$J/\Psi$ suppression at SPS, RHIC and LHC energies and the percolation of strings

E. G. Ferreiro, F. del Moral and C. Pajares

Departamento de Física de Partículas
Universidade de Santiago de Compostela
15706 Santiago de Compostela, Spain

N. Armesto

Departamento de Física, Módulo C2, Pl. Baja
Campus de Rabanales, Universidad de Córdoba
14071 Córdoba, Spain

Abstract

We study the enhancement of $c\bar{c}$ pair production that takes place in central heavy ion collisions due to the formation of clusters of strings. These clusters produce heavy flavors more efficiently due to their higher color. We discuss the competition between this mechanism and the well-known screening of color charge, which, above a critical string density, reduces strongly the probability of binding these $c\bar{c}$ pairs to form $J/\Psi$ particles. The dependence of $J/\Psi$ suppression on the centrality shows a peak at both RHIC and LHC energies corresponding to the percolation critical density.

25.75.Dw, 12.38.Mh, 13.87.Ce, 24.85.+p
In most of the hadronic models of multiparticle production, color strings are exchanged between projectile and target. These strings decay afterwards into the observed hadrons. Color strings may be viewed as small areas $\pi r_0^2$, $r_0 \approx 0.2$ fm, in the transverse space, filled with the color field created by the colliding partons. Particles are produced via emission of $q\bar{q}$ pairs in this field. The number of exchanged strings grows with the energy, the centrality and the atomic number of the colliding particles; thus it is natural to consider that they start to overlap, forming clusters, very much like disks in continuum two-dimensional percolation theory. At a certain critical density a large cluster appears, which signs the percolation phase transition \[1–4\].

A cluster of $n$ strings behaves as a single string with a higher color field $\vec{Q}_n$, corresponding to the vectorial sum of the color charge of each individual $\vec{Q}_1$ string. The resulting color field covers the area $S_n$ of the cluster. As $\vec{Q}_n^2 = (\sum_1^n \vec{Q}_1)^2 \[3\], and the individual string colors may be oriented in an arbitrary manner respective to one another, the average $<\vec{Q}_{1i}\vec{Q}_{1j}>$ is zero, so $<\vec{Q}_n^2> = <n\vec{Q}_1^2> \[5\].

The production of $c\bar{c}$ pairs via tunneling effect in a single string is usually assumed to be quite negligible compared with the production in hard collisions, and also negligible compared with the light flavor pair production. However, a cluster formed by many strings has a very high color and therefore a very large string tension which can enhance the $c\bar{c}$ pair production several orders of magnitude \[5,6\]. This effect works in the opposite direction to the Debye screening \[7\] which makes that above the percolation threshold the probability of binding the $c\bar{c}$ pair to form a $J/\Psi$ is strongly reduced.

In this paper, we compute in a single and direct way the two effects at SPS, RHIC and LHC energies. The $J/\Psi$ suppression as an evidence \[8\] of the obtention of the Quark Gluon Plasma has been extensively discussed in the last years \[1,2,9\]. We would like to answer whether the abnormal $J/\Psi$ suppression configuration pattern for central Pb-Pb collisions at SPS energies is going to be modified at RHIC and/or LHC energies. Recently, a picture of the $J/\Psi$ creation via $c\bar{c}$ coalescence (recombination) has been subsequently developed within different model formulations \[10–14\]. Charmonium states are assumed to be created at the
hadronization stage of the reaction, being formed due to the coalescence of $c$ and $\bar{c}$, which were produced by some primary mechanism (hard parton collisions or statistical decay of a fireball) at the initial stage. In these approaches, it is found, instead of suppression, an enhancement of the $J/\Psi$ production at RHIC and LHC energies.

On the contrary, in our approach we find that the $J/\Psi$ suppression survives at RHIC and LHC energies and only a relative enhancement can be seen close to the percolation critical density. We are aware of the existence of other effects like shadowing and the existence of coherence length [15,16], which we do not take into account. These effects at high energies are very important for open charm production. However, in the central rapidity region for the case of $J/\Psi$ production, they are expected to be of little importance (less than 5-10 %). Also, we do not pay attention to whether there is one or more steps in the suppression pattern corresponding to the $J/\Psi$ directly produced in the collisions or considering also the suppression of other resonances which decay into $J/\Psi$ [17]. The inclusion of this possibility could be done easily but this is not the main goal of our study: our computation is focused on the qualitative behavior produced by the competition of suppression and enhancement coming from the same origin, the high color fields created by the overlapping strings exchanged in the collision.

Let us start by considering the extension of the Schwinger formula [5,6] for the production of $q-\bar{q}$ pairs of mass $m_j$ in a uniform color field with charge $g_j$, per unit space-time volume

$$\frac{dN_{q-\bar{q}}}{dy} = \frac{1}{8\pi^3} \int_0^\infty d\tau \int d^2x_T |g_j E|^2 \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(-\frac{\pi n m_j^2}{|g_j E|}\right). \quad (1)$$

The strings form clusters, each of them with a constant color field $E_i = Q_i/S_i$, where $Q_i$ and $S_i$ correspond to the cluster color charge and the cluster area, respectively. Hence, the integral in transverse space in the above equation transforms into a sum of areas $S_i$ of the clusters.

On the other hand, we take into account the evolution of the field and the charge with the decay of the cluster,
\[ E_i = E_{i0} \frac{1}{(1 + \tau_{i0})^2}, \quad Q_i = Q_{i0} \frac{1}{(1 + \tau_{i0})^2}, \quad (2) \]

where \( \tau \sim 1/\sqrt{E_{i0}} \).

In this way, equation (1) transforms into the equation

\[ \frac{dN_{q \bar{q}}}{dy} \propto M \sum_{i=1}^{M} Q_{i0} \int_0^\infty dx \frac{1}{(1 + x)^4} \sum_{n=1}^\infty \frac{1}{n^2} \exp \left[-\frac{\pi n m_j^2}{|g_j E_{i0}|(1 + x)^2}\right], \quad (3) \]

where \( M \) is the total number of clusters.

The charge and the field of each cluster before the decay, \( Q_{i0} \) and \( E_{i0} \), depend on the number \( n_i \) of strings and the area \( S_1 \) of each individual string that comes into the cluster, as well as on the total area of the cluster \( S_i \),

\[ Q_{i0} = \sqrt{\frac{n_i S_i}{S_1}} Q_{10}, \quad E_{i0} = \frac{Q_{i0}}{S_i} = \sqrt{\frac{n_i S_1}{S_i}} E_{10}. \quad (4) \]

Notice that if the strings are just touching each other, \( S_i = n_i S_1 \) and \( Q_{i0} = n Q_{10}, \)
\[ E_{i0} = E_{10} = 0.2 \text{ GeV}^2, \] so the strings are independent each other. On the contrary, if they fully overlap, \( S_i = S_1 \) and \( Q_{i0} = \sqrt{n_i} Q_{10} \) and \( E_{i0} = \sqrt{n_i} E_{10} \), so the field reaches its maximum strength.

In order to compute \( J/\Psi \) production, we proceed as reference [18]. We shall consider that when \( \nu \) collisions occur they occupy an interaction volume \( V(\nu) \) characterized by a transverse area \( A(\nu) \) and a mean longitudinal length \( L(\nu) \),

\[ V(\nu) \equiv A(\nu) L(\nu). \quad (5) \]

The density of strings is

\[ \rho_s = \frac{N_s}{A(\nu) L(\nu)}, \quad (6) \]

where \( N_s \) is the number of strings. We introduce the survival probability \( P_s(\nu) \), to take care of the \( J/\Psi \) absorption [19] in the usual form

\[ P_s(\nu) = \exp(-L(\nu)\rho_s \sigma), \quad (7) \]
σ being the pre resonant \(cc\)-nucleon absorption cross section. This corresponds to the usual picture of the conventional mechanism proportional to \(A\) plus absorption by nuclear matter.

Next, we include the probability of quark-gluon plasma formation in a very simple continuum two-dimensional percolation model. In an event with \(\nu\) elementary collisions, there is a probability \(P_{np}(\nu)\) of percolation not to occur, so a probability \(1 - P_{np}(\nu)\) of percolation to occur. It is assumed that the \(J/\Psi\) is formed only in events in which there is not percolation.

The probability of having an infinite cluster in terms of \(\eta = \pi r_0^2 N_s/A(\nu), N_s = 2\nu\), is

\[
P_{\text{perc}} = \theta(\eta - \eta_c)
\]

where the percolation threshold has been computed by several authors to be in the range 1.12-1.17. Because of the finite size of the colliding system, the theta function will be approximate by a smoother function. Indeed [18]

\[
P_{\text{perc}} = 1/(1 + \exp(-(\eta - \eta_c)/a))
\]

approximates very well the percolation behavior with \(\eta_c = 1.15\) and \(a = 0.04\).

Let \(N(\nu)\) be the total number of events with \(\nu\) elementary collisions, and \(N_c(\nu)\) the number of events when a rare event \(C\) (an event is called rare if, in good approximation, it only occurs once in each collision) occurring [20],

\[
N_C(\nu) = \alpha C \nu N(\nu)
\]

where \(\alpha_C\) is the probability of event \(C\) occurring in an elementary collision. Corrections to this formula due to several \(cc\) pairs in a collision are proved to be small [21]. Now we can apply the formulae developed before to \(J/\Psi\) and Drell-Yan production.

The probability to find a Drell-Yan event when there are \(\nu\) elementary collisions is

\[
P(DY|\nu) = \alpha_{DY} \nu
\]

while for \(J/\Psi\) production one has

\[
P(J/\Psi|\nu) = \alpha_{J/\Psi} \nu e^{-\sigma_\eta/\pi r_0^2} \frac{1}{\exp(\eta - \eta_c/a) + 1}
\]
and the ratio $R$ of $J/\Psi$ to D-Y events is

$$R = k \exp(-\sigma \eta / \pi \eta_0^2) / [\exp((\eta - \eta_c) / a) + 1].$$

(13)

However, as we said before, the probability of $c\bar{c}$ production increases with $\eta$. In order to include this fact, we multiply the expression (13) by

$$P_{c\bar{c}}(\eta) / P_{c\bar{c}}(\eta_{SPS})$$

(14)

assuming that the leading $c\bar{c}$ pair production for central Pb-Pb collisions at SPS energies is given by the Schwinger mechanism, expression (3) and (4). $P_{c\bar{c}}(\eta)$ is the probability of $c\bar{c}$ production at a given $\eta$ value and is normalized to the corresponding probability for central Pb-Pb collisions at SPS energies in such a way that the correction factor is just one at SPS energies. Similar evaluations have been extensively used in strangeness production giving reasonable results [22–25].

We use formulae (13) and (14) to compute the ratio $J/\Psi/DY$ at RHIC and LHC as a function of the transverse energy $E_T$ and the average interaction distance $L$, which are two usual variables to measure the degree of centrality of the collisions. At SPS we used the results of reference [18] directly obtained from formula (13). To compute the ratio (14) we use formula (3) and (4) where the clusters of strings and their areas are evaluated generating localized strings is impact parameter plane by means of a Monte-Carlo code based on the Quark Gluon String Model.

In figures 1 and 2 our results for the ratio $J/\Psi/DY$ as a function of $E_T$ and $L$ are plotted. It is seen that at RHIC and LHC energies an increase appears just before the percolation critical point which is marked by arrows in fig. 1. At higher centralities the ratio $J/\Psi/DY$ drops sharply. The same pattern is seen in figure 2 where it is used $L$ instead of $E_T$.

In fig. 3 we plot the correction ratio (14) as a function of $E_T$ for RHIC and LHC energies. Notice that in spite of becoming very large for $E_T > 40$ GeV at LHC its effect is quite negligible in the production of $J/\Psi$ in that range. Only, just before the percolation critical points, the large $c\bar{c}$ production gives rise to noticeable effects. We are aware of some
uncertainties of our evaluations, related to the normalization used in (14). However we have checked that a change in (14) by a factor 2 would not kill the reported effect.

Our results are different from other models [10–14] based on statistical hadronization of charm quarks without color screening scenario, which predict $J/\Psi$ enhancements at RHIC and LHC energies. In those models, the $J/\Psi$ is produced at the end of the process, due to hadronization of the quarks, and this is the main reason of the enhancement. In our approach, we cannot exclude the formation of some $J/\Psi$ particles after the hadronization of the plasma, but this production will be proportional to the number of $c\bar{c}$ pairs computed by means of the ratio (14) plotted in fig. 3. At RHIC energies this ratio is very small compared to the suppression. The same is true at LHC energies in the range $20 \leq E_T \leq 100$ GeV. Therefore, we expect that our general pattern of $J/\Psi$ suppression will not be modified by the hadronization of the plasma. This effect would be important only at LHC energies for very high $E_T$. Notice that the enhancement of $c$ quarks is due in our case to the higher tension of the string clusters, while in those models is due to statistical exponentials. These clear differences between different predictions make the verification more relevant.

Finally, let us summarize our main results. We have computed the enhancement of $c\bar{c}$ pair production in heavy ion collisions due to the formation of clusters of string with high color. This enhancement is not enough to prevent the suppression of the $J/\Psi$ once the percolation critical density is reached and the Quark Gluon Plasma is formed. The dependence of the $J/\Psi$ suppression with the centrality shows a peak located just before the percolation critical density.

ACKNOWLEDGMENTS

This work has been done under contracts AEN99-0589-C02 of CICYT of SPAIN, PGID-TOOPXI20613PN of Xunta de Galicia. F. del M. thanks Xunta de Galicia for a fellowship. N. Armesto thanks Univ. de Córdoba for financial support. We thank M. A. Braun for useful discussions.
REFERENCES

[1] N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Rev. Lett. 77, 3736 (1996).

[2] M. Nardi and H. Satz, Phys. Lett. B442, 14 (1998); H. Satz, Nucl. Phys. A642, 130c (1998).

[3] M. A. Braun and C. Pajares, Eur. Phys. J. C16, 349 (2000); M. Braun, C. Pajares and J. Ranft, Int. J. of Mod. Phys. A14, 2689 (1999).

[4] M. A. Braun and C. Pajares, Phys. Rev. Lett. 85, 4864 (2000); M. A. Braun, F. del Moral and C. Pajares, hep-ph/0105263.

[5] T. Matsui, MIT preprint MIT-CTP1510 (1987).

[6] J. Schwinger, Phys. Rev. 82, 664 (1951); T. S. Biro, H. B. Nielsen and J. Knoll, Nucl. Phys. B245, 449 (1984); A. Bialas and W. Czyz, Nucl. Phys. B267, 242 (1986).

[7] T. Matsui and H. Satz, Phys. Lett. B178, 416 (1986).

[8] M. C. Abreu et al., NA50 Collaboration, Phys. Lett. B477, 28 (2000).

[9] J. Blaizot and J.-Y. Ollitrault, Phys. Rev. Lett. 77, 1703 (1996); J. Blaizot, M. Dinh and J.-Y. Ollitrault, Phys. Rev. Lett. 85, 4012 (2000); C. Y. Wong, Phys. Rev. Lett. 76, 196 (1996); Phys. Rev. C55, 2621 (1997); N. Armesto, A. Capella, E. G. Ferreiro, Phys. Rev. C59, 395 (1999); A. Capella, E. G. Ferreiro and A. B. Kaidalov, Phys. Rev. Lett. 85, 2080 (2000); A. Capella, A. B. Kaidalov and D. Sousa, nucl-th/0105021 (2001); J. Geis, C. Greiner, E. L. Bratkovskaya, W. Cassing and U. Mosel, Phys. Lett. B447, 31 (1999); J. Qin, J. P. Vary and X. Zhang, nucl-th/0106040 (2001).

[10] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C63, 054905 (2001).

[11] M. I. Gorenstein, A. P. Kostyuk, L. McLerran, H. Stöcker and W. Greiner, Brookhaven preprint BNL-NT-00/27 (2000).
[12] P. Braun-Munzinger and J. Stachel, Phys. Lett. B490, 196 (2000).

[13] P. Levai, T. S. Biro, P. Csizmadia, T. Csörgö and J. Zimanyi, J. Phys 27, 703 (2001).

[14] S. Kabana, hep-ph/0004138.

[15] N. Armesto, M. A. Braun, A. Capella, C. Pajares and C. A. Salgado, Nucl. Phys. B509, 357 (1998); C. A. Salgado, hep-ph/0105231.

[16] B. Z. Kopeliovich, A. Tarasov and J. Hübner, hep-ph/0104256; Y. B. He, J. Hübner and B. Z. Kopeliovich, Phys. Lett. B477, 93 (2000).

[17] H. Satz, Nucl. Phys. A661, 104c (1999).

[18] J. Dias de Deus, R. Ugoccioni and A. Rodrigues, Eur. Phys. J. C16, 537 (2000).

[19] A. Capella, J. A. Casado, C. Pajares, A. V. Ramallo and J. Tran Thanh Van, Phys. Lett. B206, 354 (1988); C. Gerschel and J. Hübner, Phys. Lett. B207, 253 (1988).

[20] J. Dias de Deus, C. Pajares and C. A. Salgado, Phys. Lett. B407, 335 (1997); B409, 474 (1997).

[21] J. Dias de Deus and C. Pajares, Phys. Lett. B442, 395 (1998).

[22] N. S. Amelin, M. A. Braun and C. Pajares, Phys. Lett. B306, 312 (1993); Z. Phys. C63, 507 (1994).

[23] N. S. Amelin, N. Armesto, C. Pajares and D. Sousa, hep-ph/0103060.

[24] Y. M. Shabelski, Surveys in High Energy Physics 9, 1 (1995); P. Koch and U. Heinz in “Quark Gluon Plasma Signatures”, Editions Frontieres (1991).

[25] M. Bleicher, M. Belkacem, S. A. Bass, S. Soff and H. Stöcker, Phys. Lett. B485, 133 (2000).

[26] M. C. Abreu et al. (NA50 Collab.), Phys. Lett. B409, 474 (1997); C. Cicalo (NA50 Collab.), Nucl. Phys. A661, 93c (1999).
FIG. 1. Ratio of $J/\Psi$ to Drell-Yan events as predicted by (13) and (14) for Pb-Pb collisions at SPS energies (solid line), Au-Au collisions at RHIC energies (130 GeV/n) (dotted line), Au-Au collisions at RHIC energies (200 GeV/n) (dashed-dotted line) and Pb-Pb collisions at LHC energies (dashed line) as a function of $E_T$. Arrows mark the percolation critical points and experimental data for SPS are from NA50 Collaboration [8,26].
FIG. 2. Ratio of $J/\Psi$ to Drell-Yan events as predicted by (13) and (14) for Pb-Pb collisions at SPS energies (solid line), Au-Au collisions at RHIC energies (130 GeV/n) (dotted line), Au-Au collisions at RHIC energies (200 GeV/n) (dashed-dotted line) and Pb-Pb collisions at LHC energies (dashed line) as a function of $L$. 
FIG. 3. Ratio of predictions for $J/\Psi$ suppression with and without clustering of strings, equation \([\text{Eq.} 14]\), for Au-Au collisions at RHIC energies (130 GeV/n) (dotted line), Au-Au collisions at RHIC energies (200 GeV/n) (dashed-dotted line) and Pb-Pb collisions at LHC energies (dashed line) as a function of $E_T$. 