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Quarkonium correlation functions at finite temperature in the charm to bottom region

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Quarkonium correlation functions at finite temperature were studied in a region of the quark mass for charmonia to bottomonia in quenched lattice QCD with $O(a)$-improved Wilson quarks. Our simulations were performed on large isotropic lattices at temperatures in the range from about $0.80T_c$ to $1.61T_c$. We investigated quarkonium behavior in terms of temperature dependence as well as quark mass dependence of the quarkonium correlation functions and related quantities at both vanishing and finite momenta.

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1. Introduction

Quarkonium is an important probe to investigate properties of strongly interacting matters in hot medium. In heavy ion collisions suppression of quarkonium production can signal formation of the deconfined quark and gluon phase called quark-gluon plasma due to the color screening of the quark-antiquark potential [1]. In fact, suppression of yields of J/ψ has been observed in nucleus-nucleus collisions at SPS [2], RHIC [3] and LHC [4, 5, 6]. Moreover, recently, the CMS collaboration has also reported suppression of the excited Υ state at LHC [7]. Because bottomonia are much heavier than charmonia, suppression signals of the bottomonia should suffer from smaller effects of cold nuclear matters and are expected to be cleaner comparing to the charmonium case. Therefore, theoretical understanding of bottomonium behavior at finite temperature is significant.

To study strongly interacting systems theoretically, a first principle calculation with lattice quantum chromodynamics (QCD) is one of reliable approaches. There are indeed many studies on charmonium behavior at finite temperature, which suggested that the S-wave states survive up to about $1.5T_c$, where T_c is the critical temperature. Some studies also indicated dissociation of the P-wave states just above T_c [8, 9, 10]. A most recent study with large fine lattices, however, showed a possibility of melting of the S-wave states below $1.46T_c$ [11] in contrast. For bottomonia, due to large mass of the bottom quark, only studies with an effective field theory called the non-relativistic QCD have been done, which suggested survival of the S-wave states up to $2T_c$ and dessication of the P-wave states immediately above T_c [12, 13]. A study without effective theory thus is desirable.

In this study we investigated quarkonium behavior at finite temperature in a region of the quark mass for charmonia to bottomonia with quenched lattice QCD simulation. Basically, the spectral function of the quarkonium has all the information of its in-medium properties and the spectral function $\rho_H(\omega,\vec{p},T)$ at certain temperature T is related to the Euclidean temporal correlator $G_H(\tau,\vec{p})$ as

$$G(\tau,\vec{p}) = \int_0^\infty \frac{d\omega}{2\pi}\rho(\omega,\vec{p},T)\frac{\cosh[\omega(\tau-1/2T)]}{\sinh[\omega/2T]}, \tag{1.1}$$

where $G_H(\tau,\vec{p})$ is defined by

$$G(\tau,\vec{p}) \equiv \int d^3x\, e^{-i\vec{p}\cdot\vec{x}}\langle J(\tau,\vec{x})J^\dagger(0,\vec{0})\rangle. \tag{1.2}$$

Here $J(\tau,\vec{x}) \equiv \bar{\psi}(\tau,\vec{x})\Gamma\psi(\tau,\vec{x})$ is the meson operator and $\Gamma = \gamma_5,\ \gamma_i,\ 1, \gamma_5\gamma_i\ (i=1,2,3)$ correspond to the pseudo-scalar (PS), vector (V), scalar (S) and axial-vector (AV) channels, respectively. In general, to extract $\rho(\tau,\vec{p},T)$ from $G(\tau,\vec{p})$ is quite difficult since it requires many data points in the temporal direction with statistically high precision. Therefore, as a first step, we focused on following two quantities instead of the spectral function itself: One is the screening mass $M_{\rm scr}$ defined by the spatial correlator $G(z)$ as

$$G(z)\underset{z\to\infty}{\longrightarrow} e^{-M_{\rm scr}z}, \tag{1.3}$$

where $G(z)$ is also related to $\rho(\omega,\vec{p},T)$ as

$$G(z) = \int_0^\infty \frac{2d\omega}{\omega}\int dp^3\delta(p_x)\delta(p_y)\, e^{i\vec{p}\cdot\vec{x}}\rho(\omega,\vec{p},T). \tag{1.4}$$

Table 1: Temporal extent N_τ, corresponding temperature T in the unit of T_c and number of configurations.

N_τ	48	32	28	24
T/T_c	0.80	1.21	1.38	1.61
# confs.	259	476	336	336

Table 2: κ value and corresponding vector meson mass m_V.

κ	0.13194	0.13150	0.13100	0.13000	0.12800	0.12257
m_V [GeV]	3.106(3)	3.442(3)	3.823(3)	4.565(3)	5.978(3)	9.464(3)

If there is a quarkonium ground state, the screening mass should be equal to corresponding mass while, in the free quark case, it can be written by the lowest Matsubara frequency πT and the quark mass m_q as $M_{\rm scr} = 2\sqrt{(\pi T)^2 + m_q^2}$. Another quantity investigated in this study is the reconstructed temporal correlator $G_{\rm rec}(\tau, T; T')$, where momentum $\vec{p}$ is abbreviated. This quantity is defined by using the spectral function at temperature T' and the integration kernel at T as

$$G_{\rm rec}(\tau, T; T') \equiv \int_0^\infty \frac{d\omega}{2\pi} \rho(\omega, T') \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh[\omega/2T]}. \tag{1.5}$$

Especially in case that $T/T' = N'_\tau/N_\tau$ is some integer, where N_τ and N'_τ are temporal extents, one can construct $G_{\rm rec}(\tau, T; T')$ with the conventional correlator $G(\tau, T')$ by

$$G_{\rm rec}(\tau, T; T') = \sum_{\tau'=\tau;\Delta\tau'=N_\tau}^{N'_\tau - N_\tau + \tau} G(\tau', T') \tag{1.6}$$

[11]. Then the ratio $G(\tau, T)/G_{\rm rec}(\tau, T; T')$ reduces the influence of trivial T dependence of the integration kernel and thus one can discuss temperature dependence of the spectral function itself.

2. Numerical results

Our simulations were performed by using the standard plaquette gauge and $O(a)$-improved Wilson fermion actions with the quenched approximation. The bare gauge coupling is $\beta = 7.192$, which corresponds to the lattice spacing $a \simeq 0.0190$ fm ($a^{-1} \simeq 10.4$ GeV) determined from Sommer scale $r_0 = 0.49$ fm. The lattice size is $96^3 \times N_\tau$ with the temporal extent $N_\tau = 48, 32, 28, 24$ corresponding to temperatures at $0.80T_c$, $1.21T_c$, $1.38T_c$ and $1.61T_c$, respectively, where $T_c \simeq 270$ MeV. On each lattice the gauge configurations were generated with the pseudo-heatbath algorithm and after 2000 sweeps for the thermalization, every 500 trajectories were stored for measurement. The temporal extent, corresponding temperature and number of configurations are summarized in Table 1. We chose 6 κ values as listed in Table 2, where corresponding vector meson mass m_V was given by the screening mass at $T = 0.80T_c$. Here the screening mass was estimated by fitting the spatial vector correlator to a single exponential. The largest and smallest κ values were tuned to reproduce the experimental values of J/ψ and Υ masses [14], respectively.

In Figure 1 temperature and quark mass dependence of the screening masses is shown, where each data is normalized by that for same quark mass and channel but at $T = 0.80T_c$. In case of the

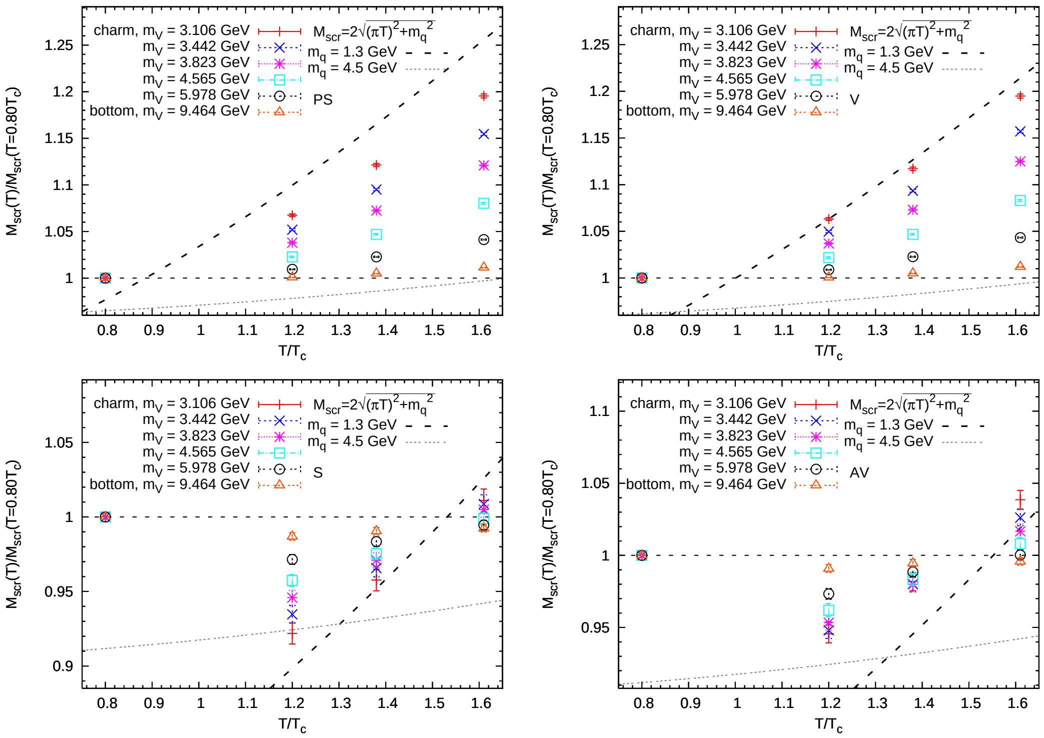

Figure 1: Temperature and quark mass dependence of the screening masses for PS (top-left), V (top-right), S (bottom-left) and AV (bottom-right) channels. Each data is normalized by that for same quark mass and channel but at $T = 0.80T_c$. Free quark cases with $m_q = 1.3$ GeV and 4.5 GeV are also plotted with bold-dashed and dotted curves, respectively.

S-wave channels the screening mass increases as temperature increases for all the quark masses and the temperature dependence is smaller for larger quark mass. Especially for the bottomonia the thermal effect is negligibly small up to $1.21T_c$ and only about 1% even at $1.61T_c$. This means that there is no clear evidence of the dissociation of the S-wave bottomonium states at least up to $1.21T_c$. On the other hand, the P-wave channels have quite different temperature dependence for all quark masses comparing to the S-wave case, namely, the screening mass decreases above T_c at first and then increases as increasing temperature. This suggests that not only the charmonia but also the bottomonia can have non-negligible thermal contribution just above T_c. In addition, the non-monotonic temperature dependence seems to be related to the fact that the quarkonium mass can be larger than the screening mass in the free quark case in the most of the temperature range investigated in this study, although one should carefully check the m_q dependence.

Figure 2 shows quark mass dependence of the ratio of the temporal correlator at $T = 1.61T_c$ to the corresponding reconstructed correlator given by using the $T = 0.80T_c$ data. For all channels the ratio has some quark mass dependence only at larger τ/a part, where small ω part of the spectral function would be dominate. Since the small ω part of the spectral function is expected to consist of some bound state and transport peaks if they exist, this quark mass dependence should correspond to the quark mass dependence for the modification of the bound state and transport peaks due to the thermal effect. In this sense the bound state or transport peaks of the V, S and AV spectral functions seem to be strongly modified above T_c. Here, to separate the $\omega = 0$ contribution, which

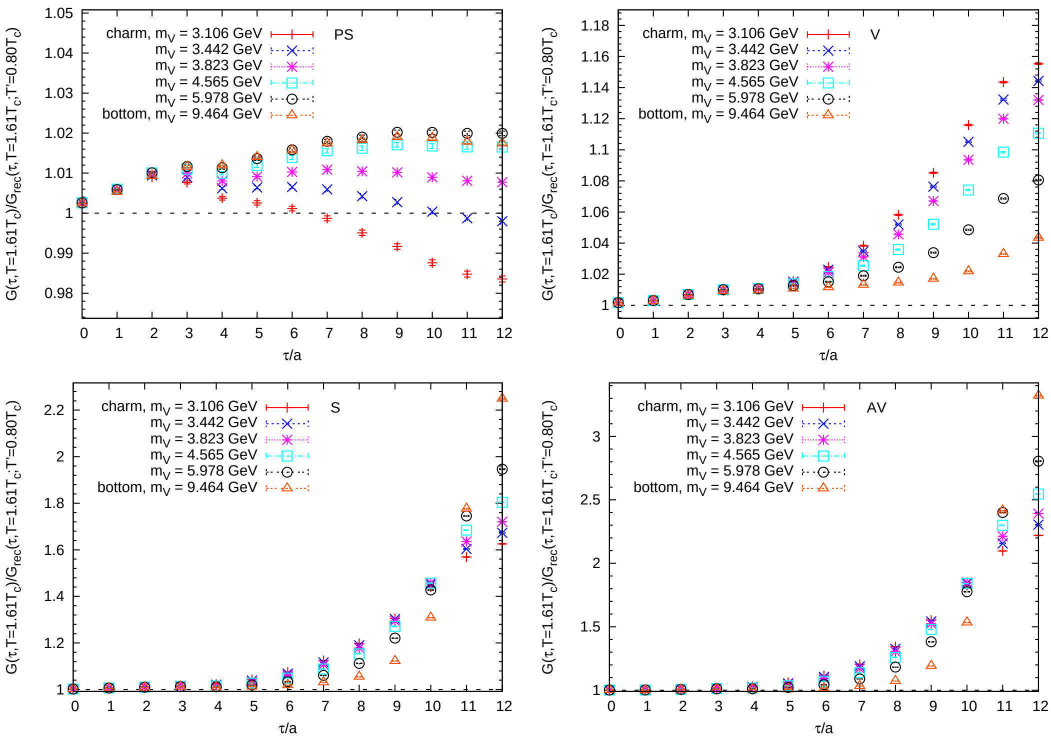

Figure 2: Quark mass dependence of the ratio of the temporal correlator at $T = 1.61T_c$ to the corresponding reconstructed correlator given from the $T = 0.80T_c$ data for PS (top-left), V (top-right), S (bottom-left) and AV (bottom-right) channels.

would be most dominant part of the transport peak, from the other part in the spectral function, we adopted the midpoint subtraction technique [15] to both the denominator and the numerator of the ratio. Figure 3 shows similar result to Figure 2 but the midpoint subtraction technique is applied. In this case the strong modification mentioned above disappears. This means that the most part of the strong modification at small ω part in the spectral function is due to the transport contribution and the PS channel doesn't have such contribution. Moreover, the S-wave channels have similar quark mass dependence to each other and the modification of the spectral function is larger for larger quark mass. On the other hand, the both of P-wave channels have small quark mass dependence and the modification is large for all quark masses.

Finally, we consider non-zero momentum case, which is related to quarkonia moving in medium. Momentum dependence of the same ratio discussed above is shown in Figure 4. For the charmonia there is about 10–20% momentum dependence at the largest τ/a for all channels while the bottomonia have small momentum effect within the range of momentum investigated in this study, except for the AV channel.

3. Conclusions

We studied quarkonium behavior at finite temperature in the region of the quark mass for charmonia to bottomonia on large isotropic lattices. We investigated the screening mass and the reconstructed correlator. The screening masses for the S-wave channels had larger thermal effect

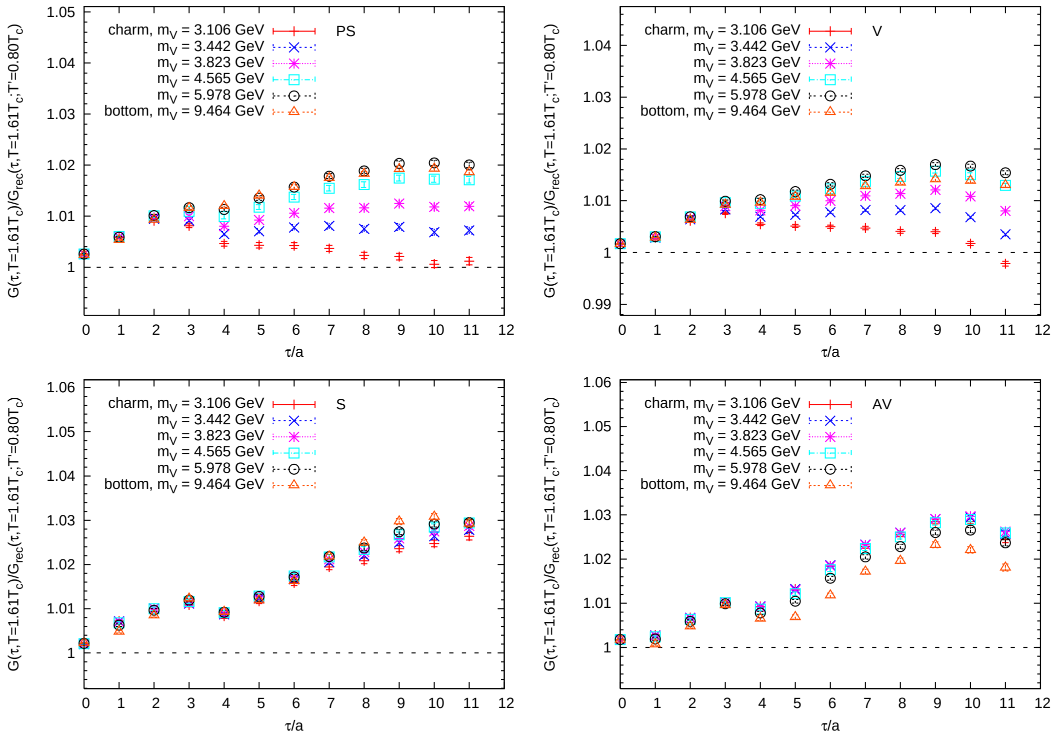

Figure 3: Same as Figure 2 but the midpoint subtraction technique is applied.

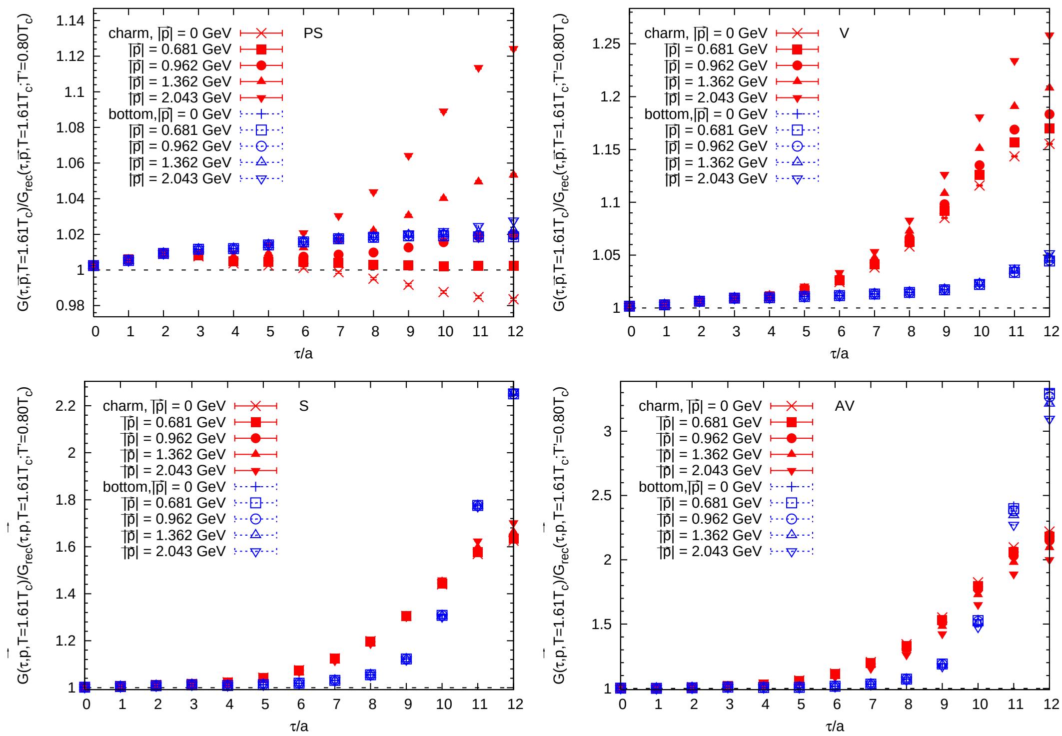

Figure 4: Momentum dependence of the same quantity shown in Figure 2.

for lighter quark mass and it was negligibly small for the bottomonia up to $1.21T_c$. In case of the P-wave the screening mass was modified just above T_c even for the bottomonia. According to the reconstructed correlator study at $1.61T_c$, it was found that the spectral function for V, S and AV channels had large transport contribution. The remaining part had larger thermal effect for larger quark mass for the S-wave states but only small quark mass dependence for the P-wave states. The reconstructed correlator was also investigated at finite momenta and the bottomonia except for the AV channel had quite small momentum dependence in the range of momentum we investigated.

Direct investigation of the spectral function, computing transport coefficients and performing simulation on finer and larger lattices to take a continuum limit are our future plan.

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