# Hydrodynamical model for $J/\psi$ suppression and elliptic flow

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In a hydrodynamic model, we have studied $J/\psi$ suppression and elliptic flow in Au + Au collisions at the Relativistic Heavy Ion Collider (RHIC) energy $\sqrt{s} = 200$ GeV. At the initial time, $J/\psi$'s are randomly distributed in the fluid. As the fluid evolves in time, the free-streaming $J/\psi$'s are dissolved if the local fluid temperature exceeds a melting temperature $T_{J/\psi}$. Sequential melting of charmonium states ($\chi_c$, $\psi'$, and $J/\psi$), with melting temperatures $T_{\chi_c} = T_{\psi'} \approx 1.2T_c$ and $T_{J/\psi} \approx 2T_c$ and a feed-down fraction $F \approx 0.3$, is consistent with the PHENIX data on $J/\psi$ suppression and near-zero elliptic flow for $J/\psi$'s. It is also shown that the model will require substantial regeneration of charmonium if the charmonium states dissolve at a temperature close to the critical temperatures, $T_{\chi_c} = T_{\psi'} \leqslant T_c$ and $T_{J/\psi} \approx 1.2T_c$. The regenerated charmonium will have positive elliptic flow.

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Matsui and Satz [1] predicted that in the presence of quark-gluon plasma (QGP), because of color screening, binding of a $c\bar{c}$ pair into a $J/\psi$ meson would be hindered, leading to so-called $J/\psi$ suppression in heavy-ion collisions. Over the years, several groups have measured the $J/\psi$ yield in heavy-ion collisions (for a review of the data prior to the Relativistic Heavy Ion Collider (RHIC) energy collisions and interpretations, see Refs. [2,3]). In brief, experimental data do show suppression. However, this could be attributed to the conventional nuclear absorption, also present in $pA$ collisions. At RHIC energy ($\sqrt{s} = 200$ GeV), the PHENIX Collaboration has made systematic measurements of $J/\psi$ production in nuclear collisions. They have measured $J/\psi$ yield in $p + p$ collisions at RHIC and obtained the reference for the basic invariant yield [4–6]. Measurements of $J/\psi$ production in $d$ + Au collisions [5,7] give reference for cold nuclear matter effects. $J/\psi$ production in $d$ + Au collisions is consistent with the cold nuclear matter effect quantified in a Glauber model of nuclear absorption with $\sigma_{\text{abs}} = 2 \pm 1$ mb [8]. Cold and hot nuclear matter effects are studied in Au + Au and Cu + Cu collisions, in which yields are measured as a function of collision centrality [9–11]. At RHIC energy, it has been argued that rather than suppressed, charmonium will be enhanced [12,13]. Because of large initial energy, a large number of $c\bar{c}$ pairs will be produced in initial hard scatterings. Recombination of $c\bar{c}$ can occur, enhancing charmonium production. Apparently, the PHENIX data on $J/\psi$ production in Au + Au and Cu + Cu collisions are not consistent with models that predict $J/\psi$ enhancement [12,13]. $J/\psi$'s are suppressed both in Au + Au and Cu + Cu collisions, and suppression is greater in central collisions than in peripheral collisions.

Recently, the PHENIX Collaboration [14] measured the elliptic flow for $J/\psi$ in 20%–60% Au + Au collisions. Elliptic flow for $J/\psi$ is an important observable. It can test whether $J/\psi$ production is dominated by recombination. In $p + p$ and Au + Au collisions, PHENIX has measured semileptonic decay electrons from heavy quarks [15]. In Au + Au collisions, decay electrons have positive elliptic flow. If recombination of $c\bar{c}$ is a major source of $J/\psi$ in Au + Au collisions, as suggested in Refs. [12,13], $J/\psi$'s will inherit some of their flow. The PHENIX measurements of $J/\psi$ elliptic flow have large error bars. Integrated $v_2$ is consistent with zero, where $v_2 = -0.10 \pm 0.10 \pm 0.02$.

Recently, in a hydrodynamic-based model [16–18], the centrality dependence of $J/\psi$ suppression in Au + Au and Cu + Cu collisions was studied. In the model, $J/\psi$'s are randomly produced in initial nucleon-nucleon collisions. As the fluid evolves, free-streaming $J/\psi$'s are melted if the local fluid temperature exceeds a threshold temperature $T_{J/\psi}$. Sequential melting of charmonium states ($\chi_c$, $\psi'$, and $J/\psi$), with melting temperatures $T_{\chi_c} = T_{\psi'} \approx 1.2T_c$ and $T_{J/\psi} \approx 2T_c$ and a feed-down fraction $F \approx 0.3$, explains the PHENIX data on the centrality dependence of $J/\psi$ suppression in Au + Au collisions. $J/\psi$ $p_T$ spectra and the nuclear modification factor in Au + Au collisions are also well explained in the model. The model leaves little to no room for the regeneration of $J/\psi$ because of the recombination of $c\bar{c}$ pairs, as suggested in Refs. [12,13]. The model is also consistent with zero elliptic flow for $J/\psi$'s. Initially, $J/\psi$'s are produced randomly, and they do not have any flow. In later times, also, the free-streaming $J/\psi$'s cannot acquire any flow.

The dissociation or melting temperatures of different charmonium states obtained in Refs. [16–18] are in agreement with potential model calculations for charmonium states at finite temperature [19]. Because of the heavy mass of charm quarks, charmonium states can be studied in nonrelativistic potential models. Ground-state properties of charmonium are well explained using the Cornell potential, $v(r) = \sigma r - (\alpha/r)$, with string tension $\sigma \approx 0.2$ GeV$^2$ and gauge coupling $\alpha \approx \pi/12$ [19]. Lattice QCD can provide for the heavy quark potential at finite temperature. Finite-temperature potential models indicate that charmonium states $J/\psi(1S)$, $\chi_c(1P)$, and $\psi'(2S)$ dissociate at temperatures $T_{J/\psi} \approx 2T_c$, $T_{\chi_c} = T_{\psi'} \approx 1 - 1.2T_c$, respectively [19]. However, very recently, in Refs. [20,21], the quarkonia spectral function in QGP was determined using a potential motivated by lattice QCD results

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on the free energy of static quark-antiquark pairs. Surprisingly, charmonium is found to melt at much lower temperatures, $T_{J/\psi} \approx 1.2T_c$ and $T_{\chi_c} = T_{\psi'} \leqslant 1.2T_c$.

In this Brief Report, we show that if the charmonium states dissolve at a temperature close to the critical temperature, the PHENIX data on $J/\psi$ suppression in Au + Au collisions are not explained in the hydrodynamic model [16–18]. $J/\psi$'s will be more suppressed than in the experiment. Data on $J/\psi$ suppression can only be explained with substantial regeneration of $J/\psi$ during the evolution. It is also shown that regenerated charmonium will have positive elliptic flow. Conversely, a small, positive elliptic flow for $J/\psi$ will indicate regeneration of charmonium in RHIC energy collisions.

Details of the hydrodynamic model used here can be found in Refs. [17,18]. Briefly, it is assumed that in high-energy nuclear collisions, a deconfined phase (QGP) is produced, which expands, cools, undergoes first-order phase transition to hadronic fluid at the critical temperature ($T_c = 164$ MeV), and then further cools to freeze-out at temperature $T_F = 130$ MeV. Assuming longitudinal boost invariance, the space-time evolution of the fluid is obtained by solving the energy-momentum conservation equation $\partial_\mu T^{\mu\nu} = 0$, with initial conditions as determined in Ref. [22], for example, initial time $\tau_i = 0.6$ fm and initial central entropy density $S_{\text{ini}} = 110\,\text{fm}^{-3}$, corresponding to energy density $\varepsilon_i \approx 30\ \text{GeV/fm}^3$. To obtain the survival probability of $J/\psi$'s in an expanding medium, we proceed as follows: At the initial time $\tau_i = 0.6$ fm$/c$, we randomly distribute a fixed number of $J/\psi$'s in the transverse plane. They are assumed to be free streaming, unless dissolved in the medium. Each $J/\psi$ is characterized by four random numbers: Two random numbers ($R_1$, $R_2$) indicates its transverse position ($\mathbf{r}_\perp$), and two random numbers ($R_3$, $R_4$) indicate its transverse momentum $\vec{p}_T$. Random numbers $R_1$ and $R_2$ are distributed according to the transverse profile of the number of binary collisions ($N_{\text{coll}}$) calculated in a Glauber model. Random number $R_3$ is distributed according to the power law [23]

$$B\frac{d\sigma}{dyd^2p_T} = \frac{A}{[1+(p_T/B)^2]^6}(\text{nb/GeV}^2), \qquad (1)$$

where $A = 4.23$ and $B = 4.1$, which well describe the invariant distribution of measured $J/\psi$'s in $p + p$ collisions. The random number $R_4$ is distributed uniformly within (0–$2\pi$).

The survival probability of a $J/\psi$ inside the expanding QGP is calculated as [16]

$$S_{J/\psi}(\tau) = \exp\left(-\int_{\tau_i}^{\tau} \Gamma_{\text{dis}}\{T[\mathbf{r}_\perp(\tau')]\}\,d\tau'\right), \qquad (2)$$

where $T(\mathbf{r}_\perp)$ is the temperature of the fluid at the transverse position $\mathbf{r}_\perp$ and $\Gamma_{\text{dis}}(T)$ is the decay width of $J/\psi$ at temperature $T$; $\tau_i$ is the initial time for hydrodynamic evolution. We continue the evolution until the freeze-out time $\tau_F$ and corresponding freeze-out temperature $T_F = 130$ MeV. For the decay width $\Gamma_{\text{dis}}$, we use

$$\begin{aligned} \Gamma_{\text{dis}}(T) &= \infty; \quad T > T_{J/\psi}, \\ \Gamma_{\text{dis}}(T) &= \alpha(T/T_c - 1)^2; \quad T < T_{J/\psi}. \end{aligned} \qquad (3)$$

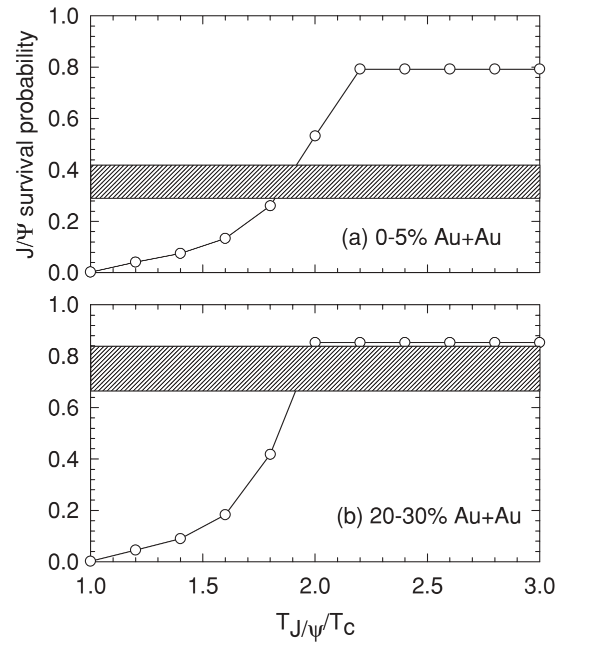


FIG. 1. The open circles are hydrodynamic model predictions for $J/\psi$ survival probability in (a) 0%–5% and (b) 20%–30% centrality Au + Au collisions, as a function of $J/\psi$ melting temperature ($T_{J/\psi}$). The shaded regions in (a) and (b) indicate PHENIX measurements for $J/\psi$ survival probability [10,25,26]. Note that if the $J/\psi$ dissociation temperature is $T_{J/\psi} \approx 1.2T_c$, experimental data will be under explained.

In Eq. (3), $\alpha$ is the thermal width of the state at $T/T_c = 2$. Next-to-leading order perturbative calculations suggest that $\alpha > 0.4$ GeV [24]. Presently, we use $\alpha = 0.4$ [18].

In Figs. 1(a) and 1(b), hydrodynamic model predictions for $J/\psi$ survival probability ($S_{J/\psi}$) in 0%–5% and 20%–30% centrality Au + Au collisions are shown as a function of the melting temperature. As expected, the survival probability increases as the melting temperature increases. Survival probability continues to increase until $T_{J/\psi}$ exceeds the peak temperature of the fluid, beyond which, even if $T_{J/\psi}$ increases, the survival probability will remain unchanged. The shaded regions in Figs. 1(a) and 1(b) represent the experimental survival probability as determined in the PHENIX experiment [10]. The cold nuclear matter effect is subtracted out [10,25,26]. It is evident from Fig. 1 that if $J/\psi$'s dissolve at temperatures close to the critical temperature, $T_{J/\psi} \approx 1.2T_c$, as predicted in recent calculations [20,21], PHENIX data on $J/\psi$ suppression are not explained in the model. Most of the initially produced $J/\psi$'s (∼98%) are dissolved in the medium. The data could only be explained if, during the evolution, $c\bar{c}$ pairs recombine to regenerate $J/\psi$. In the discussion, we have neglected the effect of higher states $\chi_c$ and $\psi'$. Nearly 30%–40% of observed $J/\psi$'s are from the decay of the higher states. However, since $\chi_c$ and $\psi'$ melt at a temperature lower than that for $J/\psi$, their inclusion will require a further regeneration of charmonium. If, however, $J/\psi$'s do survive high temperatures (e.g., $T_{J/\psi} \approx 2T_c$), experimental data are explained in the model, without any need for the recombination of $c\bar{c}$ pairs. Indeed, as shown in Ref. [18], PHENIX data on centrality dependence of $J/\psi$ suppression are well explained in the model with sequential melting of charmonium states with melting temperatures $T_{\chi_c} = T_{\psi'} \approx 1.2T_c$ and $T_{J/\psi} \approx 2T_c$ and a feed-down fraction $F \approx 0.3$, with little or no scope for the recombination of $c\bar{c}$ pairs and regeneration of charmonium in the QGP phase.

A hydrodynamic model of $J/\psi$ suppression thus indicates that if the charmonium states dissolve at a temperature close to the critical temperature, more than $\sim$98% of observed $J/\psi$ are regenerated from $c\bar{c}$ recombination during the QGP phase. If, however, charmonium ground states survive high temperatures, regeneration of charmonium will be minimum. Regenerated charmonium can have positive elliptic flow. As mentioned earlier, the PHENIX Collaboration measured single electrons from the semileptonic decay of heavy flavors in $p + p$ and Au + Au collisions [15]. Semileptonic decay electrons in minimum-bias Au + Au collisions have positive elliptic flow, indicating positive elliptic flow for the parent heavy quarks. If $J/\psi$'s are produced from $c\bar{c}$ recombination in the QGP phase, they could inherit their flow. To obtain an idea about the elliptic flow for $J/\psi$, because of recombination, we randomly generate $J/\psi$'s at the critical temperature $T_c$, according to the equilibrium distribution

$$E\frac{dN}{d^3p} \propto \exp[-p \cdot u(x)/T_c], \tag{4}$$

where $u(x)$ is fluid velocity at the freeze-out surface at $T = T_c$. Equation (4) is certainly an assumption. $J/\psi$'s can be regenerated throughout the deconfined phase. However, Eq. (4) suffices to give the general idea of flow for the regenerated $J/\psi$'s. Fluid velocity distribution at the critical temperature $T_c$ can be obtained from the hydrodynamical model of evolution. In Fig. 2, differential elliptic flow for $J/\psi$'s, randomly generated according to the distribution in Eq. (4), in 0%–5%, 20%–30%, and 20%–60% Au + Au collisions are shown. While in central (0%–5%) collisions, the elliptic flow is small, in peripheral (20%–30% or 20%–60%) Au + Au collisions, regenerated charmonium has substantial elliptic flow. For example, $J/\psi$'s produced randomly according to the distribution of Eq. (4) have $\sim$15%–20% $v_2$ at $p_T = 2$ GeV. In Fig. 2, black circles are PHENIX measurements for $J/\psi$ elliptic flow in 20%–60% Au + Au collisions. The error bars are large, and a definitive conclusion about $J/\psi$ elliptic flow cannot be drawn. Apparently, regenerated charmions have more elliptic flow than in the experiment. In Fig. 2, we have also shown the elliptic flow for $J/\psi$ in the hydrodynamic model [18], with melting temperatures $T_{J/\psi} = 2T_c$ and $T_{\chi_c} = T_{\psi'} = 1.2T_c$ and feed-down fraction $F = 0.3$ (the black circles). As stated earlier, the model is consistent with PHENIX data on $J/\psi$ suppression without any recombination. The elliptic flow in the hydrodynamic model is consistent with zero flow, and it is also expected. In the model, $J/\psi$'s are randomly generated within the angular range 0–$2\pi$. Initially, they have zero elliptic flow. Also, during the evolution, free-streaming $J/\psi$'s do not acquire flow.

Before we summarize, we note that it is possible that differences between elliptic flow of regenerated $J/\psi$'s and $J/\psi$'s surviving the hydrodynamic evolution may not be as

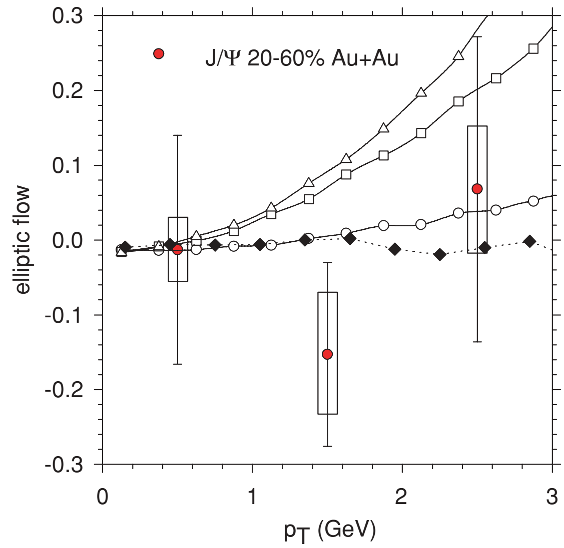


FIG. 2. (Color online) Hydrodynamic model [18] predictions for $J/\psi$ elliptic flow in 20%–60% Au + Au collisions (black diamonds). Elliptic flow for $J/\psi$s, randomly generated according to the thermal distribution in Eq. (4), in 0%–5%, 20%–30%, and 20%–60% Au + Au collisions, is shown as open circles, open squares, and open triangles, respectively. The black circles are PHENIX measurements [14] for $J/\psi$ elliptic flow in 20%–60% Au + Au collisions.

large as depicted in Fig. 2. We have assumed that $J/\psi$s are free streaming. $J/\psi$'s are formed early in the collision. The formation process may induce elliptic flow. Then elliptic flow of $J/\psi$'s surviving hydrodynamical evolution will be larger than obtained presently with the assumption of free steaming. It is difficult to ascertain the induced elliptic flow in initial $J/\psi$'s, and the uncertainty in the present evaluation cannot be quantified. This model, with the assumption of free streaming, gives the lower limit of the elliptic flow of $J/\psi$'s surviving the hydrodynamic evolution. Also, it is unlikely that regenerated $J/\psi$'s will be equilibrated at $T_c$. $J/\psi$'s are massive. Their mass is much larger than $T_c$. Elliptic flow of nonequilibrated or partially equilibrated $J/\psi$'s will be less than that for completely equilibrated $J/\psi$'s. This evaluation, with the assumption of equilibration, then gives the upper limit of elliptic flow of regenerated $J/\psi$'s.

To summarize, in a hydrodynamical model, we have studied $J/\psi$ suppression in Au + Au collisions at RHIC. In the model, at the initial time, $J/\psi$'s are randomly distributed in the fluid. As the fluid evolves in time, the free-streaming $J/\psi$'s are dissolved if the local fluid temperature exceeds a threshold temperature $T_{J/\psi}$. It is shown that if, as suggested in some recent works [20,21], $J/\psi$'s do not survive much above the critical temperature, PHENIX data on $J/\psi$ suppression are not explained in the model. Most of the initially produced $J/\psi$'s are dissolved in the medium, and the model predictions severely underestimate the PHENIX data on $J/\psi$ suppression in Au + Au collisions. The data will demand a recombination of $c\bar{c}$ pairs in the QGP phase. In a simple model, we have also shown that the regenerated $J/\psi$'s will have positive elliptic flow. However, if $J/\psi$'s can survive at high temperature (e.g., $T_{J/\psi} \approx 2T_c$), sequential melting of charmonium states ($\chi_c$, $\psi'$, and $J/\psi$), with melting temperatures $T_{\chi_c} = T_{\psi'} \approx 1.2T_c$ and $T_{J/\psi} \approx 2T_c$ and a feed-down fraction $F \approx 0.3$, is consistent with PHENIX data on $J/\psi$ suppression. There is no scope for recombination of $c\bar{c}$ pairs. The model also predicts zero elliptic flow for $J/\psi$'s.


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