J/ψ suppression in the threshold model and QGP formation time

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In the QGP motivated threshold model, in addition to the normal nuclear absorption, J/ψ’ s are subjected to an additional ”anomalous” suppression. We have analysed the recently published PHENIX data on the participant number dependence of the nuclear modification factor for J/ψ’ s in Au+Au collisions and extracted the anomalous suppression required to explain the data. At mid rapidity J/ψ’ s are anomalously suppressed only above a threshold density \( n_\text{c} = 3.73 \text{ fm}^{-2} \). The forward rapidity data on the other hand require that J/ψ’ s are continuously ”anomalously” suppressed. The analysis strongly indicate that in mid rapidity J/ψ’ s are suppressed in a deconfined medium. Using the PHENIX data on the participant number dependence of the Bjorken energy density, we have also estimated the QGP formation time. For critical temperature \( T_c = 192 \text{ MeV} \), estimated QGP formation time ranges between 0.06-0.08 fm/c.

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Recently, PHENIX collaboration have published their measurements of the centrality dependence of J/ψ suppression in Au+Au collisions at RHIC energy, \( \sqrt{s} = 200 \text{ GeV} \) [1]. Data are taken at mid rapidity (\(|y| < 0.35\)) and at forward rapidity (1.2 < \(|y| < 2.2\)). In most central Au+Au collisions, J/ψ’ s are more suppressed at forward rapidity than at mid rapidity. Suppression factor is \( \sim 3 \) at mid rapidity and \( \sim 6 \) at forward rapidity.

There is growing consensus that in central Au+Au collisions at RHIC, a deconfined state of quarks and gluons (QGP) is produced. It is expected that a deconfined medium, if produced in Au+Au collisions will leave its imprint in J/ψ production. Long back, Matsui and Satz [2] predicted that in a deconfined medium, binding of a c\bar{c} pair into a J/ψ meson will be hindered, leading to the so called J/ψ suppression in heavy ion collisions [2]. However, J/ψ’ s are also suppressed in a nuclear medium. Inelastic interactions of J/ψ’ s with the nucleons can dissociate them. Suppressed J/ψ production not necessarily imply a deconfined matter formation. At RHIC energy, it has been further argued that rather than suppression, J/ψ production will be enhanced [2, 3]. Due to large initial energy, large number of c\bar{c} pairs will be produced in initial hard scatterings. Recombination of c\bar{c} can occur, enhancing the charmonium production. However, as mentioned earlier, PHENIX data do not show any indication of J/ψ enhancement.

PHENIX data on the centrality dependence of J/ψ suppression has been analysed in several models, e.g. e.g. conover model [3], statistical coalescence model [6], the kinetic model [7, 8] or the QCD based nuclear absorption model [9]. None of the models give satisfactory description of the experimental data. Recently, we have analysed [10] the PHENIX data in the threshold model and found that it do explain the PHENIX mid rapidity data, but not the forward rapidity data. In the present paper, we refine the analysis and extracted the threshold density required to fit the mid rapidity and the forward rapidity PHENIX data. Extracted threshold density is then used to obtain a physical parameter, the QGP formation time. We find that QGP formation time is quite small, \( \tau \approx 0.06 - 0.08 \text{ fm} \).

Blaziot et al [11, 12], proposed the threshold model to explain the NA50 data on anomalous J/ψ suppression in 158 AGeV Pb+Pb collisions at SPS energy [13]. Threshold model tries to mimic the sudden melting of J/ψ in a deconfined medium. In the model fate of a J/ψ depend on the local energy density. If the energy density exceeds a critical value, the inter quark potential can not bind a c\bar{c} pair into a J/ψ. It is also assumed that ”local” energy density is proportional to 'local' transverse density. Then if the "local" transverse density exceeds a critical or threshold value, deconfined matter is formed and all the J/ψ’ s are completely destroyed (anomalous suppression). One must remember that the anomalous suppression is in addition to the "conventional nuclear absorption". The model neglects the transverse expansion of the system. It is implicitly assumed that J/ψ’ s are absorbed before the transverse expansion sets in.

In the threshold model, number of J/ψ mesons, produced in a AA collision, at impact parameter \( b \) can be written as,

\[
N_{JJ/ψ}^{AA}(b) = N_{NN}^{J/ψ} \int d^2 s T_{eff}^{AA} (s) T_{B}^{eff} (b - s) \times S_{anom}(b, s),
\]

where \( T_{eff}^{AA} (b) \) is the effective nuclear thickness,

\[
T_{eff}^{AA} (b) = \int_{-\infty}^{\infty} dz \rho(b, z) \exp (-\sigma_{abs} \int_{z}^{\infty} dz' \rho(b, z')), \]

\( \sigma_{abs} \) being the J/ψ-nucleon absorption cross-section. For the density we use the Woods-Saxon form.
\[ \rho(r) = \frac{\rho_0}{1 + e^{\exp((R - R)/a)}}, \quad \int d^3r \rho(r) = A \]  

(3)

with \( R = 6.38 \text{ fm} \) and \( a = 0.535 \text{ fm} \).

\( S_{anom}(b, s) \) in Eq.1 is the anomalous suppression factor introduced by Blaizot et al. \([11, 12]\). Assuming that all the \( J/\psi \)'s get suppressed above a threshold density \( n_c \), the anomalous suppression can be written as,

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

(4)

where \( n_c \) is the critical or the threshold density. \( n(b, s) \) is the local transverse density. It was observed \([11]\) that by smearing the threshold density by a small amount, one can obtain better fit to the data, but at the expense of an additional parameter \( \lambda \),

\[ S_{anom}(b, s) = \frac{1}{2} [1 - \tanh(\lambda(n(b, s) - n_c))] \]  

(5)

Critical ingredient of the threshold model is the "local" transverse density. At impact parameter \( b \) and at the transverse position \( s \), local transverse density it can be obtained as,

\[ n(b, s) = T_A(s)[1 - \exp(-\sigma_{NN}T_B(s - b))] 
+ T_B(b - s)[1 - \exp(-\sigma_{NN}T_A(s))] \]  

(6)

However, experiments do indicate otherwise. In \( Au+Au \) collisions, \( J/\psi \)'s are more suppressed at forward rapidity than at mid rapidity. In the threshold model, such a dependence can only be accommodated if parameters of the model, \( \sigma_{abs} \), \( n_c \), and \( \lambda \) depend on the rapidity variable. We thus separately fit the mid rapidity and the forward rapidity PHENIX data to extract those parameters. Before we proceed further, we would like to note that it is not unnatural to have rapidity dependence on the critical parameter \( n_c \). For example, it is well known that the critical temperature of the confinement-deconfinement phase transition depend on the baryon density of the system. Mid-rapidity region is essentially baryon free while at forward rapidity baryon content is non-negligible. Rapidity dependence of the critical parameter \( n_c \) will then implicitly account for the baryon dependence of the critical parameter.

In Fig.1 PHENIX data are shown. Data points are few and it is not judicious to fit all the three parameters simultaneously. With the Glauber model of nuclear absorption, we first fit the few peripheral collision (up to \( N_{part} = 150 \)) in mid rapidity data and extract the \( J/\psi \)-nucleon absorption cross-section \( \sigma_{abs} \), the threshold density \( n_c \) and its smearing \( \lambda \). Best fit to the mid rapidity data is obtained with \( n_c = 3.73 \pm 0.29 \text{ fm}^{-2} \) and \( \lambda = 8.96 \pm 9.72 \text{ fm}^2 \). The solid line in Fig.1 shows the fit. The quality of fit is very good. For the forward rapidity data sets also we use the \( \sigma_{abs} = 4.39 \text{ mb} \). As seen in Fig.1 at extreme peripheral collisions, \( J/\psi \) suppression in mid and forward rapidity is similar. Best fit to the forward rapidity data set is ob-
tained with \( n_c = 2.96 \pm 0.42 \text{fm}^{-2} \) and \( \lambda = 0.99 \pm 0.94 \text{fm}^2 \). Here again, as shown in Fig[1] the quality of fit is very good. While the threshold model do explain the centrality dependence of \( J/\psi \) suppression at mid rapidity as well as at forward rapidity, the anomalous suppression \((S_{anom})\) required for the two data sets are widely different. In Fig[2] we have shown the anomalous suppression \( S_{anom} \) as required by the mid and the forward rapidity data. At mid rapidity, true to the spirit of the threshold model, anomalous suppression shows a step like behavior. At mid rapidity, \( J/\psi \) are “anomalously” suppressed only above the threshold transverse density \( n_c = 3.73 \text{fm}^{-2} \). But at forward rapidity \( J/\psi \)’s are continuously “anomalously” suppressed. Even though the model fits the data, the spirit of the model is lost. Step function like anomalous suppression in mid rapidity give strong indication that at mid rapidity, \( J/\psi \)’s are suppressed in a deconfined medium. Continuous anomalous suppression at forward rapidity on the other hand indicate that \( J/\psi \)’s are possibly suppressed due a mechanism not related to the confinement-deconfined phase transition. However at forward rapidity, \( J/\psi \) suppression is more complex than envisaged in a simple Glauber like model. Simple Glauber model can not explain either of the two data sets.

Before we proceed further, we would like to note that the threshold density as determined here represents the upper limit. Threshold model neglects some very important effects, e.g. (i) feed back from \( \psi' \) and \( \chi \) states and (ii) transverse expansion. A considerable fraction (\( \sim 40\% \)) of \( J/\psi \)’s are from decay of \( \psi' \) and \( \chi \) states [16]. That part is completely neglected here. Threshold density for anomalous suppression of higher states, \( \psi' \) and \( \chi \) should be less than that for a \( J/\psi \). Then presently estimated threshold density \( n_c \) represent an upper limit. Additionally, at RHIC, model studies indicate that in the deconfined phase, the system undergoes significant transverse expansion [10]. The local transverse density is a key ingredient to the Threshold model. In an expanding system, local transverse density will be diluted. \( J/\psi \)'s, which are anomalously suppressed in a static system, may survive in an expanding system due to dilution. Then, the presently estimated threshold density will again represent an upper limit.

We now try to connect the estimated threshold density with some physical parameters like threshold energy density or temperature above which \( J/\psi \) are anomalously suppressed. As mentioned earlier, threshold density is assumed to be proportional to energy density. If the proportionality factor is known, we can estimate the threshold energy density above which the \( J/\psi \)’s are anomalously suppressed. As given in Eq[5] local transverse density is a function of the impact parameter (\( b \)) and the transverse position (\( s \)). For collisions between two identical nucleus at impact parameter \( b \), maximum transverse density is achieved at the transverse position \( s = b/2 \). In Fig[4] we have plotted the transverse density \( n_p^{max}(b) = n_p(b, s = b/2) \) as a function of participant number. \( n_p^{max} \) increases with the collision centrality. If in a collision with participant number \( N_{part} \), deconfined matter is produced and \( J/\psi \)’s are anomalously suppressed, at the minimum \( n_p^{max} \) should exceed the threshold density. As seen from Fig[4] estimated threshold density, \( n_c = 3.73 \pm 0.29 \text{fm}^{-2} \) corresponds to Au+Au collisions with participant number \( N_{part} = 199.6 \pm 56.5 \).

Experimentally one estimate the initially produced energy density by measuring the total transverse energy \( E_T \) and using an estimate for the initial reaction volume. In the Bjorn model with longitudinal boost-invariance, the energy density is obtained as,

\[
\varepsilon_{BJ} = \frac{1}{\tau A_T} \frac{dE_T}{dy} \tag{7}
\]

where \( \tau \) is the formation time, \( A_T \) is the overlap area and \( dE_T/dy \) transverse energy per unit rapidity. QGP formation time is an important parameter. Experimental determination of energy density then depends strongly on the estimate of the initial time. PHENIX collaboration have measured the transverse energy \( E_T \). Since QGP formation time is not known, they have tabulated the Bjorn energy density times the formation time as a function of the participant number. In Fig[5] we have shown the PHENIX data on the participant number dependence of the \( \varepsilon_{BJ} \) [17]. Like \( n_p^{max}, \varepsilon_{BJ} \) increases as the collision centrality increases. PHENIX data indicate that a collision with participant number \( N_{part} = 199.6 \pm 56.5 \), corresponds to \( \varepsilon_{TH} \approx 3.98^{+1.02}_{-1.48} \text{GeVfm}^{-2} \). \( \varepsilon_{TH} \) is the threshold energy density above which \( J/\psi \)'s are anomalously suppressed. Corresponding threshold temperature (\( T_{TH} \)) can be easily obtained using the relation, \( \varepsilon = g_{QGP} \frac{T^4}{4\pi^2} T^4 \) with \( g_{QGP} = 47.5 \), for a QGP with three flavors.
confinement-deconfinement transition for various choices of $\bar{J}/\psi$'s get dissociated and critical temperature ($T_c$) for the confinement-deconfinement transition for various choices of QGP formation time ($\tau$).

| $\tau$ (fm) | $T_{th}$ (MeV) | $T_c$ (MeV) |
|-------------|----------------|-------------|
| 0.02        | 558.6$^{+32.8}_{-61.3}$ | 266.0$^{+15.6}_{-29.2}$ |
| 0.04        | 469.7$^{+27.6}_{-51.5}$ | 223.7$^{+13.1}_{-24.5}$ |
| 0.06        | 424.4$^{+24.9}_{-46.6}$ | 202.1$^{+11.9}_{-22.2}$ |
| 0.08        | 395.0$^{+23.2}_{-43.3}$ | 188.1$^{+11.0}_{-20.6}$ |
| 0.10        | 373.6$^{+21.9}_{-41.0}$ | 177.9$^{+10.4}_{-19.5}$ |
| 0.12        | 356.9$^{+20.9}_{-39.2}$ | 170.0$^{+10.0}_{-18.7}$ |
| 0.14        | 343.4$^{+20.2}_{-37.7}$ | 163.5$^{+9.6}_{-17.9}$ |
| 0.16        | 332.1$^{+19.5}_{-36.5}$ | 158.9$^{+9.3}_{-17.4}$ |
| 0.18        | 322.5$^{+18.9}_{-35.4}$ | 153.6$^{+9.0}_{-16.9}$ |
| 0.20        | 314.1$^{+18.4}_{-34.5}$ | 149.6$^{+8.8}_{-16.4}$ |

$T_{th}$ is the temperature above which $\bar{J}/\psi$ get dissociated. Lattice based potential models indicate that in a deconfined medium, at the critical temperature $T_c$, interquark potential is not sufficiently screened to dissociate $\bar{J}/\psi$’s. Model calculations indicate that $\bar{J}/\psi$’s can survive up to a temperature of $2.1T_c$ [12]. In table II for a choice of formation time $\tau$, we have tabulated the threshold temperature ($T_{th}$) and the critical temperature ($T_c$). For formation time varying between 0.02 fm to 0.2 fm, the critical temperature varies from 150 MeV to 265 MeV. Critical temperature for the confinement-deconfinement transition has been accurately estimated in recent lattice calculations, $T_c \sim 192\pm7\pm4$ MeV [18]. As seen from table II, it corresponds to formation time $\tau$ ranging between 0.06-0.08 fm. The time is considerably smaller than the thermal equilibration time $\tau_{eq} \approx 0.6 fm$ [16]. QGP is produced early in the collisions.

To summarise, in the QGP motivated threshold model, we have analyzed the PHENIX data on the centrality dependence of $\bar{J}/\psi$ suppression in Au+Au collisions. In the threshold model, in addition to the normal nuclear absorption, $\bar{J}/\psi$’s are anomalously suppressed, such that, if the local transverse density exceeds a threshold density $n_c$, all the $\bar{J}/\psi$’s are absorbed. In a careful analysis, we have extracted the threshold density required to explain the mid rapidity and the forward rapidity PHENIX data. Mid rapidity data are well explained in the model with threshold density $n_c = 3.73 \pm 0.29 fm^{-2}$. The data require very small smearing of the threshold density, $\lambda = 8.96 \pm 9.72 fm$. The forward rapidity data on the other hand require very large smearing, $n_c = 2.963 \pm 0.42 fm^{-2}$ and $\lambda = 0.99 \pm 0.04 fm$. Very large smearing required for the forward rapidity data defeat the essence of the threshold model which tries to mimic the sudden onset of $\bar{J}/\psi$ in a deconfined medium. We conclude that $\bar{J}/\psi$ suppression at forward rapidity, though more complex than envisaged in the Glauber model of nuclear absorption, do not indicate a deconfinement phase transition. $\bar{J}/\psi$ suppression at mid rapidity which require sudden on set of anomalous suppression above the threshold value $n_c = 3.73 \pm 0.29 fm^{-2}$, possibly indicate a deconfined matter formation. Using the PHENIX data on participant number dependence of Bjorken energy density times the formation time, we have estimated the QGP formation time as $\tau \approx 0.06 \sim 0.08 fm$ for critical temperature $T_c \approx 192$ MeV.

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