Sequential Charmonium Dissociation

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Abstract:

Finite temperature lattice QCD indicates that the charmonium ground state $J/\psi$ can survive in a quark-gluon plasma up to 1.5 $T_c$ or more, while the excited states $\chi_c$ and $\psi'$ are dissociated just above $T_c$. We assume that the $\chi_c$ suffers the same form of suppression as that observed for the $\psi'$ in SPS experiments, and that the directly produced $J/\psi$ is unaffected at presently available energy densities. This provides a parameter-free description of $J/\psi$ and $\psi'$ suppression which agrees quite well with that observed in SPS and RHIC data.

Recent studies of the behavior of charmonium states in a deconfined medium show that the ground state $J/\psi(1S)$ survives up to considerably higher temperatures than initially expected. In quenched QCD \cite{1}-\cite{4}, charmonium correlators show no signs of medium-induced suppression at least up to 1.5 $T_c$, while above 2 - 2.5 $T_c$, the signal is strongly modified or disappears. First work in QCD with two quark flavors supports these results \cite{5}. In contrast, the higher excited states seem to disappear very near $T_c$; in quenched calculations, no signal for the $\chi_c$ is seen at $T = 1.1 T_c$ \cite{3}.

The results of direct spectral function studies are further supported by potential model analyses \cite{6}-\cite{9}, using the color-singlet free energy obtained in (quenched as well as unquenched) lattice QCD to determine the heavy quark potential. These also lead to a $J/\psi$ dissociation temperature of 2 $T_c$ or higher, while $\chi_c$ and $\psi'$ disappear in the vicinity of 1.1 $T_c$. In contrast, earlier potential model work \cite{10}-\cite{12}, based on a heavy quark
interaction which underestimated the actual $Q\bar{Q}$ potential, had predicted a considerably lower $J/\psi$ dissociation temperature.

Since $J/\psi$ suppression was proposed as a signature for quark-gluon plasma formation in nuclear collisions [13], this modification of our understanding of the in-medium behavior of charmonia can be quite important for the interpretation of relativistic heavy ion data. Lattice calculations show that a temperature of $1.5 T_c$ corresponds to an energy density around 10 GeV/fm$^3$, and $2 T_c$ to around 30 GeV/fm$^3$, which could move the suppression of direct $J/\psi$ production out of the range of RHIC.

In hadron-hadron collisions [14] it is found that about 60% of the observed $J/\psi$’s are directly produced as (1S) states, with the remainder coming to about 30% from $\chi_c$ and 10% from $\psi'$ decay. The hierarchy of suppression temperatures thus leads to a sequential suppression pattern [11, 15], with an early suppression of the $\psi'$ and $\chi_c$ decay products and a much later one for the direct $J/\psi$ production.

In this note, we want to consider the experimental results available now from the SPS and from RHIC, and show that the new theoretical understanding can be used to formulate a rather natural parameter-free description of the essential features of the data.

Our considerations are based on the following scenario. The $J/\psi$ survival probability $S_{J/\psi}$ in $A-A$ collisions is defined as the ratio of the measured rate to that expected if the only modifications are due to the presence of normal nuclear matter. We assume that $S_{J/\psi}$ consists of one term $S_{\psi}$ corresponding to the survival of directly produced $J/\psi$’s and a second term $S_x$ for those coming from the decay of the higher excited states $\chi_c$ and $\psi'$,

$$S_{J/\psi} = 0.6 S_{\psi} + 0.4 S_x. \quad (1)$$

The relative contributions here are those observed in hadron-hadron collisions [14]. From the mentioned QCD studies we expect $S_{\psi} \simeq 1$ for energy densities up to 10 GeV/fm$^3$ or more, while $S_x$ is expected to show suppression effects around the deconfinement point, i.e., for $\epsilon \simeq 0.5 - 1.5$ GeV/fm$^3$. In principle, $S_x$ could consist of two distinct terms, with different dissociation onsets for $\chi_c$ and $\psi'$. At present, however, neither calculational nor experimental accuracy seems to permit such fine structure studies, and we shall therefore combine the decay of the two states into one term.

We first turn to the onset pattern of suppression and consider the SPS data for $J/\psi$ production from $Pb-Pb$ [16] and $In-In$ interactions [17], together with $\psi'$ data from $Pb-Pb$ collisions [18]; the analysis of $\psi'$ production in the $In-In$ data is not yet completed\(^1\). In addition, there are reference data from $p-A$ collisions with several nuclear targets [19], which define the necessary baseline for modifications of the production due to normal nuclear matter. The combined effect of all possible modifications was here parametrized in the form of nuclear absorption, leading to the absorption cross sections

$$\sigma_{J/\psi} = 4.3 \pm 0.3 \text{ mb} \quad (2)$$

for the $J/\psi$ and

$$\sigma_{\psi'} = 7.1 \pm 1.6 \text{ mb}, \quad (3)$$

\(^1\)We restrict ourselves here to symmetric ($A-A$) data and comment on the $S-U$ results later on.
for the \( \psi' \), respectively \[19\]. Using these in a Glauber analysis of \( A-A \) data provides the production rates \( (d\sigma_i/dy)_G \), with \( i = J/\psi, \psi' \), as they would be if there were no effects beyond those caused by the presence of normal nuclear matter \[20\]. The survival probability is then defined as

\[
S_i = \frac{(d\sigma_i/dy)}{(d\sigma_i/dy)_G},
\]

(4)
describing whatever anomalous effects arise. The centrality dependence of the \( A-A \) data is determined through the number \( N_{\text{part}} \) of participants, which is measured directly through a zero degree calorimeter. A Glauber analysis then provides the density \( n_{\text{part}} \) of participants in the transverse overlap region \( A \) of the collision \[20\], and the corresponding energy density is given by the Bjorken estimate

\[
\epsilon = \frac{w_h}{A\tau_0} \left( \frac{dN_h}{dy} \right)_{AA} = \frac{\nu_h w_h}{\tau_0} n_{\text{part}}; 
\]

(5)
here \( (dN_h/dy)_{AA} \) denotes the hadron multiplicity at the given centrality, \( w_h \) the average hadron energy, and \( \nu_h \) the average number of hadrons emitted per participant nucleon (the values of \( \nu_h \) and \( w_h \) can depend on centrality). For the equilibration time of the medium, we take \( \tau_0 = 1 \) fm, so that corrections for other possible values can easily be carried out. In our context, however, the formation time of the charmonium states in question should be less than the formation time of the medium, which is the case if \( \tau_0 = 1 \) fm. The actual values of \( \epsilon \) we will cite here were obtained by an event generator determination of the NA60 collaboration and is based on VENUS \[17\]. It should be noted, however, that with constant \( \nu_h \approx 2 \) and \( w_h \approx 0.5 \) GeV, we get very similar results, while an event generator determination based on RQMD as input (used by the NA50 collaboration \[16\]) leads to values which are higher by about 10%.

We now return to our basic scenario, assuming that at present energy densities the directly produced \( J/\psi \) are unaffected, and the suppression patterns of the excited states \( \chi_c \) and \( \psi' \) are about the same. This implies that if we use the \( \psi' \) data to form \( 0.4 S_{\psi'} + 0.6 \), then as function of the energy density this should coincide with the measured \( J/\psi \) results. In Fig. 1 we see that this is indeed quite well fulfilled, for the overlap of \( J/\psi \) and \( \psi' \) data as well as for the convergence to the \( J/\psi \) “saturation” value of about 60%.

![Figure 1: Universal \( \psi' \) and \( J/\psi \) suppression at the SPS](image)
Next we want to check if this pattern continues for higher energy densities and therefore turn to the recently presented preliminary RHIC data; its higher collision energy can provide correspondingly higher energy densities. The $J/\psi$ production rate $R_{Au-Au}$ in $Au-Au$ interactions is given relative to the result from scaled $p-p$ collisions, as shown in Fig. 2 as function of the number of participant nucleons [21].

![Figure 2: $J/\psi$ production rates for $Au-Au$ collisions at $\sqrt{s} = 200$ GeV](image)

In order to convert the rates $R_{Au-Au}$ into survival probabilities, we have to know what would be expected if only normal nuclear matter were present. At RHIC, this information is provided through $d-Au$ studies [22]; the resulting nuclear modification factor, specifying the production rate relative to scaled $p-p$ collisions, is shown in Fig. 3.

![Figure 3: $J/\psi$ production in $d-Au$ collisions at $\sqrt{s} = 200$ GeV](image)

To quantify these RHIC results, with their presently rather limited statistics, we adopt a description similar to that used for SPS results and apply the well-known simplified absorption form

$$S \simeq \exp\{-n_0\sigma_{diss} L\},$$

(6)

where $L$ denotes the path of the $c\bar{c}$ in the nuclear medium and $n_0 = 0.17$ fm$^{-3}$ denotes normal nuclear density. A Glauber analysis [23] provides the relation between impact
parameter $b$ and the number of collisions $N_{\text{coll}}$, and simple geometry gives $L = [R_A^2 - b^2]^{1/2}$ in terms of $b$ and the nuclear radius $R_A$. A fit of Eq. (6) to the data of Fig. 3 gives

$$\sigma_{\text{diss}}(y = 1.8) = 3.1 \pm 0.2 \text{ mb}$$
$$\sigma_{\text{diss}}(y = 0) = 1.2 \pm 0.4 \text{ mb}$$
$$\sigma_{\text{diss}}(y = -1.7) = -0.1 \pm 0.2 \text{ mb}$$

for the corresponding $J/\psi$ dissociation cross sections; for $y = -1.7$, there are thus essentially no nuclear modifications. We note that here, as for the SPS case, these cross sections are just a global way to account for whatever nuclear effects can arise. A more detailed analysis based on shadowing and absorption is given in [24]; an analysis based on the Color Glass Condensate approach has recently been performed in [25]. In the latter approach, the factorization of the shadowing and absorption corrections does not occur; nevertheless, here we use the equation (6) just as a way to parameterize the data.

For $A-A$ collisions at RHIC energy, we make use of the same simplified form (6). The geometry connecting the impact parameter $b$ and path length $L$ in $p-Au$ and $Au-Au$ collisions is illustrated in Fig. 4, the relation between $b$ and $N_{\text{part}}$ is again given by a Glauber analysis [26]. We thus here obtain for the survival probability

$$S_{AA}^{AA}(y, N_{\text{part}}) = \frac{R_{AA}(y, N_{\text{part}})}{\exp\{-n_0[\sigma_{\text{diss}}(y) + \sigma_{\text{diss}}(-y)]L\}},$$

(8)

(corresponding to the fact that for $y \neq 0$ the charmonium state passes one nucleus at rapidity $y$, the other at rapidity $-y$.

Figure 4: Impact parameter relation between $p-A$ and $A-A$ collisions

Applying eq. (8) to the rates shown in Fig. 2 together with the nuclear modification cross sections (7) provides the survival probability as function of $N_{\text{part}}$. The corresponding energy densities have been calculated in a Glauber analysis based directly on the PHENIX $E_T$ data [27], and in Fig. 5 we compare the RHIC results to those from the SPS.

It is seen that the two data sets are quite compatible, both in the onset and in the flattening at about 50 - 60%. Concerning the RHIC data, it should be emphasized that the choice of $\tau_0 = 1$ fm is certainly debatable; a smaller value would move the RHIC points to correspondingly larger $\epsilon$ values.

2In the fit, we neglect the most peripheral point at $N_{\text{coll}}$, which corresponds to $b > R_{Au}$ and is thus due to nuclear surface rather than medium effects.
Figure 5: $J/\psi$ suppression as function of energy density

So far we have considered only symmetric ($A-A$) collisions. We find, however, that the $\psi'$ production measured in $S-U$ interactions at the SPS [28] also agrees quite well with the pattern shown in Fig. 1. In contrast, the reported $S-U$ $J/\psi$ rates [28] do not show an onset of suppression at the centrality at which it sets in for $In-In$ collisions. The reason for this is not clear, although two special features have been pointed out. The centrality dependence of the $S-U$ data is determined by transverse energy ($E_T$) measurements, not by the more reliable method based on the zero degree calorimeter specifying directly the number of spectator nucleons. For $Pb-Pb$ collisions, it is observed that the centrality dependences obtained from $E_T$ and $E_{ZDC}$ measurements can in fact show differences. Moreover, it has been noted that a 10% shift in the normalization of the $S-U$ data would lead to full agreement between all SPS data sets.

$J/\psi$ production at RHIC has also been addressed in terms of anomalous suppression followed by regeneration at hadronization [29]. Such a scenario assumes first a strong anomalous suppression of the overall $J/\psi$ production, including that of the $1S$ state, and subsequently a renewed $J/\psi$ formation at the hadronization stage, due to a pairing of $c$ and $\bar{c}$ quarks from different nucleon-nucleon collisions. The latter mechanism becomes possible at RHIC energies because of abundant $c\bar{c}$ production. It leads to rates increasing with centrality, which are taken to just compensate the dropping direct production. In such an approach, the agreement between central SPS data (with no regeneration) and RHIC rates (with considerable regeneration) is coincidental. We also note that the anomalous suppression assumed for direct $J/\psi$ production in the regeneration approach is not in accord with what we know today about $J/\psi$ survival in a quark-gluon plasma, as found in statistical QCD.

Finally we turn to a further check of these considerations. It was pointed out some time ago that the effect of $J/\psi$ suppression could also manifest itself in the transverse momentum behaviour [30, 31], and in fact the pattern resulting from sequential decay differs strongly from that due to regeneration [32].

The basic effect of a nuclear medium on the transverse momentum behaviour of hard processes is a collision broadening of the incident parton momentum; this in turn leads to a broadening of the transverse momentum distribution of the charmonia formed by hard parton interactions, (dominantly gluon fusion). It was shown that a random walk
approach leads to an average squared transverse $J/\psi$ momentum

$$\langle p_T^2/pA \rangle = \langle p_T^2 \rangle_{pp} + N^A_c \delta_0$$

(9)

for $p-A$ and to

$$\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + N^{AA}_c \delta_0$$

(10)

for $A-A$ collisions. Here $N^A_c$ denotes the average number of pre-fusion collisions of the projectile parton in the target nucleus $A$, and $N^{AA}_c$ the sum of the average number of collisions of a projectile parton in the target and vice versa, at the given centrality. The parameter $\delta_0$ specifies the average “kick” which the incident parton receives in each subsequent collision. The basic parameters determining the $p_T$-broadening in nuclear matter are thus the elementary $\langle p_T^2 \rangle_{pp}$ from $p-p$ interactions and the value of $\delta_0$, determined by corresponding $p-A$ data; both depend on the collision energy. The $A$-dependence of $N^A_c$ as well as the behaviour of $N^{AA}_c$ as function of centrality can be obtained through a Glauber analysis; the latter defines the “normal” centrality dependence of $\langle p_T^2 \rangle_{AA}$. Such an analysis also has to include the normal absorption of the produced charmonia in nuclear matter; this effectively shifts the fusion point for the observed charmonia further “down-stream” [31].

A compilation of $J/\psi$ transverse momentum data from the SPS [33] is shown in Fig. 6, it clearly indicates first the increase of the average transverse momentum from $p-p$ to $p-A$ (for $A = Pb$), and then a further increase with centrality for nucleus-nucleus collisions. The preliminary data for the average $p_T^2$ observed in $J/\psi$ production at RHIC is shown in Fig. 7 [21, 34]. Here we note that while the muon arm data ($|y| \in [1.2, 2.2]$) shows the expected broadening when going from $p-p$ to $d-Au$, the central electron data ($|y| \leq 0.35$) does not follow this pattern. Since our analysis is based on such a broadening, we concentrate here on muon data. More statistics at central rapidity should clarify this problem. We note that since both $\langle p_T^2 \rangle_{pp}$ and $\langle p_T^2 \rangle_{dA}$ can in general depend on rapidity as well as on collision energy, each data set requires a separate analysis.

Figure 6: $J/\psi$ transverse momentum behaviour at the SPS [33]

Figure 7: $J/\psi$ transverse momentum behaviour at RHIC [21, 34]

At SPS energy, one has $\langle p_T^2 \rangle_{pp} = 1.25 \pm 0.05$ (GeV/c)$^2$ and $\langle p_T^2 \rangle_{pU} = 1.49 \pm 0.05$ (GeV/c)$^2$ [33]. The average number of pre-fusion collisions is calculated in a Glauber analysis [31],...
and with the normal nuclear absorption specified by the average of eqns. (2/3) it is found to be about 3. From eq. (9) we then obtain

$$\delta_0^{SPS} = 0.083 \pm 0.023 \text{ GeV}^2$$

(11)

for the average projectile parton broadening in the target nucleus.

From the RHIC $\mu^+\mu^-$ data, we obtain $<p_T^2>_{pp} = 2.51 \pm 0.21$ (GeV/c)\(^2\) and $<p_T^2>_{dAu} = 3.96 \pm 0.28$ (GeV/c)\(^2\) [21 34]; for the latter value, we have taken the average of the positive and negative rapidity ranges, since this is also done for the corresponding $Au-Au$ data. A corresponding Glauber analysis, with normal nuclear absorption specified by eq. (7), gives nearly 3.5 pre-fusion parton collisions and leads to

$$\delta_0^{RHIC} = 0.42 \pm 0.09 \text{ GeV}^2$$

(12)

for the corresponding parton broadening in the large rapidity region.

In a sequential dissociation scenario, the transverse momentum behaviour below the onset of excited state suppression is that of charmonia suffering only initial state broadening and normal nuclear absorption. Once the higher states are suppressed, one has once again only direct $J/\psi$’s experiencing initial state effects and normal absorption. Hence apart from possible fluctuations in the suppression region, one should observe the $p_T$ behaviour as given by eqs. (9) and (10). In other words, the $J/\psi$ transverse momentum should be determined only by the initial nuclear medium. This again predicts a common behaviour of measurements from SPS and RHIC. Given the values of $\delta_0$ as determined above, data for $\langle p_T^2 \rangle_{AA}$ and $\langle p_T^2 \rangle_{pp}$ define

$$N_{c}^{AA} = \frac{\langle p_T^2 \rangle_{AA} - \langle p_T^2 \rangle_{pp}}{\delta_0}$$

(13)

as a characteristic measure of transverse momentum behaviour. In Fig. 8 we show the SPS data from $Pb-Pb$ [33] and $In-In$ [35] collisions together with the RHIC muon data [21 34] and find that they indeed agree quite well. Once the corresponding broadening pattern for the RHIC electron data is determined, it should also follow this curve, even though the centrality dependent values for $\langle p_T^2 \rangle_{AA}$ can be quite different.

As mentioned, the centrality dependence of $N_{c}^{AA}$ has also been calculated directly in a Glauber analysis [31]; the result is included in Fig. 8. It lies consistently somewhat higher than the results obtained from the data, which presumably comes from using a larger normal suppression.

In contrast to the increasing $p_T$-broadening determined by initial state parton scattering, $J/\psi$ production through $c\bar{c}$ pairing at hadronization leads to a centrality-independent $\langle p_T^2 \rangle_{AA}$ [32]. Remnant direct production will of course modify this, but a strong regeneration component should in any case considerably weaken the centrality dependence.

The lack of the feed-down contributions to the observed $J/\psi$’s and the presence of the plasma may also affect $J/\psi$ polarization [36 37], even though the theoretical description of quarkonium polarization has so far been notoriously difficult. Nevertheless, the predicted change of polarization may occur, and should be investigated experimentally.
We conclude that present $J/\psi$ production data agree quite well with the expectations based on quark-gluon plasma formation. The observed onset of anomalous $J/\psi$ suppression now coincides, within errors, with that found for $\psi'$ production, and the corresponding energy density agrees with that expected from finite temperature QCD for the dissociation of higher excited charmonium states. The $J/\psi$ production remaining beyond this initial anomalous suppression, at about 60%, agrees with that predicted by a survival of directly produced $1S$ charmonium states and thus is also in accord with present QCD calculations. Further checks can come from measurements of $\psi'$ production in $In-In$ collisions, from an eventual onset of direct $J/\psi$ suppression at higher $\epsilon$ (LHC), and from similar results for $\Upsilon$ production in nuclear collisions.

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