Charmonia above the Deconfinement Phase Transition

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Analyzing correlation functions of charmonia at finite temperature ($T$) on $32^3 \times (32 - 96)$ anisotropic lattices by the maximum entropy method (MEM), we find that $J/\psi$ and $\eta_c$ survive as distinct resonances in the plasma even up to $T \simeq 1.6 T_c$ and that they eventually dissociate between $1.6 T_c$ and $1.9 T_c$ ($T_c$ is the critical temperature of deconfinement). This suggests that the deconfined plasma is non-perturbative enough to hold heavy-quark bound states. The importance of having sufficient number of temporal data points in the MEM analysis is also emphasized.

1. INTRODUCTION

Whether hadrons survive even in the deconfined quark-gluon plasma is one of the key questions in quantum chromodynamics (QCD). This problem was first examined in \cite{1} and \cite{2} in different contexts. The fate of the heavy mesons such as $J/\psi$ in the deconfined plasma was also investigated in a phenomenological potential picture taking into account the Debye screening \cite{3}. In general, there is no a priori reason to believe that dissociation of the bound states should take place exactly at the phase transition point \cite{4}.

From the theoretical point of view, the spectral function (SPF) at finite temperature $T$, which has all the information of in-medium hadron properties, is a key quantity to be studied. Recently, the present authors have shown \cite{5} that the first-principle lattice QCD simulation of SPFs is possible by utilizing the maximum entropy method (MEM). We have also formulated the basic concepts and applications of MEM on the lattice at $T = 0$ and $T \neq 0$ in \cite{6}. To draw the conclusion with a firm ground, in the following we put special emphases on \textbf{I} the MEM error analysis of the resultant SPFs and \textbf{II} the sensitivity of the SPFs to $N_{\text{data}}$ (the number of temporal data points adopted in MEM). These tests are crucial to prevent fake generation and/or smearing of the peaks and must be always carried out as emphasized in \cite{6,7,8}.

2. LATTICE SIMULATION

The applications of MEM to $T \neq 0$ system have been known to be a big challenge \cite{6}. The difficulty originates from the fact that the temporal lattice size $L_\tau$ is restricted as $L_\tau = 1/T = N_\tau a_\tau$, where $a_\tau$ ($N_\tau$) is the temporal lattice spacing (number of temporal lattice sites). Because of this, it becomes more difficult to keep enough $N_{\text{data}}$ to obtain reliable SPFs as $T$ increases. Thus, simulations up to a few times $T_c$ with $N_{\text{data}}$ as large as 30 \cite{7} inevitably require an anisotropic lattice.

On the basis of the above observation, we have carried out quenched simulations with $\beta = 7.0$ on $32^3 \times N_\tau$ anisotropic lattice with $N_\tau = 32, 40, 46, 54$, and 96. The renormalized anisotropy is $\xi = a_\sigma/a_\tau = 4.0$ with $a_\sigma$ being the spatial lattice spacing. We take the naive plaquette gauge action and the standard Wilson quark action. Corresponding bare anisotropy $\xi_0 = 3.5$ is determined from the data given in \cite{9,10}. The fermion anisotropy $\gamma_F \equiv \kappa_\tau/\kappa_\sigma = 3.476$ with $\kappa_\sigma = 0.08285$ ($\kappa_\tau = 0.2880$) being the the spatial (temporal) hopping parameter is determined by comparing the temporal and spatial effective masses of pseudoscalar and vector mesons on a...
32^2 \times 48 \times 128 \text{ lattice. } a_\tau = a_x / 4 = 9.75 \times 10^{-3} \text{ fm is determined from the } \rho \text{ meson mass in the chiral limit. The masses determined on } T = 0 \text{ (32^2 \times 48 \times 128) lattice are } m_{J/\psi} = 3.10 \text{ GeV and } m_{\eta_c} = 3.03 \text{ GeV. If the temporal distance between the source and the sink is closer than } \xi a_\tau, \text{ lattice artifact due to anisotropy would appear in the SPFs for } \omega \geq \pi/\xi a_\tau. \text{ To avoid this, we exclude the six points near the edge } (\tau_i = 1, 2, 3 \text{ and } N_\tau - 3, N_\tau - 2, N_\tau - 1) \text{ and adopt the points } \tau_i = 4, 5, \cdots \text{ and } N_\tau - 4, N_\tau - 5, \cdots \text{ until we reach the total number of points } N_{\text{data}}(< N_\tau - 7)^1.

3. RESULTS

Shown in Fig. 1 are \( \rho(\omega) \)’s for \( J/\psi \) at \( T/T_c = 0.78, 1.38, \) and 1.62 (Fig. 1(a)) and those at \( T/T_c = 1.87 \) and 2.33 (Fig. 1(b)) (Corresponding \( N_{\text{data}} \) used in these figures are \( N_{\text{data}} = 89, 40, 34, 33, \) and 25 from low \( T \) to high \( T \). If the deconfined plasma were composed of almost free quarks and gluons, SPFs would show a smooth structure with no pronounced peaks above the \( q\bar{q} \) threshold. To the contrary, we find a sharp peak near the zero temperature mass even up to \( T \approx 1.6T_c \) as shown in Fig. 1(a), while the peak disappears at \( T \approx 1.9T_c \) as shown in Fig. 1(b). The width of the first peak in Fig. 1(a) partly reflects the unphysical broadening due to the statistics of the lattice data and partly reflects possible physical broadening at finite \( T \). At the moment, the former width of a few hundred MeV seems to dominate and we are not able to draw definite conclusions on the thermal mass shift and broadening.

Let us now evaluate the reliability of the existence (absence) of the sharp peak at \( T/T_c = 1.62(1.87) \) by the two tests [I] and [II] mentioned before. First test is the error analysis of the peak. Shown in Fig. 2 are the SPFs for \( J/\psi \) at \( T/T_c = 1.62 \) and 1.87 with MEM error bars (The frequency interval over which the SPF is averaged is characterized by the horizontal position and extension of the bars, while the mean value and the \( 1 \sigma \) uncertainty of the integrated strength within the interval are characterized by the heights of the bars). The sharp peak at \( T = 1.62T_c \) is statistically significant, and the absence of the peak at the same position at \( T = 1.87T_c \) is also statistically significant. The features found for \( J/\psi \) in Figs. 1 and 2 are also observed for \( \eta_c \).

The second test is the \( N_{\text{data}} \) dependence of the SPFs. Shown in Fig. 3(a) is the comparison of SPF obtained with \( N_{\text{data}} = 34 \) and that of \( N_{\text{data}} = 39 \) for the same temperature \( T = 1.62T_c \) \( (N_\tau = 46) \). The two curves are almost identical with each other. Fig. 3(b) shows SPFs obtained with \( N_{\text{data}} = 26 \) and 33 for higher temperature \( T = 1.87T_c \) \( (N_\tau = 40) \). Again the two curves are almost identical. Therefore, the qualitative change of the SPF between \( T = 1.62T_c \) and \( 1.87T_c \) is the real thermal effect and not caused by the artifact of the insufficient number of data points.

To conclude, we have studied the spectral functions of \( J/\psi \) and \( \eta_c \) in the deconfined plasma us-

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1 For further details of the lattice simulation, see [3].

2 Following [3], we define dimensionless SPFs: \( A(\omega) = \omega^2 \rho(\omega) \) for \( \eta_c \) and \( A(\omega) = 3\omega^2 \rho(\omega) \) for \( J/\psi \).
ing lattice Monte Carlo data and the maximum entropy method. The number of temporal sites \( N_r \) is taken as large as 46 and 40 for \( T/T_c = 1.62 \) and 1.87, respectively. Careful analyses of the MEM errors and the \( N_{\text{data}} \) dependence of the results are carried out. It is found that there are distinct resonances up to \( T \simeq 1.6T_c \) and they disappear between 1.6\( T_c \) and 1.9\( T_c \).

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