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Mass and Pole Residue of $Y_b(10890)$ State with $J^{PC} = 1^{--}$ at Finite Temperature

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Abstract. The status of the hidden beauty state Y_b is not clear up to now. The deviations from the expected behavior can provide a clue to consider it as an exotic meson candidate. Assuming the Y_b resonance as a tetraquark, we estimated its mass and pole residue, both at vacuum and $T \neq 0$ temperatures by calculating hot-medium contributions to hadronic parameters in the framework of Thermal QCD sum rules. Our results depict that the mass and pole residue values decrease dramatically at the vicinity of a critical temperature. Comparison of our results with the recent experimental data and theoretical results might be helpful in understanding the internal structure of bottomonium-like Y_b state.

INTRODUCTION

Recently B factories has announced observation of exotic mesons, including the newfound tetraquark family such as charmonium-like state $X(3872)$ [1], the bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ [2], and the open-heavy flavor meson $X(5568)$ [3]. These exotic structures containing more quarks than the standard quark content ($q\bar{q}$ or qqq) were estimated by a perceptible model for tetraquarks developed by Jaffe in 1976 [4]. Even though these exotic multiquark systems exhibit a new face of QCD, their dynamics is both challenging and currently not well understood. Additionally, discovery of these enigmatic particles may give information on the death of stars, aftermath of the Big Bang and the evolution of the universe, because it is likely that some fraction of the matter in neutron stars might consist of tetraquarks. These exotic QCD structures might have played important role in the early phases of the universe, when the temperature was decreasing rapidly. Thus, it is very crucial to explore the properties of these tetraquark states in hot medium. In the hidden bottom sector, Y_b is a good candidate to investigate. In the tetraquark interpretation, Y_b is described as a $J^{PC} = 1^{--}$ bound diquark-antidiquark system having the flavor content $Y_b = [bq][\bar{b}\bar{q}](q = u, d \text{ or } s)$ [5, 6]. It is first observed by Belle Collaboration in 2007 in the process $e^+e^- \to Y_b \to (\Upsilon(1S), \Upsilon(2S), \Upsilon(3S))\pi^+\pi^-$ [7].

This work is arranged as follows. In the next section, the theoretical framework of Thermal QCD sum rules (TQCDSR) approach and its application to Y_b is summarized briefly. The temperature dependent expressions of mass and pole residue up to dimension six operators are obtained via TQCDSR. Later numerical results are presented in the following section. Final remarks and discussions are presented in the closing section.

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THERMAL SUM RULES FOR Y_b STATE IN TETRAQUARK SCENARIO

TQCDSR were first proposed by Bochkarev and Shaposnikov in 1986 and led to countless applications [8, 9, 10, 11]. The QCD sum rules at finite temperature starts with the two-point correlation function [12, 13]

$$\Pi_{\mu\nu}(q,T) = i\int d^4x\, e^{iq\cdot x} Tr\{\rho\mathcal{T}[\eta_\mu(x)\eta_\nu^\dagger(0)]\}, \tag{1}$$

where $\eta_\mu(x)$ is the interpolating current of the Y_b state, $\mathcal{T}$ denotes the time ordering operator, $\rho = e^{-\beta\mathcal{H}}/Tr(e^{-\beta\mathcal{H}})$ is the thermal density matrix of QCD, where $\mathcal{H}$ is the QCD Hamiltonian, $\beta = 1/T$ is the inverse of temperature, and T is the temperature of the heat bath. Chosen current $\eta_\mu(x)$ must contain all information on the meson under investigation, like quantum numbers, quark contents and so on. In the diquark-antidiquark model, tetraquark current describing Y_b and like states can be expressed as [14]

$$\eta_\mu(x) = \frac{i\epsilon\tilde{\epsilon}}{\sqrt{2}}\Big\{\Big[\, s_a^T(x)C\gamma_5 b_b(x)\Big]\Big[\,\overline{s}_d(x)\gamma_\mu\gamma_5 C\overline{b}_e^T(x)\Big] + \Big[\, s_a^T(x)C\gamma_5\gamma_\mu b_b(x)\Big]\Big[\,\overline{s}_d(x)\gamma_5 C\overline{b}_e^T(x)\Big]\Big\}, \tag{2}$$

where a, b, c, d, e are color indices, C is the charge conjugation matrix and the shorthand notations $\epsilon = \epsilon_{abc}$ and $\tilde{\epsilon} = \epsilon_{dec}$ are used in Eq. (2).

According to the QCD sum rules approach, correlation function can be calculated in two different regions, via two different perspectives, namely physical and QCD side. Then, by equating these expressions obtained from both sides by using the selected Lorentz structure, the sum rules for the considered state are achieved. To derive the expressions of mass and pole residue of Y_b via TQCDSR, we start to calculate the correlation function in terms of the hadronic degrees of freedom. By inserting the complete set of intermediate physical states which have the same quantum number as the chosen interpolating current into Eq. (1), and performing integral over x, the below expression is acquired

$$\Pi_{\mu\nu}^{\text{Phys}}(q,T) = \frac{\langle\Omega|\eta_\mu|Y_b(q)\rangle_T\langle Y_b(q)|\eta_\nu^\dagger|\Omega\rangle_T}{(m_{Y_b}^2(T) - q^2)} + \textit{subtracted terms}, \tag{3}$$

where Ω symbolizes the hot medium and $m_{Y_b}(T)$ is the temperature-dependent mass of Y_b. Pole residue $\lambda_{Y_b}(T)$ depending on temperature is described with the matrix element as

$$\langle\Omega|\eta_\mu|Y_b(q)\rangle_T = \lambda_{Y_b}(T) m_{Y_b}(T)\,\varepsilon_\mu, \tag{4}$$

where ε_μ is the polarization vector of the Y_b state. Next, the correlation function depending on $m_{Y_b}(T)$ and $\lambda_{Y_b}(T)$ can be written in the following form

$$\Pi_{\mu\nu}^{\text{Phys}}(q,T) = \frac{m_{Y_b}^2(T)\lambda_{Y_b}^2(T)}{(m_{Y_b}^2(T) - q^2)}\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m_{Y_b}^2(T)}\right) + \ldots. \tag{5}$$

The required sum rules can be obtained by choosing a certain Lorentz structure from the $\Pi^{\text{Phys}}(q,T)$, which is $g_{\mu\nu}$ in this work, and equating the coefficient of this structure. Additionally, the standard Borel transformation is also applied in order to suppress the unwanted contributions to the correlation function. After these steps, the physical side is obtained as

$$\mathcal{B}(q^2)\Pi^{\text{Phys}}(q,T) = m_{Y_b}^2(T)\lambda_{Y_b}^2(T)\, e^{-m_{Y_b}^2(T)/M^2}. \tag{6}$$

In the QCD side, the correlation function is calculated in terms of quark-gluon degrees of freedoms. First, the interpolating current given in Eq. (2) is inserted into the correlation function given in Eq. (1) and all heavy and light quark fields are contracted, and the following expression is obtained

$$\begin{aligned}\Pi_{\mu\nu}^{\text{QCD}}(q,T) = -\frac{i}{2}\int d^4x e^{iq\cdot x}\epsilon\tilde{\epsilon}\epsilon'\tilde{\epsilon}'\langle\{&\text{Tr}[\gamma_\mu\gamma_5\widetilde{S}_b^{aa'}(-x)\gamma_5\gamma_\nu S_s^{bb'}(-x)]\text{Tr}[\gamma_5\widetilde{S}_s^{dd'}(x)\gamma_5 S_b^{ee'}(x)]\\ &+\text{Tr}[\gamma_5\widetilde{S}_b^{aa'}(-x)\gamma_5 S_s^{bb'}(-x)\gamma_\mu]\text{Tr}[\gamma_5\widetilde{S}_s^{dd'}(x)\gamma_5\widetilde{S}_b^{ee'}(x)\gamma_\nu\gamma_5 S_b^{bb'}(x)] + \text{Tr}[\gamma_5\widetilde{S}_b^{aa'}(-x)\gamma_5\gamma_\nu S_s^{bb'}(-x)]\\ &\times\text{Tr}[\gamma_5\widetilde{S}_s^{dd'}(x)\gamma_5\gamma_\mu S_b^{ee'}(x)] + \text{Tr}[\gamma_5\widetilde{S}_b^{aa'}(-x)\gamma_5 S_s^{bb'}(-x)]\text{Tr}[\gamma_5\widetilde{S}_s^{dd'}(-x)\gamma_5 S_b^{ee'}(x)\gamma_\nu]\}\rangle_T,\end{aligned} \tag{7}$$

where $S^{ij}_{b(s)}(x)$ is the heavy(light) quark propagator, and the shorthand notation $\widetilde{S}^{ij}_{b(s)}(x) = CS^{ijT}_{b(s)}(x)C$, is employed. In hot medium, as a result of broken Lorentz invariance due to the selection of reference frame and manifestation of the residual $O(3)$ symmetry, the new operators arise in the operator product expansion (OPE) in the QCD side. Thus, the thermal quark propagator involves extra new terms with respect to the quark propagator in vacuum [15]. In coordinate space, thermal heavy-quark propagator can be formulated as

$$\begin{aligned} S^{ij}_{b}(x) &= i\int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot x}\Bigg[\frac{\delta_{ij}\Big(\not{k}+m_b\Big)}{k^2-m_b^2} - \frac{gG^{\alpha\beta}_{ij}}{4}\frac{\sigma_{\alpha\beta}\Big(\not{k}+m_b\Big)+\Big(\not{k}+m_b\Big)\sigma_{\alpha\beta}}{(k^2-m_b^2)^2} \\ &+ \frac{g^2}{12}G^A_{\alpha\beta}G^{\alpha\beta}_A\delta_{ij}m_b\frac{k^2+m_b\not{k}}{(k^2-m_b^2)^4}+\ldots\Bigg], \end{aligned} \tag{8}$$

where $G^{\alpha\beta}_{ij} = G^{\alpha\beta}_A t^A_{ij}$ is the external gluon field with $A = 1, 2, ...8$, $t^A_{ij} = \lambda^A_{ij}/2$, λ^A_{ij} being the Gell-Mann matrices and the gluon field strength tensor $G^{\alpha\beta}_A \equiv G^{\alpha\beta}_A(0)$ is fixed at $x = 0$. The thermal light-quark propagator S_q, being $q = u, d$ or s is chosen as

$$\begin{aligned} S^{ij}_{q}(x) &= i\frac{\not{x}}{2\pi^2x^4}\delta_{ij} - \frac{m_q}{4\pi^2x^2}\delta_{ij} - \frac{\langle\bar{q}q\rangle}{12}\delta_{ij} - \frac{x^2}{192}m_0^2\langle\bar{q}q\rangle\Big[1-i\frac{m_q}{6}\not{x}\Big]\delta_{ij} + \frac{i}{3}\Big[\not{x}\Big(\frac{m_q}{16}\langle\bar{q}q\rangle - \frac{1}{12}\langle u\Theta^f u\rangle\Big) \\ &+ \frac{1}{3}(u\cdot x)\not{u}\langle u\Theta^f u\rangle\Big]\delta_{ij} - \frac{ig_s\lambda^A_{ij}}{32\pi^2x^2}G^{\mu\nu}_A\Big(\not{x}\sigma_{\mu\nu}+\sigma_{\mu\nu}\not{x}\Big), \end{aligned} \tag{9}$$

where m_q denotes the light quark mass, u_μ is the four-velocity of the heat bath, $\langle\bar{q}q\rangle$ is the temperature-dependent light quark condensate and $\Theta^f_{\mu\nu}$ is the fermionic part of the energy momentum tensor. Also, for the gluon condensate regarding the gluonic part of the energy-momentum tensor $\Theta^g_{\lambda\sigma}$, the following relation is used (see for details Ref. [15])

$$\begin{aligned} \langle Tr^c G_{\alpha\beta}G_{\mu\nu}\rangle &= \frac{1}{24}(g_{\alpha\mu}g_{\beta\nu}-g_{\alpha\nu}g_{\beta\mu})\langle G^a_{\lambda\sigma}G^{a\lambda\sigma}\rangle + \frac{1}{6}\Big[g_{\alpha\mu}g_{\beta\nu}-g_{\alpha\nu}g_{\beta\mu} \\ &-2(u_\alpha u_\mu g_{\beta\nu}-u_\alpha u_\nu g_{\beta\mu}-u_\beta u_\mu g_{\alpha\nu}+u_\beta u_\nu g_{\alpha\mu})\Big]\langle u^\lambda\Theta^g_{\lambda\sigma}u^\sigma\rangle. \end{aligned} \tag{10}$$

The correlation function $\Pi^{\rm QCD}_{\mu\nu}(q,T)$ can be separated into two parts over the Lorentz structures as

$$\Pi^{\rm QCD}_{\mu\nu}(q,T) = \Pi^{\rm QCD}_S(q^2,T)\frac{q_\mu q_\nu}{q^2} + \Pi^{\rm QCD}_V(q^2,T)(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}), \tag{11}$$

where $\Pi^{\rm QCD}_S(q^2,T)$ and $\Pi^{\rm QCD}_V(q^2,T)$ are invariant functions related to the scalar and vector currents, respectively. In the rest frame of the meson, i.e. $\mathbf{q} = 0$, $\Pi^{\rm QCD}_V(q_0^2,T)$ can be stated as a dispersion integral

$$\Pi^{\rm QCD}_V(q_0^2,T) = \int_{4(m_b+m_s)^2}^{s_0(T)}\frac{\rho^{\rm QCD}(s,T)}{(s-q_0^2)}ds + ..., \tag{12}$$

where the spectral density is given by $\rho^{\rm QCD}(s,T) = \frac{1}{\pi}Im\Pi(s,T)$. In order to calculate $\rho^{\rm QCD}(s,T)$, the spectral density is written in terms of perturbative and nonperturbative parts as

$$\rho^{\rm QCD}(s,T) = \rho^{\rm pert.}(s) + \sum_{i=1}^{4}\rho_i(s,T), \tag{13}$$

where $i = 1, 2, 3, 4$ represents the nonperturbative terms corresponding to the quark, gluon, mix condensates and six dimensional condensates, respectively. After inserting Eq. (8), (9) and (10) into the Eq. (7), and proceeding with standard evaluations, the expressions of the perturbative and nonperturbative spectral densities are archived. Since these expressions are too long, all of them are not presented here, explicitly. Only perturbative term is presented here

as an example. The expression of $\rho^{\text{pert.}}(s)$ is obtained by the integrals over the Feynman parameters z and w with the θ step function as

$$\rho^{\text{pert.}}(s) = \frac{1}{3\cdot 2^{10}\pi^6}\int_0^1 dz\int_0^{1-z} dw \frac{1}{\xi^2\kappa^8}\Bigg\{\Big[-\kappa m_b^2(z+w)+szw\xi\Big]^2\Big[\kappa^2 m_b^4 zw(z+w)[w^2+(-1+w)w+$$

$$\times 7w^2]+sz^2w^2(12(-1+z)z+(-12+25z)w+12w^2)\Big]\xi+szw(12m_s^2\Phi^2+35sz^2w^2)\xi^3\Big]\Bigg\}\theta[L(s,w,z)], \tag{14}$$

where explicit expression of the function $L(s,w,z)$ is given as

$$L(s,w,z) = \frac{(-1+w)\Big[(-1+w)w^2+2(-1+w)wz+(-1+2w)z^2-swz\xi+z^3m_b^2\Big]}{\kappa^2}. \tag{15}$$

In the expressions above, we have employed the following abbreviations for simplicity: $\kappa = z^2+z(w-1)+(w-1)w$, $\Phi = (z-1)\,w+(z-1)\,w+w^2$, $\xi = z+w-1$. To get rid of the contributions stemming from higher states, a Borel transformation on the variable q_0^2 is also applied on the QCD side. Using the same structure in both expressions $\Pi_{\mu\nu}^{\text{Phys}}(q,T)$ and $\Pi_{\mu\nu}^{\text{QCD}}(q,T)$, and equating the coefficients, the sum rules for Y_b in hot medium is obtained as

$$\lambda_{Y_b}^2(T)\,e^{-m_{Y_b}^2(T)/M^2} = \frac{1}{m_{Y_b}^2(T)}\int_{4(m_b+m_s)^2}^{s_0(T)} ds\rho^{\text{QCD}}(s,T)\,e^{-s/M^2}. \tag{16}$$

The value of the pole residue can be obtained from this relation. However, to reach the mass sum rule, hadronic coupling constant should be eliminated from Eq. (16). Thus, taking the derivative of the sum rule given in Eq. (16) with respect to $(-1/M^2)$ and then dividing by itself, temperature dependent mass sum rules are obtained as

$$m_{Y_b}^2(T) = \frac{\int_{4(m_b+m_s)^2}^{s_0(T)} ds\; s\,\rho^{\text{QCD}}(s,T)\,e^{-s/M^2}}{\int_{4(m_b+m_s)^2}^{s_0(T)} ds\,\rho^{\text{QCD}}(s,T)\,e^{-s/M^2}}, \tag{17}$$

where M^2 is the Borel parameter and $s_0(T)$ is the temperature-dependent continuum threshold parameter.

NUMERICAL ANALYSIS

In this section, numerical analysis of the sum rules obtained in previous section are presented. The values of mass and pole residue of Y_b state at the vacuum and also non-zero temperature are estimated. Analyzing our computations, the hot medium effects on the hadronic parameters of the investigated Y_b state can be seen. The input parameters that we employed in our computation are: $m_s = (0.13\pm0.03)$ MeV, $m_b = (4.24\pm0.05)$ GeV (see for details Refs. therein [16, 17]), $m_0^2 = (0.8\pm0.2)\text{GeV}^2$, $\langle s\bar{s}\rangle = -0.8\times(0.24\pm0.01)^3$ GeV^3, $\langle 0|\frac{1}{\pi}\alpha_s G^2|0\rangle = (0.012\ \text{GeV}^4)$ [18, 19, 20, 21]. In addition to these input parameters, temperature-dependent quark and gluon condensates, and the energy density expressions are needed. For the thermal quark condensate, the fit function obtained in Refs. [22, 23], which is also in agreement with the Lattice QCD results [24, 25], is utilized in the evaluation and expressed in terms of quark vacuum condensate $\langle 0|\bar{q}q|0\rangle$ in the following form

$$\langle\bar{q}q\rangle = \frac{\langle 0|\bar{q}q|0\rangle}{1+exp\Big[18.10042\Big(1.84692\Big[\frac{1}{\text{GeV}^2}\Big]T^2+4.99216\Big[\frac{1}{\text{GeV}}\Big]T-1\Big)\Big]}, \tag{18}$$

which is credible up to a critical temperature $T_c = 190$ MeV. For the temperature-dependent gluon condensate the below parametrization is used [22, 26]:

$$\langle G^2\rangle = \langle 0|G^2|0\rangle\Bigg[1-1.65\left(\frac{T}{T_c}\right)^{8.735}+0.04967\left(\frac{T}{T_c}\right)^{0.7211}\Bigg], \tag{19}$$

which is extracted from both QCD sum rules and Lattice QCD data, where $G^2 = G^A_{\alpha\beta}G^{\alpha\beta}_A$, $\langle 0|G^2|0\rangle$ is the gluon condensate at $T = 0$. Lastly, the gluonic and fermionic parts of the energy density parameterized via relation [22]

$$\langle\Theta^g_{00}\rangle = \langle\Theta^f_{00}\rangle = T^4 exp\left(113.867\Big[\frac{1}{\text{GeV}^2}\Big]T^2 - 12.190\Big[\frac{1}{\text{GeV}}\Big]T\right) - 10.141\Big[\frac{1}{\text{GeV}}\Big]T^5, \tag{20}$$

which is extracted from the Lattice QCD results presented in Ref. [27]. To continue the computation one should also determine the temperature-dependent continuum threshold for the Y_b meson. The temperature dependent continuum threshold expression is given by [11, 28];

$$s_0(T) = s_0\left[1 - \left(\frac{T}{T_c}\right)^8\right] + 4(m_b + m_s)^2\left(\frac{T}{T_c}\right)^8, \tag{21}$$

where s_0 is the continuum threshold at zero temperature. In reality this parameter is not completely arbitrary but characterizes the beginning of the first excited state in continuum with the same quantum numbers as the chosen interpolating currents for the considered particle.

The physical results obtained by the QCD sum rules method should be independent of the auxiliary parameters s_0 and M^2. However in the QCD sum rule approach, OPE of the correlation function is an approximation. As a result the hadronic dispersion integral in the physical side is sophisticated and its explicit structure is unknown. Hence, match of the two sides is not independent of M^2, but the physical results such as mass and pole residue should be. To fix the working region for the Borel parameter M^2, the convergence of OPE is necessary. The OPE convergence is commonly tested by the criterion; the perturbative contribution must be larger than the condensate contributions. In this work, the working regions of Borel parameter M^2 is determined by respecting OPE convergence and also by testing the pole contribution. Within this range, hadronic parameters doesn't depend on auxiliary parameters, and they are stable. We obtained these working region as 6 $\text{GeV}^2 \leq M^2 \leq 10$ GeV^2, 132 $\text{GeV}^2 \leq s_0 \leq 134$ GeV^2. In this region, the obtained QCDSR predicts reliable results. Following our analysis, we employed the following fit functions to parameterize the temperature dependence of the hadronic parameters

$$m_{Y_b}(T) = Ae^{\alpha T} + B, \quad \lambda_{Y_b}(T) = Ce^{\beta T} + D \tag{22}$$

where the temperature T is in units of GeV. The variables A, B, C, D, α and β are obtained from TQCDSR and given in Table 1.

TABLE 1. Values of parameters A, B, C, D, α and β in fit functions.

State	A [GeV]	α[GeV^{-1}]	B [GeV]	C [GeV^4]	β[GeV^{-1}]	D [GeV^4]
Y_b	-6.981×10^{-6}	10.383	1.003	-3.803×10^{-5}	10.137	1.003

After fixing the fit variables, the temperature dependence of the mass and the pole residue of the Y_b resonance can be analyzed. It is seen that, the mass and the pole residue of the Y_b state stay nearly unchanged until $T \cong 0.12$ GeV. However, after this point, they begin to decrease promptly with increasing temperature. At near critical temperature, the pole residue decreases roughly by 56%, and the mass decreases by 13%. Numerical results obtained for the mass in vacuum are shown in Table 2. Our results are in good agreement with the results given in Refs. [18, 29, 16].

TABLE 2. At $T = 0$ mass values of the Y_b state in tetraquark picture.

	m_{Y_b}(MeV)	
Our Work	10735^{+122}_{-107}	
Experiment	$10889.9^{+3.2}_{-2.6}$	[18]
QCDSR	10880 ± 130	[29]
	10910 ± 70	[16]

CONCLUSION

In this study, we investigated the enigmatic bottomonium state Y_b, by extending QCD sum rules from zero temperature to hot medium. To determine the effects of heat bath on the hadronic parameters of the Y_b state, Thermal QCD sum rules method is used by considering the contributions of condensates up to dimension six. According to our results, until temperature $T \simeq 120$ MeV the mass and the pole residue values stay almost same with the QCD vacuum values, however after this point their trend is remarkably changed and their values are decreased approximately to 87% and 44% of their vacuum values, respectively. The behavior of Y_b state in terms of temperature might be a helpful tool to deeply understand the non-standard mesons and the results coming from heavy-ion collision experiments. Our estimates for the hadronic features of the Y_b meson can be extended to other Y_b like exotic structures, and these results can be tested in the forthcoming experiments.

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