Threshold model and the latest NA50 data on $J/\psi$ suppression in Pb+Pb collisions

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Using the QGP motivated threshold model, where all the $J/\psi$’s are suppressed above a threshold density, we have analyzed the latest version of the NA50 data on the centrality dependence of the $J/\psi$ over Drell-Yan ratio. The data are not well explain in the model, unless the threshold density is largely smeared. Large smeared threshold density effectively excludes creation of any deconfined medium in the collision.

I. INTRODUCTION

In relativistic heavy ion collisions $J/\psi$ suppression has been recognized as an important tool to identify the possible phase transition to quark-gluon plasma. Because of the large mass of the charm quarks, $c\bar{c}$ pairs are produced on a short time scale. Their tight binding also makes them immune to final state interactions. Their evolution probes the state of matter in the early stage of the collisions. Matsui and Satz [1] predicted that in presence of quark-gluon plasma (QGP), binding of $c\bar{c}$ pairs into a $J/\psi$ meson will be hindered, leading to the so called $J/\psi$ suppression in heavy ion collisions [1]. Over the years several groups have measured the $J/\psi$ yield in heavy ion collisions (for a review of the data and the interpretations see Refs. [2,3]). In brief, experimental data do show suppression. However this could be attributed to the conventional nuclear absorption, also present in pA collisions.

In 1998 NA50 collaboration [4] published the results of centrality dependence of $J/\psi$ suppression in 158 GeV/c Pb+Pb collisions. Data gave the first indication of the anomalous mechanism of charmonium suppression, which goes beyond the conventional suppression in a nuclear environment. The ratio of $J/\psi$ yield to that of Drell-Yan pairs decreases faster with $E_T$ in the most central collisions than in the less central ones. It has been suggested that the resulting pattern can be understood in a deconfinement scenario in terms of successive melting of charmonium bound states [4]. Later, the data were analyzed in a variety of models, with or without the assumption of deconfining phase transition [5–7,?].

Recently, in Quark Matter 2002, NA50 collaboration presented preliminary analysis of the $E_T$ dependence of the $J/\psi$ over Drell-Yan ratio, obtained in the 2000 Pb+Pb run [9]. The suppression pattern is changed, presumably due to changed method of analysis. In 1998, NA50 collaboration performed two types of analysis, the standard analysis where the $J/\psi$ and Drell-Yan cross sections were measured directly to obtain the ratio. In the other analysis, called the minimum bias (MB) analysis, the Drell-Yan cross sections were replaced by the minimum bias cross section, to obtain,

$$\frac{\sigma(J/\psi)}{\sigma(DY)}_{MB} = \frac{\sigma(J/\psi)}{\sigma(MB)}_{EX} \frac{\sigma(MB)}{\sigma(DY)}_{TH} \quad (1)$$

The data beyond 100 GeV were obtained entirely from the MB analysis [4]. The latest NA50 data are obtained from the standard analyzed only. Compared to 1998 data [4], 2000 data [9] are flatter, suppression being more at low $E_T$ and less at high $E_T$. However, the suppression obtained is still anomalous in the sense that normal nuclear absorption model fails to explain it. In Quark Matter 2002, NA50 collaboration also presented their analysis of the nuclear absorption of $J/\psi$ in high statistics 450 GeV pA collisions [10]. 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 $\sigma_{abs}^{J/\psi N} = 4.4 \pm 1.0$ mb [10]. They also estimate a common $\sigma_{abs}^{J/\psi N}$ from latest pA and NA38 200 GeV/c S+U data [11], $\sigma_{abs}^{J/\psi N} = 4.4 \pm 0.5$ mb. The extracted absorption cross section is much smaller than the earlier value of 6.4 $\pm 0.8$ mb extracted from fit to earlier NA50 data [12] or 7.1 $\pm 3.0$ mb obtained from a fit to NA38 S+U data [11]. Within error, the S+U cross sections are compatible with pA cross sections.

The changed suppression pattern in the latest NA50 data [9], along with the high statistics pA data [10], with the implication of smaller $J/\psi$-nucleon absorption cross section, necessitated re-examination of the models, which were successful in explaining the earlier version of the NA50 data. Recently we have analyzed the latest NA50 data in the QCD based nuclear absorption model [13]. The parameters of the model were fixed from the recent high statistics pA data. Without any free parameter the model could explain the latest NA50 data. Capella et al [14] also analyzed the data in the comover model. $J/\psi$-nucleon absorption cross section was fixed at 4.5 mb. The latest NA50 data are explained with comover-$J/\psi$ absorption cross section, $\sigma_{abs}=0.65$ mb.

Blaizot et al [5] proposed the QGP motivated threshold model to explain the earlier version of the NA50 data [4]. To mimic the onset of deconfining phase transition above a critical energy density and subsequent melting of $J/\psi$’s, $J/\psi$ suppression was linked with the local energy density. If the energy density at the point where
$J/\psi$ is formed, exceeds a critical value ($\varepsilon_c$), $J/\psi$'s disappear. The critical energy density was then related with the (transverse) density and its value was obtained from a fit to the NA50 experimental data [4]. The NA50 data were well fitted with critical (threshold) density $n_c=3.7-3.75$ fm$^{-2}$ and $\sigma_{abs}^{J/\psi N}=6.4$ mb. The model needs to be tested against the latest NA50 data [9], with changed suppression pattern, taking into consideration the new data on pA collisions [10].

Aim of the present paper is to analyze the latest NA50 data [9] on the centrality dependence of $J/\psi$ over Drell-Yan ratio, in the threshold model [5]. Plan of the paper is as follows: In section 2, we present a brief description of the threshold model. In section 3, NA50 data are analyzed in the model. Summary and conclusions are drawn in section 4.

II. $J/\psi$ SUPPRESSION IN THRESHOLD MODEL

The details of the threshold model could be found in [5]. In addition to the 'conventional' nuclear absorption, Blaizot et al [5] introduced an anomalous suppression factor, $S_{anom}$, such that all the $J/\psi$'s are totally suppressed above a critical (threshold) density $n_c$. The $J/\psi$ cross section at an impact parameter $b$ as a function of $E_T$ is then written as,

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

(2)

where $T^{eff}(b)$ is the effective nuclear thickness, $T^{eff}(b) = \int_{-\infty}^{\infty} dz \rho(b,z) \exp(-\sigma_{abs}^{J/\psi N} \int_z^\infty dz' \rho(b,z')).$

For the density $\rho$, we use a Woods-Saxon form

$$\rho(r) = \frac{\rho_0}{1 + exp[(r-R)/a]} , \int d^3 \rho(r) = A$$

(3)

In [5], Blaizot et al used $R = 1.1 A^{1/3} = 6.52 fm$ and $a=0.53$ fm. However, nuclear absorption has a sensitive (exponential) dependence on density and it is better to use more realistic values for the radius and the diffusiveness parameters. For Pb we use, $R = 6.624 fm$ and $a=0.549$ fm [15]. $\sigma_{abs}^{J/\psi N}$ is the $J/\psi$-nucleon absorption cross section for which a value of $=4.4$ mb [10] is used.

In Eq.2, $P(b,E_T)$ is the $E_T - b$ correlation function for which a Gaussian form is used [5],

$$P(b,E_T) \propto \exp(-(E_T - qN_p(b))^2/2q^2aN_p(b))$$

(4)

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 respectively [5].

$S_{anom}(b,s)$ in Eq.2 is the anomalous suppression factor introduced by Blaizot et al [5]. They considered two forms for $S_{anom}$. Assuming that all the $J/\psi$'s get suppressed above a threshold density ($n_c$), the anomalous suppression factor can be written as,

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

(5)

where $n$ is the transverse density (Eq.3 of [5]). In ref. [5] it was seen that if the theta function is smeared by a small amount, at the expense of another parameter, such that suppression is gradual rather than abrupt, the quality of fit to data improves considerably. This was done by writing,

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

(6)

In both the forms, effect of $E_T$ fluctuations at a fixed impact parameter is taken into account by rescaling the density as, $n \rightarrow nE_T/ <E_T> (b)$ [5]. Threshold model parameters $n_c$ and $\lambda$ can be obtained by fitting the latest NA50 data on centrality dependence of $J/\psi$ over Drell-Yan ratio.

The Drell-Yan pairs do not suffer any final state interaction and the cross section at impact parameter $b$ as a function of $E_T$ can be calculated as,

$$\frac{d^3\sigma^{DY}}{dE_Td^2b} = \sigma_{NN}^{DY} \int d^2s T_A(s) T_B(b-s) P(b,E_T)$$

(7)

FIG. 1. The NA38 data on the centrality dependence of $J/\psi$ over Drell-Yan ratio in 200 GeV/c S+U collisions. The line is the Glauber model of nuclear absorption with $\sigma_{abs}^{J/\psi N}=4.4$ mb. For the $E_T - B$ correlation, we have used Gaussian form Eq.4, with $a=3.2$ and $q=0.74$ GeV [2].

III. COMPARISON WITH LATEST NA50 DATA

For comparison with NA50 experimental data on the centrality dependence of $J/\psi$ over Drell-Yan ratio, normalizing factor $N = B_{\mu\nu}^{J/\psi}/\sigma_{NN}^{DY}$ is needed. It can
also be considered as a fitting parameter and obtained along with the threshold model parameters, \( n_c \) and \( \lambda \). However, normalizing factor and threshold model parameters are correlated. Higher normalizing factor can be compensated by increasing the threshold density. Noting that the ratio of Pb+Pb to S+U normalizations is equal to 1.051 \pm 0.026 [10,14], NA38 data on the centrality dependence of \( J/\psi \) over Drell-Yan ratio in 200 GeV S+U data [11] can be fitted to obtain the normalizing factor for S+U collisions and can be rescaled to obtain the same for Pb+Pb collisions. In S+U collision, deconfinement transition is not expected. The observed suppression is due to nuclear absorption only. Fixing \( \sigma_{abs}^{J/\psi} = 4.4 \text{ mb} \), NA38 data are fitted in the conventional nuclear absorption model to obtain the normalizing factor. In Fig.1, NA38 data along with the best fit obtained with \( B_{\mu\mu}\sigma_{NN}^{J/\psi}/\sigma_{NN}^{DY} = 39.65 \) is shown. Within the error bars, the data are well explained in the nuclear absorption model. Normalizing factor for Pb+Pb collision is obtained by scaling the normalizing factor for S+U collisions by 1.051 [10].

We may mention that recently, Capella et al [14] analyzed the S+U data in the comover model. With \( \sigma_{abs}^{J/\psi} = 4.5 \text{ mb} \), data allow for a small comover interaction, \( \sigma_{co} = 0.65 \). For the \( B_{\mu\mu}\sigma_{NN}^{J/\psi}/\sigma_{NN}^{DY} \) they used a value of 47, obtained from a fit to latest NA50 Pb+Pb data in the comover model. However, as we find the data are well explained in terms of nuclear absorption only, use of comover interaction in S+U collision is debatable.

![Fig. 2. The latest NA50 data on the centrality dependence of \( J/\psi \) over Drell-Yan ratio in Pb+Pb collisions. The dotted line is the Glauber model of nuclear absorption with \( \sigma_{abs}^{J/\psi} = 4.4 \text{ mb} \). The dash-dotted line is the ratio in the threshold model with \( n_c = 3.61 \text{ fm}^{-2} \). The dash-dot-dot line is obtained with \( n_c = 3.72 \text{ fm}^{-2} \) and \( \lambda = 2 \text{ fm}^2 \) (fixed). The solid line is obtained with \( n_c = 3.82 \text{ fm}^{-2} \) and \( \lambda = 0.77 \text{ fm}^2 \).](image)

In Fig.2, latest NA50 data [9] on the centrality dependence of \( J/\psi \) over Drell-Yan ratio in Pb+Pb collisions, is shown. Just to show that the latest data are also anomalous, we have shown the Glauber model calculation with \( \sigma_{abs}^{J/\psi} = 4.4 \text{ mb} \) (the dashed 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.1, the dash-dotted line is the best fit obtained to the data in the threshold model, without any smearing of the threshold density. We obtained threshold density \( n_c = 3.61 \pm 0.06 \text{ fm}^{-2} \). The value is less than value \( n_c = 3.7 \text{ fm}^{-2} \), obtained by Blaizot et al [5] from the earlier version of the data, mainly due to lesser value of the \( J/\psi \)-Nucleon absorption cross section. To produce similar suppression, \( \sigma_{abs}^{J/\psi} \) being less, anomalous suppression has to increase.

Interestingly, we find that the threshold model with a single parameter does not give a proper description to the data. In the intermediate range of \( E_T \), agreement with data is not good. Smearing the threshold density by a small amount do not improve the quality of fit. In Fig.2, the dash-dot-dot line is obtained with smearing the threshold density by a small amount (\( \lambda \) fixed at 2 \text{ fm}^2). The best fit to the data is then obtained with threshold density, \( n_c = 3.72 \text{ fm}^{-2} \). Again the data are not well explained. In Fig.2, the solid line is the best fit obtained to the data varying both the parameters. We obtain, \( n_c = 3.82 \pm 0.09 \text{ fm}^{-2} \) and \( \lambda = 0.77 \pm 0.14 \text{ fm}^2 \). 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 NA50 data. The anomalous suppression is not abrupt but increases gradually with density. The analysis suggest that with \( \sigma_{abs}^{J/\psi} = 4.4 \text{ mb} \), unless the threshold density is largely smeared, threshold model do not give a proper description of the latest NA50 data on the centrality dependence of the \( J/\psi \) suppression.

**IV. SUMMARY AND CONCLUSIONS**

To summarize, the latest NA50 data on the centrality dependence of \( J/\psi \) over Drell-Yan ratio in Pb+Pb collisions are analyzed in the QGP motivated threshold model. In the threshold model, in addition to the conventional nuclear absorption, an anomalous suppression is introduced, such that above a threshold density, all the \( J/\psi \)’s are absorbed. To be consistent with latest pA data on \( J/\psi \) absorption, we have used \( \sigma_{abs}^{J/\psi} = 4.4 \text{ mb} \). Threshold model with a single parameter, the threshold density \( n_c \) donot give a proper description of the centrality dependence of \( J/\psi \) over Drell-Yan ratio. The best fit to data is obtained with threshold density \( n_c = 3.61 \text{ fm}^{-2} \) fails to explain the data in the intermediate \( E_T \) range. If the threshold density is smeared at the expense of another parameter \( \lambda \) the model could explain the latest NA50 data with \( n_c = 3.82 \text{ fm}^{-2} \) and \( \lambda = 0.77 \text{ fm}^2 \).
Small value of $\lambda=0.77 \text{ fm}^2$ indicate that for a proper description to the NA50 data, the threshold density has to be smeared considerably. Thus onset of anomalous suppression is not sudden, rather gradual. Over a density range of 2.4-5.2 $\text{fm}^{-2}$, anomalous suppression factor change from 0.9 to 0.1. Originally, threshold model was devised to mimic the melting of $J/\psi$'s in a deconfining medium. With nominal smearing of the threshold density, the essence of the model is not lost. Large smearing of the threshold density, as required to fit the latest NA50 data, effectively excludes formation of deconfining medium. The medium where the anomalous suppression is taking place, do not melt the $J/\psi$ suddenly, but rather gradually, more like in a nuclear/comover environment.

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