Simple models of the contribution of intermediate stage gluons to $J/\psi$ suppression at the CERN SPS

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Abstract

We construct three simple scenarios of the time – dependence of density of intermediate stage gluons in nuclear collisions in the CERN SPS energy range. Gluons with energy of about 0.6 – 1.0 GeV are assumed to be produced in nucleon–nucleon collisions in a Glauber type model. The rate of gluon production is given by the parameter $n_{g/nn}$ equal to the average number of gluons produced per nucleon - nucleon collision. The value of this parameter determines the behaviour of the gas of gluons. The number of gluons increases due to gluon branching and processes like $g+g\rightarrow g+g+g$ and decreases due to the hadronization. Gluons are assumed to be able to dissociate $J/\psi$ in $g+J/\psi$ collisions, the dissociation cross-section $\sigma_{g\psi}$ is taken as a free parameter. In the first scenario, the energy density of the gas of gluons never reaches the critical energy density $\epsilon_c \approx 0.7$ GeV/fm$^3$ and gluons rapidly hadronize. In the second scenario, the critical energy density is reached but the system of gluons is unable to reach thermalization. In the third scenario gluons reach thermalization and the thermalized system suppresses $J/\psi$ by the Matsui–Satz mechanism. The third scenario under the assumption of a small value of $\sigma_{g\psi}$ is able to describe qualitatively the data on $J/\psi$ suppression in Pb–Pb interactions obtained by the NA50 Collaboration. Other scenarios have problems with getting the rather abrupt onset of $J/\psi$ suppression.
1 Introduction

Suppression of $J/\psi$ in heavy-ion collisions has been suggested by Matsui and Satz as a signature of the Quark-Gluon Plasma (QGP) formation in heavy-ion collisions. The observation of $J/\psi$ suppression by NA38 and NA50 collaborations in collisions of lighter beams, up to $^{32}S$, with heavy targets has been basically explained by Gerschel and Hüfner, and Capella et al. as due to the disintegration of $J/\psi$ by nucleons present in the colliding ions. We shall refer to this mechanism as to the nuclear absorption (NA). Some role might also be played by the disintegration of $J/\psi$ by collisions with secondary hadrons produced during the collisions. The "anomalous" $J/\psi$ suppression observed by the NA50 collaboration in Pb–Pb collisions at the CERN-SPS at $E_{Lab}=160\text{GeV}/\text{nucleon}$, cannot be explained by nuclear absorption alone and models based on $J/\psi$ disintegration by secondary hadrons meet difficulties.

Simple models of anomalous $J/\psi$ suppression by QGP have been proposed by Blaizot and Ollitrault (in what follows referred to as the BO model) and by Kharzeev, Lourenço, Nardi and Satz (KLNS model). Both models are based on the dynamics of tube-on-tube collisions within the Glauber model and assume that in a given tube-on-tube collision QGP is produced provided that a certain condition involving the lengths of the two tubes is satisfied.

A combination of $J/\psi$ suppression by QGP, by nuclear absorption and by hadron gas has been considered by Chaudhuri. Kharzeev and Satz have argued that cross-section for disintegration of $J/\psi$ by thermal hadrons are very low and that the contribution to $J/\psi$ suppression by this mechanism is negligible. The arguments seem to be convincing but the question is not yet solved completely.

Another possible source of anomalous $J/\psi$ suppression may be due to $J/\psi$ disintegration by the intermediate stage gluons. The evolution of gluon cascades has been studied e.g. in Monte Carlo cascade codes.

The purpose of the present paper is to study $J/\psi$ suppression by Intermediate Stage Gluons (ISG). Model of this type has been discussed in Ref. but it was oversimplified and no definite conclusions could have been reached.

We shall consider here three simple scenarios of $J/\psi$ suppression in Pb–Pb collisions at the CERN SPS. In each of them $J/\psi$ is suppressed by the gluon gas and by nuclear absorption. Only in the third one there is the additional suppression by the thermalized system of gluons, described by the Matsui –
Satz mechanism.

(i) In the first scenario, the energy density of the gas of gluons never reaches the critical energy density $\epsilon_c \approx 0.7 \text{ GeV/fm}^3$ and gluons rapidly hadronize.

(ii) In the second scenario, the critical energy density is reached but the system of gluons is unable to reach thermalization, since the energy density becomes subcritical before the system is thermalized.

(iii) In the third scenario, gluons reach thermalization in collisions of tubes of appropriate lengths and the thermalized system suppresses $J/\psi$ by the Matsui–Satz mechanism. Under the assumption of a small value of $\sigma_{g\psi}$ this scenario is able to describe the data on $J/\psi$ suppression in Pb–Pb interactions obtained by the NA50 Collaboration.

Anticipating the results described below we find it rather improbable that $J/\psi$ disintegration by intermediate stage gluons provides a substantial part of $J/\psi$ suppression as observed by the NA50 collaboration in Pb–Pb interactions. In this sense our results give an indirect support to the idea that a phase transition to QGP is responsible for the anomalous $J/\psi$ suppression. The key arguments is that the onset of anomalous $J/\psi$ suppression is too ”abrupt” to be ascribed to the ISG which do not reach the thermalized state.

The paper is organised as follows. In Sect.2 we briefly discuss different contributions to the $J/\psi$ suppression and give the corresponding formulas. In Sect.3 we describe the three scenarios of the behaviour of intermediate stage gluons (ISG). $J/\psi$ suppression by ISG in the three scenarios is discussed in Sect. 4. Reasons why scenarios without thermalized gluons cannot describe the NA50 data are quite simple - the suppression as function of $E_T$ is ”too continuous”, whereas the data seem to indicate some abrupt increase of $J/\psi$ suppression. Comments and conclusions are deferred to Sect.5. Some details concerning possible sources of intermediate stage gluons are presented in the Appendix.

2 Contributions to $J/\psi$ suppression

In a simple model of spherical nuclei with constant nucleon density the $J/\psi$ survival probability $S^{J/\psi}_{AB}(b)$, where $b$ is the impact parameter, is given as

$$S^{J/\psi}_{AB}(b) = \frac{\sigma^{J/\psi}_{AB}(b)}{n^{AB}_{\text{coll}}(b)\sigma_{nn}}$$  \hspace{1cm} (1)
where the total $J/\psi$ production cross-section in $AB$ interaction is denoted as $\sigma_{AB}^{J/\psi}(b)$ and $\sigma_{nn}^{J/\psi}$ is the average $J/\psi$ production cross-section in nucleon-nucleon collision. Frequently discussed contributions to the $J/\psi$ survival probability are given by the following expression

$$S = \frac{N}{N_0} \quad (2)$$

The numerator $N$ is given as

$$N = \int_0^{R_A} ds \int_0^{2\pi} d\theta \int_{-L_A(s)}^{L_A(s)} dz_A \int_{-L_B(b,s,\theta)}^{L_B(b,s,\theta)} dz_B$$

$$e^{-\rho_A \sigma_a[z_A+L_A(s)]}e^{-\rho_B \sigma_a[z_B+L_B(b,s,\theta)]}$$

$$F_{sh} F_{hJ/\psi} F_{gJ/\psi} F_{QGP} \quad (3)$$

where

$$L_A(s) = \sqrt{R_A^2 - s^2}, \quad L_B(b,s,\theta) = \sqrt{R_B^2 - b^2 - s^2 + 2bs\cos(\theta)}$$

when the expression under the square-root in $L_B$ is positive, and $L_B(b,s,\theta) = 0$ when this expression is negative.

The term containing $\sigma_a$ corresponds to the nuclear absorption with $\sigma_a$ being the absorption cross-section and the terms $F_{sh}$, $F_{hJ/\psi}$, $F_{gJ/\psi}$, $F_{QGP}$ correspond to the shadowing of gluon structure functions, $J/\psi$ suppression by secondary hadrons, $J/\psi$ suppression by intermediate stage gluons and $J/\psi$ suppression by QGP, respectively. $N_0$ is obtained from $N$ by putting $\sigma_a = 0$ and $F_{sh} = F_{hJ/\psi} = F_{gJ/\psi} = F_{QGP} = 1$.

The geometrical notation used in Eq.(3) is standard, $\vec{s}$ is the vector connecting the position in the transverse plane to the center of nucleus $A$ and $\theta$ is the angle between $\vec{b}$ and $\vec{s}$.

In what follows we shall consider the $AB$ interaction in the center of mass of nucleon-nucleon collisions, thus $L_A$ and $L_B$ will be contracted by the Lorentz factor $\gamma$ and nuclear densities $\rho_A$ and $\rho_B$ will be multiplied by $\gamma$. We shall use the notation $l_A = L_A/\gamma$ and $l_B = L_B/\gamma$.

The position of a nucleon within the tube in nucleus $A$ is denoted as $z_A$, $-l_A \leq z_A \leq l_A$, in nucleus $B$ as $z_B$, $-l_B \leq z_B \leq l_B$ with $z_A, z_B$ increasing in the direction of motion of nuclei $A, B$. Nucleon densities $\rho_A, \rho_B$ are given
as \( \rho_A = \gamma \rho_0 \), \( \rho_B = \gamma \rho_0 \), where \( \rho_0 \) is the density of nucleons in a nucleus at rest, \( \rho_0 = 0.138 \text{fm}^{-3} \), corresponding to a spherical nucleus with the radius \( R_A = 1.2A^{1/3} \text{fm} \).

Comparison with earlier as well as with recent NA50 data \cite{24} indicates that nuclear absorption (NA) can describe \( J/\psi \) suppression up to S+U interactions and only Pb-Pb case cannot be described by NA. According to the Blaizot-Ollitrault (BO) \cite{14} mechanism of \( J/\psi \) suppression by QGP, all \( J/\psi \)’s produced in tube-on-tube collisions are totally absorbed, provided that

\[
\kappa_{BO}(b,s,\theta) = \rho_A \sigma_{nn} 2l_A(s) + \rho_B \sigma_{nn} 2l_B(b,s,\theta) \geq \kappa_{BO,c} \tag{4}
\]

where \( \kappa_{BO,c} = 9.75 \) and \( \sigma_{nn} \) denotes the non-diffractive nucleon–nucleon cross-section. We are using here the notation of Ref.\cite{26}. In this case, the factor \( F_{QGP} \) in Eq.(3) becomes simply

\[
F_{QGP} = \Theta(\kappa_{BO,c} - \kappa_{BO}(b,s,\theta)) \tag{5}
\]

where \( \Theta(x) \) is the Heavyside function.

In the Kharzeev, Nardi, Lourenço, and Satz (KLNS) \cite{16} model of \( J/\psi \) suppression by QGP one defines

\[
\kappa_{KS}(b,s,\theta) = \frac{\rho_A \sigma_{nn} 2l_A(s) \cdot \rho_B \sigma_{nn} 2l_B(b,s,\theta)}{\rho_A \sigma_{nn} 2l_A(s) + \rho_B \sigma_{nn} 2l_B(b,s,\theta)} \tag{6}
\]

and it is assumed that all \( J/\psi \)’s produced in a tube-on-tube interaction are completely suppressed, provided that

\[
\kappa_{KS}(b,s,\theta) \geq \kappa_{KS,c} \tag{7}
\]

This is equivalent to the factor

\[
F_{QGP} = \Theta(\kappa_{KS,c} - \kappa_{KS}(b,s,\theta)) \tag{8}
\]

in Eq.(3). In their model KLNS take into account that 60\% of \( J/\psi \)’s in the final state is produced directly (after \( \psi' \) decays have been subtracted, since \( \psi' \) is suppressed already in S+U interactions) and 40\% come from \( \chi_c \) decays. The value \( \kappa_{KS,c} = 2.43 \) corresponds to \( \chi_c \) suppression and the threshold for the suppression of directly produced \( J/\psi \) is higher. In our notation the second threshold would appear at about \( \kappa_{J/\psi,KS,c} \approx 2.9 \). The corresponding \( F_{QGP} \) in Eq.(3) would then become

\[
F_{QGP} = 0.4\Theta(2.43 - \kappa_{KS}(b,s,\theta)) + 0.6\Theta(2.9 - \kappa_{KS}(b,s,\theta)) \tag{9}
\]
Since we are mostly interested in the first threshold we shall use below $F_{QGP}$ as given by Eq.(8). The value of the transverse energy $E_T$ (in GeV) in NA50 experiments is approximately given as

$$E_T(b) = 0.325N_w(b)$$  \hspace{1cm} (10)

where $N_w(b)$ is the number of participating (wounded) nucleuses in a Pb-Pb collision at the impact parameter $b$.

The onset of anomalous $J/\psi$ suppression as given by both BO and KLNS models is rather abrupt and it seems that this is also required by the data, see, however, Refs.[27, 28].

3 Model of the space and time dependence of density of intermediate stage gluons

Intermediate stage gluons are supposed to be produced in individual nucleon-nucleon collisions by the mechanism $g+g \rightarrow g+g$. The arguments supporting this possibility are summarized in Appendix A. We assume that the dynamics of the formation of the gluon gas is –at least in the first stage of the collision when nuclei pass through each other – basically longitudinal and that we can treat separately gluons produced in different tube-on-tube collisions. Some support to this simplification comes from the fact that $\sigma(g + g \rightarrow g + g)$ is peaked in forward and backward directions. In the calculations below we shall use the c.m.s. of nucleon-nucleon collision. The tubes pass through each other at the time

$$t_1 = l_A + l_B$$

The total number of nucleon-nucleon collisions before time $t_1$ is

$$N_{nn} = \rho_A\sigma_{nn}2l_A(s)\cdot \rho_B\sigma_{nn}2l_B(b, s, \theta)$$  \hspace{1cm} (11)

where $\rho_A = \rho_B = \gamma \rho_0$ and $\rho_0$ is the nucleon density for nucleus at rest. At the time $t_1$ the volume of the two tubes is $V = (2l_A + 2l_B)\sigma_{nn}$. Denoting the average number of gluons per nucleon-nucleon collision as $n_{g/nn}$ and assuming the density of gluons to be homogeneous within the two tubes, just after they have passed through each other, we obtain for the density of gluons at the time $t_1$

$$n(t_1) = \frac{\rho_A\sigma_{nn}2l_A(s)\cdot \rho_B\sigma_{nn}2l_B(b, s, \theta)}{(2l_A + 2l_B)\sigma_{nn}}n_{g/nn}$$  \hspace{1cm} (12)
For $t \leq t_1$ we shall assume that

$$n(t) = \frac{t}{t_1} n(t_1), \quad t \leq t_1 \tag{13}$$

Gluons, when produced in nucleon–nucleon collisions are supposed to have energies mostly in the interval of 0.6 – 1.0 GeV and for estimates we shall take the average energy of a gluon at $t_1$ as $E_g(t_1) = 0.8$ GeV. The energy density of the system of gluons at the time $t_1$ corresponding to the density in Eq.(12) then becomes

$$\epsilon_g(t_1) = 0.8 \text{GeV}.n(t_1) \tag{14}$$

Depending on the value of $\epsilon(t_1)$ we shall define below three regimes

i) The energy density $\epsilon(t_1)$ is lower than the critical value $\epsilon(t_1) \leq \epsilon_c$, where $\epsilon_c$ corresponds to the energy density of the phase transition to thermalized gluons or QGP. For numerical estimates we shall take here the value obtained in the lattice calculations $\epsilon_c = 0.7 \text{GeV}/\text{fm}^3$. In this case the system of gluons rapidly hadronizes. We shall describe the hadronization by

$$n(t) = n(t_1) \exp \left( \frac{t - t_1}{\tau_h} \right) \tag{15}$$

where $\tau_h$ is the hadronization time. For numerical estimates we shall take $\tau_h = 1\text{fm}/c$.

ii) The energy density $\epsilon(t_1)$ is larger than $\epsilon_c$, but due to the longitudinal expansion the energy density of ISG becomes lower than $\epsilon_c$ before ISG thermalizes. Supposing that ISG expands with velocity $v_0$ (we have in mind the rapidity interval $-0.5 \leq y \leq 0.5$ and $v_0/2$ is the velocity at $y=0.5$ ). In the c.m. frame of nucleon–nucleon collision we have from the energy conservation

$$\epsilon(t) = \epsilon(t_1) \frac{2l_A + 2l_B}{2l_A + 2l_B + v_0(t - t_1)}, \quad t \geq t_1 \tag{16}$$

denoting the thermalization time as $t_{Th}$, the condition for reaching the thermalization becomes

$$\epsilon(t_1 + t_{Th}) \geq \epsilon_c \tag{17}$$

If this is not true the system will reach the energy density $\epsilon_c$ before it is thermalized. In that case there exists the time $t_2 \leq t_1 + t_{Th}$ for which it holds

$$\epsilon(t_2) = \epsilon_c = \epsilon(t_1) \frac{2l_A + 2l_B}{2l_A + 2l_B + v_0(t_2 - t_1)} \tag{18}$$
From Eq.(18) we find

\[ t_2 = t_1 + \frac{1}{v_0} \left[ \frac{\epsilon(t_1)}{\epsilon_c} - 1 \right] (2l_A + 2l_B) \]  

(19)

The system thus does not reach thermalization provided that

\[ \frac{1}{v_0} \left[ \frac{\epsilon(t_1)}{\epsilon_c} - 1 \right] (2l_A + 2l_B) \leq t_{Th} \]  

(20)

During the approach to thermalization the average energy per gluon will decrease from the original value of about 0.8 GeV to the thermal value of about 0.2 GeV. This can happen by the branching of originally produced off–the–mass–shell gluons or by processes like \( g + g \rightarrow g + g + g \). Since the emission of a gluon with energy of about \( \Delta E \sim 0.2 \) GeV takes the time interval \( \Delta t \sim \frac{\hbar}{\Delta E} \sim 1 \) fm/c we expect that the time of thermalization \( t_{Th} \) satisfies the condition

\[ 2 \text{fm/c} \leq t_{Th} \leq 3 \text{fm/c} \]  

(21)

for numerical estimates we shall take \( t_{Th} = 2.6 \) fm/c. In the case that \( t_2 - t_1 \leq t_{Th} \) the density of gluons within the time interval \( t_1 \leq t \leq t_2 \) will be described as

\[ n(t) = \left[ n(t_1) + \frac{t - t_1}{\tau_{em}} n(t_1) \right] \frac{2l_A + 2l_B}{2l_A + 2l_B + v_0(t - t_1)} \]  

(22)

and at \( t_2 \) given by Eq.(19) the density of gluons becomes

\[ n(t_2) = \left[ n(t_1) + \frac{t_2 - t_1}{\tau_{em}} n(t_1) \right] \frac{2l_A + 2l_B}{2l_A + 2l_B + v_0(t_2 - t_1)} \]  

(23)

where \( \tau_{em} \approx 1 \) fm/c is the time for the emission of an additional gluon, we shall take \( \tau_{em} = 1 \) fm/c. Since thermalization has not been reached the system after the time \( t_2 \) hadronizes according to

\[ n(t) = n(t_2) \exp \left( -\frac{t - t_2}{\tau_h} \right) \]  

(24)

(iii) In this case ISG reaches thermal equilibrium. For \( t_1 \leq t \leq t_1 + t_{Th} \) the density of gluons depends on time according to Eq.(22). We shall assume that in this case \( J/\psi \) will be suppressed by the Matsui–Satz mechanism [1]. Since the mechanism is supposed to dissolve \( J/\psi \) rapidly, we do not need to specify further evolution of \( n(t) \) for these tube–on–tube collisions.
The density of gluons corresponding to the three possible types of the evolution of gluon densities is shown in Fig.1, where we consider collisions of the longest possible tubes in central Pb–Pb interaction.

Note that the time of thermalization in the case (a) in Fig. 1 is about 4 fm/c what is probably the maximum one can expect to be reasonable for a purely longitudinal expansion of the system.
4 \( J/\psi \) suppression by intermediate stage gluons

We shall now study \( J/\psi \) suppression by intermediate state gluons. To see the gluon contribution better we shall switch off all the other contributions. The suppression factor \( F_{gJ/\psi} \) is given as

\[
F_{gJ/\psi} = \exp \left( - \int_{t_0}^{\infty} v_g n(t) \sigma_{gJ/\psi} \, dt \right)
\]

where \( t_0 \) is the time when \( J/\psi \) has been produced in a collision of two nucleons, \( t_0 \) is given by \( z_A \) and \( z_B \),

\[
t_0 = (l_A - z_A + l_B - z_B)/2
\]

\( v_g \) is the relative velocity of the gluon and \( J/\psi \) (we shall take \( v_g = 1 \) in \( c = 1 \) units) and \( \sigma_{gJ/\psi} \) is the averaged cross-section for the dissociation of \( J/\psi \) in a collision with a gluon. This expression is valid for each tube - on - tube collision. In Fig. 2 we show the \( E_T \) dependence of the \( F_{gJ/\psi}(E_T) \) factor for cases corresponding to the function \( n(t) \) presented in Fig.1. Results in Fig. 2 allow us to make a few conclusions

- Cases (a1) and (a2) never lead to energy density larger than the critical. This results in a rapid hadronization of gluons. The factor \( F_{gJ/\psi}(E_T) \) is rather large and does not show any rapid onset of \( J/\psi \) suppression at some value of \( E_T \). This is true even for rather large values of the dissociation cross-section \( \sigma_{g\psi} \).

- Cases (b1) and (b2) correspond to larger gluon densities. Assuming that \( \sigma_{g\psi} \) is as large as 1 - 2 mb, the factor \( F_{gJ/\psi}(E_T) \) can go down to values of about 0.5 for large values of \( E_T \). In combination with the effects of nuclear absorption it could lead to values of \( J/\psi \) survival probability consistent with data. On the other hand this mechanism does not show any rapid onset of \( J/\psi \) suppression at some value of \( E_T \)

- In the case of (c1) and (c2) the value of \( n_{g/nn} \) is chosen in such a way that the thermalization of gluon gas appears first in Pb-Pb collisions at around \( E_T = 40 \) GeV. The Matsui – Satz mechanism leads to an onset of \( J/\psi \) suppression at around this value of \( E_T \). The rapid onset is visible in the curve (c1), but it is washed out in the curve (c2).
Figure 2: The factor $F_{gJ/\psi}(E_T)$ for $J/\psi$ suppression in Pb–Pb collisions at the SPS. The following parameters have the same values in all cases: $\epsilon_g = 0.8$ GeV, $\tau_{em} = 1$ fm/c, $\epsilon_c = 0.7$ GeV/fm$^3$. Other parameters are different in individual cases. For (a1) $n_{g/nn} = 0.24$, $\sigma_{g\psi} = 1$mb, (a2) $n_{g/nn} = 0.24$, $\sigma_{g\psi} = 2$mb, (b1) $n_{g/nn} = 0.42$, $\sigma_{g\psi} = 1$mb, (b2) $n_{g/nn} = 0.42$, $\sigma_{g\psi} = 2$mb, (c1) $n_{g/nn} = 0.58$, $\sigma_{g\psi} = 1$mb, (c2) $n_{g/nn} = 0.58$, $\sigma_{g\psi} = 2$mb.

We shall now study in more detail the case when dissociation of $J/\psi$ is present together with the Matsui – Satz mechanism. In Fig.3 we present the $J/\psi$ survival probability for $n_{g/nn} = 0.58$ and with the nuclear absorption switched off.

In Fig.3 we see again that with increasing $\sigma_{g\psi}$ the survival probability decreases, but the abrupt onset of increasing $J/\psi$ suppression is gradually washed out.

Finally, in Fig. 4 we present the results of the same calculation as shown in Fig. 3 with only one difference: nuclear absorption with $\sigma_a = 4.2$ mb, [24] is included. Results presented in Fig. 4 summarize the situation. The curve (a) shows the well known fact that the nuclear absorption alone cannot
Figure 3: The survival probability $S(E_T)$ in Pb–Pb collisions at the SPS for the case of vanishing nuclear absorption, Matsui–Satz mechanism and $J/\psi$ dissociation of gluons present. In all cases $n_g/n_n = 0.58$, (d1) $\sigma_{g\psi} = 0.0$ mb; (d2) $\sigma_{g\psi} = 0.2$ mb; (d3) $\sigma_{g\psi} = 0.4$ mb; (d4) $\sigma_{g\psi} = 0.6$ mb; (d5) $\sigma_{g\psi} = 0.8$ mb; (d6) $\sigma_{g\psi} = 1.0$ mb; (d7) $\sigma_{g\psi} = 1.5$ mb. Other parameters fixed: $\epsilon_g = 0.8$ GeV, $\tau_{em} = 1$ fm/c, $\epsilon_c = 0.7$ GeV/fm$^3$.

reproduce $J/\psi$ suppression in Pb–Pb interactions as observed by the NA50 Collaboration [35]. The curve (f1) agrees in a qualitative way with the patterns of the data [35]. This curve corresponds to the Matsui–Satz mechanism [1] in the KLNS formalism [16]. This is seen from from the calculation of $n(t_1)$ as given by Eq. (12) and of the energy density of the system of gluons according to Eq. (14). Note that for the curve (f1) the cross-section $\sigma_{g\psi}$ for the dissociation of $J/\psi$ by gluons vanishes. The curves (f2) to (f8) contain both the Matsui–Satz mechanism and the dissociation of $J/\psi$ by gluons, but $\sigma_{g\psi}$ is gradually increasing. The abrupt onset of $J/\psi$ suppression at $E_T \approx 40$ GeV is gradually washed-out. This is also natural since with increasing $\sigma_{g\psi}$ more and more of $J/\psi$'s are suppressed by interactions with gluons and the
Figure 4: The survival probability \( S(E_T) \) in Pb–Pb collisions at the SPS for the case of nuclear absorption with \( \sigma_a = 4.2 \text{ mb} \), Matsui–Satz mechanism and \( J/\psi \) dissociation of gluons present. In all cases \( n_g/n_n = 0.58 \), (a) only nuclear absorption. In further cases Matsui–Satz mechanism included. (f1) \( \sigma_{g\psi} = 0.0 \text{ mb} \); (f2) \( \sigma_{g\psi} = 0.2 \text{ mb} \); (f3) \( \sigma_{g\psi} = 0.4 \text{ mb} \); (f4) \( \sigma_{g\psi} = 0.6 \text{ mb} \); (f5) \( \sigma_{g\psi} = 0.8 \text{ mb} \); (f6) \( \sigma_{g\psi} = 1.0 \text{ mb} \); (f7) \( \sigma_{g\psi} = 1.5 \text{ mb} \). Other parameters fixed: \( \epsilon_g = 0.8 \text{ GeV} \), \( \tau_{em} = 1 \text{ fm/c} \), \( \epsilon_c = 0.7 \text{ GeV/fm}^3 \). Data taken from Ref. 35.

Matsui–Satz mechanism dissolves only those \( J/\psi \)'s that survived interaction with gluons.

5 Comments and conclusions

The purpose of the present paper was not to make detailed analysis of \( J/\psi \) suppression by the ISG. We were more interested in qualitative features of the ISG model and its possibilities to approach the results following from models based on \( J/\psi \) suppression by QGP. More detailed analysis would
certainly require using Woods-Saxon densities, using more accurate relationship between $E_T$ and $b$, respecting fluctuations, etc. But we are convinced that qualitative features of prediction of our version of the ISG model and in particular of its differences with respect to the QGP model would survive the improvements brought in by more sophisticated analysis. The question of whether $J/\psi$ is suppressed by QGP or by another mechanism will be finally decided by experiment, hopefully by the forthcoming data by NA60 Collaboration. If the anomalous $J/\psi$ suppression will turn up to be really as abrupt as possible, and this is the case of QGP model, other interpretation will be in problems. If it will turn out to be less abrupt, it will be easy for other models to fit the data.

As a by–product the present model provides a sketch of a possible space–time picture of the dynamics of nuclear collisions at the CERN SPS. The picture contains the following ingredients

- When nuclei traverse each other, each nucleon looses energy in semi–hard nucleon–nucleon collisions. The cross–section of this process is about 10mb and in each of the collisions two gluons with energy of about 0.6 – 1.0 GeV are produced. When traversing the Lorentz contracted length $2L_B \approx 1.1$ fm in the other nucleus, a nucleon makes about 1.4 collisions and looses in average about 1 GeV of energy.

- During the time when nuclei cross each other there is no production of hadrons or gluons with lower transverse momenta because of reasons described in the Appendix, see also Ref. 36.

- The fragmentation of nucleons starts only after the two tubes have crossed each other.

The picture indicates why on the one hand the Wounded Nucleon Model 34 is a reasonable first approximation to particle production and on the other hand it shows that production of energy densities permitting the formation of QGP can be caused by semi–hard processes.

**Appendix**

In nuclear interactions soft exchanges in nucleon–nucleon subcollisions are suppressed by the Landau-Pomeranchuk-Migdal (LPM) mechanism, for a review see Ref. 37. If time interval and longitudinal distance between two subsequent collisions of a nucleon from nucleus A with nucleons in nuclei B are $\Delta t$ and $\Delta z$ the LPM mechanism suppresses processes with energy and
momentum transfer obeying the condition

$$\Delta p_z < \frac{\hbar}{\Delta z}, \quad \Delta E < \frac{\hbar}{\Delta t}$$  \hspace{1cm} (26)$$

Mean free path for a nucleon passing through a nucleus at rest is about 3fm. When considering a collision of two nuclei at $E_{lab} \approx 200\text{GeV}$, in the c.m.s. of nucleon-nucleon collision both nuclei are contracted by the Lorentz factor $\gamma \approx 10$, the mean free path becomes shorter by the factor $\gamma$ and Eq.(26) leads to suppression of energy and momentum transfers with

$$\Delta p_z < 600\text{MeV/c}, \quad \Delta E < 600\text{MeV}$$  \hspace{1cm} (27)$$

The problem with estimating the density of intermediate stage gluons in nuclear collisions is due to the fact that there is no reliable theory of nuclear interactions in the CERN SPS energy region. In this situation we can use only models which might reflect to some extent what is really happening. The venerable Wounded Nucleon Model (WNM) \cite{33} describes the production of secondary hadrons in nuclear collisions as a fragmentation of participating (wounded) nucleons. The fragmentation is independent of the number of preceding collisions. The model does not describe details of the transverse energy production in nuclear collisions and proton stopping. Apparently there exists also some contribution to the total transverse energy in nuclear collisions given roughly by the number of nucleon-nucleon interactions.

There are two groups of models indicating that even in the CERN SPS energy region this does happen and partonic degrees of freedom may play an important role.

First, in Glauber type models of multiparticle production, see Refs.\cite{38,39,40,42} aiming to describe the proton stopping and the production of total transverse energy in pA (and AB) collisions one has to assume some loss of proton momentum in each of $\nu$ sub-collisions. For instance in Ref.\cite{42} the author requires the degradation of proton’s momentum by $\Delta y \approx 0.5$ (in the c.m.s. of proton-nucleon collisions). This means that the proton’s momentum is changing in an SPS experiment from the original 10GeV/c (in the c.m.s.) to 6.05 GeV/c after the first collision, to 3.62 GeV/c after the second one, to 2.13 GeV/c after third one, and to 1.25GeV/c after the fourth one. The corresponding momentum losses are: 4 GeV/c; 2.4 GeV/c; 1.3 GeV/c and 0.8 GeV/c. The average of these four momentum losses is 2.13 GeV/c, and although this indicates that perhaps the collisions may be
considered as semi-hard and that the partonic degrees of freedom might be relevant.

In models of this type there has always been a problem of why secondary hadrons assumed to be produced in individual nucleon-nucleon collisions do not cause intense cascades in the region of $E_{lab}$ of a few hundreds of GeV. The standard solution of the problem is to introduce for secondary hadrons a formation time $\tau_f$ with Lorentz dilated $\tau_f$ responsible for the attenuation of cascade effects.

Second, in their analysis of the magnitude of the nucleon-nucleon non-diffractive cross-section ($\sigma_{ND}$) the authors of Refs.\cite{44, 45, 46} have shown that most of or the whole of $\sigma_{ND}$ can be described as due to semihard QCD processes. Abou-El-Naga, Geiger and Müller \cite{44} have calculated $\sigma_{ND} = \sigma_{QCD}$ by using the perturbative QCD expressions (in the lowest order) for the elastic parton-parton scattering. The parameter $Q^2$ entering the structure functions and the $\theta$- function is taken as $Q^2 = p_T^2 = u\hat{t}/\hat{s}$ with $\hat{s} = x_1x_2s$. Cross-sections for $Q^2 \leq (p_T^{min})^2$ were put equal to zero. The value of $p_T^{min}$ was taken as a free parameter to be determined by the requirement that the whole of $\sigma_{ND}$ is given by the perturbative QCD calculation. Structure functions were taken either from Eichten et al.\cite{48} (EHLQ) or from Glück et al.\cite{49}.

The magnitude of $\sigma_{ND}$ depends in a crucial way on the value of $Q^2$ at a given value of $s$. The measured value of $\sigma_{ND}$ is equal to $\sigma_{QCD}$ (most of that being due to gg interaction) provided that

$$\sqrt{Q^2} = p_T^{min} = p_0 \left(\frac{s}{GeV^2}\right)^\alpha$$

with parameters $\alpha = 0.115$ and $p_0 = 0.485 GeV/c$ for the EHLQ structure functions and $\alpha = 0.151$ and $p_0 = 0.357$ for GRV structure functions.

For $s=400 GeV^2$ corresponding to the CERN SPS this gives $p_T^{min} = 0.97$ GeV/c for the EHLQ case and 0.88 GeV/c for the GRV one. Of course, the pQCD is used in the situation when extrapolations are not reliable, neither in what concerns the $Q^2$ dependence of structure functions nor in calculations of parton-parton cross-sections. But it is still reasonable to assume that some fraction of $\sigma_{ND}$ is due to parton-parton (mostly gg) interactions.

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