Calculating the rates of charmonium dissociation and recombination reactions in heavy-ion collisions using Bateman equation

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Abstract

The charmonium states with their different binding energies and radii dissolve at different temperatures of the medium produced in relativistic heavy-ion collisions. Relative yields of charmonium and thus their survival have potential to map the properties of Quark Gluon Plasma. In this study, we estimate the combined effect of color screening, gluon-induced dissociation and recombination on charmonium production in heavy-ion collisions (Pb+Pb ions) at centre of mass energy ($\sqrt{s_{NN}}$) = 5.02 TeV. The rate equations of dissociation and recombination are solved separately with a 2-dimensional accelerated expansion of fireball volume. To solve the recombination rate equation, we have used an approach of Bateman solution which ensures the dissociation of the recombined charmonium in the QGP medium. The modifications of charmonium states are estimated in an expanding QGP with the conditions relevant for Pb+Pb collisions at LHC.

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I. INTRODUCTION

The relativistic heavy ion collisions paved the way for a comprehensive study of strongly interacting nuclear matter at high energy density and temperature. According to the theory of Quantum Chromo Dynamics (QCD), when the temperature of the nuclear matter is increased above a certain value, say critical temperature $T_C \sim 165$ MeV \cite{1}, the matter undergoes a phase transition to another state of QCD matter called Quark Gluon Plasma (QGP). The results from RHIC/LHC experiments \cite{1} are showing signs of formation of this high temperature medium. One of the most important and interesting signal of QGP is the modification of quarkonium production and their suppression in the QGP medium. The major cause of the suppression can be Debye Color Screening \cite{2} which eventually lead to the dissociation of the states. The ATLAS, CMS and ALICE experiments have performed quarkonia measurements with Pb+Pb data collected at energies $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV. Measurement of inclusive $J/\psi$ and their nuclear modification factor, $R_{AA}$ computed with Pb+Pb data collected at ALICE shows a constant rate of suppression in central collisions, throwing some hints of recombination/regeneration of charmonia \cite{3, 4}. The ATLAS and CMS measurements show suppression of inclusive, prompt and non-prompt charmonia in central Pb+Pb collisions compared to peripheral collisions at $\sqrt{s_{NN}} = 2.76$ TeV and at $\sqrt{s_{NN}} = 5.02$ TeV \cite{5–8}. Since Debye screening length decreases as medium temperature increases, the dissociating pattern of the quarkonia states depends on their binding energy and radii in the medium.

As an additional source of quarkonium production, recombination/regeneration, would enhance the number of charmonia in heavy ion collisions, contradicting with the Debye screening scenario \cite{9, 10}. Signs of recombination can be seen in the recent results from the ALICE Collaboration at the LHC, which measured a lesser $J/\psi$ suppression than at RHIC \cite{3, 4}, despite the higher energy collisions. Also, the production of quarkonia in heavy ion collisions are modified due to non-QGP (non-hot medium) effects such as shadowing \cite{11} with change in nuclear parton distribution function in the small $x$ region compared to that of nucleon \cite{12}.

In this paper, we calculate survival probability of charmonium states($J/\psi$, $\psi(2S)$, $\chi_c$) in
the deconfined medium of QGP using an extended color screening model of Chu and Matsui [13]. A study was performed on bottomonia suppression using the model and reported in [14]. The present model is improved by adding mechanism like thermal gluon-dissociation, recombination of charm-quark pairs to have more realistic dynamics of charmonium states in the medium. The competition among the formation time \( \tau_F \), medium temperature \( T(\tau) \) and lifetime \( \tau_{QGP} \) and fireball expansion decide the trends of the survival probabilities of \( \psi \) states in the kinematics of transverse momentum, \( p_T \) and centrality, \( N_{part} \) (geometry of the heavy-ion collision). We start by describing the model which provides survival probabilities of \( \psi \) states due to color screening in the medium. Then we describe briefly about the rates of gluon-dissociation and recombination with the expansion of QGP fireball in transverse and longitudinal direction. We have used a separate solution for the rate equations of the gluon-dissociation and regeneration reactions in our calculation which enable us to decouple these processes. The rate equation of gluon-dissociation is solved using first-order differential equation method and that of recombination is solved by Bateman equation. In the final section, we present our results from the model calculations followed by a brief discussion and comparison with experimental data measured at LHC. Details of the other suppression model are available in the published Ref [14–16].

II. THEORETICAL MODEL FORMALISM

A. Debye color screening

According to the model, the QGP is formed at initial entropy density \( s_0 \) corresponding to initial temperature \( T_0 \) at time \( \tau_0 \) which then undergoes an isotropic expansion by Bjorken’s hydrodynamics [17]. The plasma cools to an entropy density \( s_D \) corresponding to the dissociation temperature \( T_D \) in time \( \tau_D \) which is given by

\[
\tau_D = \tau_0 \left( \frac{s_0}{s_D} \right) = \tau_0 \left( \frac{T_0}{T_D} \right)^3,
\]

\( \tau_0 \) is the initial time required for formation of QGP. As long as \( \tau_D/\tau_F > 1 \), the QGP medium will be at high temperature and quarkonium formation will be suppressed. A charm-quark
TABLE I. Charmonia properties from non-relativistic potential theory [18, 19].

| Properties       | $J/\psi$ | $\psi(2S)$ | $\chi_c(1P)$ |
|------------------|----------|------------|--------------|
| Mass [GeV/c$^2$] | 3.1      | 3.68       | 3.53         |
| Radius [fm]      | 0.50     | 0.90       | 0.72         |
| $\tau_F$ [fm] [18] | 0.89     | 1.5        | 2.0          |
| $T_D$ [GeV] used in work | 1.4 $T_C$ | 1.0 $T_C$ | 1.0 $T_C$ |

Pair can escape the suppression region, $r_D$ and form $\psi$ if the position at which it is created satisfies the condition

$$|\mathbf{r} + \frac{\tau_F p_T}{M}| > r_D,$$

where the suppression region $r < r_D$ is shrinking because of the cooling of the system. Let the probability of a charm quark pair to be created at $\mathbf{r}$ is $\rho(\mathbf{r})$, then survival probability of charmonium in QGP medium becomes

$$S(p_T, R(N_{\text{part}})) = \frac{\int_0^R dr \ r \ \rho(\mathbf{r}) \ \phi(\mathbf{r}, p_T)}{\pi \int_0^R dr \ r \ \rho(\mathbf{r})}.$$  (3)

where $\phi$, the angle between $\mathbf{p_T}$ and $\mathbf{r}$, provides the range of escaping possibility. Integrating over $p_T$, Eq (3) becomes the survival probability as a function of centrality

$$S(N_{\text{part}}) = \int S(p_T, R(N_{\text{part}})) \ dp_T.$$  (4)

Where $R = R(N_{\text{part}})$ is the medium size/radius, obtained in terms of the radius of the Pb nucleus given by $R_0 = r_0 A^{1/3}$ and the initial temperature of fireball, $T(N_{\text{part}})$ created in each centrality of the collisions is calculated as mentioned in the ref [14]. With QGP formation time $\tau_0 = 0.15$ fm/c at LHC [20, 21], we obtain the initial temperature $T_0$ in most central collision is 0.65 GeV.
B. Medium dynamics at LHC

The dynamics of central relativistic heavy ion collisions is modeled using the Bjorken boost invariant picture with accelerated transverse expansion, resulting in a cylindrical volume in the geometry of the collision. Usually the system volume \( V(\tau) \) is described as a system undergoing a isentropic expansion of QGP fireball with the time-dependence of the volume \( V(\tau) = V_0\tau/\tau_0 \) and the initial volume \( V_0 = \pi R^2(N_{\text{part}})\tau_0 \) \[22, 23\]. Introducing an acceleration term \( a \), the transverse radius increases with proper time as

\[
R(N_{\text{part}}, \tau) = R(N_{\text{part}}) + a(\tau - \tau_0)^2/2
\]  

with \( a = 0.1 \ c^2/fm \) \[22\]. Now the expansion of fireball volume as function of radius and proper time is

\[
V(\tau) = \pi R(N_{\text{part}}, \tau)^2(\tau p_Z/M)
\]  

The new term \( (p_Z/M) \) is used to take into account the longitudinal momentum \( (p_Z) \) of the charm-quark pairs, which ensures the longitudinal expansion of the volume during the QGP lifetime. Thus we can have 2-dimensional (longitudinal+transverse) expansion of the fireball volume and the temperature of the volume is decreasing as proper time \( \tau \) increases as \( T(\tau) = (\tau_{\text{med}}/\tau)^{1/3} T_0 \). The Fig[1](Left) shows 3D view of the fireball volume with transverse radius \( R(N_{\text{part}}, \tau) \) and with proper time multiplied by \( (p_Z/M) \) in the collision centrality 0-5% and (Right) shows the variation of the volume size in different centrality regions.

C. Recombination probability and formation rate

The charmonium formation is happening in the deconfined medium through combination one of the \( N_c \) charm quarks with one of the \( N_{\bar{c}} \) anti-charm quarks produced initially in a central heavy ion collision. For a given charm quark, the probability \( P \) to form a \( \psi \) is proportional to the number of available anti-charm quarks relative to the number of light anti-quark \[24\].
We get the total number of $\psi$ expected in a given event by multiplying by the number of charm quarks $N_c$, \[ N_\psi \approx \frac{N_c^2}{N_{ch}} \] (8)

We used the initial values $N_{c\bar{c}} = N_c = N_\tau$. From the above two equations we get the probability of charmonium formation in deconfinement medium.

\[ \frac{N_\psi}{N_{c\bar{c}}} \approx \frac{N_{c\bar{c}}}{N_{ch}} \approx P_{c\rightarrow \psi} \] (9)

1. **Kinetic model of formation and dissociation**

The recombination mechanism is the inverse process of thermal gluon dissociation of charmonium states, that a free charm quark and anti-quark are captured in the $\psi$ bound state, emitting a color octet gluon. It is to be noted that the recombination process is
significant at low $p_T$, typically for values smaller than the charmonium mass $[24, 25]$. The time evolution of charm quarks and charmonium states in the deconfined region, according to Boltzmann equation is

$$\frac{dN_\psi}{d\tau} = \Gamma_F N_c N_{\pi} [V(\tau)]^{-1} - \Gamma_D N_\psi n_g,$$

(10)

where $n_g$ is the number density of gluons depending on the medium temperature. The widths $\Gamma_{F,D}$ are formation and dissociation reaction rates $\langle \sigma v_{rel} \rangle$ averaged over the momentum distribution of the participants ($c$ and $\bar{c}$ for $\Gamma_F$ and $\psi$ and $g$ for $\Gamma_D$) respectively $[24–26]$. There are analytical and numerical solutions for the equation Eq (10). We use a different approach to calculate the final number of charmonium and their survival probability in the medium.

2. **Decoupling dissociation and recombination**

In this study, we consider the rates of the dissociation and recombination as two separate processes, find their solutions and add them together to get the total number of survived charmonium states. The dissociation and the recombination rates are given as

$$\frac{dN^D_\psi}{d\tau} = -\Gamma_D N_\psi(0) n_g$$

(11)

$$\frac{dN^F_\psi}{d\tau} = \Gamma_F N_c N_{\pi} [V(\tau)]^{-1}$$

(12)

For the gluon dissociation rate, the solution of Eq (11) gives the number of charmonium states survived the reaction.

$$N^D_\psi = N_\psi(0) \exp^{-\int_{\tau_0}^{\tau_f} \Gamma_D n_g d\tau}$$

(13)

The $N_\psi(0) (= \sigma^{NN}_\psi T_{AA}(\tau_0, b))$ is number of initially produced charmonia in the collisions. $\sigma^{NN}_\psi$ is the production cross section in p+p collision and $T_{AA}$ is nuclear overlap function taken from the ref $[27]$ and $[28]$ respectively. Before going to the solution of recombination rate, the probability that some of the newly formed $\psi$ could be dissociated by thermal gluons
(although the rate will be very low initially), is to be taken into account in the recombination process. As we assume $N_\psi = N_c = N_{\bar{c}}(Tot)$, the Eq (12) becomes

$$\frac{dN_{\psi}^F}{d\tau} = \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1} - \Gamma_D N_{\psi} n_g$$

(14)

Where $N_{c\bar{c}}(Tot)$ is the sum of the $c\bar{c}$ pair produced in the initial collisions, $N_{c\bar{c}}(0)$ and those charm and anti-charm quarks separated in the dissociation of charmonium bound states $N_{\bar{c}c}^{Diss}$. The $N_{c\bar{c}}(Tot)$ is

$$N_{c\bar{c}}(Tot) = N_{c\bar{c}}(0) + N_{\bar{c}c}^{Diss}$$

(15)

with $N_{c\bar{c}}(0) = \sigma_{c\bar{c}}^{NN} T_{AA}(\tau_0, b)$. Here $\sigma_{c\bar{c}}^{NN}$ is the cross section for $c\bar{c}$ pair production in $p+p$ collision [29]. The new formation equation Eq (14) is analogous to that of radioactive decay chain reaction. In the decay chain, the parent nucleus decays (here instead of decay, charmonium forms from two charm quarks, then the number of charm quarks decreases as formation rate increases) to daughter nuclei which decays again (here dissociate) to third nuclei. The solution of such differential equation can be found by Bateman equation which take into account the effects of correlated mechanism of recombination from two charm quarks and the dissociation of newly formed pairs. The solution of Eq (14) is then

$$N_{\psi}^F = \frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{c\bar{c}}(Tot)[e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1}d\tau} - e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}] + N_{c\bar{c}}^{Diss} e^{-\int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau}.$$  

(16)

with $\Lambda_F = \int_{\tau_0}^{\tau_{QGP}} \Gamma_F N_{c\bar{c}}^2(Tot)[V(\tau)]^{-1}d\tau$ and $\Lambda_D = \int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau$.

Suppose there are $N_{\psi}(0)$ charmonium states initially at $\tau = 0$ and each one has probability $Pr(\tau)$ to dissociate in the time interval $\delta \tau$. With the dissociation rate $\Gamma_D$ (probability to dissociate per unit time), the probability to dissociate is $Pr = \Gamma_D n_g d\tau$. Then the average number of $\psi$ that can be dissociated during the QGP lifetime is $\int_{\tau_0}^{\tau_{QGP}} Pr N_{\psi}(0)$ which is roughly equal to the number of charm quarks ($N_{c\bar{c}}^{Diss}$) produced from the dissociated $\psi$ in the medium.

$$\int_{\tau_0}^{\tau_{QGP}} Pr N_{\psi}(0) = N_{\psi}(0) \int_{\tau_0}^{\tau_{QGP}} \Gamma_D n_g d\tau = N_{c\bar{c}}^{Diss}$$

(17)
Now the Eq (15) becomes

\[
N_{\psi}(T_{\text{tot}}) = \sigma_{\psi}^{NN} T_{AA}(\tau_0, b) + N_{\psi}(0) \int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau
\]  

(18)

The number of recombined and survived \( \psi \) is determined by the rates of dissociation and recombination during the QGP lifetime. The solutions of these differential rate equations are already found separately in earlier equations (Eq(13) and (16)). To get the total number of \( \psi \) survived at the end of QGP lifetime, we add the number of \( \psi \) survived/recombined from the respective reactions. The total number of \( \psi \) survived the medium effect is

\[
N_{\psi}(\tau_{\text{QGP}}) = \frac{\Lambda_F}{\Lambda_D - \Lambda_F} N_{\psi}(T_{\text{tot}})[e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_F N_{\psi}^2(T_{\text{tot}})[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau}] + N_{\psi}(0) e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau}
\]  

(19)

As mentioned in Eq (9), we can calculate the probability of the survival/recombination by dividing the number of respective charmonium with sum of the initially produced \( \psi \) and the total number of charm-quarks pairs produced in the medium. Therefore, we can have the survival probability of the \( N_{\psi}^D \) (fractional of the survival of the gluon-dissociation) as

\[
S(D) = \frac{N_{\psi}^D}{N_{\psi}(0) + N_{\psi}(T_{\text{tot}})} = \frac{N_{\psi}(0)}{N_{\psi}(0) + N_{\psi}(T_{\text{tot}})} e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau}
\]  

(20)

Similarly the probability of recombination (fractional of the formation/recombination) in the medium is

\[
S(F) = \frac{N_{\psi}^F}{N_{\psi}(0) + N_{\psi}(T_{\text{tot}})} = \frac{\Lambda_F}{N_{\psi}(T_{\text{tot}}) \Lambda_D - \Lambda_F} \frac{\Lambda_F}{\Lambda_D - \Lambda_F} [e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_F N_{\psi}^2(T_{\text{tot}})[V(\tau)]^{-1} d\tau} - e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau}] + \frac{N_{\psi}(0)}{N_{\psi}(0) + N_{\psi}(T_{\text{tot}})} e^{-\int_{\tau_0}^{\tau_{\text{QGP}}} \Gamma_{\text{D}n_g} d\tau}
\]  

(21)

Since the \( N_{\psi}^{\text{Diss}} \) is very small number compared to \( N_{\psi}(0) \), the last term of the above equation can be omitted in the final calculation of survival probability.
The total survival probability of the charmonium in the medium is the product of Eq (3), (20) and (21).

\[
S(p_{T}, R(N_{\text{part}})) = \frac{1}{N_{\psi}(0) + N_{c\bar{c}}(\text{Tot})} \int_{0}^{R} dr \, r \, \rho(r, p_{T}) \\
\left( \frac{\Lambda_{F}}{\Lambda_{D} - \Lambda_{F}} N_{c\bar{c}}(\text{Tot}) e^{-\int_{t_{0}}^{t_{QGP}} \Gamma_{F} N_{c\bar{c}}(\text{Tot}) [V(\tau)]^{-1} dr} - e^{-\int_{t_{0}}^{t_{QGP}} \Gamma_{D} N_{\phi} dr} \right) N_{\psi}(0) e^{-\int_{t_{0}}^{t_{QGP}} \Gamma_{D} N_{\phi} dr}
\]

(22)

The nuclear modification factor, \( R_{AA} \), is obtained from survival probability taking into account the feed-down corrections as follows,

\[
R_{AA}(\chi_{c}(1P)) = S(\chi_{c1} + \chi_{c2})
\]
\[
R_{AA}(\psi(2S)) = S(2S)
\]
\[
R_{AA}(\psi(1S)) = g_{1} S(1S) + g_{2} S(1P) + g_{3} S(2S)
\]

(23)

The factors \( g \)'s are obtained from the measurement in proton-nucleon and pion-nucleon interactions at 300 GeV [30]. The values of \( g_{1} \), \( g_{2} \) and \( g_{3} \) are 0.62, 0.3 and 0.08 respectively.

III. RESULTS AND DISCUSSIONS

With the model calculation, we calculated the nuclear modification factor, \( R_{AA} \) of \( J/\psi \) and \( \psi(2S) \) as function of \( p_{T} \) and centralities relevant for LHC experiments. The calculations are compared with the data measured at CMS and ALICE Experiments. The survival probabilities of resonance states has a unique \( p_{T} \) dependence decided by the \( T_{D}, \tau_{F}, T(\tau) \) and \( \tau_{med} \) for each \( \psi \) state. The \( R_{AA} \) of \( J/\psi \) and \( \psi(2S) \) as a function of \( p_{T} \) is shown in Figure 2 (Left). The solid circles and squares are the measured \( R_{AA} \) for \( J/\psi \) and \( \psi(2S) \) respectively in high \( p_{T} \) (6.5-30.0 Gev/c) and mid rapidity region, with CMS experiment in Pb+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV [8]. Similarly the \( R_{AA} \) as a function of \( p_{T} \) (0-12 GeV/c) is shown
FIG. 2. (a) The nuclear modification factor, $R_{AA}$, as a function of $p_T$ for $J/\psi$ and $\psi(2S)$. The solid points are measured $R_{AA}$ by CMS experiment in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (b) The nuclear modification factor, $R_{AA}$, as a function of $p_T$ for $J/\psi$ measured with ALICE experiment. The solid and dashed lines in all figures represent the model calculations.

in Figure 2 (Right). The solid and dashed lines are the model calculations for $R_{AA}$ in the respective $p_T$ regions. The interplay between different medium-induced reactions decides the trend of $p_T$ curve in all regions. The model replicates the trend of the $p_T$ dependence of the measured $R_{AA}$ except in the last bin of $J/\psi$ high $p_T$ region. This may be because of less energy loss of high $p_T$ charmonia as predicted in an energy loss model [16].

Figure 3 shows the $R_{AA}$ as a function of $N_{\text{part}}$ for $J/\psi$ and $\psi(2S)$ with $p_T < 12.0$ GeV/c. The solid red circles are $R_{AA}$ data measured by ALICE experiment in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward rapidity and $p_T < 8.0$ GeV/c [4]. The solid line, the present model calculation agrees well with the measured data keeping in mind that the measured $R_{AA}$ is for inclusive $J/\psi$ while the model calculation is for prompt $J/\psi$ and $\psi(2S)$. Figure 4 shows the the nuclear modification factor, $R_{AA}$, as a function of $N_{\text{part}}$ for $J/\psi$ and $\psi(2S)$ with low $p_T$ (3-30 GeV/c) and forward rapidity (Left) and with high $p_T$ (6.5-30 GeV/c) and mid rapidity (Right). The lines in both figures are representing the model calculations. The
model reproduces well the measured nuclear modification factors of both $J/\psi$ and $\psi(2S)$ in all centralities.

The suppression of resonance states increases with increasing centrality (increasing $N_{\text{part}}$) as expected. Also the $\psi(2S)$ is more suppressed than $J/\psi$ matching with the scenario of sequential suppression in the measured $R_{AA}$ [7-8]. The calculated suppression is the combined result of color screening, gluon-dissociation and recombination reactions. In Figure 3, the suppression increases steeply up-to $N_{\text{part}} = 100$ and then it becomes a slow suppression indicating the overplay of recombination reaction in lower $p_T$ region. To note that the inclusive $J/\psi$ consists of prompt charmonium (directly produced from parton collisions and feed-down contribution) and non-prompt charmonium (decayed from the B-meson). At higher $p_T$ region, the calculation shows a smooth suppression plotted as in Figure 4. Since the medium effects are not significant in peripheral collision (lower $N_{\text{part}}$), the $R_{AA}$ values go beyond the unity as shown in Figure 3 and 4. There can be other sources which may contribute in the suppression of charmonia states, like suppression due to initial nuclear suppression (shadow-
FIG. 4. (Left) The nuclear modification factor, $R_{AA}$ as a function of $N_{\text{part}}$ for $J/\psi$ and $\psi(2S)$ with low $p_T$ (3-30 GeV/c) and forward rapidity. The solid circles and squares are the measured $R_{AA}$ of $J/\psi$ and $\psi(2S)$ respectively with CMS experiment in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [8]. (Right) Same as in Left with high $p_T$ (6.5-30 GeV/c) and mid rapidity. The lines represent the present model calculations.

We calculate the nuclear modification factors of charmonia states ($J/\psi$ and $\psi(2S)$) in an expanding QGP of finite lifetime and size produced in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The nuclear modification is resulted from the combined effect of color screening, gluon-dissociation and recombination reactions. The competition between the resonance...
formation time $\tau_F$, the medium temperature $T(\tau)$, $\tau_{QGP}$ and etc decide the dependence of the survival probabilities of $\psi$ states in different kinematic regions. The dynamics of central relativistic heavy ion collisions is modeled using the Bjorken boost invariant picture with accelerated transverse expansion resulting in a cylindrical volume of fireball. The calculated suppressions are compared with the $R_{AA}$ measured at CMS and ALICE Experiments. The model reproduces well the measured nuclear modification factors of both $J/\psi$ and $\psi(2S)$ in most of the centrality regions. In addition, the scenario of sequential suppression in the measured $R_{AA}$ at LHC experiments are reflected well in the model calculations.

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VI. REFERENCES

[1] B. Muller, J. Schukraft and B. Wyslouch, Ann. Rev. Nucl. Part. Sci., arXiv:1202.3233.
[2] T. Matsui and H. Satz, Phys. Lett. B178, 416 (1986).
[3] [ALICE Collaboration], Phys. Rev. Lett.109, 072301 (2012). arXiv:1202.1383.
[4] [ALICE Collaboration], Phys. Lett. B766, 212 (2017). arXiv:1606.08197.
[5] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B697, 294 (2011); arXiv:1012.5419.
[6] [ATLAS Collaboration], ATLAS-CONF-2016-109 (2016).
[7] S. Chatrchyan et al. [CMS Collaboration] J. High Energy Phys. 1205, 63 (2012). arXiv:1201.5069.
[8] A.M. Sirunyan et al. [CMS Collaboration] Eur. Phys. J. C 78 509 (2018).
[9] P. Braun-Munzinger, J. Stachel, Phys. Lett. B 490, 196 (2000).
[10] X. Zhao and R. Rapp, Nucl. Phys. A859, 114 (2011). arXiv:1102.2194.
[11] R. Vogt, Phys. Rev. C 81, 044903 (2010).
[12] A. H. Muller and J. W. Qin, Nucl. Phys. B 268, 427 (1986).
[13] M.C. Chu and T. Matsui, Phys. Rev. D 37, 1851 (1988).
[14] Abdulla Abdulsalam and Prashant Shukla, Int. J. Mod. Phys. A, Vol. 28, No. 21, 1350105 (2013).
[15] Vineet Kumar, Prashant Shukla and Abhijit Bhattacharyya, J. Phys. G 47, 1 (2019).
[16] François Arleo, Phys. Rev. Lett. 119, 062302 (2017).
[17] J.D. Bjorken, Phys. Rev. D 27, 140 (1983).
[18] F. Karsch and H. Satz, Z. Phys. C 51, 209 (1991).
[19] H. Satz, J. Phys. G 32, R25 (2006).
[20] Captain R. Singh, S. Ganesh, M. Mishra, Eur. Phys. J. C 79, 143 (2019).
[21] Baoyi Chen, Chinese Physics C 43, 12 (2019) 124101; Rupa Chatterjee et al., Phys. Rev. C 88, 034901 (2013).
[22] Ben-Wei Zhang, Che Ming Ko, Wei Liu, Phys. Rev. C 77, 024901,2008.
[23] C.M. Ko, X.N. Wang, B. Zhang, X.F. Zhang, Phys. Lett. B 444, 237 (1998).
[24] R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C 63, 054905 (2001).
[25] D. Kharzeev and H. Satz, Phys. Lett. B 334 155 (1994).
[26] X. M. Xu, D. Kharzeev, H. Satz, and X. N. Wang, Phys. Rev. C 53, 3051 (1996).
[27] R. Vogt, Phys. Rev. C 81, 044903 (2010).
[28] C.Loizides, J. amin and D. d’Enterria, Phys. Rev. C 97,054910 (2018).
[29] R. L. Thews, Eur. Phys. J. C 43, 97 (2005); Nucl. Phys. A 702, 341 (2002).
[30] S. Digal, P. Petreczky, H. Satz, Phys. Rev. D 64 094015 (2001).
[31] A. Mocsy and P. Petreczky, Phys. Rev. D 77, 014501 (2008).