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On Charmonia Survival Above Deconfinement

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We study charmonium correlators and spectral functions at zero and finite temperature using anisotropic lattices at several different lattice spacings. We find evidence for survival of 1S charmonia states at leas till $1.5T_c$ and dissolution of 1P states at $1.16T_c$.

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1. Introduction

Heavy quarkonia can play an important role in studying hot and dense strongly interacting matter. Because of the heavy quark mass quarkonia binding can be understood in terms of the static potential. Also becasue of their relatively small size they do not experience the medium till relatively high temperatures. General considerations suggest that quarkonia will melt at temperatures right above the deconfinement temperature as a result of modification of inter-quark forces (color screening). Thus it was conjectured by Matsui and Satz [1] that melting of different quarkonia states due to color screening can signal Quark Gluon Plasma formation in heavy ion collisions. Classic studies of quarkonia dissolution [2, 3, 4, 5, 6, 7] rely heavily on potential models. However it is very unclear if such models are valid at finite temperature [8]. As an alternative method to approach this problem we may use lattice to determine meson spectral functions. For charmonium such studies appeared only recently and suggested, contrary to potential models, that J/ψ and η_c survive at temperatures as high as $1.6T_c$ [9, 10, 11]. It has been also found that χ_c melts at temperature of about $1.1T_c$ [11]. In principle, meson spectral functions offer an attractive possibility to study the properties of radially excited quarkonium states. In particular it is straightforward to determine quarkonium decay width to dilepton. In recent studies of charmonium spectral functions several peaks were identified beyond and ground state [9, 10, 11]. It is not clear, however, if any of those peak correspond to radial excitation. Moreover it has been argued that all peaks in the spectral functions except the first one are lattice artifacts [11].

In this contribution we focus on our updated results for the charmonium; bottonium results and detailed study of the Maximum Enthropy Method reliability will be presented in our upcoming paper. Preliminary results for bottomonium can be also found in Ref. [12].

2. Meson correlators and spectral functions

In our lattice investigation we calculate correlators of point meson operators of the form

$$J_H(t,x) = \bar{q}(t,x)\Gamma_H q(t,x), \tag{2.1}$$

where $\Gamma_H = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \gamma_\mu\gamma_\nu$ fixes the quantum number of the channel to scalar, pseudo-scalar, vector, axial-vector and tensor channels correspondingly. The relation of these quantum number channels to different meson states is given in Tab. 1.

Γ	$^{2S+1}L_J$	J^{PC}		$c\bar{c}(n=1)$	$c\bar{c}(n=2)$
γ_5	$^1S_0$	0^{-+}		η_c	η_c'
γ_s	$^3S_1$	1^{--}		J/ψ	ψ'
$\gamma_s\gamma_{s'}$	$^1P_1$	1^{+-}		h_c	
1	$^3P_0$	0^{++}		χ_{c0}	
$\gamma_5\gamma_s$	$^3P_1$	1^{++}		χ_{c1}	
		2^{++}		χ_{c2}	

Table 1: Charmonia states in different channels

Most dynamic properties of a finite temperature system are incorporated in the spectral function. The spectral function $\sigma_H(p_0,\vec{p})$ for a given mesonic channel H in a system at temperature T can be defined through the Fourier transform of the real time two-point functions $D^>$ and $D^<$ or, equivalently, as the imaginary part of the Fourier transformed retarded correlation function [13],

$$\sigma_H(p_0,\vec{p}) = \frac{1}{2\pi}(D_H^>(p_0,\vec{p}) - D_H^<(p_0,\vec{p})) = \frac{1}{\pi} Im D_H^R(p_0,\vec{p}) \tag{2.2}$$

$$D_H^{>(<)}(p_0,\vec{p}) = \int \frac{d^4p}{(2\pi)^4} e^{ip.x} D_H^{>(<)}(x_0,\vec{x}) \tag{2.3}$$

$$D_H^>(x_0,\vec{x}) = \langle J_H(x_0,\vec{x}), J_H(0,\vec{0})\rangle$$

$$D_H^<(x_0,\vec{x}) = \langle J_H(0,\vec{0}), J_H(x_0,\vec{x})\rangle, \quad x_0 > 0 \tag{2.4}$$

The Euclidean time correlator calculated on the lattice

$$G_H(\tau,\vec{p}) = \int d^3x e^{i\vec{p}.\vec{x}} \langle T_\tau J_H(\tau,\vec{x}) J_H(0,\vec{0})\rangle \tag{2.5}$$

is an analytic continuation of the real time correlator $G_H(\tau,\vec{p}) = D^>(-i\tau,\vec{p})$.

Using this equation and the Kubo-Martin-Schwinger (KMS) condition [13] for the correlators

$$D_H^>(x_0,\vec{x}) = D^<(x_0 + i/T,\vec{x}), \tag{2.6}$$

one can relate the Euclidean propagator $G_H(\tau,\vec{p})$ to the spectral function, Eq. (2.2), through the integral representation

$$G(\tau,\vec{p}) = \int_0^\infty d\omega \sigma(\omega,\vec{p}) K(\omega,\tau)$$

$$K(\omega,\tau) = \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)}. \tag{2.7}$$

To reconstruct the spectral function from the lattice correlator $G(\tau,T)$ this integral representation should be inverted. Since the number of data points is less than the number of degrees of freedom (which is $\mathcal{O}(100)$ for reasonable discretization of the integral) spectral functions can be reconstructed only using the Maximum Entropy Method (MEM) [14]. In order to have sufficient number of data points either very fine isotropic lattices [11] or anisotropic lattices [9, 10] should be used. Another difficulty arises due to the large quark mass; discretization errors $\mathcal{O}(am_{c,b})$ are present in the heavy quark system. To remove these discretization errors we use the Fermilab approach [15, 16].

We performed calculation of charmonia correlators in quenched QCD using anisotropic lattices and Wilson gauge action. For charmonium we use following gauge coupling values $\beta =$ 5.6, 5.7, 5.9, 6.1 with anisotropy $\xi = a_s/a_t = 2$ and $\beta = 6.1$, 6.5 with $\xi = 4$. When the lattice spacing is set using the Sommer scale $r_0 = 0.5$ fm the above gauge coupling correspond to lattice spacing $a_t^{-1} = 1.56$, 1.91, 2.91, 4.11, 8.18, 14.12 GeV. Further details of the lattice action together with the parameters can be found in Ref. [17, 18].

To be able to reconstruct the spectral functions high statistical accuracy for charmonia correlators is required. This makes calculations computationally intensive, so we performed them on a

prototypes of RBRC QCDOC machine. It is a dedicated Lattice QCD machine developed by physicists from Columbia University, BNL, RIKEN and UKQCD. Three such machines, each reaching about 10TFlops peak performance, are currently installed at BNL and EPCC. Our prototypes were single-motherboard machine at about 50 GFlops peak. Such resources are still not adequate for the full QCD simulations, so we use quenched approximation, which is equivalent to neglecting quark loops. Typical statistics gathered was 500 to 1000 measurements, separated by 400 updates.

3. Bayesian analysis of meson correlators

In Bayesian analysis of the correlator one looks for a spectral function which maximizes the conditional probability $P[\sigma|DH]$ of having the spectral function σ given the data D and some prior knowledge H (for a reviews see [14, 19]). Different Bayesian methods differ in the choice of the prior knowledge. One version of this analysis which is extensively used in the literature is the *Maximum Entropy Method* (MEM) [12, 9, 10, 11, 14]. In this method the basic prior knowledge is the positivity of the spectral function and the prior knowledge is given by the Shannon - Janes entropy

$$S = \int d\omega \left[\sigma(\omega) - m(\omega) - \sigma(\omega) \ln(\frac{\sigma(\omega)}{m(\omega)}) \right]. \tag{3.1}$$

The real function $m(\omega)$ is called the default model and parametrizes all additional prior knowledge, about the spectral functions, such as the asymptotic behavior at high energy [14]. For this case the conditional probability

$$P[\sigma|DH] = \exp(-\frac{1}{2}\chi^2 + \alpha S), \tag{3.2}$$

with χ^2 being the standard likelihood function and α a real parameter. To maximize $P[\sigma|DH]$ usually the Bryan algorithm [20] is used. We use a new approach (to be described in [17]) which through exact mathematical transforamtions reduces the problem to the task of minimization of a function with positive definite second derivative. This is a minimization problem in number-of-data dimensions, which is not any more difficult task than applying a χ^2 method. The Bryan algorithm takes different approach of singular value decomposition in order to find a relevant subspace, where minimization is performed.

4. Spectral functions at zero temperature

The spectral function for pseudo-scalar charmonium spectral functions is shown in Fig. 1. The first peak in the spectral function corresponds to $\eta_c(1S)$ state. The position of the peak and the corresponding amplitude (i.e. the area unders the peak) are in good agreement With the results of simple exponential fit. The second peak in the spectrak function is most likely the combination of the excited states as its position and amplitude is higher than what one would expect for 2S state. The spectral function becomes sensitive to the effects of the lattice spacings for $\omega > 5$GeV. In this ω region the spectral functions becomes sensitive to the choice of the default model. This is because only a very few data points in the correlator carry information about the spectral function in that region.

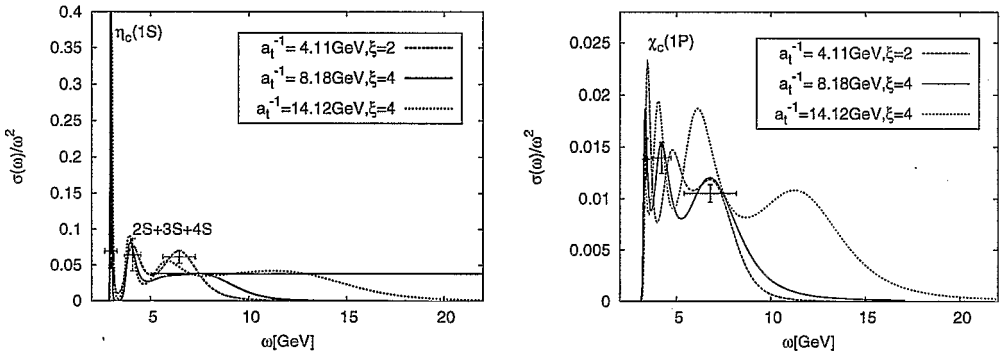

Figure 1: Charmonium spectral function in the psuedoscalar channel (left) and the scalar channel (right) at different lattice spacings and zero temperature.

Also shown in Fig.1 is the spectral function in the scalar channel. The 1st peak corresponds to $\chi_{c0}(1P)$ state. The correlator is more noisy in the scalar channel than in the pseudo-scalar one. As the results the $\chi_{c0}(1P)$ peak is less pronounced and has larger statistical errors. The peak position and the area unders the peak is consistent with the simple exponential fit. As in the psudo-scalar case individula excited states are not resolved and the spectral function depends on the lattice spacing and default model for $\omega > 5$GeV.

Similar results have been found for the vector and axial-vector channels which correspond to J/ψ and χ_{c1} states respectively.

We would like to know what happens to different charmonia states at temperatures above the deconfinement temperature T_c. With increasing temperature it becomes more and more difficult to reconstruct the spectral functions as both the number of available data points as well as the physical extent of the time direction (which is $1/T$) decreases. Therefore it is useful to study the temperature dependence of charmonia correlators first. From Eq. (2.7) it is clear that the temperature dependence of charmonia correlators come from two sources: the temperature dependence of the spectral function and temperature dependence of the integration kernel $K(\tau,\omega,T)$. To separate out the trivial temperature dependence due to the integration kernel, following Ref [11] at each temperature we calculate the so-called reconstructed correlator

$$G_{recon}(\tau,T) = \int_0^\infty d\omega\sigma(\omega,T=0)K(\tau,\omega,T) \tag{4.1}$$

Now if we assume that there is no temperature dependence in the spectral function - then the ratio of the original and the reconstructed correlator should be close to one, $G(\tau,T)/G_{recon}(\tau,T) \sim 1$. This way we can identify the cases when spectral function itself changes dramatically with temperature. This gives reliable information about the fate of charmonia states above deconfinement.

In Fig. 2 we show this ratio at $\beta = 6.5$ and 6.1 for pseudoscalar and scalar channels of charmonium correspondingly.

>From the figures one can see that the pseudo-scalar correlators shows only very small changes till $1.5T_c$ indicating that the η_c states survives till this temperature with little modification of its properties. On the other hand the scalar correlator shows large changes already at $1.16T_c$ suugesting strong modification or dissolution of the χ_{c0} state at this temperature.

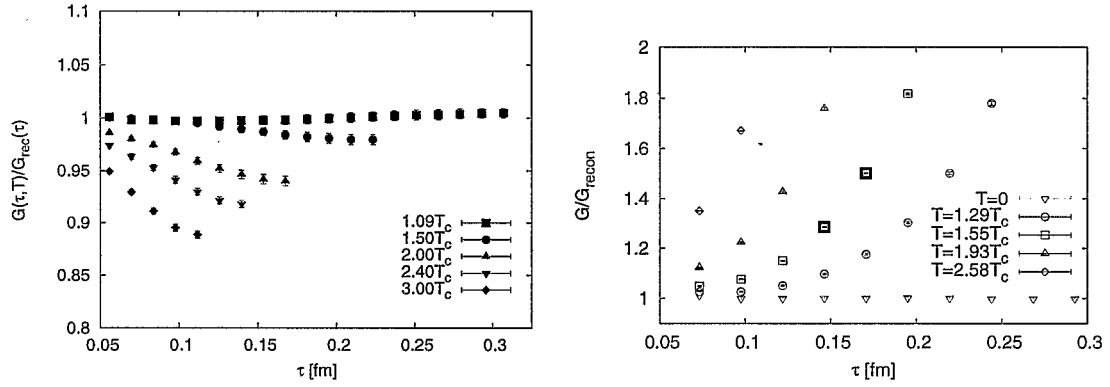

Figure 2: The ratio $G(\tau,T)/G_{recon}(\tau,T)$ of charmonium for pseudoscalar channel at at $a_t^{-2} = 14.11\text{GeV}$ (left) and scalar channel at at $a_t^{-2} = 8.18\text{GeV}$ (right) at different temperatures.

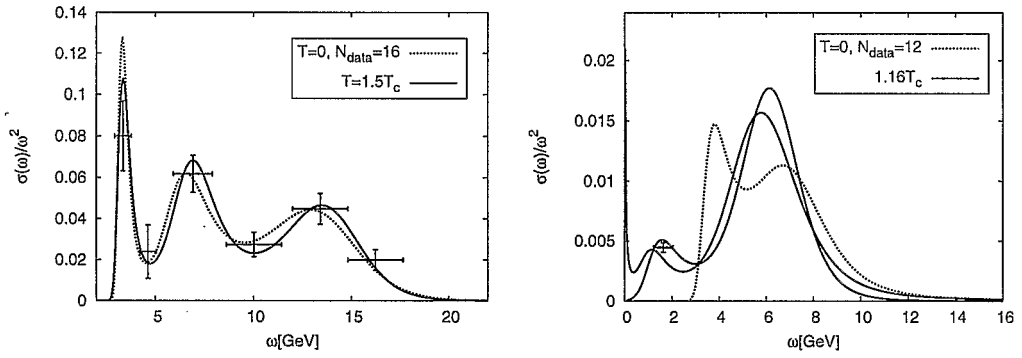

Figure 3: Charmonium spectral function in the psuedoscalar channel at $a_t^{-2} = 14.11\text{GeV}$ (left) and the scalar channel (right) at $a_t^{-2} = 8.18\text{GeV}$ at zero and above deconfinement temperatures. For finite temperature scalar chanel two different default models are shown.

More detailed information on different charmonia states at finite temperature can be obtained by calculating spectral functions using MEM. The result of these calculation is show in Figs. 3. Because at high temperature the temporal extent and the number of data points where the correlators are calculated become smaller the spectral functuon reconstructed using MEM are less reliable. To study the temperature modifications of the spectral function we compare the finite temperature spectral functions against the zero spectral functions obatined from the correlator using the same time interval and number of data points available at finite temperature. We see that spectral function in the pseudo-scalar channel show no temperature dependence within the statistical errors shown in the figure in accord with the analysis of the correlation functions. Also the spectral functions show very little dependence on the default model.

The scalar spectral function on the other hand shows large changes at $1.16T_c$ which is consistent with correlator-based analysis. Also default model dependence of the scalar correlator is large above the deconfinement transition (c.f. Fig. 3, right).

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