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J/ψ suppression and enhancement in Au + Au collisions at the BNL RHIC

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Abstract

We consider J/ψ production in heavy ion collisions at RHIC energies in the statistical coalescence model with exact (canonical ensemble) charm conservation. Charm quark–antiquark pairs are assumed to be created in primary hard parton collisions, but open and hidden charm particles are formed at the hadronization stage according to the laws of statistical mechanics. The dependence of the J/ψ production on both the number of nucleon participants and the collision energy is studied. The model predicts J/ψ *suppression* for low energies, whereas at the highest RHIC energy the model reveals J/ψ *enhancement*.

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The experimental program for studies of the charmonium production in nucleus–nucleus ($A+A$) collisions at CERN SPS over last 15 year was mainly motivated by the suggestion of Matsui and Satz [1] to use the J/ψ meson as a probe of the state of matter created at the early stage of the collision. The original picture [1] (see also Ref. [2] for a modern review) assumes that charmonium states are produced in the primary collisions of nucleons from colliding nuclei. The number of created charmonia is then reduced because of inelastic interactions with sweeping nucleons of colliding nuclei. Additional suppression may occur due to J/ψ interaction with secondary hadrons ('co-movers') [3]. The probability to destroy a charmonium state increases obviously with the number of nucleon participants N_p. Similar behavior is expected when the collision energy $\sqrt{s}$ increases as the number of produced hadrons ('co-movers') becomes larger. This is known as *normal J/ψ suppression*. Furthermore, J/ψ (and other charmonia) are assumed to be formed mainly from $c\bar{c}$ pairs with invariant mass below the $D\overline{D}$ threshold [4]. A fraction of these subthreshold pairs in the total number, $N_{c\bar{c}}$, of created $c\bar{c}$ pairs also decreases with $\sqrt{s}$. Therefore, the ratio

$$R\left(N_p,\sqrt{s}\right) \equiv \frac{\langle J/\psi\rangle}{N_{c\bar{c}}} \quad (1)$$

is expected to decrease with increasing N_p and/or $\sqrt{s}$. Note that only a tiny fraction of $c\bar{c}$ pairs are transformed into charmonia, therefore, $N_c + N_{\bar{c}} \equiv 2N_{c\bar{c}}$ is approximately equal to the number of produced open charm and anticharm hadrons (D, $\overline{D}$, D^*, $\overline{D}^*$, Λ_c, $\bar{\Lambda}_c$ etc.). At large values of $\sqrt{s}$ and N_p formation of quark–gluon plasma (QGP) is expected which is

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supposed to be signaled by *anomalous* J/ψ *suppression* [2], i.e., a sudden and strong decrease of ratio (1) is considered as a signal of QGP formation. The above arguments show that a decrease of the ratio (1) with increasing N_p and/or $\sqrt{s}$ (J/ψ suppression) is an unambiguous consequence of the standard picture [1–3].

A very different approach of statistical J/ψ production, proposed in Ref. [5], assumes that J/ψ mesons are created at the hadronization stage similar to other (lighter) hadrons. The picture of J/ψ creation via c and $\bar{c}$ coalescence (recombination) was subsequently developed within different model formulations [6–11]. Similar to the suggestion of Ref. [5], charmonium states are assumed to be created at the hadronization stage of the reaction, but they are formed due to coalescence of c and $\bar{c}$, which were produced by primary hard parton collisions at the initial stage.

In this Letter the N_p and $\sqrt{s}$ dependences of ratio (1) will be studied for Au + Au collisions at RHIC energies. We use the canonical ensemble (c.e.) formulation of the statistical coalescence model (SCM) [8,11]. The number $N_{c\bar{c}}$ of the produced $c\bar{c}$ pairs, which is the input for the SCM calculations, will be estimated within the perturbative QCD (pQCD). The considered pQCD + SCM approach reveals both J/ψ *suppression* (at $N_{c\bar{c}} < 1$) and J/ψ *enhancement* (at $N_{c\bar{c}} \gg 1$) effects.

In the framework of the ideal hadron gas (HG) model in the grand canonical ensemble (g.c.e.) formulation hadron multiplicities are given by

$$N_j = \frac{d_j V}{2\pi^2} \int_0^\infty k^2\, dk \left[\exp\left(\frac{\sqrt{m_j^2 + k^2} - \mu_j}{T}\right) \pm 1\right]^{-1}, \tag{2}$$

where V and T correspond to the volume [1] and temperature of the HG, m_j and d_j denote particle masses and degeneracy factors. Eq. (2) describes a quantum HG: Bose and Fermi distributions for mesons and (anti)baryons, respectively. Quantum effects, however, are found to be noticeable for pions only, so that Eq. (2) for all other hadrons can be simplified to the Boltzmann result:

$$N_j = \frac{d_j}{2\pi^2} V \exp\left(\frac{\mu_j}{T}\right) T m_j^2 K_2\left(\frac{m_j}{T}\right), \tag{3}$$

where K_2 is the modified Bessel function.

In the case of complete chemical equilibrium the chemical potential μ_j in Eq. (3) is defined as [14]

$$\mu_j = b_j\mu_B + q_j\mu_Q + s_j\mu_S + c_j\mu_C, \tag{4}$$

where b_j, q_j, s_j, c_j denote, respectively, the baryonic number, electric charge, strangeness and charm of hadron j. The baryonic chemical potential regulates a non-zero (positive) baryonic density of the HG system created in $A + A$ collisions. The chemical potentials μ_S and μ_C should be found as functions of T and μ_B from the requirements of zero value for the total strangeness and charm in the system, and the chemical potential μ_Q from the requirement of fixed ratio of the electric charge to the baryonic number (this ratio is defined by the numbers of protons and neutrons in the colliding nuclei).

Applications of the HG model for fitting the hadron abundances in particle and nuclear collisions revealed, however, a deviation of strange hadron multiplicities from the complete chemical equilibrium [15]. It was suggested that strange quarks and antiquarks are distributed among hadrons according to the laws of HG equilibrium, but the total number of strange quarks and antiquarks inside the hadrons is smaller than that in the equilibrium HG and it remains (approximately) constant during the lifetime of the HG phase. Therefore, not only the "strange charge" $N_s - N_{\bar{s}} = 0$ but also the "total strangeness" $N_s + N_{\bar{s}}$ should be then considered as a conserved quantity. In the language of thermodynamics, it means an introduction of an additional chemical potential $\mu_{|S|}$ which regulates now this new "conserved" number $N_s + N_{\bar{s}}$. Then an additional term, $(n_s^j + n_{\bar{s}}^j)\mu_{|S|}$, should be added to μ_j (4), where n_s^j and $n_{\bar{s}}^j$ are the numbers of strange quarks and antiquarks inside hadron j. Introducing the notation, $\gamma_s \equiv \exp(\mu_{|S|}/T)$ [15], one can implement this additional conservation law according to the following simple rule: the hadron multiplicities N_j (3) are multiplied by the factor $\gamma_s^{(n_s^j + n_{\bar{s}}^j)}$, e.g., the factor γ_s appears for K, $\overline{K}$, Λ, $\bar{\Lambda}$, Σ, $\overline{\Sigma}$, the factor γ_s^2 for Ξ, $\overline{\Xi}$ and the

[1] To avoid complications we neglect the excluded volume corrections. The thermodynamical consistent way to treat the excluded volume effects was suggested in Ref. [12] (see also [13] for further details). If the excluded volume parameter is the same for all hadrons, its effect is reduced only to rescaling of the volume V: all particle number ratios remain the same as in the ideal hadron gas.

factor γ_s^3 for $\Omega, \overline{\Omega}$. For mesons with hidden strangeness, like $\eta, \eta', \omega, \phi$, having the wave function of the form

$$C_u|u\bar{u}\rangle + C_d|d\bar{d}\rangle + C_s|s\bar{s}\rangle, \tag{5}$$

the factor $\gamma_s^{2|C_s|^2}$ is used. From fitting the data on hadron yields in particle and nuclear collisions it was found that $\gamma_s \leqslant 1$ for all known cases. The parameter γ_s is called, therefore, a strangeness suppression factor.

Recently, an analogous procedure was suggested for charm hadrons [7]. A new parameter γ_c has been introduced to treat simultaneously both open and hidden charm particles within statistical mechanic HG formulation. Multiplicities N_j (3) of single open charm and anticharm hadrons should be multiplied by the factor γ_c and charmonium states by the factor γ_c^2. In contrast to strangeness suppression in the HG ($\gamma_s \leqslant 1$), one observes an enhancement of charm hadron yields in comparison with their HG equilibrium values. It means that $\gamma_c \geqslant 1$ and this parameter is called a charm enhancement factor [7].

To take into account the requirement of zero "charm charge" of the HG in the exact form the c.e. formulation was suggested in Ref. [8]. In the c.e. formulation the charmonium multiplicities are still given by Eq. (3) as charmonium states have zero charm charge. The multiplicities (3) of *open* charm hadrons should be, however, multiplied by the 'canonical suppression' factor (see, e.g., [18]). This suppression factor is the same for all individual single charm states. It leads to the total open charm multiplicity N_O^{ce} in the c.e.:

$$N_O^{\text{ce}} = N_O \frac{I_1(N_O)}{I_0(N_O)}, \tag{6}$$

where N_O is the total g.c.e. multiplicity of all charm and anticharm mesons and (anti)baryons calculated with Eq. (3) and I_0, I_1 are the modified Bessel functions. For $N_O \ll 1$ one has $I_1(N_O)/I_0(N_O) \simeq N_O/2$ and, therefore, the c.e. total open charm multiplicity is strongly suppressed in comparison with the g.c.e. result. For $N_O \gg 1$ one finds $I_1(N_O)/I_0(N_O) \to 1$ and, therefore, $N_O^{\text{ce}} \to N_O$, i.e., the c.e. and the g.c.e results coincide. In high energy $A + A$ collisions the total number of strange and antistrange hadron is much larger than unity. Hence the strangeness conservation can be considered in the g.c.e. approach. The same is valid for the baryonic number and the electric charge. This is, however, not the case for the charm. At SPS energies the c.e. suppression effects are always important: even in most central Pb + Pb collisions the total number of open charm hadrons is expected to be smaller than one. It will be shown that the c.e. treatment of charm conservation remains crucially important also at RHIC energies for the studies of the N_p dependence of the open charm and charmonium production. Therefore, in what follows the baryonic number, electric charge and strangeness of the HG are treated according to the g.c.e. but the charm is considered in the c.e. formulation where an exact "charm charge" conservation is imposed.

Let us summarize the basic assumptions of our model consideration. Charm quark–antiquark pairs are assumed to be created in hard parton collisions at the early stage of $A + A$ reaction. In the subsequent evolution of the system the number of these pairs remains approximately constant and it is not necessarily equal to the equilibrium value. The deviation from the HG chemical equilibrium for charm should be taken into account by the charm enhancement factor γ_c. The *distribution* of created $c\bar{c}$ pairs among open and hidden charm hadrons is regulated by the statistical model according to Eq. (3) with account for the canonical suppression (6). Our statistical coalescence model in the c.e. is therefore formulated as:

$$N_{c\bar{c}} = \frac{1}{2}\gamma_c N_O \frac{I_1(\gamma_c N_O)}{I_0(\gamma_c N_O)} + \gamma_c^2 N_H, \tag{7}$$

where N_H is the total multiplicities of hadrons with hidden charm. Note that, as was already mentioned, most of $c\bar{c}$ pairs are transformed into open charm hadrons, therefore the second term in the right-hand side of Eq. (7) gives only a tiny correction to the first term. To find N_O and N_H we use Eq. (3) for the individual hadron thermal multiplicities in the g.c.e. and take summation over all known particles and resonances [19] with open and hidden charm, respectively.[2]

Provided that N_O, N_H and $N_{c\bar{c}}$ are known, γ_c can be found from Eq. (7). The J/ψ multiplicity is then

$$\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}^{\text{tot}}, \tag{8}$$

[2] Note that possible (very small) contributions of particles with double open charm are neglected in Eq. (7).

where $N_{J/\psi}^{\rm tot}$ is given by

$$N_{J/\psi}^{\rm tot} = N_{J/\psi} + {\rm Br}(\psi')N_{\psi'} + {\rm Br}(\chi_1)N_{\chi_1} + {\rm Br}(\chi_2)N_{\chi_2}, \tag{9}$$

$N_{J/\psi}, N_{\psi'}, N_{\chi_1}, N_{\chi_2}$ are calculated according to Eq. (3) and ${\rm Br}(\psi') \simeq 0.54$, ${\rm Br}(\chi_1) \simeq 0.27$, ${\rm Br}(\chi_2) \simeq 0.14$ are the decay branching ratios of the excited charmonium states into J/ψ.

Hence, to calculate the J/ψ multiplicity (8) in the SCM we need:
(1) the chemical freeze-out (hadronization) parameters V, T, μ_B for $A + A$ collisions at high energies (to calculate N_O and N_H in the right-hand side of Eq. (7));
(2) the number of $c\bar{c}$ pairs, $N_{c\bar{c}}$, created in hard parton collisions at the early stage of $A + A$ reaction (the left-hand side of Eq. (7)).

For RHIC energies the chemical freeze-out temperature T is expected to be close to that for the SPS energies: $T = 175 \pm 10$ MeV. To fix the volume V and baryonic chemical potential μ_B we use the parametrization of the total pion multiplicity [20]:

$$\frac{\langle\pi\rangle}{N_p} \simeq C\frac{(\sqrt{s} - 2m_N)^{3/4}}{(\sqrt{s})^{1/4}}, \tag{10}$$

where $C = 1.46\ {\rm GeV}^{-1/2}$ and m_N is the nucleon mass. For RHIC energies the nucleon mass in Eq. (10) can be neglected so that

$$\langle\pi\rangle \simeq CN_p\left(\sqrt{s}\right)^{1/2}. \tag{11}$$

Eq. (10) is in agreement with both the SPS data and the preliminary RHIC data in Au + Au collisions at $\sqrt{s} = 56$ GeV and $\sqrt{s} = 130$ GeV. The pion multiplicity (10) should be equated to the total HG pion multiplicity $N_\pi^{\rm tot}$ which includes the pions coming from resonance decays (similar to Eq. (9)). The HG parameters V and μ_B are found then as the solution of the following coupled equations:

$$\langle\pi\rangle = N_\pi^{\rm tot}(V, T, \mu_B) \equiv Vn_\pi^{\rm tot}(T, \mu_B), \tag{12}$$

$$N_p = Vn_B(T, \mu_B), \tag{13}$$

where n_B is the HG baryonic density. In these calculations we fix the temperature parameter T. The baryonic chemical potential for Au + Au collisions at RHIC energies is small ($\mu_B < T$) and decreases with the collision energy. Therefore, most of the thermal HG multiplicities become close to their limiting values at $\mu_B \to 0$. Consequently most of hadron ratios $N_j^{\rm tot}/N_i^{\rm tot}$ become independent of the collision energy [21]. The volume of the system is approximately proportional to the number of pions:

$$V \sim \langle\pi\rangle \sim N_p\left(\sqrt{s}\right)^{1/2}. \tag{14}$$

Note that $T = 170$–180 MeV leads to the HG value of the thermal ratio:

$$\frac{\langle\psi'\rangle}{\langle J/\psi\rangle} = \left(\frac{m_{\psi'}}{m_{J/\psi}}\right)^{3/2} \exp\left(-\frac{m_{\psi'} - m_{J/\psi}}{T}\right) = 0.04\text{–}0.05, \tag{15}$$

in agreement with the data [16] for central ($N_p > 100$) Pb + Pb collisions at the CERN SPS. This fact was first noticed in Ref. [17]. At small N_p as well as in $p + p$ and $p + A$ collisions the measured value of the $\langle\psi'\rangle/\langle J/\psi\rangle$ ratio is several times larger than its statistical mechanics estimate (15). Our analysis of the SCM will be, therefore, restricted to $A + B$ collisions with $N_p > 100$. We do not intend to describe the open and hidden charm production in $p + p$, $p + A$ and in very peripheral $A + B$ collisions within the SCM.

The number of directly produced $c\bar{c}$ pairs, $N_{c\bar{c}}$, in the left-hand side of Eq. (7) will be estimated in the Glauber approach. For $A + B$ collision at the impact parameter b, this number is given by the formula:

$$N_{c\bar{c}}(b) = ABT_{AB}(b)\sigma(NN \to c\bar{c} + X), \tag{16}$$

where $\sigma(NN \to c\bar{c} + X)$ is the cross section of $c\bar{c}$ pair production in $N + N$ collisions and $T_{AB}(b)$ is the nuclear overlap function (see Appendix A for details).

The cross section of $c\bar{c}$ pair production in $N + N$ collisions can be calculated in pQCD. Such calculations (in the leading order of pQCD) were first done in Ref. [22]. We use the next-to-leading order result presented in Ref. [23]. This result was obtained with the GRV HO [24] structure functions, the c-quark mass and the renormalization scale were fixed at $m_c = \mu = 1.3$ GeV to fit the available experimental data. We parametrize the $\sqrt{s}$-dependence of the cross section for $\sqrt{s} = 20$–200 GeV as:

$$\sigma(pp \to c\bar{c}) = \sigma_0\left(1 - \frac{M_0}{\sqrt{s}}\right)^\alpha\left(\frac{\sqrt{s}}{M_0}\right)^\beta, \tag{17}$$

with $\sigma_0 \approx 3.392$ μb, $M_0 \approx 2.984$ GeV, $\alpha \approx 8.185$ and $\beta \approx 1.132$. Note that free parameters of the pQCD calculations in Ref. [23] were fitted to the existing data, therefore, our parametrization (17) is also in agreement with the data on the total charm production in $p+p$ collisions.

The average number of participants ('wounded nucleons') in $A+B$ collisions at impact parameter b is given by [25]

$$N_p(b) = A \int_{-\infty}^{+\infty} dx \int_{-\infty}^{+\infty} dy\, T_A\left(\sqrt{x^2+y^2}\right) \times \left[1-\left(1-\sigma_{NN}^{\text{inel}} T_B\left(\sqrt{x^2+(y-b)^2}\right)\right)^B\right] + B \int_{-\infty}^{+\infty} dx \int_{-\infty}^{+\infty} dy\, T_B\left(\sqrt{x^2+(y-b)^2}\right) \times \left[1-\left(1-\sigma_{NN}^{\text{inel}} T_A\left(\sqrt{x^2+y^2}\right)\right)^A\right], \quad (18)$$

where $T_A(\vec{s})$ ($T_B(\vec{s})$) is the nuclear thickness function for the nucleus A (B) and $\sigma_{NN}^{\text{inel}}$ is the total inelastic cross section of $N+N$ interaction. To parametrize the $\sqrt{s}$-dependence of $\sigma_{NN}^{\text{inel}}$ we follow an assumption that in the energy range $\sqrt{s} = 10$–200 GeV it is proportional to the total NN cross section σ_{NN} and use the standard fit for σ_{NN} [19]:

$$\sigma_{NN}^{\text{inel}} \approx 0.7\sigma_{NN} \simeq 0.7\left(X_{pp}s^{\epsilon} + Y_{1pp}s^{-\eta_1} - Y_{2pp}s^{-\eta_2}\right), \quad (19)$$

where $\epsilon = 0.093$, $\eta_1 = 0.358$, $\eta_2 = 0.560$, $X_{pp} = 18.751$, $Y_{1pp} = 63.58$ and $Y_{2pp} = 35.46$.

Eqs. (16) and (18) provide parametric dependence of the number of produced $c\bar{c}$ pairs on the number of participating nucleons, $N_{c\bar{c}} = N_{c\bar{c}}(N_p)$, which is shown in Fig. 1 for Au + Au collisions. It is seen that the dependence is represented by a straight line in a double-logarithmic scale, so that

$$N_{c\bar{c}} \sim (N_p)^k \quad (20)$$

for $N_p > 50$. We find that[3] $k = 1.31$–$1.35 \cong 4/3$. Using Eq. (17) one finds then the following behavior

[3] It is interesting to note that for the most central $A+A$ collisions ($N_p \approx 2A$) the number of $N_{c\bar{c}}$ has approximately the same dependence on the atomic weight of the colliding nuclei: $N_{c\bar{c}} \sim A^{4/3} \sim (N_p)^{4/3}$.

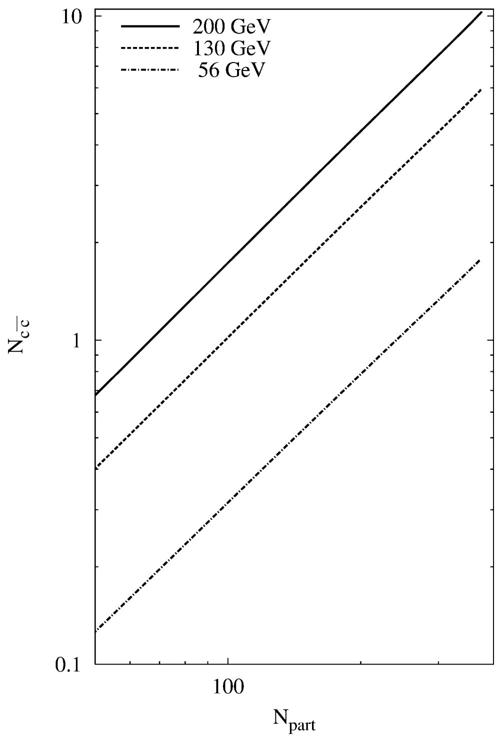

Fig. 1. $N_{c\bar{c}}$ versus N_p for $\sqrt{s} = 56, 130, 200$ GeV.

of $N_{c\bar{c}}$ at high energies:

$$N_{c\bar{c}} \sim (N_p)^k \left(\sqrt{s}\right)^{\beta}. \quad (21)$$

Now we are able to calculate the ratio R (1) in the SCM and study its dependence on N_p and $\sqrt{s}$. The dependence of R on the number of participants is shown in Fig. 2. It is seen that the ratio has *qualitatively* different behavior at different energies. At the lowest RHIC energy $\sqrt{s} = 56$ GeV, the SCM predicts decreasing of the ratio with the number of participants (J/ψ suppression). In contrast, at the highest RHIC energy $\sqrt{s} = 200$ GeV the ratio increases with the number of participant (J/ψ enhancement) for $N_p > 100$. Both suppression (at $N_p < 150$) and enhancement (at $N_p > 200$) are seen at the intermediate RHIC energy $\sqrt{s} = 130$ GeV.

Similarly, there are qualitatively different dependencies of R on the collision energy for small ($N_p = 100$) and for large ($N_p = 350$) numbers of participants. This can be seen in Fig. 3. Non-monotonic dependence of the ratio R on $\sqrt{s}$ is expected at $N_p = 100$. At $N_p = 350$, the ratio R increases monotoni-

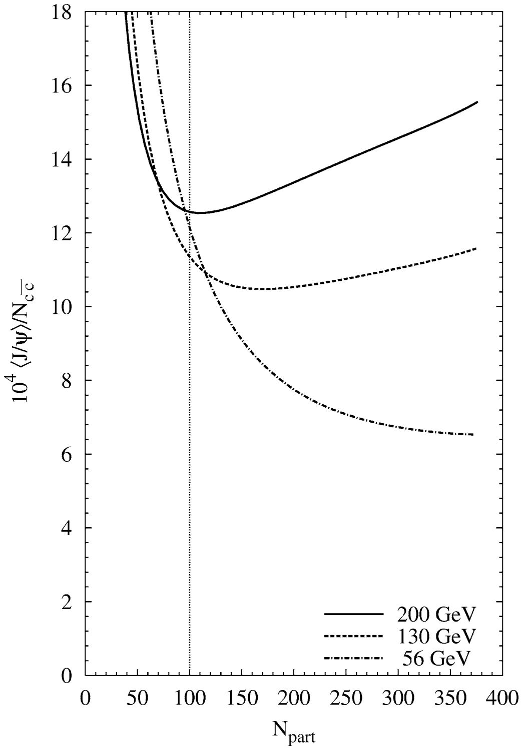

Fig. 2. $\langle J/\psi\rangle/N_{c\bar{c}}$ versus N_p for $\sqrt{s}=56, 130, 200$ GeV. The vertical line shows the lower bound of the applicability domain of the SCM.

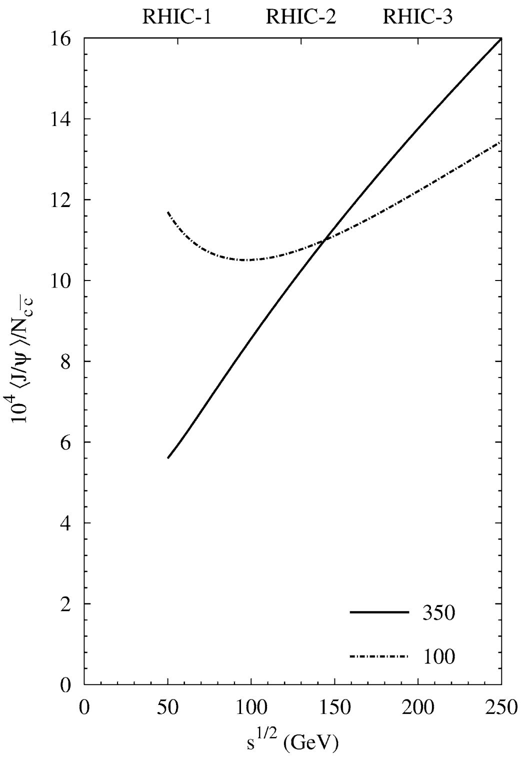

Fig. 3. $\langle J/\psi\rangle/N_{c\bar{c}}$ versus $\sqrt{s}$ for $N_p=100$ and 350.

cally with $\sqrt{s}$ at all RHIC energies $\sqrt{s}=56$–200 GeV. The minimum of R in this case corresponds to the energy region between the SPS and RHIC: $\sqrt{s}\approx 30$ GeV.

To understand the behavior of R it is instructive to study the limiting cases: $N_{c\bar{c}}\ll 1$ and $N_{c\bar{c}}\gg 1$. Neglecting the hidden-charm term in Eq. (7) one finds for $N_{c\bar{c}}\ll 1$:

$$N_{c\bar{c}}\simeq \frac{1}{4}\gamma_c^2 N_O^2, \tag{22}$$

hence,

$$R\equiv \frac{\langle J/\psi\rangle}{N_{c\bar{c}}}\simeq \frac{N_{J/\psi}^{\rm tot}}{N_O^2/4}\sim \frac{1}{V}\sim N_p^{-1}\left(\sqrt{s}\right)^{-0.5}. \tag{23}$$

Eq. (23) shows *universal* $1/V$ suppression of the ratio R. This ratio decreases as N_p^{-1} and $(\sqrt{s})^{-0.5}$ and the shape of this *J/ψ suppression* is essentially independent of the functional dependence of $N_{c\bar{c}}$ on N_p and $\sqrt{s}$.

If $N_{c\bar{c}}\gg 1$ one finds from Eq. (7):

$$N_{c\bar{c}}\simeq \frac{1}{2}\gamma_c N_O, \tag{24}$$

so that $\gamma_c\simeq 2N_{c\bar{c}}/N_O\sim N_{c\bar{c}}/V$ and, hence,

$$R\equiv \frac{\langle J/\psi\rangle}{N_{c\bar{c}}} \simeq \frac{\gamma_c N_{J/\psi}^{\rm tot}}{\gamma_c N_O/2}\sim \frac{N_{c\bar{c}}}{V}\sim (N_p)^{k-1}\left(\sqrt{s}\right)^{\beta-0.5}. \tag{25}$$

According to Eq. (25) the ratio R increases with both N_p and $\sqrt{s}$. This *J/ψ enhancement* takes place due to the fact that $N_{c\bar{c}}$ increases with $\sqrt{s}$ and N_p much stronger $N_{c\bar{c}}\sim (N_p)^k(\sqrt{s})^\beta$ ($\beta\cong 1.1$, $k\cong 4/3$) than the system volume $V\sim\langle\pi\rangle\sim N_p(\sqrt{s})^{0.5}$.

It is seen from Fig. 1 that $N_{c\bar{c}}\ll 1$ at the lowest RHIC energy ($\sqrt{s}=56$ GeV) for small numbers of participants ($N_p=100$), hence, the SCM predicts the *J/ψ suppression*. In contrast, for the highest RHIC energy ($\sqrt{s}=200$ GeV) and large N_p the opposite limit $N_{c\bar{c}}\gg 1$ is reached. This leads to the *J/ψ enhancement*.

In conclusion, the production of J/ψ mesons is studied in Au + Au collisions at RHIC energies in the statistical coalescence model with exact charm conservation. Charm quark–antiquark pairs are assumed to be created in primary hard parton collisions at the early stage of $A + A$ reaction and the number of $c\bar{c}$ pairs is estimated within the pQCD. At the hadronization stage the c and $\bar{c}$ (anti)quarks are distributed among open charm and charmonium particles according to the hadron gas statistical mechanics in the canonical ensemble formulation. This SCM formulation requires additional γ_c parameter to adjust the c.e. HG picture with a given pQCD number, $N_{c\bar{c}}$, of created earlier $c\bar{c}$ pairs.

Decreasing of the $\langle J/\psi \rangle$ to $N_{c\bar{c}}$ ratio with the number of nucleon participants N_p is found at the lowest RHIC energy $\sqrt{s} = 56$ GeV (see Fig. 2). At fixed *small* number of participants ($N_p \approx 100$) the ratio R decreases with $\sqrt{s}$ up to $\sqrt{s} \approx 100$ GeV (see Fig. 3). Both these SQM predictions are similar to the standard picture [1,2] of J/ψ *suppression*. In contrast, an increase of the $\langle J/\psi \rangle$ to $N_{c\bar{c}}$ ratio with the collision energy is predicted for central Au + Au collisions ($N_p = 350$ in Fig. 3). Moreover, at the highest RHIC energy, the ratio R is expected to grow with the number of participants ($\sqrt{s} = 200$ GeV in Fig. 2), which is in drastic contradiction with the standard picture. The matter is that in the standard picture hidden charm mesons are supposed to be created *exclusively* in the primary (hard) nucleon–nucleon collisions. It is assumed that all other interaction can only destroy them. Especially strong suppression of charmonia is expected, according to the standard picture, in the quark–gluon plasma ('anomalous J/ψ suppression'). In contrast, the statistical coalescence model considers a possibility for charmonium states to be formed from c and $\bar{c}$ at the stage of the quark–gluon plasma hadronization. This possibility definitely cannot be ignored when the number of produced $c\bar{c}$ pairs per $A + A$ collision becomes large: $N_{c\bar{c}} \gg 1$ (this happens in central Au + Au collisions at the highest RHIC energy). In this case, c and $\bar{c}$ initially produced in different hard parton collisions can also recombine into a hidden charm meson. Therefore, an increase of the $\langle J/\psi \rangle$ to $N_{c\bar{c}}$ ratio should be expected.

Hot quark–gluon plasma is most probably formed at RHIC energies and this destroys all primarily produced charmonium states [26]. However, the hadronization of the quark–gluon plasma within the SCM reveals itself not only in J/ψ *suppression*, but also in J/ψ *enhancement*. Another interesting phenomena may also take place: when the number of $c\bar{c}$ pairs becomes large, two c quarks (or two $\bar{c}$) can combine with a light (anti)quark and form a double charmed (anti)baryon. These baryons are predicted by the quark model but have not been observed yet. We expect that double (and probably triple) charmed baryons may be discovered in the Au + Au collisions at RHIC [27].

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Appendix A. Nuclear geometry

The spherically symmetrical distribution of the nucleons in the Au-197 nucleus can be parametrized by a two-parameter Fermi function [28] (this parametrization is also known as Woods–Saxon distribution):

$$\rho(r) = \rho_0 \left[1 + \exp\left(\frac{r - c}{a}\right)\right]^{-1} \tag{A.1}$$

with $c \approx 6.38$ fm, $a \approx 0.535$ fm and ρ_0 is given by the normalization condition:

$$4\pi \int_0^\infty dr\, r^2 \rho(r) = 1. \tag{A.2}$$

The nuclear thickness distribution $T_A(b)$ is defined by the formula

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho\left(\sqrt{b^2 + z^2}\right), \tag{A.3}$$

and the nuclear overlap function is defined as

$$T_{AB}(b) = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, T_A\left(\sqrt{x^2 + y^2}\right) \times T_B\left(\sqrt{x^2 + (y-b)^2}\right). \quad (A.4)$$

From Eq. (A.2), one can deduce that the above functions satisfy the following normalization conditions:

$$2\pi \int_0^{\infty} db\, b T_A(b) = 1,$$
$$2\pi \int_0^{\infty} db\, b T_{AB}(b) = 1. \quad (A.5)$$

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