Strangeness and charm signatures in A+A collisions

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Abstract. Two signatures of the quark-gluon plasma – strangeness ‘enhancement’ and J/ψ ‘suppression’ – in nucleus–nucleus collisions are critically discussed. A recently developed statistical coalescence model for J/ψ production is presented. The measurements at the RHIC energies are crucial for disentangling the different scenarios of J/ψ formation.

1. Strangeness “enhancement”? 

The idea of strangeness enhancement as a quark-gluon plasma (QGP) signal in nucleus-nucleus (A+A) collisions was formulated a long time ago [1]. It was based on the estimate that the strangeness equilibration time in QGP is of the same order (∼ 10 fm/c) as the expected life time of the fireball formatted in A+A collisions. Thus in the case of QGP creation the strangeness is expected to approach its equilibrium value in QGP. This equilibrium value is significantly higher than the strangeness production in nucleon–nucleon (N+N) collisions. Strangeness production in secondary hadronic interactions was estimated to be negligible small (this appears to be not correct!). Therefore, if QGP is not formed, the strangeness yields would be expected to be much lower than those predicted by equilibrium QGP calculations. Thus at that time a simple and elegant signature of QGP creation appeared: a transition to QGP should be signaled by an increase of the strangeness production to the level of QGP equilibrium value.

How to check this prediction? The actual study has been done in the following way. The strangeness to pion ratio,

\[ E_s = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle}, \]  

was measured and analyzed. Different ratios of this type, \( f_s = \frac{\langle K^\pm \rangle}{\langle \pi \rangle}, ..., \frac{\langle \Omega \rangle}{\langle \pi \rangle}, \frac{\langle K^\pm \rangle}{\langle N_p \rangle}, ..., \frac{\langle \Omega \rangle}{N_p}, \) have been also studied (\( N_p \) is the number of nucleon participants in A+A collision). One expected that all these ratios should increase strongly in A+A collisions if the QGP was formed. On the other hand, the strangeness to pion ratio (1) (as well as other specific ratios \( f_s \)) increases with collision energy \( \sqrt{s} \) in N+N collision too. To reveal the specific strong increase of the strangeness/pion ratio in A+A collisions due to the QGP formation the strangeness enhancement factor was introduced:

\[ R_s = \frac{E_{sA}^{AA}(\sqrt{s})}{E_{sN}^{NN}(\sqrt{s})}, \]
where $E_{AA}^s$ and $E_{NN}^s$ correspond respectively to A+A and N+N collisions at the same c.m. energy $\sqrt{s}$. Does the strangeness enhancement factor $R_s$ (2) become large if the QGP is formed? The confrontation of this expectation with the data was for the first time possible in 1988 when the results from S and Si beams at SPS and AGS were presented. The experiment NA35 reported that in central S+S collisions at 200 AGeV the strangeness to pion ratio is indeed 2 times higher than in N+N interactions at the same energy per nucleon. But even larger enhancement ($R_s$ is about of 3) was measured by E802 in Si+A collisions at AGS. Recent data on central Au+Au collisions at low AGS energies $4 \div 10$ AGeV completed the picture: strangeness enhancement is observed at all energies, and it is stronger at lower energies, i.e. the function $R_s$ (2) increases monotonously with decreasing of $\sqrt{s}$. At the low AGS energies one does not expect a creation of the QGP and therefore a substantial strangeness enhancement is evidently of a different origin. Thus AGS measurements of strangeness enhancement larger than that at SPS show clearly that the simple concept of strangeness enhancement as a signal of QGP does not work.

Let me return to the observable $E_{AA}^s$ and its energy dependence shown in Fig. 1.

![Figure 1](image-url)

**Figure 1.** Collision energy ($F \equiv (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$) dependence of strangeness to pion ratio (1) for central A+A collisions (closed points), N+N and $p+p$ collisions (open points). The prediction of the statistical model of Ref. [2] is shown by solid line. A transition to the QGP is expected between the AGS ($F \approx 2$ GeV$^{1/2}$) and the SPS ($F \approx 4$ GeV$^{1/2}$) energies and leads to the non-monotonic dependence of the strangeness to pion ratio. At high collision energies the ratio saturates at the value characteristic for equilibrium QGP.

The statistical model of the early stage [2] leads to the following predictions for strangeness production:

1. A non-monotonic collision energy dependence of the strangeness to pion ratio (1). This is due to the fact that the phase transition is expected to occur at an energy where the strangeness to entropy (pion) ratio in the confined (hadron) matter is higher
than in the QGP. Therefore, a creation of the QGP in the energy region between the AGS and SPS would change an initial fast increase of the ratio $E_s$ (1) in the hadron gas by a decrease to the level expected in equilibrium QGP.

b). Very similar strangeness to pion ratio is predicted for SPS, RHIC and LHC energies as strangeness/entropy ratio in the QGP is almost independent of temperature (collision energy).

Preliminary SPS data in Pb+Pb at 40 and 80 AGeV and RHIC data in Au+Au at $\sqrt{s} = 200$ GeV seem to be in agreement with the above conclusions (see Fig. 1).

2. $J/\psi$ suppression and enhancement

A standard picture of $J/\psi$ production in hadron and nuclear collisions assumes a two step process: the creation of $c\bar{c}$ pair in hard parton collisions at the very early stage of the reaction and the subsequent formation of a bound charmonium state. Matsui and Satz proposed [3] to use $J/\psi$ as a probe for deconfinement in the study of A+A collisions. They argued that in QGP the colour screening dissolves initially created $J/\psi$ mesons into $c$ and $\bar{c}$ quarks which at hadronization form open charm hadrons. As the initial yield of $J/\psi$ is believed to have the same $A$-dependence as the Drell–Yan lepton pairs, the measurement of a weaker $A$–dependence of final $J/\psi$ yield ($J/\psi$ suppression) would signal charmonium absorption and therefore creation of QGP. 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. There are two unambiguous consequences of the standard $J/\psi$ suppression picture [3]. First, the number of $J/\psi$ particles produced before the suppression should be directly proportional to the number of $c\bar{c}$ pairs, $N_{c\bar{c}}$. Second, when the energy $\sqrt{s}$ and/or the number of nucleon participants $N_p$ of the colliding nuclei increase, the $J/\psi$ suppression becomes stronger, i.e. for the measured $J/\psi$ yield, $\langle J/\psi \rangle$, the ratio

$$R \equiv \frac{\langle J/\psi \rangle}{N_{c\bar{c}}}$$

(3)
decreases with increasing of $\sqrt{s}$ and/or $N_p$.

Recently the thermal model [4] and the statistical coalescence model [5, 6] were suggested for the charmonium production in A+A collisions. This statistical description makes very different assumptions about the underlying physics which generates charmonium. In the statistical coalescence model [5, 6] the $J/\psi$ particles are produced by recombination of $c$ and $\bar{c}$ at the hadronization stage, and the picture is much different from the standard suppression scenario. For large number of $c\bar{c}$ pairs, $N_{c\bar{c}} >> 1$, the multiplicity of $J/\psi$ due to recombination of $c$ and $\bar{c}$ should be roughly proportional to:

$$\langle J/\psi \rangle \sim \frac{N^2_{c\bar{c}}}{V},$$

(4)

where $V$ is the system volume. In this case the ratio $R$ (3) is expected to increase with increasing of $\sqrt{s}$ and/or $N_p$. We call this $J/\psi$ enhancement.

The equilibrium hadron gas (HG) model describes the hadron yields measured in A+A collisions in terms of three parameters: volume $V$, temperature $T$ and baryonic chemical potential $\mu_B$. This model reproduces basic features of the data in the whole AGS–SPS–RHIC energy region describing successfully the hadron yields (see e.g. [7]). For the RHIC energies the temperature parameter $T$ is expected to be similar to that
for the SPS energies: \( T = 170 \pm 10 \) MeV. The baryonic chemical potential becomes small (\( \mu_B < T \)) and decreases with the collision energy.

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 \( m_j, d_j \) denote particle masses and degeneracy factors. The particle chemical potential \( \mu_j \) in Eq.(5) is defined as

\[
\mu_j = b_j \mu_B + s_j \mu_S + c_j \mu_C, \tag{6}
\]

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:

\[
N_j^{\text{tot}} = N_j + \sum_R B(R \to j) N_R, \tag{7}
\]

where \( B(R \to j) \) are the corresponding decay branching ratios. The hadron yield ratios \( N_j^{\text{tot}}/N_i^{\text{tot}} \) in the g.c.e. are then the functions on \( T \) and \( \mu_B \) variables and are independent of the volume parameter \( V \).

For the thermal multiplicities of both open charm and charmonium states the Bose and Fermi effects are negligible, and \( m_j \gg T \). Therefore, Eq.(5) is simplified to:

\[
N_j \approx d_j V e^{\mu_j/T} \left( \frac{m_j T}{2\pi} \right)^{3/2} \exp \left( -\frac{m_j^2}{T} \right). \tag{8}
\]

The HG model gives the \( J/\psi \) yield:

\[
N_{J/\psi}^{\text{tot}} = N_{J/\psi} + R(\psi') N_{\psi'} + R(\chi_1) N_{\chi_1} + R(\chi_2) N_{\chi_2}, \tag{9}
\]

where \( N_{J/\psi}, N_{\psi'}, N_{\chi_1}, N_{\chi_2} \) are calculated according to Eq.(8) and \( R(\psi') \equiv 0.54, R(\chi_1) \equiv 0.27, R(\chi_2) \equiv 0.14 \) are the decay branching ratios of the excited charmonium states into \( J/\psi \).

In the canonical ensemble (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.(8) as charmonium states have zero charm charge. The multiplicities (8) of open charm hadrons will however be multiplied by an additional ‘canonical suppression’ factor (see e.g. [8]). This suppression factor is the same for all individual open single charm states. Therefore, if \( N_O \) is the total g.c.e. multiplicity of all open charm and anticharm mesons and (anti)baryons, the c.e. value of the total open charm is equal to:

\[
N_{O}^{\text{c.e.}} = N_O I_1(N_O) \frac{I_1(N_O)}{I_0(N_O)}, \tag{10}
\]

where \( I_0, I_1 \) are the modified Bessel functions. To find \( N_O \) we use Eq.(8) for thermal multiplicities of the open charm hadrons in the g.c.e. and take the summation over
all known particles and resonances with open charm [9]. The canonical suppression factor $I_1(N_0)/I_0(N_0)$ in Eq.(10) is due to the exact charm conservation. Therefore, the baryonic number, strangeness and electric charge of the HG system are treated according to the g.c.e. but charm is considered in the c.e. formulation where the exact charge conservation is imposed. For $N_0 << 1$ one has $I_1(N_0)/I_0(N_0) \equiv N_0/2$ and, therefore, the c.e. total open charm multiplicity is strongly suppressed in comparison to the g.c.e. result. At the SPS energies the c.e. suppression effects are important for the thermal open charm yield even in the most central Pb+Pb collisions. These suppression effects become crucial when the number of participants $N_p$ decreases. Note that for $N_0 << 1$ the multiplicities of the open charm hadrons are proportional to $V^2$ in the c.e. HG formulation (instead of $V$ in the g.c.e.).

The statistical coalescence model (SCM) [5, 6] assumes that the charmonium states are formed at the hadronization stage. This is similar to the thermal model of Ref. [4]. The thermal model [4] predicts that the $J/\psi$ to $\pi$ ratio is independent of $\sqrt{s}$ and $N_p$ at high collision energies. This is because both $\langle J/\psi \rangle$ and $\langle \pi \rangle$ are proportional to the system volume and they both depend only on the hadronization temperature, $T_H = 170 \pm 10$ MeV, which is expected to be independent of $\sqrt{s}$ and $N_p$ at high collision energies. However, in the SCM the charmonium states are produced via a coalescence of created earlier $c\bar{c}$ quarks at the early stage of A+A reaction by the hard parton collisions. One needs then an additional parameter $\gamma_c$ [5] to adjust the thermal HG results to the required number of $N_\sigma$. This is analogous to the introduction of the strangeness suppression factor $\gamma_s < 1$ [10] in the HG model, if the total strangeness observed is smaller than its thermal equilibrium value. We find $\gamma_c > 1$ so that 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. The c.e. formulation of the SCM is [6]:

$$N_\sigma = \frac{1}{2} \gamma_c N_0 \frac{I_1(\gamma_c N_0)}{I_0(\gamma_c N_0)} + \gamma_c^2 N_H,$$  \hspace{1cm} (11)

where $N_H$ is the total HG multiplicity of particles with hidden charm. Note that the second term in the right-hand side of Eq.(11) 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. If $N_\sigma >> 1$ one finds from Eq.(11) that $\gamma_c N_0 >> 1$, therefore, $I_1(\gamma_c N_0)/I_0(\gamma_c N_0) \to 1$, i.e. the g.c.e. and c.e. results for the open charm coincide. In this case Eq.(11) is simplified to [5]: $N_\sigma = \gamma_c N_0/2 + \gamma_c^2 N_H$. This happens for central Au+Au collisions at upper RHIC energy $\sqrt{s} = 200$ GeV. For lower RHIC energy $\sqrt{s} = 56$ GeV the value of $N_\sigma$ could be close to (or even smaller than) unity so that the c.e. suppression effects for the open charm are still important. Note that for the non-central $A+A$ collisions the c.e. suppression effects become evidently stronger, hence their consideration are necessary to study the $N_p$ dependence of the charmonium production even at upper RHIC energy.

Eq.(11) will be used to find the charm enhancement factor $\gamma_c$ and calculate then the $J/\psi$ multiplicity:

$$\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}^\text{tot},$$ \hspace{1cm} (12)

where $N_{J/\psi}^\text{tot}$ is given by Eq.(9). Note that $T = 170 \div 180$ MeV leads to the value of the thermal ratio,

$$\frac{\langle \psi' \rangle}{\langle J/\psi \rangle} = \left( \frac{m_{\psi'}}{m_{J/\psi}} \right)^{3/2} \exp \left( - \frac{m_{\psi'} - m_{J/\psi}}{T} \right) \approx 0.04 \div 0.05,$$ \hspace{1cm} (13)
in agreement with data [11] in Pb+Pb collisions at SPS for \( N_p > 100 \). This fact was first noticed in Ref. [12]. Recent results [13] on transverse mass spectra of \( J/\psi \) and \( \psi' \) mesons in central Pb+Pb collisions at 158 AGeV also support a hypothesis of statistical production of charmonia at hadronization (see Ref. [14]).

The number of directly produced \( \bar{c}c \) pairs in the left-hand side of Eq.(11) should be estimated in the pQCD approach and used then as the input for the SCM. The pQCD calculations for \( \bar{c}c \) production cross sections were first done in Ref.[15]. For the cross section \( \sigma(pp \rightarrow \bar{c}c) \) of the charm production in p+p collisions we use the results presented in Ref.[16]. This leads to the value of \( \sigma(pp \rightarrow \bar{c}c) \approx 0.35 \) 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:

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

(14)

with \( \sigma_0 \approx 3.392 \) \( \mu b \), \( M_0 \approx 2.984 \) GeV, \( \alpha \approx 8.185 \) and \( \beta \approx 1.132 \).

The number of produced \( \bar{c}c \) pairs in A+A collisions is proportional to the number of primary N+N collisions, \( N_{AA_{coll}} \), which in turn is proportional to \( N_p^{4/3} \) [17]:

\[
N_{\bar{c}c} = N_{AA_{coll}}(N_p) \frac{\sigma(pp \rightarrow \bar{c}c)}{\sigma_{NN}} \approx C \sigma(pp \rightarrow \bar{c}c) N_p^{4/3} ,
\]

(15)

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

The results of the SCM can be studied analytically in the limiting cases of small and large numbers of \( N_{\bar{c}c} \). For \( N_{\bar{c}c} \ll 1 \) one finds from Eq. (11) that \( \gamma_c \approx 4N_{\bar{c}c}/N_O^2 \) and then from Eq. (9)

\[
R = \frac{\gamma_c^2 N_{J/\psi}^\text{tot}}{N_{\bar{c}c}} \approx \frac{4N_{J/\psi}^\text{tot}}{N_O^2} \sim \frac{1}{V} \sim \frac{1}{N_i} \sim (\sqrt{s})^{-1/2} N_p^{-1} .
\]

(16)

This behavior is similar to the standard picture of the \( J/\psi \) suppression: the ratio \( R \) decreases with increasing both \( \sqrt{s} \) and \( N_p \). Therefore, the SCM predicts the \( J/\psi \) suppression at the SPS energy. This energy is still too “low” as \( N_{\bar{c}c} < 1 \) even in the most central Pb+Pb collisions at 158 AGeV. This behavior is however dramatically changed at the RHIC energies [18]. In most central Au+Au collisions \( (N_p \approx 2A) \) at \( \sqrt{s} = 200 \) GeV the expected number of \( N_{\bar{c}c} \) is essentially larger than unity. For \( N_{\bar{c}c} \gg 1 \) one finds from Eq. (11) that \( \gamma_c \approx 2N_{\bar{c}c}/N_O \) and then from Eq. (9)

\[
R = \frac{\gamma_c^2 N_{J/\psi}^\text{tot}}{N_{\bar{c}c}} \approx \frac{2N_{J/\psi}^\text{tot}}{N_O} \sim \frac{N_{\bar{c}c}}{V} \sim \frac{N_{\bar{c}c}}{N_i} \sim (\sqrt{s})^{\beta-1/2} N_p^{1/3} ,
\]

(17)

where \( \beta \approx 1.132 \). Eqs. (16,17) reveal a remarkable prediction of the SCM: the \( J/\psi \) to \( N_{\bar{c}c} \) ratio decreases with both \( \sqrt{s} \) and \( N_p \) (\( J/\psi \) suppression (16)) when \( N_{\bar{c}c} \ll 1 \) and it increases with both \( \sqrt{s} \) and \( N_p \) (\( J/\psi \) enhancement (17)) when \( N_{\bar{c}c} \gg 1 \). The measurements in Au+Au collisions at RHIC give a unique possibility to check simultaneously both these predictions: at \( \sqrt{s} = 56 \) GeV and \( N_p = 100 \) the expected value of \( N_{\bar{c}c} \) from Eq. (15) is \( N_{\bar{c}c} \approx 0.2 << 1 \), but at \( \sqrt{s} = 200 \) GeV and \( N_p \approx 2A \) one expects from Eq. (15) that \( N_{\bar{c}c} \approx 10 >> 1 \). Therefore, changing of \( \sqrt{s} \) and \( N_p \) in Au+Au at RHIC one could observe both the \( J/\psi \) suppression and enhancement behaviors. These limiting behaviors are smoothly connected in the intermediate region of \( \sqrt{s} \) and \( N_p \) where \( N_{\bar{c}c} \approx 1 \). The results of the SCM for the \( J/\psi \) to \( N_{\bar{c}c} \) ratio are presented in Figs. 1 and 2. Both the suppression (the dashed line in Fig. 3) and enhancement (the solid lines in Figs. 2 and 3) behaviors are clearly seen.
Figure 2. The energy dependence of the \( J/\psi \) to \( N_{c\bar{c}} \) ratio in central (\( N_p \approx 2A \)) \( \text{Au+Au} \) collisions. Points are the predictions of the SCM for the RHIC energies: \( \sqrt{s} = 56, 130, 200 \) GeV. The ratio \( R \) increases by a factor of about 3 (\( J/\psi \) enhancement) in the region of RHIC energies \( \sqrt{s} = 56 \div 200 \) GeV.

Figure 3. The \( N_p \)-dependence of the \( J/\psi \) to \( N_{c\bar{c}} \) ratio. The lines are the predictions of the SCM. The dashed line corresponds to \( \sqrt{s} = 56 \) GeV and shows the \( J/\psi \) suppression behavior. The solid line corresponds to \( \sqrt{s} = 200 \) GeV and shows the \( J/\psi \) enhancement.
3. Conclusions

- The deconfinement phase transition is expected to occur at the collision energies between AGS and SPS where the strangeness to entropy (pion) ratio reveals a non-monotonic (or kinky) dependence on the collision energy [2] (see Fig. 1).

- Statistical hadronization of the QGP is probably an important source of $J/\psi$ production [4]. This fact would open a new look at $J/\psi$ ‘suppression’ signal of the QGP. The statistical coalescence model [5, 6] of the $J/\psi$ production predicts that the $J/\psi$ suppression in peripheral Au+Au collisions at lower RHIC energy should be changed into the $J/\psi$ enhancement [18] in central Au+Au collisions at the upper RHIC energy (see Figs. 2 and 3).

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