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Heavy quarkonium spectra and J/Ψ dissociation in hot and dense matter

B. Liu,[2,1] P. N. Shen,[1,2] and H. C. Chiang[2]
[1]CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China
[2]Institute of High Energy Physics, Academia Sinica, Beijing 100039, Peoples Republic of China*
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The mass spectra of charmonium and bottonium states are analyzed in terms of the error-function-type confining force and the color screened Coulomb-type potential. The Debye screening mass at finite temperature and density is studied in the thermofield dynamics approach. The critical temperature and density for J/Ψ dissociation in the hot and dense matter are obtained. [S0556-2813(97)00806-6]

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I. INTRODUCTION

It has been suggested that a phase transition would take place from hadron matter to unconfined quark-gluon matter at sufficiently high density. There has been considerable interest in relativistic heavy-ion collisions which could offer the possibility of producing a hot and dense matter and/or plasma of deconfined quarks and gluons. It was theoretically proposed [1] that the formation of a deconfined medium in high energy nucleus collisions would lead to the suppression of J/Ψ production due to the color screening. The J/Ψ suppression in relativistic heavy-ion collisions as one of the QGP signals has attracted much attention both from theoretical and experimental physicists. Subsequently, the observations [2] by the NA38 Collaboration confirmed the existence of J/Ψ suppression. However, the data observed by the NA38 Collaboration can also be explained by the conventional models. Recently, the NA50 Collaboration [3] observed the strong suppression of J/Ψ production in Pb-Pb collisions. It seems that the new data cannot be explained by conventional models of nuclear absorption. Therefore, there might be some new physics in Pb-Pb collisions [3].

J/Ψ is dominantly produced in the very early stage of the whole collision process. In the quark model, the J/Ψ is described as a nonrelativistic $c\overline{c}$ bound state. In QGP, quarks and gluons are deconfined and the confining force between c and $\overline{c}$ vanishes, the only interaction between c and $\overline{c}$ is the Coulomb-type color interaction. The color charge of the charm quark c will be screened by the quarks, antiquarks, and gluons in the plasma. The final yield of the J/Ψ resonance will be suppressed due to the color screening if a quark-gluon plasma is formed in high energy heavy-ion collisions. Therefore, the study of binding and dissociation of the J/Ψ resonance can provide information about the color screening in QGP.

The authors [4] studied the binding and deconfinement of heavy quarks in a thermal environment by using a nonrelativistic confinement potential model with color screening. They calculated the critical values of the screening masses for heavy quark resonances. Although the linear confining potential was quite successful in explaining hadronic spectra, the lattice gauge calculation [5] showed that the color screening effect caused by the quark sea can affect the color confinement. It was found that the confining potential between a quark and an antiquark is notably weaker than the linear one when the distance between quarks becomes large enough. This effect reduces the color confining force.

In this paper, in order to see the effect of the quark binding potential on deconfinement of heavy quark bound states, we use an error-function-type confining force and the color screened Coulomb-type potential to calculate the mass spectra and rms radii of heavy quark resonances. We estimate the dissociation energies for heavy quark bound states with respect to screening masses and calculate the electric screening mass of the gluon at finite temperature and density. As a result, the critical values of screening masses for $c\overline{c}$ and $b\overline{b}$ bound states are obtained and compared with the previous results. The dissociation condition of J/Ψ in the hot and dense matter is found.

II. QUARK BINDING AND DISSOCIATION OF HEAVY QUARK RESONANCES

We first study the binding of charmonium $(c\overline{c})$ and bottonium $(b\overline{b})$ in the nonrelativistic potential model. The Hamiltonian at temperature T for such a system is given by

$$H(r,T)=\frac{p^2}{2m_{\rm re}}+V(r,T), \tag{1}$$

where $m_{\rm re}$ is the reduced mass of the $c\overline{c}$ (or $b\overline{b}$) system, p denotes the relative momentum, $V(r,T)$ represents the binding potential between quark q and antiquark $\overline{q}$ at temperature T, r denotes the relative coordinate between quark q and antiquark $\overline{q}$.

A phenomenological binding potential of interacting quarks at zero temperature is given by the sum of the one-gluon-exchange Coulomb-type part and the linear confining potential, which is called the Cornell form (Cornell) [6]

$$V(r,0)=\sigma r-\frac{\alpha_{\rm eff}}{r}, \tag{2}$$

*Mailing address.

TABLE I. The mass spectra and rms radii of $c\bar{c}$ and $b\bar{b}$ bound states in the two potential models.

	nl	State	M_{ne} (GeV)		$\langle r^2\rangle^{1/2}$ (fm)	
			Cornell	erf	Cornell	erf
Charmonium	1S	J/ψ(3.097)	3.0697	3.0700	0.4490	0.4453
	2S	ψ'(3.686)	3.6978	3.6863	0.8655	0.9034
	3S	ψ''(4.040)	4.1696	4.0806	1.2025	1.3765
	1P	χ_c(3.500)	3.5003	3.5054	0.6890	0.7000
Bottonium	1S	Υ(9.460)	9.4450	9.4310	0.2245	0.2211
	2S	Υ'(10.0233)	10.0040	10.0083	0.5040	0.4998
	3S	Υ''(10.3553)	10.3547	10.3564	0.7336	0.7457
	1P	χ_b(9.9002)	9.8974	9.8981	0.4041	0.3982

where $\alpha_{\mathrm{eff}}=4/3\alpha_s$ is the effective coupling constant and σ is the confinement string tension.

In QGP, quarks and gluons are deconfined and the string tension vanishes, due to the color screening effect, the Coulomb-type interaction is replaced by the Debye screening potential

$$V(r,\mu)=-\frac{\alpha_{\mathrm{eff}}}{r}e^{-\mu r}, \tag{3}$$

where μ is the Debye screening mass and the Debye screening length r_D is defined as the inverse of the screening mass, $r_D=1/\mu$.

Karsch, Mehr, and Satz [4] (KMS) proposed a potential model to study the binding and deconfinement of heavy quark resonances in the thermodynamic environment, which gives the potential

$$V(r,\mu)=\frac{\sigma}{\mu}(1-e^{-\mu r})-\frac{\alpha_{\mathrm{eff}}}{r}e^{-\mu r}, \tag{4}$$

where the screening mass μ (also the screening length) is assumed to be a function of the temperature T. They calculated the critical values of screening masses for heavy quark resonances.

In studying the baryon and charmonium spectra, an error-function-type confining force which describes the color screening effect was employed [7]. The results showed that the color screening effect is also required at $T=0$ in order to fit the experimental properties of quark systems. In order to see the effects of different quark binding potentials on dissociations of the $c\bar{c}$ and $b\bar{b}$ systems, we use the error-function confinement force and the color screening potential (hereafter we call the erf potential or erf) to study the binding and deconfinement of heavy quark resonances

$$V(r,\mu)=\frac{\sigma}{\mu}\mathrm{erf}(\mu r)-\frac{\alpha_{\mathrm{eff}}}{r}e^{-\mu r}+V_0, \tag{5}$$

where the μ is also the screening mass, V_0 is the additional constant for fitting the mass spectra of heavy quarkonia.

The energy eigenvalues and rms radii of $c\bar{c}$ and $b\bar{b}$ bound states can be calculated by solving the Schrödinger equation

$$H(r,\mu)\Psi_{nl}(r,\mu)=\epsilon_{nl}(\mu)\Psi_{nl}(r,\mu). \tag{6}$$

The mass $M_{nl}(\mu)$ for each bound state is related to the energy eigenvalue by

$$M_{nl}(\mu)=2m_q+\epsilon_{nl}(\mu), \tag{7}$$

where m_q is the mass of quark q. In order to compare with the previous results [4], we take the same parameters as $\alpha_{\mathrm{eff}}=0.471$, $\sigma=0.192$ GeV^2, $m_c=1.32$ GeV, and $m_b=4.746$ GeV [8] in our calculations.

First we solve the Schrödinger equation with the erf potential (5) to obtain the mass spectra and rms radii of $c\bar{c}$ and $b\bar{b}$ bound states by adjusting the parameters μ and V_0 in a least squares fit where the standard deviation is defined as

$$\chi^2=\frac{\Sigma_{nl}(M_{nl}^{\mathrm{expt}}-M_{nl}^{\mathrm{theory}})^2}{N-1}, \tag{8}$$

with N to be the total number of (nl) states. We obtain $\mu=0.1$ GeV $(=\mu_0)$ and $V_0=-0.082$ GeV. The results are listed in Table I and compared with the results from the Cornell potential (2) with the same parameters. We obtain $\chi=0.0223$, 0.0511 GeV for the erf potential (5) and the Cornell potential (2), respectively. It is shown that the mass spectra given by the erf potential (5) are more consistent with

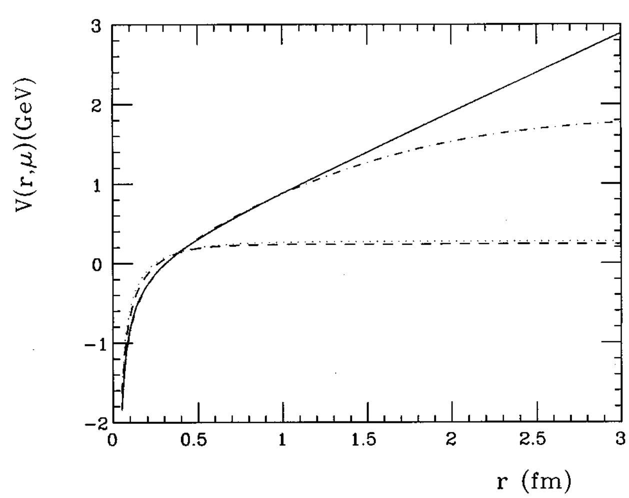

FIG. 1. The comparisons between the different potentials. The solid line is the Cornell potential, the dash-dotted line is the erf potential, the dotted line is the KMS with $\mu=700$ MeV, and the dashed line is the erf with $\mu=600$ MeV.

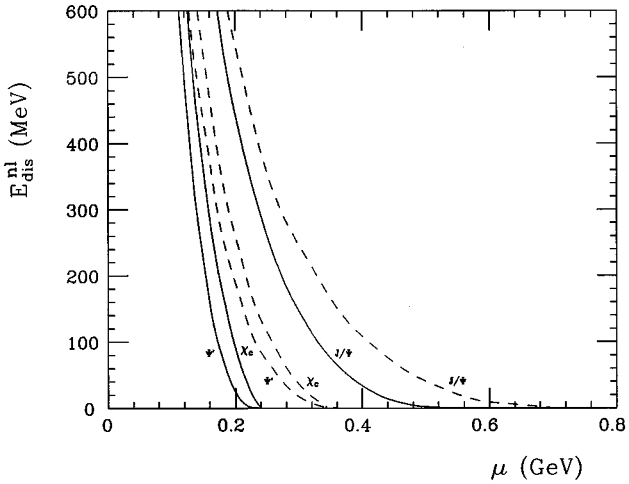

FIG. 2. The dissociation energies for $c\bar{c}$ bound states. The solid lines are the results given by the erf potential. The dashed lines are the results given by the KMS potential.

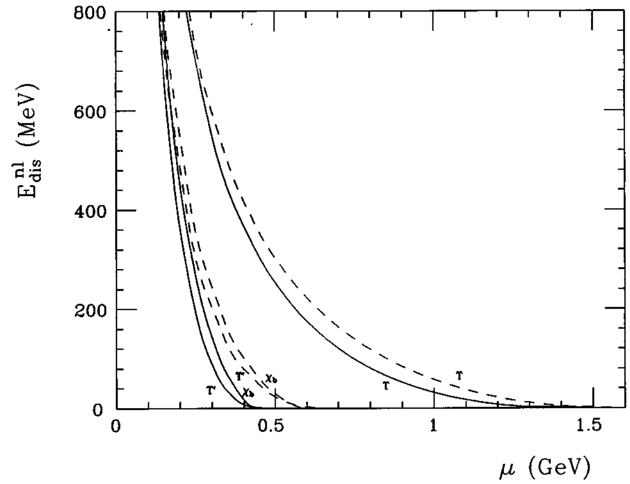

FIG. 3. The dissociation energies for $b\bar{b}$ bound states. The solid lines are the results given by the erf potential. The dashed lines are the results given by the KMS potential.

the experiment values. The comparison between the Cornell potential and the erf potential with $\mu_0=0.1$ GeV and $V_0=-0.082$ GeV is given in Fig. 1. The solid line is the Cornell potential as a function of r, the dash-dotted line is the erf potential. The results in Fig. 1 show that the behaviors of the two potentials are basically the same at small r, and the erf potential is lower than the Cornell one at larger distance r.

Next we study the dissociations of heavy quark resonances. The significant quantity is the dissociation energies for heavy quark bound states. The dissociation energy for a bound state with quantum number nl at a fixed μ can be defined as

$$E_{\rm dis}^{nl}(\mu)=2m_q+V(r\rightarrow\infty,\mu)-M_{nl}(\mu). \tag{9}$$

The dissociation energy $E_{\rm dis}^{nl}(\mu)$ is positive for bound states and turns into negative for the continuum. So the critical value of μ for a specific bound state with quantum nl can be found

$$E_{\rm dis}^{nl}(\mu_c)=0. \tag{10}$$

We use the erf potential (5) to calculate the dissociation energy $E_{\rm dis}^{nl}(\mu)$ as a function of μ for $c\bar{c}$ and $b\bar{b}$ bound states, the results are given in Figs. 2 and 3 by the solid lines, respectively, and compared with the results from the KMS potential (4) by the dashed lines. Figures 2 and 3 show that the results of the erf potential are shifted to small μ regions in comparison with the results of the KMS potential. The reason is that the color screening effect is taken into account at $T=0$.

The calculated critical values of the Debye screening masses and the $M_{nl}(\mu_c)$ for $c\bar{c}$ and $b\bar{b}$ resonances by the two potentials are given in Table II. Table II shows that the critical values of the screening masses for charmonium and bottonium dissociations given by the erf potential are less than that given by the KMS potential. This indicates that the results are dependent on the forms of the potential. Because the J/Ψ suppression is related to the color screening, the dissociation of J/Ψ resonance is more interesting and important. So we would put emphasis on analysis of the J/Ψ dissociation at finite temperature. The critical values of the screening masses for J/Ψ dissociation are about $\mu_c=600$ MeV given by the erf potential and $\mu_c=700$ MeV given by the KMS potential, respectively. Here the contribution of the color screening at $T=0$ and $\rho=0$ is included in $\mu_c=600$ MeV. In order to make comparison, we also present the erf potential (5) with $\mu=600$ MeV by the dashed line and the KMS potential (4) with $\mu=700$ MeV by the dotted line in Fig. 1, respectively. Figure 1 shows that although the erf potential is a little lower than the KMS, the behaviors of the two potentials are almost identical. At $T=0$ and $\rho=0$, $\mu=\mu_0\neq 0$ means there exists the vacuum caused color screening effect. The erf potential gives $\mu_0=100$ MeV and the KMS potential gives $\mu_0=0$. Then, in the case of the erf potential (5), the screening mass caused by the finite temperature effect for the J/Ψ dissociation is 500 MeV. The critical values of the screening lengths are $r_D^c=0.329$ and 0.282 fm for $\mu_c=600$ and 700 MeV, respectively. Naturally, the screening length given by the erf potential for J/Ψ dissociation is larger than that given by the KMS potential. The information given by the erf potential perhaps is helpful for the study and observation of the J/Ψ production in high energy nucleus collisions. A finer calculation of the screening mass for J/Ψ dissociation and/or study of quark confinement are expected.

TABLE II. The calculated μ_c and M_{nl}^c for charmonium $(c\bar{c})$ and bottonium $(b\bar{b})$ in the two potential models.

State	μ_c (GeV)		$M_{nl}(\mu_c)$ (GeV)	
	KMS	erf	KMS	erf
$J/\psi(3.097)$	0.700	0.600	2.9145	2.8779
$\psi'(3.686)$	0.360	0.260	3.1725	3.2964
$\chi_c(3.500)$	0.342	0.242	3.1982	3.3513
$\Upsilon(9.460)$	1.560	1.500	9.6108	9.5379
$\Upsilon'(10.0233)$	0.660	0.560	9.7838	9.7528
$\chi_b(9.9002)$	0.578	0.460	9.8226	9.8274

III. CRITICAL TEMPERATURE AND DENSITY FOR J/Ψ DISSOCIATION

In order to have a good understanding for the J/Ψ suppression in high energy nucleus collisions, the study of $c\bar{c}$ bound state binding and dissociation of J/Ψ resonance in the hot and dense matter is interesting. The dissociation condition at finite temperature for J/Ψ was analyzed by Matsui [9]. However, the author did not consider the effect of the baryon density.

The authors [10,11] have extensively studied properties of QCD at finite temperature and density. The electric screening mass for QCD can be obtained in the static infrared limit of the time-time component of the gluon self-energy $\Pi^{00}(q_0=0,\vec{q}\to 0)$. At finite temperature and zero baryon density, let the dynamical quark mass $m_q=0$, the electric screening mass of the gluon can be calculated based on the perturbative theory, which yields the lowest-order result in the high temperature limit [11],

$$\mu^2=-\Pi^{00}(q_0=0,\vec{q}\to 0)=\left(\frac{N}{3}+\frac{N_f}{6}\right)g^2T^2, \tag{11}$$

for color group SU(N) and N_f fermions.

The comprehensive studies of gauge theories at finite temperature and density have been done by the authors [12]. In order to consider the baryon density, the authors [13] introduced the presence of the dynamical quark with the chemical potential ν, and calculated the Debye screening mass at finite temperature and finite baryon density in the one-loop approximation in the thermo field dynamics approach [14–17]. The electric screening mass (Debye screening mass) of the gluon is given as [13]

$$\mu=g\left(\frac{1}{3}NT^2+\frac{1}{\pi^2}N_fT_D\right)^{1/2}, \tag{12}$$

where

$$T_D=\int_0^\infty \frac{k^2dk}{\sqrt{k^2+m_q^2}}[n_F(k)+\overline{n_F}(k)], \tag{13}$$

where $n_F(k)$ and $\overline{n_F}(k)$ are the fermion and antifermion distribution functions, respectively, which can be expressed as

$$n_F(k)=\frac{1}{\exp[(\sqrt{k^2+m_q^2}-\nu)/T]+1} \tag{14}$$

and

$$\overline{n_F}(k)=\frac{1}{\exp[(\sqrt{k^2+m_q^2}+\nu)/T]+1}. \tag{15}$$

The chemical potential ν of quarks is determined by the baryon density ρ as

$$\rho=\frac{\gamma}{3}\int\frac{d^3k}{(2\pi)^3}[n_F(k)-\overline{n_F}(k)], \tag{16}$$

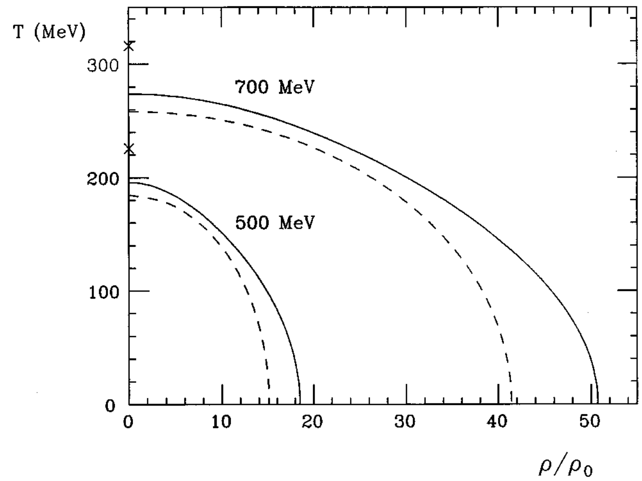

FIG. 4. The relation between critical temperature and critical density for the J/Ψ dissociation. The solid curves are the results of $N_f=2$ and dashed curves are that of $N_f=3$.

where $\gamma=$ flavor $\times$ spin$\times$ color is the degeneracy factor. In the zero temperature limit, $n_F(k)=\theta(k_F-k)$, $\overline{n_F}(k)=0$, and Eq. (12) becomes

$$\mu=\left(\frac{g^2}{\pi^2}N_f\int_0^{k_F}\frac{k^2dk}{\sqrt{k^2+m_q^2}}\right)^{1/2}, \tag{17}$$

where $k_F=[(18\pi^2/\gamma)\rho]^{1/3}$. In the case of the erf potential (5), because when $T=0$ and $\rho=0$, $\mu=\mu_0\neq 0$, Eq. (12) should be further modified by

$$\mu=g\left(\frac{1}{3}NT^2+\frac{1}{\pi^2}N_fT_D\right)^{1/2}+\mu_0(T=0,\rho=0). \tag{18}$$

The Debye screening mass μ at finite temperature and density can be calculated by using Eqs. (17) and (18). In our calculations, we take the strong coupling constant $\alpha_s=g^2/4\pi=0.39$ [9], the quark mass $m_q=10$ MeV, and $\rho_0=0.17$ fm^{-3}, here ρ_0 is the density of the nuclear matter.

We calculated the critical values of the screening masses for J/Ψ resonance by two potentials in a nonrelativistic approximation. We want to obtain the critical temperature and density of medium for corresponding μ_c. We calculated the critical temperature T_c and baryon density ρ_c for J/Ψ at two fixed μ_c. Our results are shown in Fig. 4. The solid curves are the results for $N_f=2$ and the dashed curves for $N_f=3$. The crosses on the T axis are the results of $N_f=0$, the upper one is for 700 MeV and the lower one for 500 MeV.

Our results in Fig. 4 show that the critical temperature at low baryon density is high for $\mu_c=700$ MeV. The critical density at low temperature is too large, especially for $\mu_c=700$ MeV, where ρ_c/ρ_0 reaches 50. The critical temperature for $N_f=2$ is higher than that for $N_f=3$. The critical temperature for 500 MeV at low baryon density region is about 200 MeV which is consistent with the result of lattice QCD [18].

IV. CONCLUSIONS

We have studied the mass spectra of heavy quark resonances and the dissociations of the heavy quark bound states in the erf potential. We calculate the critical values of the screening masses and compare with the previous results. The critical value of the screening mass for J/Ψ dissociation is μ_c=600 MeV given by the erf potential, where μ_0=100 MeV is included. The critical value of the screening mass given by the KMS potential for J/Ψ dissociation is μ_c=700 MeV, where $\mu_0=0$. Table II shows that the μ_c given by the erf potential for each bound state is less than that given by the KMS potential. This indicates that the magnitudes of the screening masses given by the nonrelativistic potential model for the dissociations of heavy quark resonances depend on the form of potential. So the study of the quark confining potential is very important and should be further proceeded in the future.

We have also studied the effects of temperature and density on the screening mass in the hot and dense matter. The critical temperature and density for J/Ψ dissociation are calculated based on the nonrelativistic potential models and the thermofield dynamics approach. Our calculations show that the critical density at low temperature turns out to be very large for μ_c=700 MeV. This shows that the density does not play the same role [19] as the temperature in QGP. However, we employed the erf potential to obtain μ_c=600 MeV for J/Ψ dissociation. The authors of [4] also obtained μ_c=500 MeV for J/Ψ dissociation based on the semiclassical approximation and claimed that beyond this value of μ_c all $c\bar{c}$ binding becomes impossible. The value of μ_c given by the erf potential at finite temperature is closed to the result given by the semiclassical approximation and the obtained critical temperature is reasonable. The color screening effect in the hot and dense matter is important at high temperature and low baryon density regions. This information may be useful in studying high energy nucleus collisions.

Therefore, if the J/Ψ suppression in high energy nucleus-nucleus collisions is closely related to the color screening, it could be observed in the regions of high temperature and low baryon density, i.e., in the central rapidity region.

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