Production and Suppression of Charmonium in Nuclear Collisions

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Abstract

$J/\psi$ production cross section considering the contributions of both color-singlet and color-octet $c\bar{c}$ channels is calculated. The result is used to study the suppression of $J/\psi$ in nuclear collisions. With absorption cross sections for $(c\bar{c})_8 \sigma_{abs}^8 \simeq 11mb$ and $(c\bar{c})_1 \sigma_{abs}^1 \simeq 0mb$ the p-A and A-B data except for Pb-Pb can be explained. Possible explanations of additional suppression in Pb-Pb are discussed.

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I. INTRODUCTION

It was expected 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) \cite{1}. This suppression effect was observed by NA38 collaboration later \cite{2}. However, successive research pointed out that such suppression could also exist in hadronic matter (HM), even though by a completely different mechanism \cite{3}. The anomalous $J/\psi$ suppression recently reported by the NA50 collaboration \cite{4} 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 \cite{5} \cite{6} \cite{7}. 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 theoretically and phenomenologically explanations of all production processes and the inclusion of color octet production channels removes large discrepancies between experiment and the predictions of the color singlet model for the total production cross section. In principle, the $J/\psi$ state is described in a Fock state decomposition

$$|J/\psi> = O(1)|cc\bar{c}(3S_{1}^{(1)})> + O(v)|cc\bar{c}(3P_{J}^{(8)})g> + O(v^2)|cc\bar{c}(1S_{0}^{(8)})g> +$$

$$+ O(v^2)|cc\bar{c}(3S_{1}^{(1,8)})gg> + O(v^2)|cc\bar{c}(3D_{J}^{(1,8)})gg> + ... ,$$

(1)

where $2S_{1}^{(1,8)}$ characterizes the quantum state of the $c\bar{c}$ with color-singlet or octet respectively. This expression is valid for the non-relativistic QCD (NRQCD) framework \cite{8} and the coefficients of each component depend on the relative three-velocity $|\vec{v}|$ of the heavy quark, and under the limit of $|\vec{v}| \rightarrow 0$, i.e. both $c$ and $\bar{c}$ remain relative rest, eq.(1) recovers the expression for color-singlet picture of $J/\psi$ where $O(1) \equiv 1$.

The color-octet component $(cc\bar{c})_{8}$ seems to play an important role in interpreting the Collider Detector at Fermilab (CDF ) experimental data \cite{14}, and further studies show that it may also have great influence on the quarkonium production at other collider facilities \cite{9} \cite{11} \cite{12}. The investigations \cite{12} on quarkonium hadrproduction at fixed target energies find that color-octet contribution to the cross section are very
important, and the inclusion of color-octet production channels removes large discrepancies between experiment and the predictions of the color-singlet model for the total production cross section. Therefore one can expect that the color-octet \((c \bar{c})_8\) would also manifest itself in heavy ion collisions \[15\]. From the above discussion, one can know 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 \((c \bar{c})_8\). The \(c \bar{c}\) pairs 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 need much longer time. People believed now that \(J/\psi\) suppression in hadron matter can be consider as pre-resonance absorption. Satz first proposed to use the pre-resonance absorption model to explain nuclear collisions data \[15\]. However, in their work the pre-resonance state of charmonia is only in color octet. In this paper we give a complete leading order calculation of charmonium production cross section for \((c \bar{c})_1\) and \((c \bar{c})_8\) in corresponding energies. Then the results is used to study charmonium suppression in heavy ion collisions. As it is known in the hadron-hadron collisions, the \((c \bar{c})_1\) produced is almost point like, and the color-octet can interact with nucleons much more strongly than the color-singlet \((c \bar{c})_1\), so the color-octet would dissolve much faster into \(D\) and \(\bar{D}\) than \((c \bar{c})_1\), i.e. \(\sigma_{abs}^1 \sim 0 \ll \sigma_{abs}^8\). Thus the absorption of \((c \bar{c})_1\) and \((c \bar{c})_8\) should be considered differently. We find that in our model with the absorption cross section \(\sigma_{abs}^1 \simeq 0 mb\) and \(\sigma_{abs}^8 \simeq 11 mb\) the p-A and A-B data except for Pb-Pb can be explained. To explain Pb-Pb data, additional sources causing nonlinear suppression in nuclear collisions must be onset.

Our paper is divided into four parts. In section II, we describe the color-octet scenario borrowed from pp collisions and calculate the charmonium production cross section for \((c \bar{c})_1\) and \((c \bar{c})_8\). In section III, the pre-resonance nuclear absorption model considering both \((c \bar{c})_1\) and \((c \bar{c})_8\) are described. In the last section the result of our model is compared to the experimental data. Some possible models for explaining the anomalous \(J/\psi\) suppression in Pb-Pb collisions of NA50 experiment, such as the formation of QGP are discussed.
II. FORMULATION

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

$$\sigma(ij \rightarrow H) = \sum_n \hat{\sigma}(ij \rightarrow Q\bar{Q}[n]) < \mathcal{O}^H[n] >.$$  \hfill (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. $< \mathcal{O}^H[n] >$, the vacuum expectation value of a four fermion operator in NRQCD \cite{8}, 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

$$A + B \rightarrow H + X$$  \hfill (3)

can be written as

$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1)f_{j/B}(x_2)\sigma(ij \rightarrow H),$$ \hfill (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 $^{2S+1}L_J$ state are

$$gg \rightarrow \ ^1S_0, \ ^3P_0, \ ^3P_2,$$ \hfill (5)

$$gg \rightarrow \ ^3S_1 + g, \ ^3P_1 + g,$$ \hfill (6)

$$gq \rightarrow \ ^3P_1 + q,$$ \hfill (7)

$$q\bar{q} \rightarrow \ ^3P_1 + g.$$ \hfill (8)

The corresponding formulae of the above processes can be found in refs. \cite{12} and \cite{13}. 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 prompt $J/\psi$ production.

Under the NRQCD factorization scheme, to calculate the quarkonium production cross section, one use a double expansions: 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{align}
q\bar{q} & \rightarrow c\bar{c}[8,^3S_1] \rightarrow J/\psi + X, \\
        \quad (9) \\
gg & \rightarrow c\bar{c}[8,^1S_0] \rightarrow J/\psi + X, \\
        \quad (10) \\
gg & \rightarrow c\bar{c}[8,^3P_J] \rightarrow J/\psi + X, \\
        \quad (11) \\
q\bar{q} & \rightarrow c\bar{c}[8,^3P_J] \rightarrow \chi_J + X \rightarrow J/\psi + \gamma + X. \\
        \quad (12)
\end{align}

Their cross sections are proportional to the NRQCD matrix elements

\begin{align}
< 0\mid O_{J/\psi}^{\psi}(^3S_1) \mid 0 > & \sim m_c^3v^7, \\
< 0\mid O_{J/\psi}(^1S_0) \mid 0 > & \sim m_c^3v^7, \\
< 0\mid O_{J/\psi}(^3P_J) \mid 0 > & \sim m_c^3v^7, \\
< 0\mid O_{\chi J}(^3S_1) \mid 0 > & \sim m_c^3v^5. \\
\end{align}

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 makes the color-octet processes non-negligible in reproducing the fixed target experiment data.

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

With the understanding of quarkonium production, in the calculation we can assume that the color-singlet and octet $c\bar{c}$ are produced at early stage of heavy ion
collisions and later evolve according to the environment. Here we assume that the \( c\bar{c} \) are produced at the early stage of the ion collisions through hard N-N collisions when the phase transition has not yet occurred, and then the system would either remains in HM or a new phase QGP is formed at later time. Thus we only need to deal with the evolution of \((c\bar{c})\), while the production of \( c\bar{c} \) by the deconfined quarks or gluons in QGP is ignored.

**III. ABSORPTION IN HADRONIC MATTER**

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

\[
R_A = \frac{1}{A} \frac{\sigma_{pA}}{\sigma_{pp}} = \int d^2b dz \rho_A(b, z) \exp\left\{ -(A - 1) \int_z^\infty d'z' \rho_A(b, z') \sigma_{abs} \right\} = \exp(-L \rho_0 \sigma_{abs}) \tag{17}
\]

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 an absorption cross section. \( L \) is the effective length of the \( J/\psi \) trajectory. It can be derived as

\[
L = \frac{3}{4} \frac{A - 1}{A} r_0 A^{1/3}, \quad \text{for heavy nucleus}
\]

\[
= \frac{1}{2} \frac{A - 1}{A} r_0 A^{1/3} \frac{r_0^2}{r_0'}, \quad \text{for light nucleus},
\tag{18}
\]

where \( \rho_0 = 0.14 \text{fm}^{-3} \) and \( r_0 = 1.2 \text{fm}, r'_0 = 1.05 \text{fm} \)

As \( c\bar{c} \) pairs are produced almost instantaneously and the formation of a physical states \( J/\psi \) need a much longer time, people now believe that \( J/\psi \) suppression in hadronic matter 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 \((c\bar{c})_1 \) produced is almost point like. 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 extend the Eq.(17) to
\[ R_A = \frac{1}{A} \sigma_{pA} \sigma_{pp} \]
\[ = f_1 \int d^2b dz \rho_A(b, z) \exp \left\{ -(A - 1) \int_z^\infty dz' \rho_A(b, z') \sigma_{abs}^1 \right\} \]
\[ + f_8 \int d^2b dz \rho_A(b, z) \exp \left\{ -(A - 1) \int_z^\infty dz' \rho_A(b, z') \sigma_{abs}^8 \right\} \]

(19)

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

**IV. RESULTS AND DISCUSSIONS**

Before embarking on the computation of cross sections the parameters used in the computation should be fixed up. The value of \(< 0 | \mathcal{O}_8^{J/\psi}(3S_1) | 0 > \) can be obtained by fitting the theoretical predictions to the CDF Collaboration data at large \( p_T \). The number of independent matrix elements can be reduced by using the spin symmetry relations up to corrections of order \( v^2 \)

\[ < 0 | \mathcal{O}_1^{J}(3P_J) | 0 > = (2J + 1) < 0 | \mathcal{O}_1^{\bar{\chi}}(3P_J) | 0 > , \]

(20)

\[ < 0 | \mathcal{O}_8^{J/\psi}(3P_J) | 0 > = (2J + 1) < 0 | \mathcal{O}_8^{J/\psi}(3P_J) | 0 > , \]

(21)

\[ < 0 | \mathcal{O}_8^{\bar{\chi}}(3S_1) | 0 > = (2J + 1) < 0 | \mathcal{O}_8^{\bar{\chi}}(3S_1) | 0 > . \]

(22)

Therefore, the matrix elements \( < 0 | \mathcal{O}_8^H(1S_0) | 0 > \) and \( < 0 | \mathcal{O}_8^H(1P_0) | 0 > \) enter fixed target production of \( J/\psi \) and \( \psi' \) in the combination

\[ \Delta_8(H) \equiv < 0 | \mathcal{O}_8^H(1S_0) | 0 > + \frac{7}{m_Q^2} < 0 | \mathcal{O}_8^H(3P_0) | 0 > . \]

(23)

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,

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

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

(24)

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

The values of these parameters, which we use, are [12].
< 0|\mathcal{O}_1^{J/\psi} (^3S_1)|0 >= 1.16 \text{ GeV}^3, \quad < 0|\mathcal{O}_8^{J/\psi} (^3S_1)|0 >= 6.6 \times 10^{-3} \text{ GeV}^3, \quad (25)
< 0|\mathcal{O}_1^{\psi'} (^3S_1)|0 >= 0.76 \text{ GeV}^3, \quad < 0|\mathcal{O}_8^{\psi'} (^3S_1)|0 >= 4.6 \times 10^{-3} \text{ GeV}^3, \quad (26)
< 0|\mathcal{O}_1^{Y_{0}} (^3P_0)|0 > /m_c^2 = 4.4 \times 10^{-2} \text{ GeV}^3, \quad < 0|\mathcal{O}_8^{Y_{0}} (^3S_1)|0 >= 3.2 \times 10^{-3} \text{ GeV}^3, \quad (27)
\Delta_a(J/\psi) = 3.0 \times 10^{-2} \text{ GeV}^3, \quad \Delta_a(\psi') = 5.2 \times 10^{-3} \text{ GeV}^3. \quad (28)

We use the Glück-Reya-Vogt (GRV) leading order (LO) parameterization for the parton distributions of the protons. The $c$ quark mass is fixed to be $m_c = 1.5$ 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.

In the equation (19) there are two parameters $\sigma_{abs}^1$ and $\sigma_{abs}^8$, which is different from Satz's model [15]. 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 $\sigma_{abs}^8 = 11mb$ we get quite good agreement with the data except for Pb-Pb data. So our pre-resonance absorption model of color singlet and color octet can explains both the proton-nucleus and nucleus-nucleus data up to S-U system. To explain the non-linear suppression of $J/\psi$ additional source of charmonium in nuclear collisions must be included.

The anomalous suppression has been interpreted as a hint of QGP [3]. If the QGP is formed, the interaction region consists of a hot part where a $J/\psi$ can be dissociated. Ref [6] modelled the effect of quark-gluon plasma formation by assuming that the $J/\psi$ produced in those region is completely destroyed whereever the density of the participants exceeds a critical value. The survival probability then becomes

$$R_{AB} = f_1 \int d^2b d^2A dz_A d^2b d^2z_B \rho_A(b_A, z_A)t(b - b_A - b_B)\rho_B(b_B, z_B)\theta(n_c - n_p(b, b_A, b_B))$$
$$\exp\left\{-(A - 1) \int_{z_A}^{\infty} dz'_{A}\rho_A(b_A, z'_{A})\sigma_{abs}^1\right\} \exp\left\{-(B - 1) \int_{-\infty}^{z_B} dz'_{B}\rho_B(b, z'_{B})\sigma_{abs}^1\right\}$$
$$+ f_8 \int d^2b d^2A dz_A t(b - b_A - b_B)\rho_A(b_A, z_A)d^2b d^2z_B\rho_B(b_B, z_B)\theta(n_c - n_p(b, b_A, b_B))$$
$$\exp\left\{-(A - 1) \int_{z_A}^{\infty} dz'_{A}\rho_A(b_A, z'_{A})\sigma_{abs}^8\right\} \exp\left\{-(B - 1) \int_{-\infty}^{z_B} dz'_{B}\rho_B(b, z'_{B})\sigma_{abs}^8\right\}, \quad (29)$$
where $t(b - b_a - b_B)$ is called the thickness function, $n_p$ is the density of participants per unit transverse area. $n_c$ is the critical value. If $n_c$ is chosen to be the highest value attained in S-U collisions, i.e., $3.3 fm^{-2}$ as suggested in Ref \[5\], only in 66% part of the interaction region the $J/\psi$ can survive \[4\]. Using this result, in Fig.2 we give a rough analysis of our model with QGP and it is compared with the result of our nuclear absorption model. From Fig.2 we can see that using the mechanism of QGP, the anomalous suppression in Pb-Pb can be explained.

However there have been other alternative explanations of the Pb-Pb data by NA50, such as collisions with secondary hadrons (co-mover) and the energy loss model \[6\] \[7\]. To distinguish these mechanisms much more work should be done in this field.

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**Figure Captions**

Fig.1, The $J/\psi$ survival probability obtained using Eq.(19) with $\sigma_{abs}^8 = 11 mb$ and $\sigma_{abs}^1 = 0 mb$ compared to the experimental data of p-A and A-A collisions at different energies.

Fig.2, The $J/\psi$ survival probability obtained using our nuclear absorption model for p-A and A-A collisions at $E = 200 GeV$ and the result of Pb-Pb $E = 158 GeV$ without and with QGP formation in 34% part of the interaction region compared to the experimental data.

**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    |
