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Heavy meson dissociation in a plasma with magnetic fields

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ABSTRACT

The fraction of heavy vector mesons detected after a heavy ion collision provides information about the possible formation of a plasma state. An interesting framework for estimating the degree of dissociation of heavy mesons in a plasma is the holographic approach. It has been recently shown that a consistent picture for the thermal behavior of charmonium and bottomonium states in a thermal medium emerges from holographic bottom up models. A crucial ingredient in this new approach is the appropriate description of decay constants, since they are related to the heights of the quasiparticle peaks of the finite temperature spectral function.

Here we extend this new holographic model in order to study the effect of magnetic fields on the thermal spectrum of heavy mesons. The motivation is that very large magnetic fields are present in non central heavy ion collisions and this could imply a change in the dissociation scenario. The thermal spectra of $c\bar{c}$ and $b\bar{b}$ S wave states is obtained for different temperatures and different values of the magnetic eB field.

1. Introduction

A consistent picture for the thermal behavior of heavy vector mesons in a plasma was obtained recently using holographic bottom up models [1–3]. A central point in these works is the connection between the finite temperature spectral function and the zero temperature decay constants. The spectral function – that describes the thermal behavior of quasiparticles inside a thermal medium – is the imaginary part of the retarded Green's function. At zero temperature, the essential part of the Green's function has the following spectral decomposition in terms of masses m_n and decay constants f_n of the states:

$$\Pi(p^2) \sim \sum_{n=1}^{\infty} \frac{f_n^2}{(-p^2) - m_n^2 + i\epsilon} \,. \tag{1}$$

The imaginary part of this expression is a sum of Dirac deltas with coefficients proportional to the square of the decay constants: $f_n^2\,\delta(-p^2 - m_n^2)$. At finite temperature, the quasi-particle states appear in the spectral function as smeared – finite size – peaks with a height that decrease as the temperature T and/or the density μ of the medium increase. This analysis strongly suggests that in order to extend a hadronic model to finite temperature, the zero temperature case should provide a consistent description of decay constants.

Decay constants for mesons are associated with non-hadronic decay. They are proportional to the transition matrix from a state at excitation level n to the hadronic vacuum: $\langle 0|\, J_\mu(0)\, |n\rangle = \epsilon_\mu f_n m_n$. Experimental data show that for heavy vector mesons the decay constants decrease monotonically with radial excitation level, as revised in [2,3].

Holographic models, inspired in the AdS/CFT correspondence [4–6], provide nice estimates for hadronic masses. However neither the hard wall [7–9], the soft wall [10] or the D4–D8 [11] models provide decay constants decreasing with excitation level.

An alternative bottom up holographic model was developed in ref. [12] in order to overcome this problem. The decay constants are obtained from two point correlators of gauge theory operators calculated at a finite value of the radial coordinate of AdS space. This way an extra energy parameter, associated with an ultraviolet (UV) energy scale, is introduced in the model. The extension of this model to finite temperature in [1] and finite density in [2] provided consistent pictures for the dissociation of heavy vector mesons is the plasma. An improved version of the model of ref. [12], that provides a better fit for the charmonium states at zero temperature and thus a better picture for the finite temperature and density cases, was then proposed in [3].

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An interesting tool to investigate the possible existence of a plasma state in a heavy ion collision is to analyze the fraction of heavy vector mesons produced. The suppression of such particles indicates their dissociation in the medium [13] (see also [14]). This effect corresponds to a decrease in the height of the quasi particle peaks of the spectral function. The influence of temperature and density of the medium in heavy vector meson spectral functions was studied in [1–3]. However, there is another important factor that deserves consideration. In non central heavy ion collisions strong magnetic fields can be produced for short time scales [15–17].

The presence of a magnetic field eB has important consequences for hadronic matter. Lattice results [18] indicate a decrease in the QCD deconfinement temperature with increasing eB field. Similar results show up also from the MIT bag model [19] and also from the holographic D4–D8 model [20]. The effect of a magnetic field in the transition temperature of a plasma has been studied using holographic models in many works, as for example [21–26].

Here we extend the holographic bottom up model of [3] in order to include the presence of a magnetic field. This way it is possible to investigate the change in the spectral function peaks that represent the quasiparticle heavy meson states as a function of the intensity of the eB field. In section 2 we describe the model at zero temperature showing the results for masses and decay constants. Then, in section 3 we present the extension to finite temperature in the presence of a magnetic field. Section 4 is devoted to show how to calculate the spectral functions. Finally, in section 5 we present the results as discuss their implication in terms of heavy vector meson dissociation.

2. Holographic model

The model proposed in ref. [3] was conceived for describing charmonium states. At zero temperature the background geometry is the standard 5D anti-de Sitter space–time

$$ds^2 \;=\; \frac{R^2}{z^2}(-dt^2 + d\vec{x}\cdot d\vec{x} + dz^2)\,. \tag{2}$$

The mesons are described by a vector field $V_m = (V_\mu, V_z)$ ($\mu = 0,1,2,3$), which is dual to the gauge theory current $J^\mu = \bar{\psi}\gamma^\mu\psi$. The action is:

$$I \;=\; \int d^4x dz \sqrt{-g}\; e^{-\phi(z)} \left\{ -\frac{1}{4g_5^2} F_{mn}F^{mn} \right\} , \tag{3}$$

where $F_{mn} = \partial_m V_n - \partial_n V_m$ and $\phi(z)$ is a background dilaton field that here we choose to have the form

$$\phi(z) = k^2 z^2 + Mz + \tanh\left(\frac{1}{Mz} - \frac{k}{\sqrt{\Gamma}}\right) , \tag{4}$$

in order to represent both charmonium and bottomonium states. The parameter k represents the quark mass, Γ the string tension of the strong quark anti-quark interaction and M is a mass scale associated with non hadronic decay.

Choosing the gauge $V_z = 0$ the equation of motion for the transverse (1,2,3) components of the field, denoted generically as V, in momentum space reads

$$\partial_z\left[e^{-B(z)}\partial_z V\right] - p^2 e^{-B(z)} V = 0, \tag{5}$$

where $B(z)$ is

$$B(z) = \log\left(\frac{z}{R}\right) + \phi(z)\,. \tag{6}$$

Table 1
Holographic masses and the corresponding decay constants for the Charmonium S-wave resonances. Experimental values inside parenthesis for comparison.

Holographic (and experimental) results for charmonium		
State	Mass (MeV)	Decay constants (MeV)
$1S$	2943 (3096.916 ± 0.011)	399 (416 ± 5.3)
$2S$	3959 (3686.109 ± 0.012)	255 (296.1 ± 2.5)
$3S$	4757 (4039 ± 1)	198 (187.1 ± 7.6)
$4S$	5426 (4421 ± 4)	169 (160.8 ± 9.7)

Table 2
Holographic masses and the corresponding decay constants for the Bottomonium S-wave resonances. Experimental values inside parenthesis for comparison.

Holographic (and experimental) results for bottomonium		
State	Mass (MeV)	Decay constants (MeV)
$1S$	6905 (9460.3 ± 0.26)	719 (715.0 ± 2.4)
$2S$	8871 (10023.26 ± 0.32)	521 (497.4 ± 2.2)
$3S$	10442 (10355.2 ± 0.5)	427 (430.1 ± 1.9)
$4S$	11772 (10579.4 ± 1.2)	375 (340.7 ± 9.1)

Equation of motion (5) presents a discrete spectrum of normalizable solutions, $V(p,z) = \Psi_n(z)$ that satisfy the boundary conditions $\Psi_n(z=0) = 0$ for $p^2 = -m_n^2$ where m_n are the masses of the corresponding meson states. The eigenfunctions $\Psi_n(z)$ are normalized according to:

$$\int_0^\infty dz\, e^{-B(z)}\; \Psi_n(z)\Psi_m(z) = \delta_{mn}\,. \tag{7}$$

Decay constants are proportional to the transition matrix from the vector meson n excited state to the vacuum: $\langle 0|\, J_\mu(0)\,|n\rangle = \epsilon_\mu f_n m_n$. They are calculated holographically in the same way as in the soft wall model:

$$f_n = \frac{1}{g_5 m_n} \lim_{z\to 0}\left(e^{-B(z)}\Psi_n(z)\right) . \tag{8}$$

The values of the parameters that describe charmonium and bottomonium are respectively:

$$k_c = 1.2\,\text{GeV};\ \sqrt{\Gamma_c} = 0.55\,\text{GeV};\ M_c = 2.2\,\text{GeV}\,; \tag{9}$$

$$k_B = 2.45\,\text{GeV};\ \sqrt{\Gamma_B} = 1.55\,\text{GeV};\ M_B = 6.2\,\text{GeV}\,. \tag{10}$$

The procedure to calculate masses and decay constants is to find the normalizable solutions $\Psi_n(z)$ of eq. (5), with the background of eq. (4), that vanish at $z = 0$. Then the numerical solutions are used in eq. (8). Tables 1 and 2 show the results for charmonium and bottomonium respectively. For comparison, the experimental data from ref. [27] is show inside parenthesis. Note that the decay constants decrease with radial excitation level.

3. Plasma with magnetic field

Let us now extend the model to finite temperature and in the presence of magnetic field, assumed for simplicity to be constant in time and homogeneous in space. The extension to finite temperature is obtained replacing AdS space by a Schwarzschild AdS black hole. The presence of a magnetic field in the gauge theory side of gauge/gravity duality can also be represented geometrically in the gravity side [28,29]. The Einstein–Maxwell action is given by:

$$S = \frac{1}{16\pi G_5}\int d^5x\sqrt{-g}\left(R - F^{MN}F_{MN} + \frac{12}{L^2}\right) + S_{GH} \tag{11}$$