Mesons at high temperature in $N_f = 2$ QCD*

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We report first results for spectral functions of charmonium in 2-flavour QCD. The spectral functions are determined from vector and pseudoscalar correlators on a dynamical, anisotropic lattice. J/ψ and η_c are found to survive well into the deconfined phase before melting away at $T \lesssim 2T_c$. Current systematic uncertainties prevent us from drawing any definite conclusions at this stage.

1. INTRODUCTION

The properties of hadrons or hadronic resonances above the deconfinement transition is a subject at the heart of the current experimental programme at RHIC, where hadronic signals are used to obtain information about the state of matter inside the fireball. The questions of interest include the issue of which hadrons survive as bound states in the quark–gluon plasma, and up to which temperature; as well as the transport properties of light and heavy quarks in the plasma.

These properties are all encoded in the spectral functions $\rho(\omega, \vec{p})$, which are related to the imaginary-time correlator $G_\Gamma(\tau, \vec{p})$ according to

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

where the subscript Γ correspond to the different quantum numbers. The kernel K is given by

$$\begin{aligned} K(\tau, \omega) &= \frac{\cosh[\omega(\tau - 1/2T)]}{\sinh(\omega/2T)} \\ &= e^{\omega\tau} n_B(\omega) + e^{-\omega\tau}[1 + n_B(\omega)] \,. \end{aligned} \qquad (2)$$

and n_B is the Bose–Einstein distribution function.

The spectral function can be extracted from the lattice correlators $G(\tau)$ using the Maximum Entropy Method (MEM) [1]. For this to work and give reliable results, it is necessary to have a sufficient number of points in the euclidean time direction. This will be prohibitively expensive, especially when dynamical quarks are included, unless anisotropic lattices are used, with a temporal lattice spacing much smaller than the spatial lattice spacing.

We will here focus on the charmonium S-wave states η_c and J/ψ at zero momentum, which have attracted much attention following the suggestion [2] that J/ψ suppression could be a probe of deconfinement. Potential model calculations using the heavy quark free energy have tended to support this picture. However, previous simulations in the quenched approximation [3–5] indicate that contrary to this, J/ψ may survive up to temperatures as high as $1.5 - 2T_c$. Recently, potential model calculations using the internal energy of the heavy-quark pair have reached the same conclusion, and using the most recent lattice data [6] these models indicate a qualitatively similar picture in the case of $N_f = 2$ QCD [6,7].

In this study we attempt to determine directly the spectral functions of charmonium in 2-flavour QCD using anisotropic lattices and the Maximum Entropy Method.

2. SIMULATION DETAILS

We use the Two-plaquette Symanzik Improved gauge action [8] and the fine-Wilson, coarse-

*Talk by JIS at Workshop on Computational Hadron Physics, University of Cyprus, 14–17 September 2005.

Hamber-Wu fermion action [9] with stout-link smearing [10]. The process of tuning the action parameters, and the parameters used, are described in more detail in [11,12]. The parameters correspond to a spatial lattice spacing $a_s \approx 0.2$fm with an anisotropy $\xi = a_s/a_t \approx 6$. The sea quark mass corresponds to $m_\pi/m_\rho \approx 0.55$.

These actions are designed for large anisotropies, and a quenched study [9] found that no mass-dependent tuning of the quark anisotropy was necessary up to valence quark masses well beyond charm. This appears no longer to be the case for dynamical quarks; indeed, for the parameters used here the anisotropy determined from the pion dispersion relation was found to be $\xi_q^\ell \sim 6.4$, in rough agreement with the gluon anisotropy, while the anisotropy from the charmonium dispersion relation was found to be $\xi_q^h \sim 8$. This issue is still under investigation.

For this preliminary study we have used a spatial volume of $N_s^3 = 8^3$ and generated 100 configurations, sampled every 10 HMC trajectories, for $N_t = 48, 32, 24$ and 16. $N_t = 32$ corresponds to a temperature close to the pseudocritical temperature T_c, although larger lattices will be needed to determine this with any precision. We have computed charmonium correlators in the pseudoscalar (η_c) and vector (J/ψ) channels with bare charm quark mass $a_t m_c = 0.1$. The charmonium spectrum in the hadronic phase is presented in [12,13]. In this study we have used local (unsmeared) operators,

$$G_\Gamma(\tau) = \sum_{\vec{x},\vec{y},t} \langle M_\Gamma^\dagger(\vec{x},t) M_\Gamma(\vec{y},t+\tau)\rangle \,, \tag{3}$$

where

$$M_\Gamma(\vec{x},t) = \bar{\psi}(\vec{x},t)\Gamma\psi(\vec{x},t)\,, \quad \Gamma = \gamma_5, \gamma_i\,. \tag{4}$$

All-to-all propagators [14] have been used to improve the signal and sample information from the entire lattice. The propagators were constructed with no eigenvectors and two noise vectors diluted in time, colour and even/odd in space.

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) at $a_t\omega_{\max} = 6$.

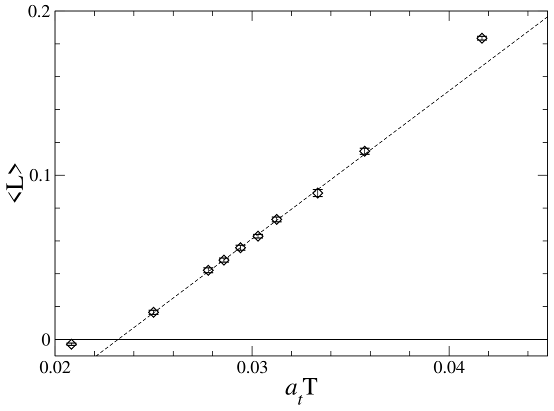

Figure 1. Average Polyakov loop as a function of temperature.

3. RESULTS

In an attempt to locate the pseudocritical temperature on these lattices, we performed simulations varying N_t in the range 28–40, measuring the real part of the Polyakov loop $\langle L\rangle$ and its susceptibility. The results for the Polyakov loop are shown in fig. 1. As can be seen from the figure, the Polyakov line in the transition region follows a linear behaviour in temperature, and therefore no pseudocritical temperature can be determined on these lattices. It will be necessary to use larger lattices to determine T_c. For this reason, and because of the uncertainties regarding the anisotropy, we will refrain from quoting results in terms of T_c.

The free-fermion spectral functions are shown in fig. 2, for $N_t = 32$ and 24, and in the continuum. The most striking feature of the lattice free spectral functions is the spike at $a_t\omega \approx 0.6$. This means that lattice artefacts are big at this point, and results for spectral functions cannot be trusted in this region. The lattice functions undershooting the continuum curve appears to be a mass-dependent, $\mathcal{O}(a_t m)$ or $\mathcal{O}(a_s^2 m)$, effect, evidenced by the effect being much larger at $a_t m = 0.2$ [15].

The spectral functions obtained from the MEM

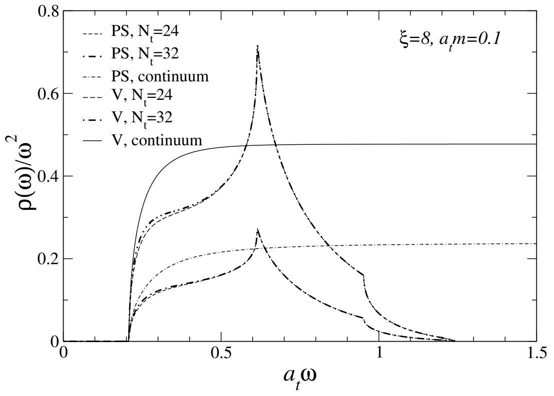

Figure 2. Free-fermion spectral functions in the pseudoscalar and vector channels, for bare quark mass $a_t m_0 = 0.1$.

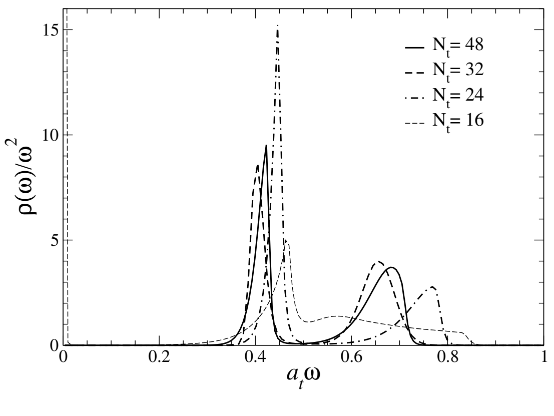

Figure 3. Pseudoscalar (η_c) spectral function for different temperatures.

analysis are shown in figs. 3 and 4 for η_c and J/ψ respectively. The main peak position for $N_t = 48$ agrees within errors with the mass obtained for the respective particles on the same lattices, using a variational basis of smeared operators [12,13]. The second peak coincides with the cusp in the free spectral function in fig. 2, and it can therefore be concluded that this is primarily a lattice artefact. The radially excited states cannot be resolved with our present statistics.

The results in figs. 3 and 4 indicate that the 1S states survive in the medium up to well beyond

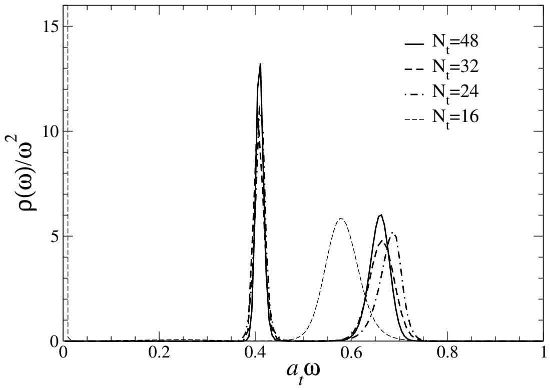

Figure 4. Vector (J/ψ) spectral function for different temperatures.

the deconfinement temperature, finally melting away at $T \lesssim 2T_c$. This is in qualitative agreement with recent potential model results using the static quark–antiquark internal energy [6]. Using the colour singlet internal energy U_1 yields a dissociation temperature of $T_{\rm dis} \sim 2T_c$, while a potential constructed to exclude the gluon internal energy [16] yields $T_{\rm dis} \sim 1.4T_c$ [7]. Given the uncertainties in this calculation, both these results are consistent with the present data.

It is not clear whether the apparent stronger binding in η_c for $N_t = 24$ is significant, in particular given that no such effect is observed for J/ψ. Higher statistics will be needed to resolve this. If it is confirmed, it might be in line with potential model calculations using U_1, which is strongly peaked around T_c.

4. OUTLOOK

Using an anisotropic lattice, we have performed the first calculation of charmonium spectral functions in 2-flavour QCD. The results appear to confirm the picture emerging from quenched simulations, that J/ψ and η_c survive until well into the deconfined phase.

These simulations have been performed with parameters that are not fully tuned, giving rise to significant systematic uncertainties. A particular issue is the tuning of the charm quark anisotropy. We are in the process of obtaining a fully tuned parameter set, and simulations at these parameters will be carried out in the very near future. Firm conclusions will have to await these simulations.

The small lattice volume — only $(1.6\text{fm})^3$ — is also a major source of systematic uncertainty, in particular as it has prevented a determination of the pseudocritical temperature. Future simulations will be carried out on larger spatial volumes. It will also be important to increase the statistics, in order to resolve excited states and disentangle the effects of thermal width and finite statistics. We will also be carrying out a systematic study of the effects of using different default models, including the free lattice spectral functions, and different time and energy ranges in the MEM analysis. Initial indications are that our results are relatively robust against such changes.

The coarse spatial lattice is an issue in that it gives rise to significant, mass-dependent, lattice artefacts as shown in fig. 2. It will ultimately be necessary to repeat the calculation on a finer lattice; this will however require a new nonperturbative tuning and is therefore not on the immediate horizon. Some information about lattice spacing effects may be gleaned from quenched studies using the same action, which are considerably cheaper as the quark and gluon anisotropies can be tuned independently.

We are planning to compute the spectral functions also at non-zero momentum [17], which contain additional information not found at zero momentum, and which may relate more directly to experimental data taken at non-zero momentum.

We will also study light vector meson correlators at zero and non-zero momentum, which can be related to dilepton production rates in the plasma. Finite lattice spacing effects are expected to be less of a problem in this case, so the current lattices are likely to be suitable for this purpose. This will proceed once the fully tuned parameter set is ready.

Acknowledgments

We thank the organisers of *Workshop on Computational Hadron Physics* for a pleasant and interesting workshop. This work has been supported by the IRCSET Embark Initiative award SC/03/393Y, SFI grant 04/BRG/P0275 and the IITAC PRTLI initiative. We wish to thank Jimmy Juge, Sinéad Ryan and Simon Hands for stimulating and fruitful discussions.

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