Enhanced J/ψ suppression due to gluon depletion

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The nonlinear effect of gluon depletion in the collision of large nuclei can be large. It is due to multiple scatterings among comoving partons initiated by primary scattering of partons in the colliding nuclei. The effect can give rise to substantial suppression of J/ψ production in very large nuclei, even if the linear depletion effect is insignificant for the collisions of nuclei of smaller sizes. This mechanism offers a natural explanation of the enhanced suppression in the Pb-Pb data recently observed by NA50. [S0556-2813(98)02307-3]

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I. INTRODUCTION

In a previous paper [1] we examined the issues involved in ascribing some aspect of the phenomenon of J/ψ suppression in heavy-ion collisions [2] to the depletion of gluons prior to the hard subprocess of $c\bar{c}$ production. What we found is that the data on the survival probability S without the points from Pb-Pb collisions [3,4], by themselves, cannot distinguish whether the suppression is due to gluon depletion or hadronic-nuclear absorption. That is, both mechanisms contribute to an exponential dependence of S on the effective path length L (or on $\ln AB$). We now consider the enhanced suppression in the Pb-Pb data of NA50 [4] and show how gluon depletion can naturally account for it. Furthermore, it is possible for that to happen even if the ''normal'' suppression in the lighter-ion data is due mainly to the absorption mechanism with negligible depletion effect.

Many suggestions have been advanced to account for the enhancement of J/ψ suppression observed in the Pb-Pb collision data [5–11]. They all refer to the absorption processes *after* the production of the $c\bar{c}$ state. Our suggestion is concerned with the depletion of gluons *before* the $gg\to c\bar{c}$ subprocess. The basic idea is rather intuitive and can be described qualitatively before we go into the details. Consider a row of nucleons in nucleus A colliding with another row in nucleus B, and suppose that the n_Ath one from the front of the former (call it a) collides with the n_Bth one in the latter (call it b) in a hard process creating $c\bar{c}$. The gluon depletion mechanism discussed in Ref. [1] takes into account the loss of gluons in a (due primarily to $g\to q\bar{q}$) as it goes through B until $gg\to c\bar{c}$ occurs with a gluon in b; similarly, the gluons in b are depleted as b traverses A. We shall refer to this process as *linear* depletion for reasons that will become clear below. What we now want to emphasize is that a *nonlinear* depletion process may be even more important. Such a process is due to the interaction of the gluons in a with the slower partons liberated from the n_A-1 forerunners in A broken by earlier interactions, and likewise b with the partons of the n_B-1 forerunners in B. In an imperfect, yet helpful, analogy one may think of a multicar accident on a busy, foggy highway and recognize that most of the collisions are between cars originally going in the same direction.

In this paper the linear depletion effect can be turned off and replaced by the usual absorption effect, if it helps to be uncontroversial; yet the nonlinear depletion effect to be described is nevertheless capable of accounting for the enhanced suppression seen in the Pb data. As will become clear, the nonlinear effect is most important if the $gg\to c\bar{c}$ fusion point occurs late in the collision process to allow more $g\to q\bar{q}$ to take place before fusion. Various issues associated with gluon depletion, such as the gain of gluons from $g\to gg$, soft production of quarks and antiquarks, and the possible increase of dilepton production, are discussed in Sec. II. A quantitative treatment of the gluon depletion effect is given in the subsequent sections.

It should be emphasized that we do not regard the usual explanation of J/ψ suppression through absorption and deconfinement as being superseded by the gluon depletion mechanism. We actually have no doubt that absorption and deconfinement are operative at some level. However, our main point is that the third possibility of gluon depletion can also contribute, and that until it is convincingly ruled out, we should keep an open mind on all possible causes of the suppression phenomenon. In this paper we go so far as to demonstrate that by an appropriate choice of parameters it is possible to fit the suppression data totally in the gluon depletion scenario. It does not mean that the other two mechanisms are ruled out; they can be incorporated by further adjustments of the parameters. Our aim is only to suggest that at this point the gluon depletion mechanism should be included as one of the various contributing causes.

II. ISSUES SURROUNDING GLUON DEPLETION

There are various issues and questions concerning the gluon-depletion mechanism that should be discussed before we go into the quantitative details about J/ψ suppression. Since the proposed mechanism is unconventional, it is perhaps more important to address the skepticism that arises from the conventional point of view than to claim how well the data can be fitted by some new formulas.

The first question is whether there is any experimental evidence in favor of gluon depletion. The answer is no; there is no direct evidence, whether for or against gluon depletion. If there is gluon depletion, then the reduction of D-$\bar{D}$ pair production rate should be an unambiguous signature. We urge a dedicated search for back-to-back D-$\bar{D}$ pairs, since the D-meson single inclusive cross section includes contributions from processes that are not due to the $g+g\to c+\bar{c}$ subprocess.

Secondly, the absence of quark depletion may be taken to imply that gluon depletion may also be absent. It is known that the dilepton production through $q+\bar{q}\to\ell+\bar{\ell}$ depends on the nuclear sizes A and B according to AB without significant deviation. This fact would seem to place a constraint on the possibility of gluon depletion, since the gluon and quark sectors are expected to have coupled behaviors. We first note that because of the overwhelming abundance of the gluons relative to the antiquarks, the reaction $g+g\to q+\bar{q}$ is far more dominant than the reverse process. That is the origin of gluon depletion. With the rise of the $q\bar{q}$ density, one would expect the dilepton production rate to increase, but that is not observed. We comment on this point in the next paragraph. Here we mention that the rise of $q\bar{q}$ *does* result in the rise of hadron production rate even in pp collisions—relative to the hadron inclusive cross section calculated from the q and $\bar{q}$ distributions alone using the recombination model [12]. The point is that the gluons must hadronize in soft interaction. Since glueballs are not observed, the only route is for the gluons to convert to q and $\bar{q}$ first and then hadronize; the normalization of the resultant pion inclusive cross section agrees with the experiment [13].

Now we come to dilepton production rate. In order for that rate to increase, the $q\bar{q}$ produced from gluon fusion must be formed in the nuclear medium so that the subprocess $q+\bar{q}\to\ell+\bar{\ell}$ may take place. Since $g+g\to q+\bar{q}$ need not be a hard process, ΔE not only can be small, but is predominantly small in soft interaction. The corresponding Δt can therefore be long—long enough so that the q and $\bar{q}$ are formed outside the domain where they are to find other q and $\bar{q}$ to make the $\ell\bar{\ell}$ pair. In that case the excess q and $\bar{q}$ can only produce hadrons, so the net effect is that the gluons hadronize via the $q\bar{q}$ intermediate states without increasing the dilepton production rate. Since the gluon depletion effect is most severe in large nuclei, it suggests that the nonlinear depletion is most effective for the gluons that are originally in the nucleons residing in the rear parts of the colliding nuclei. For those gluons the produced $q\bar{q}$ pairs have the least likelihood to find partners to create $\ell\bar{\ell}$ pairs. Thus when the gluon depletion effect is most pronounced, the dileptons are least likely to be produced. Of course, $q\bar{q}$ pairs can also be produced with short formation time, but at a reduced rate appropriate for hard subprocesses. In the early part of the nuclear collision history, those pairs can lead to a small enhancement of dileptons. Since there are excess dileptons found in the low-mass region rising above the Drell-Yan level, the experimental data still have room to accommodate unusual sources of dilepton production. Thus in our view the data on dilepton production do not place a strong constraint on the gluon depletion process, especially for the nonlinear effect in Pb-Pb collisions that we shall address in this paper.

The fusion process of $g+g\to c+\bar{c}$ has been simulated in the parton cascade model for heavy-ion collisions at high energy [14]. It is found in that model that the $c\bar{c}$ production rate is increased, contrary to the expectation in the gluon depletion scenario. However, it is essential to recognize that a model based on perturbative QCD (PQCD) is reliable only at very high energy—at least, say, RHIC energy. For $\sqrt{s}\sim 200$ GeV, the momentum fraction for gluons to create $c\bar{c}$ pairs at J/ψ mass is roughly $x\sim 0.015$. That is an order of magnitude lower than the value $x\sim 0.15$ for the corresponding gluons at CERN-SPS energy. At any energy the depletion of gluons at $x\sim 0.15$ is nearly certain to enhance the gluon density at the lower $x\sim 0.015$. However, at CERN-SPS, gluons with such low momentum fractions cannot produce $c\bar{c}$ pairs. Thus there is no conflict between what the parton cascade model can reliably predict at high $\sqrt{s}$ and the gluon depletion process relevant to the experiments at hand on J/ψ suppression at lower $\sqrt{s}$.

Since the nonlinear effect that we shall consider below relies on the possibility that gluons in a nucleon in the rear part of a tube can interact with the gluons emitted by the forerunners, i.e., the nucleons in the front part of the tube, it is appropriate to examine whether there is time for such interactions to take place. The mean free path in a nucleus is about 3.5 fm in the rest frame, so in the c.m. system with $\gamma=10$ that distance is contracted to 0.35 fm in the longitudinal direction. Gluons that are produced with $\Delta E>0.5$ GeV can then have enough time within $\Delta t<0.4$ fm/c to form and interact with the gluons that come from behind. Such gluons produced by the forerunners are the products of very modest semihard processes, and should be produced in abundance. Thus the requirement for the nonlinear depletion process to be operative can readily be satisfied at CERN-SPS.

Our final remark in this section concerns the use of PQCD. In order that the PQCD method be reliable, the virtuality of the hard process should be high, say $Q>5$ GeV. For the fusion process $g+g\to c+\bar{c}$ at the J/ψ mass region, Q is low enough to question the reliability of lowest-order calculations. Nevertheless, let us accept its use, as is generally done. However, the $g+g\to q+\bar{q}$ subprocess that leads to gluon depletion need not involve high virtuality, and hence is not perturbative. Although perturbative calculations cannot be done, it is still possible to make certain meaningful statements independent of the details of PQCD. For example, based on the fact that the gluon density is higher than the $\bar{q}$ density in the region of interest, the rate of the process $g+g\to q+\bar{q}$ is much higher than that of the reversed process, $q+\bar{q}\to g+g$. Similarly, since the gluon distribution falls off roughly as $(1-x)^5$, one can reasonably state that the gain in gluon density at $x\sim 0.15$ due to $g\to g+g$ from higher x is unimportant compared to the loss of gluons due to $q+\bar{q}$ at $x\sim 0.15$. Thus as we focus on the balance of gain versus loss of gluons in the momentum cell of interest, there are less gluons at $x>0.15$ feeding into the cell at $x\sim 0.15$ than there are leaving the cell. The net effect is gluon depletion. Details of PQCD are not needed for that observation. Since reliable calculation cannot be done, we shall in the following parametrize the gluon depletion effect by a simple parameter D for linear depletion and D' for nonlinear depletion. Those parameters can be varied in suitable phenomenological analyses of the data.

III. SUPPRESSION FACTORS AT FIXED *b* AND *z*

Let us first summarize the essence of the linear effect considered in Ref. [1]. Our notation will follow that of Ref. [1], but abbreviated for clarity's sake. The probability that a nucleon in A makes ν_1 collisions in B before the hard subprocess is

$$\pi_{\nu_1}=\frac{1}{\nu_1!}\,n_B^{\nu_1}e^{-n_B},\quad n_B=\sigma_{\rm in}T_B^-,\tag{1}$$

where T_B^- is the path length that is traversed in B before the $c\bar{c}$ production and is dependent on the impact parameter b_B and longitudinal position z_B, both being suppressed [but defined in Eq. (8) below]. If the depletion factor per collision at fixed momentum fractions x_1 and x_2 is D ($D=1$ for no depletion), then the suppression factor at fixed b and z in A and B is

$$\Gamma_{AB}^{(d)}=\sum_{\nu_1,\nu_2}\pi_{\nu_1}\pi_{\nu_2}D^{\nu_1+\nu_2}=\exp[-(1-D)(n_A+n_b)],\tag{2}$$

where π_{ν_2} is defined as in Eq. (1), but with B replaced by A. It is the simple sum, n_A+n_B, in Eq. (2) that leads us to call the effect linear. The exponential behavior of $\Gamma_{AB}^{(d)}$ is what generates, after integration over b and z, the approximate exponential dependence of S on L that is indistinguishable from the Gerschel-Hüfner formula [15], derived from purely absorptive consideration.

The nonlinear effect that we now describe arises from the interactions with the forerunners. At the partonic level the linear effect is due to the primary interactions of gluons in nucleons going in opposite directions, while the nonlinear effect is due to the secondary, tertiary, etc., interactions among partons moving in the same direction, initiated by primary interactions. The rapidity separation Δy between the participants of the primary interaction is large because they belong to the nuclei A and B separately. On the other hand, Δy between the partons involved in the secondary (or tertiary, etc.) interactions is small because they belong to the same nucleus. Ordinarily, in an unperturbed nucleus or in deep inelastic scattering of a nucleus, those partons in different nucleons do not interact except in the context of nuclear binding and shadowing. However, if a primary interaction has taken place between two colliding nuclei, the scattered parton in A, whether at large or small angle, can interact with a parton coming from behind in the same or neighboring rows. Since they are comovers, their interaction can be much stronger than the primary interaction, a property that is consistent with the general notion of strong interaction in soft processes being short ranged (in rapidity). Thus even if the linear depletion effect is small, the nonlinear effect need not be.

If we consider an $n_A\times n_B$ matrix, representing the possible pairings of n_A and n_B nucleons in collisions, the last row and last column contribute to the linear depletion effect. [Their sum n_A+n_B-1 appears as n_A+n_B in Eq. (2) in compensation for the fact that the first collision of a nucleon with a row of nucleons is the normal pp collision, whose cross section is larger than those of the subsequent collisions that involve the broken nucleon propagating downstream. To elaborate on this point is too much of a digression that is not germane to the following discussion.] The remaining part of the matrix having $(n_A-1)(n_B-1)$ pairings contributes to the quadratic depletion effect due to multiple parton scatterings. Let us define

$$n_A'=(n_A-1)\Theta(n_A-1),\tag{3}$$

and similarly for n_B'. Then, assuming $A\leqslant B$, the average number of collisions that the forerunners of a in A make with the forerunners of b in B, producing comoving partons that can interact with the partons of a, is $n_A'n_B'-n_A'^2/2$; that for producing comoving partons with the ones in b is $n_A'^2/2$. This way of partitioning the $n_A'n_B'$ pairings can be visualized in the forward light cone of AB collision, where the former lie on the A side of the interaction region, i.e., the left side of the light cone for the right-moving nucleus A, while the latter lie on the B side, i.e., the right side of the light cone for the left-moving nucleus B. The precise method of partitioning is unimportant, as will become evident presently.

The probabilities that a and b can interact ν_1' and ν_2' times with their respective forerunners are

$$\pi_{\nu_1'}'=\frac{1}{\nu_1'!}\,(n_A'n_B'-n_A'^2/2)^{\nu_1'}e^{-(n_A'n_B'-n_A'^2/2)},\tag{4}$$

$$\pi_{\nu_2'}'=\frac{1}{\nu_2'!}\,(n_A'^2/2)^{\nu_2'}e^{-n_A'^2/2}.\tag{5}$$

If D' is the effective gluon depletion factor for each of those interactions, then the corresponding suppression factor, analogous to Eq. (2), is

$$\Gamma_{AB}'^{(d)}=\sum_{\nu_1',\nu_2'}\pi_{\nu_1'}'\pi_{\nu_2'}'D'^{\nu_1'+\nu_2'}=\exp[-(1-D')n_A'n_B'].\tag{6}$$

We refer to this as the quadratic depletion effect, since it is $n_A'n_B'$ that appears in the exponent, as opposed to n_A+n_B in Eq. (2). As it is in Eq. (2), the dependences on b_A, z_A, b_B, and z_B have been suppressed in Eq. (6).

IV. EFFECTS DUE TO LINEAR AND QUADRATIC DEPLETION

The combined suppression factor due to both linear and quadratic depletion as well as absorption [1] is now

$$P=\exp[-(1-D)(n_A+n_B)-(1-D')n_A'n_B'-\sigma_a(T_A^++T_B^+)],\tag{7}$$

where σ_a is the absorption cross section and T_A^+ is the path length in A traversed by the J/ψ system. Exhibiting the b and z dependences, we have [1]

$$T_A^{\pm}=\left(1-\frac{1}{A}\right)\rho_0(L_A\pm z_A),\quad L_A=(R_A^2-s^2)^{1/2}, \tag{8}$$

and similarly for $T_B^{\pm}$, with $\vec{b}_A=\vec{s}$ and $\vec{b}_B=\vec{b}-\vec{s}$. The average overall suppression factor (more precisely, survival probability) is

$$S_{J/\psi}^{AB}=N_{AB}^{-1}\int d^2b\int d^2s\int_{-L_A}^{L_A}dz_A\int_{-L_B}^{L_B}dz_B P, \tag{9}$$

where N_{AB} is the same integral as in Eq. (9) but with P replaced by 1.

To see how $S_{J/\psi}^{AB}$ depends on A and B, let us examine the parameters in the formula. Without the quadratic depletion terms in Eq. (7), we have

$$P_1\equiv P(D'=1)=\exp[-\sigma_d(T_A^-+T_B^-)-\sigma_a(T_A^++T_B^+)], \tag{10}$$

where $\sigma_d=\sigma_{\rm in}(1-D)$, $\sigma_{\rm in}$ being the inelastic cross section already used in Eq. (1). As pointed out in Ref. [1], Eq. (10) exhibits the symmetry between the depletion effect before the formation of J/ψ and the absorption effect afterwards. That is why the exponential dependence of the empirical $S_{J/\psi}^{AB}$ on the effective length L (or $\ln AB$) cannot distinguish the two effects. So long as the combined cross section $\sigma_c=\sigma_a+\sigma_d$ is around 7 mb, the heavy-ion data, excluding the Pb-Pb collisions, can be fitted by any ratio $\eta=\sigma_d/\sigma_a$. Now, we consider the contribution from the quadratic depletion term in Eq. (7) only, giving

$$\begin{aligned}P_2&\equiv P(D=1,\sigma_a=0)\\&=\exp[-\tau(n_A-1)(n_B-1)\Theta(n_A-1)\Theta(n_B-1)],\end{aligned} \tag{11}$$

where $\tau=1-D'$, a parametrization, similar to σ_d, having the more proper sense of depletion in that $\tau=0$ means no depletion. There are a number of features of Eq. (11) worth noting.

(a) While the discussions in the introduction and in the paragraph containing Eq. (3) regard n_A and n_B as integers for the sake of ease in describing the nonlinear depletion mechanism, they can in reality have any positive value by virtue of their definitions $n_{A,B}=\sigma_{\rm in}T_{A,B}^-$. That is why the step functions in Eqs. (3) and (11) are important to ensure that the participants of the process, n_A' and n_B', are nonnegative. As a consequence there is a threshold effect, i.e., A and B must be large enough for the mechanism to be operative.

(b) The inelastic cross section $\sigma_{\rm in}$ is relevant in the determination of the position of the threshold. It is not the $\sigma_{\rm in}^{pp}$ for pp collision because, except for the first collisions on the front sides of the nuclei, most of the collisions are between broken nucleons [16], which consist mainly of the parton fluxes that propagate downstream after the bound nucleons are broken by the first collisions. $\sigma_{\rm in}$ is an effective cross section for the collision of such broken nucleons, and there exist no reliable estimates for its value. Using p' to denote broken nucleon, and taking $\sigma_{\rm in}^{pp}\approx 30$ mb, it is not unreasonable to consider $\sigma_{\rm in}^{p'p}\approx 20-25$ mb, and $\sigma_{\rm in}^{p'p'}\approx(\sigma_{\rm in}^{p'p})^2/\sigma_{\rm in}^{pp}\approx 13-21$ mb. We shall adopt $\sigma_{\rm in}\approx 15-25$ mb as typical values.

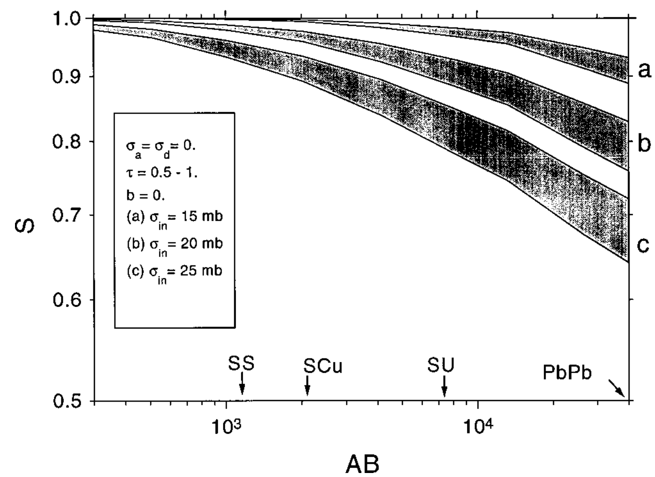

FIG. 1. The suppression factor $S_{J/\psi}^{AB}$, abbreviated as S, is plotted against AB, when only the quadratic depletion effect is taken into account. The shaded regions are for τ having values between 0.5 (upper boundaries) and 1.0 (lower boundaries). Three values of $\sigma_{\rm in}$ are used, as indicated.

(c) The quadratic depletion parameter τ can be substantially different from zero, even if the linear effect measured by σ_d is zero, since, as discussed earlier, the interaction between partons with small rapidity separation can be much greater than that between partons with large Δy. Since the determination of τ from first principles is difficult, we shall use it as a free parameter in the following. It should be noted that even if $D'=0$, i.e., total depletion per collision, τ attains its maximum value 1, so Eq. (11) does not give $P_2=0$. That is because the Poissonian fluctuations in Eqs. (4) and (5) allow for $\nu_1'=\nu_2'=0$, which result in a nonvanishing probability for the passage of the gluon fluxes with minimal influence by the depletion mechanism.

V. SOME NUMERICAL RESULTS

To gain some further insight in the quadratic depletion effect, let us compute $S_{J/\psi}^{AB}$, taking only P_2 into account, i.e., by substituting Eq. (11) alone into Eq. (9). Using the integration procedure developed in Ref. [1], we obtain the results shown in Fig. 1, where $\sigma_{\rm in}$ is set at 15, 20, and 25 mb; the shaded regions are bounded by $\tau=0.5$ from above (for illustrative purpose) and $\tau=1.0$ from below. Evidently, the threshold for the quadratic depletion effect is higher at smaller $\sigma_{\rm in}$, since there would be less participants for the multiscattering subprocesses unless A is higher. Furthermore, even at maximum depletion ($\tau=1$) there is still a residual rate of J/ψ production because of the aforementioned probability of gluon passage without depletion. We note that, although the parameters $\sigma_{\rm in}$ and τ are not empirically familiar, their values used in Fig. 1 are sensible estimates, so the suppression effect revealed is a natural consequence of a physical process that is not contrived to explain the data.

For a comparison with the data [3,4] we include both P_1

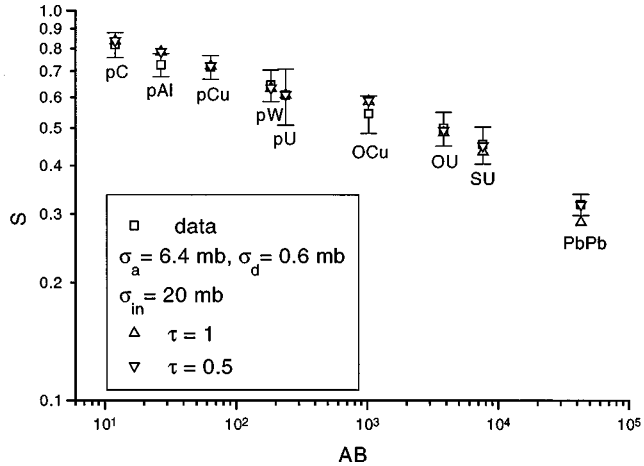

FIG. 2. The suppression factor $S^{AB}_{J/\psi}$, abbreviated as S, is plotted against AB, when both the usual linear (mainly absorption) effect and the quadratic depletion effect are taken into account. The data are from Ref. [4]. Typical values for the parameters in the theoretical calculations have been used.

and P_2 in Eq. (9) and calculate the overall suppression factor. Since, as found in Ref. [1], the combined effect of absorption and linear depletion is insensitive to the ratio $\eta=\sigma_d/\sigma_a$, we choose the uncontroversial values $\sigma_c=\sigma_a+\sigma_d=7$ mb and $\eta\approx 0.1$. For quadratic depletion effect we use $\sigma_{\rm in}=20$ mb and $\tau=0.5$–1.0. The result is shown by the triangles in Fig. 2. The agreement with the data [4] is evidently very good. Of course, if there exists enhanced nuclear, hadronic, or plasma absorption at high AB, it can be accommodated by reducing the value of τ. What is shown here is that the quadratic gluon depletion effect by itself is able to account for the enhanced suppression in the Pb-Pb data.

VI. CONCLUSION

A concomitant phenomenon associated with quadratic gluon depletion is the suppression of back-to-back $D\bar{D}$ production in Pb-Pb collision, but not in AB collisions where A is smaller. Photon production would not necessarily be suppressed, since the quarks produced by gluon conversion can carry on the γ-producing subprocess without inhibition. Dilepton production may or may not be enhanced, depending on whether the extra quarks and antiquarks are produced inside or outside the interaction region. It is therefore important that all those signatures should be examined experimentally in the collisions of very heavy ions.

Whether or not the nonlinear gluon depletion process can wholly or partially account for the enhanced J/ψ suppression phenomenon, what we have discovered here is that there is a whole class of parton interactions whose role in heavy-ion collisions has hitherto been overlooked, but they are of crucial importance to any process whose rate depends on the magnitude of the gluon flux available in large nuclei. Since what is done in this paper is only a phenomenological fit of the J/ψ suppression data, we cannot claim that gluon depletion is necessary and sufficient to explain the data. Any admixture with absorption and deconfinement can no doubt fit the data also. The main point to be emphasized here is that gluon depletion constitutes a third possible cause of suppression that should be considered and excluded before a definitive conclusion on the evidence for deconfinement is reached.

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