J/ψ suppression in ultrarelativistic nuclear collisions

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Using a multiphase transport model, we study the relative importance of J/ψ suppression mechanisms due to plasma screening, gluon scattering, and hadron absorption in heavy ion collisions at the Relativistic Heavy Ion Collider. We find that for collisions between heavy nuclei such as Au+Au, both plasma screening and gluon scattering are important. As a result, the effect due to absorption by hadrons becomes relatively minor. The final J/ψ survival probability in these collisions is only a few percent. In the case of collisions between light nuclei such as S+S, the effect of plasma screening is, however, negligible in spite of the initial high parton density. The final J/ψ survival probability thus remains appreciable after comparable absorption effects due to gluons and hadrons.

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I. INTRODUCTION

According to the fundamental theory of strong interactions, quantum chromodynamics (QCD), normal nuclear matter is expected to undergo a phase transition to deconfined quarks and gluons when its density and/or temperature are high [1]. To produce such a quark-gluon plasma (QGP) in the laboratory, experiments involving collisions of nuclei at relativistic energies have been carried out at the CERN SPS [2]. Possible evidence for the production of this new phase of matter has recently been announced [3]. Further experiments at the Relativistic Heavy Ion Collider (RHIC), which allows collisions at much high energies than those available previously, are expected to provide a better opportunity to create the quark-gluon plasma and to study its properties.

Since quarks and gluons cannot be directly detected in experiments, many indirect observables have been proposed as possible signatures for the QGP. These include enhanced production of strange hadrons as a result of the short strangeness equilibration time in QGP [4], suppression of J/ψ production due to color screening in QGP [5], quenching of high p_t jets due to passage through the QGP [6–8], and enhancement of low mass dileptons as a result of medium modifications of hadron properties in high density matter [9,10]. Although all these signals have been observed in heavy ion collisions at CERN SPS, alternative explanations without invoking the formation of the quark-gluon plasma have also been proposed. As the QGP is expected to be produced at RHIC, it is of interest to study these signatures in heavy ion collisions at such high energies. Since the quark-gluon plasma has a finite size, exists for a finite time, and may not be in equilibrium, it is important to use a dynamical model to take into account these effects. Using the parton cascade model [11], Satz and Srivastava [12] have recently studied the time evolution of the density profile of the parton system

in these collisions and demonstrated the possibility of using a dynamical model to study the onset of deconfinement and its effect on quarkonium suppression. In this paper, we shall investigate explicitly J/ψ suppression in central nucleus-nucleus collisions at RHIC energies using a multiphase transport (AMPT) model [13]. Since the AMPT model includes both initial partonic and final hadronic interactions as well as the transition between these two phases of matter, it allows us to study the relative importance of the partonic and hadronic effects on J/ψ suppression.

This paper is organized as follows. In Sec. II, we briefly describe the AMPT model for ultrarelativistic heavy ion collisions and its extension to include J/ψ production. The mechanisms for J/ψ suppression are given in Sec. III. Results for Au+Au and S+S collisions at RHIC are given in Sec. IV. First, we show the time evolution of the particle number and energy densities in both partonic and hadronic matter. This is then followed by the time evolution of various J/ψ suppression effects and the J/ψ survival probability. Finally, a summary is given in Sec. V.

II. MULTIPHASE TRANSPORT MODEL

In the AMPT model, the initial conditions are obtained from the minijets generated by the Heavy Ion Jet Interaction Generator (HIJING) [14] by using a Woods-Saxon radial shape for the colliding nuclei and including the nuclear shadowing effect on partons via the gluon recombination mechanism by Mueller and Qiu [15]. After passage of the colliding nuclei, the Gyulassy-Wang model [7] is then used to generate the initial space-time information of partons. The subsequent time evolution of the parton phase-space distribution is modeled by Zhang's parton cascade (ZPC) [16,17], which at present includes only the gluon elastic scattering. After partons stop interacting, the Lund string fragmentation model [18,19] is used to convert them into hadrons. The dynamics of resulting hadronic matter is described by a relativistic transport (ART) model [20]. Details of the AMPT model can be found in [13].

To include J/ψ in the AMPT model, we use the perturbative approach [10] as its production probability is small in

heavy ion collisions. Specifically, the reaction $gg \rightarrow J/\psi g$ is selected from the PYTHIA program whenever there is an inelastic scattering between projectile and target nucleons. Instead of allowing the produced J/ψ to undergo multiple interactions, fragmentation, and decay in the PYTHIA, its momentum is stored in a file and read into HIJING. The transverse position of the J/ψ is determined by propagating it to the time of formation from the average transverse position of the colliding projectile and target nucleons. Since the J/ψ production probability is increased from $\sigma(NN \rightarrow J/\psi X)$ to σ_{inel}, each J/ψ is given a probability of $\sigma(NN \rightarrow J/\psi X)/\sigma_{inel}$ in order to have the correct number in an event, given by the total probability of all J/ψ's. The J/ψ formation time is taken to be 0.5 fm/c, which is suggested by the virtuality argument of Kharzeev and Satz [21] and is also consistent with the uncertainty principle used for estimating the lifetime of an expanding $c\bar{c}$ [22,23]. Before this time, the $c\bar{c}$ pair is considered a precursor J/ψ.

III. J/ψ ABSORPTION

After a pair of $c\bar{c}$ is produced in the initial collisions, whether it can materialize as a J/ψ depends on its interactions in the initial partonic and final hadronic matter. In the partonic matter, the $c\bar{c}$ pair, which are initially close in phase space and would normally form a J/ψ after the formation time of 0.5 fm/c, will move beyond the confinement distance of J/ψ and become unbound if the plasma screening remains strong [5]. They will later combine with the more abundant light quarks to form instead charm hadrons when the parton density is low. The critical density for the plasma screening to be effective can be estimated using $n_c = (2k_0\mu_c^2)/(3\pi^2\alpha_S)$ [24], where μ_c is the critical Debye screening mass, α_S is the QCD coupling constant, and k_0 is the slope parameter of the transverse momentum distribution. Using $\mu_c = 0.7$ GeV, $\alpha_S = 0.47$, and $k_0 = 0.6$ GeV, one obtains a critical density of 5 fm^{-3}. Following the method of Ref. [12], we first determine from the AMPT model the time evolution of the radius of the volume in which the parton density is above the critical density. A J/ψ is thus not formed from the $c\bar{c}$ pair if its radial position after the formation time of 0.5 fm/c is within the critical radius at that time.

Besides dissociation due to plasma screening, a J/ψ may also be dissociated by collisions with gluons in the partonic matter [25]. The cross section for $gJ/\psi \rightarrow c\bar{c}$ has been estimated in Ref. [25] to be 3 mb. Similarly, a precursor J/ψ can also be dissociated by gluon scattering. The cross section is expected to be smaller as its size is smaller than a physical J/ψ. In the present study, we ignore the difference between the scattering of a gluon with precursor and physical J/ψ, and use the same cross section. Since this cross section is not well known, we have also used a value of 1 mb in the following study.

In the hadronic matter following the parton stage, a J/ψ can be further destroyed by collisions with hadrons. The J/ψ absorption cross section by baryons is taken to be 6 mb [26] while that by meson is taken to be 3 mb [27] above their
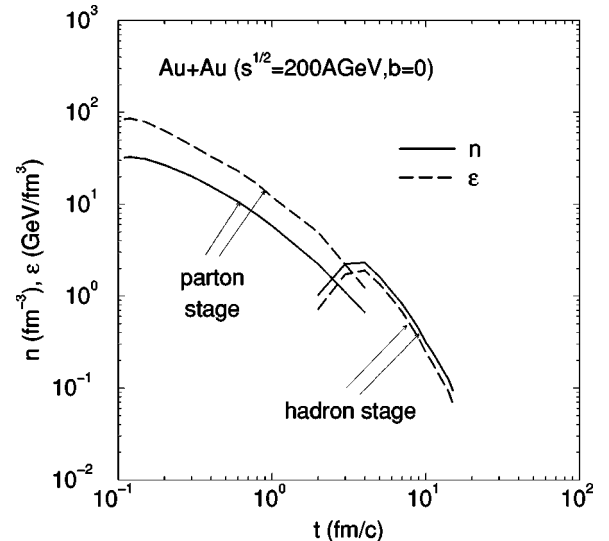

FIG. 1. Time evolution of particle number and energy densities in the central cell around $\eta = 0$ and $r = 0$ for central ($b = 0$) Au+Au collisions at RHIC.

respective thresholds. Although earlier studies based on the perturbative QCD [28] and simple hadronic model [29] give much smaller J/ψ absorption cross sections by hadrons, the above values are consistent with recent studies using the quark-interchange model [30] and the more complete hadronic model [31,32]. Using these cross sections in the transport model, it has been found that the observed suppression of J/ψ production in heavy ion collisions at SPS energies can be reasonably described except for the most central collisions [33–35]. As the formation time of J/ψ is comparable to the passing time (0.1 fm/c) of two colliding nuclei at RHIC energies, J/ψ absorption by the projectile and target nucleons is not expected to be important [36] and will be ignored in the present study. We note that as the J/ψ is treated perturbatively in the simulation, the momenta of other hadrons are not affected by their interactions with J/ψ [37].

IV. RESULTS

A. Time evolution of particle number and energy densities

In Fig. 1, we show the time evolution of the particle number and energy densities of partons and hadrons in central Au+Au collisions at $\sqrt{s} = 200$ GeV. They are the densities in the central cell, which has a transverse radius of 1 fm for partons and 2 fm for hadrons. The longitudinal dimension of the central cell is taken to be $\pm 5\%$ of the time t, which is equivalent to taking the central space-time rapidity cell. The results are not significantly changed if $\pm 10\%$ of the time is used for the longitudinal dimension. We see that the initial parton density is about 30 fm^{-3} and is much higher than the J/ψ dissociation critical density (about 5 fm^{-3}) given above. The time evolution of these densities is seen to deviate from that based on the ideal Bjorken boost invariant scenario [38], which would lead to a linear curve on the log-log plot. This difference is mainly due to the more realistic treatment of
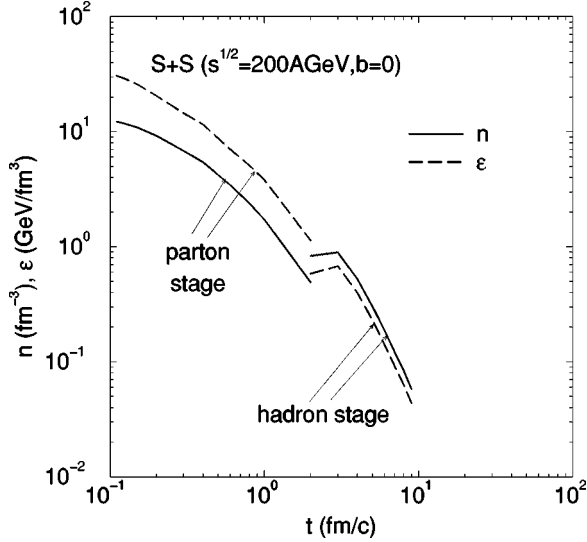
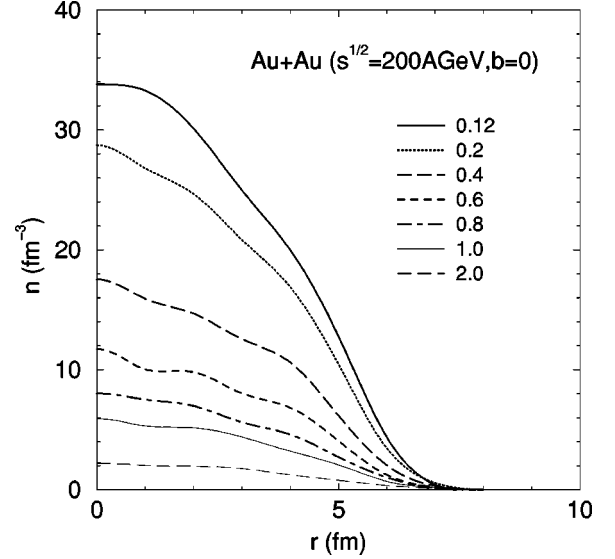FIG. 2. Same as Fig. 1 for central ($b=0$) S+S collisions at RHIC.

FIG. 3. Parton density in central ($b=0$) Au+Au collisions at RHIC at different times. The numbers are the proper times in fm/c for the density measurements.

initial collisions by using the Gyulassy-Wang model for the formation time and the presence of radial flow as well as a gradual freeze-out [39] at the later hadronic stage. From the ratio of the parton energy density to its number density, one sees that the average energy of a parton is more than 1 GeV. The parton stage lasts about $2-3$ fm/c, while the hadron stage starts gradually at around $3-4$ fm/c and lasts until about 10 fm/c. The average energy of a hadron is less than 1 GeV, since the central rapidity is dominated by mesons instead of baryons in ultrarelativistic nuclear collisions. In Fig. 2, we show the results for central collisions of S+S at $\sqrt{s}=200A$ GeV. Because of the smaller size of the system compared to that of Au+Au collisions, the plasma lifetime is shorter, i.e., about $1-2$ fm/c, and the hadron stage sets in at about $2-3$ fm/c. We note that even in the smaller parton system produced in S+S collisions, the initial density is much higher than the critical density for J/ψ dissociation.

In Fig. 3 and Fig. 4, we show, respectively, the parton density in central Au+Au and S+S collisions at different times. As minijet gluons are produced from initial hard collisions, their densities at different radii reflect the number of initial binary nucleon-nucleon collisions. As seen from the figure, they are different from the initial nuclear density distribution given by a Woods-Saxon form. As expected, both the size and lifetime of the partonic matter produced in S+S collisions are smaller than those in Au+Au collisions. From the time evolution of the parton density, one can determine the time evolution of the critical radius for J/ψ dissociation, and this is shown in Fig. 5 by solid circles for Au+Au collisions and open circles for S+S collisions. The solid lines are polynomial fits to the above results using the form $r_c(t)=a_0+a_1t+a_2t^2+a_3t^3$ for $t_{min}<t<t_{max}$, with $r_c(t)=r_c(t_{min})$ for $t<t_{min}$ and $r_c(t)=0$ for $t>t_{max}$. For the partonic matter produced in Au+Au collisions, we have $t_{min}=0.15$ fm/c, $t_{max}=1.2$ fm/c, $a_0=6.39$, $a_1=-4.06$, $a_2=4.79$, and $a_3=-4.86$. For S+S collisions, they are $t_{min}=0.12$ fm/c, $t_{max}=0.5$ fm/c, $a_0=3.278$, $a_1=-11.949$, $a_2=31.514$, and $a_3=-41.428$. In Au+Au collisions, the criti-

cal radius for J/ψ dissociation extracted from our model is about 6 fm at the beginning of the parton cascade and vanishes after about 1.2 fm/c. The critical radius is reduced to about 2 fm initially and vanishes after only about 0.5 fm in S+S collisions. Since the duration of the partonic matter that is above the critical density for J/ψ dissociation is shorter than the J/ψ formation time, J/ψ suppression due to plasma screening is therefore unimportant in central S+S collisions.

B. Time evolution of J/ψ survival probability

Including the above three mechanisms for J/ψ suppression in the AMPT model, we have evaluated the J/ψ survival probability in ultrarelativistic heavy ion collisions at RHIC
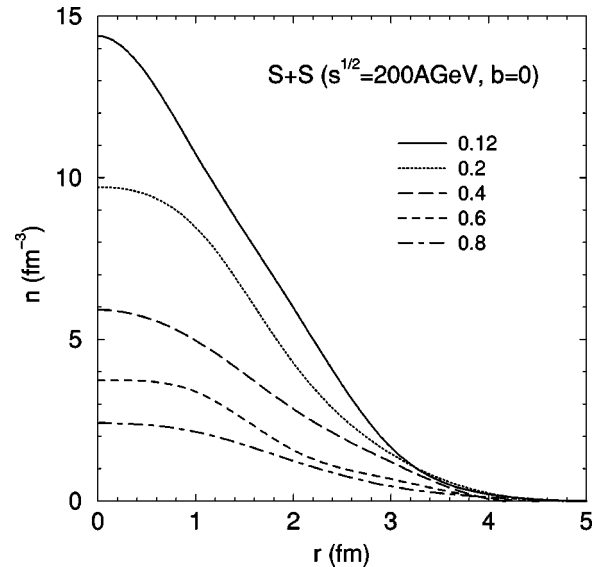

FIG. 4. Parton density in central ($b=0$) S+S collisions at RHIC at different times.
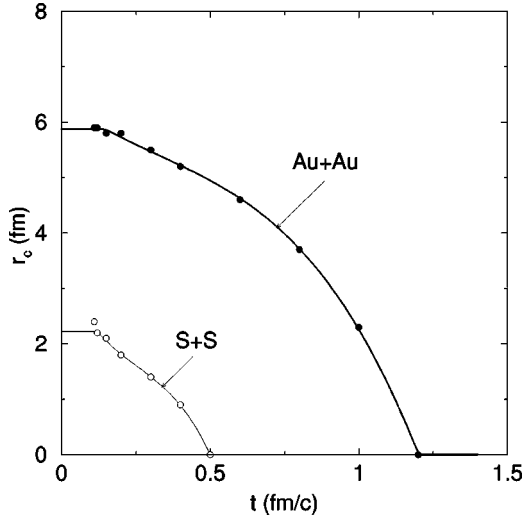
FIG. 5. Time evolution of the critical radius for plasma disso-ciation of J/ψ in central Au+Au and S+S collisions at $\sqrt{s}=200A$ GeV.

energies. In Fig. 6, we show for central Au+Au collisions the time evolution of the J/ψ formation probability $P_f(t)$, the J/ψ absorption probability $P_c^g(t)$ by gluon scattering, the J/ψ dissociation probability $P_d(t)$ by plasma screening, the J/ψ absorption probability $P_c^h(t)$ by hadrons, and the J/ψ survival probability $P_s(t)=1-P_c^g(t)-P_d(t)-P_c^h(t)$. The results are taken for the J/ψ produced in the central rapidity interval $|y_{J/\psi}|<1$. It is seen that the J/ψ formation probabil-ity increases quickly with time and about 90% of the J/ψ are formed by 0.5 fm/c. Absorption by gluons starts very early in the process and ends at about 1 fm/c after dissociation due to plasma screening begins. The latter also ends at about
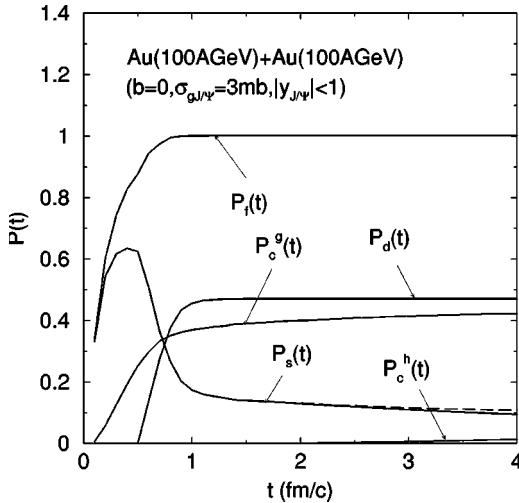

FIG. 6. Time evolution of the J/ψ formation probability $P_f(t)$, the J/ψ absorption probability $P_c^g(t)$ by gluon scattering, the J/ψ dissociation probability $P_d(t)$ by plasma screening, the J/ψ absorp-tion probability $P_c^h(t)$ by hadrons, and the J/ψ survival probability $P_s(t)$. For the survival probability, the solid curve includes absorp-tion by both gluons and hadrons, while the long-dashed curve in-cludes only absorption by gluons.
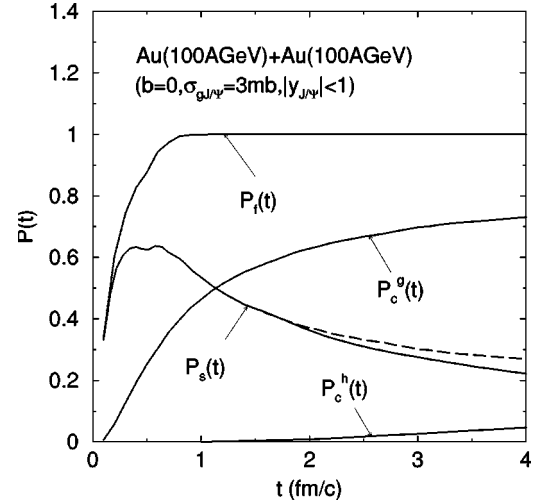

FIG. 7. Same as Fig. 6 without plasma dissociation.

1 fm/c. Both dissociation due to plasma screening and ab-sorption by gluon collisions give comparable contributions, accounting for the suppression of about 90% of the J/ψ, while absorption by hadrons contributes only about a few percent. The final J/ψ survivability is about 6%.

The results for the case without plasma screening is shown in Fig. 7. Comparing to Fig. 6, we see that the J/ψ absorption probability by gluons is similar for time up to 0.5 fm/c, but it lasts longer until 2–3 fm/c. This indicates that there is a competition between J/ψ suppression due to gluon scattering and plasma screening; i.e., some J/ψ's that are destroyed by collisions with gluons would have been dissociated by plasma screening if they are not allowed to scatter with gluons. Figure 8 shows the results without J/ψ absorption by gluon scattering. In this case, the plasma dis-sociation probability saturates quickly. Compared to that shown in Fig. 7, the J/ψ suppression probability is seen to start late but saturate early. This difference in the survival probability may be seen by studying the azimuthal distribu-tion of final survival J/ψ in midcentral collisions. It is inter-
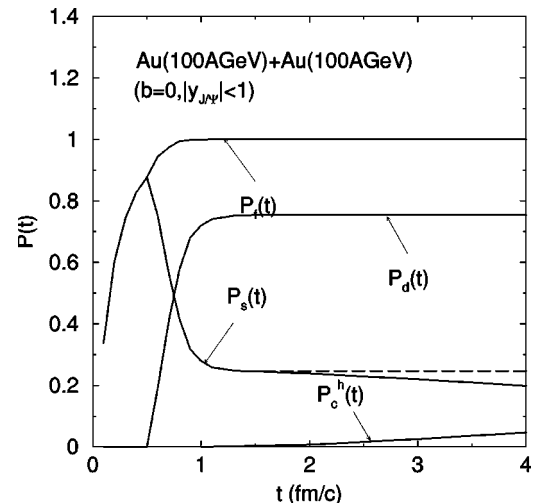

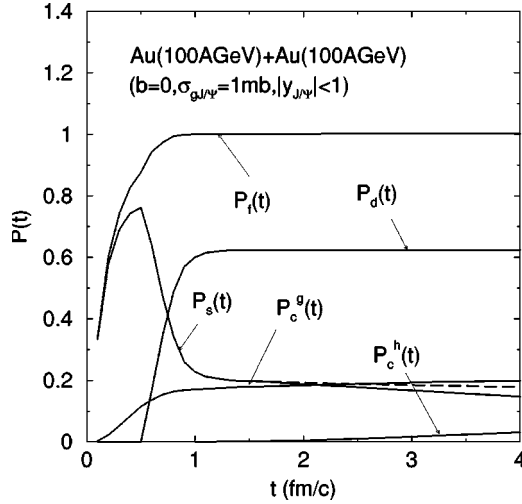FIG. 8. Same as Fig. 6 without gluon destruction.

FIG. 9. Same as Fig. 6 with a reduced J/ψ absorption cross section by gluons.

esting to note that J/ψ suppression during the parton stage is similar whether when both plasma screening and gluon scattering are present or when only one of them is present. The effect of reducing the J/ψ scattering cross section by gluon is shown in Fig. 9. Compared with Fig. 6, we see that the decrease in the contribution from gluon scattering is partly compensated by the plasma screening.

In Table I, we summarize the final absorption probabilities due to gluons (P_c^g), hadrons (P_c^h), plasma dissociation (P_d), and the survival probability (P_s) in central Au+Au collisions. It is seen that the J/ψ survival probability after the parton stage, $S_g = 1 - P_c - P_d$, is about 9% and 17% for $\sigma_{gJ/\psi} = 3$ mb and 1 mb, respectively. The parton stage thus has a large effect on J/ψ suppression in heavy ion collisions at RHIC. In both cases, the J/ψ suppression factor in the hadron stage is $S_h = P_h/S_g \sim 35\%$. Depending on the different assumptions on the mechanisms for J/ψ suppression, the final survival probability can range from about 6% to about 26%. This indicates that finite size effects may be important in J/ψ suppression at RHIC energies. We have also studied J/ψ suppression in S+S collisions at RHIC energies, and the results are summarized in Table II. As expected from the discussion of Fig. 5, there is no contribution from plasma screening in collisions of such light system, although the initial density is above the critical density. As a result, the

TABLE II. Same as Table I for S+S ($b=0$, $\sqrt{s}=200A$ GeV).

	P_c^g	P_d	P_c^h	P_s
Screening+$(gJ/\psi)_a$+hJ/ψ	39.3%	0	10.6%	50.1%
Screening+$(gJ/\psi)_b$+hJ/ψ	16.8%	0	16.0%	67.2%
hJ/ψ	0	0	19.6%	80.4%

J/ψ has an appreciable survival probability (about 50%) after absorption by gluons and hadrons. Since J/ψ absorption by gluon scattering still contributes appreciably to the final J/ψ suppression, it may provide an opportunity for studying this mechanism. We note that the J/ψ suppression factor in the hadron stage is about $S_h \sim 16\%$, which is smaller than in Au+Au collisions.

V. SUMMARY

In summary, we have studied J/ψ suppression in Au+Au and S+S collisions at RHIC energies in a multiphase transport model. It is found that finite size effects may be important in J/ψ suppression at RHIC energies even in central Au+Au collisions. Both J/ψ suppressions due to plasma screening and gluon scatterings are important in Au+Au collisions, leading to a final J/ψ survival probability of only about 6%. For S+S collisions, even though the initial energy density is above the critical density for J/ψ dissociation, only J/ψ absorption by gluon and hadron scatterings contribute to its suppression as a result of the short lifetime of the plasma. J/ψ suppression in heavy ion collisions between light nuclei thus provides a possible opportunity for studying the interactions between J/ψ and gluon.

In our study, we have ignored both J/ψ formation from the recombination of $c\bar{c}$ pairs during hadronization and J/ψ production from charm mesons in the final hadronic matter. The number of J/ψ formed from charm quarks during hadronization can be roughly estimated from considerations of the phase space and the spin and color factors. At the end of parton stage, the volume of the partonic matter in the central unit of rapidity is approximately given by $V = \pi R^2 \tau$, where R and τ are the transverse radius and longitudinal dimension, respectively. For Au+Au collisions, they are $R \sim 7$ fm and $\tau \sim 3$ fm. The probability that an anticharm quark is found within a distance of the J/ψ radius from a charm quark is given by the ratio of the size of the J/ψ to the size of the

TABLE I. Final J/ψ absorption probability P_c^g by gluon scattering, J/ψ dissociation probability P_d by plasma screening, J/ψ absorption probability P_c^h by hadrons, and J/ψ survival probability P_s for Au+Au ($b=0$, $\sqrt{s}=200A$ GeV). Here $(gJ/\psi)_a$ indicates $\sigma_{gJ/\psi}=3$ mb while $(gJ/\psi)_b$ indicates $\sigma_{gJ/\psi}=1$ mb.

	P_c^g	P_d	P_c^h	P_s
Screening+$(gJ/\psi)_a$+hJ/ψ	43.9%	47.1%	2.9%	6.1%
Screening+$(gJ/\psi)_b$+hJ/ψ	20.6%	62.4%	6.5%	10.5%
screening+hJ/ψ	0	75.4%	10.2%	14.4%
$(gJ/\psi)_a$+hJ/ψ	78.3%	0	10.6%	11.0%
$(gJ/\psi)_b$+hJ/ψ	42.9%	0	31.1%	26.0%
hJ/ψ	0	0	56.7%	43.3%

partonic matter. With a J/ψ radius $r_{J/\psi} \sim 0.3$ fm, one obtains the probability 2.5×10^{-4}. In order for this charm pair to form a J/ψ, their spins must be parallel and their total color should be neutral. This reduces the probability by the factor $(3/4) \times (1/9) \sim 0.083$. Requiring that the charm pair have a relative momentum distribution within $p_0 \sim 1/r_{J/\psi} \sim 0.67$ GeV at $T \sim 200$ MeV further suppresses the probability by a factor of 0.29. Since there are about 1.5 charm pairs per unit rapidity per central Au+Au collision at RHIC, the number of J/ψ formed from their recombination is about $1.5^2 \times 2.5 \times 10^{-4} \times 0.083 \times 0.29 \sim 1.4 \times 10^{-5}$, which is much smaller than the expected number of J/ψ, i.e., $1.5/40 \times 0.061 \sim 2.3 \times 10^{-3}$. In the above, the factor of 40 is the ratio of charm to J/ψ production in initial hard collisions [40] and the factor of 0.061 is the final J/ψ survival probability from Table I. As to J/ψ production from charm mesons in hadronic matter, it has been shown to be insignificant in heavy ion collisions at RHIC, although it may not be negligible at LHC [41,42].

We have studied only the suppression of directly produced J/ψ. There are also J/ψ's which are produced indirectly from the decay of ψ' and χ_c. In pp collisions, the latter constitute about 5% and 40% of the measured final J/ψ, respectively [43]. Since ψ' and χ_c are less bound than J/ψ, they are more likely to be dissociated and absorbed in both the quark-gluon plasma and the hadronic matter. As a result, inclusion of ψ' and χ_c suppression is expected to reduce the final J/ψ survivability obtained in the present study by at most 45%. Also, we have used the default gluon shadowing in HIJING without flavor and scale dependence, which is different from the one suggested by Eskola *et al.* [44], which includes such dependence. If the latter is used, then we also expect a reduction of the J/ψ survival probability as the gluon density would be higher at RHIC energies [45]. These effects will be studied more quantitatively in the future.

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