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J/ψ, ψ' and χ suppression in nucleus-nucleus collisions at SPS energies ★

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Abstract

A quantum-mechanical treatment for the evolution of a $c-\bar{c}$ pair inside a quark-gluon plasma and subsequent mixed phase is presented. It is shown, that contrarily to the expectation of the semi-classical approach, the ψ' and J/ψ suppression at SPS energies are not consistent with the existence of a plasma. An alternative explanation involving the formation of a medium with partial screening is proposed.

Keywords: Quark-gluon plasma; J/ψ and ψ' suppression

The so-called J/ψ suppression [1,2] observed in relativistic heavy ion reactions at SPS energies has been considered as a possible signature of the presence of a quark-gluon plasma, after the original suggestion of Matsui and Satz [3]. One has to underline readily that the present experimental situation is also consistent with conventional (hadronic) scenarios [4–7], although a recent work by Kharzeev and Satz [8] shed doubt about this explanation. However, at the beginning, the analysis of the data in terms of a plasma suppression of the J/ψ production was carried out with semi-classical arguments, assuming some sharply defined formation time and a suppression which is total or absent depending on the time spanned in the plasma being shorter or longer than the formation time. Refinements have since been introduced, concerning the corrections due to the rescattering of the partons prior to fusion [9] and more importantly the introduction of a quantum mechanical treatment of the evolution of the $c-\bar{c}$ state in Refs. [10–14]. It seems that the uncertainty between a plasma or a hadronic origin of the J/ψ suppression cannot be removed by these improvements. As stressed by Satz [15], only a consistent treatment of the whole $c-\bar{c}$ wave packet (and not of its components individually) in systematically varied kinematical conditions and a simultaneous treatment of all the resonances could remove the indeterminacy. This may become soon possible, since the ψ' production has been recently measured by the NA36 Collaboration [16,17].

In this paper, we want to investigate whether a quantum mechanical treatment of the evolution of the $c-\bar{c}$ wave packet in the plasma with a reasonable initial wave packet, handling all the components of the $c-\bar{c}$ wave could explain the existing data and possibly give clear evidence for the presence of a plasma.

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The central part of this work is the study of the evolution of the internal $c-\bar{c}$ wave packet by means of the non-relativistic Schrödinger equation

$$i\hbar\frac{\partial\psi}{\partial t} = [T + V(t) + iW(t)]\psi(t)\,. \tag{1}$$

The time dependence of the $c-\bar{c}$ potential $V(t)$ is assumed to reflect the evolution of the medium surrounding the $c-\bar{c}$ pair. In the plasma phase, the potential reduces to the Debye screened potential. In the following, we consider that the $c-\bar{c}$ pair stays a (proper) time τ_p in the plasma, and a time τ_m in a mixed phase. In the latter, it is assumed that the potential $V(t)$ interpolates smoothly between the Debye screened potential and the full $c-\bar{c}$ potential, which is recovered after the time span τ_m . The imaginary part $W(t)$ accounts for the flux removed owing of the coupling to the $D-\overline{D}$ channel (see Refs. [13,14,19] for more detail). It translates the fact that the $c-\bar{c}$ "string" breaks into two pieces when its size becomes sufficiently large Similarly to the real potential, $W=0$ in the plasma, and $W\approx 40$ MeV in the hadronic phase, which is consistent with the static properties of high mass charmonium resonances [19]. Let us mention that such a model (except for the imaginary part) was used recently to study the evolution of ϕ and ϕ' mesons in matter [18].

The important point of the above approach is the initial wave packet. Usually, the latter is chosen rather arbitrarily [12,23,24]. However, the wave packet may be calculated microscopically, as explained below. Here, we will adopt the results of the microscopic calculation of Ref. [25] as our starting point. Let us call $\tau=\tau_p+\tau_m$. The suppression of the J/ψ , i.e. the ratio of J/ψ probability after the travel in the plasma (plus the mixed phase) and the final decays to the J/ψ probability in the absence of matter is given by

$$S_{J/\psi}(\tau) = \frac{P(\psi')\,s_{\psi'}(\tau)\mathrm{BR}(\psi'\to J/\psi) + P(\chi)\,s_\chi(\tau)\,\mathrm{BR}(\chi\to J/\psi) + P(J/\psi)\,s_{J/\psi}(\tau)}{P(\psi')\,\mathrm{BR}(\psi'\to J/\psi) + P(\chi)\,\mathrm{BR}(\chi\to J/\psi) + P(J/\psi)}\,, \tag{2}$$

where $P(\psi')$, $P(\chi)$, $P(J/\psi)$ are the probabilities of finding the indicated resonances in the initial wave packet $(i=\psi',\chi,J/\psi)$:

$$P(i) = |\langle i|\psi(0)\rangle|^2\,. \tag{3}$$

The quantities BR are the branching ratios for the indicated decays and the quantities $s_i(\tau)$ are defined by $(i=\psi',\chi,J/\psi)$

$$s_i(\tau) = \left|\frac{\langle\psi(\tau)\,|i\rangle}{\langle\psi(0)\,|i\rangle}\right|^2. \tag{4}$$

Assuming that the initial wave packet $\psi(0)$ can be identified to the $c-\bar{c}$ wave function issued from pp collisions (i.e. after the interaction of the $c-\bar{c}$ with the rest of the system has ceased), one can relate the probabilities $P(i)$ to primordial (i.e. production prior to ψ' and χ decays) cross-sections. In fact, here, only ratios of these probabilities are needed. One has

$$\frac{P(\psi')}{P(J/\psi)} = \left|\frac{\langle\psi(0)\,|\psi'\rangle}{\langle\psi(0)\,|J/\psi\rangle}\right|^2 = \frac{\sigma_{\rm prim}(\psi')}{\sigma_{\rm prim}(J/\psi)} \tag{5a}$$

and

$$\frac{P(\chi)}{P(J/\psi)} = \left|\frac{\langle\psi(0)\,|\chi\rangle}{\langle\psi(0)\,|J/\psi\rangle}\right|^2 = \frac{\sigma_{\rm prim}(\chi)}{\sigma_{\rm prim}(J/\psi)}. \tag{5b}$$

There is a relationship between the primordial and the inclusive cross-sections, namely

$$\sigma_{\rm incl}(J/\psi) = \sigma_{\rm prim}(J/\psi) + \sigma_{\rm prim}(\chi)\,\mathrm{BR}(\chi\to J/\psi) + \sigma_{\rm prim}(\psi')\,\mathrm{BR}(\psi'\to J/\psi)\,, \tag{6a}$$

$$\sigma_{\rm incl}\left(\psi'\right) = \sigma_{\rm prim}\left(\psi'\right)\left[1 - {\rm BR}\left(\psi' \to J/\psi\right)\right] , \tag{6b}$$

$$\sigma_{\rm incl}\left(\chi \to J/\psi\ \gamma\right) = \sigma_{\rm prim}\left(\chi'\right){\rm BR}\left(\chi \to J/\psi\ \gamma\right) . \tag{6c}$$

From the known branching ratios [26,27] and the measured values of the inclusive cross-sections, it is possible to determine the ratios (4a) and (4b) (see Refs. [25,28] for more detail). At $\sqrt{s}$ = 23.6 GeV, all the cross-sections (6a)–(6c) have been measured. One obtains $P(\psi')/P(J/\psi) = 0.14/0.617$ and $P(\chi)/P(J/\psi) = 0.296/0.617$.

It is therefore important to use an initial wave function $\psi(0)$ which is consistent with these experimental constraints. This is the case for the microscopically calculated wave packet of Ref. [25]. In this work, the Fourier transform of the wave packet is assumed to satisfy

$$|\psi_{\boldsymbol{k}}(0)|^2 \propto |A(\boldsymbol{k})|^2 , \tag{7}$$

where $A(\boldsymbol{k})$ is the calculated amplitude for production of a $c-\overline{c}$ pair with relative momentum $\boldsymbol{k}$ in pp collisions. The wave function is totally determined if one assumes that it has the smallest spatial extension (r.m.s. radius) compatible with (7), which seems reasonable as $\psi(0)$ is supposed to represent the $c-\overline{c}$ wave packet just after its formation in pp collisions. This implies

$$\psi_{\boldsymbol{k}}(0) \propto |A(\boldsymbol{k})| . \tag{8}$$

In Ref. [25], the wave function is calculated along these lines, with $A(\boldsymbol{k})$ given by the usual lowest order QCD diagrams. Just to give an idea, the $\ell = 0$ part of the wave packet is close to a Gaussian form

$$(\sqrt{\pi}\sigma)^{-3/2}\exp\ (-r^2/\sigma^2) , \tag{9}$$

with $\sigma \approx 0.29$ fm. The $\ell = 1$ part is similar to $\sim r\ \exp(-r^2/\sigma'^2)$, with $\sigma' \sim 0.34$ fm. The relative weight of $\ell = 0$ and $\ell = 1$ waves is consistent with the ratio $P(\chi)/P(J/\psi)$ indicated above. Neglecting feeding from higher resonances, formulae similar to Eq. (1) can be written for ψ' and χ suppression. They are simply

$$S_{\psi'}(\tau) = s_{\psi'}(\tau) , \quad S_{\chi}(\tau) = s_{\chi}(\tau) . \tag{10}$$

Two differences (beyond the complication of the final decays) appear between formulae (2) and (9) and the usual semi-classical formation time formulae : (i) quantum interferences in the $\ell = 0$ wave packet are neglected in the semi-classical treatment. This amounts to replace the quantities $s_{\psi'}$ and $s_{J/\psi}$ by

$$s_{\psi'} \to \tilde{s}_{\psi'}(\tau) = \left|\langle\tilde{\psi}(\tau)\,|\psi'\rangle\right|^2 , \quad s_{J/\psi} \to \tilde{s}_{J/\psi}(\tau') = \left|\langle\tilde{\psi}(\tau)\,|J/\psi\rangle\right|^2 , \tag{11}$$

where $\tilde{\psi}$ is the solution of Eq. (1) with the initial wave packet identical to the ψ' or the J/ψ, respectively ; (ii) the formation time concept corresponds to ($i = \psi', \chi, J/\psi$)

$$\tilde{s}_i(\tau) = s_i^{\rm SC}(\tau) = \theta(\tau - \tau_i) , \tag{12}$$

where τ_i is the corresponding formation time and where $\theta(x)$ is the Heaviside function. An absorption describable by the inelastic cross-section picture would correspond to (for an homogeneous medium)

$$\tilde{s}_i(\tau) = s_i^{\rm ABS}(\tau) = \exp\left(-\frac{\tau}{\tau_i^{\rm ABS}}\right) . \tag{13}$$

If one starts with a pure resonance state i, the calculated functions s_i in a plasma are more or less exponentially decreasing, as depicted by Fig. 1. Note however that at the beginning the quantities $s_i(\tau)$ behaves like $1 - a\tau^2$. As for the J/ψ, this behaviour is expected, since the free expansion of a gaussian wave packet leads to

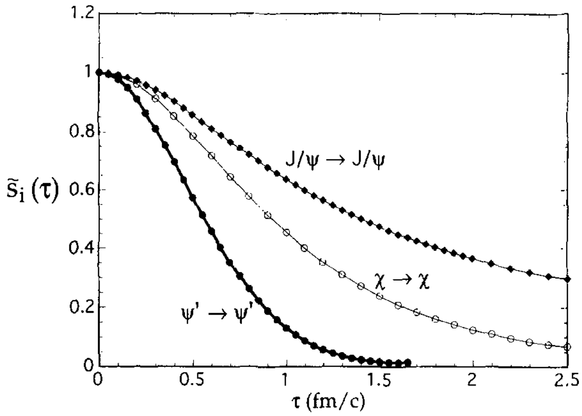

Fig. 1. Intrinsic survival probability (Eq. (10)) as a function of time of a pure $c-\bar{c}$ resonance wave packet, i.e. J/ψ, ψ' or χ_2, embedded inside a plasma. See text for details.

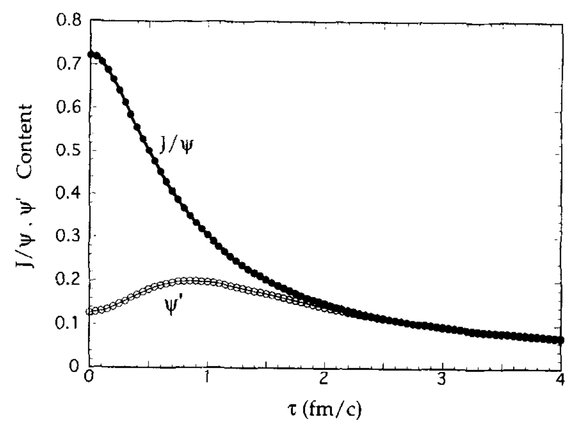

Fig. 2. Time evolution of the J/ψ and ψ' content (see Eq. (4)) of a microscopically calculated $c-\bar{c}$ wave packet embedded in a plasma.

$s(\tau) = [1+(\tau/\tau_G)^2]^{-3/2}$, where $\tau_G \propto \sigma^2 + \sigma^2_{J/\psi}$. Note however that, quantum mechanically, if one starts with a pure state, other states with the same quantum numbers are progressively populated.

Fig. 2 gives the evolution (in a plasma) of the content of the microscopically calculated $\ell = 0$ wave function, as time τ is varied (quantities $s_i(\tau)$ are obtained by dividing by the initial values). There appears a strong difference with the behaviour of the ψ' shown in Fig. 1. The ψ' content does increase at small time, reaches a maximum and finally decreases. It can be shown that the increase of the ψ' content is somehow related to the relatively small size of the initial $\ell = 0$ wave function. A free expansion of such a wave packet is bound to produce an increase at small τ. This behaviour, which may appear counterintuitive, is however unavoidable in some circumstances: if one starts with a J/ψ at $\tau = 0$ and switches on some perturbation, the ψ' content, initially equal to zero, is, of course, bound to increase,by unitarity. By continuity, this behaviour also holds for initial wave packets of similar sizes. This can be illustrated by studying the free expansion of an initial wave packet and looking at the projections on harmonic oscillator eigenstates, as a simple model for the charmonium states. Starting with a pure harmonic oscillator state leads to results in qualitative agreement with those of Fig. 1. On the other hand, if one starts with a Gaussian wave packet (Eq. (9)), it is easy to show that the projection on the harmonic oscillator states are given, for small τ, by

$$|c_n|^2 = 8\frac{[(2n+1)!!]^2}{(2n+1)!}\tilde{\sigma}^3\left(1-\tilde{\sigma}^2\right)^{2n}\left(1+\tilde{\sigma}^2\right)^{-(2n+3)} \times\left[1+\left(\frac{n}{\left(1-\tilde{\sigma}^2\right)^2}-\frac{2n+3}{2\left(1+\tilde{\sigma}^2\right)^2}\right)\omega^2\tau^2+O(\tau^4)\right], \tag{14}$$

where $\tilde{\sigma} = \sigma/(r_0\sqrt{2})$, $r_0 = \sqrt{\hbar/(m\omega)}$ and ω is the oscillator frequency. The squared bracket can be positive , corresponding to an increasing component. In particular, for $n = 1$ (which is the analog of the ψ'), it is positive as far as $\tilde{\sigma}$ lies between 0.47 and 2.13. Our case of figure 2 corresponds to $\tilde{\sigma} = 0.6$ (taking $r_0 = 0.33$ fm to reproduce the r.m.s. radius of the J/ψ). The ψ' content evolution in Fig. 2 at small τ is thus fully justified, even if it strikingly contrasts with the general belief [24,21,29] that the suppression of the loosely bound $\psi'$is larger than the ψ one. This belief is based on the assumption that the components of the the wave packet evolves independently. Our approach circumvents this assumption.

The results shown in Fig. 2 (and similar ones for the χ) can be used to calculate the so-called suppression factor in relativistic heavy ion collisions, assuming some plasma scenario. One has to assume some extension and lifetime of the plasma, a duration time of the possible subsequent mixed phase and some distribution of

Table 1
Values of the ψ' suppression factor (Eq. (15)) for several plasma scenarios yielding a reasonable value of the J/ψ suppression

Scenario	$S'(p_\perp = 1\ \mathrm{GeV}/c) = \psi'\mathrm{HI}/\psi' pp$
∞ plasma, $\tau_p = 0.5$ fm/c	1.00
∞ mixed phase, $\tau_m = 1$ fm/c	1.01
finite plasma, $R = 7$ fm, $\tau_p = 0.5$ fm/c	1.00
contracting plasma, $R = 3$ fm, $\tau_p = 2$ fm/c	0.92

See Ref. [14] for a detailed description of the scenarios.

the initial position and direction of motion of the $c - \bar{c}$ inside the plasma. For a given scenario, it is possible to calculate the time spanned by the pair inside the medium. For a J/ψ of transverse momentum $p_\perp$, the so-called suppression factor may be expressed as

$$S(p_\perp) = \frac{\int dx\, n(x) S_{J/\psi}(\tau(x, p_\perp))}{\int dx\, n(x)}, \tag{15}$$

where x stands for the initial conditions (position, momentum) for the pair, and $S_{J/\psi}(\tau)$ is the quantity (2) and where $\tau(x, p_\perp)$ is the time spanned in the medium by the $c - \bar{c}$ pair with momentum $p_\perp$ and initial conditions x. One may write a similar expression for ψ' and χ.

It has been shown in Ref. [14] that a good agreement with the experimental data for the J/ψ [2], which correspond to $S^{\mathrm{exp}}_{J/\psi} \approx 0.6$, irrespective of $p_\perp$, after initial state correction applied by Gupta and Satz [30], could be obtained with several reasonable scenarios. As $S(p_\perp)$ is simply some average value of $S_{J/\psi}$ (see Eq. (15)), it can be conceived, from the inspection of Fig. 2, that if a plasma scenario gives a good value of the J/ψ suppression, it will hardly give a larger suppression of ψ'. Let us mention that the recent measurements of the NA38 Collaboration [16,17,29] are indicating a ψ' suppression of $S^{\mathrm{exp}}_{\psi'} \approx 0.4$. This is an average value over the transverse energy and over the momentum of the $c - \bar{c}$ pair in the $\sim$ 0–2 GeV/c range (in this first approach, we disregard the (small) E_T dependence of $\psi'/(J/\psi)$ ratio which anyway would involve the introduction of a model dependent determination of E_T). The only way to have a stronger suppression of ψ' is to have long lived plasma or mixed phase, but in that case, both reductions are too much important, as can be guessed from Fig. 2 and indicated in Table 1. In conclusion, the two experimental suppression factors at SPS energies, namely $S^{\mathrm{exp}}_{J/\psi} \approx 0.6$ and $S^{\mathrm{exp}}_{\psi'} \approx 0.4$ do not seem to be consistent with a plasma hypothesis, at least in the approach described above.

We have also looked at an alternative explanation based on what we may call "pre-plasma" scenario. In this case, we assume that a hot $B = 0$ matter, wherein the color forces are partially screened, is produced and lives for some time interval τ. More precisely, we consider that the corresponding $c - \bar{c}$ potential is given by

$$V = V_{\mathrm{OGE}}(r) \exp[-\mu_D(T) r] + \left(1 - \frac{\mu_D(T)}{\mu_D(T_c)}\right) V_{\mathrm{CON}}(r), \tag{16}$$

where V_{OGE} and V_{CON} are the usual one gluon exchange and confining parts of the charmonium potential and where $\mu_D(T)$ is the usual Debye mass. We thus assume that the reduction of the color forces are still governed by this parameter, even below the critical temperature T_c, whatever the real nature of the phase.

We give in Fig. 3 the evolution (inside the "pre-plasma") of the J/ψ and ψ' content of the microscopically calculated initial $\ell = 0$ $c - \bar{c}$ wave packet (quantities (2) and (10)) in several illustrative cases: T = 100 MeV, assuming $W = 0$ (no coupling to the $D - \overline{D}$ channel), T = 150 MeV with $W = 0$ and W = 20 MeV and, for comparison, $T = T_c$ = 200 MeV, i.e. the plasma case. In the "pre-plasma" case, a clear quantum beating is observed, due to the fact that the wave packet is confined by the second part of (16), in contrast with the almost free expansion in the plasma. The beating is somewhat damped by the addition of the imaginary part. The calculated J/ψ and ψ' suppressions approach the experimental values for some interval of values of τ only,

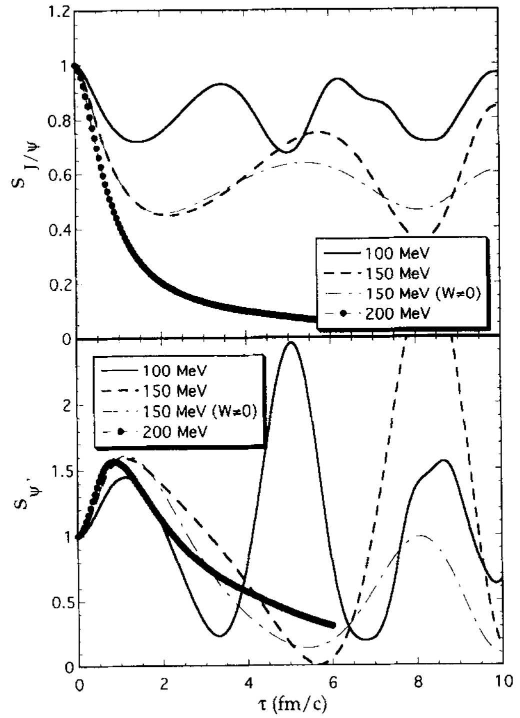

Fig. 3. J/ψ and ψ' suppression for several conditions of "pre-plasma". See text for details.

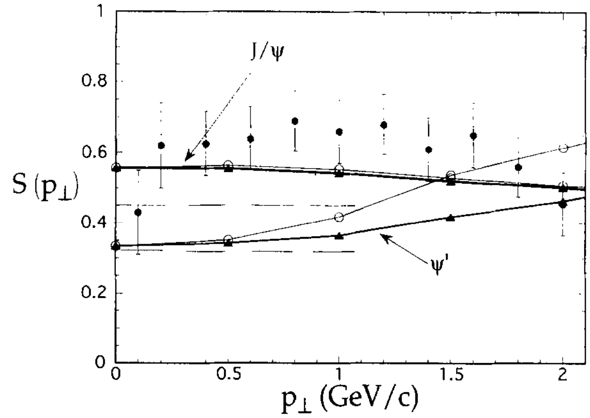

Fig. 4. Suppression factor for J/ψ and ψ' (Eq. (15)) for two scenarios of "pre-plasma" in S-U collisions at SPS energies. The black dots refer to a shrinking "pre-plasma" at T = 150 MeV, of infinite radius, and living for 6 fm/c. The open dots refer to the same conditions with an initial radius of 3 fm. The J/ψ experimental data are from Ref. [2], after the correction of initial state interaction [30]. The horizontal lines indicate the average experimental ψ' suppression factor [16,17]. See text for details.

namely 4–7 fm/c, as indicated by Fig. 3. In fact, we found that the results for the suppression factor (Eq. (15)) are rather sensitive to the scenario, in contrast with the J/ψ suppression factor in a plasma. We show in Fig. 4 the results obtained by two of the best scenarios. It is essential to have a "pre-plasma" living for $\sim$ 5–6 fm/c and shrinking to a phase without screening in this time span. The reason for the difference of behaviour with the plasma is the fact that the intrinsic suppression factor (Eq. (2)) is rather smooth for the plasma (see Fig. 2) and somewhat widely varying for the "pre-plasma".

The present model assumes that colour neutralisation is fast enough. This question is delicate. It has been proved on pretty general considerations [20] that J/ψ production at large energy and large x_F is consistent with the crossing of the whole nucleus by an initially colour octet $c-\bar{c}$ object. This indicates that the time for colour neutralisation is larger that the time necessary to cross the nucleus. In the rest frame of the $c-\bar{c}$, this is about 0.05 fm/c. On the other side, the neutralisation time cannot be larger than 1 fm/c, which seems to be the upper limit for strong interaction processes.

More detailed information about the neutralisation time can be obtained within specific models only and are therefore subject to large uncertainties. For instance, considerations about the gluon fusion model and the decolourisation by gluon bremsstrahlung indicate that the intrinsic neutralisation time is of the order of about 0.25 fm/c [21]. The question of the effect of the collisions (in a hadronic phase) on the neutralisation time is starting to be investigated only and controversial results are given. According to Ref. [22], this effect is very small, whereas the authors of Ref. [21] mention that the neutralisation time may be enhanced (remaining below 1 fm/c anyway) at large x_F. At moderate x_F ($x_F \sim 0$), it seems that the neutralisation time remains smaller than the characteristic suppression times that we found above. In the absence of a clear cut situation, we have here sticked to the same point of view as in most of the previous approaches [3–14,22,23], disregarding the colour structure and leaving this point for future investigations.

We stress that our results basically involve the spatial structure of the initial wave packet and would hold even if the initial wave packet is in an octet colour state, provided the colour neutralisation mechanism does not distort the spatial structure of the wave packet too much. This may may appear unrealistic if colour neutralisation proceeds through the emission of a hard gluon, which implies a change of angular momentum of at least one unit. However,it is more probable that the mechanism is the emission of one (or several) soft gluon. Since the latter can be viewed as the emission of several correlated gluons, it does not exclude zero angular momentum transfer. This remains an open issue.

In conclusion, our quantum mechanical model for the evolution of a $c-\bar{c}$ pair shows that the observed suppression of J/ψ and ψ' at SPS energies are not consistent with the existence of the plasma, but could be consistent with the existence of a "pre-plasma" in some scenarios. Note however that the quantum coherence observed in the evolution of the wave packet at large values of τ is not expected to survive in a realistic situation, where fluctuations of the medium are expected to reduce it progressively. This would probably increase the range of values of τ for which good agreement can be obtained. This however deserves further studies.

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