral functions of bottomonia at finite temperature from MEM. Upper left : vector (Υ), upper right : pseudoscalar (η_b), lower left : scalar (χ_{b0}), lower right : axial-vector (χ_{b1}) [9].

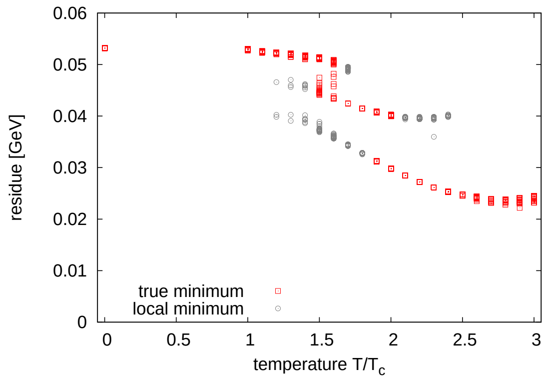

Figure 3: Temperature dependence of the residue for the vector channel bottomonium peak fitted with a Breit-Wigner + continuum. Squares are corresponding to true minima, and circles are local minima [9].

Furthermore, the obtained lowest peak position of each spectral function is shown in Table 1. The peak positions of charmonia are consistent with the experimental values of the masses of the ground states. For the bottomonia, the peak positions are shifted to higher energy regions than the experimental values. This behavior is caused by additional contributions of excited states to the lowest peaks as well as that of the ground state. To investigate thermal behavior of the excited states, we analyze the residue of the obtained peak for the vector channel. In order to exclude the continuum contributions to the peak and to estimate the sum of the residues only of the ground and excited states, we fit the obtained spectral functions by using a Breit-Wigner function for the peak and some suitable parametrization for the continuum. The result is shown in Fig. 3. It is observed that the residue of the Υ peak decreases gradually with increasing temperature and approaches a constant value at higher temperature. Especially, a rapid reduction of the residue is seen at $T/T_c = 1.5-2.0$. If we assume the disappearance of the excited states at lower temperature than the ground state, our results suggest that $\Upsilon(2S)$ and $\Upsilon(3S)$ disappear at $T/T_c = 1.5-2.0$, while $\Upsilon(1S)$ survives up to $T/T_c = 3.0$.

4. Conclusion and Outlook

In summary, we have analyzed the quarkonium spectral functions at zero and finite temperatures by using QCD sum rules and MEM. As a result, it is found that the charmonium ground states of both S-wave and P-wave channels disappear at temperatures around or slightly above T_c, while the bottomonium states are more stable. Namely the S-wave states survive up to about $2.5T_c$ or higher and P-wave dissolve about $2.0T_c$. Furthermore, to extract more detailed information on the bottomonium excited states of the vector channel, we have investigated the temperature dependence of the residue of the obtained lowest peak. Doing this, we have observed that the residue decreases with increasing temperature. The results are consistent with the experimental behaviors observed from LHC [2, 3].

As a next step, we will consider higher order terms in the quarkonium OPE. For example, in our previous works, we have only included 1st order α_s contribution for the perturbative part.

Higher order α_s corrections, however, are expected to improve the resolution of the spectral property at zero temperature, so it may give further detailed information on the different melting temperatures. A calculation including this contribution to the vector channels is presently ongoing [15].

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