BI-TP 2004/07, DESY 04-049

Charmonium systems after the deconfinement transition

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Abstract. The behavior of charmonia after the deconfinement transition is investigated on quenched lattices. Analysis of temporal correlators on fine lattices at temperatures upto 3 T_c show that the J/ψ and η_c survive the deconfinement transition with little significant changes, and survive as bound states at least upto 2.25 T_c. The spatially excited χ_{c_i} states suffer serious system modifications, maybe dissolution, already a little above T_c.

The behavior of charmonia in heavy ion collisions has received considerable attention ever since Matsui & Satz suggested absence of J/ψ bound states as a signal of deconfinement, based on nonrelativistic potential model arguments [1]. A different, more dynamical line of argument supported this suggestion, showing that the hard gluons available in the deconfined plasma will readily break the J/ψ (treating J/ψ as a Coulombic state) [2]. Direct studies on quenched lattices, however, show a quite different picture: the 1S states like J/ψ and η_c survive the deconfinement transition with little significant change, and bound states survive in gluonic plasma at least upto temperatures of 1.5 T_c [3, 4, 5]. Here we report an update of our results in reference [3]. Further details, including discussion of systematics, can be found in [6].

Lattice studies of finite temperature QCD employ the Matsubara formalism, in which field theory at thermal equilibrium is studied by trading the time axis for the inverse temperature. The detailed properties of mesonic states can be obtained from the Matsubara correlators

$$G_H(\tau,T) = \langle J_H(\tau) J_H^{\dagger}(0)\rangle_T. \quad (1)$$

Here J_H is the suitable hadronic operator, τ denotes the Euclidean time and we consider zero momentum operators only. An integral equation then connects $G_H(\tau,T)$ to the spectral function, $\sigma_H(\omega,T)$, for the operator:

$$G_H(\tau,T) = \int_0^{\infty} d\omega \sigma_H(\omega,T) \frac{\cosh(\omega(\tau-1/2T))}{\sinh(\omega/2T)}. \quad (2)$$

The high temperatures that are of interest to us correspond to a small temporal extent. In order to have a reasonable number of data points for the correlator, we use very fine lattices. We present results here for two sets of lattices, with lattice spacings ~ 0.02 and 0.04 fm, respectively, using the finer set to reach higher temperatures and the coarser set for temperatures closer to T_c. For each set, we use a quark mass close

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to the charm ($m_{J/\psi} \sim 3.1$ GeV for the coarser set and ~ 3.7 GeV for the finer set), and change the time extent N_τ to vary the temperature. Details of the lattices studied and the corresponding temperatures are tabulated below.

a[fm]	$N_\sigma^3 \times N_\tau$	T/T_c	# configs.	a[fm]	$N_\sigma^3 \times N_\tau$	T/T_c	# configs.
	$48^3 \times 24$	0.75	100		$40^3 \times 40$	0.9	85
0.04	$48^3 \times 16$	1.12	50	0.02	$64^3 \times 24$	1.5	80
	$48^3 \times 12$	1.5	60		$48^3 \times 16$	2.25	100
					$48^3 \times 12$	3.0	90

The ill-defined problem of inverting Equation (2) to extract $\sigma(\omega, T)$ can be handled with the "maximum entropy method" (MEM) [7], which provides a prior guess for the solution through a Shannon-Jaynes "entropy" term(see [8] for a review). The application of this method at finite temperature has led to important qualitative information about the dilepton yield from an equilibriated plasma [9]. However, the small extent of the Euclidean time direction at finite temperature makes the problem even more difficult [4], and the role of the prior information becomes important (see [6] for details).

The pseudoscalar and vector states are explored by using the point-point operators $J_H = \bar{c}\gamma_5 c$ and $\bar{c}\gamma_\mu c$, respectively. The lightest states in these channels correspond to η_c and J/ψ respectively. The extraction of the spectral functions below T_c, using Equation (2) and applying the MEM procedure, is stable and reproduces the properties of the ground state reasonably well. The spectral functions for these states at 0.9 T_c (for the lattice with lattice spacing 0.02 fm; see table above) are shown in Figure 1 a). Here we plot $\rho(\omega, T) = \sigma(\omega, T)/\omega^2$. The ground state peaks and their strengths reproduce reasonably well the mass and amplitude obtained from a fit. The peaks at higher ω scale roughly with the lattice spacing and are probably dominated by lattice artefacts (see the discussion in reference [6]).

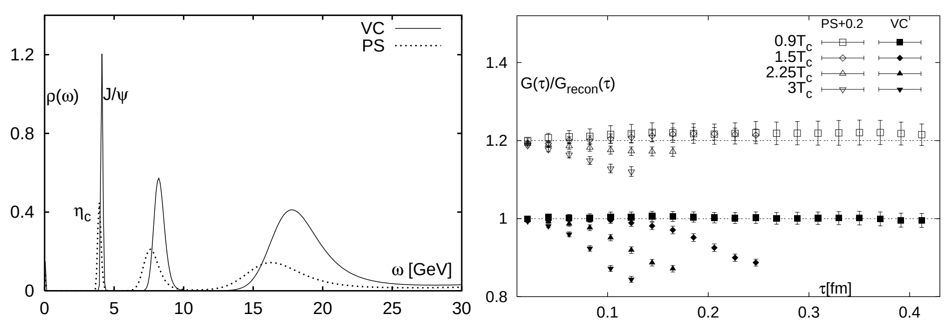

Figure 1. a) The spectral function extracted from the temporal correlators at 0.9 T_c in pseudoscalar and vector channels. The first peaks correspond to η_c and J/ψ respectively. b) $G(\tau, T)/G_{\mathrm{recon,T^*}}(\tau, T)$, where $G_{\mathrm{recon,T^*}}(\tau, T)$ is constructed from the spectral functions in a) (see text).

As a first step towards looking for the effect of the deconfinement transition on the J/ψ , one can ask the question whether the spectral functions in Figure 1 a) explain the correlators above T_c. We construct the model correlators above T_c according to Equation (2),

$$G_{\mathrm{recon,T^*}}(\tau, T) = \int_0^\infty d\omega \sigma(\omega, T^*) \frac{\cosh(\omega(\tau - 1/2T))}{\sinh(\omega/2T)} \qquad (3)$$

where T^* is a temperature below T_c, in this case 0.9 T_c. A comparison of $G_{\mathrm{recon,T^*}}(\tau, T)$ with the directly measured correlators $G(\tau, T)$ give an indication of temperature modification of the mesonic properties above the transition.

This simple comparison turns out to reveal a lot about the properties of J/ψ and η_c above the transition. Figure 1 b) shows the result of such a comparison. For the η_c channels, the spectral function at 0.9 T_c is seen to completely explain the measured correlators at 1.5 T_c, indicating that there is no significant change in this channel upto this temperature. At 2.25 T_c, $G(\tau, T)$ shows only small deviations from $G_{\mathrm{recon,T^*}}(\tau, T)$, while at 3 T_c significant changes are seen. For the vector channel, at 1.5 T_c $G(\tau, T)$ is described by $G_{\mathrm{recon,T^*}}(\tau, T)$ at small distances, while small deviations are seen at larger distances. The deviations appear at shorter distances at 2.25 T_c, while pretty large deviations are seen at all distances at 3 T_c.

A more detailed view of the temperature modifications of the mesons can be obtained by extracting the spectral function directly at higher temperatures, by application of the MEM. At these temperatures, the small extent of the temporal direction makes a reliable extraction of the spectral function difficult without proper a-priori information. However, precise information about the structure of $\rho(\omega, T)$ at large ω, obtained from Figure 1 a), allows a reliable extraction of the spectral function [6]. As part of the prior guess, we provide the large ω structure from Figure 1 a), smoothly connected to $\sim \omega^2$ behavior at low ω. The spectral functions extracted with such a prior guess are shown in Figure 2.

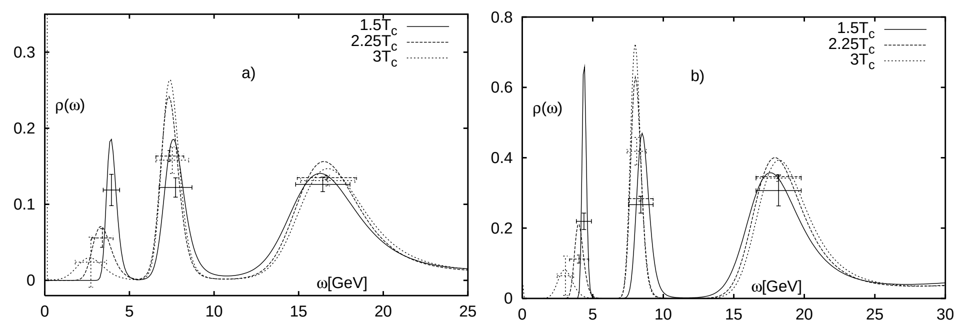

Figure 2. Spectral functions in the deconfined plasma, for a) η_c and b) J/ψ channels.

Figure 2 supports the trend seen in Figure 1 b). In the η_c channel, a strong peak is seen at 1.5 T_c, with an essentially unchanged position and strength from that below T_c. In the J/ψ also a strong peak is seen upto 1.5 T_c; no significant reduction in mass or peak strength is seen upto this temperature (see refernce [6] for a discussion of possible changes at this temperature). At 2.25 T_c, a significant peak is still seen in both the channels, but with a much reduced strength. Furthermore, we do not see a statistically significant peak at 3 T_c. (The error bars are standard deviations over the integrated strength, integrated over the marked region in the x direction; see reference [8].)

While the 1S states seem to be little affected by the deconfinement transition, the situation seems to be quite different for the 1P states χ_{c_0} and χ_{c_1} . A similar analysis indicates that these states are significantly modified on crossing the transition point. In order to study these states, we use the point operators $J_H(x) = \bar{c}c$ and $\bar{c}\gamma_5\gamma_\mu c$, respectively. A reliable extraction of the spectral function below T_c is possible, with the ground state peak reproducing the mass and strength obtained from a fit. At high

ω, lattice artefacts similar to those in Figure 1 a) dominate. In Figure 3 a) we show the comparison of the correlators for the axial vector and scalar channels at 1.1 and 1.5 T_c with those reconstructed from the spectral function at 0.75 T_c. The figure indicates a very significant modification of the properties of the states in these channels, already at 1.1 T_c. Figure 3 b) shows the spectral functions extracted above T_c for the scalar channel. As above, we use the high energy structure below T_c as part of the prior guess. The figure indicates that the χ_{c_0} state may have dissolved already at 1.1 T_c. A very similar figure is also obtained for the χ_{c_1} state.

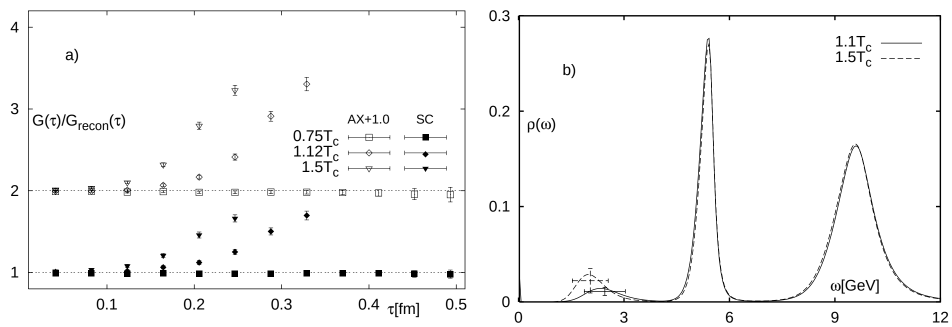

Figure 3. a) $G(\tau,T)/G_{\rm recon}(\tau, 0.75T_c)$ for the scalar and axial vector channels. b) The spectral function for the scalar channel.

These results have direct experimental relevance for the dilepton signal from an equilibriated plasma. The differential dilepton rate is directly related to $\rho(\omega, T)$ in the vector channel:

$$\frac{dW}{dwd^3p}|_{\vec{p}=0} = \frac{5\alpha^2}{27\pi^2}\frac{1}{(e^{\omega/T}-1)}\rho_V(\omega,T). \tag{4}$$

Therefore our results for spectral function indicate that the dilepton signal should have a significant J/ψ peak even for plasma temperatures above 2 T_c. On crossing T_c, the absence of the χ_{c_i} states will cause a reduction of the J/ψ peak due to the absence of the "indirect" J/ψ from χ_{c_i} decay (this may happen even below T_c for full QCD). No further significant reduction of the peak strength will be seen at least upto temperatures of 1.5 T_c, while reaching even higher temperatures will result in a weakening of the peak (possibly due to collision broadening). The results presented here, of course, only refer to a gluonic plasma. However, in a deconfined quark-gluon plasma the collision of the J/ψ with the hot thermal gluons is expected to be the significant mechanism for dissolving the J/ψ [2]; the above results thus should hold at least qualitatively also for full QCD.

This research is supported by BMBF under grant no. 06BI102.

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