A mechanism for the effective dissociation of a $c\bar{c}$ pair in the colour electric field of strings is introduced into a hadron and string cascade model, i.e. JPCIAE, which is based on the LUND model, simulating ultra-relativistic nucleus-nucleus collisions. This new mechanism together with the known mechanism of nuclear absorption (both baryons and mesons) could reproduce fairly the data of the normal and anomalous $J/\psi$ suppressions in minimum bias pA, AB (with light projectile), and Pb + Pb collisions at 200 A GeV/c. However the impact parameter ($E_T$) dependence of the $J/\psi$ suppression factor, both, in S + U and Pb + Pb reactions at 200 A GeV/c and 158 A GeV/c, respectively, is not well reproduced. We also tested the additional mechanism of the energy degradation of leading particles, with which both, the normal and anomalous $J/\psi$ suppressions in minimum bias pA, AB, and Pb + Pb collisions and the $E_T$ dependence of the $J/\psi$ suppression factor are better reproduced.

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I. INTRODUCTION

It was suggested by Matsui and Satz [1] that the suppression of the $J/\psi$ yield in relativistic nucleus-nucleus collisions might be a powerful signature for the Quark Gluon Plasma (QGP) formation. Since that time, a number of corresponding experiments have been stimulated [2-4] to measure the $J/\psi$ yield via its dimuon decay. A significant suppression of the $J/\psi$ yield from pA collisions to AB collisions has already been observed in these experiments. However, except the anomalous suppression observed in Pb + Pb reactions at 158 A GeV/c [4] the normal suppression in pA and AB collisions with light projectiles has been well explained within the hadronic regime [5-6] either by Glauber theory (absorption model) [7-16] or by transport (cascade) model simulations [17-20]. The mechanism of
the anomalous $J/\psi$ suppression in Pb + Pb collisions is, however, still a question of current debate [10 - 16, 18, 21 - 25].

Refs. [22] and [24] claim that the anomalous suppression can be explained within the Glauber approach by introducing the comover absorption. However, in Ref [23] one author of [22] has made a reexamination of the comover effect and indicated that the comover mechanism “cannot explain the observed $J/\psi$ suppression in Pb + Pb interactions”. On the other hand, in Refs. [11 - 14, 16, 25] different extra suppression mechanisms due to the formation of the QGP have been introduced to explain the anomalous $J/\psi$ suppression in Pb + Pb collisions.

Recently in [26] the mechanism of the dissociation of $c\bar{c}$ pairs in the colour electric field of a string as proposed in [27 - 28] has been included in a transport approach by a purely geometrical way. In [26] it is claimed that both, the data showing normal and anomalous $J/\psi$ suppression, can be reproduced without assuming the formation of QGP in these collisions.

In this paper a mechanism for the effective dissociation of $c\bar{c}$ pairs in the colour electric field of strings is introduced into the hadron and string cascade model, i.e. JPCIAE [19], which is based on the LUND model and the PYTHIA event generator [29]. This new mechanism together with the already existing mechanisms, i.e. the nuclear absorption (both by baryons and mesons) could explain fairly both, the normal and anomalous $J/\psi$ suppression in minimum bias pA, AB, and Pb + Pb collisions at 200 A GeV energy. However the impact parameter ($E_T$) dependence of the $J/\psi$ suppression factor both in S + U and Pb + Pb reactions at 200 A GeV/c and 158 A GeV/c, respectively, is not well reproduced. We investigated also the additional mechanism of the energy degradation of leading particles. Including this effect we obtain a better description of both, the normal and anomalous $J/\psi$ suppressions in minimum bias pA, AB, and Pb + Pb collisions. In particular, the $E_T$ dependence of the $J/\psi$ suppression factor is better reproduced by reducing the effective cross sections and the model parameter concerning to the colour dissociation mechanism.

II. BRIEF DESCRIPTION OF THE MODEL

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

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 $\sqrt{\sigma_{tot}/\pi}$, where $\sigma_{tot}$ is the total cross section of the colliding pair [30 - 32, 19]. The minimum distance is calculated in the CMS 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 CMS 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). Otherwise no string state is formed and the conventional scattering process (elastic and inelastic scatterings or resonance production) [30 - 32, 19] is executed. 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 collision occurs in the system.

In our model the $J/\psi$ is produced via QCD hard process

$$g + g \rightarrow J/\psi + g.$$  \hspace{1cm} (1)

In PYTHIA a large number of QCD parton - parton processes have been considered, including the $J/\psi$ production, Eq. (1). A user is allowed to run the program with any desired subset of these processes. Thus, when $\sqrt{s}$ is larger or equal $\sim 10$ GeV the PYTHIA generator with the selection of $J/\psi$ production is called. The produced particles as well as the $J/\psi$ are then transported in the Monte Carlo simulation in the same way as the nucleons. Any operation of desired processes, including the $J/\psi$ 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, the execution of PYTHIA with the $J/\psi$ production channel is additionally weighted with a production probability. This probability is equal to the parameterized $J/\psi$ hadronic production cross section [33]

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

(with $c=3.097$ GeV, $d=2.37/B_{\mu\mu}$ nb, and $B_{\mu\mu} = 0.0597$ is the branching ratio of a $J/\psi$ to dimuon) multiplied by a factor. That factor is adjusted such that the number of $J/\psi$ produced in each event is around one, the same as in the experiments.

One point which should also be mentioned here is the fact 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 proton - nucleus and nucleus - nucleus collisions at relativistic energies reveal that, on the average, the produced nucleon carries only a smaller fraction of initial energy in each binary nucleon - nucleon collision [34]. A stopping law has been proposed in [34 - 36] to handle this situation. We have also applied this stopping law to calculate the energy fraction which the leading particle keeps after each binary nucleon - nucleon collision.
III. EFFECTIVE DISSOCIATION OF A $c\bar{c}$ STATE IN THE COLOUR ELECTRIC FIELD OF STRING

In [19] we have demonstrated that the hadron and string cascade model (usual scenario simulation in [19]) could reproduce all the NA38 pA and AB (with light projectile) data but could not reproduce the NA50 data of Pb + Pb collisions even the effective cross sections ($\sigma_{J/\psi-B}^{abs} = 6$ mb and $\sigma_{J/\psi-M}^{abs} = 3$ mb, where the subscripts B and M refer to baryon and meson, respectively) have been enlarged by twenty percent. Thus in order to understand the NA50 data of Pb + Pb collisions one has to invoke some new mechanism which is more or less absent in pA and AB (with light projectile) collisions but plays a role in large systems as Pb + Pb.

As discussed in [37] the object which is followed on its way out of hadronic medium is not a $J/\psi$ but a meson “in the making”, which is called a “premeson” or a “pre-resonant state”. The exact nature of the premeson is still debated [37 - 38]. However, in the early stage of the nucleus - nucleus collision this premeson or $c\bar{c}$ state should be surrounded by strings [26] and once the $c\bar{c}$ state gets into the colour electric field of a string it might be dissociated [26 - 27]. As a first step towards this scenario, we treat this dissociation mechanism before the formation of a physical $J/\psi$ in an effective way.

One knows that this dissociation effect increases with an increasing energy density stored in the strings, which, in turn, would be increase with the reaction energy, the centrality, and the size of reaction system [39]. Since the production and dissociation of $c\bar{c}$ state are mainly hard processes, the size dependence should follow an “AB scaling” [4, 23, 26] (A (B) stands for the atomic mass number of projectile (target) nucleus, respectively). The centrality (impact parameter) dependence of this effective dissociation is modelled by a Gaussian distribution, in common use [24 - 25, 40].

Thus, the effective dissociation probability of a $J/\psi$ premeson, $c\bar{c}$ state, is assumed to be

$$P_d = \frac{\rho_s - \rho_s^{min}}{\rho_s^{max} - \rho_s^{min}}$$

$$\rho_s = a_s \sqrt{s_{NN} f(b)} AB,$$

$$f(b) = \exp(-\frac{b^2}{R^2_L}).$$

In these equations $\rho_s$ refers to the energy density stored in the strings, $\rho_s^{min}$ and $\rho_s^{max}$ are the corresponding lower and upper limits : $P_d = 0$ when $\rho_s = \rho_s^{min}$ and $P_d = 1$ when $\rho_s = \rho_s^{max}$. $\sqrt{s_{NN}}$ is the CMS energy of initial nucleon - nucleon system. $R_L$ refers to the larger value between the $R_A$ and $R_B$ (radii of projectile and target nuclei, respectively). Since it is reasonable to assume $\rho_s^{min} = 0$, the value of $\rho_s^{max}$ can be absorbed into the model parameter and $P_d$ is reduced to

$$P_d = c_s \sqrt{s_{NN} f(b)} AB.$$

The $c\bar{c}$ state created by calling PYTHIA has now the probability $(1 - P_d)$ to survive, it is regarded as a physical $J/\psi$ after formation time and joined into the transport processes together with hadrons. Doing this, the physical $J/\psi$ may interact with baryons and mesons which is described by the effective cross sections [7 - 14, 41]: $\sigma_{J/\psi-B}^{abs} = 6$ mb and $\sigma_{J/\psi-M}^{abs} =$...
3 mb. The formation time of meson and \( J/\psi \) are assumed, as the same as in [19], to be \( \tau_M = 1.2 \text{ fm/c} \) and \( \tau_{J/\psi} = 0.6 \text{ fm/c} \), respectively. The following reactions of a \( J/\psi \) with baryons and mesons [17 - 19, 38] are considered

\[
\begin{align*}
J/\psi + N &\rightarrow \Lambda_c + \bar{D}, \\
J/\psi + \pi &\rightarrow D + D^*, \\
J/\psi + \rho &\rightarrow D + \bar{D}.
\end{align*}
\]

The experimental \( J/\psi \) suppression factor is defined as [4, 41]

\[
S^{J/\psi}_{\text{exp.}} = \left( \frac{B_{\mu\mu}\sigma_{AB}^{J/\psi}}{AB} \right) / \left( B_{\mu\mu}\sigma_{pp}^{J/\psi} \right),
\]

and the theoretical \( J/\psi \) suppression factor is expressed as [18 - 19, 41]

\[
S^{J/\psi}_{\text{theo.}} = \frac{M_{J/\psi}}{M_{J/\psi}(0)}
\]

where \( M_{J/\psi}(0) \) refers to the multiplicity of the primary \( J/\psi \) generated by PYTHIA and \( M_{J/\psi} \) to the multiplicity of \( J/\psi \)'s which actually have survived the dissociation and the final state interactions.

Fig. 1 compares the \( J/\psi \) suppression factors in minimum bias pA, AB, and Pb + Pb collisions at 200 A GeV/c as a function of AB to the corresponding NA38 and NA50 data. In the calculations the total cross sections are assumed to be \( \sigma_{J/\psi-B}^{\text{tot}} = 8.64 \text{ mb} \) and \( \sigma_{J/\psi-M}^{\text{tot}} = 4.80 \text{ mb} \) which correspond to twenty percent enlarged values of \( \sigma_{J/\psi-B}^{\text{abs}} = 6 \text{ mb} \) and \( \sigma_{J/\psi-M}^{\text{abs}} = 3 \text{ mb} \) above. The model parameter \( c_s \) in Eq. (6) is treated as a fit parameter which is mainly adopted to the Pb+Pb datum point. It takes the value 1.*10^{-6}. The open circles with error bars in Fig. 1 indicate the preliminary experimental data (cited directly from [41]). In Fig. 1 the dashed and dash-dotted curves are the theoretical results of the calculations with abs. + dis. (absorption + dissociation) and with abs. only. One sees from Fig. 1 that the effective dissociation mechanism of a \( c\bar{c} \) pair in the colour electric field of strings does not contribute in pA and AB (with light projectile) collisions but plays a significant role in Pb + Pb collision which allows the reproduction of NA50 data.

In Figs. 2 and 3 the \( J/\psi \) suppression factor is shown as a function of the neutral transverse energy \( E_T \) (GeV)

\[
E_T = \sum_i E_i \times \sin(\theta_i)
\]

(\( \text{where } E_i \text{ and } \theta_i \text{ are the total energy and the polar angle of neutral particle } i \text{, respectively} \)) for S + U reactions at 200 A GeV/c and Pb + Pb reactions at 158 A GeV/c, respectively. The total cross section used in calculations are \( \sigma_{J/\psi-B}^{\text{tot}} = 8.64 \text{ mb} \) and \( \sigma_{J/\psi-M}^{\text{tot}} = 4.80 \text{ mb} \). The full squares with error bars in Fig. 2 and the full squares and circles with error bars in Fig. 3, respectively, refer to the preliminary NA38 and NA50 data (cited directly from [26]). The different curves in these figures correspond to the different calculations as explained in Fig. 1. Figs. 2 and 3 show that the experimentally observed \( E_T \) dependence of the \( J/\psi \) suppression factor is not well reproduced by the theoretical results, in particular in the Pb
+ Pb reaction. It should, however, be mentioned that the calculated transverse energy $E_T$ in Pb + Pb collisions is less than experimentally observed. In [42] it is mentioned: “... recently the $E_T$ scale has been recalibrated to be $\sim 10 - 20$ smaller than shown here, ... the data situation remain unclear for both, the low and the high $E_T$ limit, ...”. Taking this reduction into account the calculated transverse energy $E_T$ is still a little lower than the data. This could be attributed to the fact that the transverse flow is not described in JPCIAE. There is, however, experimental evidence for a strong transverse flow in central Pb + Pb collisions [43].

IV. TEST OF THE MECHANISM OF LEADING PARTICLE ENERGY DEGRADATION

The energy degradation of leading particles (mainly nucleons) refers to the following: If a projectile nucleon collides sequentially with two target nucleons, the energy of projectile nucleon in the second collision is reduced comparing to incident energy. Thus the corresponding probability of the $J/\psi$ production in the second collision should be reduced as well according to the parameterised $J/\psi$ hadronic production cross section, Eq. (2).

Presently, the influence of this mechanism in $J/\psi$ suppression is a strongly debating issue. One might assume that this mechanism could lead to a violation of the AB scaling of the Drell - Yan production. However, there is really a violation of a strict AB scaling in $J/\psi$ production, since after rescaling the NA38 and NA50 data from different energies to 200 A GeV all the data except Pb + Pb lie on the universal curve $\langle AB \rangle^{0.91} \times \sigma_{pp}^{J/\psi}$. Thus, one should not rule out the effect of leading particles energy degradation on the $J/\psi$ suppression before more detailed further investigations.

Indeed, in [44] it was proved that the nuclear Drell - Yan ratio is suppressed because of the energy loss of leading particle. In [45] it has been declared that “Precisely measured Drell - Yan cross sections for 800 GeV protons incident on a variety of nuclear targets exhibit a deviation from linear scaling in the atomic number A. ... this deviation can be accounted for by energy degradation of the proton as it passes through the nucleus if account is taken of the time delay of particle production due to quantum coherence.”. It is also mentioned in [42] that “Quantum effects such as energy dependent formation and coherence lengths must be taken into account before definite statements can be made with regard to the nature of the $J/\psi$ suppression.”. It is worthy, however, to test the role played by the mechanism of leading particle energy degradation in the $J/\psi$ suppression.

We repeat the calculations of Fig. 1 to 3 with the additional mechanism of leading particle energy degradation and the results are given in Fig. 4 to 6, respectively. The effective cross sections used in the calculations are reduced to $\sigma_{J/\psi-B}^{tot} = 7.2$ mb and $\sigma_{J/\psi-M}^{tot} = 4.0$ mb (which are corresponding to $\sigma_{J/\psi-B}^{abs} = 6$ mb and $\sigma_{J/\psi-M}^{abs} = 3$ mb) and the model parameter $c_s$ is also reduced to $6.10^{-7}$.

In Fig. 4 the open circles with error bars indicate the preliminary experimental data (cited directly from [41]) and the solid, dashed, dotted, and dash-dotted curves are the theoretical results of the calculations including the abs. + dis. + deg. (degradation) mechanisms, with abs. + dis., with abs. + deg., and with abs. only. One sees from Fig. 4 that all the four curves are passing quite well through the pA and the AB (with light projectile) data, however, only the solid curve can reproduce the Pb + Pb datum point.
The calculations with only absorption or the calculations with abs. + deg. are not able to describe both, the Pb + Pb as well as the other data points. However, the calculations with abs. + dis. might be able to do so by an increase of the model parameter \( c_s \) and the effective cross sections as shown by the dashed curve in Fig. 1.

In Figs. 5 and 6 the \( J/\psi \) suppression factor is shown as a function of the neutral transverse energy \( E_T \) (GeV) for S + U reactions at 200 A GeV/c and Pb + Pb reactions at 158 A GeV/c, respectively. The full squares with error bars in Fig. 5 and the full squares and circles with error bars in Fig. 6, respectively, refer to the preliminary NA38 and NA50 data (cited directly from [26]). The different curves in these figures correspond to the different calculations as explained in Fig. 4. Comparing Fig. 5 with Fig. 2 and Fig. 6 with Fig. 3 we find that the additional mechanism of leading particle energy degradation improves the description of the \( E_T \) distribution of the \( J/\psi \) suppression factor.

V. SUMMATION AND ACKNOWLEDGEMENTS

In summary, we have introduced a mechanism for the effective dissociation of \( c\bar{c} \) pairs in the colour electric field of strings into a hadron and string cascade model, i.e. JPCIAE [19]. This model is based on the LUND model and the PYTHIA event generator, simulating ultra-relativistic nucleus-nucleus collisions. The normal and the anomalous \( J/\psi \) suppression in minimum bias pA, AB, and Pb + Pb collisions at 200 A GeV/c are qualitatively reproduced by this model relying on the mechanisms of the dissociation of \( c\bar{c} \) states in the colour electric field of strings and of the nuclear absorption (both baryon and meson). However, the experimental data for the impact parameter (\( E_T \)) dependence of the \( J/\psi \) suppression factor, both in S + U and Pb + Pb reactions at 200 A GeV/c and 158 A GeV/c, respectively, are not well reproduced. We also tested the additional mechanism of leading particles energy degradation. Reducing the values of the effective cross sections and the model parameter \( c_s \) we are able to reproduce the data of \( J/\psi \) suppression factor vs. AB with the same quality as without this additional mechanism. However, the description of the \( E_T \) distribution of the \( J/\psi \) suppression factor is improved.

Although it is not clear whether the environment of a \( c\bar{c} \) state in the colour electric field of strings should be regarded as dense hadronic matter or as a QGP, the statement that any significant reduction of \( J/\psi \) formation in nuclear collisions would signal the creation of quark-gluon plasma has to be revised [38, 46]. However, the origin of the dissociation of \( c\bar{c} \) states in the colour electric field of strings should be studied further.

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FIGURE CAPTIONS

Fig. 1: The $J/\psi$ suppression factor versus the product of the atomic mass numbers of projectile and target nuclei, $AB$, in minimum bias pA and AB collisions at 200 A GeV/c. The open circles with error bars are the preliminary experimental data [4] taken directly from [41]. The dashed and dash-dotted lines refer to the theoretical calculations including absorption + dissociation (abs. + dis.) mechanisms and abs. only.

Fig. 2: The $J/\psi$ suppression factor as a function of the neutral transverse energy in S + U reactions at 200 A GeV/c. The full squares with error bars are the preliminary NA38 data taken from [26]. The various curves refer to the different types of theoretical calculations as explained in Fig. 1.

Fig. 3: The $J/\psi$ suppression factor as a function of the neutral transverse energy in Pb + Pb reactions at 158 A GeV/c. The full squares and circles with error bars show the preliminary NA50 data taken from [26]. The various curves refer to the different types of theoretical calculations as explained in Fig. 1.

Fig. 4: The $J/\psi$ suppression factor versus the product of the atomic mass numbers of projectile and target nuclei, $AB$, in minimum bias pA and AB collisions at 200 A GeV/c. The open circles with error bars are the preliminary experimental data [4] taken directly from [41]. The solid, dashed, dotted, and dash-dotted lines refer to the theoretical calculations including absorption + degradation + dissociation (abs. + deg. + dis.) mechanisms, abs. + dis., abs. + deg., and abs. only.

Fig. 5: The $J/\psi$ suppression factor as a function of the neutral transverse energy in S + U reactions at 200 A GeV/c. The full squares with error bars are the preliminary NA38 data taken from [26]. The various curves refer to the different types of theoretical calculations as explained in Fig. 4.

Fig. 6: The $J/\psi$ suppression factor as a function of the neutral transverse energy in Pb + Pb reactions at 158 A GeV/c. The full squares and circles with error bars show the preliminary NA50 data taken from [26]. The various curves refer to the different types of theoretical calculations as explained in Fig. 4.
FIG. 1.
Fig. 2.

$S_{\psi^{'}}$

$S+U$, 200 GeV/A

$E_T$ [GeV]

Fig. 2
$S^{J/\psi}_{abs}$ vs. $E_T$ [GeV]

Pb+Pb, 158 GeV/A

Fig. 3
Fig. 4

\[ S^{J/\psi} \]

| AB | 10^0 | 10^1 | 10^2 | 10^3 | 10^4 | 10^5 |
|----|------|------|------|------|------|------|
| pD |      |      |      |      |      |      |
| pC |      |      |      |      |      |      |
| pAl |     |      |      |      |      |      |
| pCu |    |      |      |      |      |      |
| pW |     |      |      |      |      |      |
| pU  |    |      |      |      |      |      |
| OU  |    |      |      |      |      |      |
| OCu |   |      |      |      |      |      |
| SU  |   |      |      |      |      |      |
| PbPb |  |      |      |      |      |      |

FIG. 4.
Fig. 5

S+U, 200 GeV/A
Fig. 6.

$S_{J/\psi}^{\text{abs}}$

Pb+Pb, 158 GeV/A