

Onset of J/ψ melting in a quark-gluon fluid at RHIC

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(Received 6 March 2007; revised manuscript received 6 July 2007; published 2 November 2007)

A strong J/ψ suppression in central Au+Au collisions has been observed by the PHENIX experiment at the Relativistic Heavy Ion Collider. We develop a hydro+ J/ψ model in which hot quark-gluon matter is described by the full (3+1)-dimensional relativistic hydrodynamics and J/ψ is treated as an impurity traversing through the matter. The experimental J/ψ suppression pattern in midrapidity is reproduced well by the sequential melting of χ_c , ψ' , and J/ψ in dynamically expanding fluid. The melting temperature of directly produced J/ψ is well constrained by the participant-number dependence of the J/ψ suppression and is found to be about $2T_c$ with T_c being the pseudocritical temperature.

DOI: [10.1103/PhysRevC.76.051901](https://doi.org/10.1103/PhysRevC.76.051901)

PACS number(s): 25.75.Nq, 25.75.Dw, 24.10.Jv

A new state of matter composed of deconfined quarks and gluons, the quark-gluon plasma (QGP), is expected to be formed in relativistic heavy-ion collisions if the system reaches a temperature larger than the critical value $T_c \sim 160\text{--}190$ MeV as predicted by the lattice quantum chromodynamics (QCD) [1]. To find the experimental evidence of QGP, the heavy quarkonia (J/ψ , ψ' , χ_c , and Υ) have long been considered the most promising probe, because they are supposed to melt away due to the color Debye screening at sufficiently high temperature [2]. Recent lattice QCD studies show that J/ψ would survive even up to about $2T_c$ whereas χ_c and ψ' would be dissociated at different temperature [3–5]. Therefore, the heavy quarkonia may be used as a thermometer of QGP in relativistic heavy-ion collision experiments [6].

Recently, high statistics data of Au+Au collisions at the center-of-mass energy per nucleon ($\sqrt{s_{NN}}$) of 200 GeV at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL) become available [7]. It is observed that J/ψ yield in central Au+Au collisions at RHIC is suppressed by a factor of 4 at midrapidity and 5 at forward rapidity relative to that in $p+p$ collisions scaled by the average number of binary collisions. Cold nuclear matter (CNM) effects due to the gluon shadowing and nuclear absorption of J/ψ at the RHIC energy were evaluated from the J/ψ measurement in d +Au collisions [8]. Trend of the J/ψ suppression in d +Au collisions as a function of rapidity is reasonably well reproduced by the gluon shadowing with the Eskola-Kolhinen-Salgado (EKS) parametrization [9] and the nuclear absorption cross section $\sigma_{\text{abs}} \sim 1$ mb [8]. Then, a comparison of the J/ψ yield observed in Au+Au collisions at RHIC to that expected from CNM effects [10] reveals that J/ψ is anomalously suppressed in central collisions [11].

So far, two scenarios have been proposed for the J/ψ suppression at RHIC energies. The first scenario is based on the sequential melting of the charmonia [12]: The J/ψ

suppression previously observed at Super Proton Synchrotron (SPS) in European Center for Nuclear Research (CERN) may be ascribed to the complete melting of χ_c and ψ' and associated absence of the feed down to J/ψ , whereas at RHIC, extra melting of J/ψ could be seen due to higher initial temperature [13]. This approach is still in a qualitative level and the space-time evolution of the system has not been taken into account. The second scenario is based on the substantial charmonium dissociation due to gluons and comovers supplemented with the regeneration of J/ψ due to $c\bar{c}$ recombination [14–17]. In this scenario, a large amount of regeneration is expected at RHIC in comparison to SPS.

The purpose of this Rapid Communication is to make a first attempt to investigate the sequential charmonia suppression in a dynamically evolving matter produced in Au+Au collisions at RHIC energy. We develop a hydro+ J/ψ model in which hot quark-gluon matter is described by the full (3+1)-dimensional relativistic hydrodynamics [18] and J/ψ , χ_c , and ψ' are treated as impurities traversing through the matter. We will focus on the J/ψ data in the midrapidity region, because the hydrodynamical description of various observables is best established in that region. The J/ψ suppression in forward rapidity will be remarked at the end of this Rapid Communication.

Hereafter we study the survival probability of J/ψ , $S_{J/\psi}^{\text{tot}} = R_{AA}/R_{AA}^{\text{CNM}}$, as a function of the number of participants N_{part} [11]. R_{AA} is the standard nuclear modification factor defined by

$$R_{AA} = \frac{dN_{\text{Au+Au}}^{J/\psi}/dy}{\langle N_{\text{col}} \rangle dN_{p+p}^{J/\psi}/dy}, \quad (1)$$

where $dN_{\text{Au+Au}}^{J/\psi}/dy$ and $dN_{p+p}^{J/\psi}/dy$ are the invariant J/ψ yield in Au+Au and $p+p$ collisions, respectively. $\langle N_{\text{col}} \rangle$ is the average number of nucleon-nucleon collisions. R_{AA}^{CNM} is a contribution to R_{AA} originating from the CNM effects constrained by the data of the d +Au collisions.

We solve the equations of energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$ in full (3+1)-dimensional space-time (τ, x, y, η_s)

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under the assumption that the local thermal equilibrium is reached at initial time $\tau_0 (= 0.6 \text{ fm}/c)$ [19]. Here τ and η_s are the proper time and the space-time rapidity, respectively, and x and y are transverse coordinates. The centers of two colliding nuclei are located at $(x, y) = (b/2, 0)$ and $(-b/2, 0)$ before collision with an impact parameter b . The ideal hydrodynamics is characterized by the energy-momentum tensor,

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}, \quad (2)$$

where e , P , and u^μ are energy density, pressure, and local four-velocity, respectively. We neglect the finite net-baryon density which is small near the midrapidity at RHIC. The equation of state (EOS) of massless parton gas composed of u , d , and s quarks and gluons is employed in the QGP phase ($T > T_c = 170 \text{ MeV}$), whereas a hadronic resonance gas model is employed for $T < T_c$. The initial energy-density distribution in the transverse plane is parametrized in proportion to $d^2N_{\text{col}}/dx dy$ according to the Glauber model. The pseudo-rapidity distribution of charged particle multiplicity $dN^{\text{ch}}/d\eta$ for various centralities observed at RHIC has been well reproduced by the (3 + 1)-dimensional hydrodynamics simulations with the above setups [18].

The same space-time evolution of the QGP fluid obtained as above, which is now open to public [20], has been also exploited to study hard probes such as azimuthal jet anisotropy, nuclear modification factor of identified hadrons, and disappearance of back-to-back jet correlation [21]. Figure 1 shows the local temperature as functions of x (upper) and y (lower) for various proper time at midrapidity ($\eta_s = 0$). The left and right panels are for the case at $b = 2.1 \text{ fm}$ ($N_{\text{part}} = 351$) and $b = 8.5 \text{ fm}$ ($N_{\text{part}} = 114$), respectively.

We distribute the initial J/ψ 's in the transverse plane at $\eta_s = 0$ according to the spatial distribution of N_{col} calculated from the Glauber model for a given impact parameter. Since we focus on the midrapidity, only transversal motion of J/ψ is considered. Transverse momentum (p_T) of J/ψ is distributed according to the invariant p_T spectrum of J/ψ measured by PHENIX [7]. This corresponds to a weak coupling case where J/ψ is assumed to follow the free-streaming path inside the hot matter unless it is dissociated [22].

The survival probability of J/ψ suffering from dissociation along its path inside the expanding fluid may be expressed as

$$S_{J/\psi}[\mathbf{x}_{J/\psi}(\tau)] = \exp\left(-\int_{\tau_0}^{\tau} \Gamma_{\text{dis}}\{T[\mathbf{x}_{J/\psi}(\tau')]\} d\tau'\right), \quad (3)$$

where $\Gamma_{\text{dis}}\{T[\mathbf{x}_{J/\psi}(\tau)]\}$ is the decay width at temperature T and $\mathbf{x}_{J/\psi}(\tau)$ is the transverse position of J/ψ at proper time τ . Information on $\Gamma_{\text{dis}}(T)$ is rather scarce at present because the matter is still in nonperturbative region $T/T_c \sim 1-2$. We will first make a simplest threshold ansatz according to the similar one in Ref. [23]: $\Gamma_{\text{dis}}(T > T_{J/\psi}) = \infty$ and $\Gamma_{\text{dis}}(T < T_{J/\psi}) = 0$, where $T_{J/\psi}$ is the melting temperature of J/ψ . A more sophisticated parametrization of $\Gamma_{\text{dis}}(T)$ will be discussed later.

We assume the same p_T distribution for χ_c and ψ' as that for J/ψ and estimate their survival probabilities in a similar way as Eq. (3) with a common melting temperature $T_{\psi'} = T_{\chi_c} \equiv T_\chi$. Thus, the total survival probability of J/ψ is obtained by taking into account the total feed-down fraction f_{FD} from $\chi_c + \psi'$ to J/ψ as

$$S_{J/\psi}^{\text{tot}} = (1 - f_{\text{FD}})S_{J/\psi} + f_{\text{FD}}S_\chi, \quad (4)$$

where S_χ denotes the survival probability of χ_c or ψ' .

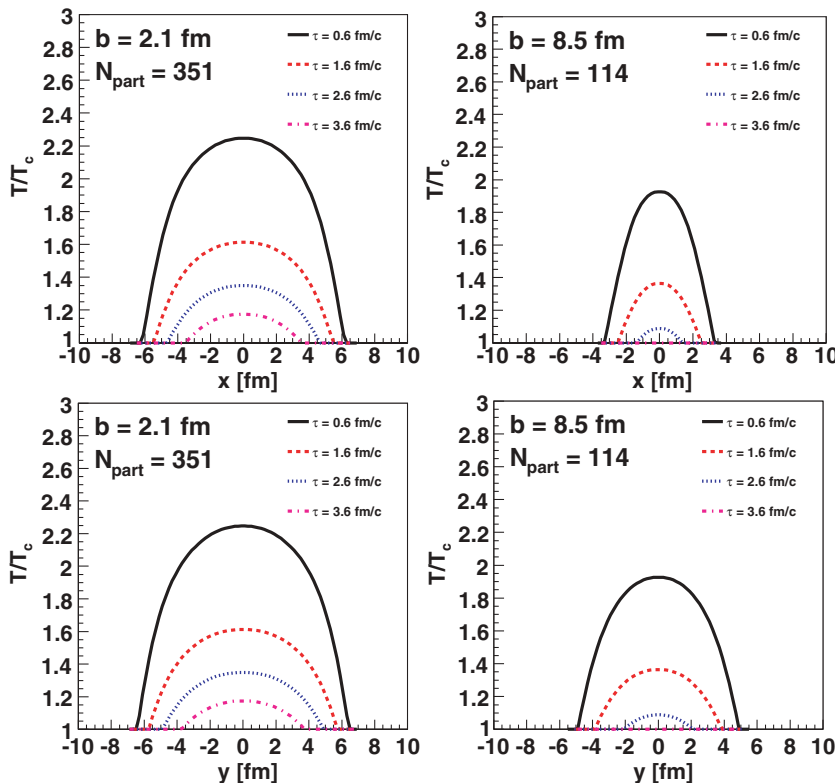


FIG. 1. (Color online) Local temperature in the unit of T_c as functions of the transverse coordinates, x (upper) and y (lower), for various proper time (τ) at midrapidity ($\eta_s = 0$). The impact parameter $b = 2.1 \text{ fm}$ (the left panel) corresponds to $\langle N_{\text{part}} \rangle = 351$, whereas $b = 8.5 \text{ fm}$ (the right panel) corresponds to $\langle N_{\text{part}} \rangle = 114$.

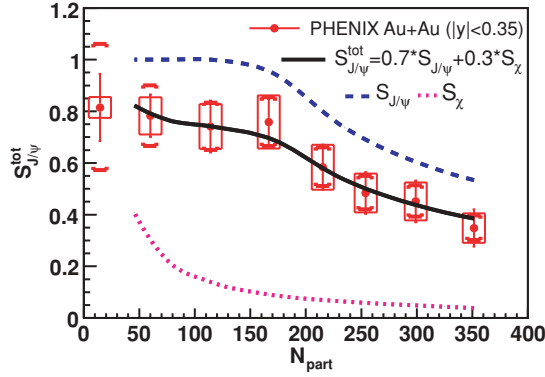


FIG. 2. (Color online) Survival probabilities $S_{J/\psi}^{\text{tot}}$ (solid line), $S_{J/\psi}$ (dashed line), and S_{χ} (dotted line) in the hydro+ J/ψ model as a function of the number of participants N_{part} with $(T_{J/\psi}, T_{\chi}, f_{\text{FD}}) = (2.02T_c, 1.22T_c, 0.30)$. Filled symbols are the experimental survival probability in the midrapidity of J/ψ in Au+Au collisions at RHIC [7,11].

Although the precise values of $T_{J/\psi, \chi, \psi'}$ should be eventually calculated from lattice QCD simulations with dynamical light quarks, we take those as free parameters to fit the present experimental data of $S_{J/\psi}^{\text{tot}}$. The feed-down fraction f_{FD} is also treated as a free parameter. At present, its value measured at different energies has a large uncertainty, 15–74% [24]. Moreover, it may well depend on collision energy and has not yet been measured at the RHIC energy. As we will see below, the shape (magnitude) of $S_{J/\psi}^{\text{tot}}$ as a function of N_{part} is essentially determined by $T_{J/\psi}$ (f_{FD}).

Experimental survival probability of J/ψ in the midrapidity region in Au+Au collisions at RHIC is shown as filled circles in Fig. 2, where gluon shadowing and nuclear absorption with $\sigma_{\text{abs}} = 1$ mb are taken into account as CNM effects [11]. Bars and brackets correspond to the uncorrelated and correlated errors with respect to N_{part} , respectively [7]. Boxes correspond to the uncertainties associated with the nuclear absorption cross section of 0–2 mb [11].

The solid line corresponds to the net survival probability $S_{J/\psi}^{\text{tot}}$ obtained from our hydro+ J/ψ model with the best fit parameters ($\chi^2 = 0.86$ for $N_{\text{part}} \geq 50$),

$$(T_{J/\psi}, T_{\chi}, f_{\text{FD}}) = (2.02T_c, 1.22T_c, 0.30), \quad (5)$$

whereas $S_{J/\psi}$ and S_{χ} are shown by dashed and dotted lines, respectively.

Decreasing of $S_{J/\psi}^{\text{tot}}$ with increasing N_{part} is reproduced quite well with the scenario of sequential melting in expanding fluid: Onset of genuine J/ψ suppression around $N_{\text{part}} \sim 160$ can be clearly seen by the dashed line in Fig. 2, which results from the fact that the highest temperature of the matter reaches to $T_{J/\psi}$ at this centrality (see Fig. 1 for comparison). Gradual decrease of $S_{J/\psi}^{\text{tot}}$ above $N_{\text{part}} \sim 160$ reflects the fact that the transverse area with $T > T_{J/\psi}$ increases.

Sensitivity of $S_{J/\psi}^{\text{tot}}$ to the melting temperature of J/ψ is shown in Fig. 3. Here, f_{FD} and T_{χ} are fixed to be 30% and $1.22T_c$, respectively, as given in Eq. (5). The shape of the theoretical curve of $S_{J/\psi}^{\text{tot}}$ is sensitive to $T_{J/\psi}$: Even the 6% change of the melting temperature of J/ψ from the

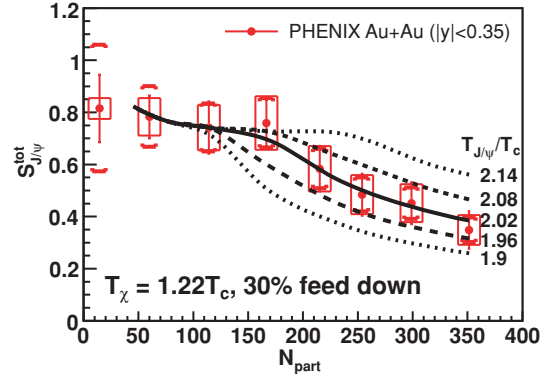


FIG. 3. (Color online) Survival probability $S_{J/\psi}^{\text{tot}}$ as a function of the number of participants N_{part} , where melting temperature of J/ψ is $1.90T_c$ (dashed), $1.96T_c$ (dotted), $2.02T_c$ (solid with open circles), $2.08T_c$ (dash-dotted), and $2.14T_c$ (solid).

best fit value $2.02 T_c$ causes a substantial deviation from the experimental data. To make this point clearer, we show, in Fig. 4, the χ^2 contour plot in the plane of $T_{J/\psi}/T_c$ and T_{χ}/T_c with f_{FD} being fixed to 0.30. The cross symbol corresponds to Eq. (5), which gives minimum χ^2 . Solid and dashed lines correspond to the 1σ and 2σ contours, respectively. It is seen that $T_{J/\psi}$ can be determined in a narrow region around $2T_c$, whereas T_{χ} is not well determined because the feed-down effect is not a dominant contribution to $S_{J/\psi}^{\text{tot}}$.

$T_{J/\psi}$ is also insensitive to the nuclear absorption cross section. Taking $\sigma_{\text{abs}} = 0$ mb (2 mb) as an upper (lower) bound [11], we found $(T_{J/\psi}, T_{\chi}, f_{\text{FD}}) = (2.00T_c, 1.02T_c, 0.35)$ with minimum χ^2 of 0.97 for $N_{\text{part}} \geq 50$ [$(T_{J/\psi}, T_{\chi}, f_{\text{FD}}) = (2.02T_c, 1.02T_c, 0.15)$ with minimum χ^2 of 0.87 for $N_{\text{part}} \geq 50$]. The change of σ_{abs} affects only the overall normalization of $S_{J/\psi}^{\text{tot}}$, whose effect is mostly absorbed by the change of f_{FD} . In other words, the value of $T_{J/\psi}$ is intimately linked to the shape of $S_{J/\psi}^{\text{tot}}$ around $N_{\text{part}} \sim 160$.

It is noticeable that the RHIC data analyzed with the state-of-the-art hydrodynamics leads to a rather stable value for the melting temperature of J/ψ to be around $T/T_c \simeq 2$ [25]. In fact, this number is not in contradiction to the result of

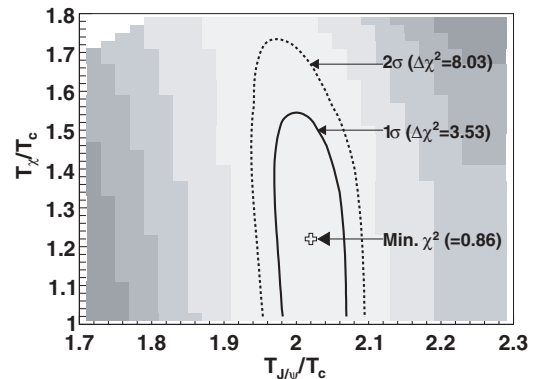


FIG. 4. χ^2 contour plot in $T_{J/\psi}/T_c - T_{\chi}/T_c$ plane with f_{FD} being fixed to 0.30. Cross symbol corresponds to $(T_{J/\psi}, T_{\chi}) = (2.02T_c, 1.22T_c)$, which gives minimum χ^2 . Solid and dashed lines correspond to the 1σ and 2σ contours, respectively.

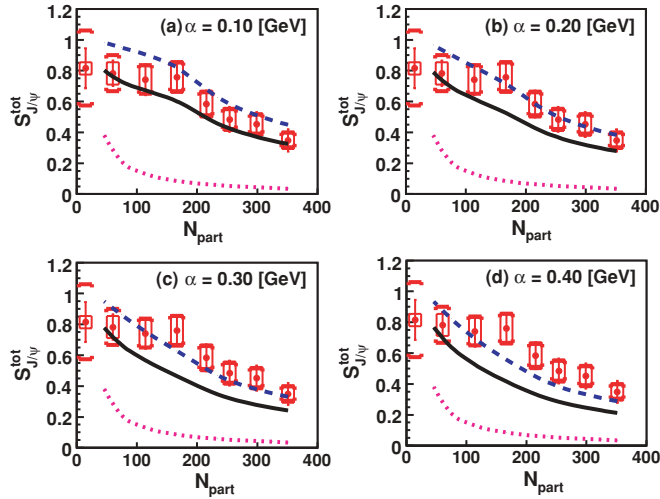


FIG. 5. (Color online) Survival probability $S_{J/\psi}^{\text{tot}}$ as a function of N_{part} , where melting temperatures of J/ψ and χ and feed-down fraction are $2.02T_c$, $1.22T_c$, and 30%. (a–d) The results using the decay width parametrized by Eq. (6) with α of 0.1, 0.2, 0.3, and 0.4 GeV, respectively.

recent quenched and full lattice QCD simulations that suggest the survival of J/ψ above T_c [3–5]. To make a quantitative comparison, however, we need to wait for further progresses in lattice QCD simulations with dynamical quarks [5].

The results presented so far are obtained by assuming that the decay width of charmonia changes abruptly from zero to infinity across the melting temperature. To make smooth connection with the scenario of the J/ψ dissociation due to thermal quarks and gluons in QGP, we introduce the following parametrization for the charmonia width motivated by the T dependence in [26]:

$$\Gamma_{\text{dis}}(T < T_{J/\psi}) = \alpha(T/T_c - 1)^2, \quad (6)$$

with $\Gamma_{\text{dis}}(T > T_{J/\psi}) = \infty$. α is nothing but the thermal width of J/ψ at $T/T_c = 2$. The J/ψ dissociation width in NLO perturbative QCD calculation suggests $\alpha > 0.4$ GeV [26], whereas we leave it as a free parameter to take into account the fact that the system is still in the nonperturbative regime.

Figure 5 shows the survival probability as a function of N_{part} , where the model calculations shown in Figs. 5(a)–5(d) are obtained for $\alpha = 0.1, 0.2, 0.3$, and 0.4 GeV, respectively. The melting temperatures of J/ψ and χ and feed-down fraction are fixed to be $2.02T_c$, $1.22T_c$, and 30%. It is seen that the suppression pattern has a smooth change from the shoulder shape to the monotonic shape as α increases. The data are not reproduced well for $\alpha > 0.1$ GeV. It is unclear whether the gap between the data and the solid curve for $\alpha > 0.1$ GeV can be filled by the charmonium regeneration, because the regeneration is a monotonically increasing function of N_{part} .

Let us here make a brief remark on the J/ψ suppression at forward rapidity that is reported to be even stronger than that at midrapidity [7]. Experimentally, there is still a sizable systematic error for relative normalization between the two cases [11]. This could reduce the apparent difference of R_{AA} between the data at mid- and forward rapidities. Theoretically, a part of the difference may come from gluon saturation. According to color glass condensate (CGC) model, the charm production at forward rapidity ($y \sim 2$) may become as low as 60% of that at midrapidity in most central Au+Au collisions [27]. If we take this number literally, the J/ψ suppressions in both rapidities become almost comparable. There is also a possibility that σ_{abs} depends on the J/ψ rapidity and is larger in forward rapidity [28]. With all these uncertainties, we leave the J/ψ suppression in forward rapidity as an interesting subject for future works.

In summary, we have investigated J/ψ yield at midrapidity in the relativistic heavy-ion collisions by using hydro+ J/ψ model that serves as a dynamical approach to the sequential charmonia suppression. The space-time dependence of the local temperature T of the fluid is described by the state-of-the-art relativistic hydrodynamic simulations, and the J/ψ dissociation is assumed when T exceeds the melting temperature $T_{J/\psi}$. Comparing the survival probability $S_{J/\psi}^{\text{tot}}$ from the hydro+ J/ψ model with the one in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV obtained by the PHENIX experiment at RHIC, observed J/ψ suppression pattern is described quite well with $T_{J/\psi}/T_c \simeq 2$. This value is determined primarily by the N_{part} dependence of $S_{J/\psi}^{\text{tot}}$ and is insensitive to the magnitude of the nuclear absorption. Occurrence of the suppression of directly produced J/ψ around $2 T_c$ is in accordance with the spectral analysis of J/ψ in lattice QCD simulations. Trend of the suppression can be described well with the small decay width inside the fluid below the melting temperature.

There are a number of issues to be studied further: They include (i) better treatment of the J/ψ propagation in hot matter beyond the free-streaming or the complete thermalization, (ii) detailed study on the azimuthal anisotropy (v_2) of J/ψ , (iii) effect of relative velocity between J/ψ and the hot fluid on the p_T distribution of J/ψ [29], (iv) better understanding of the suppression in forward rapidity in connection with the CGC, (v) the application to lighter system such as Cu+Cu, (vi) effect of the charmonia regeneration processes to $S_{J/\psi}^{\text{tot}}$ in conjunction with the sequential suppression, and (vii) the theoretical investigation of the melting temperatures and the widths of J/ψ , χ_c and ψ' in full QCD simulations.

The authors thank M. Natsuume and K. Rajagopal for the discussions on the J/ψ dissociation under the hot wind. This work was partially supported by JSPS grant No. 16-11332 (T. Gunji), No. 14204021 (H. Hamagaki), no. 18540254 (T. Hatsuda), and no. 18-10104 (T. Hirano).

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