Melting Spectral Functions of the Vector Mesons in a Holographic QCD Model

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Based on MF, K. Fukushima, T. Misumi, and M. Murata,
Phys. Rev. D 80, 035001 (2009)

And MF, T. Kikuchi, K. Fukushima, T. Misumi, M. Murata,
Phys.Rev.D81:065024 (2010)

Introduction

- Strongly correlated quark gluon plasma (QGP) has interesting non-perturbative properties.

Example (1) The gauge/gravity correspondence → the shear viscosity/ entropy ratio $\eta/s = 1/(4\pi)$ for D=4 N=4 SYM, while It is difficult to reproduce this result from gauge theory side.

(2) Heavy mesons like J/ψ survive in the deconfinement phase and melt as temperature increases.

T. Umeda, et. al. "02, M. Asakawa and T. Hatsuda "03

The screening of color forces weaken $\bar{c}c$ pair binding, manifesting J/ψ suppression

- We want to compute the finite temperature spectral functions of heavy mesons by using the Soft wall AdS/QCD model.

Non-perturbative corrections!

A table of contents

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Gauge theory side (large N_c QCD)

- Large Nc and strongly coupled SU(N_c) QCD ($g_{YM}^2 N_c >> 1$)

▪ Matter field: (u,d,s) transforming under U(3) and heavy charm quark c (M_c~1.3 GeV)

▪ The spontaneous breaking of chiral symmetry: $\langle \bar{c}c \rangle \neq 0$

▪(C-)Meson field :

		J^{pc}			J^{pc}
scalar	$\bar{c}c,$	0++	pseudo-scalar	$\bar{c}\gamma_5 c,$	0-+
vector	$\bar{c}\gamma_\mu c,$	1--	axial-vector	$\bar{c}\gamma_5\gamma_\mu c,$	1++

Quantum number and Mass of c-mesons

$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $X(3945)$	$?^?(?^{?+})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
• $X(4260)$	$?^?(1^{--})$
$X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4660)$	$?^?(1^{--})$

- Mass of mesons

  M(η_c(1S))=3.0 [GeV],

  M(J/ψ(1S))=3.1 [GeV],

  M(χ_{c0}(1P)) =3.4 [GeV],

  M(χ_{c1}(1P)) =3.5 [GeV],

  M(η_c(2S))=3.6 [GeV],

  M(ψ(2S))=3.7 [GeV].

Regge trajectory of c-mesons?

- Regge trajectory of light mesons!

  $m_n^2 \sim 4cn$

  Spectrum of ρ meson ($u\bar{d}$) :
  ρ(770[MeV]), ρ(1450), ρ(1700)…

- The spectrum of heavy mesons doesn't obey Regge trajectory in general.

- For charmonium, it is known that mesons also obey Regge trajectory up to the first and second level.

  S. Gershtein, A. Likhoded and A. Luchinsky ``06

  See also H. Grigoryan, P. Hohler, and M. Stephanov ``10

Thermal Field Theory

- The retarded Green's function and spectral function of a conserved current

$$C_{xx}(x-y) = -i\theta(x^0 - y^0)\langle[J_x(x), J_x(y)]\rangle$$

$$C_{xx}(x-y) = \int \frac{d^4k}{(2\pi)^4} e^{ik(x-y)} C_{xx}(k)$$

$$\rho(k) = -\mathrm{Im}\, C_{xx}(k)$$

- Conservation law means $C_{\mu\nu}(k) = P_{\mu\nu}\Pi(k^2),\ \ P_{\mu\nu} = \eta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}$

$\rightarrow \quad C_{xx}(k) = \Pi(k^2) \quad for \quad k_\mu = (-\omega, 0, 0, q)$

Transverse component is chosen.

Dual gravity side: Soft-wall model

Soft-wall model includes smooth dilaton cut off

$\phi = cz^2$ (z is the radial direction of AdS_5)

Action: $S = \int dx^5 \quad e^{-\Phi}\sqrt{-g} \quad \mathrm{Tr}[-|DX|^2 + 3|X|^2$

$$-\frac{1}{4g_5^2}(g^{MN}g^{PQ}F^{\mathcal{L}}_{MP}F^{\mathcal{L}}_{NQ} + g^{MN}g^{NQ}F^{\mathcal{R}}_{MP}F^{\mathcal{R}}_{NQ})]$$

with $M = 0, 1, 2, 3, 4$

A. Karch, E. Katz, D. T. Son, and M. A. Stephanov ``06

In zero temperature, the soft-wall model reproduces

Regge trajectory of light mesons!

$m_n^2 \sim 4cn$

Spectrum of ρ meson ρ(770[MeV]), ρ(1450), ρ(1700)…

can be compared with the above result and then $c = 0.151\ \mathrm{GeV}^2$

Flavor dependent soft wall model

$$S = \int d^5x \sqrt{-g}\, \mathrm{tr}\left(e^{-c_\rho z^2} \mathcal{L}_{\mathrm{light}} + e^{-c_{J/\psi} z^2} \mathcal{L}_{\mathrm{heavy}}\right),$$

- L_{heavy} and L_{light} take almost same structure:

$$= \mathrm{tr}\left[-|DX|^2 + \frac{3}{L^2}|X|^2 - \frac{1}{4g_5^2}(g^{MN} g^{PQ} F_{L,MP} F_{L,NQ} + g^{MN} g^{PQ} F_{R,MP} F_{R,NQ}) \right]$$

- Fields in L_{heavy} and L_{light} belong to U(3) and U(1), decoupling each other.

- The lowest exitation of heavy mesons → $c_{J/\psi}$=2.43 GeV^2
  In our presentation, we consider only the heavy meson.

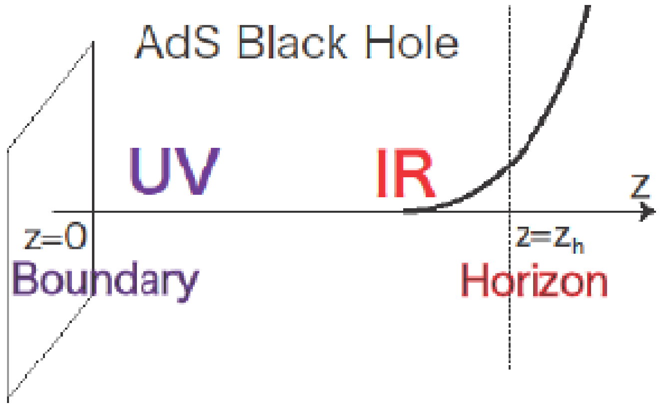
Soft-wall model at finite temperature *T*

Metric: AdS Black Hole $g_{MN}dx^M dx^N = \frac{L^2}{z^2}[-f(z)dt^2 + d\mathbf{x}^2 + \frac{1}{f(z)}dz^2]$

with $f(z) = 1 - z^4/z_h^4$ z_h:Horizon

Hawking temperature $T_H = \frac{1}{\pi z_h}$

→ Temperature of the medium



◆ Action at the quadratic order

$$S = \int dx^5 e^{-\Phi}\sqrt{-g}\,\mathrm{Tr}[-\frac{1}{2g_5^2}(F^V F^V + F^A F^A) -(2X_0\partial\pi + [V, X_0] + \{A, X_0\})(2X_0\partial\pi - [V, X_0] + \{A, X_0\})]$$

→ Linearized EOM

Axial: $\partial_N[e^{-\Phi}\sqrt{-g}g^{MP}g^{NQ}F^A_{PQ}] - e^{-\Phi}\sqrt{-g}g^{MN}\{X_0, \{A_N, X_0\}\} = 0$

Vector: $\partial_N[e^{-\Phi}\sqrt{-g}g^{MP}g^{NQ}F^V_{PQ}] + \underline{e^{-\Phi}\sqrt{-g}g^{MN}[X_0, [V_N, X_0]]} = 0$

⇩

This term vanishes for U(1) case.

- Note that AdS BH is unstable at low temperature and the Hawking-Page phase transition takes place at

$$T_c = 0.492\sqrt{c_\rho} = 0.19\ GeV$$ C. Herzog, ``07

- Note that the transition temperature is determined only by ρ meson mass c_ρ.

In this presentation, we consider the region $T>T_c$.

▪Chiral symmetry breaking parameter is obtained from the scalar *X*

Scalar EOM: $$X_0''(z) + \left(-2cz + \frac{f-4}{zf}\right)X_0'(z) + \frac{3}{z^2 f}X_0(z) = 0,$$

$$L^{3/2}X_0(z) \sim \frac{1}{2}(M_q z + \Sigma z^3),$$ at z~0

Mq: Mass of c-quark 1.3 GeV → *Σ* : Chiral condensate $(-3.1\ \mathrm{GeV})^3$

In-falling solution and Spectral function of the vector meson

- Infalling solution: linear combination of two solutions

$$V(z) = \Phi_2(z) + B(\omega,q)\Phi_1(z) \xrightarrow{z \to z_h} (1 - z/z_h)^{-i\omega z_h/4}$$

Boundary solutions $\Phi_2 \approx 1, \quad \Phi_1 \approx z^2 \quad z \to 0$

- Retarded Green's function:

$$D^R(\omega,\mathbf{q}) = \lim_{\epsilon\to 0} \frac{\delta^2}{\delta V_0(p)\delta V_0(p)} \exp(-S_{5d}[\bar{V}(p,\epsilon)])|_{V_0=0}$$: GKP-W relation

$$= -C \lim_{\xi\to 0}\left(\frac{1}{\xi}V(\xi)^*\partial_\xi V(\xi)\right) = -2C\left[B(\omega,q) - \frac{\omega^2-q^2}{2}\ln\left(\frac{e^{\gamma_E}}{2}\sqrt{|\omega^2-q^2|}\,\epsilon\right)\right],$$

⇧ Factor

with $\bar{V}(p,z) = V(p,z)V_0(p)$

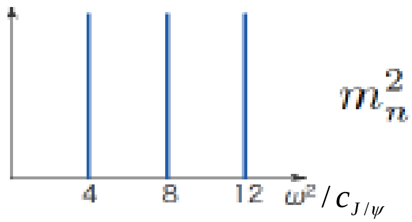
- Spectral function: the imaginary part of *B(ω,q)*

$$\rho(\omega,q) = -\frac{1}{\pi}\mathrm{Im}D^{\mathrm{R}}(\omega,q) = \frac{2C}{\pi}\mathrm{Im}B(\omega,q).$$

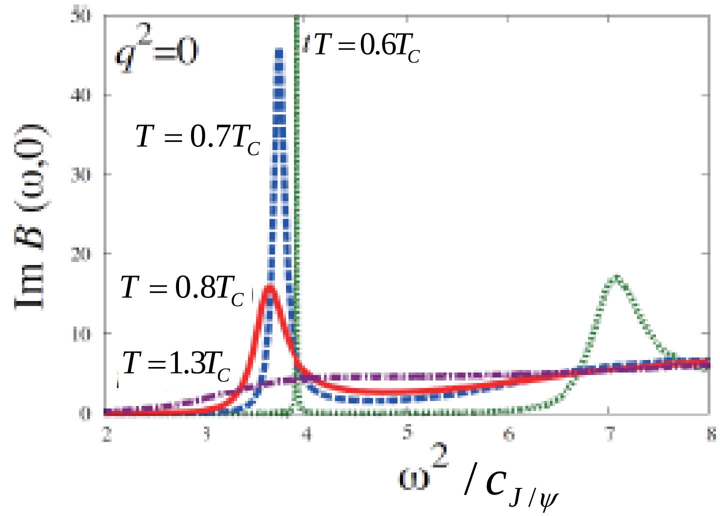
◆ The Numerical Results

1. Spectral functions for q = 0

At low temperature, sharp peaks stand in accord with t=0 spectrum.



$$m_n^2 = 4n, \quad (n = 1, 2, 3\ldots)$$



➢ Properties

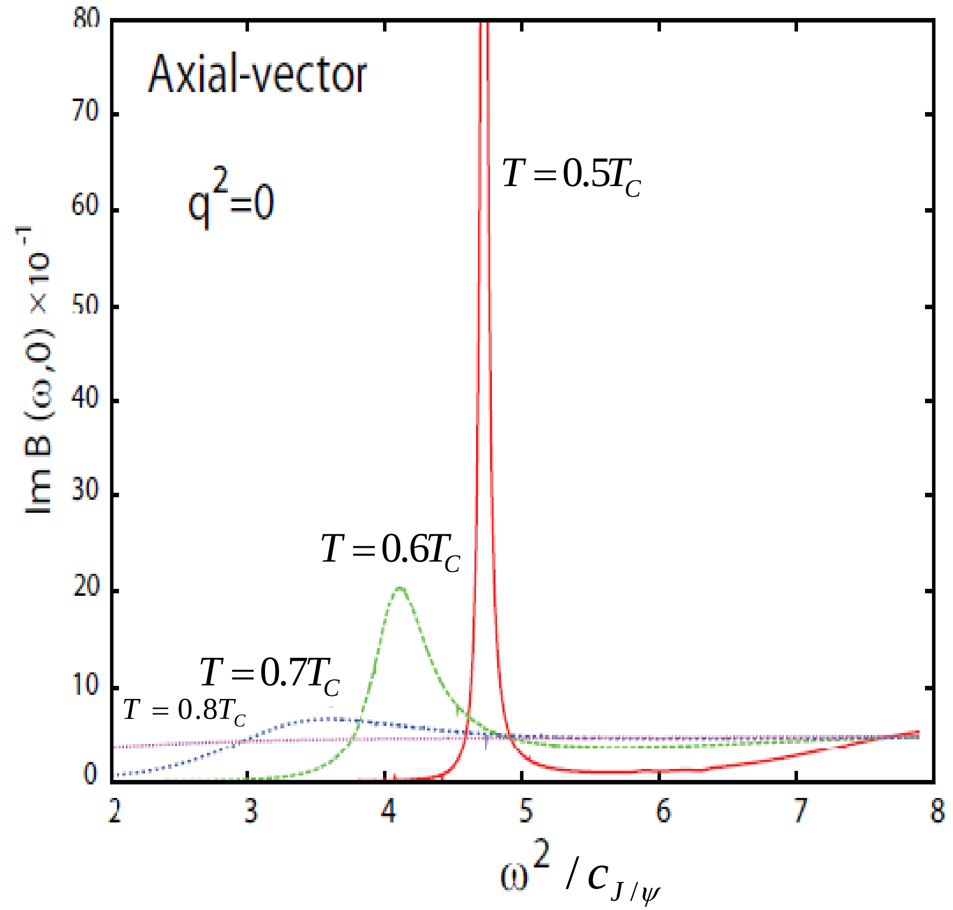
1. The lowest-lying state melts gradually as T increases.

2. The peak moves to a smaller mass with increasing T.

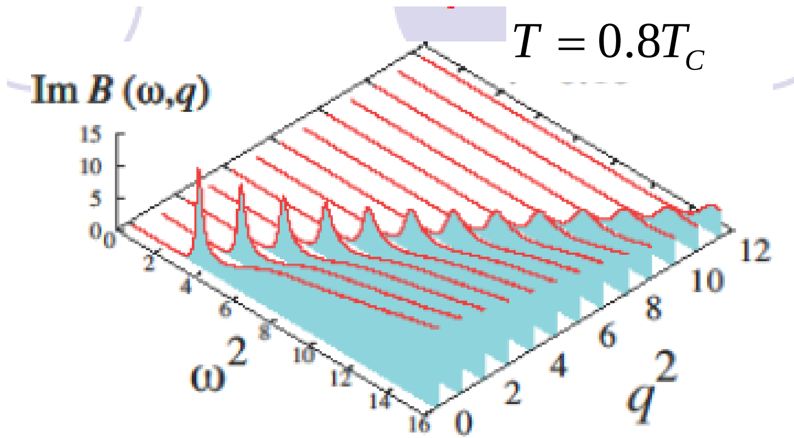
3. The excited states melt much earlier and shift more.

Spectral function of axial vector mesons

- χ_{c1} doesn't survive above *Tc* .
- Note that chiral condensate Σ = -(3.1[GeV])^3 is not much bigger than the mass → Σ doesn't contribute to the spectra function much.
- Zero temperature Mass ofX_{c1} 3.4 [GeV] is consistent with experimental result 3.51 [GeV].



Finite momentum of vector mesons



- The peaks move to a larger mass with increasing q.
- The Vector Mesons are suppressed under the hot wind.

(This is consistent with the previous study for N=4 SYM.)

H. Liu, et. al. ``07

Summary and Discussions

- J/ψ survives above the deconfinement temperature (T~1.2Tc), while χ_{c1} melts at T_c.
- The spectral functions of scalar and pseudoscalar can also be computed and are melt at the deconfinement temperature.