J/ψ dynamical suppression in a hadron and string cascade model

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A hadron and string cascade model, JPCIAE, for simulating ultrarelativistic nucleus-nucleus collisions based on the LUND model and PYTHIA event generator especially, is used to investigate J/ψ suppression due to nuclear absorption in minimum bias pA and AB collisions at $200A$ GeV/c. With different sets of reasonable formation time for a J/ψ and a meson the results of the J/ψ suppression factor from both the usual scenario simulation (i.e., standard cascade simulation) and the Glauber-like simulation are comparable with all the NA38 pA and AB data, except the NA50 data of Pb+Pb collisions. However, the difference between the usual scenario simulation and the Glauber-like simulation, with the same parameter set of formation time, is noticeable. Meanwhile, the sensitive effect of formation time and the effect of the possible uncertainty in the absorption cross sections on J/ψ suppression are studied in detail. [S0556-2813(99)06105-1]

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I. INTRODUCTION

More than ten years ago Matsui and Satz [1] suggested that the suppression of J/ψ yield in relativistic nucleus-nucleus collisions might be a powerful signature for quark-gluon plasma (QGP) formation. Since then, a number of corresponding experiments have been stimulated [2–4] to measure the J/ψ yield via its dimuon decay. A significant suppression of the J/ψ yield from pA collisions to AB collisions has already been observed in these experiments. So far, except the anomalous suppression observed in Pb+Pb reactions at $158A$ GeV/c [4], the normal suppression has been well explained within Glauber theory (absorption model) [5–14]. However, the mechanism for the anomalous suppression in Pb+Pb collisions is still a debated issue [9–15].

Recently in [16,17] a covariant transport approach has been used to investigate both the normal and anomalous nuclear suppression of the J/ψ yield. They concluded that the data of J/ψ suppression from pA to AB collisions, including Pb+Pb at $158A$ GeV/c, can be described without assuming the formation of QGP in these collisions.

In this paper we propose a hadron and string cascade model, JPCIAE, for simulating relativistic nucleus-nucleus collisions based on the LUND model and PYTHIA event generator [18]. We first inspect this model and the corresponding event generator via comparing model predictions with the NA35 data of the negative charge multiplicity, the rapidity, and transverse momentum distributions of the negative charge particles (h^-) and the participant protons in pp, pA, and AB collisions [19,20]. The model and the corresponding event generator are then used to investigate the J/ψ dynamical suppression and the effects of the dynamical ingredients. The results seem to declare that all the NA38 data of J/ψ normal suppression from pA to AB collisions [2,3] can be fairly well described by this model, except the NA50 data of Pb+Pb collisions [4]. By contrast, the authors of Refs. [16,17] claimed that the NA50 data could be reproduced under the absorption mechanism as well.

In our calculation two kinds of treatments for the reinteraction are investigated; one is the complete rescattering among spectator nucleons and produced particles (including J/ψ) and the other is the rescattering between a J/ψ (as a partner) and a spectator nucleon or a produced particle (as another partner) only. They are called, respectively, the usual scenario simulation and the Glauber-like simulation. Although both the usual scenario simulation and the Glauber-like simulation, with different parameter sets of formation time, are comparable with all the NA38 pA and AB data except the NA50 data of Pb+Pb collisions, the difference between these two kinds of simulations, with the same parameter sets of formation time, is noticeable. Meanwhile, the sensitive effects of the formation time and the effect of the possible uncertainty in the absorption cross sections on J/ψ suppression are studied in detail.

II. BRIEF DESCRIPTION OF THE MODEL

In JPCIAE the simulation is performed in the laboratory system. The origin of coordinate space is positioned at the center of the target nucleus and the beam direction is taken as the z axis. As for the origin of time it is set at the moment when the distance between the projectile and target nucleus along the z direction is equal to zero (the collision time can be negative).

A colliding nucleus is depicted as a sphere with radius $\sim 1.05A^{1/3}$ (A refers to the atomic mass number of this nucleus) in its rest frame. The spatial distribution of nucleons in this frame is sampled randomly due to the Woods-Saxon distribution. The projectile nucleons are assumed to have an

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incident momentum and the target nucleons are at rest. That means the Fermi motion in a nucleus and the mean field of a nuclear system are here neglected due to the relativistic energy in question. For the spatial distribution of the projectile nucleons the Lorentz contraction is taken into account. A formation time is given to each particle and a particle starts to scatter with others after it is ''born.'' The formation time is a sensitive parameter in this model as will be seen in Sec. III.

A collision time is calculated according to the requirement that the minimum approaching distance of a colliding pair should be less or equal to the value $\sqrt{\sigma_{\rm tot}/\pi}$, where $\sigma_{\rm tot}$ is the total cross section of the colliding pair. The minimum distance is calculated in the center-of-mass system (c.m.s.) frame of the two colliding particles. If these two particles are moving towards each other at the time when both of them are ''born,'' the minimum distance is defined as the distance perpendicular to the momenta of both particles. If the two particles are moving back to back, the minimum distance is defined as the distance at the moment when both of them are ''born.'' All the possible collision pairs are then ordered into a collision time sequence, called the collision time list. The initial collision time list is composed of the colliding nucleon pairs; in each pair here one partner is from the projectile nucleus and the other from the target nucleus.

Then the pair with the least collision time in the initial collision time list is selected to start the first collision. If the c.m.s. energy $\sqrt{s}$ of this colliding pair (a hadron-hadron collision) is larger than or equal to $\sim$4 GeV, two string states are formed and PYTHIA (with default parameters) is called to produce the final state hadrons (scattered states); no string state is formed and the conventional scattering process (elastic scattering or resonance production) [21–23] is executed otherwise. After the scattering of this colliding pair, both the particle list and the collision time list are then updated and they are now not only composed of the projectile and target nucleons but also the produced hadrons. Repeat the previous steps to perform the second collision, the third collision, . . . , until the collision time list is empty; i.e., no more collisions occur in the system.

In our model the J/ψ is produced via the QCD process

$$g+g\rightarrow J/\psi+g. \tag{1}$$

However, in [16,17] the cross section of $\sigma_{BB\rightarrow J/\psi+X}$ (the subscript B here refers to the baryon) was assumed to be equal to the product of $\sigma_{BB\rightarrow BB+X}$ and a probability factor W (a model parameter). In PYTHIA a lot of QCD parton-parton processes have been considered, including J/ψ production, Eq. (1). A user is allowed to run the program with any desired subset of these processes. However, any operation of user-desired processes, including the J/ψ production channel defined here, is a kind of bias sampling, which enhances the probabilities of those desired processes. In order to overcome the corresponding bias, executing PYTHIA with the J/ψ production channel is decided by a probability. This probability is equal to the parametrized J/ψ hadronic production cross section [24]

TABLE I. Negative charge multiplicity in pp and minimum bias pA collisions at 200 GeV/c.

	$p+p$	$p+$S	$p+$Ag
NA35 data	2.85±0.3	5.7±0.2	6.2±0.2
JPCIAE	2.84	4.91	5.81

$$\sigma_{NN\rightarrow J/\psi+X}=d\left(1-\frac{c}{\sqrt{s}}\right)^{12} \tag{2}$$

(with $c=3.097$ GeV, $d=2.37/B_{\mu\mu}$ nb, $B_{\mu\mu}=0.0597$, the branching ratio of J/ψ dimuon decay) multiplied by a factor. That factor is adjusted so that the number of J/ψ produced in each simulating event is around 1, the same as in the experiment [2].

One more point needed to be mentioned here is that in the original JETSET program, which deals with the fragmentation of a string and runs together with PYTHIA, the leading particle in a nucleon-nucleon collision is assumed to carry about half of the incident energy. But the experiments of nucleus-nucleus collisions at relativistic energies reveal that an incoming nucleon loses a smaller fraction of its energy in each binary nucleon-nucleon collision except its last collision with a target nucleon, where it loses about half of its energy, and the stopping law is proposed in [25,26] to handle this situation. We have also applied this stopping law to calculate the energy fraction that a leading particle takes after each binary nucleon-nucleon collision.

III. RESULTS AND CONCLUSIONS

For inspecting this model and the corresponding program (event generator) we first compare the calculated (with default PYTHIA parameters) negative charge multiplicity, rapidity, and transverse momentum distributions of the negative charge particles and the participant protons in pp, pA, and AB collisions at 200A GeV/c with the corresponding data [19,20]. The comparisons of negative charge multiplicity for pp and pA reactions at 200 GeV/c are shown in Table I and for AB reactions at 200A GeV/c in Table II. Figure 1 gives the comparisons for the rapidity distributions of h^- in central S+S and N+N minimum bias collisions (upper frame) and of the participant protons in S+S central and peripheral collisions (lower frame) at 200A GeV/c. The transverse momentum distributions in central S+S collisions at 200A GeV/c are given in Fig. 2, of which the upper and the lower frames are for h^- and participant protons, respectively. One sees from these tables and figures that the agreement between theory and experiment is reasonably good.

We now turn to the calculations with J/ψ production channel. As is mentioned in [27], the object which is attenu-

TABLE II. Negative charge multiplicity in central AB collisions at 200A GeV/c.

	S+S	S+Ag
NA35 data	98±3	170±8
JPCIAE	107	173

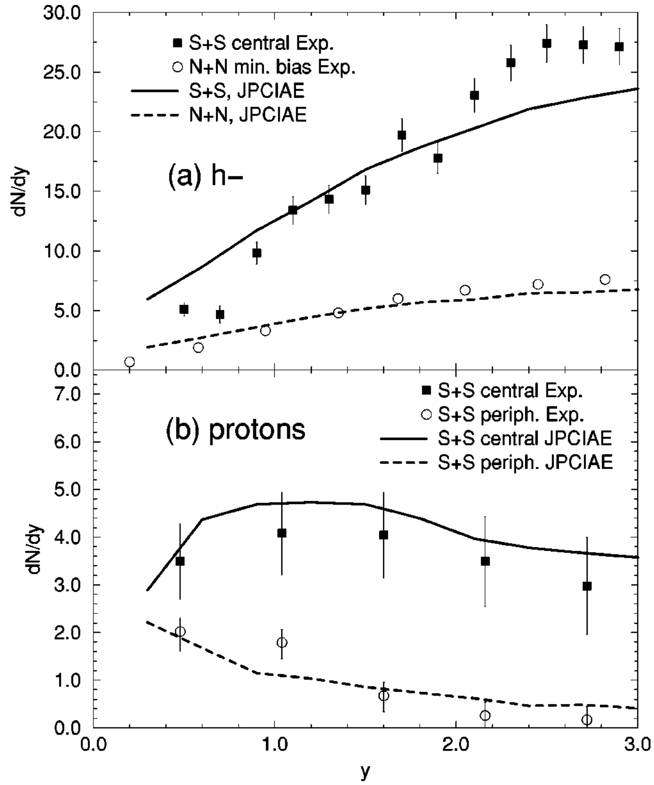

FIG. 1. The rapidity distributions (a) for h^- in central S+S and N+ N minimum bias collisions at 200*A* GeV/*c*, the N+N data, and corresponding results of JPCIAE have been multiplied by 10 for the convenience of comparison, and (b) for participant protons in S+S central and peripheral collisions at 200*A* GeV/*c*. In the figure the labels are the experimental data and the curves are the corresponding results of JPCIAE.

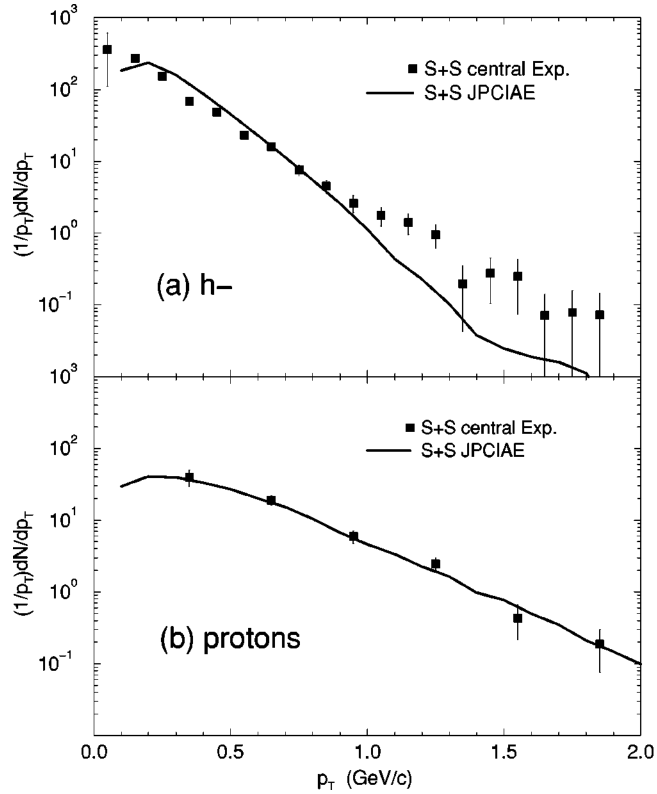

FIG. 2. The transverse momentum distributions in central S+S collisions at 200*A* GeV/*c*, (a) for h^- and (b) for participant protons. In the figure the labels are the experimental data and the curves are the corresponding results of JPCIAE.

ated on its way out of the hadronic medium is not a J/ψ but a meson (''in the making''), which is called a ''premeson'' or a ''preresonant state.'' However, the exact nature of the premeson is now still debated. Thus as the first step towards this scenario we do not distinguish here a J/ψ from its premeson state but give it proper effective cross sections interacting with baryons and mesons, as done in [5–12].

Since the purpose of this paper is to explore the physics behind the NA38 and NA50 data, not to fit the data as good as possible, we first fix two reasonable sets of parameters to calculate the J/ψ suppression factors in minimum bias pA and AB collisions at 200*A* GeV/*c* as a function of the product of the atomic mass numbers of projectile and target nuclei ($A*B$) and compare them with the corresponding data in Fig. 3. The experimental J/ψ suppression factor is defined as

$$S_{\rm expt}^{J/\psi}=\left(\frac{B_{\mu\mu}\sigma_{AB}^{J/\psi}}{AB}\right)/(B_{\mu\mu}\sigma_{pp}^{J/\psi}). \tag{3}$$

As for the theoretical definition of the J/ψ suppression factor it is expressed as [17,28]

$$S_{\rm theo}^{J/\psi}=\frac{M_{J/\psi}}{M_{J/\psi}(0)}, \tag{4}$$

where $M_{J/\psi}(0)$ refers to the multiplicity of the primary J/ψ and $M_{J/\psi}$ to the multiplicity of the J/ψ after final interactions. The open circles with error bars in Fig. 3 are the experimental data (cited directly from [28]). In Fig. 3 the solid circles are the results of the usual scenario simulations with parameter set 1: the meson formation time $\tau_M=1.2$ fm/c and the J/ψ formation time $\tau_{J/\psi}=0.6$ fm/c (denoted as ''JPCIAE 1'' in Fig. 3), the solid triangles are the results of Glauber-like simulations with parameter set 2: $\tau_M=0.8$ fm/c, and $\tau_{J/\psi}=0.4$ fm/c (denoted as ''JPCIAE 3'' in Fig. 3); and the open triangles are the results of Glauber-like simulations with parameter set 1 (denoted as ''JPCIAE 2'' in Fig. 3). The effective cross section of the J/ψ-hadron interaction is assumed to be $\sigma_{J/\psi-B}^{\rm Abs}=6$ mb and $\sigma_{J/\psi-M}^{\rm Abs}=3$ mb (the subscripts B and M refer to baryon and meson, respectively) as usual [6–12,28]. The corresponding total cross sections used in the program are $\sigma_{J/\psi-B}^{\rm tot}=7.2$ mb and $\sigma_{J/\psi-M}^{\rm tot}=4.0$ mb. The following reactions of J/ψ with baryons and mesons are considered:

$$J/\psi+B\rightarrow\Lambda_c+\overline{D}, \tag{5}$$

$$J/\psi+M\rightarrow D+\overline{D}. \tag{6}$$

Although the experimental data in Fig. 3 have been all rescaled to 200*A* GeV/*c* beam momentum, the kinematical domains of the dimuon measurement in different experiments are not completely the same. Since we calculate here the yield of J/ψ directly, not counting via its dimuon decay, we do the same as in [5–12,28] to obtain all the theoretical results in Fig. 3 in full phase space.

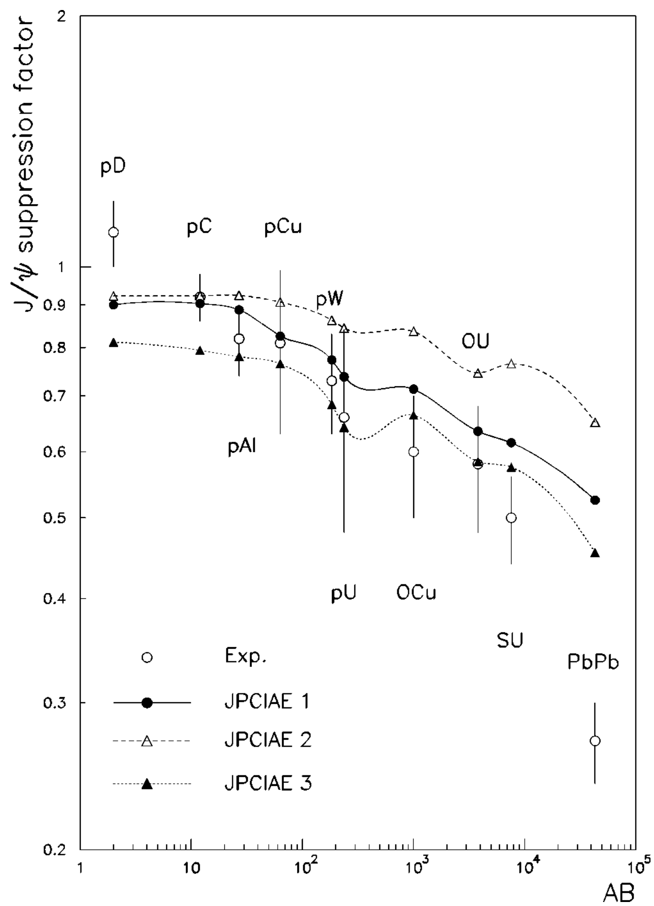

FIG. 3. The J/ψ suppression factor versus the product of the atomic mass numbers of projectile and target nuclei in minimum bias pA and AB collisions at 200A GeV/c. See text for details.

One sees from Fig. 3 that both the results of the usual scenario simulations with parameter set 1 and the results of Glauber-like simulations with parameter set 2, i.e., the solid circles and the solid triangles, are comparable with the corresponding experimental data, except the NA50 data of Pb+Pb reactions. However, in order to describe the data the Glauber-like simulation needs to have a smaller J/ψ formation time than the usual scenario. Comparing the results of the usual scenario simulations with parameter set 1 to the results of the Glauber-like simulations with the same parameter set, i.e., comparing the solid circles to the open triangles in Fig. 3, one knows that the difference between the usual scenario simulation and Glauber-like simulation is noticeable. This conclusion is in consistent with [16,17]. Of course, the difference between the usual scenario simulation and Glauber-like simulation is also formation time dependent.

Table III gives the J/ψ suppression factor resulting from the usual scenario simulations with various $\tau_{J/\psi}$ and fixed $\tau_M = 1.2$ fm/c for minimum bias $p+$Al, $p+$Cu, $p+$Ag, $p+$U, O+Cu, and O+U collisions at 200A GeV/c. This table indicates that the J/ψ suppression factor is very sensitive to the formation time of a J/ψ. At the same formation time of a J/ψ, the J/ψ suppression factor, both in pA and AB collisions, decreases with an increase of the target mass.

As for the role of produced mesons (comover) in J/ψ suppression, there is no experimental evidence, indeed. Because of different theoretical analyses, different conclusions are drawn. Some physicists believe that the produced mesons (comover) have no effect on J/ψ suppression at all from pA up to S+U reactions [14,17]. Others think that the produced mesons play no role in pA collisions but play some role in AB collisions [6–9,13]. Since it is a common belief that ρ and ω mesons are more important than pions [7,13,16,17], with respect to the J/ψ suppression we have calculated (the usual scenario simulation with parameter set 2) three cases concerning different ways of dealing with ρ and ω decay for reactions of $p+$Cu and O+Cu at 200A GeV/c energy. In case 1, a ρ (or ω) is assumed to decay after it has no more interaction with other hadrons. A ρ (or ω) is allowed to decay due to its proper probability (determined by its lifetime) at any moment during the transport process in case 2. In case 3, a ρ (or ω) produced from PYTHIA decays immediately. The corresponding results of percentages for the produced mesons (pion$+\rho+\omega$), pions, and $\rho+\omega$ to contribute to the J/ψ suppression factor are given in Tables IV and V for $p+$Cu and O+Cu reactions, respectively. One sees from these tables that ρ and ω mesons play a much more important role than pions, indeed. In the extreme case 3, the produced mesons (comover) really have no effect on J/ψ suppression. However, in a more reasonable case, i.e., case 2, the produced mesons (comover) do play some role, although they are more important in O+Cu than in $p+$Cu reactions. Although the theoretical concept of formation time is still an open question, it must be introduced into the dynamical simulation. Thus the effect of produced particles on J/ψ suppression strongly depends on the assumption about the formation time both for a J/ψ and the produced particles.

TABLE III. J/ψ suppression factor in the reactions of $p+$Al, $p+$Cu, $p+$Ag, $p+$U, O+Cu, and O+U at 200A GeV/c, $\tau_M = 1.2$ fm/c.

$\tau_{J/\psi}$	$p+$Al	$p+$Cu	$p+$Ag	$p+$U	O+Cu	O+U
0.30	0.538	0.496	0.472	0.453	0.389	0.343
0.60	0.888	0.836	0.799	0.738	0.713	0.635
0.90	0.943	0.932	0.921	0.859	0.832	0.773

TABLE IV. Meson effect on J/ψ suppression (in percentage) in the reactions of $p+$Cu at 200A GeV/c, $\tau_M = 0.8$ fm/c, and $\tau_{J/\psi} = 0.4$ fm/c.

Case	Meson	Pion	$\rho+\omega$
1	0.110	0.0029	0.107
2	0.074	0.011	0.063
3	0.009	0.003	0.006

TABLE V. Meson effect on J/ψ suppression (in percentage) in the reactions of O+Cu at 200A GeV/c, $\tau_M = 0.8$ fm/c, and $\tau_{J/\psi} = 0.4$ fm/c.

Case	Meson	Pion	$\rho+\omega$
1	0.155	0.0111	0.144
2	0.135	0.0263	0.109
3	0.0128	0.00856	0.00429

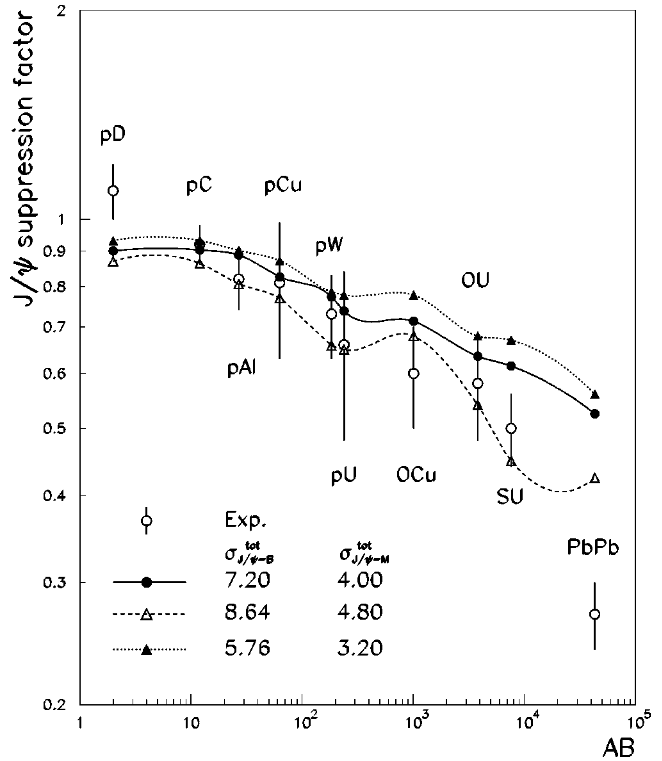

FIG. 4. The J/ψ suppression factor versus the product of the atomic mass numbers of projectile and target nuclei in minimum bias pA and AB collisions at 200A GeV/c. See text for the detail.

As the effective cross sections of $\sigma^{\rm abs}_{J/\psi-B}$ and $\sigma^{\rm abs}_{J/\psi-M}$ might have large errors we repeat the usual scenario simulations with parameter set 1 and with effective cross sections increased or decreased by 20%, respectively. Those results are plotted in Fig. 4 as a dashed line ($\sigma^{\rm tot}_{J/\psi-B}=8.64$ mb and $\sigma^{\rm tot}_{J/\psi-M}=4.80$ mb) and dotted line ($\sigma^{\rm tot}_{J/\psi-B}=5.76$ mb and $\sigma^{\rm tot}_{J/\psi-M}=3.20$ mb) together with the solid line of the results of ''JPCIAE 1'' in Fig. 3. One sees from this figure that by considering the possible uncertainty in the effective cross sections (increasing 20%) the Pb+Pb datum point is no longer too far away from the model prediction.

In summary we have proposed a hadron and string cascade model, JPCIAE, for simulating ultrarelativistic nucleus-nucleus collisions based on the LUND model and PYTHIA event generator especially. It has been used to investigate the J/ψ suppression in minimum bias pA and AB collisions at 200A GeV/c. With different sets of reasonable formation time of a J/ψ and a meson the results of J/ψ suppression factor from both the usual scenario simulations and the Glauber-like simulations are comparable with all the NA38 pA and AB data, except the NA50 data of Pb+Pb collisions. However, the difference between the usual scenario simulation and the Glauber-like simulation, with the same parameter sets of formation time, is noticeable. The sensitive effect of the formation time is studied in detail. Although by considering the possible uncertainty in the effective cross sections our model calculation can become close to the Pb+Pb datum point, new mechanisms are still needed in order to explain the anomalous J/ψ suppression in Pb+Pb collisions. Work is in progress where the dissociation mechanism of a J/ψ's premeson in the color electric field of strings [29] is added to JPCIAE in a parametrized way and the E_T distribution of J/ψ is being investigated. Since the intensity of the color electric field of strings depends on the string density which in turn depends on the beam energy, the centrality, and the size of reaction system [30], the anomalous J/ψ suppression in Pb+Pb collisions might be explained by such a dissociation mechanism of a J/ψ's premeson in the strong color electric field established during the collisions.

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