Nuclear Effects on Charmonium Production

Xiao-Fei Zhang\textsuperscript{a,b}, Cong-Feng Qiao\textsuperscript{a}, Xiao-Xia Yao\textsuperscript{a,b} and Wei-Qin Chao\textsuperscript{a,b}

\textsuperscript{a} CCAST (World Laboratory), Beijing, 100080, P.R. China
\textsuperscript{b} Institute of High Energy Physics, Academia Sinica, P.O.Box 918-4, 100039, P.R.China

Abstract

$J/\psi$ and $\psi'$ production cross sections in fixed-target experiment is calculated, considering the contributions from both color-singlet and color-octet mechanisms. The results are applied to the investigations of the $J/\psi$ suppression and the $\psi'/\psi$ ratio problems in p-A collisions. The results agree with the experimental data as the $(c\bar{c})$–nucleon absorption cross sections $\sigma_{abs}^8 \simeq 10\,mb$ for $(c\bar{c})_8$ and $\sigma_{abs}^1 \simeq 0\,mb$ for $(c\bar{c})_1$. The model is further used to investigate A-A collisions when comover absorption mechanism is also considered. It is found that the observed experiment data of $J/\psi$ and $\psi'/\psi$ ratio in S-U collisions and Pb-Pb collisions can not be explained consistently within this model. The possibility of QGP formation in S-U and Pb-Pb collisions is also discussed.

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I. Introduction

Matsui and Satz proposed that a suppression of $J/\psi$ production in relativistic heavy ion collisions can serve as a clear signature for the formation of a new matter phase Quark Gluon Plasma (QGP) [1]. This suppression effect was observed by NA38 collaboration later [2]. However, it has been found that $J/\psi$ suppression exists also in p-A collisions where QGP formation is not possible [3]. The successive theoretical researches pointed out that $J/\psi$ suppression could also exist in hadronic matter (HM), even though by completely different mechanisms [4]. The anomalous $J/\psi$ suppression was recently reported by the NA50 collaboration [5] [6] and there have been a number of attempts to explain it, such as the onset of deconfinement, hadronic co-mover absorption and the energy loss model [7] [8] [9]. To understand the experimental data clearly, the formation and absorption mechanism of $J/\psi$ must be studied carefully.

Quarkonium production has traditionally been calculated in the color singlet model. However, it has become clear now that the color singlet model fails to provide a theoretical and phenomenological explanation of all $J/\psi$ production processes and it is necessary to include the color octet production channel. In principle, the $J/\psi$ state is described in a Fock state decomposition

$$|J/\psi> = O(1)|cc(3S_1) > + O(v)|cc(3P_1^{(8)})g > + O(v^2)|cc(1S_0^{(8)})g > +$$

$$O(v^2)|cc(3S_1^{(1,8)})gg > + O(v^2)|cc(3D_{1,8}^{(1,8)})gg > +...,$$

where $2S+1L_{J}^{(1,8)}$ characterizes the quantum state of the $cc$ in color-singlet or octet [10], respectively. This expression is valid for the non-relativistic QCD (NRQCD) framework and the coefficient of each component depends on the relative three-velocity $|\vec{v}|$ of the heavy quark. Under the limit of $|\vec{v}| \to 0$, i.e. $c$ and $\bar{c}$ remain relatively at rest, Eq.(1) recovers the expression for color-singlet picture of $J/\psi$, where $O(1) \equiv 1$.

The color-octet component $(cc)_8$ seems to play an important role in interpreting the experimental data by Collider Detector at Fermilab (CDF) [11], and further studies show that it may also have great influence on the quarkonium production at other collider facilities [12] [13]. The investigations [14] on quarkonium hadrproduction at fixed target energies find that the color-octet contribution to the production cross section is very important, and the inclusion of color-octet production channels removes the large discrepancies of
the total production cross section between experimental data and the predictions of the color-singlet model. Therefore, it has been suggested that the color-octet \((c\bar{c})_8\) would also manifest itself in heavy ion collisions \[17\]. Based on the above discussion, one can accept the following physical picture that the charmonium production can be divided into two steps. The first step is the production of a \(c\bar{c}\) pair. The \(c\bar{c}\) pairs can be either \((c\bar{c})_1\) or \((c\bar{c})_8\), which are produced perturbatively and almost instantaneously, with a formation time \(\tau_f \simeq (2m_c)^{-1} \simeq 0.07\,fm\) in the \(c\bar{c}\) rest frame. The second step is the formation of a physical states of \(J/\psi\), that needs a much longer time. People believe now that \(J/\psi\) suppression in hadron matter can be considered as the pre-resonance absorption. Satz first proposed the pre-resonance absorption model to explain the nuclear collision data and got some encouraging results \[17\]. However, in their work the pre-resonance state of charmonia is only in color-octet, the color-singlet counterpart is believed having a minor influence, therefore negligible. In this paper we make a complete leading order calculation of charmonium production cross section for \((c\bar{c})_1\) and \((c\bar{c})_8\) in concerned energies. The results are used to study the charmonium suppression in heavy ion collisions.

As it is known, in hadron-hadron collisions the initial \((c\bar{c})\) pair produced from the parton interaction are almost point like. It can be in color-singlet or -octet configurations. The \((c\bar{c})\) pair in the color-octet state may interact with the nucleon environment much stronger than that in the color-singlet, which means that the color-octet pair would be dissolved in a much shorter time than the color-singlet pair. Based upon this, the absorptions of \((c\bar{c})_1\) and \((c\bar{c})_8\) by nucleon environment should be considered differently. In the framework of this paper, we suppose that the \((c\bar{c})-nucleon\) absorption cross sections \(\sigma^1_{abs}\) for \((c\bar{c})_1\) and \(\sigma^8_{abs}\) for \((c\bar{c})_8\) satisfy the condition \(\sigma^1_{abs} \sim 0 << \sigma^8_{abs}\), however the color-singlet part is not completely negligible. With this assumption the \(J/\psi\) suppression data in p-A collision can be explained. The experimental data of \(\psi'/\psi\) ratio in p-A collisions can also be explained quite well. For nucleus–nucleus (A-A) collisions, in addition, the comover absorption is investigated as well and we find that the experimental data of \(J/\psi\) suppression and \(\psi'/\psi\) ratio can not be described consistently in S-U and Pb-Pb collisions. The possibility for the production of QGP is also discussed.

Our paper is divided into four parts. In section II, we describe how to introduce the color-octet scenario borrowed from p-p collisions and calculate the charmonium produc-
tion cross section through both color-singlet and color-octet mechanisms. In section III, the pre-resonance nuclear absorption model relating to both \((c\bar{c})_1\) and \((c\bar{c})_8\) is described and used to discuss the \(J/\psi\) and \(\psi'\) suppression in p-A collisions. In section IV, the nucleon and comover absorption model for \(J/\psi\) suppression is investigated. In the last section, some further discussions are given.

II. Formulation

According to the NRQCD factorization formalism, the inclusive production rate of heavy quarkonium \(H\) in parton level can be factorized as

\[
\sigma(ij \rightarrow H) = \sum_n \hat{\sigma}(ij \rightarrow Q\bar{Q}[n]) \langle O^H[n] \rangle. \tag{2}
\]

Here, \(\hat{\sigma}(Q\bar{Q}[n]+X)\) describes the short distance production of a \(Q\bar{Q}\) pair in the color, spin and angular momentum state \(n\), which can be calculated perturbatively using Feynman diagram methods. \(\langle O^H[n] \rangle\), the vacuum expectation value of a four fermion operator in NRQCD \([10]\), describes the nonperturbative transition of the \(Q\bar{Q}\) pair hadronizing into the quarkonium state \(H\). The relative importance of the various contributions of \(n\) in Eq.(2) can be estimated by using NRQCD velocity scaling rules. An important feature of this equation is that \(Q\bar{Q}\) pairs in a color-octet state are allowed to contribute to the production of a color singlet quarkonium state \(H\) via nonperturbative emission of soft gluons. Accordingly, the production cross section for a quarkonium state \(H\) in the hadron process

\[
A + B \rightarrow H + X \tag{3}
\]

can be written as

\[
\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1)f_{j/B}(x_2)\sigma(ij \rightarrow H), \tag{4}
\]

where the parton scattering cross section is convoluted with parton distribution functions \(f_{i/A}\) and \(f_{j/B}\), and the sum runs over all partons in the colliding hadrons.

At leading twist and at leading order in \(\alpha_s\), the color-singlet \(Q\bar{Q}\) production subprocesses for \(2S+1L_J\) state are
\begin{equation}
    gg \rightarrow 1S_0, \ 3P_{0,2}, \quad (5)
\end{equation}
\begin{equation}
    gg \rightarrow 3S_1 + g, \ 3P_1 + g, \quad (6)
\end{equation}
\begin{equation}
    gg \rightarrow 3P_1 + g, \quad (7)
\end{equation}
\begin{equation}
    q\bar{q} \rightarrow 3P_1 + g. \quad (8)
\end{equation}

The corresponding formulae of the above processes can be found in refs. [14] and [15]. Because the radiative decays \( \chi_{1,2} \rightarrow J/\psi + \gamma \) are known to have a large branching ratios to \( J/\psi \) and the feeddown of the \( \psi' \) to \( J/\psi \) is also important, their contributions should be included in the calculation in reproducing the fixed target experimental data of the prompt \( J/\psi \) production.

It has long been known that the total cross sections of quarkonium production are rather large in comparison with the fixed-target experiment data with respect to the parton-parton fusion predictions [18]. However, after including the color-octet production mechanism an overall agreement can be obtained [14].

Under the NRQCD factorization scheme, to calculate the quarkonium production cross section, one use a double expansion: the perturbative expansion of the short distance production amplitude in strong coupling constant \( \alpha_s \) and the expansion of the nonperturbative long distance hadronization amplitude in typical velocity of heavy quark inside the heavy quarkonium. At leading order in perturbative theory and up to next-to-leading order in the velocity expansion, the subprocesses for leading-twist \( J/\psi \) production through color-octet intermediate states are

\begin{equation}
    q\bar{q} \rightarrow c\bar{c}[8, 3S_1] \rightarrow J/\psi + X, \quad (9)
\end{equation}
\begin{equation}
    gg \rightarrow c\bar{c}[8, 1S_0] \rightarrow J/\psi + X, \quad (10)
\end{equation}
\begin{equation}
    gg \rightarrow c\bar{c}[8, 3P_J] \rightarrow J/\psi + X, \quad (11)
\end{equation}
\begin{equation}
    q\bar{q} \rightarrow c\bar{c}[8, 3P_J] \rightarrow \chi_J + X \rightarrow J/\psi + \gamma + X. \quad (12)
\end{equation}

Note that the process \( q\bar{q} \rightarrow c\bar{c}[8, 3P_J] \rightarrow J/\psi(\psi') + g \) is of higher order in \( v^2 \) since the lowest-order nonperturbative transition if forbidden by charge conjugation, and the amplitude \( A(gg \rightarrow c\bar{c}[8, 3S_1]) \) vanishes in leading order in \( \alpha_s \), which is consistent with Yang’s theorem which forbids a massive \( J = 1 \) vector boson from decaying to two massless
$J = 1$ bosons. In fact, the theorem requires that the $A(gg \to c\bar{c}[8,3S_1])$ vanish to all orders as the gluons on the massshell.

The cross sections of Eq.(9) are proportional to the NRQCD matrix elements

\[<0|O^{J/\psi}(3S_1)|0> \sim m_c^3 v^7,\]
\[<0|O^{J/\psi}(1S_0)|0> \sim m_c^3 v^7,\]
\[<0|O^{J/\psi}(3P_j)|0> \sim m_c^3 v^7,\]
\[<0|O^{\chi_J}(3S_1)|0> \sim m_c^3 v^5.\]  

It is obvious that the above matrix elements are higher order in $v^2$ compared to the leading color-singlet ones, but their corresponding short-distance processes are lower order in $\alpha_s$ than that in color-singlet processes. This causes the color-octet processes to make substantially enhancements in reproducing the fixed target experiment data.

For $\psi'$ production the cross section does not receive contributions from radiative decays of higher charmonium states. $\sigma(\psi')$ differs from the direct $J/\psi$ production cross section $\sigma(J/\psi)_{dir}$ only in the replacement of $J/\psi$ matrix elements in Eq.(13) by $\psi'$ matrix elements.

Before embarking on the computation of cross sections the parameters used in the computation should be fixed up. The uncertainties in the theoretical prediction at fixed-target energies are substantial and it is impossible at present to extract the non-perturbative universal color-octet matrix elements by fitting the theoretical predictions to the experiment data. The value of $<0|O^{J/\psi(\psi')}(3S_1)|0>$ used here is obtained by fitting the theoretical predictions to the CDF Collaboration data at large $p_T$. In addition, the number of independent matrix elements can be reduced by using the spin symmetry relations up to corrections of order $v^2$

\[<0|O^{1J}(3P_j)|0> = (2J + 1) <0|O^{X_0}(3P_0)|0>,\]
\[<0|O^{J/\psi}(3P_j)|0> = (2J + 1) <0|O^{J/\psi}(3P_0)|0>,\]
\[<0|O^{X_1}(3S_1)|0> = (2J + 1) <0|O^{X_0}(3S_1)|0>.\]

Therefore, the matrix elements $<0|O^{H}(1S_0)|0>$ and $<0|O^{H}(1P_0)|0>$ enter fixed target production of $J/\psi$ and $\psi'$ in the combination
\[ \Delta_8(H) \equiv <0|\mathcal{O}_8^H(1S_0)|0> + \frac{7}{m_c^2} <0|\mathcal{O}_8^H(3P_0)|0>. \] (20)

Up to corrections in \( v^2 \), the relevant color-singlet production matrix elements are related to radial wave functions at the origin or their derivatives,

\[ <0|\mathcal{O}_1^H(3S_1)|0> = \frac{9}{2\pi} |R(0)|^2, \quad <0|\mathcal{O}_1^H(3P_0)|0> = \frac{9}{2\pi} |R'(0)|^2, \] (21)

which can be determined from potential model or from quarkonium leptonic decays.

The values of these parameters, which we use, are \([14]\]

\[ <0|\mathcal{O}_J^{3/2}(3S_1)|0> = 1.16 \text{ GeV}^3, \quad <0|\mathcal{O}_8^{J/2}(3S_1)|0> = 6.6 \times 10^{-3} \text{ GeV}^3, \] (22)

\[ <0|\mathcal{O}_1^{3/2}(3S_1)|0> = 0.76 \text{ GeV}^3, \quad <0|\mathcal{O}_8^{3/2}(3S_1)|0> = 4.6 \times 10^{-3} \text{ GeV}^3, \] (23)

\[ <0|\mathcal{O}_1^{3/2}(3P_0)|0> / m_c^2 = 4.4 \times 10^{-2} \text{ GeV}^3, \quad <0|\mathcal{O}_8^{3/2}(3S_1)|0> = 3.2 \times 10^{-3} \text{ GeV}^3, \] (24)

\[ \Delta_8(J/\psi) = 3.0 \times 10^{-2} \text{ GeV}^3, \quad \Delta_8(\psi') = 5.2 \times 10^{-3} \text{ GeV}^3. \] (25)

In the numerical calculation, we use the Glück-Reya-Vogt (GRV) leading order (LO) \([20]\) parameterization for the parton distributions of the protons. The c quark mass is fixed to be \( m_c = 1.5 \text{ GeV} \) and the strong coupling is evaluated at the scale \( \mu = 2m_c \), that is \( \alpha_s \approx 0.26 \). The results of the integrated cross sections for color singlet and color octet channels at several different energies are listed in Table I. We must admit that the results are far from precision because of some important contributions may be precluded as claimed by authors \([14] [21]\). e.g., the effects of higher twist, the beyond leading order contributions in \( \alpha_s \), as well as the kinematic, etc..

### III. Pre-resonance Absorption in p-A Collisions

The conventional survival probability for a \( J/\psi \) produced in a p-A collision is given by:

\[ S_A = \frac{1}{A} \frac{\sigma_{pA}}{\sigma_{pp}} = \int d^2\rho_A(b, z) e^{\rho_A(b, z') \sigma_{abs}} \exp\left\{ -(A-1) \int_z^{\infty} dz' \rho_A(b, z') \sigma_{abs} \right\} \]

\[ = e^{\exp(-L_A \rho_0 \sigma_{abs})}, \] (26)
where $\sigma_{pp}$ and $\sigma_{pA}$ are the $J/\psi$ production cross section in proton-proton collisions and proton-nucleus collisions, respectively, $\rho_A$ is the nuclear density distribution. $\sigma_{abs}$ is the absorption cross section. L is the effective length of the $J/\psi$ trajectory. It can be derived as

$$L = \frac{3A - 1}{4} r_0 A^{1/3}, \quad \text{for heavy nucleus}$$
$$L = \frac{1A - 1}{2} r_0 A^{1/3} \frac{r_0^2}{r_0'}, \quad \text{for light nucleus},$$

where $\rho_0 = 0.14 fm^{-3}$ and $r_0 = 1.2 fm$, $r_0' = 1.05 fm$.

As $c\bar{c}$ pairs are produced almost instantaneously and the formation of the physical states $J/\psi$ or $\psi'$ need a much longer time, people now believe that $J/\psi$ and $\psi'$ suppression in p-A can be considered as an absorption of pre-resonance $c\bar{c}$ pairs. As discussed in former section, there are both $(c\bar{c})_1$ and $(c\bar{c})_8$ pairs. The color-octet can interact with gluons much more strongly than the color-singlet $(c\bar{c})_1$, and therefore would dissolve much faster into $D$ and $\bar{D}$ than $(c\bar{c})_1$. Thus their absorption cross section are different. Considering these facts, we rewrite Eq.(26) as

$$S_A = \frac{1}{A} \frac{\sigma_{pA}}{\sigma_{pp}}$$
$$= f_1 \int d^2b d\rho_A(b, z) \exp\left\{-(A - 1) \int_0^\infty dz' \rho_A(b, z') \sigma_{abs}^1 \right\}$$
$$+ f_8 \int d^2b d\rho_A(b, z) \exp\left\{-(A - 1) \int_0^\infty dz' \rho_A(b, z') \sigma_{abs}^8 \right\},$$

where $f_1, f_8$ are relative fractions of $(c\bar{c})_1$ and $(c\bar{c})_8$. $\sigma_{abs}^1, \sigma_{abs}^8$ are the absorption cross sections for $(c\bar{c})_1$-nucleon and $(c\bar{c})_8$-nucleon, correspondingly.

In Eq.(28) there are two parameters, $\sigma_{abs}^1$ and $\sigma_{abs}^8$, which is different from Satz’s model [7]. As $(c\bar{c})_1$ produced is almost point like, $\sigma_{abs}^1$ is very small. Thus we take $\sigma_{abs}^1 = 0$ and the value of $\sigma_{abs}^8$ is considered as an open parameter and determined such as to get the best agreement with the data. In Fig.1 we see that with $\sigma_{abs}^8 = 10 mb$ we get quite good agreement with the p-A data.

Next we turn to discuss the ratio $\psi'/\psi$ in p-A collisions. As $J/\psi$ and $\psi'$ suppression in p-A can be considered as an absorption of pre-resonance $c\bar{c}$ pairs, there is no difference for $J/\psi$ and $\psi'$ in p-A collisions. Then the $\psi'/\psi$ ratio in p-A collisions can be expressed as
\[ R_A = \frac{B(\psi' \to \mu^+\mu^-) \sigma_{p-A \to \psi'}}{B(J/\psi \to \mu^+\mu^-) \sigma_{p-A \to J/\psi}} = \frac{B(\psi' \to \mu^+\mu^-)[\sigma'_1 \exp(-L_{A\rho_0}\sigma_{abs}^1) + \sigma'_8 \exp(-L_{A\rho_0}\sigma_{abs}^8)]}{B(J/\psi \to \mu^+\mu^-)[\sigma_1 \exp(-L_{A\rho_0}\sigma_{abs}^1) + \sigma_8 \exp(-L_{A\rho_0}\sigma_{abs}^8)]}, \]

where \( B \) is the corresponding branch ratio, \( \sigma_1, \sigma_8 \) are the production cross section of color singlet and color octet for \( J/\psi \) in p-p collisions, respectively. \( \sigma'_1, \sigma'_8 \) are the production cross section of color singlet and color octet for \( \psi' \) in p-p collisions, respectively.

Using the same parameters as those in Fig. 1, the result of Eq. (29) is shown in Fig. 2, where one can see that the ratios \( \psi'/\psi \) obtained in our model, being almost independent of the c.m.s. energy, agree with the experimental data quite well. The results show that including both the contribution of color singlet and color octet does not introduce any unusual \( A \) dependence.

**IV. Comover Absorption in A-A Collisions**

In A-A collisions, except for \((c\bar{c})\)-nucleon absorption, charmonium may also suffer interaction with secondaries that happen to travel along with them. The \( J/\psi \) survival probability due to absorption with comover hadrons is

\[ S^{co} = \exp\left\{ -\int d\tau \sigma_{co} n_{co}(\tau, b) \right\}, \]

where \( \sigma_{co} \) is the \( J/\psi \)-comover absorption cross section, \( n_{co}(\tau, b) \) is the density of the comovers at time \( \tau \) and impact parameter \( b \). The relative velocity between \( J/\psi \) and the comover is included in the definition of the absorption cross section.

Integrating over time \( \tau \), assuming that the comovers undergo an isentropic longitudinal expansion, Eq. (30) can be expressed as

\[ S^{co} = \exp\left\{ -\sigma_{co} n_0 \tau_0 \frac{n_0}{n_f} \right\}, \]

or,

\[ S^{co} = \exp\left\{ -\sigma_{co} n_0 \tau_0 \frac{\tau_\psi}{\tau_0} \right\}, \]

where \( \tau_0 \) is the production time of the comovers and \( \tau_\psi \) is the time the comovers and \( J/\psi \) stay together. \( n_0 \) and \( n_f \) are the initial density and freezeout density of the comovers.
separately. When $\tau_\psi$ is smaller than the life time of the comovers $t_\psi$, Eq. (32) describes the comover survival probability, otherwise Eq. (31) works. For $\psi'$, there are similar equations except that $\sigma_{co}$ is replaced by $\sigma'_{co}$ which is the $\psi'$-comover absorption cross section. As the mass of $\psi'$ is much closer to the $D\bar{D}$ threshold, only a 50MeV excitation is needed to break up a $\psi'$, while for $J/\psi$, nearly 650MeV is needed to be above the $D\bar{D}$ threshold. Thus $\sigma'_{co}$ should be much larger than $\sigma_{co}$.

Considering the effects of both the $(c\bar{c})$—nucleon absorption and $J/\psi$—comover absorption, the $J/\psi$ survival probability in A-B collisions is

$$S = S^{co} \times S^{nuc},$$

(33)

where $S^{nuc}$ is the $J/\psi$ survival probability in A-B collision due to the $(c\bar{c})$—nucleon absorption. It is similar with Eq. (28) and can be expressed as

$$S^{nuc} = f_1 e^{\exp(-(L_A + L_B)\rho_0\sigma_{abs}^1)} + f_8 e^{\exp(-(L_A + L_B)\rho_0\sigma_{abs}^8)},$$

(34)

where $L_A$ and $L_B$ are the effective length of the $J/\psi$ trajectory in A and B nucleus correspondingly.

From the above equations, one can see that there are some parameters in the comover model. In Eq. (31), the parameters are: $n_0$, $\sigma_{co}$, $\tau_0$, $n_f$. In Eq. (32), the parameters are: $n_0$, $\sigma_{co}$, $\tau_0$, $\tau_\psi$. We first discuss the data at different $E_T$-bins and analyze the $E_T$ dependence of the parameters. In this paper we wish to adjust these parameters consistently for S-U and Pb-Pb collisions. The comover density is taken to be proportional to the energy density at a certain space-time point, which can be expressed as the density of the transverse energy according to Bjorken’s assumption [22]. Therefore, the comover density could be expressed as

$$n_0 \sim \frac{E_T}{\Delta V} \sim \frac{E_T}{S(b)\Delta y\tau_0},$$

(35)

where $\Delta V$ is the corresponding volume. $S(b)$ is the overlapping area of the two nuclei. $\Delta y$ is the corresponding rapidity windows in the central rapidity region. $\Delta y = 2.4$ for S-U collisions and $\Delta y = 1.2$ for Pb-Pb collisions.

Considering Eq. (35), the $E_T$ dependence of the comover density in S-U and Pb-Pb collisions can be described at the same time based on collision geometry. Now we use
Eq. (33) and Eq. (31) to fit the experimental data in S-U and Pb-Pb collisions. The parameters $\sigma_{abs}^1$ and $\sigma_{abs}^8$ used in considering the $(c\bar{c})$-nucleon absorption in A-B collisions is taken to be the same as those obtained in fitting the data in p-A collisions. We treat the comover density in the first $E_T$ bin of S-U collisions, $n_0^1$, as an open parameter, adjust $n_0^1, n_f, \sigma_{co}$ to fit the $J/\psi$ suppression data in S-U collision, then choose $\sigma_{co}'$ to get the best fit for $\psi'/\psi$ ratio data in S-U and Pb-Pb collisions. The results for S-U and Pb-Pb collisions are shown in Fig. 3-4, with parameters $n_0^1 = 0.2 fm^{-3}, \sigma_{co} = 3 mb, \sigma_{co}' = 23 mb,$ and $n_f = 0.1 fm^{-3}$.

If $\tau_\psi < t_\psi$, one should use Eq. (32) to describe the comover absorption. It is reasonable to choose $\tau_\psi$ proportional to the square root of the transverse overlapping area of the two nuclei

$$\tau_\psi \sim \sqrt{S(b)}.$$  \hspace{1cm} (36)

Using Eqs. (35), (33), (32) and (36), with the parameters $n_0^1 = 0.2 fm^{-3}, \sigma_{co} = 3 mb, \sigma_{co}' = 13 mb,$ and $\tau_\psi^1 = 6.5 fm$, which is the $\tau_\psi$ for the first $E_T$ bin in S-U collisions, the results are shown in Fig. 5 and Fig. 6.

Fig.3-6 show that neither of the two comover absorption expressions of Eq. (31) and Eq. (32) can explain the data of $\psi'$ and $J/\psi$ suppression in S-U and Pb-Pb collisions consistently. Fig. 3(a) shows that the $J/\psi$ suppression in S-U collisions could be described very well, based on the above chosen parameters for Eq. (31), however Fig. 3(b) shows that the $\psi'/\psi$ ratio data in S-U collisions could not be fitted using the same set of parameters. The data show an anomalous $\psi'$ suppression from the second $E_T$ bin. Furthermore, Fig. 4(a) shows that the comover absorption which explains the $J/\psi$ suppression in S-U collisions can not explain the $J/\psi$ suppression in Pb-Pb collision, where an anomalous suppression exists from the second $E_T$ bin. This seems to show that the anomalous $\psi'$ suppression begins already in S-U collisions at an energy density much lower than the corresponding density for anomalous $J/\psi$ suppression in Pb-Pb collisions. This may reflect the fact that the dissociation temperature for $J/\psi$ in QGP is higher than the dissociation temperature of $\psi'$. From Fig. 4(b) one can find that the same comover absorption can explain the data of $\psi'/\psi$ ratio in Pb-Pb collisions. This could be explained as that the anomalous $J/\psi$ and $\psi'$ suppressions are canceled in the $\psi'/\psi$ ratio data. The
results of using Eq.(32) to include the comover absorption are shown in Fig. 5-6, which are similar to Fig. 3-4.

Now we turn to discuss the case of minimum biased data, where the result is shown in a simple and clear way. With the parameters $n_f = 0.1 \text{fm}^{-3}$, $\tau_0 = 1 \text{fm}$, $\sigma_{co} = 3 \text{mb}, \sigma'_{co} = 23 \text{mb}$ which is the same as that we used in obtaining Fig.3-4, taking the average comover density $\bar{n}_{su} = 0.28$ in S-U collision and the average comover density $\bar{n}_{pb} = 0.4$ in Pb-Pb collisions, the results of using Eq.(33) and Eq.(31) for the minimum biased data are shown in Fig. 7. From it one can see clearly that using the comover absorption expressions of Eq.(31) the $J/\psi$ suppression data for S-U collisions is fitted based on the above parameters, but one can not explain the data of $\psi'$ suppression in S-U collisions, neither the $J/\psi$ suppression in Pb-Pb collision. The good fitting of $\psi'/\psi$ ratio data in Pb-Pb collisions may caused by the same anomalous absorption of $\psi'$ and $J/\psi$. The results of using Eq.(33) and Eq.(32) is similar to Fig. 7.

V. Results and Discussions

In this paper, $J/\psi$ and $\psi'$ production cross section is calculated considering the contributions of both color-singlet and color-octet $c\bar{c}$ channels. The pre-resonance absorption model for charmonium is extended to consider both the color singlet and color octet contribution. Using this model the $J/\psi$ and $\psi'$ suppression in p-A collision are explained very well. Based on above calculation, the comover absorption is discussed for A-A collisions and it is found that the observed experimental data of $J/\psi$ and $\psi'/\psi$ ratio in S-U collision and Pb-Pb collision can not be explained consistently by this mechanism. This indicates that other sources of charmonium suppression should be included.

The situation in explaining the data of strangeness production is similar. To explain the enhanced production of strangeness, some kind of collective interaction among individual excited nucleon states, such as the colour ropes in RQMD [24], the multiquark clusters in VENUS [25], firecracker in LUCIAE [26], must be considered. Some authors also have reported the possibility of QGP formation at CERN SPS from the strangeness puzzle [27]. There is no strict way to distinguish these different kinds of collective motions from the formation of QGP till now.
Now we consider the possibility of QGP formation from our discussion. In QGP, charmonium breaks up due to color screen. As the radius of $\psi'$ is larger than that of $J/\psi$, the critical temperature $T'_c$ for $\psi'$ to be dissociated in QGP should be much lower than the critical temperature $T_c$ for $J/\psi$ to break up. So if QGP is formed, $\psi'$ will begin to break up earlier than $\psi$. As has been pointed out above, Fig. 3(b) and Fig. 5(b) indicate that from the second $E_T$ bin (or the third $E_T$ bin) in S-U collisions there is an anomalous $\psi'$ suppression, which may be the effect of QGP production. Fig.4(a) and Fig. 6(a) show that the anomalous suppression of $J/\psi$ really begins after the second $E_T$ bin in Pb-Pb collision because it needs a higher critical temperature. If deconfined phase is attained, when $J/\psi$ begin to be suppressed due to Debye screen, $\psi'$ should already be broken up by Debye screen. These two anomalous suppressions in QGP may cancel each other in $\psi'/\psi$ ratio, which leads to the result that $\psi'/\psi$ ratio in Pb-Pb collisions seems to be explained by the comover absorption, while in fact, neither $J/\psi$ nor $\psi'$ anomalous suppression could be explained by comover absorption. Fig.4(b) and Fig. 6(b) agree with the above picture of $J/\psi$ and $\psi'$ suppression by QGP.

Although our results indicate the possibility of production of QGP in S-U and Pb-Pb collisions, and to explain enhanced strangeness production some collective motion which can not be distinguished from QGP formation must also be considered, further study is still needed to distinguish if QGP are really formed.

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Figure Captions

Fig.1: The $J/\psi$ survival probability obtained using Eq.(28) with $\sigma_{abs}^8 = 10mb$ and $\sigma_{abs}^1 = 0mb$ is compared to the experimental data of p-A collisions at different energies.

Fig.2: The $\psi'/\psi$ ratio obtained using Eq.(29) with $\sigma_{abs}^8 = 10mb$ and $\sigma_{abs}^1 = 0mb$ is compared to the experimental data of p-A collisions at different energies.

Fig.3: (a) $J/\psi$ over DY ratio versus $E_T$ and (b) $B_{\mu\nu}\sigma(\psi')/B_{\mu\nu}\sigma(\psi)(b)$ versus $E_T$ in S-U collision are compared to the results based on Eq.(33) using the comover absorption Eq.(31). The parameters are $n_0^1 = 0.2 fm^{-3}, \sigma_{co} = 3 mb, \sigma_{co}' = 23 mb$, and $n_f = 0.1 fm^{-3}$.

Fig.4: The same as Fig.3 for Pb-Pb collisions.

Fig.5: The same as Fig.3 using the comover absorption Eq.(32) with the parameters $n_0^1 = 0.2 fm^{-3}, \sigma_{co} = 3 mb, \sigma_{co}' = 13 mb$ and $\tau_1^\psi = 6.5 fm$.

Fig.6: The same as Fig.5 for Pb-Pb collisions.

Fig.7: The same as Fig. 3 in the minimum bias case with $\bar{n}_{su} = 0.28, \bar{n}_{pb} = 0.4$.

Table Caption

Table I. The integrated cross sections for color singlet and color octet processes.
Table I

|       | E=450 GeV | E=200 GeV | E=158 GeV |
|-------|-----------|-----------|-----------|
| $\sigma_1$ | 49.64 nb  | 24.56 nb  | 19.54 nb  |
| $\sigma_8$  | 95.66 nb  | 55.48 nb  | 45.94 nb  |
| $\sigma'_1$ | 7.76 nb   | 3.72 nb   | 2.86 nb   |
| $\sigma'_8$ | 20.04 nb  | 12.11 nb  | 11.06 nb  |
Fig. 1
Fig. 4
Fig. 6
Fig. 3
Fig. 5
Fig. 7
