# $p_T$ distribution of $J/\psi$ in a quark-gluon plasma

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We consider the contributions of both color-singlet and octet $c\bar{c}$ bound states for studying $p_T$ dependence of $J/\psi$ suppression in quark gluon plasma (QGP). It has been found that the existence of the color-octet $c\bar{c}$ may cause a turning over of the $J/\psi$ $p_T$ distribution $R(p_T;E_T^H,E_T^L)$ in Pb-Pb collisions and $R(p_T;E_T^H,E_T^L)$ decreases with $p_T$ after a critical value $(p_T)_{max}$. This is quite different from the behavior of $R(p_T;E_T^H,E_T^L)$ in hadronic matter (HM) where it always increases with $p_T$. [S0556-2813(98)01705-1]

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## I. INTRODUCTION

It was expected that a suppression of $J/\psi$ production in relativistic heavy ion collisions could serve as a clear signature for the formation of a new matter phase quark gluon plasma (QGP) [1]. This suppression effect was observed by the NA38 Collaboration later [2]. However, successive research pointed out that such a suppression could also exist in hadronic matter (HM), even though by a completely different mechanism [3]. Therefore it is believed that an observation of a mere $J/\psi$ production rate suppression is not sufficient to confirm QGP formation, and a more thorough study on the characteristics of the $J/\psi$ suppression is necessary and may lead to final confirmation of QGP state. The $p_T$ distribution of $J/\psi$ may be a good candidate, since the different mechanisms which result in $J/\psi$ suppression in both HM and QGP may provide different $p_T$ distributions of $J/\psi$ [4–7]. Our numerical results confirm this conjecture (see below).

In this work, we discuss the $p_T$ distribution of $J/\psi$ in QGP and analyze the differences from that in HM.

In principle, the $J/\psi$ quarkonium is described in a Fock state decomposition

$$\begin{aligned}|J/\psi\rangle=&O(1)|c\bar{c}(^3S_1^{(1)})\rangle+O(v)|c\bar{c}(^3P_J^{(8)})g\rangle\\&+O(v^2)|c\bar{c}(^1S_0^{(8)})g\rangle+O(v^2)|c\bar{c}(^3S_1^{(1,8)})gg\rangle\\&+O(v^2)|c\bar{c}(^3D_J^{(1,8)})gg\rangle+\cdots,\end{aligned}\tag{1}$$

where $^{2s+1}L_J^{(1,8)}$ characterizes the quantum state of the $c\bar{c}$ with color-singlet or octet, respectively. This expression is valid for the nonrelativistic QCD (NRQCD) framework and the coefficients of each components depend on the three-velocity $|\vec{v}|$ of the heavy quark, and under the limit of $|\vec{v}|\to 0$, i.e., both $c$ and $\bar{c}$ remain at rest; Eq. (1) recovers the expression for color-singlet picture of $J/\psi$ where $O(1)\equiv 1$.

From the above discussion, one can know that the charmonium production can be divided into two steps [8]. 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 $\tau_{\rm for}\simeq(2m_c)^{-1}\simeq 0.07$ 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. The color-octet component $(c\bar{c})_8$ has been proved to play an important role in interpreting the CDF experimental data [9] (see next section for more detail), therefore, as has been pointed out by Kharzeev and Satz [10], one can expect that the color-octet $(c\bar{c})_8$ would also manifest itself in heavy ion collisions. As the color octet is especially important in explaining the $p_T$ distribution of $J/\psi$ in $p$-$p$ collisions, it is a necessary task to investigate the effects of the color octet on the $p_T$ dependence of $J/\psi$ suppression in heavy ion collisions and to see if it can provide information about QGP signature. This is the purpose of our paper. Consider the fact that the operator $\langle 8|(\lambda^a/2)(\lambda^a/2)|8\rangle=+3>0$ and the Coulomb-type potential is repulsive for a color octet $(c\bar{c})_8$, contrary to the case in color singlet where the Coulomb type potential is attractive, one can find that the color octet manifests itself quite differently in HM and QGP. In HM, as it is a color confined phase, when the color octet is formed, it will in general neutralize its color by combining nonperturbatively with an additional collinear gluon, thus producing the $(c\bar{c})_8g$ component of $J/\psi$ (see discussion of Kharzeev and Satz in Ref [10]). In QGP, as it is a deconfined phase, there is no necessity for a colored state to neutralize itself quickly and as the Coulomb-type potential between $c$ and $\bar{c}$ in the color octet is repulsive, $c$ and $\bar{c}$ cannot be bound together in an octet in QGP, and the original color-octet state $(c\bar{c})_8$ which is produced at the early stage of the collision would dissolve. In other words, the color octet $(c\bar{c})_8$ does exist and becomes the $(c\bar{c})_8g$ component of $J/\psi$ in HM, but it could not survive in QGP.

In this scenario, the $(c\bar{c})_8$ does not make as substantial contribution to $J/\psi$ in QGP, as it does in $p$-$\bar{p}$ collisions where the color octet $(c\bar{c})_8$ constitutes the dominate part of the produced $J/\psi$ at large $p_T$. Thus one would expect that the large $p_T$ contribution of $J/\psi$ would be more suppressed than the smaller $p_T$ one in QGP, but this does not occur for HM and we will discuss it in more detail later.

 

In the next section, we describe the color-octet scenario borrowed from the $p$-$\bar{p}$ collisions and discuss the simple but popular model for $J/\psi$ suppression in HM and QGP. In the third section we present the numerical results, while the last section is devoted to our conclusion and discussion.

## II. FORMULATION

### A. The color-octet $J/\psi$

It has already been demonstrated that the Fock decomposition form of $J/\psi$ can be expressed as Eq. (1) and the coefficients of each term are functions of the velocities. Calculating the coefficients has been proved to be beyond the present ability, since this is a nonperturbative QCD process. In principle, by the information gained in $p$-$p$ collisions, the produced $c\bar{c}$ can be in either color-singlet or color-octet. According to the newly developed factorization formalism [11], the inclusive $J/\psi$ production amplitude from the collision of partons $a$, $b$ can be factorized into short- and long-distance pieces:

$$\mathcal{A}(ab\to J/\psi+X)=\sum_{(c)L,J}\mathcal{A}[ab\to c\bar{c}(^{2s+1}L_J^{(c)})X]\times\mathcal{A}[c\bar{c}(^{2s+1}L_J^{(c)})\to J/\psi]. \quad (2)$$

The short-distance part for the hard production of $c\bar{c}$ pair can be calculated within perturbative QCD. On the other hand, the long-distance component of the hadronization $c\bar{c}[^{2s+1}L_J^{(c)}]\to J/\psi$ is a nonperturbative process, which can be calculated by lattice simulation or expressed in terms of some phenomenological parameters.

For the $p_T$ distribution, the differential cross section reads [12,13]

$$\frac{d\sigma(p\bar{p}\to J/\psi+X)}{dp_T}=\frac{d\sigma(p\bar{p}\to(J/\psi)_{octet}+X)}{dp_T}+\frac{d\sigma(p\bar{p}\to(J/\psi)_{singlet}+X)}{dp_T}, \quad (3)$$

where the subscripts denote different color components of Eq. (1). At the large $p_T$ limit, the main contribution comes from gluon fragmenting into a color-octet $c\bar{c}$ pair.

With this understanding, we can assume that the color-singlet and octet $c\bar{c}$ are produced at the early stage of heavy ion collisions and later evolve in the environment. If the temperature and density have not reached the phase transition, the system remains in HM, but if the phase transition indeed occurs, a QGP phase is formed; thus the $(c\bar{c})_1$ and $(c\bar{c})_8$ would have different evolution rules. It is assumed here that the $c\bar{c}$ are produced at the early stage of the heavy ion collisions through hard $N$-$N$ collisions when the phase transition has not occurred yet, and then the system would either remain in HM or enter a new QGP phase formed at a later time. Thus we only need to deal with the evolution of $(c\bar{c})$. Namely we ignore the production of $c\bar{c}$ by the deconfined quarks or gluons in QGP.

### B. $p_T$ dependence of $J/\psi$ in HM

It has been shown in [14] that the initial state parton scattering describes the change of the $p_T$ dependence observed in $J/\psi$ production from $p$-$p$ to $p$-$A$ and to central $S$-$U$ collisions. Only the initial state gluon scattering is considered there since gluon fusion dominates the production of $c\bar{c}$ pairs. Assuming the initial state interaction is the same for color octet and color singlet, considering the initial state interaction, the relation between the mean squared transverse momentum of the observed $J/\psi$, $\langle p_T^2\rangle^{\psi}$ in $p$-$A$, $A$-$B$ collisions and the mean squared transverse momentum of $J/\psi$, $\langle p_T^2\rangle_{pp}^{\psi}$ in $p$-$p$ collisions can be expressed as [14]

$$\langle p_T^2\rangle^{\psi}=\langle p_T^2\rangle_{pp}^{\psi}+\langle p_T^2\rangle_{gN}L\rho_0\sigma_{gN}, \quad (4)$$

where $L$ is the average length of the gluon trajectory before fusion and is equal to the average length of the $J/\psi$ trajectory inside the nucleus after the formation. $\sigma_{gN}$ is the gluon-nucleon cross section, $\langle p_T^2\rangle_{gN}$ is the mean squared transverse momentum acquired in one $gN$ collision; $\rho_0$ is the density.

The transverse momentum distribution of $J/\psi$, $F(p_T)$ in $p$-$p$, $p$-$A$, and $A$-$B$ can be parameterized as

$$F(p_T)=\frac{1}{\pi\langle p_T^2\rangle}\exp\frac{-p_T^2}{\langle p_T^2\rangle}. \quad (5)$$

Considering Eq. (4) and Eq. (5), using the parameter $\sigma_{gN}\langle p_T^2\rangle_{gN}=0.39\pm0.08\ \mathrm{fm}^2(\mathrm{GeV}/c)^2$, the experimental $p_T$ distributions of $J/\psi$ in $O$-$U$ and $S$-$U$ collisions can be explained very well [14]. Here, we will extend the above discussion to include the color-octet contribution. At the initial stage of the $A$-$B$ collisions, just in analog to the hadron-hadron collisions, there are both $(c\bar{c})_1$ and $(c\bar{c})_8$ produced. By the information gained from hadron collisions, their relative fractions are $p_T$ dependent and can be expressed as $f_1(p_T)$ and $f_8(p_T)$, respectively [a simplified notation from Eq. (1)]. They would also make different contributions to the $p_T$ distribution of $J/\psi$. Here $f_1(p_T)$ and $f_8(p_T)$ are proportional to the first and second terms of Eq. (3), respectively, while the normalization is $f_1(p_T)+f_8(p_T)=1$. We will use the theoretical results in Ref. [13] for $J/\Psi$ production at $p$-$p$ collisions, in which the color-singlet contribution comes from the evolution of $Q\bar{Q}(^3S_1^{(1)})$ pairs and the color-octet contribution comes from the evolution of $Q\bar{Q}(^3S_1^{(8)})$, $Q\bar{Q}(^1S_0^{(8)})$, and $Q\bar{Q}(^3P_J^{(8)})$. They include all lowest order effects from both parton fusion and parton fragmentation processes. Obviously at high $p_T$ the gluon fragmentation to color-octet pairs gives a dominant contribution, and at low $p_T$ parton fusion is dominant. Considering both the contribution of color-octet and color-singlet, including the initial state interaction and nucleon absorption, the ratio of $J/\psi$ production in $p$-$A$ or $A$-$B$ collisions to the corresponding one in $p$-$p$ collisions, where no initial state interaction and nucleon absorption exists can be parametrized as

$$R(p_T)=\frac{1}{\pi\langle p_T^2\rangle^{\psi}F_{pp}(p_T)}\exp\frac{-p_T^2}{\langle p_T^2\rangle^{\psi}}[f_1(p_T)\exp(-\rho_0L\sigma_{\mathrm{abs}}^1)+f_8(p_T)\exp(-\rho_0L\sigma_{\mathrm{abs}}^8)], \quad (6)$$

where $F_{pp}(p_T)$ is expressed as Eq. (5); $\sigma^1_{\rm abs},\sigma^8_{\rm abs}$ are $(c\bar{c})_1$-nucleon and $(c\bar{c})_8$-nucleon absorption cross section, correspondingly. In principle, we should consider the interaction between the different configuration $Q\bar{Q}(^{2S+1}L_J^{(c)})$ and the nucleon separately. Here we assume that the cross sections for all color-octet $Q\bar{Q}$ pairs and color-singlet $Q\bar{Q}$ pairs with a nucleon are equal to $\sigma^1_{\rm abs}$ and $\sigma^8_{\rm abs}$, respectively. We will use the above equation to discuss the $p_T$ dependence of $J/\psi$ in $S$-$U$ collisions, where people now believe that there is no QGP.

### C. A typical mechanism for suppression of $J/\psi$ production in QGP

The $p_T$ distribution of $J/\psi$ can be described by a fundamental picture [4,5]. Due to the Debye screening, when Debye screening length $r_D$ is sufficiently small, $(c\bar{c})_1$ can no longer form $J/\psi$. In addition, as discussed above, due to the repulsive interaction between $c\bar{c}$ in octet state in QGP, the $(c\bar{c})_8$ produced at the early stage of the collision, in principle, cannot form $J/\psi$ in the QGP background if there is enough time or the size of the QGP region is sufficiently large. As for the case in HM, $(c\bar{c})_1$ and $(c\bar{c})_8$ also have the possibility of dissolving into $D\bar{D}$ pairs by scattering with the hadronic matter to reduce the $J/\psi$ production rate. It is noted that the mechanisms for the dissolution in HM and QGP are different, for the color-singlet and octet; they lead to quite different results.

To concretely calculate the changes, let us take a reasonable and simplified physical picture [4,5]. Provided that in $A$-$B$ collisions the initially produced bound state $(c\bar{c})_1$ has a very small radius and needs approximately $\tau_\psi\sim 0.7$ fm to reach the intrinsic size of $J/\psi$. Thus the $(c\bar{c})_1$ bound state of small volume does not suffer from the Debye screening in QGP. In the laboratory frame, due to time dilation, one has $t_\psi=\tau_\psi\sqrt{1+(p_T/M)^2}$, which turns out to be the formation time assuming $p_z=0$. It is reasonable to take $p_z\sim 0$ since the observed $J/\psi$ are mainly in the central rapidity region. Therefore if the bound state $(c\bar{c})_1$ emerges from the QGP region, within a time interval $t_f$ less than $t_\psi$, it can ignore the QGP effect and eventually form a $J/\psi$ meson which can be observed experimentally. There are two models, the static [4] and the plasma expansion [5]. Because the QGP phase is produced in relativistic heavy ion collisions and evolves very fast, we take the second model to study the $p_T$ distribution of $J/\psi$. Although the formation time of the $J/\psi$ is rather short, it is assumed that the deconfined phase (whether it is QGP in equilibrium or not) is formed immediately after the collision. $(c\bar{c})_8$ suffers the effect of this deconfined phase immediately. Therefore the corresponding time $t_\psi^{(8)}$, being the time for $(c\bar{c})_8$ starting to suffer from the QGP effect, should be much shorter than the corresponding time $t_\psi$ for $(c\bar{c})_1$, which is the Lorentz delayed formation time of $J/\psi$.

Introducing $R_1$ as the ratio of the number of produced $(c\bar{c})_1$, which eventually forms $J/\psi$ when a possible QGP effect is considered, to the total number of $(c\bar{c})_1$ forming $J/\psi$ when a QGP effect is not included in corresponding collisions. Similarly, we could also define a ratio $R_8$ for $(c\bar{c})_8$. Obviously,

$$\begin{cases} R_1=0 & \text{if } t_f\geqslant t_\psi, \\ R_1=1 & \text{if } t_f<t_\psi, \end{cases} \tag{7}$$

where $t_f$ is the time as $(c\bar{c})_1$ lingers in a QGP. By the Bjorken hydrodynamic model,

$$R_1(p_T)=\frac{\int_0^{R_0}dr\int_0^{\pi}d\phi r\rho(r)\,\theta(t_\psi-t_f(r,\phi))}{\pi\int_0^{R_0}drr\rho(r)}, \tag{8}$$

where we assume $\rho(r)=(1-r^2/R_0^2)^b\,\theta(R_0-r)$ with $b=1$, which is the initial distribution density of the $(c\bar{c})_1$ located at $\vec{r}$ from the center. Strictly speaking, this initial distribution only gives a good description for central collisions, however for a qualitative analysis we will use this approximate distribution for all transverse energy bins. It is easy to find that there is a maximum transverse momentum $(p_T)_{\rm max}$ and one has $R_1=1$ as long as $p_T\geqslant(p_T)_{\rm max}$,

$$(p_T)_{\rm max}=M\sqrt{(t_m/\tau_\psi)^2-1}, \tag{9}$$

where $t_m$ is the lifetime of the QGP and $M$ is the mass of the $J/\psi$ meson. Actually Eq. (9) holds only in the case where the plasma lives for a time shorter than the average transit time $t_1$ of a $c\bar{c}$ in the system. This is because of the finite size effect. As has been discussed in Refs. [5,15], in general, for $A$-$B$ collisions the condition $t_m<t_1$ is satisfied.

When $d=v\cdot t_\psi\ll R(t_\psi)$, where $v$ is the velocity of $c\bar{c}$, one obtains an approximate expression

$$R_1=\left(\frac{\tau_\psi}{t_m}\sqrt{1+(p_T/M)^2}\right)^{(b+1)/a} \tag{10}$$

with $a=1/2$. In this expression, the surface effects are neglected compared to Eq. (8). For not too large $p_T$ and large nuclei, the results by the two expressions are very close [5,15]. Therefore, we will use this approximate one to make a qualitative discussion on the problem below.

### D. The effects of $(c\bar{c})_8$ on the $p_T$ distribution in QGP

Considering the discussion in the above section, The ratio of $J/\psi$ produced in QGP to the one produced without any absorption and initial state interaction can be expressed as

$$R(p_T)=\frac{1}{\pi\langle p_T^2\rangle^\psi F_{pp}(p_T)}\exp\frac{-p_T^2}{\langle p_T^2\rangle^\psi}[R_1(p_T)f_1(p_T) \\ +R_8(P_T)f_8(p_T)], \tag{11}$$

where $R_1$ and $R_8$ are the corresponding ratios for $(c\bar{c})_1$ and $(c\bar{c})_8$, respectively, as defined above.

We have argued that since $(c\bar{c})_8$ is colored, it interacts strongly with gluons in the environment of QGP and can dissolve much faster than $(c\bar{c})_1$ which is color blind. One can expect that the $(c\bar{c})_8$ does not contribute to $p_T$ distribution much if QGP is formed, namely, $R_8\ll R_1$ in QGP. If the

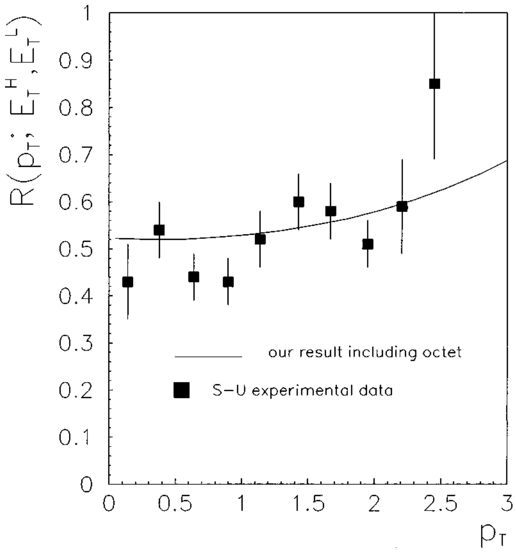


FIG. 1. The ratio $R(p_T;E_T^H,E_T^L)$ of the number of events with large values of $E_T$ to the number of events with small $E_T$ for sulfur-uranium collisions at 200 GeV/nucleon. The data are from Ref. [16]. The solid line is our calculation, with an overall factor to consider the co-mover effect for different $E_T$ bins.

time the $(c\bar{c})_8$ needs to traverse across the QGP region is very long, there would be no $(c\bar{c})_8$ contribution to $J/\psi$.

## III. NUMERICAL RESULTS

With our simple model, we have calculated the $p_T$ distribution of $J/\psi$ in $S$-$U$ collisions. The available data [16] for $J/\psi$ production vs transverse momentum is $R^{EXP}(p_T;E_T^H,E_T^L)$. Therefore, the ratio of the $J/\psi$ products at $p_T$ between the low transverse energy $E_T^L$ data and high transverse energy $E_T^H$ data is

$$R^{EXP}(p_T;E_T^H,E_T^L)=\frac{R[p_T;L(E_T^H)]}{R[p_T;L(E_T^L)]}, \tag{12}$$

and, for $S$-$U$ collisions, the two $E_T$ bins are related to the absorption length as [16]

$$L(E_T)=\frac{3}{4}r_0+4\ \ \text{fm},\quad E_T=E_T^L,$$

$$L(E_T)=\frac{3}{4}r_0+6.5\ \ \text{fm},\quad E_T=E_T^H, \tag{13}$$

where $r_0$ is the radius of sulfur. We fit the $S$-$U$ data using Eq. (6). The parameters we used are $\langle p_T^2\rangle_{pp}^{\psi}=1.3(\text{GeV}/c)^2$, $\sigma_{gN}\langle p_T^2\rangle_{gN}=0.35\ \text{fm}^2(\text{GeV}/c)^2$, and $\sigma_{\text{abs}}^1=0$ mb, $\sigma_{\text{abs}}^8=10$ mb, which are the results of our recent paper where the $J/\psi$ suppression from $p$-$A$ to $S$-$U$ data has been explained [18]. The numerical results are depicted in Fig. 1.

Now, we turn to discuss the situation in Pb-Pb collisions. We will discuss two cases: where the QGP is formed and where the QGP is not. The corresponding transverse energy bins are chosen as $E_T=34$ GeV and $E_T=88$ GeV, the related absorption lengths are [17]

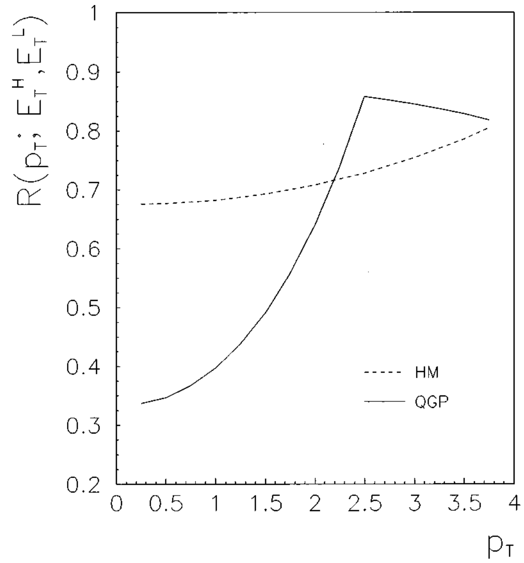


FIG. 2. The ratio $R(p_T;E_T^H,E_T^L)$ of the number of events with large values of $E_T$ to the number of events with small $E_T$ for Pb-Pb collisions at 200 GeV/nucleon. The two lines correspond to the deconfined case and confined case separately.

$$L(E_T)=10.0\ \ \text{fm},\quad E_T=E_T^L,$$

$$L(E_T)=11.0\ \ \text{fm},\quad E_T=E_T^H. \tag{14}$$

When the transverse energy is larger than $E_T^H$ the corresponding absorption length does not increase much in Pb-Pb collisions. For the low transverse energy bin where QGP cannot be formed, we use Eq. (6). For the high transverse energy bin we use Eq. (11) and Eq. (6) for the two cases where QGP is formed and QGP is not formed, separately. The parameters used here are the same as those used in the discussion of $S$-$U$ data.

Because the $(p_T)_{\max}$ [see Eq. (9)] depends on the formation time of $J/\psi$ and the lifetime of the QGP, its estimation cannot be accurate in our present knowledge, so that we take it as a free parameter. Thus one can note that the position of $(p_T)_{\max}$ is fixed just because we take it as a parameter and everything is scaled with this value. We have found that changes of $(p_T)_{\max}$ do not affect our qualitative conclusion.

We predict that $R(p_T;E_T^H,E_T^L)$ increases smoothly with increasing $p_T$ in HM. However, there is a turning point at $p_T=(p_T)_{\max}$ for $p_T$ distribution of $J/\psi$ in QGP. When $p_T<(p_T)_{\max}$, the $R(p_T;E_T^H,E_T^L)$ value increases much more steeply with the increase of $p_T$ in QGP than that in HM. However, the $R(p_T;E_T^H,E_T^L)$ value decreases with increasing $p_T$ after $p_T\geqslant(p_T)_{\max}$, and it is contrary to the behavior of $R(p_T;E_T^H,E_T^L)$ in HM where $R(p_T;E_T^H,E_T^L)$ always increases with $p_T$. The result is shown in Fig. 2.

It can be seen from the figure that the transverse momentum dependences of $J/\psi$ in HM and QGP are quite different. More discussions will be given in the next section.

## IV. CONCLUSION AND DISCUSSION

We employ a simple model to estimate the $p_T$ distribution of $J/\psi$ emerging from the QGP and HM regions. The data of hadron collisions indicate that the $(c\overline{c})_8$ component is not negligible and plays a crucial role for the large $p_T$ distribution of produced $J/\psi$. It motivates us to consider effects of the $(c\overline{c})_8$ component on the $p_T$ distribution of $J/\psi$ in relativistic heavy ion collisions, especially when the excited region turns into the QGP phase. Indeed, $(c\overline{c})_8$ produced at the early stage of collision would have a completely different behavior of evolution in QGP and HM. The QGP phase provides the deconfined phase which strongly interacts with the color-octet $(c\overline{c})_8$; however, in the confined HM phase the interaction is much weaker. Therefore the $p_T$ distribution may be taken as a signature of QGP formation.

We calculated the $p_T$ dependence of $J/\psi$ production in $S$-$U$ collisions using the initial state interaction, including the color octet channel of $J/\psi$ formation and compared with the existing data. For Pb-Pb collisions, we compare the $p_T$ distributions of $J/\psi$ in HM and QGP. We find that these two results are quite different: The curve increases smoothly with increasing $p_T$ in HM. However, there is a turning point at $p_T=(p_T)_{\max}$ for $p_T$ distribution of $J/\psi$ in QGP. When $p_T<(p_T)_{\max}$, $R(p_T;E_T^H,E_T^L)$ value increases much more steeply with the increase of $p_T$ in QGP than that in HM. However, $R(p_T;E_T^H,E_T^L)$ value decreases with increasing $p_T$ after $p_T\geqslant(p_T)_{\max}$, and it is contrary to the behavior of $R(p_T;E_T^H,E_T^L)$ in HM where $R$ always increases with $p_T$.

It is believed that, in the previous $O$-$U$ and $S$-$U$ experiments, the energy scale was not high enough to produce a QGP state, and then the observed $R(p_T;E_T^H,E_T^L)$ value indeed kept increasing with an increase of $p_T$. The hadron picture gives a satisfactory description to the result so it confirms that a turning over of the dependence of $R(p_T;E_T^H,E_T^L)$ on $p_T$ may signify a QGP formation. A recent paper discussed the effect of QGP on initial state parton scattering and found that the deconfinement will reduce the normal $p_T$ broadening [7]. If this effect is considered when $p_T>(p_T)_{\max}$, the $R(p_T;E_T^H,E_T^L)$ value in Pb-Pb collisions will decrease even faster with $p_T$ increasing for the case when QGP is formed. An unusual suppression of $J/\psi$ has been observed at a present Pb-Pb collision experiment and there have been some discussions about the possible mechanisms [19]. Based on our model, further measurement of the $p_T$ dependence of the $J/\psi$ suppression may provide additional information about the formation of QGP.

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