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The Thermal Properties of Pseudoscalar Heavy Quarkonium

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Study of heavy quarkonia is one of the most interesting fields and plays an important role in understanding the properties of QCD vacuum as well as nonperturbative behavior of strong interaction. In this study we investigated the temperature dependence of leptonic decay constants for pseudoscalar heavy quarkonium states. We took into account the additional operators in the Wilson expansion at finite temperature and calculated thermal spectral density in the QCD side. The analysis of obtained thermal QCD sum rules shows that at critical temperature the decay constant decreases approximately 50% for η_c and 57% for η_b and this situation can be seen of a sign of QGP phase transition. The results at zero temperature are in a good consistency with the existing experimental values as well as predictions of the other nonperturbative approaches.

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1. Temperature Behavior of the Decay Constants

The discussion of heavy-meson properties has a rather long history and the heavy mesons play a very important role in our understanding of nonperturbative dynamics of QCD. Recently, an important progress has been achieved by BABAR Collaboration and they observed η_b in the photon spectrum of $\Upsilon(3S)\rightarrow\gamma\eta_b$ [1]. The interpretation of in-medium hot matter effects requires investigation of hadron properties at finite temperature. Our aim in this work is to investigate the temperature dependence of leptonic decay constants of the pseudoscalar η_b and η_c mesons. Using the thermal quark propagator, we find the imaginary part of the correlation function in the following form:

$$Im\Pi(q_0,T) \;=\; -q_0N_c\int\frac{d\mathbf{k}}{8\pi^2\omega}(1-2n(\omega)+n^2(\omega))\delta(q_0-2\omega), \tag{1.1}$$

To calculate the nonperturbative part in QCD side, we use the nonperturbative part of the quark propagator in an external gluon field, $A^a_\mu(x)$ in the Fock-Schwinger gauge, $x^\mu A^a_\mu(x)=0$. Taking into account one and two gluon lines attached to the quark line, the massive quark propagator up to terms necessary for our calculations can be written as:

$$\begin{aligned} S^{aa'nonpert}(k) \;&=\; -\frac{i}{4}g(t^c)^{aa'}G^c_{\kappa\lambda}\frac{1}{(k^2-m^2)^2}\Big[\sigma_{\kappa\lambda}(\not k+m)+(\not k+m)\sigma_{\kappa\lambda}\Big] \\ &+\; \frac{i\,g^2\,\delta^{aa'}}{9\,(k^2-m^2)^4}\Big\{\frac{3m(k^2+m\,\not k)}{4}\langle G^c_{\alpha\beta}G^{c\alpha\beta}\rangle+\Big[m\Big(k^2-4(k\cdot u)^2\Big) \\ &+\; \Big(m^2-4(k\cdot u)^2\Big)\,\not k+4(k\cdot u)(k^2-m^2)\,\not u\Big]\langle u^\alpha\Theta^g_{\alpha\beta}u^\beta\rangle\Big\}. \end{aligned} \tag{1.2}$$

where u^μ is the four-velocity of the heat bath and $\Theta^g_{\lambda\sigma}$ is the traceless, gluonic part of the energy-momentum tensor of the QCD. Taking into account additional operators arising at finite temperature, nonperturbative part of the correlation function can be expressed as:

$$\begin{aligned} &\hat{B}\;\Pi^{np}=\int_0^1 dx\,\frac{1}{24\,\pi\,M^6\,x^4\,(-1+x)^4}\exp\Big[\frac{m^2}{M^2x(-1+x)}\Big]\Big\{\langle\alpha_sG^2\rangle\Big[m^6(1-2x)^2 \\ &+\;6\,M^2\,m^2\,x^2\,(-1+x)^2-12\,M^6\,x^4\,(-1+x)^4+6\,M^4\,m^2\,x^2\,(-1+x)^2\,(-1-4x+4x^2)\Big] \\ &+\;\alpha_s\langle\Theta^g\rangle\Big[\Big[(m^6(1-2x)^2+M^6\,x^3\,(-1+x)^3\,(9-11x+11x^2)-m^2\,M^4\,(-1+x)^2\,x^2 \\ &\times\;(1-17x+17x^2)-2\,m^4\,M^2\,x\,(-1+2x-2x^2+x^3))\Big]\Big]\Big\}, \end{aligned} \tag{1.3}$$

where M^2 is the Borel mass parameter and $\omega=\sqrt{\mathbf{k}^2+m^2}$. Matching the phenomenological and QCD sides of the correlation function, sum rules for the decay constant of pseudoscalar meson is obtained:

$$f_P^2(T)m_P^4(T)\exp\Big(-\frac{m_P^2}{M^2}\Big)\;=\;4m^2\Big\{\int_{4m^2}^{s_0(T)}ds(\rho^{a,pert}(s)+\rho_{\alpha_s}(s))\exp\Big(-\frac{s}{M^2}\Big)+\widehat{B}\Pi^{np}\Big\}, \tag{1.4}$$

where $\rho^{a,pert}(s)$ and $\rho_{\alpha_s}(s)$ are annihilation part of thermal spectral density and the perturbative two-loop order correction, respectively.

2. Conclusions and Discussions

The sum rules for the masses and decay constants include two auxiliary parameters, namely continuum threshold s_0 and Borel mass parameter M^2. Therefore, we should look for working regions for these parameters such that the dependences of the masses and decay constants on these parameters is weak. The continuum threshold, s_0 is related to the energy of the first exited state with the same quantum numbers as the interpolating currents. We choose the values $11\ GeV^2 \leq s_0 \leq 12\ GeV^2$ and $97\ GeV^2 \leq s_0 \leq 100\ GeV^2$ for the continuum threshold in accordance with η_c and η_b channels, respectively.

Taking into account the temperature dependencies of hadronic threshold, energy density, quark and gluon condensates, we obtained that decay constants are well described by the following fit functions:

$$f_{\eta_b}(T) = -2.09497 \times 10^{-4}\ \exp\Big(44.3066\ T\Big) + 0.69914, \tag{2.1}$$

$$f_{\eta_c}(T) = -4.41028 \times 10^{-5}\ \exp\Big(49.776\ T\Big) + 0.42098. \tag{2.2}$$

Here decay constants and temperature are expressed in units of GeV. These parameterizations are valid only in the interval $0 \leq T \leq 0.17\ GeV$.

Our investigations show that the masses and decay constants remain unchanged approximately up to $T \simeq 100\,MeV$, but after this point, they start to diminish with increasing the temperature. Near the critical or deconfinement temperature, the decay constants reach approximately to 50%, 57% of their values in vacuum, while the masses are decreased about 12%, 2% comparing with their values at zero temperature for η_c, η_b mesons, respectively.

At $T = 0$, values of the masses and leptonic decay constants for η_c and η_b are obtained as $m_{\eta_c} = 2.996 \pm 0.035 GeV$, $f_{\eta_c} = 0.420 \pm 0.015 GeV$, $m_{\eta_b} = 9.650 \pm 0.034 GeV$ and $f_{\eta_b} = 0.696 \pm 0.049 GeV$. The obtained results are in good consistency with the existing experimental data and predictions of other nonperturbative models [2] (for more details see [3]). Our results on the leptonic decay constants of η_b and η_c at zero temperature as well as the behavior of the masses and decay constants of the considered pseudoscalar heavy mesons with respect to the temperature can be checked in the future experiments.

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