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# Bottomonium dissociation in a finite density plasma

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ABSTRACT

We present a holographic description of the thermal behavior of $b\bar{b}$ heavy vector mesons inside a plasma at finite temperature and density. The meson dissociation in the medium is represented by the decrease in the height of the spectral function peaks. In order to find a description for the evolution of the quasi-states with temperature and chemical potential it is crucial to use a model that is consistent with the decay constant behavior. The reason is that the height of a spectral function peak is related to the value of the zero temperature decay constant of the corresponding particle. AdS/QCD holographic models are in general not consistent with the observation that decay constants of heavy vector mesons decrease with radial excitation level. However, it was recently shown that using a soft wall background and calculating the correlation functions at a finite position of anti-de Sitter space, associated with an ultraviolet energy scale, it is possible to describe the observed behavior. Here we extend this proposal to the case of finite temperature $T$ and chemical potential $\mu$. A clear picture of the dissociation of bottomonium states as a function of $\mu$ and $T$ emerges from the spectral function. The energy scales where the change in chemical potential leads to changes in the thermal properties of the mesons is consistent with QCD expectations.



## 1. Introduction

Understanding the thermal properties of heavy vector mesons inside a plasma of quarks and gluons can be a helpful tool for investigating heavy ion collisions. The dissociation of such particles may indicate the formation of a thermal medium. This type of proposal, considering charmonium states, appeared a long time ago in [1] (see also [2]).

A holographic description of the dissociation of charmonium and bottomonium states in a plasma at finite temperature but zero density appeared recently in ref. [3]. In this article the first radial excitations $1S, 2S$ and $3S$ appear as clear peaks of the spectral function. The height of the peaks decrease as the temperature of the medium increases, as expected. This reference used a finite temperature version of the holographic AdS/QCD model proposed in ref. [4] for calculating decay constants and masses of vector mesons. For completeness we mention that a previous model that describes the thermal behavior of the first excited state of charmonium appeared before in ref. [5].

AdS/QCD models, inspired in the AdS/CFT correspondence [6–8], provide nice fits for hadronic mass spectra. The simplest one is the hard wall AdS/QCD model, proposed in refs. [9–12] and consists in placing a hard cutoff in anti-de Sitter (AdS) space. Another AdS/QCD model is the soft wall that has the property that the square of the mass grow linearly with the radial excitation number [13]. In this case the background involves AdS space and a scalar field that acts effectively as a smooth infrared cutoff. A review of AdS/QCD models can be found in [14].

It is possible to use holographic models to calculate another hadronic property: the decay constant. The non-hadronic decay of mesons is represented as a transition from the initial state to the hadronic vacuum. For a meson at radial excitation level $n$ with mass $m_n$ the decay constant is defined by the relation $\langle 0|\, J_\mu(0)\, |n\rangle = \epsilon_\mu f_n m_n$, where $J_\mu$ is the gauge current, $\epsilon_\mu$ the polarization and there is no implicit sum over $n$. Note that one finds other definitions for the decay constants, involving different factors of the mass, in the literature.

The two point function has a spectral decomposition in terms of masses and decay constants of the states:

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

Calculating the left hand side of this equation using holography, one can find the mass and decay constant spectra [13,15].

In the finite temperature case, the particle content of a theory is described by the thermal spectral function, that is the imaginary part of the retarded Green's function. The quasi-particle states ap-

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**Table 1**
Experimental masses and electron–positron widths from [16] and the corresponding decay constants for the Bottomonium S-wave resonances.

| | Bottomonium data | | |
|---|---|---|---|
| | Masses (MeV) | $\Gamma_{V\to e^+e^-}$ (keV) | Decay constants (MeV) |
| $1S$ | $9460.3 \pm 0.26$ | $1.340 \pm 0.018$ | $715.0 \pm 2.4$ |
| $2S$ | $10023.26 \pm 0.32$ | $0.612 \pm 0.011$ | $497.4 \pm 2.2$ |
| $3S$ | $10355.2 \pm 0.5$ | $0.443 \pm 0.008$ | $430.1 \pm 1.9$ |
| $4S$ | $10579.4 \pm 1.2$ | $0.272 \pm 0.029$ | $340.7 \pm 9.1$ |

pear as peaks that decrease as the temperature or the density of the medium increase. The limit of the spectral function when $T$ and $\mu$ vanish is a sum of delta peaks with coefficients proportional to the square of the decay constants: $f_n^2\,\delta(-p^2 - m_n^2)$, arising from the imaginary part of eq. (1). So, the decay constants control the amplitude of the delta function peaks that appear in the spectral function at zero temperature. When the temperature is raised, the peaks are smeared. The height and the width of the peaks become finite. But a consistent extension to finite temperature must take into account the zero temperature behavior of the decay constants. That is why it is important to use a model that provides nice fits for the decay constants when one wants to find a reliable picture of the thermal spectral function.

In order to illustrate the behavior of the decay constants we show on Table 1 the experimental values of masses and electron positron decay widths $\Gamma_{V\to e^+e^-}$ for bottomonium vector meson $\Upsilon$, made of a bottom quark anti-quark pair and for the first three radially excited S-wave resonances. We also show the associated decay constants, with the corresponding uncertainties. The experimental values for masses and decay widths are taken from ref. [16]. The decay constant of a vector meson state is related to it's mass and width by [17]:

$$f_V^2 \;=\; \frac{3 m_V \Gamma_{V\to e^+e^-}}{4\pi\alpha^2 c_V}\,, \tag{2}$$

where $\alpha = 1/137$ and $c_V$ is $c_\Upsilon = 1/9$. The decay constants decrease monotonically with the radial excitation level. A similar behavior is observed for charmonium vector states [4]. In contrast, the soft wall model as originally formulated leads to decay constants for radial excitations of a vector meson that are degenerate The hard wall model provides decay constants that increase with the excitation level. The alternative version of the soft wall model developed in ref. [4] is consistent with the observed behavior. The decay constants are obtained from two point correlators of gauge theory operators calculated at a finite value $z = z_0$ of the radial coordinate of AdS space. This way an extra energy parameter $1/z_0$, associated with an ultraviolet (UV) energy scale, is introduced in the model.

In the subsequent article of ref. [3] this model was applied to the finite temperature and zero chemical potential case. A nice picture for the dissociation of $1S, 2S$ and $3S$ states of bottomonium emerged, consistent with previous results [18]. The purpose of the present letter is to extend the study of bottomonium vector meson dissociation for the case of finite density.

Heavy mesons have also been discussed in the context of holography in some interesting articles as, for example, refs. [19–30]. However the picture for the dissociation of $1S$ and $2S$ states of bottomonium in a medium with finite temperature and density that we show here is not yet present in the literature.

The article is organized as follows. In section 2 we explain the relation between the decay constants and the spectral function peaks. We also review the model of refs. [3,4] and explain the reason for using such a model with UV cut off in the finite temperature and density case. In section 3 we present an extension to finite chemical potential. Then is section 4 we develop the calculation of the vector meson spectral function using the membrane paradigm. In section 5 we analyze the bottomonium thermal spectrum as a function of $T$ and $\mu$ and discuss the results obtained.

## 2. Holographic model for decay constants

### 2.1. Decay constants in the soft wall

In the soft wall model [13] vector mesons are described by a vector field $V_m = (V_\mu, V_z)$ $(\mu = 0, 1, 2, 3)$, assumed to be 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 $\Phi = k^2 z^2$ is the soft wall dilaton background, that plays the role of a smooth infrared cut off and $k$ is a constant representing the mass scale.

The background geometry of the model is anti-de Sitter $AdS_5$ space, with metric

$$ds^2 \;=\; e^{2A(z)}(-dt^2 + d\vec{x}\cdot d\vec{x} + dz^2)\,, \tag{4}$$

where $A(z) = -log(z/R)$ and $(t, \vec{x}) \in \mathcal{R}^{1,3},\; z \in (0, \infty)$.

One uses the gauge $V_z = 0$. The boundary values of the other components of the vector field: $V_\mu^0(x) = \lim_{z\to 0} V_\mu(x, z)$, $\mu = 0, 1, 2, 3$ are assumed to be, as in AdS/CFT correspondence, sources of correlation functions of the boundary current operator

$$\langle 0|\, J_\mu(x) J_\nu(y)\,|0\rangle \;=\; \frac{\delta}{\delta V^{0\mu}(x)}\frac{\delta}{\delta V^{0\nu}(y)} \exp\left(-I_{onshell}\right)\,, \tag{5}$$

where the on shell action is given by the boundary term:

$$I_{on\,shell} \;=\; -\frac{1}{2\tilde{g}_5^2}\int d^4x \left[ \frac{e^{-k^2z^2}}{z} V_\mu \partial_z V^\mu \right]_{z\to 0}\,. \tag{6}$$

For convenience we introduced $\tilde{g}_5^2 = g_5^2/R$, the relevant dimensionless coupling of the vector field. One can write the on shell action in momentum space and decompose the field as

$$V_\mu(p, z) \;=\; v(p, z) V_\mu^0(p)\,, \tag{7}$$

where $v(p, z)$ is called bulk to boundary propagator and satisfies the equation of motion:

$$\partial_z\Big(\frac{e^{-k^2z^2}}{z}\partial_z v(p, z)\Big) + \frac{p^2}{z} e^{-k^2z^2} v(p, z) \;=\; 0\,. \tag{8}$$

The factor $V_\mu^0(p)$ works as the source of the correlators of gauge theory currents, so one imposes the boundary condition: $v(p, z = 0) = 1$. On the other hand, the two point function in momentum space is related to the current-current correlator by:

$$\Big(p^2\eta_{\mu\nu} - p_\mu p_\nu\Big)\; \Pi(p^2) \;=\; \int d^4x\; e^{-ip\cdot x} \langle 0|\, J_\mu(x) J_\nu(0)\,|0\rangle\,. \tag{9}$$

The two point function is expressed as:

$$\Pi(p^2) \;=\; \frac{1}{\tilde{g}_5^2\,(-p^2)} \left[ \frac{e^{-k^2z^2}\; v(p, z)\partial_z v(p, z)}{z} \right]_{z\to 0}\,, \tag{10}$$

and has the spectral decomposition shown in eq. (1), in terms of masses and decay constants. The result for the decay constants, following this soft wall approach is [13]:

$$f_n \;=\; k\sqrt{2}/\tilde{g}_5\,. \tag{11}$$