Charmonium Suppression in Heavy Ion Collisions by Prompt Gluons

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Abstract

In relativistic heavy ion collisions, also the bremsstrahlung of gluons in the fragmentation regions of the nuclei suppresses the produced charmonium states. In the energy range of the SPS, the radiation of semi-hard gluons occurs in the Bethe-Heitler regime and the density of gluons and therefore the suppression goes like \((AB)^{3/4}\), where \(A\) and \(B\) are the nucleon numbers of the projectile and target nuclei. In contrast, the suppression via collisions with nucleons is proportional to \((A^{3/4} + B^{3/4})\). Parameter free perturbative QCD calculations are in a good agreement with the data on \(J/\Psi\) and \(\Psi'\) suppression in heavy ion collisions at SPS CERN. At higher energies (RHIC, LHC) the number of gluons which are able to break-up the charmonium substantially decreases and the additional suppression is expected to vanish.

Challenges in charmonium production off nuclei

Charmonium production in heavy ion collisions is considered as one of several sensitive probes for the formation of a quark-gluon plasma. This idea has led the NA38 and NA50 collaborations at SPS CERN to perform a series of measurements of nuclear suppression for charmonium production in \(pA\) and \(AB\) collisions. We recall some remarkable observations (see the collection of data in [3]):

(i) If \(J/\Psi\) suppression in proton-nucleus collisions is treated as a final state absorption phenomenon one extracts an absorption cross section \(\sigma_{\text{abs}}(J/\Psi N) \approx 6 - 7 \text{ mb}\) from the data. At the same time, the vector dominance model applied to \(J/\Psi\) photoproduction data on protons results in a much smaller value \(\sigma_{\text{tot}}(J/\Psi N) \approx 1.1 \text{ mb}\), which increases to a value of \(3 - 4 \text{ mb}\) for a coupled-channel analysis of the photoproduction data [3]. However, a discrepancy of about \(3 \text{ mb}\) still remains to be explained. A part of this extra suppression of
$J/\Psi$ may arise due to a stronger absorption of $\chi_c$ states which contribute to the production of $J/\Psi$ about 30\% via decay\(^1\).

(ii) The $\Psi'(2S)$ state is expected to have a radius about twice as large as the $J/\Psi$ and, therefore, to have a few times stronger final state interaction. However, in proton nucleus collisions both $J/\Psi$ and $\Psi'$ are suppressed by nearly the same amount. This is an effect of the finite formation time of the $J/\Psi$ and $\Psi'$ and can be quantitatively explained in the coupled channel approach \(^2\).

(iii) However, in $S-U$ and $Pb-Pb$ collisions $\Psi'$ is much stronger suppressed than $J/\Psi$. This is partially an effect of the formation time together with the inverse kinematics for the projectile nucleus \(^3\). Nevertheless nearly a half of the observed suppression still needs to be explained.

(iv) Final state absorption on nucleons well describes the data on $J/\Psi$ suppression in $p-A$, $O-Cu$, $O-U$ and $S-U$ collisions with light projectiles. However, it fails in the case of $Pb-Pb$ collision where data show a much stronger suppression of $J/\Psi$. This observation presented at QM’96 \(^4\) and published in \(^5\) has led to intensive theoretical work (for a recent review we refer to \(^6\)). At present there are two main schools of thought: A number of authors consider the strong suppression in the $Pb-Pb$ data as a proof for the formation of a QGP, in the spirit of the original idea by Matsui and Satz \(^1\). Other authors explain the strong suppression of $J/\Psi$ and $\Psi'$ in $Pb-Pb$ by hadronic ”comovers”, i.e. via destruction of the charmonium by the hadrons which are produced in the final state of a nucleus-nucleus collision with the same velocity as the charmonium. Both approaches, via QGP or comovers, introduce a number of free adjustable parameters, and it is only then that they can account for the data. For this reason it is not possible yet to decide about the mechanism.

In this paper we are able to explain the same set of data by invoking – an addition to the normal suppression via collisions with nucleons – the charmonium suppression due to gluon bremsstrahlung produced in multiple nucleon interaction. Since we deal with semi-hard processes, pQCD is expected to work reasonably well and no adjustable parameters have to be introduced.

**Charmonium break-up via interaction with nucleons and gluons**

Final state interaction of a charmonium in nuclear medium which leads to the nuclear suppression is usually described in terms of collisions of the charmonium with undisturbed bound nucleons. This might not be fully correct. A nucleus-nucleus collision is illustrated in Fig. 1 on a two dimensional (time – longitudinal coordinate) plot which corresponds to the $NN$ c.m. frame. One can see that some of the nucleon trajectories cross the charmonium after they have interacted with nucleons from another nucleus. A natural question arises, whether the charmonium interacts with such debris of a nucleon in the same way as with an intact one?

To answer this question note, that a small-size $\bar{c}c$ pair interacts mostly with only one of the valence quarks in a large-size proton. This is because of color screening which cuts off the gluons propagating far away from the charmonium (the Van der Waals forces are supposed to be cut off by confinement). Thus, the charmonium acts like a counter of the number of constituents in the nucleon. In the constituent quark model we expect

$$\sigma_{in}(\Psi n) \approx 3 \sigma_{in}(\Psi q) .$$

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\(^1\)We are thankful to Mark Strikman for this comment.
Figure 1: A two-dimensional (time - longitudinal coordinate) plot for charmonium production in a collision of nuclei A and B in the c.m. of the colliding nucleons. The solid and dashed lines show the nucleon and gluon trajectories, respectively.

Interacting with the debris of a "wounded" nucleon ($N^*$) the charmonium can find more constituents in it than in the original nucleon, particularly gluons shown by dashed lines in Fig. 1, which had a sufficiently short radiation time. In this case the $\bar{c}c$ break-up cross section increases,

$$\sigma_{in}(\Psi N^*) = \sigma_{in}(\Psi N) + \sigma_{in}(\Psi g) \langle n_g \rangle,$$

where $\langle n_g \rangle$ is the mean number of gluons radiated in a $NN$ interaction preceding the collision with the charmonium.

Interaction of the $\bar{c}c$ pair with "wounded" and intact nucleons leads to the following suppression of charmonium in $AB$ collision,

$$S^A_{\Psi} = \frac{1}{AB} \int d^2b \int d^2s \int dA \rho_A(s,z_A) \int dB \rho_B(\vec{b} - \vec{s},z_B)$$

$$\times \exp \left[ -\sigma_{eff}^A(\Psi N) \int dz A(s,z) - \sigma_{eff}^B(\Psi N) \int dz B(\vec{b} - \vec{s},z) \right]$$

$$\times \exp \left[ -\sigma_{eff}^A(\Psi g) \langle n_g \rangle \sigma_{in}(NN) \int dz A(s,z) - \sigma_{eff}^B(\Psi g) \langle n_g \rangle \sigma_{in}(NN) \int dz B(\vec{b} - \vec{s},z) \right]$$

$$\times \exp \left[ -\sigma_{eff}^A(\Psi g) \langle n_g \rangle \sigma_{in}(NN) \int dz A(s,z) - \sigma_{eff}^B(\Psi g) \langle n_g \rangle \sigma_{in}(NN) \int dz B(\vec{b} - \vec{s},z) \right]$$

$$\times \exp \left[ \sigma_{in}(NN) \frac{\langle n_g \rangle}{2} \left[ \sigma_{eff}^A(\Psi g) + \sigma_{eff}^B(\Psi g) \right] \int dz A(s,z) - \sigma_{eff}^B(\Psi g) \langle n_g \rangle \sigma_{in}(NN) \int dz B(\vec{b} - \vec{s},z) \right].$$
Here $\Psi$ denotes either $J/\Psi$ or $\Psi'$. Effective absorption cross sections of the $\bar{c}c$ pair $\sigma_{\text{eff}}^{A,B}(\Psi N)$ and $\sigma_{\text{eff}}^{A,B}(\Psi g)$ may be different for nuclei $A$ and $B$ (for nonzero $x_F$) and depend on where and when the $J/\Psi$ or $\Psi'$ is produced (see below).

In Eq. (3) the coordinates of the production point for the $\bar{c}c$ pair are assumed to be $(\vec{s},z_A)$ and $(\vec{b} - \vec{s},z_B)$ in the nuclei $A$ and $B$, respectively, and $\vec{b}$ is the impact parameter for the $AB$ collision; $\rho_{A,B}(\vec{r})$ is the density of the nuclei $A$ or $B$.

The first exponential in (3) accounts for a suppression due to interaction of the charmonium with the nucleons, both in nuclei $A$ and $B$. The second and the third exponential factors include suppression of the charmonium due to interaction with the gluons radiated in the fragmentation regions of the nuclei $A$ and $B$, respectively. The last exponential eliminates a double counting in number of interacting nucleons (assuming for this purpose that the charmonium is produced with $x_F = 0$).

Gluon bremsstrahlung will also affect nuclear suppression in proton-nucleus collision. Reducing Fig. 1 to the case of $pA$ collision one can see that some of gluons radiated by the projectile proton cross the trajectory of the charmonium. The expression for nuclear suppression is simpler than (3),

$$S_{\Psi}^{pA} = \frac{1}{A} \int d^2b \int_{-\infty}^{\infty} dz_A \rho_A(b,z_A) \exp \left[ -\sigma_{\text{eff}}^{A}(\Psi N) \int_{z_A}^{\infty} dz \rho_A(b,z) \right]$$

$$\times \exp \left[ -\sigma_{\text{eff}}^{A}(\Psi g) \int_{z_A}^{\infty} dz \rho_A(b,z) \right] ,$$

Here we neglect the possible effect of dilution of the gluon density due to transverse motion of the gluons, since for the time interval less than one Fermi most of them stay within the nucleon size in transverse plane.

In order to evaluate expressions (3) - (4), we have to discuss the input parameters, the mean number of produced gluons $\langle n_g \rangle$, the charmonium break-up cross sections $\sigma_{\text{in}}(\Psi N)$ and $\sigma_{\text{in}}(\Psi g)$ which are effective cross sections because of the formation time effects. All the quantities can be estimated fairly reliably. We concentrate on the kinematics of SPS which corresponds to about $10 \text{ GeV}$/per nucleon in c.m. frame. All the longitudinal distances in the nuclei are contracted by a factor of $\gamma = 10$.

**Mean number $\langle n_g \rangle$ of radiated gluons**

A quark in a projectile nucleon radiates only if interacts with a target nucleon [8]. The mean free path for a quark in nuclear medium is three times longer than for a nucleon, $\lambda_q \approx 6 \text{ fm}$. One has a maximal number of produced gluons, namely, the transversal density of gluons proportional to $(AB)^{1/3}$, if the gluons are radiated independently in each $NN$ interaction in Fig. [4]. This is possible only if the radiation happens in the Bethe-Heitler regime, i.e. if the formation length $l_f^q$ of the radiation in the c.m. frame does not exceed the mean free path of a quark $\Delta z = \lambda_q/\gamma \approx 0.6 \text{ fm}$:

$$l_f^q = \frac{2 E_q \alpha(1 - \alpha)}{\alpha^2 m_q^2 + k^2} \leq \Delta z ,$$

where $E_q$ and $m_q$ are the initial energy and the mass of the radiating quark; $\alpha$ and $k$ are the fraction of the quark light-cone momentum and the transverse momentum carried by the gluon.
The transverse momentum of the quark is calculated in \([9]\), LHC energies including also the energy growth of the gluon spectrum. C. separation \([10, 9]\). PQCD predicts radiation of gluons with rather small \(k\) field in a color-flux tube (string). Energy because of Lorentz contraction of the nuclei. J/\(\psi\) the energy dependence of \(\langle n_g \rangle\) because of the step function in (6) suppresses \(k > \omega_{\min}\). Those which contribute have \(\omega_{\min} > 0.3 - 0.5 GeV\). These are semi-hard gluons which do not overlap with the soft gluonic field in a color-flux tube (string).

The cross section of gluon radiation as function of \(\alpha\) and \(\vec{k}\) integrated over the final transverse momentum of the quark is calculated in \([9]\).

\[ \frac{d\sigma(qN \rightarrow gX)}{d\alpha dk^2} = \frac{3 \alpha_s(k^2) C}{\pi} \frac{2 m_g^2 \alpha^4 k^2 + [1 + (1 - \alpha)^2] (k^4 + \alpha^2 m_g^4)}{(k^2 + \alpha^2 m_g^4)^2} \left[ \alpha + \frac{9}{4} \frac{1 - \alpha}{\alpha} \right] \]  

(7)

Here \(\alpha_s(k^2)\) is the QCD running coupling; \(C\) is the factor for the dipole approximation for the cross section of a \(\bar{q}q\) pair with a nucleon, \(\sigma^{q\bar{q}}(r_T) \approx C r_T^2\), where \(r_T\) is the \(\bar{q}q\) transverse separation \([10, 9]\). PQCD predicts \(C \approx 3\). Note that (7) is supposed to work well even for radiation of gluons with rather small \(k\) \([9]\).

We are left with only one parameter \(\omega_{\min}\) in (3) which brings the main uncertainty in the value of \(\langle n_g \rangle\). In accordance with the consideration in next section we try two values \(\omega_{\min} = 0.5\) and \(1\) GeV, which result in \(\langle n_g \rangle\) = 0.69 and 0.25, respectively.

Note that the radiation spectrum steeply grows with energy \([9]\) since we select gluons with relatively large \(k_T\). According to the analysis \([11, 9]\) of HERA data for the proton structure function we expect energy dependence \(dn_g/d\alpha dk^2 \propto (s/s_0)^{0.2}\). However, the restriction for the formation length imposed by the step function in (\(\mathcal{B}\)) suppresses \(\langle n_g \rangle\) much more at high energy because of Lorentz contraction of the nuclei.

We compare \(\langle n_g \rangle\) for \(AB\) collision calculated for \(\omega_{\min} = 0.5\) GeV at SPS, RHIC and LHC energies including also the energy growth of the gluon spectrum.

\[ \langle n_g \rangle = \begin{cases} 
6.9 \times 10^{-1} & (SPS, \sqrt{s} = 20 GeV) \\
6.9 \times 10^{-3} & (RHIC, \sqrt{s} = 200 GeV) \\
1.2 \times 10^{-3} & (LHC, \sqrt{s} = 1200 GeV) 
\end{cases} \]  

(8)

In the rest frame of either of the colliding nuclei the main fraction of gluons are radiated at high energies later than the charmonium is produced.

**The inelastic gluon - charmonium cross section \(\sigma_{in}(\Psi g)\)**

The choice of \(\omega_{\min}\) deserves a special discussion since it is related to the problem of the energy dependence of \(J/\Psi - g\) break-up cross section \(\sigma_{in}(J/\Psi)\). At high energies it is
dominated by gluonic exchange in $t$-channel and slightly grows with energy \[^3\]. According to the previous discussion and Eq. (\[^3\]) the inelastic cross section with a quark is known. The one with a gluon differs by a color factor $9/4$. Therefore, we expect

$$
\sigma_{in}(J/\Psi g) \approx \frac{3}{4} \sigma_{in}(J/\Psi N) .
$$

In the energy range of interest a coupled-channel analysis of $J/\Psi$ photoproduction data gives $\sigma_{in}(J/\Psi N) \approx 4 \text{mb}$. Correspondingly, $\sigma_{in}(J/\Psi g) \approx 3 \text{mb}$. For $\psi'(2S)$ we expect a larger cross section. If the cross section is proportional to $\langle r^2 \rangle$ of the charmonium state, one has a factor of $7/3$ in an oscillator model, or a factor of $4$ for $\langle r^2 \rangle$ calculated from realistic wave functions \[^12\].

One could expect a vanishing $\sigma_{in}(\Psi N)$ down to the threshold energy which is about $0.6 \text{GeV}$ lower for $\psi'$ than for $J/\Psi$. However, since radiation time is of the order of nuclear radius, the gluons cross the charmonium trajectory in Fig. 1 at about the same time as the wounded nucleons, i.e., when the charmonium is not yet formed. One cannot require energy conservation to hold with accuracy better than $\Delta E \approx 1/\Delta t$ where $\Delta t$ is the time interval between the production moment of $\bar{c}c$ (the production/coherence time is quite short at the SPS energy) and its crossing with a gluon. The mean time of crossing in Fig. 1 is $\Delta t \approx (1/3) R_A/\gamma \approx 1 \text{GeV}^{-1}$. Therefore, one can disregard energy conservation, binding energy and the difference in threshold energy between $J/\Psi$ and $\Psi'$ with accuracy $\Delta E \sim 1 \text{GeV}$. For the same reason, the energy threshold has no influence on $\sigma_{in}(\Psi g)$.

There is also another mechanism of charmonium break up by gluons via direct absorption of the gluon \[^3\] which has a pick about $\sigma_{in}(\Psi g) \approx 5 \text{mb}$ near the threshold with a width of the order of binding energy and falls steeply at higher energies. In this case one should replace the binding energy by the $\Delta E$.

To simplify calculations we fix $\sigma_{in}(J/\Psi g) \approx 3 \text{mb}$ at $\omega > \omega_{min}$. We try $\omega_{min} = 0.5$ and $1 \text{GeV}$ in accordance with the scale imposed by the estimated uncertainty in energy.

**Effective absorption cross sections**

The produced $\bar{c}c$ colorless pair propagates through the nucleus with a smaller size and a smaller absorption than that for either of $J/\Psi$ and $\Psi'$, unless time exceeds the formation length $l_f^\psi$ for the charmonium wave function \[^13\], \[^4\],

$$
l_f^\psi = \frac{2E_\psi}{M_\psi^2 - M_{J/\psi}^2} .
$$

Here $E_\psi$ is the charmonium energy in the rest frame of the nucleus. The transition between short and long times is controlled by the nuclear formfactor \[^4\], which for the charmonium production point with impact parameter $\vec{s}$ reads,

$$
F_A(q_L, s) = \frac{1}{T(s)} \int_{-\infty}^{\infty} dz e^{iq_Lz} \rho_A(s, z) ,
$$

where the longitudinal momentum transfer is related to \[^13\], $q_L = 1/l_f^\psi$, and $T(b) = \int_{-\infty}^{\infty} dz \rho_A(b, z)$ is the nuclear thickness function.
The break-up of the colorless $\bar{c}c$ pair during its evolution is described by the effective cross section \[12\],
\[
\sigma_{\text{eff}}^A(J/\Psi N) = \sigma_{\text{in}}(J/\Psi N) \left[ 1 + \epsilon R F_A^2(q_L^A, s) \right]
\]
\[
\sigma_{\text{eff}}(\Psi' N) = \sigma_{\text{in}}(\Psi' N) \left[ 1 + \frac{\epsilon}{rR} F_A^2(q_L^A, s) \right].
\]

The parameters here are defined in \[4\]. We use the values given by the harmonic oscillator model, \( r = \langle \Psi | \hat{\sigma} | \Psi \rangle / (\langle J/\Psi | \hat{\sigma} | J/\Psi \rangle = 7/3, \epsilon = \langle \Psi | \hat{\sigma} | J/\Psi \rangle / (J/\Psi | \hat{\sigma} | J/\Psi \rangle = -\sqrt{2}/3 \). The relative production rate of $\Psi'$ to $J/\Psi$ in a $NN$ collision is known from experiment, \( R \approx 0.4 \).

We expect different effective cross sections for absorption in the nuclei $A$ and $B$, since the charmonium with \( \langle x_F \rangle = 0.15 \) (NA38, NA50) propagates through these nuclei with different energies in their rest frames, \textit{i.e.} $q_L^A$ and $q_L^B$ are different. In an $AB$ collision with $E_{\text{lab}} = 158 \text{ GeV}/A$ and $x_F = 0.15$ one has $l_f^A = 2 \text{ fm}$ and $l_f^B = 4 \text{ fm}$ in the rest system of the projectile ($A$), target ($B$), respectively. The values for the effective cross sections in a $Pb-Pb$ collision are (Eqs. \[12\]-\[13\]) $\sigma_{\text{eff}}^A(J/\Psi N) = 3.9 \text{ mb}$, $\sigma_{\text{eff}}^B(J/\Psi N) = 3.3 \text{ mb}$, $\sigma_{\text{eff}}^A(\Psi' N) = 8.6 \text{ mb}$ and $\sigma_{\text{eff}}^B(\Psi' N) = 4.8 \text{ mb}$ (for $\sigma_{\text{in}}(J/\Psi N) = 4 \text{ mb}$ and $\sigma_{\text{in}}(\Psi' N) = 9.3 \text{ mb}$).

Due to the uncertainty for the radiation time one can assume that the gluons radiated by the "wounded" nucleons cross the $\Psi$ trajectory at about the same points as the nucleons. Therefore, we can use the same form of the effective cross sections \[12\] - \[13\] for interaction with gluons.

**Results of calculations**

To simplify the calculations we use a constant nuclear density $\rho(r) = \rho_0 \Theta(R_A - r)$ with $\rho_0 = 0.16 \text{ fm}^{-3}$, except the nuclear formfactor where a realistic density is used. We calculate \[3\] and \[4\] using the values of the parameters fixed in previous sections. We use two values of $\langle n_g \rangle = 0.25$ and 0.5 to characterize of the uncertainty in our calculations.

The results are plotted in Fig. 2a for $J/\Psi$ and Fig. 2b for $\Psi'$ as function of $A \times B$ together with available experimental data for $pA$ and $AB$ collisions. We reproduce the data for $J/\Psi$ suppression quite well, including the $S-U$ and $Pb-Pb$ points. We obtained a reasonable agreement with the data for $\Psi'$ suppression as well, although the curves seem to be a bit too high. In this respect we should note that the two coupled channel model we use with oscillator potential might be a poor approximation in the case of $\Psi'$. Indeed, as was mentioned, the ratio of mean square radiuses of $\Psi'$ to $J/\Psi$ which is $7/3$ in the oscillator model, is predicted to be nearly 4 in a more realistic approach. As an example we tried another value $r = 3$ in \[12\] - \[13\]. The result is shown by the dashed curve in Fig. 2b which is in a better agreement with the data. Our results for $J/\Psi$ suppression are very stable against this modification.

Note that our curves are not straight lines even for $pA$ collisions. This is mostly due to the formation time effects, \textit{i.e.} is a result of $A$-dependence of the effective cross sections \[12\] - \[13\]. Furthermore, we are able to account for the $J/\Psi$ suppression in $pA$ collisions, although we use $\sigma_{\text{in}}(J/\Psi N) = 4 \text{ mb}$. The additional suppression (even in $pA$) comes from the gluons with absorption cross section of $3 \text{ mb}$. At larger values $A \times B$ for nuclear collisions our curves deviate even more from straight lines (in agreement with the data!) due to the nonlinear dependence on nuclear radius, as is brought into \[3\] by the gluon radiation, whose density is proportional to $(AB)^{1/3}$. 

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Figure 2: (a) Nuclear suppression of $J/\Psi$ production in $pA$ and $AB$ collisions as function of the product $A \times B$. The two curves correspond to $\langle n_g \rangle = 0.25$ and 0.5. The lines connect the point calculated for $A \times B$ corresponding to each experimental point. (b) The same as on (a), but for $\Psi'$ production rescaled by factor $10^{-2}$. The circles and squares correspond to $pA$ and $AB$ data, respectively. The data points are from [2, 5, 6].

Formulas (3) and (4) can be also used for calculation of nuclear suppression of charmonia as a function of impact parameter or of the mean length $L$ of the total path of $\Psi$ in nuclear matter. Our results for S-U and Pb-Pb collisions are plotted in Fig. 3 by dotted and solid curves respectively. We use $\langle n_g \rangle = 0.5$ at 200 GeV and $\langle n_g \rangle = 0.57$ at 158 GeV in accordance with Eq. (6). The overall normalization is free.

Following recommendation of the referee for our paper we compare the calculations with the published data [3] depicted in Fig. 3 by round and triangle points for S-U and Pb-Pb collisions respectively. However, the assignment for $L$ corresponding to the measured transverse energy is not trustable. It is based on an oversimplified model, particularly neglecting the Landau-Pomeranchuk suppression (at low $k$) and enhancement (at high $k$) of the gluon radiation spectrum [3]. The cascading of gluons radiated in the Bethe-Heitler regime which increases the transverse energy, is also neglected. Besides, the normalization on the cross section of the Drell-Yan reaction brings an additional uncertainty (especially at high energies). We plan to do our own calculations for the transverse energy produced in heavy ion collisions which would allow an unbiased comparison with data.

Conclusions
Charmonium suppression in $pA$ and $AB$ collisions at SPS energies can be calculated as arising from two sources:
Figure 3: Nuclear suppression of $J/\Psi$ relative to Drell-Yan lepton pairs as function of the mean length of total path of the charmonium in the colliding nuclei. The dashed (round points) and solid (triangles) curves correspond to S-U and Pb-Pb collisions, respectively. The data points are from [6].

(i) Collisions with nucleons, the cross section for which is the one deduced from photo-production data modified because of the formation time effects. The suppression from this source essentially scales like $A^{1/3} + B^{1/3}$.

(ii) Collisions of charmonia with gluons which have been produced in multiple $NN$ collisions. In the Bethe-Heitler regime - good at SPS energies - about $\langle n_g \rangle = 0.25 - 0.5$ gluons contribute per $NN$ collision. This additional effect scales with $(AB)^{1/3}$ and accounts for the "anomalous" $J/\Psi$ and $\Psi'$ suppression in nucleus-nucleus collisions. We conclude that the results of the NA38/50 experiments do not signal about QGP formation.

Nonetheless, the suggested mechanism leaves room for other contributions to the charmonium suppression within the uncertainty of calculations. Particularly, as was mentioned above, a "wounded" nucleon is not a colorless system of partons any more. Therefore, color screening does not cut off (only the charmonium formfactor does) soft gluon exchanges in contrast to $\Psi N$ interaction. However this correction to (4), which we do not expect to be large, scales with $(A^{1/3} + B^{1/3})$ and leads to a renormalization of $\sigma_m(\Psi N)$.

According to (8) the suppression of charmonium by gluon radiation vanishes at high energies due to the formation time effect. We expect practically no additional suppression by prompt gluons at RHIC, while the suppression via interaction with "comovers" (either QGP or hadrons) increases with energy. Therefore, one has less freedom in interpretation of data on nuclear suppression of charmonium at RHIC.

The main parameter which controls the charmonium suppression via interaction with
prompt gluons in (3) is the product \( \langle n_g \rangle \sigma_{\text{eff}}(\Psi N) \). We estimated this factor and allowed it to vary within a factor of 2. We think that this uncertainty covers other possible corrections, for instance, the contribution of \( \chi_c \) decays to the production of \( J/\Psi \).

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**References**

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

[2] C. Lourenco, in Proc. of the Quark Matter Conf. 1996, Nucl. Phys. **A610** (1996) 552c

[3] J. H"ufner and B.Z. Kopeliovich, Phys. Lett. **B426** (1998) 154

[4] J. H"ufner and B.Z. Kopeliovich, Phys. Rev. Lett. **76** (1996) 192

[5] M. Gonin, in proc. of the Quark Matter Conf. 1996, Nucl. Phys. **A610** (1996) 404c

[6] M.C. Abreu et al., Phys. Lett. **B410** (1997) 337

[7] D. Kharzeev, invited talk at the Quark Matter Conf. 1997, [nucl-th/9802037](http://arxiv.org/abs/nucl-th/9802037)

[8] J.F. Gunion and G. Bertsch, Phys. Rev. **D25** (1982) 746

[9] B.Z. Kopeliovich, A. Sch"afer and A.V. Tarasov, [hep-ph/9808378](http://arxiv.org/abs/hep-ph/9808378)

[10] A.B. Zamolodchikov, B.Z. Kopeliovich and L.I. Lapidus, JETP Lett. **33** (1981) 595.

[11] B.Z. Kopeliovich and B. Povh, [hep-ph/9806284](http://arxiv.org/abs/hep-ph/9806284)

[12] W. Buchmüller and S.-H. H. Tye, Phys. Rev. **D24** (1981) 132

[13] E.V. Shuryak, Sov. J. Nucl. Phys. **28** (1978) 408

[14] B.Z. Kopeliovich and B.G. Zakharov: Phys.Rev. **D44** (1991) 3466.