Open Charm Enhancement in Pb+Pb Collisions at SPS

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The statistical coalescence model for the production of open and hidden charm is considered within the canonical ensemble formulation. The data for the J/ψ multiplicity in Pb+Pb collisions at 158 A·GeV are used for the model prediction of the open charm yield. We find a strong enhancement of the open charm production, by a factor of about 2–4, over the standard hard-collision model extrapolation from nucleon-nucleon to nucleus-nucleus collisions. A possible mechanism of the open charm enhancement in A+A collisions at the SPS energies is proposed.

The charmonium states J/ψ and ψ' have been measured in nucleus-nucleus (A+A) collisions at CERN SPS over the last 15 years by the NA38 and NA50 Collaborations. This experimental program was motivated by a suggestion [1] to use the J/ψ as a probe of the state of matter created in the early stage of the collision. In this approach a significant suppression of J/ψ production relative to Drell–Yan lepton pairs is predicted when going from peripheral to central Pb+Pb interactions at 158 A·GeV. This is originally attributed to the formation of a quark-gluon plasma, but could be also explained in microscopic hadron models as secondary collision effects (see [2] and references therein).

The statistical approach, formulated in Ref. [3], assumes that J/ψ mesons are created at hadronization according to the available hadronic phase-space similar to other (lighter) hadrons. We call this a hadron gas (HG) model. The HG model offers a natural explanation of the proportionality of the J/ψ and pion yields in nuclear collisions.

Recently a picture of the J/ψ creation via coalescence (recombination) of charmed quarks was developed within several model approaches [4–7]. Similar to the HG model [3], the charmonium states are assumed to be formed at the hadronization stage. However, they are produced as a coalescence of created earlier c and $\overline{c}$ quarks and therefore the multiplicities of open and hidden charm hadrons are connected in the coalescence models. In Ref. [5] the charm quark-antiquark pairs are assumed to be created at the early stage of A+A collision and the average number of directly produced c-$\overline{c}$ pairs, $N_{c\overline{c}}^{dir}$, is fixed by the model consideration based on the hard scattering approach. This requires the introduction of a new parameter in the HG approach – the charm enhancement factor γ_c [5]. This is analogous to the introduction of the strangeness suppression factor γ_s [8] in the HG model, where the total strangeness observed is smaller than its thermal equilibrium value. Within this approach the open charm hadron yield is enhanced by a factor γ_c and the charmonium yield by a factor γ_c^2 in comparison with the equilibrium HG predictions.

As the total number of charmed hadrons is expected to be smaller than unity, even for the most central Pb+Pb collisions at the SPS energy, an exact charm conservation within the canonical ensemble (c.e.) should be imposed. This has been done in Ref. [9]. Note also that the c.e. formulation was successfully used in Ref. [10] to calculate the open charm hadron abundances in e^+e^- collisions with an experimental input of the total open charm production.

In this letter we consider the c.e. formulation [9] of the statistical coalescence model [5]. The experimental value of the J/ψ multiplicity $\langle J/\psi\rangle$ will be used to predict the open charm yield within the statistical coalescence model. We find a strong enhancement of the open charm production, by a factor of about 3, over the standard hard-collision model extrapolation from nucleon-nucleon to A+A collisions.

In the grand canonical ensemble (g.c.e.) the thermal multiplicities of both open charm and charmonium states are given as (Bose and Fermi effects are negligible):

$$N_j \;=\; \frac{d_j V\; e^{\mu_j/T}}{2\pi^2}\; T\; m_j^2\; K_2\left(\frac{m_j}{T}\right)\;, \tag{1}$$

where V and T correspond to the volume* and temperature of HG system, m_j, d_j denote particle masses and degeneracy factors and K_2 is the modified Bessel function. The particle chemical potential μ_j in Eq.(1) is defined as

$$\mu_j \;=\; b_j\mu_B \;+\; s_j\mu_S \;+\; c_j\mu_C\;, \tag{2}$$

where b_j, s_j, c_j denote the baryonic number strangeness and charm of particle j. The baryonic chemical potential μ_B regulates the baryonic density of the HG system whereas strange μ_S and charm μ_C chemical potentials should be found from the requirement of zero value for the total strangeness and charm in the system (in our

*To avoid further complications we use ideal HG formulae and neglect excluded volume corrections.

consideration we neglect small effects of a non-zero electrical chemical potential).

In the c.e. formulation (i.e. when the requirement of zero "charm charge" of the HG is used in the exact form) the thermal charmonium multiplicities are still given by Eq.(1) as charmonium states have zero charm charge. The multiplicities (1) of *open* charm hadrons will, however, be multiplied by the additional 'canonical suppression' factor (see e.g. [11]). This suppression factor is the same for all individual open single charm states. It leads to the total open charm multiplicity N_O^{ce} in the c.e.:

$$N_O^{ce} \ = \ N_O \ \frac{I_1(N_O)}{I_0(N_O)} \ , \tag{3}$$

where N_O is the total g.c.e. multiplicity of all open charm and anticharm mesons and (anti)baryons calculated with Eq.(1) and I_0, I_1 are the modified Bessel functions. For large open charm multiplicity $N_O >> 1$ one finds $I_1(N_O)/I_0(N_O) \rightarrow 1$ and therefore $N_O^{ce} \rightarrow N_O$, i.e. the g.c.e. and c.e. results coincide. For $N_O << 1$ one has $I_1(N_O)/I_0(N_O) \cong N_O/2$ and $N_O^{ce} \cong N_O \cdot N_O/2$, therefore, N_O^{ce} is strongly suppressed (like $N_O/2$, $N_O << 1$) in comparison to the g.c.e. result, N_O .

Assuming the presence of the charm enhancement factor γ_c the statistical coalescence model within the c.e. is formulated as:

$$N_{c\bar{c}}^{dir} = \frac{1}{2} \ \gamma_c \ N_O \ \frac{I_1(\gamma_c N_O)}{I_0(\gamma_c N_O)} + \gamma_c^2 \ N_H \ , \tag{4}$$

when N_H is the total (thermal) multiplicity of particles with hidden charm. Therefore, the baryonic number, strangeness and electric charge of the HG system are treated in our approach according to the g.c.e. but charm is considered in the c.e. formulation where the exact charge conservation is imposed.

We will proceed with Eq.(4) in the following way. As the $\langle J/\psi \rangle$ multiplicities can be extracted from the NA50 data on Pb+Pb collisions at 158 A·GeV for different values of N_p, we start from the requirement:

$$\langle J/\psi \rangle \ = \ \gamma_c^2 \ N_{J/\psi}^{tot} \ , \tag{5}$$

to fix the γ_c factor. In Eq.(5) the total J/ψ thermal multiplicity is calculated as

$$N_{J/\psi}^{tot} = N_{J/\psi} + R(\psi')N_{\psi'} \tag{6}$$

$$+R(\chi_1)N_{\chi_1} + R(\chi_2)N_{\chi_2} \ , \tag{7}$$

where $N_{J/\psi}$, $N_{\psi'}$, N_{χ_1}, N_{χ_2} are given by Eq.(1) and $R(\psi') \cong 0.54$, $R(\chi_1) \cong 0.27$, $R(\chi_2) \cong 0.14$ are the decay branching ratios of the excited charmonium states into J/ψ. Eq.(4) will be used then to calculate the value of $N_{c\bar{c}}^{dir}$. This value will be considered as a prediction of the statistical coalescence model: the open charm yield has not yet been measured in Pb+Pb collisions at SPS.

A reliable extraction of the J/ψ yields from the published data appears to be non-trivial[†]. The results for $\langle J/\psi \rangle$ presented in Ref. [3] were evaluated from the data of the NA50 Collaboration [13] using the procedure described in [14]. These results are presented in Table 1 to be used in the present analysis.

We use the set of the chemical freeze-out parameters [15]:

$$T \ = \ 168 \text{ MeV}, \ \ \mu_B \ = \ 266 \text{ MeV} \ . \tag{8}$$

They are fixed by fitting the HG model to the hadron yield data in Pb+Pb collisions at 158 A·GeV (the inclusion of open charm and charmonium states does not modify the rest of the hadron yields). For a fixed number of participants, N_p, the volume V is calculated from $N_p = V n_B$, where $n_B = n_B(T, \mu_B)$ is the baryonic density calculated in the g.c.e.. With the chemical freeze-out parameters (8) we find the $N_{J/\psi}^{tot}$ and N_O values using Eq.(1). Then we calculate γ_c from Eq.(5). Finally, $N_{c\bar{c}}^{dir}$ is calculated from Eq.(4). Note that $T \cong 170$ MeV leads to the HG value of the thermal ratio of $\langle \psi' \rangle / \langle J/\psi \rangle \cong 0.04$ in agreement with data [16] at $N_p > 100$. This fact was first noticed in Ref. [17].

The model results for central Pb+Pb interactions at 158 A·GeV ($N_p = 100 \div 400$) are presented in Table 1. Assuming that $N_{c\bar{c}}^{dir}$ scales as N_p^{α} we find $\alpha \cong 1.7$. This value is larger than $\alpha \cong 4/3$ expected in the hard-collision model.

pQCD inspired models suggest values of $N_{c\bar{c}}^{dir} = 0.15 \div 0.3$ in central Pb+Pb collisions at 158 A·GeV (a value of $N_{c\bar{c}}^{dir} \cong 0.17$ is estimated in Ref. [5]). The results presented in Table 1 correspond to an enhancement of the open charm production by a factor of about 2–4. Although the values of $N_{J/\psi}^{tot}$, N_O and γ_c are rather sensitive to the temperature parameter, the model predictions for $N_{c\bar{c}}^{dir}$ remain essentially unchanged when $T = 170 \pm 10$ MeV is used. Note that a recent analysis of the dimuon spectrum measured in central Pb+Pb collisions at 158 A·GeV by NA50 Collaboration [18] suggests a significant enhancement of dilepton production in the intermediate mass region (1.5÷2.5 GeV) over the standard sources. The primary[‡] interpretation attributes this observation to the enhanced production of open charm [18]: about 3 times above the pQCD prediction for the open charm yield in Pb+Pb collisions at SPS. This value is in agreement with our model analysis. Moreover, the analysis of the centrality dependence of the dimuon excess was done in Ref. [4] assuming that additional dimuon pairs come

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[‡]Alternative explanations are also suggested [19–21].

entirely from decays of D and $\bar{D}$. The open charm yield was found to be proportional to $N_p^{1.7}$. This precisely coincides with our result.

A possible source of the open charm enhancement in A+A collisions with respect to the direct extrapolation from p+p data may be the broadening of the phase space available for the open charm due to the presence of the hadron and/or the quark-gluon medium:

Let a $c\bar{c}$ pair with an invariant mass below the open charm threshold, $2M_D \cong 3.7$ GeV, be created in a p+p collision. In the vacuum it cannot hadronize to an open charm hadron pair and thus it has to be transformed into non-charmed states to respect energy-momentum conservation. In A+A collisions, however, such a pair has a chance to shift its invariant mass above the open charm threshold due to secondary interactions with hadron and/or quark-gluon medium, thus resulting in additional open charm production. The strongest enhancement of the open charm production should be expected in the quark-gluon plasma. Due to the Debye screening, c and $\bar{c}$ behave like free particles. Therefore, almost all subthreshold $c\bar{c}$-pairs created in the hard collisions hadronize into open charm mesons and baryons at the later stage of the A+A reaction. This effect can be substantial at moderate center-of-mass energies per nucleon, while at higher energies the threshold effects becomes less important. A quantitative estimate of this effect is under way [22]. The above mechanism does not alter the production of direct Drell-Yan pairs: both the threshold effects and the interaction with the nuclear medium are negligible in that case.

In conclusion, the statistical coalescence model with exact charm conservation has been formulated. The canonical ensemble suppression effects are important for the thermal open charm yield even at $N_p \cong 400$. These effects become crucial when the number of participants N_p decreases. From the J/ψ multiplicity data in Pb+Pb collisions at 158 A·GeV the open charm yield is predicted:

$$N_{c\bar{c}}^{dir} = 0.6 \div 0.7$$

in central collisions. This is about a factor 3 above the pQCD prediction for the open charm yield in Pb+Pb collisions at SPS. The statistical coalescence model predicts also an N_p dependence of $N_{c\bar{c}}^{dir} \sim N_p^{1.7}$, which is stronger than the standard dependence, $N_p^{4/3}$, in the hard-collision model. These predictions of the statistical coalescence model can be tested in the near future at the CERN SPS, where measurements of the open charm are planned.

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Table 1

N_p	$\langle J/\psi \rangle \cdot 10^4$ NA50 data [13] Compil. [3]	$N_{J/\psi}^{tot} \cdot 10^4$ Eq.(6)	N_O	γ_c Eq.(5)	$N_{c\bar{c}}^{dir}$ Eq.(4)
100	2.2 $\pm$ 0.2	0.56	0.26	2.0	0.066
200	3.9 $\pm$ 0.2	1.1	0.52	1.9	0.21
300	6.4 $\pm$ 0.6	1.7	0.79	2.0	0.46
360	6.9 $\pm$ 0.7	2.0	0.94	1.9	0.57