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Charmonium spectral functions in Nf=2 QCD

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We report on a study of charmonium at high temperature in 2-flavour QCD. This is the first such study with dynamical fermions. Using an improved anisotropic lattice action, spectral functions are extracted from correlators in the vector and pseudoscalar channels. No signs of medium-induced suppression of the ground states are seen for temperatures up to $1.5T_c$, while at $T \sim 2T_c$ there are clear signs of modifications. The current systematic and statistical uncertainties in our data, in particular the relatively coarse lattice and small volume, do not allow us to draw a firm conclusion at this stage.

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1. Introduction

The fate of charmonium states in the deconfined phase of QCD has long been a subject of interest, following the suggestion [1] that J/ψ suppression may be a signature of deconfinement in heavy-ion collisions. Potential model calculations indicated that J/ψ might disappear from the spectrum almost immediately after deconfinement, providing an unambiguous signature. Recent lattice calculations [2, 3, 4] have cast doubt over this, indicating instead that J/ψ may survive in the plasma up to temperatures as high as $1.5-2T_c$. However, all these studies have been carried out in the quenched approximation, raising serious questions about their reliability.

The properties of hadrons in the medium are encoded in the spectral functions $\rho(\omega,\vec{p})$, which are related to the imaginary-time correlator $G(\tau,\vec{p})$ according to

$$G_\Gamma(\tau,\vec{p}) = \frac{1}{2\pi}\int_0^\infty \rho_\Gamma(\omega,\vec{p})K(\tau,\omega)d\omega, \tag{1.1}$$

where

$$K(\tau,\omega) = \frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)} = e^{\omega\tau}n_B(\omega)+e^{-\omega\tau}[1+n_B(\omega)]\,. \tag{1.2}$$

Here, n_B is the Bose–Einstein distribution function. Spectral functions may also be used to extract transport coefficients, while at non-zero momentum they contain information about phenomena such as Landau damping [5].

Determining $\rho(\omega)$ from lattice correlators $G(\tau)$ is an ill-posed problem, but it is possible to get a handle on it using the Maximum Entropy Method (MEM) [6]. It is however crucial to have a sufficient number of points in the euclidean time direction, and for this purpose anisotropic lattices have a strong advantage over the more common isotropic formulation. A further advantage is that it allows the temperature to be varied in small steps while keeping the lattice spacing and spatial volume fixed.

2. Simulation details

We use the Two-plaquette Symanzik Improved gauge action [7] and the fine-Wilson, coarse-Hamber-Wu fermion action [8] with stout-link smearing [9]. The fermion action has been designed with heavy quarks in mind, and a quenched study [8] found that the same bare anisotropy can be used for valence quark masses ranging from well below strange to well beyond charm. All-to-all propagators [10] with no eigenvectors and two noise vectors diluted in time, colour and even/odd in space, were used to improve the signal. The parameters correspond to point 5 in [11]. Using the 1S–1P splitting in charmonium to set the scale, the lattice spacings were found to be $a_t = 0.025$fm, $a_s = 0.2$fm, with the (quark) anisotropy $\xi \sim 8$ determined from the charmonium dispersion relation. The sea quark mass corresponds to $m_\pi/m_\rho \approx 0.55$.

Anisotropic lattices with dynamical fermions involve problems that are not present in the quenched approximation: since the gauge fields depend on the fermions, it is not possible to first fix the gauge anisotropy and then tune the fermion anisotropy so that the physical (measured) anisotropy for the fermions matches that of the gauge fields. Instead, the fermion and gauge anisotropies must be tuned simultaneously [11]. We do not as yet have data at the fully tuned point given in [11], so unequal quark and gluon anisotropies are still a significant source of systematic uncertainty.

We have performed simulations on $N_s^3 = 8^3$ lattices with $N_t = 48, 32, 24$ and 16, corresponding to $T \approx 0.75, 1.1, 1.5$ and $2.2T_c$ respectively. In all three cases we have used 100 configurations, sampling configurations every 10 HMC trajectories. In addition we have simulated at $N_t = 28, 30, 33-35$ in an attempt to locate T_c.

In this preliminary study we only look at zero momentum. The euclidean correlators have been computed using local (unsmeared) operators:

$$G_\Gamma(\tau) = \sum_{\vec{x},\vec{y},t} \langle \overline{\psi}(\vec{x},t)\Gamma\psi(\vec{x},t)\overline{\psi}(\vec{y},t+\tau)\Gamma\psi(\vec{y},t+\tau)\rangle\,, \tag{2.1}$$

with $\Gamma = \gamma_5, \gamma_i, 1, i\gamma_5\gamma_i$, corresponding to the pseudoscalar, vector, scalar and axial-vector channel respectively. The signal in the scalar and axial-vector channels is poor and those results will not be shown here.

The MEM analysis has been performed with the continuum free spectral function ω^2 as default model, using the euclidean correlators in a time window starting at $\tau = 2$, and cutting off the energy integral in (1.1) at $a_t\omega_{\max} = 6$.

3. Results

Figure 1 shows the average Polyakov loop $\langle L\rangle$ as a function of $1/N_t$. We find that with our small volume and large lattice spacing it is not possible to determine the critical temperature, since no region exhibits a particularly rapid change in this quantity. In agreement with this, the Polyakov loop susceptibility has no discernable peak in this region. Larger lattices will be required to determine T_c. In the absence of any such determination we take T_c to be in the region where $\langle L\rangle$ begins to assume a value significantly above zero.

We have computed correlators for bare quark masses $a_t m_0 = 0.1, 0.2$, where 0.1 is close to but slightly lighter than the physical charm quark mass. Figure 2 shows the spectral function obtained from MEM for the pseudoscalar (η_c) and vector (J/ψ) channels. The position of the main peak for $N_t = 48$ agrees with the mass obtained for the respective particles on the same lattices, using a variational basis of smeared operators [12]. The second peak cannot be identified with the first radially excited state, which on these lattices is found to be $a_t m' = 0.52$ [12], in agreement with the PDG value for ψ'. It is most likely a combination of lattice artefacts and contributions from excited states 2S, 3S etc, which cannot be resolved by the present data.

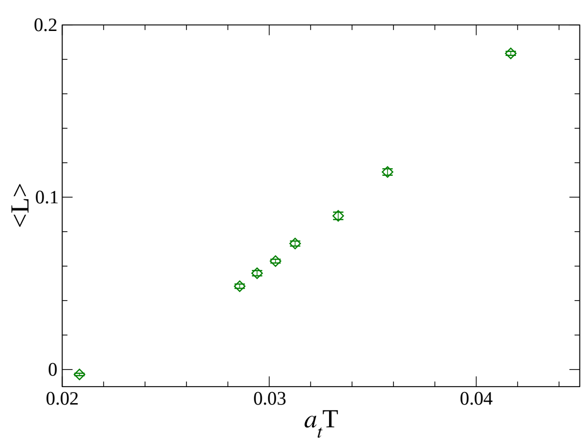

Figure 1: Average Polyakov loop as a function of temperature.

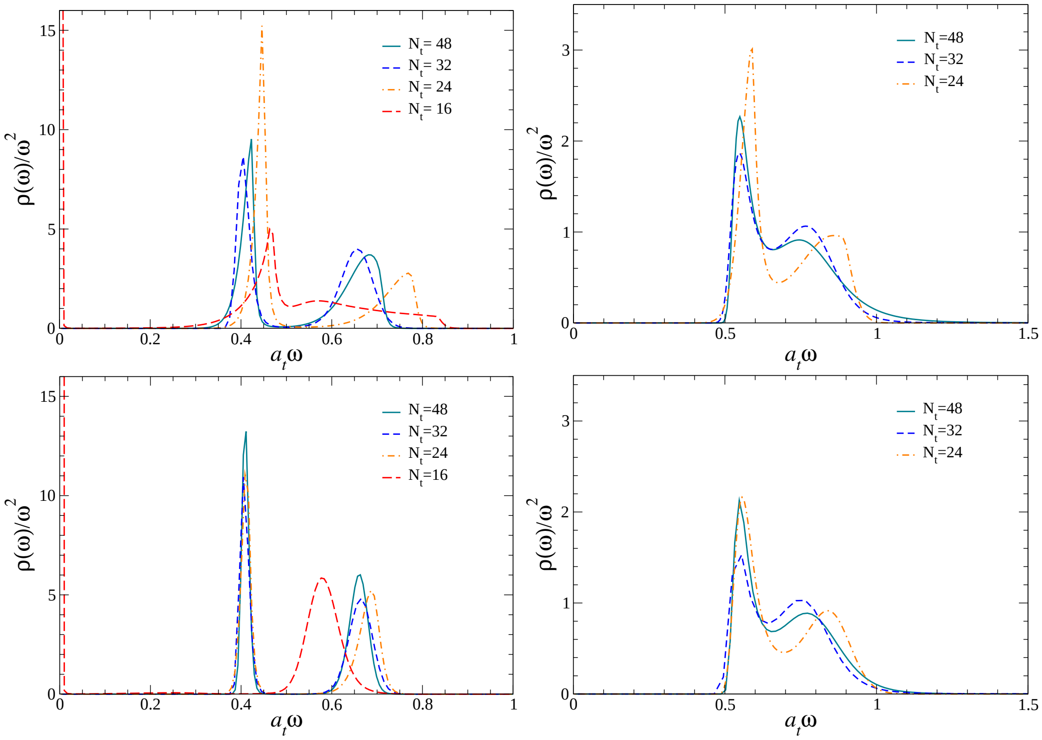

Figure 2: Pseudoscalar (η_c, top) and vector (J/ψ, bottom) spectral function for different temperatures and bare quark mass $a_t m_0 = 0.1$ (left) and 0.2 (right).

The issue of lattice artefacts can be addressed by comparing with the free lattice spectral function, which is shown in fig. 3, together with the continuum free spectral functions. The most striking feature is the cusp at $a_t\omega \sim 0.6(0.77)$ for $a_t m_0 = 0.1(0.2)$, which coincides with the second peak in our data. It is thus not possible to attribute any physical significance to the second peak in our data. The lattice spectral functions also undershoot the continuum curve at an early stage, indicating that a finer lattice is highly desirable. Due to the lattice cutoff, the free spectral functions go to zero for $a_t\omega \gtrsim 1.25$, and it would thus be sensible to also cut off the integral in (1.1) near this point.

Taken at face value, the results shown appear to indicate that the 1S states remain unchanged, or may even (in the case of η_c) become more strongly bound, at temperatures 1–1.5T_c. This would not be entirely surprising in light of recent calculations of heavy quark internal energies [13]. However, it will be necessary to investigate to what extent these results remain unchanged with

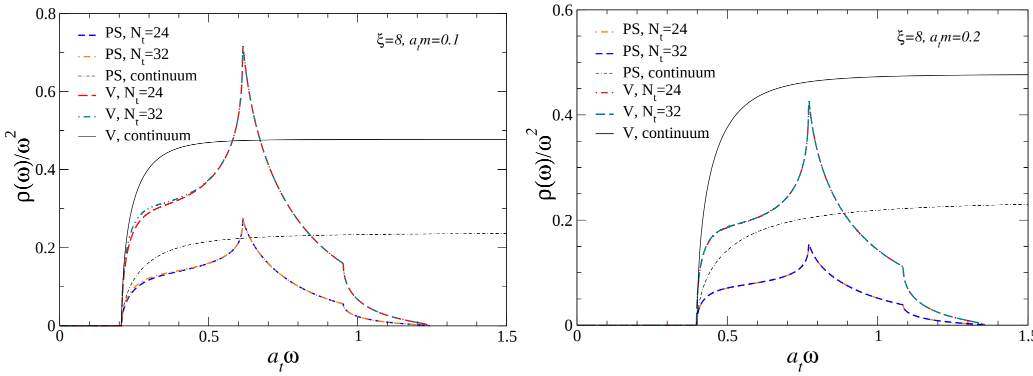

Figure 3: Free-fermion spectral functions in the pseudoscalar and vector channels, for bare quark mass $a_t m_0 = 0.1$ (left) and 0.2 (right).

increased statistics. We find some dependence on the range of time separations used in the analysis; this may be statistics-related.

At $N_t = 16$ the signal has changed substantially: the second peak has disappeared, while the primary peak is substantially weakened and shifted to higher energies, indicating a melting of the charmonium 1S states. There is also a non-zero signal at low ω, but whether this reults in a non-zero conductivity requires further investigation.

4. Discussion and outlook

The results presented here appear to confirm the picture emerging from quenched simulations, that J/ψ and η_c survive in the medium up to $1.5T_c$ or higher, while excited states begin to melt away at lower temperatures. There are even indications that η_c might be more strongly bound at intermediate temperatures, which, if true, would be in accordance with recent results for the internal quark–antiquark internal energy [13]. No such changes are seen for J/ψ, spoiling this agreement. There are, however, a number of issues that must be addressed before any conclusions can be drawn with confidence.

An important source of systematic uncertainty is that the anisotropy has not been completely tuned: the quark anisotropy is significantly larger than the gluon anisotropy. This can lead to the quarks "feeling" a higher temperature than the gauge fields. It will be important to repeat these calculations with a fully tuned parameter set.

The lattice volume used in this initial study is quite small, at only 1.6 fm^3, so finite volume effects may have a substantial impact on the results. Future simulations will be carried out on a larger volume. It is also important to increase the statistics, in particular if we wish to study the effects on higher excited states, which will only be clearly resolved with higher statistics. This is also necessary if the effects of the zero-temperature decay width (negligible for J/ψ), thermal width and effects of finite statistics are to be resolved.

As the free spectral functions in fig. 3 indicate, our coarse spatial lattice means that lattice artefacts are substantial even at relatively low energies. Although this problem may be ameliorated somewhat by using the free lattice spectral functions as part of the prior knowledge, it will ultimately be necessary to repeat the calculation at smaller lattice spacing. This will however require a new nonperturbative tuning process.

These results have been obtained using the continuum free spectral function as default model. We are planning to repeat our analysis using other default models, in particular the free lattice spectral function, to provide a check on the systematics of the MEM analysis.

In the future, we plan to extend this study to light vector meson correlators at zero and non-zero momentum, which will yield information about dilepton production rates in the plasma. Lattice artefacts are expected to be less severe at smaller quark masses, so this may be feasible even on current lattices. We also intend to study Landau damping by investigating the behaviour of light- and heavy-quark spectral functions at non-zero momentum below the lightcone.

Acknowledgments

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