Statistical J/ψ production and open charm enhancement in Pb+Pb collisions at CERN SPS

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Abstract. The production of open and hidden charm hadrons in heavy ion collisions is considered within the statistical coalescence model. Charmed quarks and antiquarks are assumed to be created at the initial stage of the reaction and their number is conserved during the evolution of the system. They are distributed among open and hidden charm hadrons at the hadronization stage in accordance with the laws of statistical mechanics. The model is in excellent agreement with the experimental data on J/ψ production in lead-lead collisions at CERN SPS and predicts a strong enhancement of the open charm multiplicity over the standard extrapolation from nucleon-nucleon to nucleus-nucleus collisions. A possible mechanism of the charm enhancement is proposed.

J/ψ meson plays a special role in heavy ion physics. The interest to it was mainly motivated by the suggestion of Matsui and Satz [1] to use charmonia as a probe of the state of matter created in the early stage of the collision.

The standard picture assumes that charmonia are created exclusively at the initial stage of the reaction in primary nucleon-nucleon collisions. During the subsequent evolution of the system, the number of hidden charm mesons is reduced because of (a) absorption of pre-resonance charmonium states in the nuclei (normal nuclear suppression), (b) interactions of charmonia with secondary hadrons (comovers), (c) dissociation of $c\bar{c}$ bound states in a deconfined medium. It was found that the J/ψ suppression with respect to Drell-Yan muon pairs measured in proton-nucleus and nucleus-nucleus collisions with light projectiles can be explained by normal nuclear suppression alone [2]. In contrast, the NA50 experiment with the heavy projectile and target (lead-lead) revealed essentially stronger J/ψ suppression for central collisions [3]. This *anomalous* J/ψ suppression was attributed to formation of quark-gluon plasma [4].

Much less attention was paid to the fact that the J/ψ to Drell-Yan ratio *does not* follow the normal nuclear suppression pattern for *peripheral* collisions: the experimental points lie *above* the normal nuclear suppression curve (see Fig. 1). This behavior cannot be explained within the standard scenario: presence of either of two additional mechanisms (b) or (c) can only destroy the quarkonia, that survived absorption by the nuclear nucleons.

A completely different picture of charmonium production was proposed by Gaździcki and Gorenstein [5]: hidden charm mesons are supposed to be created at the hadronization stage. Similar to all other hadrons, their abundancies can be described within the thermal model [6]. However, the production of heavy quarks

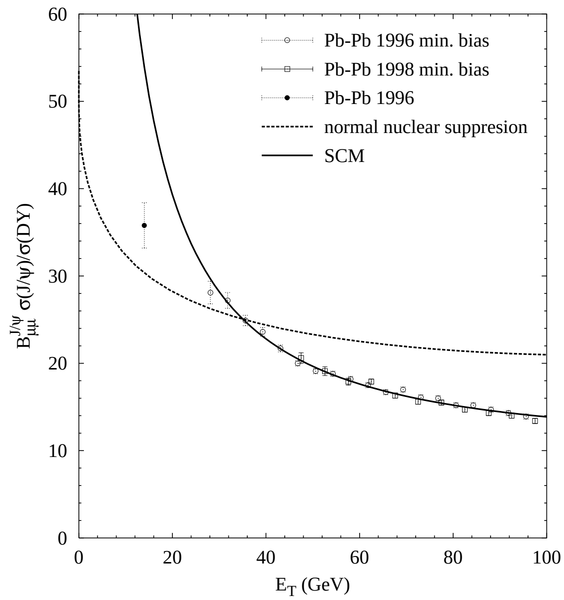

Figure 1. The dependence of the J/ψ to Drell-Yan ratio on the transversal energy. The normal nuclear suppression curve is obtained at $\sigma_{abs} = 6.4$ mb, where σ_{abs} is the absorption cross section of preresonant charmonia by nuclear nucleons.

in soft processes is expected to be negligible. Most likely, they are produced at the hard stage. Therefore, their number can, generally speaking, deviate from the thermal equilibrium value [7]. Because of smallness of this number, canonical treatment of the system is important [8].

In this talk, I present the results [9] obtained within the statistical coalescence model [8]:

- c and $\bar{c}$ are created at the initial stage of the reaction in primary hard parton collisions;
- their number remains approximately unchanged during the subsequent evolution;
- they are distributed over open charm hadrons and charmonia at the hadronization stage in accordance with the laws of statistical mechanics.

The model demonstrates excellent agreement ($\chi^2/\mathrm{dof} = 1.18$) with the NA50 data on J/ψ production in nonperipheral collisions (see figure 1).

Extrapolating the fit to peripheral collisions reveals an interesting feature: our model predicts sharp increase of the ratio with decreasing the number of participants, leading to J/ψ *enhancement* over the nucleon-nucleon collision value. Such behavior is easy to understand: the smaller the volume of the system the larger is the probability that c and $\bar{c}$ meet each other at the hadronization stage and form a hidden charm meson. As is seen from the figure, this enhancement is not obviously supported by the data: our theoretical curve lies far above the leftmost experimental point from the 1996 standard analysis set. On the other hand, the normal nuclear suppression model also fails to explain this point (as well as two points from the 1996 minimum bias set), the theoretical calculations underestimate the experimental values. It is natural to assume that an intermediate situation takes place. Some fraction of peripheral Pb+Pb collisions result in formation of a deconfined medium. In these collisions, charmonia are formed at the hadronization stage, and their multiplicities are given by the statistical coalescence model. The rest collisions (we shall call them 'normal collisions') do not lead to color deconfinement, therefore charmonia are formed exclusively at the initial stage and then suffer normal nuclear suppression. The experiment measures the average value, which lies between these two curves. The fraction of 'normal' events decreases with growing centrality. Their influence on J/ψ production becomes negligible at $N_p \gtrsim 100$.

The model has two free parameters: $\sigma_{c\bar{c}}^{NN}$, the effective cross section of charm production by a nucleon pair, and η, the fraction of J/ψ satisfying the kinematical conditions of the NA50 spectrometer.

Our analysis predicts an enhancement of the total charm by the factor of 4.5–7.5 ($\sigma_{c\bar{c}}^{NN} = 34\pm9\ \mu$b, comparing with $\sigma_{c\bar{c}}^{NN} \approx 5.5\ \mu$b in nucleon-nucleon collisions. On the other hand, the small value of $\eta \approx 0.14$ (comparing with $\eta \approx 0.24$ in nucleon-nucleon collisions) suggest essential broadening of the J/ψ rapidity distribution. Assuming approximately the same broadening for the open charm, we obtain the open charm enhancement by the factor of about 2.5–4.5 within the rapidity window of the NA50 spectrometer. This is consistent with the indirect experimental result [10].

Direct measurement of open charm in heavy ion collisions is planed at CERN SPS. If this measurement confirms the enhancement, what kind of mechanism can stay behind the phenomenon?

We have demonstrated [11] that the heavy flavor enhancement may be a signature of color deconfinement. A deconfined medium (quark-gluon plasma or its precursor) can influence the hadronization of heavy quarks and antiquarks. This leads to an enhanced production of hadrons with open charm and bottom with respect to the direct extrapolation of proton-proton data to heavy nuclei collisions.

To get an intuitive picture of possible medium effects let us start from open charm production in electron-positron annihilation. A charm quark-antiquark pair is created in a hard perturbative process. Then it hadronizes into observed particles. The dynamics of the hadronization can be qualitatively understood in the framework of the string picture. When the distance between c and $\bar{c}$ reaches the range of confinement forces, a string connecting these colored objects is formed. If the invariant mass of the quark-antiquark pair $M_{c\bar{c}}$ lies well above the open charm meson threshold $2m_D$, c and $\bar{c}$ break the string into two (or more) peaces, so that the final state contains an open charm hadron pair (and possibly a number of light hadrons). However, when the center-of-mass energy of the initial electron-positron pair exceeds the charm quark threshold ($\sqrt{s} > 2m_c$), but lies below the meson threshold ($\sqrt{s} < 2m_D$), a $c\bar{c}$ pair can be created, but it cannot break the string. An open charm hadron pair *cannot* be formed. Eventually the c and $\bar{c}$ have to annihilate into lighter hadrons (or form charmonium states, provided that the energy is sufficient).

Let us imagine now e^+e^- annihilation inside a deconfined medium. Due to the Debye screening, no string is formed between colored objects. If c and $\bar{c}$ are created, they *can* fly apart within the medium as if they were free particles. It does not matter whether their initial invariant mass $M_{c\bar{c}}$ exceeds the the meson threshold or not. The created $c\bar{c}$ pair *is able* to form an open charm hadron pair at the hadronization. This means that e^+e^- *annihilation inside a deconfined medium would produce open charm hadrons even if the collision energy is not sufficient for producing these hadrons in* *vacuum.*

In proton-proton or nucleus-nucleus collisions charm quark-antiquark pairs are produced due to hard *parton* interactions. Calculations in the leading order of perturbative quantum chromodynamics show that a great fraction of $c\bar{c}$ pairs is created with invariant masses $M_{c\bar{c}}$ below the corresponding meson threshold $2m_D$. Despite of essential differences between e^+e^- annihilation and nucleon-nucleon (or nucleus-nucleus) collisions (see [11] for details), it is natural to expect that a deconfined medium essentially increase the probability of hadronization of $c\bar{c}$ pairs with low invariant mass. *This should lead to enhanced production of the total charm in nucleus-nucleus collisions in comparison to the standard result obtained within the direct extrapolation of nucleon-nucleon data.*

We have estimated the upper bound of this enhancement. At SPS energies, one can expect a maximal enhancement by the factor of about 6, which is consistent with our fit for the J/ψ to Drell-Yan ratio.

I conclude that the NA50 data for not very peripheral lead-lead collisions ($N_p > 100$) are consistent with the following scenario:

Formation of a deconfined medium prevents annihilation of charm-anticharm quark pairs with low invariant mass. This reveals itself in an enhanced production of open charm hadrons. Charmonia as well as other hadrons are formed at the hadronization stage. The distribution of the charm quarks and antiquarks over open and hidden charm hadrons follows the laws of statistical mechanics.

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