Can $J/\psi$ suppression and $p_T$ broadening signal the deconfinement transition at RHIC?

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We have analyzed the latest NA50 data on $J/\psi$ suppression in Pb+Pb collisions at CERN SPS. It is shown that a QCD based nuclear absorption model, where $J/\psi$’s are absorbed in nuclear medium could explain the latest NA50 data on the centrality dependence of the $J/\psi$ over Drell-Yan ratio. The model also explains the NA50 data on $J/\psi$ over minimum bias ratio and the $p_T$ broadening of $J/\psi$’s. A QGP based threshold model where all the $J/\psi$’s are suppressed above a threshold density, also explains the data sets with smeared threshold density. Even at RHIC energy, centrality dependence of $J/\psi$ suppression or $p_T$ broadening could not distinguish between the two models.

I. INTRODUCTION

$J/\psi$ suppression in heavy ion collisions is recognized as an important signal of the confinement-deconfinement phase transition. NA50 collaboration, at CERN, is a dedicated experiment, measuring $J/\psi$ cross sections in pA/AA collisions. Recently, they have published the results of 2000 run of 158 AGeV Pb+Pb collisions [1]. The preliminary analysis of 2000 run was presented in Quark Matter 2002 [2]. The suppression obtained is still anomalous in the sense that the normal nuclear absorption model fails to explain it. Compared to 1998 run [3], 2000 data are flatter, suppression being more at low and intermediate $E_T$. Preliminary analysis indicated less suppression (compared to 1998 run) at large $E_T$, but in the final analysis suppression is compatible with the 1998 run. 1998 NA50 data gave the first indication of anomalous $J/\psi$ suppression and were analyzed in a variety of models, with and without the assumption of QGP [4–9]. We have shown that a QCD based nuclear absorption model, where $J/\psi$’s are absorbed in nuclear medium, could explain the data [7,8]. We have also shown that the model reproduces the NA50 data on the centrality dependence of $p_T$ broadening of $J/\psi$’s [10]. What is more intriguing is that the predicted $J/\psi$ over Drell-Yan ratio or the $p_T$ broadening at RHIC energy matches with the prediction obtained in the QGP based threshold model [10]. It seems that even at RHIC energy, $E_T$ (centrality) dependence of the $J/\psi$ suppression or $p_T$ broadening may not distinguish a deconfining phase transition.

NA50 collaboration also published the analysis of the nuclear absorption of $J/\psi$ in high statistics 450 GeV pA collisions [11]. They estimated the $J/\psi$ nucleon absorption cross section ($\sigma_{abs}^{J/\psi N}$) in the framework of Glauber model. High statistics 450 GeV pA data yield $\sigma_{abs}^{J/\psi N}=4.4\pm1.0$ mb [11]. They also estimate a common $\sigma_{abs}^{J/\psi N}$ from latest pA and NA38 200 GeV/c S+U data [12], $\sigma_{abs}^{J/\psi N}=4.4 \pm 0.5$ mb. The extracted absorption cross section is much smaller than the earlier value of 6.4 ± 0.8 mb extracted from fit to earlier NA50 data [13] or 7.1 ± 3.0 mb obtained from a fit to NA38 S+U data [12]. Within error, the 200 AGeV S+U cross sections are compatible with 450 AGeV pA cross sections.

In an earlier publication we have analysed the preliminary NA50 data of 2000 run [14]. It was shown that QCD based nuclear absorption model, with parameters fixed from the high statistics pA data give consistent description of $J/\psi$ suppression in 158 AGeV Pb+Pb collisions. The preliminary data were also analysed in the QGP based threshold model [15]. In the threshold model [4], in addition to ‘conventional’ (Glauber) nuclear absorption, an anomalous suppression is used such that all the $J/\psi$’s are totally suppressed above a critical (threshold) density $n_c$. 1998 version of NA50 data [3] were well explained in the threshold model, with $n_c=3.7-3.75 f m^{-2}$ and $J/\psi$-nucleon absorption cross section $\sigma_{abs}^{J/\psi N}=6.4$ mb [4]. $J/\psi$-nucleon absorption cross section 6.4 mb is large compared to the recently extracted value of from the high statistics pA data, $\sigma_{abs}^{J/\psi N}=4.4$ mb [11]. It was shown that with $\sigma_{abs}^{J/\psi N}=4.4$ mb, the threshold model fails to explain the preliminary NA50 data [2] on the centrality dependence of $J/\psi$ over Drell-Yan ratio, unless the threshold density is largely smeared [15].

In the present paper, we have analysed the latest NA50 data [1] on $J/\psi$ suppression in Pb+Pb collisions. The QCD based nuclear absorption model, with parameters fixed from the high statistics pA data, still give consistent description the latest data. QGP based threshold model also explains the data if the threshold density is smeared. In addition, we have analysed the NA50 data on the centrality dependence of $J/\psi$ over minimum bias ratio [16] and on the centrality dependence of $p_T$ broadening of $J/\psi$’s [17]. Both the models, QCD based nuclear absorption model and the QGP based threshold model, explain these data. The NA50 data of 158 AGeV Pb+Pb collisions could not discriminate between the two models. It is also shown that even at RHIC energy, centrality dependence of $J/\psi$ suppression or $p_T$ broadening could not distinguish between the two models.

The paper is organised as follows: in section II we have briefly described the QCD based nuclear absorption model and the threshold model. In section III, NA50...
data on the centrality dependence of $J/\psi$ over Drell-Yan ratio and the $J/\psi$ over minimum bias ratio are analyzed.

In section IV, it is shown that both the models could explain the NA50 $p_T$ broadening data. Predicted centrality dependence of $J/\psi$ over Drell-Yan ratio and $p_T$ broadening at RHIC energy are given in section V. Lastly the summary and conclusions are given in section VI.

II. MODELS FOR $J/\psi$ SUPPRESSION

A. QCD based nuclear absorption model

In the QCD based nuclear absorption model [7,9], $J/\psi$ production is assumed to be a two step process, (a) formation of a $c\bar{c}$ pair, which is accurately calculable in QCD and (b) formation of a $J/\psi$ meson from the $c\bar{c}$ pair, which is conveniently parameterized. The $J/\psi$ cross section in $AB$ collisions, at center of mass energy $\sqrt{s}$ is written as,

$$\sigma^{J/\psi}(s) = K \sum_{a,b} \int dq^2 \left( \frac{\hat{\sigma}_{ab\rightarrow c\bar{c}}}{Q^2} \right) \int dx_F \phi_{a/A}(x_a, Q^2)$$

where $\sum_{a,b}$ runs over all parton flavors, and $Q^2 = q^2 + 4m_c^2$. The $K$ factor takes into account the higher order corrections. The incoming parton momentum fractions are fixed by kinematics and are $x_a = (\sqrt{x_F^2 + 4Q^2/s} + x_F)/2$ and $x_b = (\sqrt{x_F^2 + 4Q^2/s} - x_F)/2$. $\hat{\sigma}_{ab\rightarrow c\bar{c}}$ are the subprocess cross section and are given in [18]. $F_{c\bar{c}\rightarrow J/\psi}(q^2)$ is the transition probability that a $c\bar{c}$ pair with relative momentum square $q^2$ evolve into a physical $J/\psi$ meson. It is parameterized as,

$$F_{c\bar{c}\rightarrow J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\theta(4m_c^2 - 4m_c^2 - q^2)$$

where $N_{J/\psi}$ is the transition probability and is related to the $\sigma_{J/\psi}$. It is parameterized as,

$$F_{c\bar{c}\rightarrow J/\psi}(q^2) = 1 - \frac{q^2}{4m_c^2 - 4m_c^2}$$

In a nucleon-nucleus/nucleus-nucleus collision, the produced $c\bar{c}$ pairs interact with nuclear medium before they exit. It is argued [9] that the interaction of a $c\bar{c}$ pair with nuclear environment increases the square of the relative momentum between the $c\bar{c}$ pair. As a result, some of the $c\bar{c}$ pairs can gain enough relative square momentum to cross the threshold to become an open charm meson. Consequently, the cross section for $J/\psi$ production is reduced in comparison with nucleon-nucleon cross section. If the $J/\psi$ meson travel a distance $L$, $q^2$ in the transition probability is replaced to $q^2 \rightarrow q^2 + \epsilon^2L$, $\epsilon^2$ being the relative square momentum gain per unit length. In [7], parameters of the model ($\alpha_F, KN_{J/\psi}$ and $\epsilon^2$) were fixed from experimental data on total $J/\psi$ cross section in pA/AA collisions, $KN_{J/\psi}$ = 0.458, $\epsilon^2 = 0.225 GeV^2/fm$ and $\alpha_F = 1.0$ [7].

As mentioned in the beginning, recently NA50 collaboration measured $J/\psi$ cross section in pA collisions [11]. They have measured $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$. In Fig. 1, experimental data are shown as a function of the nuclear length $L$. The Drell-Yan cross sections donot have any A or alternately any L-dependence. The observed L dependence is then due to $J/\psi$'s only. We fit the data with two parameters, $N_{norm} = KN_{pA}/\sigma_{DY}(nb)$ and square momentum gain factor $\epsilon^2$ ($\alpha_F$ being kept fixed at 1). In Fig.1, the fit obtained to the data are shown. The two sets of data at 200 GeV/c and 450 GeV/c could be fitted with a common square momentum gain factor, $\epsilon^2 = 0.187 GeV^2/fm$, a value 20% lower than the value obtained earlier [7]. Lowering of $\epsilon^2$ indicate less absorption of $J/\psi$'s in nuclear medium, in agreement with the Glauber model calculations. While the square momentum gain factor do not show energy dependence, the evident energy dependence of the cross section ratios shows up in the other parameter of the model $N_{norm}$. We obtain $N_{norm} = 10.18$ at 200 GeV/c and $N_{norm} = 4.43$ at 450 GeV/c. The energy dependence of $J/\psi$ cross section being taken care of in the model (Eq.1), the energy dependence of $N_{norm}$ is due to the Drell-Yan cross sections only. In the mass range, $2.9 > M > 4.5$ GeV, the Craigie parameterization [19], of the Drell-Yan cross section, $\sigma(DY) \propto e^{4.9M/\sqrt{s}}$, gives for the ratio $\sigma(DY)_{450 GeV}/\sigma(DY)_{200 GeV} = 2.1 - 3.1$, consistent with the presently obtained ratio of 2.29.

With the parameters of the model fixed from high statistic pA data, $J/\psi$ production cross section in Pb+Pb collisions are obtained following the standard procedure. At an impact parameter $b$, $J/\psi$ production cross section, as a function of $E_T$ is written as [7],

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The latest NA50 experimental ratio of the total $J/\psi$ cross sections and Drell-Yan cross sections in pp and pA collisions [11]. The solid lines are the fit obtained in the QCD based nuclear absorption model.}
\end{figure}
\[
\frac{d^3\sigma^{J/\psi}}{dE_T d^2b} = \sigma^{J/\psi}_{NN} \int d^2s T_A(s) T_B(b-s) S(L(b,s)) P(b, E_T)
\]

where \(T_{A,B}\) is the nuclear thickness function, \(T(b) = \int_{-\infty}^{\infty} dz \rho(b, z)\). \(P(b, E_T)\) is the \(E_T - b\) correlation function. We have used the Gaussian form for the \(E_T - b\) correlation,

\[
P(b, E_T) \propto \exp\left(-\left(E_T - q N_p(b)\right)^2/2q^2 a N_p(b)\right)
\]

where \(N_p(b)\) is the number of participant nucleons at impact parameter \(b\). \(a\) and \(q\) are parameters related to dispersion and average transverse energy. For Pb+Pb collisions the parameters are, \(a=1.27\) and \(q=0.274\) GeV [4]. \(S(L)\) is the suppression factor due to passage through a length \(L\) in nuclear environment. At a fixed impact parameter \(b\) and at point \(s\), the transverse density is calculated as,

\[
n(b, s) = T_A(s)[1 - e^{-\sigma_{NN}T_B(b-s)}] + [A \leftrightarrow B]
\]

and the length \(L(b,s)\) that the \(J/\psi\) meson will traverse is obtained as,

\[
L(b,s) = n(b,s)/2\rho_0
\]

At a fixed impact parameter \(E_T\) fluctuates. \(E_T\) fluctuations at a fixed impact parameter plays an important role in \(J/\psi\) suppression. The second drop in the \(J/\psi\) over Drell-Yan ratio, beyond 100 GeV is due to \(E_T\) fluctuations [4]. Following Blaizot et al [4], we take into account \(E_T\) fluctuations at a fixed impact parameter \(b\), by the replacement:

\[
L(b,s) \rightarrow L(b,s) E_T/ \langle E_T \rangle (b).
\]

B. QGP based threshold model

We have also analyzed the data in the threshold model [4]. The details of the model could be found in [4]. Briefly, in the threshold model, in addition to Glauber type ‘nuclear’ absorption, an anomalous suppression factor \(S_{anom}\) is used. The \(J/\psi\) cross section at an impact parameter \(b\) as a function of \(E_T\) is then written as,

\[
\frac{d^3\sigma^{J/\psi}}{dE_T d^2b} = \sigma^{J/\psi}_{NN} \int d^2s T_A^{eff}(s) T_B^{eff}(b-s) S_{anom}(b,s) P(b, E_T)
\]

where \(T^{eff}(b)\) is the effective thickness, \(T^{eff}(b) = \int_{-\infty}^{\infty} dz \rho(b, z)\). \(T^{eff}(b)\) is the \(J/\psi\)-nucleon absorption cross-section. In [4], Blaizot et al used \(\sigma^{J/\psi}_{abs} = 6.4\) mb. In the present analysis, we have used \(\sigma^{J/\psi}_{abs} = 4.4\) mb, as extracted from the recent pA data [11]. In Eq.8, \(S_{anom}(b,s)\) is the anomalous suppression factor. Blaizot et al [4] considered two types of form for \(S_{anom}\). Assuming that all the \(J/\psi\)’s get suppressed above a threshold density (\(n_c\)), the anomalous suppression factor was written as,

\[
S_{anom}(b,s) = \Theta(n(b,s) - n_c)
\]

where \(n\) is the transverse density (Eq.5). In ref. [4] it was seen that if the theta function is smeared at the expense of another parameter, such that suppression is gradual rather than abrupt, the quality of fit to data improves considerably. This was implemented by writing,

\[
S_{anom}(b,s) = 0.5[1 - tanh(\lambda(n(b,s) - n_c))]
\]

In both the form, effect of \(E_T\) fluctuations at a fixed impact parameter was taken into account by rescaling the density as, \(n \rightarrow n E_T/ \langle E_T \rangle (b)\). The parameters \(n_c\) and \(A\) are then obtained by fitting the latest NA50 data on centrality dependence of \(J/\psi\) over Drell-Yan ratio.

The Drell-Yan pairs do not suffer final state interactions and the cross section at an impact parameter \(b\) as a function of \(E_T\) could be written as,

\[
\frac{d^3\sigma^{DY}}{dE_T d^2b} = \sigma^{DY}_{NN} \int d^2s T_A(s) T_B(b-s) P(b, E_T)
\]

III. RESULTS

A. \(E_T\) dependence of \(J/\psi\) over Drell-Yan ratio

In Fig.2, centrality dependence of \(J/\psi\) over Drell-Yan ratio, as obtained by the NA50 collaboration in their final analysis of the 2000 Pb+Pb run, is shown. Just to show, how the Pb+Pb data are changed with time, we have also shown the results of 1996-1998 run and the preliminary analysis of the 2000 run. Final analysis of 2000 run differ considerably from the first version of the data, presumably due to different analysis method. In Fig.2, model predictions for \(J/\psi\) suppression are also depicted. We have used \(B_{DY}^{J/\psi}/\sigma^{DY}_{NN} = 38, 17\%\) lower than the value obtained from extrapolating 200 AGeV pA/SU data (Fig.1) to pp collisions. 200 AGeV pA/SU data is limited to \(L > 3fm\) and extrapolation to pp data may not be very accurate.

Just to show that the latest data are also anomalous, we have shown the Glauber model calculation with \(\sigma^{J/\psi}_{abs} = 4.4\) mb (the dash-dot-dot line). Only for very peripheral collisions, the Glauber model of nuclear absorption fits the data. For more central collisions, it produces much less suppression than the data exhibit. In Fig.2, the solid line is the calculated ratio in the QCD based nuclear absorption model. It agrees well with the experiment. The parameters of the model were obtained from fitting pA data. In pA collisions we donot expect a
deconfining phase transition. Ability of the model to reproduce Pb+Pb data, with the same parameters, clearly indicate that nuclear absorption alone, treated in an unconventional manner, is capable of explaining the data.

B. $E_T$ dependence of minimum bias cross section

In 1996 and 1998 runs, NA50 collaboration obtained $E_T$ dependence of the $J/\psi$ over minimum bias cross sections [16]. The minimum bias cross sections are easy to calculate. It is essentially the inelastic cross-section. In the Glauber model, at impact parameter $b$ and at transverse energy $E_T$, the minimum bias cross section is written as,

$$\frac{d^3\sigma^{MB}}{dE_T^2 b} \propto (1 - e^{-\sigma_{NN}T_{AB}(b)})P(b, E_T)$$

where $T_{AB}(b) = \int d^2sT_A(s)T_B(s - b)$.

The QGP based threshold model [4] with only one parameter, the threshold density, on the other hand fails to give proper description of the data. In Fig.2 the dash-dot-dot line is the best fit obtained to the data with threshold density $n_c = 3.78 \text{ fm}^{-2}$. In the intermediate range of $E_T$, agreement with data is not good. Much better fit to data is obtained, when the threshold density is smeared. The dash-dot line is the best fit obtained to the data with $n_c = 3.98 \text{ fm}^{-2}$ and $\lambda = 0.82 \text{ fm}^2$. The model then reproduces the data through out the $E_T$ range. Small value of $\lambda$ required for good fit to data indicate that considerable smearing of the threshold density is required for proper description of the data. The anomalous suppression is not abrupt but increases gradually with density. The threshold density $n_c$ we obtain from fitting is also larger than the value of 3.7-3.75 obtained by Blaizot et al [4]. This is presumably due to smaller value of the $J/\psi$-nucleon absorption cross-section.

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IV. $p_T$ BROADENING OF $J/\psi$

It is well known that in pA and AA collisions, the secondary hadrons generally shows a $p_T$ broadening [20,21].
Kharzeev et al. [21] suggested $p_T$ broadening as a probe for the deconfining transition. They argued that in a deconfining medium, $p_T$ broadening will visibly decrease at large $E_T$, in contrast to a gradually increasing $p_T$ broadening in a nuclear medium. Recently we have shown that decreasing $p_T$ broadening can not be considered as a signal of deconfining phase transition, as such a trend is also obtained in the QCD based nuclear absorption model [10]. It was also shown that $E_T$ fluctuations, at a fixed impact parameter plays an important role in explaining the experimental data on $p_T$ broadening of $J/\psi$'s. The QCD based nuclear absorption model [7] could explain the NA50 $p_T$ broadening data if the effect of $E_T$ fluctuations are properly accounted for. In [10], we have also obtained $p_T$ broadening in the threshold model, with a single parameter, the threshold density, $n_c=3.7 \text{ fm}^{-2}$ and $\sigma_{abs}^{J/\psi N}=6.4 \text{ mb}$. One parameter threshold model could not fit the data. As it was shown in last two sections, with the latest NA50 data [2,11], parameters of both the models are changed and it interesting to see the consequence on $p_T$ broadening.

The natural basis for the $p_T$ broadening is the initial state parton scatterings. For $J/\psi$'s, gluon fusion being the dominant mechanism for $c\bar{c}$ production, initial state scattering of the projectile/target gluons with the target/projectile nucleons causes the intrinsic momentum broadening of the gluons, which is reflected in the $p_T$ distribution of the resulting $J/\psi$'s. Parameterizing the intrinsic transverse momentum of a gluon, inside a nucleon as,

$$f(q_T) \sim \exp(-q_T^2/ <q_T^2>)$$

momentum distribution of the resulting $J/\psi$ in NN collision is obtained by convoluting two such distributions,

$$f_{NN}(p_T) \sim \exp(-p_T^2/ <p_T^2>_{J/\psi})$$

where $<p_T^2>_{J/\psi}=<q_T^2> + <q_T^2>$. In nucleus-nucleus collisions at impact parameter $b$, if before fusion, a gluon undergo random walk and suffer $N$ number of subcollisions, its square momentum will increase to $q_T^2 \rightarrow q_T^2 + N\delta_0$, $\delta_0$ being the average broadening in each subcollisions. Square momentum of $J/\psi$ then easily obtained as,

$$<p_{T,J/\psi}^2>b = <p_{T,J/\psi}^2>N_N + \delta_0 N_{AB}(b)$$

where $N_{AB}(b)$ is the number of subcollisions suffered by the projectile and target gluons with the target and projectile nucleons respectively.

Average number of collisions $N_{AB}(b)$ can be obtained in a Glauber model [21]. At impact parameter $b$, the positions $(s, z)$ and $(b - s, z')$ specifies the formation point of $c\bar{c}$ in the two nuclei, with $s$ in the transverse plane and $z, z'$ along the beam axis. The number of collisions, prior to $c\bar{c}$ pair formation, can be written as,

$$N(b, s, z, z') = \sigma_{gN} \int_{-\infty}^{s} dz_{A} \rho_{A}(s, z') + \sigma_{gN} \int_{-\infty}^{z'} dz_{B} \rho_{B}(b - s, z')$$

where $\sigma_{gN}$ is the gluon-nucleon cross section. Above expression should be averaged over all positions of $c\bar{c}$ formation with a weight given by the product of nuclear densities and survival probabilities $S$,

$$N_{AB}(b) = \int d^2s \int_{-\infty}^{\infty} dz_{A} \rho_{A}(s, z) \int_{-\infty}^{\infty} dz' \rho_{B}(b - s, z') \times$$

$$S(b, s, z, z') N(b, s, z, z')/ \int d^2s \int_{-\infty}^{\infty} dz \rho_{A}(s, z) \times \int_{-\infty}^{\infty} dz' \rho_{B}(b - s, z') S(b, s, z, z')$$

Finally, corresponding quantity at fixed transverse energy $E_T$ is obtained as,

$$N_{AB}(E_T) = \int d^2bP(b, E_T) \sigma_{AB} N_{AB}(b)/$$

where $\sigma_{AB}$ is the inelastic cross section for AB collisions.

![Figure 4](image-url)

**FIG. 4.** (a) NA38 experimental data on the centrality dependence of $J/\psi$ over Drell-Yan ratio, in 200 GeV/c S+U collisions. The solid line is the ratio obtained in the QCD based nuclear absorption model. (b) The centrality dependence of $p_T$ broadening in S+U collisions. The solid line is a fit to the data in the QCD based nuclear absorption model.
Fluctuations of $E_T$ at a fixed impact parameter will also affect the average number of collisions $N_{AB}(E_T)$. We have taken into account the $E_T$ fluctuations by the replacement,

$$N_{AB}(b) \rightarrow E_T/\langle E_T \rangle (b) N_{AB}(b). \quad (19)$$

$p_T$ broadening of $J/\psi$’s in AA collisions depends on two parameters, (i) $\langle p_T^2 \rangle_{NN}$, the mean squared transverse momentum in NN collisions, a measurable quantity and (ii) the product of the gluon-nucleon cross section and the average parton momentum broadening per collision, $\sigma_g N \delta_0$. Since gluons are not free, the second quantity is essentially non measurable. We obtain $\sigma_g N \delta_0$ from a fit to the NA38 $p_T$ broadening data [12] in S+U collisions at 200 GeV/c. $\langle p_T^2 \rangle_{NN}$ at corresponding energy is known from NA3 experiment, $\langle p_T^2 \rangle_{NN} = 1.23 \pm 0.05$ [22]. The $E_T - b$ correlation parameters, $a$ and $q$ for S+U collisions are, $a=3.2$ and $q=0.74$ GeV [23]. To show that the present ‘unconventional’ nuclear absorption model also reproduces the centrality dependence of $J/\psi$ over Drell-Yan ratio in S+U collisions, in Fig.4a, we have compared our results with the experimental data. We have neglected the effect of $E_T$ fluctuations in S+U collisions. The agreement between data and theory is good. In Fig.4b, the experimental data on the $E_T$ dependence of $p_T$ broadening are shown. The solid line is a fit to the data, obtained with $\langle p_T^2 \rangle_{NN} = 1.23$ (fixed) and $\sigma_g N \delta_0 = 0.442 \pm 0.056$. Value of $\sigma_g N \delta_0$ agrees closely with the value obtained by Kharzeev et al [21] in the conventional nuclear absorption model and also with the value obtained in the conover model [24]. $\langle p_T^2 \rangle_{NN}$ increases weakly with energy. To obtain $\langle p_T^2 \rangle_{NN}$ for Pb+Pb collisions at 158 GeV/c, we have fitted the existing experimental data [22,25–27] with logarithmic energy dependence,

$$\langle p_T^2 \rangle_{NN} = a + b \ln \sqrt{s} \quad (20)$$

In Fig.5, experimental data along with the fitted curve obtained with $a = -0.38$ and $b = 0.53$. is shown. From the above parameterization, we obtain, $\langle p_T^2 \rangle_{NN} = 1.15$ GeV$^2$, for Pb+Pb collisions at CERN SPS. As we intend to predict $p_T$ broadening at RHIC energy, $\langle p_T^2 \rangle_{NN}$ at RHIC energy ($\sqrt{s}=200$ GeV) is also obtained from the above parameterization. At RHIC energy, $\langle p_T^2 \rangle_{NN} = 2.45$ GeV$^2$. However, we must warn our reader to treat the above number with caution. The experimental data being limited to 60 GeV only, extrapolation to RHIC energy is unreliable.

In Fig.6, we have shown the result of $p_T$ broadening in the model. The solid and dashed lines are the $\langle p_T^2 \rangle$ in our QCD based nuclear absorption model predictions, with and without the effect of $E_T$ fluctuations on $N_{AB}(b)$. When the $E_T$ fluctuations are not accounted for (the dashed line), the model could not explain the experiment beyond $E_T=100$ GeV. Experimentally, $\langle p_T^2 \rangle$ continues to increase with $E_T$ beyond 100 GeV, but the model predicts a decreasing trend. Beyond 100 GeV (the knee of the $E_T$ distribution), $J/\psi$’s are strongly suppressed. Strong suppression causes the $p_T$ broadening to decrease beyond 100 GeV. The decreasing trend is changed into an increasing trend if the effect of $E_T$ fluctuations on $N_{AB}(b)$ is taken into account (the solid line). $E_T$ fluctuations effectively increases the average number of collisions $N_{AB}(b)$ and counter balance the strong suppression effect beyond the knee of the $E_T$ distribution. Considering that all the parameters of the model were fixed, model describe the data very well.

In Fig.6, the one parameter threshold model prediction...
with threshold density $n_c=3.78 \text{ fm}^{-2}$ is shown. When the effect of $E_T$ fluctuations on $N_{AB}$ is neglected (the dash-dot-dot line) the model fails to explain the data. At low $E_T$, it predict $<p_T^2>$ in accordance to the QCD based nuclear absorption model, but beyond $E_T=60$ GeV, it predict less $p_T$ broadening. Also, the increasing tendency beyond 100 GeV is not reproduced. Even when the effect of $E_T$ fluctuations are taken into account (the dash-dot line), the model fails to give proper description to the data. This is expected as the one parameter threshold model do not give very good description to the centrality dependence of $J/\psi$ over Drell-Yan ratio. Huefner et al [28] also analyzed the NA50 $p_T$ broadening data in the threshold model and essentially obtain a similar result that the model could not fit the NA50 $p_T$ broadening data. As shown earlier, a two parameter threshold model, with smeared threshold density, reproduced the centrality dependence of $J/\psi$ over Drell-Yan ratio as well as $J/\psi$ over minimum bias ratio. In Fig.6, the prediction obtained in the two parameter threshold model, with the effect of $E_T$ fluctuations included, is shown as the dotted line. Considering that it is also a parameter free calculation ($<p_T^2>_{NN} \text{ and } \sigma_{NN} \delta_0$ fixed), the model describes the data well. Here, we may mention that Armesto et al [24], in the comover model also explained the NA50 $p_T$ broadening data. However, as they did not account for the $E_T$ fluctuations on $N_{AB}(b)$ the increasing trend beyond 100 GeV could not be reproduced.

V. PREDICTION FOR RHIC AU+AU COLLISIONS

Recently PHENIX collaboration published the centrality dependence of charm production in Au+Au collisions at RHIC energy [30]. Centrality dependence of charm quark production is consistent with binary collisions scaling. PHENIX collaboration also published the yield of $J/\psi$ in a few centrality ranges of Au+Au collisions at RHIC energy [31]. Data have very large error bars. Data do not show any indication of large enhancement as speculated in some models [32]. We have shown that the PHENIX data on the centrality dependence of $J/\psi$ production are well described in the QCD based nuclear absorption model [33]. In this section we compare the $J/\psi$ production at RHIC energy in the QCD based nuclear absorption model with the production in the QGP based threshold model. Model parameters are kept fixed at the values required for Pb+Pb collisions at SPS energy. At RHIC energy the so called hard scattering, proportional to number of binary collisions appear. However, PHENIX data on $J/\psi$ production [31] do not require any hard scattering component [33] and presently we neglect them.

In Fig.7, we have compared the suppression factor for $J/\psi$ production at RHIC energy in the QCD based nuclear absorption model and in the QGP based threshold model. In a centrality range of collisions, $J/\psi$ suppression factor is defined as,

$$S = \frac{\sigma_{J/\psi}^{AA}}{<N_{AA}> \sigma_{J/\psi}^{NN}}$$

where $<N>$ is the average number of NN collisions in the centrality range of collisions. As seen in Fig.7, both the QCD based nuclear absorption model and the QGP based threshold model predict nearly same suppression factor. In Fig.7 we have also shown the recent PHENIX measurement of total charm quark multiplicity per NN collisions ($N_{c}/T_{AB}$) [30]. Data were scaled by a factor of 1500. Except for the very peripheral collisions (60-92% centrality), centrality dependence of charm production agree well with the dependence predicted in both the models. Possibly centrality dependence of $J/\psi$ production will not distinguish between the models.

As told earlier, $p_T$ broadening of $J/\psi$ is considered as a probe of deconfinement transition. We have seen that at SPS $p_T$ broadening do not distinguish between the QCD based nuclear absorption model and QGP based threshold model. In Fig.8, model predictions for $p_T$ broadening of $J/\psi$’s at RHIC energy are shown. Both the models predict very similar $p_T$ broadening. As it is in SPS energy, at RHIC energy also $p_T$ broadening of $J/\psi$ do not distinguish between the QCD based nuclear absorption and QGP bases threshold models.
VI. SUMMARY AND CONCLUSIONS

To summarize, we have analyzed the latest (2000 run) NA50 data on \( J/\psi \) suppression in 158 AGeV Pb+Pb collisions. QCD based nuclear absorption model, with parameters fixed from the NA50 high statistics pA data, well explain the latest NA50 data. The model also explain the centrality dependence of \( J/\psi \) over minimum bias ratio as well as the centrality dependence of \( p_T \) broadening of \( J/\psi \)'s. The same data sets were analysed in the QGP based threshold model. Threshold model with smeared threshold density also explain those data sets. At SPS energy \( J/\psi \) 's can not distinguish between the two differeny models. We have also shown that even at RHIC energy, both the models predict nearly similar centrality dependence of \( J/\psi \) suppression and its \( p_T \) broadening. Possibly, for the deconfinement phase transition, there is no ‘smoking gun’. A variety of data, analysed in a consistent manner will be able to shed light on the possible deconfinement phase transition.

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