Charmonium dissociation at high baryon chemical potential

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We study the charmonium dissociation in the hot medium with finite baryon chemical potential $\mu_B$. Charmonium bound states are dissociated in the medium by the color screening effect and the random scatterings with thermal partons, which are included in the real and imaginary parts of the potential respectively. $J/\psi$ fraction in the $c\bar{c}$ pair defined to be the quantum overlap between the wave package and the wave function of $J/\psi$ eigenstate decreases with time due to the complex potentials. When $\mu_B$ is large compared with the medium temperature, the Deybe mass is increased evidently. We consider $\mu_B$-dependent Deybe mass in both real and imaginary parts of the potential to calculate the $J/\psi$ survival probability in the static medium and the Bjorken medium. $J/\psi$ survival probability is reduced evidently by the $\mu_B$ effect at low temperatures available in the medium produced in Beam Energy Scan experiments, while this effect becomes not apparent at high temperatures.

I. INTRODUCTION

Hot deconfined medium is believed to be produced in the relativistic heavy-ion collisions\textsuperscript{1,2}. Heavy quarkonium has been extensively studied to extract the properties of the hot QCD matter in nuclear collisions\textsuperscript{3–11}. In the hot medium, heavy quark potential is color screened by the thermal partons\textsuperscript{12–14}, which can dissociate the bound states of quarkonium. The degree of color screening depends on the densities of thermal partons represented by the medium temperature. With the increase of the temperature, different quarkonium bound states are sequentially melted due to their different binding energies. Besides, inelastic random scatterings from the thermal partons can also dissociate quarkonium bound states\textsuperscript{15–20}, where heavy quark pair is transformed from singlet to octet states. The singlet-octet transition process can be treated as an imaginary potential which reduces the normalization of the singlet states\textsuperscript{17,21–22}. One can determine the medium temperature with charmonium survival probability defined as the ratio of final and initial production of $J/\psi$ during their evolution in the hot medium. Explicit quantum treatments have been developed to study the quarkonium inner evolution in the medium, such as the Schrödinger-Langevin equation\textsuperscript{23}, which evolves the wave function of the quarkonium directly. The medium interaction is included via the screened potential and the noise term in the Hamiltonian. The Schrödinger equation model with complex potentials are also developed\textsuperscript{24–26}. The inner evolutions of the quarkonium are described with the Schrödinger equation when they move along different trajectories in the medium. Open quantum system models such as the Lindblad equation\textsuperscript{27} and the Stochastic Schrödinger equation\textsuperscript{28,29} are also developed recently which treats quarkonium as an open quantum system with the momentum-energy exchange with the thermal medium. Other semi-classical transport models are also developed to study the dissociation and recombination of quarkonium in the hot medium\textsuperscript{30–32}.

At the experiments of the Beam Energy Scan (BES), the initial energy density of the medium is much lower than the situation in AA collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC). The effects of color screening and the parton random collisions become weaker in the heavy quark potential. However, the baryon chemical potential $\mu_B$ in the medium produced in BES can be considerable. It changes the Deybe mass and the heavy quark potential.\textsuperscript{33–34} It is necessary to study the $\mu_B$-effect on charmonium evolution in the baryon-rich medium with a low temperature and a large $\mu_B$. In this work, we employ the time-dependent Schrödinger equation with the complex potential to study the evolution of charmonium wave function in the medium with high baryon chemical potential\textsuperscript{25,36}. The Deybe mass becomes larger due to the correction from $\mu_B$ term. This results in a weaker real potential and a larger imaginary potential of the quarkonium. $J/\psi$ fraction in the charm pair is more reduced after considering the $\mu_B$ effect in the static and the Bjorken medium. Studying charmonium dissociation in high $\mu_B$ medium helps to understand the charmonium evolutions at the experiments of the BES.

This work is organized as follows. In Section II, we introduce the framework of the Schrödinger equation and the parametrized in-medium heavy quark potential. In Section III, the evolutions of charmonium wave package in the static medium and the bjorken medium are studied respectively. Effects of the baryon chemical potential and the color screening are compared in the charmonium dissociations. In Section IV, a conclusion is given.

II. THEORETICAL MODEL

To describe the quantum evolutions of heavy quarkonium wave packages at finite $\mu_B$ and $T$, we employ the
time-dependent Schrödinger equation. Neglect the relativistic effect in the inner motion of charmonium, we take the classical form of the Hamiltonian of charmonium. Hot medium effects are included via the in-medium heavy quark potential. As the QCD matter produced in heavy ion collisions is close to a perfect liquid with very small viscosity, one can approximate the heavy quark potential to be a spherically symmetric potential. There is no transition between the states with different angular momentum. We separate the radial part of the Schrödinger equation in the center of mass frame [25],

\[
 i\hbar \frac{\partial}{\partial t} \psi(r, t) = \left[ -\frac{\hbar^2}{2m_c} \frac{\partial^2}{\partial r^2} + V(r, T) + \frac{(l+1)\hbar^2}{2m_r r^2} \right] \psi(r, t)
\]

(1)

where \( r \) and \( t \) are the radius and the time respectively. \( m_r = m_1 m_2 / (m_1 + m_2) = m_c / 2 \) is the reduced mass in the center of mass frame. \( m_c \) is the charm quark mass. Heavy quark potential \( V(r, T) \) depends on the temperature and the radius, which indicates that different eigenstates in the wave package experience different hot medium effects due to their geometry sizes. \( \psi(r, t) \equiv rR(r, t) \) is defined as the product of the radius and the radial part of the wave package \( R(r, t) \). The total wave package of heavy quarkonium is expanded as a spherical function, \( n, l, m, \Psi(r, \theta, \phi, t) = \sum_{nlm} c_{nlm}(t) R_{nl}(r, t) Y_{lm}(\theta, \phi) \), where \( n, l, m \) are the quantum numbers of charmonium states. The coefficient \( c_{nlm}(t) \) is defined to be,

\[
 c_{nlm}(t) = \int R_{nl}(r)e^{-iE_{nl}t} \psi(r, t) r dr
\]

(2)

where \( |c_{nlm}|^2 \) is interpreted as the fraction of the charmonium eigenstate specified with the quantum number \( (n, l, m) \) in the total wave package. The charmonium eigenstate in this work is defined as the eigenstates of the vacuum Cornell potential with a string breaking at \( r = r_{DD} \),

\[
 V_c(r) = \begin{cases} 
 -\frac{\alpha}{r} + \sigma r & r < r_{DD} \\
 -\frac{\alpha}{r_{DD}} + \sigma r_{DD} & r \geq r_{DD}
 \end{cases}
\]

(3)

where the distance of string breaking \( r_{DD} \) is determined via \( -\alpha / r_D + \sigma r_D = 2m_D - 2m_c \). Masses of D meson and charm quark is taken as \( m_D = 1.87 \text{ GeV} \) and \( m_c = 1.27 \text{ GeV} \) respectively. Fitting the masses of \( J/\psi \) and \( \psi(2s) \) given by particle data group, one can determine the values of the parameters \( \alpha = \pi / 12 \) and \( \sigma = 0.2 \text{ GeV}^2 \) [13]. With the in-medium heavy quark potential \( V(r, T) \), fractions of charmonium eigenstates in the wave package change with time. The survival probability of charmonium eigenstates is connected with the evolutions of charmonium wave package. The quantum transition between different states have been included in the wave function evolutions.

To solve the Schrödinger equation numerically, we employ the Crank-Nicolson method. It can evolve the wave package straight-forward in the spatial coordinate instead of projecting the wave package to a series of basis. The numerical errors of the wave function at different time steps is small enough and convergent when we take a small step of time and the radius in the discrete formula (in natural units \( \hbar = c = 1 \)),

\[
 T_{j,k}^{n+1} \psi_k^{n+1} = \psi_j^n.
\]

(4)

where \( j \) and \( k \) are the indexes of rows and columns in the triangular matrix \( T \). The non-zero elements in the matrix are,

\[
 T_{jj}^{n+1} = 2 + 2a + b\psi_j^{n+1},
 T_{j,j+1}^{n+1} = T_{j+1,j}^{n+1} = -a,
 \psi_j^n = a\psi_{j-1}^n + (2 - 2a - b\psi_j^n)\psi_j^n + a\psi_{j+1}^n.
\]

(5)

where \( a = i\Delta t / (2m_c(\Delta r)^2) \) and \( b = i\Delta t \). Here \( i \) is an imaginary unit. The subscript \( j \) and superscript \( n \) represent the coordinate \( r_j \) or \( T_n \) respectively. At each time step, we calculate the inverse of the matrix \( T \) with the “Gauss-Jordan element elimination” method in Eq. (4) to obtain the wave package at the next time step \( \psi_{n+1} = [T_{n+1}^{-1}] \cdot \psi^n \). The fractions of charmonium eigenstates are obtained by projecting the wave package to the wave function of the eigenstate.

The realistic in-medium heavy quark potential is between the limits of the free energy \( F \) and the internal energy \( U \). There are theoretical studies indicating that the in-medium potential is more close to the limit of \( U \) in the temperatures available in AA collisions at RHIC and LHC \([7, 37]\). Consider that the internal energy \( U = F + T(\partial F / \partial T) \) can become a bit stronger than the vacuum Cornell potential at the temperatures around \( T_c \) \([25, 26]\) which results in a oscillation behavior in the time evolution of charmonium fractions in the wave package, we take the free energy as the heavy quark potential to evolve the wave package. The real part of the potential is then parametrized with the form \([26]\),

\[
 V_R(r, T, \mu_B) = -\frac{\alpha}{r} e^{-m_r r} + \frac{\sigma}{m_d} (1 - e^{-m_r r})
\]

(6)

where the Debye mass \( m_d(T, \mu_B) \) depends on the temperature and the baryon chemical potential \( \mu_B \) \([33]\),

\[
 m_d(T, \mu_B) = T \sqrt{\frac{4\pi N_c}{3} \alpha} (1 + \frac{N_f}{6}) \sqrt{1 + \frac{3N_f}{(2N_c + N_f)\pi^2 (\mu_B / 3T)^2}}
\]

(7)

where the factors of color and flavor are taken as \( N_c = N_f = 3 \). As we focus on the effect of baryon chemical
potential $\mu_B$ at the collision energies of BES, the value of baryon chemical potential is estimated with the relation \[ 38 \text{[38]} \]

\[ \mu_B(\sqrt{\sigma_{NN}}) = \frac{1.3}{1 + 0.28\sqrt{\sigma_{NN}}} \] \[(8)\]

In order to estimate the value of $\mu_B$ at the experiments of BES, we choose $\sqrt{\sigma_{NN}} = 10$ GeV to get a value of baryon chemical potential $\mu_B \approx 0.3$ GeV. The value of $\mu_B$ can be larger than the medium temperature in the collisions of BES. The Debye mass is increased by the term with $\mu_B / (3T)$. In the following calculations, we take different values of $\mu_B$ to check the $\mu_B$ effect. The color screened potential at finite $\mu_B$ is plotted in Fig.\[1\]

FIG. 1: (Color online) The heavy quark potential as a function of radius at different temperatures. Dotted, dashed, dotted-dashed lines with different values of $\mu_B$ at the experiments of BES, the value of $\mu_B \approx 0.3$ GeV. The Cornell potential is also plotted and labeled with $V_c$.

Random inelastic scatterings with thermal partons can also dissociate quarkonium bound states in the medium which contributes an imaginary part in the potential of the singlet states. We take the parametrization based on the calculation from Hard Thermal Loop resummed perturbation theory \[10\text{[10]}\text{[11]},\]

\[ V_I(r,T,\mu_B) = -i\frac{g^2 C_F T}{4\pi} \tilde{f}(\tilde{r}) \] \[(9)\]

\[ \tilde{f}(\tilde{r}) = 2\int_0^\infty dz \frac{z^2}{(z^2 + 1)^2} \left[ 1 - \frac{\sin(z\tilde{r})}{z\tilde{r}} \right] \] \[(10)\]

where $i$ is the imaginary unit, $C_F = (N_c^2 - 1)/(2N_c)$. $\tilde{r} \equiv r\pi\alpha N_c / 3$. The value of $\alpha$ is taken as the same with the Cornell potential. With this form, the $\mu_B$ effect in $V_I$ is included via the Debye mass. The magnitude of $V_I / T$ with different values of $\mu_B$ is plotted in Fig.\[2\]

FIG. 2: (Color online) The imaginary part of the potential scaled with the temperature $V_I / T$ as a function of radius. Dotted, dashed, dotted-dashed lines with different values of $\mu_B \approx (0.0, 0.3, 0.6, 1.0)$ GeV are plotted respectively. The temperature is taken as $T = 0.15$ GeV.

III. NUMERICAL RESULTS

To study the effects of baryon chemical potential on the evolution of charmonium wave package, we take different values of $\mu_B$ in the calculations. The initial wave package is initialized with the wave function of $J/\psi$. In Fig.\[3\] the temperature of the static uniformly-distributed medium is $T = 0.15$ GeV. With only real part of the potential in Fig.\[2\] the wave package expands outside, which reduces the quantum overlap between charmonium wave package and the wave function of $J/\psi$ state. As the geometry size of the excited state $\psi(2S)$ is larger than the size of $J/\psi$ wave function, the quantum overlap between the wave package and the $\psi(2S)$ wave function increases with time, shown as the lines in Fig.\[3\] This behavior corresponds to the transitions of $J/\psi$ to $\psi(2S)$ components in the wave package. The Debye mass with the baryon chemical potential $\mu_B = 0.6$ GeV increases about 9% compared with the case of $\mu_B = 0$. At high temperatures, the corrections of the $\mu_B$-term in the heavy quark potential become smaller. Time evolutions of $J/\psi$ fraction in the wave package are close to each other when taking different values of $\mu_B$. In Fig.\[3\] the sum of the fractions of $J/\psi$ and $\psi(2S)$ states become smaller than 1, as some components of the wave package transform into higher eigenstates and scattering states due to the weak attraction in the wave package.

As introduced before, the transition from singlet to octet states induced by the parton random scatterings contributes an imaginary part in the potential of the singlet states. This reduces the normalization of the total wave package. After considering the imaginary potential given by Eq.\[9\], we study the $J/\psi$ survival probability in the static medium in Fig.\[3\] All the hot medium effects including color screening, $\mu_B$-correction, and inelastic scatterings are included. To check the contribution of the imaginary potential, we take the heavy quark poten-
FIG. 3: (Color online) The fraction of $J/\psi$ eigenstate in the wave package as a function of time. The baryon chemical potential is taken as $\mu_B = 0.3, 0.6, 1.0$ GeV respectively. Only real part of the potential is included in the calculations. The temperature of the static medium is $T = 0.15$ GeV.

In the relativistic heavy-ion collisions, hot medium is produced followed by a violent expansion. The medium temperature decreases with time. As a preliminary study, we neglect the transverse expansion of the medium and only consider the longitudinal expansion, where the temperature evolution can be characterized with the Bjorken model,

$$T(t) = \left(\frac{t_0}{t}\right)^{1/3}$$

(11)

where $t_0$ is the starting time of the Bjorken expansion. From hydrodynamic models, it is estimated to be $t_0 = 0.6$ fm/c [42, 43]. The initial temperature is chosen as $T(t_0) = 1.2 T_c$, which is close to the initial temperature of the medium produced in BES collisions. The Schrödinger equation evolves until the temperature become lower than a cut $T_f = 0.8 T_c$, which is around the temperature of the medium kinetic freeze-out. Below this cut, heavy quark potential is taken as the vacuum Cornell potential.

In Fig.5 the complex heavy quark potential is taken as the free energy plus the imaginary potential. In order to fix the value of entropy per baryon density, we take the value of $\mu_B/T = (1.0, 3.0, 6.0)$ respectively. The Deybe mass in both real and imaginary parts of the potential is taken as $\mu_B = 1.0$ GeV.

FIG. 4: (Color online) The fraction of $J/\psi$ and $\psi(2S)$ eigenstate in the wave package as a function of time. Both real and imaginary parts of the heavy quark potential are employed. Medium temperature is taken as $T=0.15$ GeV and 0.2 GeV respectively, see the subfigure (a) and (b). Black solid lines with markers employ the vacuum Cornell potential plus the imaginary potential. Other parameters are the same with Fig.3

FIG. 5: (Color online) The fraction of $J/\psi$ state in the wave package as a function of time in the Bjorken medium. Initial temperature of the medium is chosen as $T(t_0) = 1.2 T_c$. The starting time of the evolution is $t_0 = 0.6$ fm/c. Dotted, dashed, dotted-dashed lines correspond to the cases of the complex potentials $V = F + V_I$ with $\mu_B/T = (1.0, 3.0, 6.0)$ respectively.
tential depends on $\mu_B/T$. In Fig[5] one can see that the $J/\psi$ fraction is reduced by around 15% in the line with $\mu_B/T = 6.0$ compared with the situation of $\mu_B = 0$ at the end of the Bjorken medium evolution. $\mu_B$ effect can evidently reduce the charmonium survival probability in the baryon-rich medium. Note that in the dense medium, there is also Friedel oscillation in the real part of the potential [44], which may also affect the evolution of quarkonium wave package. This effect is neglected in the work and deserves further studies in the future.

IV. SUMMARY

In this work, we employ the Schrödinger equation to study the evolutions of charmonium wave package at finite baryon chemical potential. $J/\psi$ fractions in the wave package is obtained by calculating the quantum overlap between the wave package and the wave function of $J/\psi$ eigenstate. $\mu_B$ correction is included in the Deybe mass which is employed in both real and imaginary parts of the potential. With a large value of $\mu_B/T$, $J/\psi$ dissociation rate is enhanced in the baryon-rich medium. In the following work, we will also consider the $\mu_B$ dependence in the equation of state of the hot medium consistently.

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