Screening of light mesons and charmonia at high temperature

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Abstract

We present lattice QCD results for the screening masses of light mesons and charmonia. The lattice computations were performed with 2 + 1 flavors of improved staggered quarks using quark masses which correspond to realistic pion and kaon masses at zero temperature. For the light quark sector we have found that the screening masses in the pseudo-scalar and the isovector scalar channels do not become degenerate at the chiral crossover temperature indicating an effective non-restoration of the axial symmetry. Also the splitting between the vector and the pseudo-scalar screening masses persists even in the limit of zero lattice spacing and at a moderately high temperature around 420 MeV. In the charmonium sector our investigation shows that the screening masses of the pseudo-scalar and the vector charmonia are almost (within a few percent) equal to their zero temperature masses for temperatures less than 300 MeV. We also present results for the charmonium screening masses using periodic boundary conditions along the temporal direction and discuss their implications.

1. Introduction

In-medium properties of mesonic observables provide insight into the details of structure and properties of the Quark Gluon Plasma (QGP). By studying these properties one can obtain information concerning its important length-scales, relevant degrees of freedom etc. Such studies also help us to understand the nature of the chiral and $U_A(1)$ axial symmetry restorations in Quantum ChromoDynamics (QCD). Finite temperature lattice QCD simulation is, to date, the most viable and successful technique for non-perturbative
studies of such in-medium properties. Since the maximum available physical temporal extent in a finite temperature lattice QCD simulation is always limited by the inverse of the temperature it is easier to use spatial correlation functions of meson-like excitations for the study of their in-medium properties. Exponential decays of such spatial correlation functions define the so-called screening masses \[1\]. The inverse of the screening mass indicates the typical distance beyond which the influence of a meson-like excitation inside the QGP is effectively screened.

For the continuum non-interacting theory at a temperature \(T\) the value of the screening mass of a meson is given by \[2\] \[M_{\text{free}}(T) = 2 \sqrt{(\pi T)^2 + m_q^2}, \] \(m_q\) being the quark mass, independent of its spin-parity structure. At very high temperatures and in the limit of zero quark mass perturbative calculations \[3\] show that this Free continuum limit of \(M_{\text{free}}(T)/T = 2\pi\) is reached from above. Although in general the screening mass is not identical to the pole mass \(m_M\) both the spatial and the temporal correlation functions depend on the same spectral density of the meson-like excitation \[4\]. This in turn ensures \[4\] that for a stable (free) mesonic state \(M_{\text{free}}(T) = m_M\), e.g. at \(T = 0\).

Mesonic screening masses have been computed in many different lattice QCD simulations. For a review of earlier lattice results see Ref. \[4\]. Some recent lattice results can be found in Ref. \[5\] and Ref. \[6\]. In this work we present results for the mesonic screening masses from 2 + 1 flavor lattice QCD simulations with two degenerate dynamical up (u), down (d) quarks and a dynamical strange (s) quark. In this work we have not treated the charm (c) quark as a dynamical flavor. Since the mass of the c quark is much larger than our explored \(T\) range such a partially-quenched treatment is expected to be a very good approximation. For our simulations we have used an improved staggered fermion (p4fat3) action with 3 different extents in the temporal direction, viz. \(N_\tau = 4, 6\) and 8, keeping the extents of the spatial directions fixed at \(N_s = 4N_\tau\). Quarks masses have been tuned such that \(m_\pi \approx 220\) MeV, \(m_K \approx 500\) MeV, \(m_\Psi \approx 3097\) MeV and \(m_\eta_c \approx 2980\) MeV at zero temperature. Further details of our simulations can be found in Ref. \[7\] and details on the tuning of the charm quark mass can be found in Ref. \[8\]. On these gauge configurations we have analyzed screening masses using 8 different local staggered meson operators involving (isovector) scalar (SC), pseudo-scalar (PS), (transverse) vector (V) and (transverse) axial-vector (AV) channels for 4 different combinations of quark fields, viz. \(\bar{u}d, \bar{u}s, ss\) and \(cc\). More technical details on the meson operators and our analysis can be found in Ref. \[9\].

2. Results

In Fig. 1 we show our results for the screening masses in the \(\bar{u}d\) sector for the 4 different mesonic channels. Upto the chiral crossover temperature, \(T_{pc} \approx 190\) MeV, \(M_{PS}^{\bar{u}d}\) remains approximately equal to \(m_\pi\) but \(M_{SC}^{\bar{u}d}\) shows a distinct minimum around \(T_{pc}\). For \(T > T_{pc}\) screening masses in both these channels grow rapidly but stay well below the Free continuum limit of \(2\pi T\) even at \(T \approx 420\) MeV. On the other hand, for \(T \gtrsim T_{pc}\) within our errors we found that \(M_{V}^{\bar{u}d} \approx M_{AV}^{\bar{u}d} \approx 2\pi T\). The behavior of screening masses in the all four channels for the \(\bar{u}s\) and \(ss\) sectors are qualitatively similar to that of the \(\bar{u}d\) sector.

Above the chiral crossover temperature chiral symmetry gets restored and hence the \(V\) and \(AV\) are expected to become degenerate. This is exactly what we have found in
increases. In order to illustrate the distinctiveness of the $\bar{c}c$ sector more clearly in Fig. 1(e), the screening masses in the pseudo-scalar and the (isovector) scalar channels do not become degenerate in the temperature range $T_{pc} < T \lesssim 250$ MeV. This observation indicates that the effective restoration of the $U_A(1)$ axial symmetry does not coincide with the chiral symmetry restoration and takes place at a temperature $T > T_{pc}$.

We have also investigated the cut-off dependence in the meson screening masses. In Fig. 1(f) we show the continuum limit extrapolation (i.e. a linear extrapolation in the lattice spacing squared $a^2 = 1/(TN_c)^2 \to 0$) of $M^*_V$ at a temperature $T \simeq 420$ MeV. Such an extrapolation shows that even at this ‘not-so-high’ temperature $M^*_V > 2\pi T$ in accordance with the perturbative predictions \cite{3}. However, as observed in Ref. \cite{6} for simulations with quenched Wilson fermions, this overshooting of the free continuum value can very well be a finite-volume effect and may go away in the infinite volume limit.

The cut-off effects are more pronounced in the $PS$ and $SC$ channels (Fig. 1(a) and Fig. 1(b)). A similar continuum limit extrapolation, at $T \approx 420$ MeV, of $M^*_PS$ shows that the extrapolated value of $M^*_PS$ remains well below the free continuum limit and the splitting between $M^*_V$ and $M^*_PS$ persists even in the limit of zero lattice spacing (see Fig. 1(f)).

As discussed before, for a stable (free) mesonic state the screening mass and the pole mass are identical. With this hindsight one may compare the screening mass of a charmonium to its zero temperature pole mass to shed some light on the issue of survival/dissociation a charmonium in QGP. We have analyzed the mesonic screening masses in $PS$ and $V$ channels for the heavy-quark $\bar{c}c$ sector and compared them with the $T = 0$ pole masses in the corresponding channels. Amazingly, the ratios $M^*_PS/m_{pc}$ (Fig. 2(a)) and $M^*_V/m_{\eta}$ (Fig. 2(b)) stay very close to 1 (within 5\%) till $T \lesssim 300$ MeV. Beyond this temperature these ratios seem to increase rapidly as the temperature increases. In order to illustrate the distinctiveness of the $\bar{c}c$ sector more clearly in Fig. 2(c) we have plotted the ratios of the $PS$ screening masses to the corresponding zero
temperature pole masses for all the four different combinations of quark fields on $6 \times 24^3$ lattices. While around $T \simeq 275$ MeV there is almost no difference in the screening and the pole mass in the $\bar{c}c$ sector the relative difference is $\sim 90\%$ even for the $\bar{s}s$ sector.

For a deeper understanding of these results we have also analyzed the screening masses in these channels by employing periodic, in contrast to the standard anti-periodic, boundary conditions (denoted by $\tau$-$pbc$) along the temporal direction. If one employs $\tau$-$pbc$ then in the free (continuum) case the contribution to the mesonic screening mass will come from the lowest bosonic Matsubara frequency ($\omega_{\text{min}} = 0$), as oppose to the lowest fermionic Matsubara frequency ($\omega_{\text{min}} = \pi T$), and consequently $M_s^{\text{free, } \tau-pbc}(T) = 2m_q$ independent of $T$. Thus a large splitting between $M^s(T)$ and $M_s^{\tau-pbc}(T)$ will indicate that the contribution to screening mass at that temperature is coming from two quasi-quarks. On the other hand, for a free stable mesonic state one may expect that $M^s(T) \simeq M_s^{\tau-pbc}$.

In Fig. 2(a) and Fig. 2(b) we have compared our results of $M_s^{\tau-pbc}(T)$ with the corresponding $M^s(T)$. While the difference between $M^s$ and $M_s^{\tau-pbc}$ is $\gtrsim 20\%$ for $T \gtrsim 300$ MeV the difference is only at the level of a few percent around $T \approx 220$ MeV. These relatively small differences at lower temperatures are even reduced as one decreases the lattice spacing from $aT = 1/6$ to 1/8, although the qualitative picture for $T \gtrsim 300$ MeV remains almost unchanged. All these findings are very interesting and seem to suggest that $\eta_c$ and $J/\Psi$ may survive in a QGP at least for temperatures less than $1.5T_{pc}$.

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