Does the orientation of a deformed nucleus play a role in J/ψ suppression?

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Using a hadron-string cascade model, JPCIAE, we study the effect of the orientation of deformed nucleus on J/ψ suppression in the central collision of uranium bombarding with uranium at $200A$ GeV/c. We find that the J/ψ survival probability is much smaller if the major axes of both deformed nuclei are along the beam direction than if they are perpendicular to the beam direction.

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Because of color screening, J/ψ is expected to dissociate in the quark-gluon plasma (QGP) formed in relativistic heavy ion collisions [1]. The resulting suppression of J/ψ production in these collisions has been one of the most studied signals for the formation of the quark-gluon plasma. Experiments at CERN have indeed shown that J/ψ production is reduced in both proton-nucleus [2] and heavy ion collisions [3,4] compared to that expected from the superposition of proton-proton collisions at same energies. For collisions involving light projectiles such as p-A [2], O-U, and S-U collisions [3], conventional mechanisms of J/ψ absorption by nucleons [5,6] and comovers [7–16] seem to be sufficient in accounting for the measured suppression. On the other hand, in collisions with heavy projectiles such as the Pb-Pb collision [4], whether the measured anomalously large J/ψ suppression in central collisions can be explained by hadronic absorption alone is still under debate [17–19], and explanations based on QGP effects have also been proposed [12,13,16,20,21].

To study microscopically J/ψ production and absorption in heavy ion collisions, transport models have been used [22–29]. Although there are differences among them, it has been commonly found that the explanation of anomalous J/ψ suppression in Pb-Pb collisions needs to introduce new mechanism besides hadronic absorptions. It has been found in Refs. [25,26] that the inclusion of dissociation of the pre-J/ψ $c\bar{c}$ state by the color electric field in the initial dense matter can also explain the anomalous J/ψ suppression in Pb-Pb collisions. Whether a QGP is formed in heavy ion collisions at CERN SPS is still needed to have further studies. One suggestion is to study J/ψ production in collisions of deformed nuclei [30] as the large spatial anisotropy created even in the central collisions of these nuclei offers the possibility to study the mechanisms for J/ψ suppression from their final azimuthal distribution [31]. Also, it has been shown in Ref. [32] that the orientation of deformed nuclei does play a role in the collisions at AGS energies, the maximum nuclear density reached in the initial stage is higher (about 38%) and also lasts longer if the major axes of both nuclei are along the beam direction (tip-tip) than if they are perpendicular to the beam direction (body-body). In high energy density matter, J/ψ is dissociated due to either color screening if the matter is a quark-gluon plasma or the color electric field if it is a string matter. In both cases, we expect that J/ψ suppression will be more appreciable in the tip-tip collision than in the body-body collision. In this article, we shall report the results of our study of this effect in U-U collisions at SPS energies using a hadron-string cascade model, JPCIAE [24,26], which has been shown to give a satisfactory description of the J/ψ suppression data from collisions of spherical nuclei at SPS energies. As we shall show below, because of increasing energy density and collision time, a more pronounced J/ψ suppression due to the color electric dissociation is indeed seen in the tip-tip collision than in the body-body collision.

The JPCIAE model is an extension of the LUND string model [33] to include J/ψ production and absorption. In this model, a nucleus-nucleus collision is depicted as a superposition of hadron-hadron collisions. If the center-of-mass energy of a hadron-hadron collision is larger than certain value, e.g., $\geqslant 4$ GeV, the PYTHIA routines are called to describe this interaction. Otherwise, it is treated as a conventional two-body interaction as in the usual cascade model [34–36]. Furthermore, for hadron-hadron collisions with center-of-mass energy above 10 GeV, a J/ψ is produced using the PYTHIA routines through the reaction

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

where g denotes gluons in a hadron. Final-state interactions among produced particles and the participant and spectator nucleons are taken into account by the usual cascade model.

Mechanisms for J/ψ suppression in the JPCIAE model include the hadronic absorption by both baryons and mesons, the energy degradation of leading nucleons, and the dissociation of the J/ψ precursor state of $c\bar{c}$ pair in the color electric field of strings [26]. The total J/ψ suppression factor in JPCIAE is thus given by

$$S_{\rm tot}^{J/\psi}=S_{\rm abs}^{J/\psi}\times S_{\rm deg}^{J/\psi}\times S_{\rm dis}^{J/\psi}, \tag{2}$$

where $S_{\rm abs}$, $S_{\rm deg}$, and $S_{\rm dis}$ denote, respectively, the suppression factor due to the above three mechanisms. We note that

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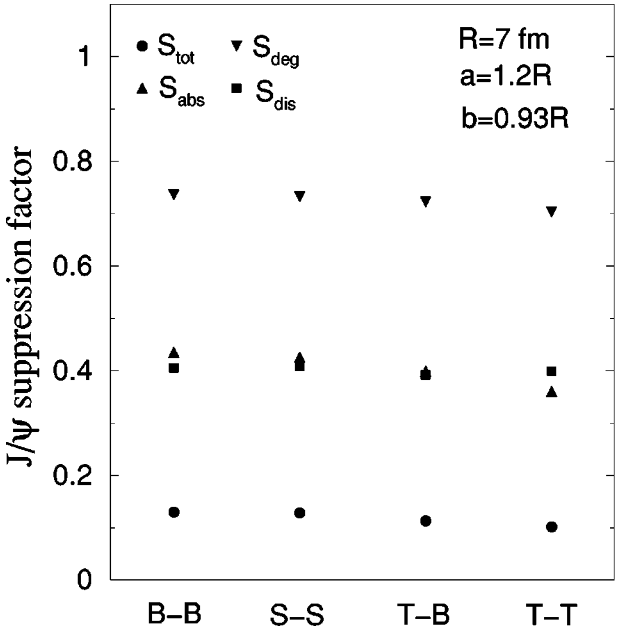

FIG. 1. J/ψ suppression factor in central U-U collisions at $200A$ GeV/c and different orientations: triangles for the nuclear absorption $S_{\rm abs}$, inverted triangles for the energy degradation $S_{\rm deg}$, squares for dissociation by the color electric field $S_{\rm dis}$, and solid circles for the total suppression factor $S_{\rm tot}$.

the first two mechanisms have also been employed recently in Ref. [28] to study J/ψ production in proton-nucleus collisions at the Fermilab energies. Details of the JPCIAE model can be found in Refs. [24,26].

For the U-U collision, the initial distribution of the projectile and target nucleons is assumed to be uniform inside an ellipsoid [32] with a major semiaxis $a=R(1+2\delta/3)=8.4$ fm and a minor semiaxis $b=R(1-\delta/3)=6.5$ fm if we use a deformation parameter $\delta=0.29$ and an equivalent spherical radius $R=7.0$ fm [37]. Other parameters in the model are kept the same as before [24,26], i.e., $\tau=1.2$ fm/c for the proper formation time of produced particles, $\sigma^{\rm abs}_{J/\psi-B}=6$ mb and $\sigma^{\rm abs}_{J/\psi-M}=3$ mb for the J/ψ absorption cross sections by baryons and mesons, respectively, and $c_s=6.0\times10^{-7}$ GeV^{-1} for the effective color electric dissociation coefficient which was determined from fitting the J/ψ suppression data from the Pb-Pb collision at $158A$ GeV/c [26].

In Fig. 1, we show by solid circles the calculated total J/ψ suppression factor in central U-U collisions at $200A$ GeV/c for different orientations of the colliding nuclei. The results labeled by body-body (B-B), tip-body (T-B), and tip-tip (T-T) correspond, respectively, to collisions in which both minor, one major and one minor, and both major axes of the projectile and target nuclei are parallel to the beam direction. For comparison, we also show the results from treating artificially both nuclei as spherical (S-S). We see that the J/ψ survival probability decreases as the orientation changes from B-B to S-S, to T-B, and to T-T. This result can be understood qualitatively from the dependence of the passing time between the two colliding nuclei and the number of participant nucleons on their orientation [30,38]. For central collisions, while the number of participant nucleons is essentially the same for the four collision geometries, the nuclear passing times are, however, different. For the B-B, S-S, T-B, and T-T collisions, the nuclear passing times are approximately given by $t^{B\text{-}B}=2b/(\beta\gamma)$, $t^{S\text{-}S}=2R/(\beta\gamma)$, $t^{T\text{-}B}=(a+b)/(\beta\gamma)$, and $t^{T\text{-}T}=2a/(\beta\gamma)$, respectively. In the above, β and γ are, respectively, the velocity and Lorentz factor in the nucleon-nucleon center-of-mass frame. Relative to the passing time for the collision of spherical nuclei, the following ratio is obtained: $t^{B\text{-}B}:t^{S\text{-}S}:t^{T\text{-}B}:t^{T\text{-}T}=0.93:1.0:1.07:1.2$. The 28% decrease in the J/ψ suppression factor for the T-T collision compared to that for the B-B collision, as shown in Fig. 1, is close to the 30% difference between the passing time in these collisions. The effect of orientation on each of the J/ψ suppression mechanisms is also shown in Fig. 1 by triangles for $S_{\rm abs}$, inverted triangles for $S_{\rm deg}$, and squares for $S_{\rm dis}$. It is seen that the hadronic absorption is increased by about 21% in the T-T collision than in the B-B collision. Effects due to the energy degradation of leading nucleons only leads to a 5% more suppression in the T-T than in the B-B collision. This small orientation effect results from the fact that J/ψ's are mainly produced in first nucleon-nucleon collisions. No orientation effect is seen from the dissociation by the effective color electric field of strings. That is because in Ref. [26] the dissociation probability of J/ψ precursor state of $c\bar{c}$ pair in initial dense string matter was assumed simply to be depending on the incident energy, centrality, and size of collision system as

$$P_d=c_s\sqrt{s_{NN}}e^{-(b/R_L)^2}AB \tag{3}$$

($S^{J/\psi}_{\rm dis}=1-P_d$), where $\sqrt{s_{NN}}$ is the initial center-of-mass energy of two colliding nucleons, b is the impact parameter of the nucleus-nucleus collision, and R_L is the radius of the larger of the projectile and target nuclei with atomic number A and B, respectively [26]. The above dissociation probability is proposed based on the continuous excitation picture of strings in LUND model. The color electric field is built up along a string through binary nucleon-nucleon (or nucleon-string is string-string) collisions. The more such collisions a string experiences, the stronger color electric field will be formed along the string, thus the more likely a J/ψ would be dissociated by such a color electric field. Therefore it is expected that the higher the initial energy density the more the J/ψ suppression. However, the above parametrization, Eq. (3), does not respond well to this point. A simple recipe, for the moment, is considering via the dissociation coefficient in Eq. (3). In the above calculations we have used the same dissociation coefficient as in Eq. (3), irrespective of the fact that energy density reached in initial string matter might be different with respect to different orientations of the colliding nuclei. In order to take into account the dependence of the dissociation coefficient c_s on the collision geometry, we first show in Fig. 2 the energy density determined from the JPCIAE model for a spherical volume with a radius of 2 fm and located at the center of the target nucleus as a function of time, which starts when the first nucleon-nucleon collision occurs. The energy density reached in the T-T collision is about 35% higher than in the B-B collision. We thus multi-

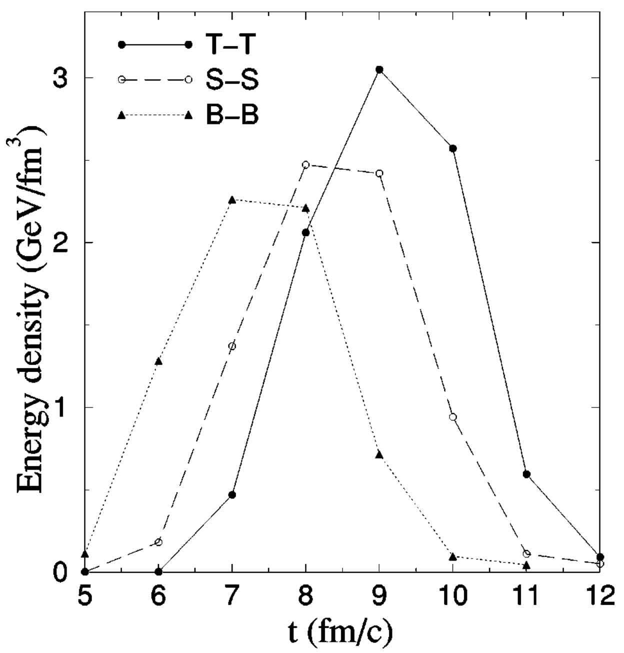

FIG. 2. Time evolution of central energy density in the U-U collision at $200A$ GeV/c.

ply the effective color electric dissociation coefficient c_s used previously for collisions of spherical nuclei by the relative increase in the maximum energy density, i.e., 1.2, 1.07, and 0.93 for the T-T, T-B, and B-B collisions, respectively. Results from using the modified color dissociation coefficients are shown in Fig. 3. We see that this leads to a more pronounced dependence of the color dissociation mechanism on the nuclear orientation than that of both the nuclear absorption and energy degradation effects. As a result, J/ψ suppression in the T-T collision is now twice as strong as in the B-B collision. This will be useful in verifying the formation of a nonhadronic dense matter in the initial stage of relativistic nucleus-nucleus collisions once the orientation of the colliding nuclei is known. The E_T dependence of the J/ψ suppression factor in central U-U collisions at $200A$ GeV/c is given in Fig. 4 for the different orientation of colliding nuclei by different solid labels: circles for T-T, triangle for T-B, squares for S-S, and inverted triangles for B-B. In Fig. 4 the upper-left panel is for total J/ψ suppression factor S_{tot}, upper-right for S_{dis}, lower-left for S_{deg}, and lower-right for S_{abs}. The neutral E_T here is counted with NA38 η cut ($1.7 \leqslant \eta \leqslant 4.1$). One sees from the upper-left panel of Fig. 4 that the E_T spectrum of the total J/ψ suppression factor, S_{tot}, becomes lower and lower as the orientation changes from B-B to S-S to T-B, and to T-T. From the comparison among the other three panels one knows further that the above behavior is even more pronounced in spectra S_{dis} than in S_{abs} and in S_{deg}. This supports again the prediction that experiments with U-U collisions can also help to discriminate different mechanisms of J/ψ suppression [30]. The E_T spectra of S_{deg} are all nearly flat due to fact that the J/ψ's are mainly produced in first nucleon-nucleon collisions. There are saturations that show up in the E_T spectra of S_{abs}, as the prediction of conventional hadronic absorption models, at E_T above 200 GeV. However, the E_T spectra of S_{dis} are falling down monotonously for the most central collisions. In the panels of Fig. 4 the largest E_T data points are all corresponding to the central collisions ($b=0$) in different orientations of the colliding nuclei. The largest E_T reached in T-T is about 10% larger than that in B-B. The largest E_T reached in T-B, S-S, and B-B are nearly the same within fluctuation.

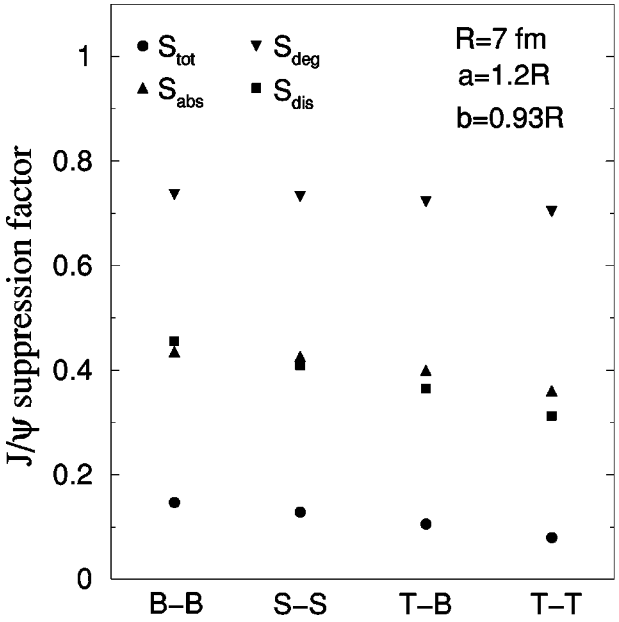

FIG. 3. Same as Fig. 1 but with an effective color electric dissociation coefficient that depends on the initial energy density. See the text for details.

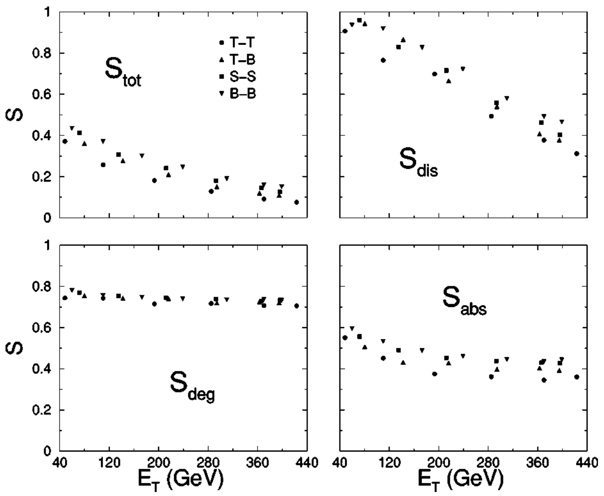

FIG. 4. E_T dependence of the J/ψ suppression factor in central U-U collisions at $200A$ GeV/c for the different orientation of colliding nuclei by different solid labels: circles for T-T, triangle for T-B, squares for S-S, and inverted triangles for B-B. The upper-left panel is for S_{tot}, the upper-right for S_{dis}, the lower-left for S_{deg}, and the lower-right for S_{abs}.

In summary, a hadron and string cascade model, JPCIAE, has been used to study the orientation effect of deformed nuclei on J/ψ suppression in U-U collisions at $200A$ GeV/c. A 35% higher initial energy density and a factor of two more J/ψ suppression are found in collisions if the major axes of both nuclei are along the beam direction than if they are perpendicular to the beam direction. Moreover, we have found a much more pronounced orientation effect on J/ψ suppression by the color electric dissociation than by the hadronic absorption and the energy degradation of leading nucleons. The study of J/ψ suppression in collisions of deformed nuclei will thus help find the signature for the formation of a quark-gluon plasma in relativistic nucleus-nucleus collisions. Of course, this study is still very preliminary, many related issues need to be investigated further, e.g., how to determine the orientation of a deformed nucleus experimentally, etc. However, the theoretical study in this paper might encourage one to explore the mechanism of J/ψ dissociation in color electric field and its orientation dependence in more detail.

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[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[2] J. Badier *et al.*, NA3 Collaboration, Z. Phys. C **11**, 195 (1981); **20**, 101 (1983).
[3] C. Baglin *et al.*, NA38 Collaboration, Phys. Lett. B **220**, 471 (1989); **251**, 465 (1990); **255**, 459 (1991); **270**, 105 (1991); **345**, 617 (1995).
[4] M. Gonin, NA50 Collaboration, Nucl. Phys. **A610**, 404c (1996).
[5] A. Capella, J. A. Casado, C. Pajares, A. V. Ramallo, and J. Tran Thanh Van, Phys. Lett. B **206**, 354 (1988).
[6] C. Gerschel and J. Hüfner, Phys. Lett. B **207**, 253 (1988).
[7] S. Gavin, M. Gyulassy, and A. Jackson, Phys. Lett. B **207**, 257 (1988).
[8] R. Vogt, M. Prakash, P. Koch, and T. H. Hansen, Phys. Lett. B **207**, 263 (1988).
[9] D. Neubauer, K. Sailer, B. Mueller, H. Stöcker, and W. Greiner, Mod. Phys. Lett. A **4**, 1627 (1989).
[10] S. Gavin and R. Vogt, Nucl. Phys. **B345**, 104 (1990).
[11] C. Gerschel and J. Hüfner, Nucl. Phys. **A544**, 513c (1992).
[12] C. Y. Wang, Phys. Rev. Lett. **76**, 196 (1996); Nucl. Phys. **A610**, 434c (1996).
[13] J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).
[14] D. Kharzeev, Nucl. Phys. **A610**, 418c (1996).
[15] S. Gavin and R. Vogt, Nucl. Phys. **A610**, 442c (1996).
[16] D. Kharzeev, M. Nardi, and H. Satz, Phys. Lett. B **405**, 14 (1997).
[17] S. Gavin and R. Vogt, Phys. Rev. Lett. **78**, 1006 (1997).
[18] N. Armesto and A. Capella, Phys. Lett. B **430**, 23 (1998).
[19] R. Vogt, Phys. Lett. B **430**, 15 (1998).
[20] E. Shuryak and D. Teaney, Phys. Lett. B **430**, 37 (1998).
[21] N. Hammon, L. Gerland, H. Stöcker, and W. Greiner, Phys. Rev. C **59**, 2744 (1999).
[22] W. Cassing and C. M. Ko, Phys. Lett. B **396**, 39 (1997).
[23] W. Cassing and E. L. Bratkovskaya, Nucl. Phys. **A623**, 570 (1997).
[24] Sa Ben-Hao, Tai-An, Wang Hui, and Liu Feng-He, Phys. Rev. C **59**, 2728 (1999).
[25] J. Geiss, C. Greiner, E. L. Bratkovskaya, W. Cassing, and U. Mosel, Phys. Lett. B **447**, 31 (1999).
[26] Sa Ben-Hao, Amand Faessler, Tai An, T. Waindzoch, C. Fuchs, Z. S. Wang, and Wang Hui, J. Phys. G **25**, 1123 (1999).
[27] D. E. Kahana and S. H. Kahana, Phys. Rev. C **59**, 1651 (1999).
[28] C. Gale, S. Jeon, and J. Kapusta, Phys. Lett. B **459**, 455 (1999).
[29] C. Spieles, R. Vogt, L. Gerland, S. A. Bass, M. Bleicher, H. Stöcker, and W. Greiner, Phys. Rev. C **60**, 054901 (1999).
[30] E. V. Shuryak, Phys. Rev. C **61**, 034905 (2000).
[31] H. Heiselberg and R. Mattiello, nucl-th/9901004; Phys. Rev. C **60**, 044902 (1999).
[32] Bao-An Li, Phys. Rev. C **61**, 021903 (2000).
[33] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).
[34] J. Cugnon, T. Mizutani, and J. Vandermeulen, Nucl. Phys. **A352**, 505 (1981).
[35] G. F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988).
[36] Sa Ben-Hao and Tai An, Comput. Phys. Commun. **90**, 121 (1995); **116**, 353 (1999).
[37] A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II, p. 133.
[38] H. Liu, S. Panitkin, and N. Xu, Phys. Rev. C **59**, 348 (1999).