Statistical coalescence model
of $J/\psi$ production at the SPS and RHIC

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Abstract
A recently developed statistical coalescence model of the $J/\psi$ production is presented. The NA50 data on the $J/\psi$ suppression pattern and the transverse mass spectra in Pb+Pb collisions at the SPS are analyzed. The model predictions for the RHIC energies are formulated. The measurements of $J/\psi$ in Au+Au collisions at RHIC are crucial for disentangling the different scenarios of charmonia formation.

1 Introduction
The experimental studies of nucleus-nucleus (A+A) collisions at the SPS and RHIC provide a rich information on hadron observables (multiplicities and momentum spectra). An extensive experimental program is motivated by a possibility to create a new state of matter – the quark gluon plasma (QGP) – in a laboratory. Any theoretical description of the QGP requires a macroscopic approach: statistical mechanics to describe the static properties of the matter and hydrodynamics to describe the system evolution. The equilibrium hadron gas (HG) model describes remarkably well the hadron multiplicities measured in Pb+Pb and Au+Au collisions at top SPS ($\sqrt{s} = 17$ GeV per nucleon pair) [1] and RHIC ($\sqrt{s} = 130$ GeV) [2] energies, where the creation of QGP is expected.

The HG model assumes the following formula for the hadron thermal multiplicities in the grand canonical ensemble (g.c.e):

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

where $V$ and $T$ are the system volume and temperature, respectively, $m_j$ and $d_j$ denote particle masses and degeneracy factors. The particle chemical potential $\mu_j$ in Eq.(1) is defined as $\mu_j = b_j \mu_B + s_j \mu_S + c_j \mu_C$, where $b_j, s_j, c_j$
denote the baryonic number strangeness and charm of particle $j$. The baryonic chemical potential $\mu_B$ regulates the baryonic density of the HG system whereas strange $\mu_S$ and charm $\mu_C$ chemical potentials should be found from the requirement of zero value for the total strangeness and charm in the system (in our consideration we neglect small effects of a non-zero electrical chemical potential). The total multiplicities $N_{j}^{\text{tot}}$ in the HG model include the resonance decay contributions:

$$N_{j}^{\text{tot}} = N_{j} + \sum_{R} Br(R \rightarrow j)N_{R},$$

where $Br(R \rightarrow j)$ are the corresponding decay branching ratios. The hadron yield ratios $N_{j}^{\text{tot}}/N_{i}^{\text{tot}}$ in the g.c.e. are the functions of $T$ and $\mu_B$ and are independent of the volume parameter $V$.

The temperature parameters extracted from fitting the multiplicity data are approximately the same for the SPS and RHIC energies: $T = 170 \pm 10$ MeV \cite{1, 2}. This value is close to an estimate of the temperature $T_c$ for the QGP–HG transition obtained in Lattice QCD simulations at zero baryonic density (see e.g. \cite{3}). One may therefore argue that QGP formed at the early stage of A+A reaction hadronizes into a locally equilibrated HG, and the chemical composition of this hadron gas is weakly affected by the subsequent hadron rescatterings.

2 Statistical coalescence model of $J/\psi$ production

The production of charmonium states $J/\psi$ and $\psi'$ have been measured in A+A collisions at CERN SPS over the last 15 years by the NA38 and NA50 Collaborations. These studies were mainly motivated by the theoretical suggestion \cite{4} to use $J/\psi$ meson as a probe for deconfinement in A+A collisions.

Recently the thermal model \cite{5} and the statistical coalescence model (SCM) \cite{6, 7} (see also \cite{8, 9, 10}) for the charmonium production in A+A collisions were formulated. The total $J/\psi$ multiplicity, $N_{J/\psi}^{\text{tot}}$, in the thermal model \cite{5} is given by Eq. (2), where $N_{J/\psi}$, $N_{\psi'}$, $N_{\chi_1}$, $N_{\chi_2}$ are calculated according to Eq. (1) and $Br(\psi') \approx 0.54$, $Br(\chi_1) \approx 0.27$, $Br(\chi_2) \approx 0.14$ are the decay branching ratios of the excited charmonium states into $J/\psi$. The thermal model \cite{5} predicts that at high collision energies the $J/\psi$ to $\pi$ ratio is independent of $\sqrt{s}$ and the number of nucleon participants $N_p$. This is because both $\langle J/\psi \rangle$ and $\langle \pi \rangle$ multiplicities are proportional to the system volume and the hadronization temperature is expected to be approximately constant at high collision energies.
The SCM [6, 7] assumes that charmonium states are formed at the hadronization stage. This is similar to the thermal model [5]. However, in the SCM the charmonium states are produced via a coalescence of $c$ and $\bar{c}$ (anti)quarks created by the hard parton collisions at the early stage of A+A reaction. The number of created $c\bar{c}$ pairs, $N_{c\bar{c}}$, in hard parton collisions, differs in general from the result expected in the equilibrium HG. One needs then a charm enhancement factor $\gamma_c$ [6] to adjust the thermal HG results to the required average number, $\langle N_{c\bar{c}} \rangle$, of $c\bar{c}$ pairs. The open charm hadron yield is enhanced by a factor $\gamma_c$ and charmonium yield by a factor $\gamma_c^2$ in comparison with the equilibrium HG predictions. This leads to a difference between the thermal model and SCM predictions for charmonia multiplicities.

The canonical ensemble (c.e.) formulation of the SCM is [7]:

\[
\langle N_{c\bar{c}} \rangle = \frac{1}{2} \gamma_c N_O \frac{I_1(\gamma_c N_O)}{I_0(\gamma_c N_O)} + \gamma_c^2 N_H ,
\]

where $N_H$ and $N_O$ are the HG multiplicities of all particles with hidden and open charm, respectively. The canonical suppression factor $I_1/I_0$ in Eq.(3) is due to the exact charm conservation (see e.g., [12], $I_0$ and $I_1$ are the modified Bessel functions).

If $\langle N_{c\bar{c}} \rangle$ is known, Eq.(3) can be used to find the charm enhancement factor $\gamma_c$ and calculate then the $J/\psi$ multiplicity:

\[
\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}^{tot} ,
\]

where $N_{J/\psi}^{tot}$ is the total (thermal plus excited charmonium decays) HG $J/\psi$ multiplicity.

Note that the second term in the right-hand side of Eq.(3) gives only a tiny correction to the first term, i.e. most of the created $c\bar{c}$ pairs are transformed into the open charm hadrons. Eqs.(3,4) lead then to:

\[
\langle J/\psi \rangle \cong \langle N_{c\bar{c}} \rangle \frac{N_{J/\psi}^{tot}}{(N_O/2)^2} , \quad \langle N_{c\bar{c}} \rangle \ll 1 ;
\]

\[
\langle J/\psi \rangle \cong \langle N_{c\bar{c}} \rangle^2 \frac{N_{J/\psi}^{tot}}{(N_O/2)^2} , \quad \langle N_{c\bar{c}} \rangle \gg 1 . \quad (5, 6)
\]

Eq.(3) assumes an exact conservation of $N_c - N_{\bar{c}} \equiv 0$ and ‘statistical fluctuations’ of $N_{c\bar{c}} \equiv (N_c + N_{\bar{c}})/2$ numbers. A more accurate treatment with

\footnote{This is formally analogous to the introduction of the strangeness suppression factor $\gamma_s < 1$ [4] in the HG model.}
‘dynamical’ (Poisson-like) distribution of $N_{c\bar{c}}$ leads to \[8\]:

$$
\langle J/\psi \rangle \cong \langle N_{c\bar{c}} \rangle \left(1 + \langle N_{c\bar{c}} \rangle\right) \frac{N_{J/\psi}^{\text{tot}}}{\langle N_O/2 \rangle^2}. \tag{7}
$$

Eq.\,(7) coincides with Eqs.\,(3,4) at both $\langle N_{c\bar{c}} \rangle << 1$ and $\langle N_{c\bar{c}} \rangle >> 1$ limits (see Eqs.\,(3,4)). This is because at $\langle N_{c\bar{c}} \rangle << 1$ the probabilities to create zero, $P(0) \approx 1 - \langle N_{c\bar{c}} \rangle$, and one, $P(1) \approx \langle N_{c\bar{c}} \rangle$, $c\bar{c}$ pairs are only important. On the other hand, at $\langle N_{c\bar{c}} \rangle >> 1$ the statistical and dynamical fluctuations of $N_{c\bar{c}}$ both obey the Poisson law distribution.

### 3 $J/\psi$ suppression in Pb+Pb collisions at the SPS

The centrality dependence of $\langle N_{c\bar{c}} \rangle$ in A+B nucleus-nucleus collisions can be calculated in Glauber’s approach, $\langle N_{c\bar{c}} \rangle(b) = \sigma_{c\bar{c}}^{NN}T_{AB}(b)$, where $b$ is the impact parameter, $T_{AB}(b)$ is the nuclear overlap function and $\sigma_{c\bar{c}}^{NN}$ is the $c\bar{c}$ production cross section for nucleon-nucleon collisions. As discussed in Ref.\,[9], the deconfined medium can substantially modify charm production at the SPS, i.e., $\sigma_{c\bar{c}}^{NN}$ in A+B collisions can be different from the corresponding cross section measured in a nucleon-nucleon collision experiment. The present analysis treats $\sigma_{c\bar{c}}^{NN}$ at the SPS energy as a free parameter. Its value is fixed by fitting the NA50 data.

In the NA50 experiments \[13\] the Drell-Yan muon pair multiplicity (either measured or calculated from the minimum bias data) is used as a reference for the $J/\psi$ “suppression pattern”. The number of Drell-Yan pairs is also proportional to the number of primary nucleon-nucleon collisions: $\langle D\gamma' \rangle(b) = \sigma_{D\gamma'}^{NN}T_{AB}(b)$, where $\sigma_{D\gamma'}^{NN}$ is the nucleon-nucleon production cross section of $\mu^+\mu^-$ Drell-Yan pairs. The prime means that the pairs should satisfy the kinematical conditions of the NA50 spectrometer. As the Drell-Yan cross section is isospin dependent, an average value is used: $\sigma_{D\gamma'}^{NN} = \sigma_{D\gamma'}^{AB}/(AB)$. For the case of Pb+Pb collisions, $A = B = 208$ and $\sigma_{D\gamma'}^{PbPb} = 1.49 \pm 0.13 \, \mu b$ \[13\].

The quantity to be studied is the ratio

$$
R_{D\gamma}(b) \equiv \frac{\eta B_{\mu\mu}^{J/\psi} \langle J/\psi \rangle(b)}{\langle D\gamma' \rangle(b)} \tag{8}
$$

$$
= \eta \frac{B_{\mu\mu}^{J/\psi}}{\sigma_{D\gamma'}^{NN}} \frac{\sigma_{c\bar{c}}^{NN}T_{AB}(b)}{N_{\mu}(b)} \frac{n_{J/\psi}^{\text{tot}}(T,\mu_B)n_B(T,\mu_B)}{(n_O(T,\mu_B)/2)^2}.
$$
\(B^\psi_{\mu\mu} \approx 0.0588\) is the decay probability of \(J/\psi\) into \(\mu^+\mu^-\). Only the fraction \(\eta\) of \(\mu^+\mu^-\) pairs satisfying the kinematical conditions of the NA50 spectrometer can be registered. We treat \(\eta\) in Eq. (8) as one more model free parameter.

In the NA50 experiment, the neutral transversal energy \(E_T\) of produced particles was used to measure centrality of the collisions. This variable, however, provides a reliable measure of the centrality only if it does not exceed a certain maximum value: \(E_T < 100\) GeV (see Ref. [8]). The average number of participants is a linear function of the transversal energy, \(\bar{N}_p = E_T/q\), in the domain \(E_T < 100\) GeV (\(q \approx 0.274\) GeV). At \(E_T > 100\) GeV the number of \(\bar{N}_p\) does not change essentially as \(E_T\) grows. Therefore, the data at \(E_T > 100\) GeV do not represent a centrality dependence of the \(J/\psi\) suppression pattern but rather its dependence on fluctuations of the stopping energy at approximately fixed number of participants. The influence of such fluctuations on \(J/\psi\) multiplicity can be studied in the framework of the SCM model [14].

Fig. 1: The dependence of the \(J/\psi\) to Drell-Yan ratio on the transversal energy. The normal nuclear suppression curve is obtained at \(\sigma_{abs} = 6.4\) mb. The SCM lines are calculated using Eq. (8). The vertical line shows the applicability domain of the SCM, \(N_p > 100\).

The SCM fit of the NA50 data with Eq. (8) is shown in Fig. 1 (see Refs. [8, 14] for details). The model parameters are:

\[
\sigma^{NN}_{c\bar{c}} \approx 35.7\ \mu b , \quad \eta \approx 0.13 ,
\]

with \(T\) and \(\mu_B\) fixed by hadron yield data. The model requires rather large enhancement for the open charm production (up to a factor of about 3.5 within the rapidity window of the NA50 spectrometer). A direct measurement of
the open charm in Pb+Pb at CERN SPS by NA60 would allow to test this prediction.

The SCM does not describe the NA50 data at small values of $E_T$ (the peripheral collisions with $E < 27$ GeV). This can be also seen from the $\psi'$ data. For $T \approx 170$ MeV the value of the thermal ratio is $\langle \psi' \rangle / \langle J/\psi \rangle \approx 0.04$. This is in agreement with data in Pb+Pb collisions at SPS for $N_p > 100$, but is in contradiction with data in p+p, p+A and very peripheral A+A collisions. This fact was first noticed in Ref. [15].

4 $J/\psi$ enhancement in A+A Collisions at the RHIC

The number of directly produced $c\bar{c}$ pairs at the RHIC energies can be estimated in the pQCD approach and used then as the input for the SCM. The pQCD calculations for $c\bar{c}$ production cross sections were first done in Ref.[16]. For the cross section $\sigma(pp \to c\bar{c})$ of the charm production in p+p collisions we use the results presented in Ref.[17]. This leads to the value of $\sigma(pp \to c\bar{c}) \approx 0.35$ mb at $\sqrt{s} = 200$ GeV and the $\sqrt{s}$-dependence of the cross section for $\sqrt{s} = 10 \div 200$ GeV is parameterized as [10]:

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

with $\sigma_0 \approx 3.392$ mb, $M_0 \approx 2.984$ GeV, $\alpha \approx 8.185$ and $\beta \approx 1.132$.

The number of produced $c\bar{c}$ pairs in A+A collisions is proportional to the number of primary N+N collisions, $N_{AA}^\text{coll}$, which in turn is proportional to $N_{4/3}^p$ [19]:

$$\langle N_{c\bar{c}} \rangle = N_{c\bar{c}}^{AA}(N_p) \frac{\sigma(pp \to c\bar{c})}{\sigma_{NN}^{\text{inel}}} \approx C \sigma(pp \to c\bar{c}) N_{4/3}^p,$$

where $\sigma_{NN}^{\text{inel}} \approx 30$ mb is the inelastic N+N cross sections, $C \approx 11$ barn$^{-1}$.

The results of the SCM can be studied analytically according to Eqs.(5,6) in the limiting cases of small and large numbers of $\langle N_{c\bar{c}} \rangle$. For $N_{c\bar{c}} \ll 1$ one finds:

$$R \equiv \frac{\langle J/\psi \rangle}{\langle N_{c\bar{c}} \rangle} \approx \frac{4N_{4/3}^{tot}}{N_O^2} \sim \frac{1}{V} \sim \frac{1}{\langle \pi \rangle} \sim \left(\sqrt{s}\right)^{-1/2} N_p^{-1}$$

where we use the energy dependence of the pion multiplicity per nucleon participant $\langle \pi \rangle / N_p \propto (\sqrt{s})^{1/2}$ [18] which approximately works in the SPS–RHIC energy region. The behavior [12] corresponds to the $J/\psi$ suppression: the ratio $R$ decreases with increasing of both $\sqrt{s}$ and $N_p$. This takes place at
the SPS: this energy is still too “low” as \( \langle N_{c\tau} \rangle < 1 \) even in the most central Pb+Pb collisions. However, the behavior of the \( J/\psi \) to \( N_{c\tau} \) ratio is changed dramatically at the RHIC energies [10] (see Fig. 2 and Ref. [10] for details).

In central Au+Au collisions at \( \sqrt{s} = 200 \text{ GeV} \) the expected value of \( \langle N_{c\tau} \rangle \) is essentially larger than unit. For \( \langle N_{c\tau} \rangle >> 1 \) one finds (\( \beta \simeq 1.1 \)):

\[
R \equiv \frac{\langle J/\psi \rangle}{\langle N_{c\tau} \rangle} \approx \frac{2\langle N_{c\tau} \rangle}{N_O} \sim \frac{\langle N_{c\tau} \rangle}{V} \sim \frac{\langle N_{c\tau} \rangle}{\langle \pi \rangle} \sim (\sqrt{s})^{\beta - 1/2} N_p^{1/3}. \tag{13}
\]

5 The \( m_T \)-spectra of \( J/\psi \) and \( \psi' \) and QGP hadronization

In Ref. [20] we formulated the hypothesis that the kinetic freeze-out of \( J/\psi \) and \( \psi' \) mesons takes place directly at hadronization. The effect of rescattering in the hadronic phase was recently studied within a “hydro + cascade” approach [21, 22]. A+A collisions are considered there to proceed in three stages: hydrodynamic QGP expansion (“hydro”), transition from QGP to HG (“switching”) and the stage of hadronic rescatterings and resonance decays (“cascade”). The switching from hydro to cascade takes place at \( T = T_c \), where the spectrum of hadrons leaving the surface of the QGP–HG transition is taken as an input for the subsequent cascade calculations. The results of Refs. [21, 22] suggest
that the transverse momentum spectra of $\Omega$ is only weakly affected during the cascade stage\(^2\) and give therefore a straightforward measure of the collective hydro velocity at the ‘switching’ surface $T = T_c$. In Ref. [23] we demonstrated that in Pb+Pb collisions at 158 A·GeV the $m_T$-spectra of $\Omega^\pm$ [24] can be explained simultaneously with the $m_T$-spectra of $J/\psi$ and $\psi'$ mesons [25] using the same set of the hadronization parameters.

Assuming the fluid freeze-out at constant temperature $T$, the transverse mass spectrum of $i$-th hadron species in cylindrically symmetric and longitudinally boost invariant fluid expansion equals approximately to (see Ref. [23] for further references and details):

$$\frac{dN_i}{m_T dm_T} \propto \sqrt{m_T} \exp \left( - \frac{m_T (1 + \frac{1}{2} v_T^2)}{T} \right) I_0 \left( \frac{p_T v_T}{T} \right), \quad (14)$$

where $m_T = (m_i^2 + p_T^2)^{1/2}$ and $v_T$ is the average transverse flow velocity.

\[\text{Fig. 3: The } m_T\text{-spectra measured at midrapidity in Pb+Pb at 158 A·GeV by WA97 [24] for } \Omega \text{ and by NA50 [25] for } J/\psi \text{ and } \psi' \text{ are presented (in arbitrary units) versus } m_T - m. \text{ The solid lines correspond to Eq.(14) with } T = 170 \text{ MeV and } v_T = 0.19. \]

In Fig. 3 we present the fit with Eq.(14) of the measured $m_T$-spectra. The temperature is fixed as $T = 170$ MeV and $v_T$ is considered as a free parameter. The shapes of all spectra are simultaneously reproduced at $v_T = 0.19 \pm 0.02$.

\(^2\)The corresponding calculation for charmonia are not yet performed within this model.
6 Conclusions

Statistical hadronization of the QGP is probably an important source of $J/\psi$ production. Within the SCM the NA50 data on the $J/\psi$ production in Pb+Pb at 158 A-GeV can be fitted (see Fig. 1) for central collisions $N_p > 100$. A large enhancement of the open charm over an extrapolation from the p+p data is however required. A direct measurement of the open charm in Pb+Pb at CERN SPS by NA60 would allow to test the SCM selfconsistency.

The SCM predicts that the $J/\psi$ suppression at the SPS should be changed into the $J/\psi$ enhancement in central Au+Au collisions at the RHIC energies (see Fig. 2).

The shapes of $m_T$-spectra for $\Omega$, $J/\psi$ and $\psi'$ are simultaneously reproduced in the hydrodynamical picture of the QGP hadronization with $T = 170$ MeV, $\tau_T = 0.19 \pm 0.02$. This supports the hypothesis that formation and the kinetic freeze-out of charmonia occurs at the hadronization.

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