Leakage Effect on $J/\psi$ $p_t$ Distributions in Different Centrality Bins for Pb - Pb Collisions at E/A = 160 GeV

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A transport approach including a leakage effect for $J/\psi$'s in the transverse phase space is used to calculate the ratios between the $J/\psi$ transverse momentum distributions in several centrality bins for Pb-Pb collisions at E/A = 160 GeV. From the comparison with the CERN-SPS data, where the centrality is characterized by the transverse energy $E_t$, the leakage effect is extremely important in the region of high transverse momentum and high transverse energy, and both the threshold and the comover models can describe the ratio well for all centrality bins except the most central one ($E_t < 100$ GeV), for which the comover model calculation is considerably better than the threshold one.

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Relativistic heavy ion collisions may be the only way to create the extreme condition for producing a new state of matter — Quark-Gluon Plasma (QGP). Among the possible signatures suggested to identify the existence of QGP, the $J/\psi$ suppression proposed by Matsui and Satz [1] is considered as a direct one of deconfinement phase transition. The discovery of anomalous $J/\psi$ suppression [2] in Pb - Pb collisions in 1996 has been one of the highlights of the research with relativistic nuclear collisions at SPS. Since different models [3,4], with and without the assumption of QGP, can describe the observed suppression, it is still not yet clear if the suppression means the discovery of QGP. Recently, the NA50 collaboration has presented the final analysis of the $J/\psi$ transverse momentum distribution [5] in Pb - Pb collisions at E/A = 160 GeV. The mean squared transverse momentum $\langle p_t^2 \rangle$ as a function of the centrality of the collisions first increases and then becomes flat when the centrality increases. The understanding of this saturation of $\langle p_t^2 \rangle$ in central collisions needs the consideration of time structure [6,7] of the anomalous suppression. With the idea of leakage, which has already been considered more than 10 years ago [1,8,9] (c.f. also more recent works [10,11]), the anomalous suppression is not an instantaneous process, but takes a certain time. During this time the $J/\psi$'s with high transverse momenta may leak out of the source of the anomalous suppression. As a consequence, low $p_t$ $J/\psi$'s are absorbed preferentially, and the mean $p_t$ of the survived $J/\psi$'s in central collisions will not drop down but become flat. From the comparison of the theoretical calculations [7] using two different models, the threshold [12,13] and comover [14,15] models, with the data, the average anomalous suppression time $t_A$ is extracted to be $3 - 4$ fm/c for central Pb - Pb collisions. Obviously, the leakage mechanism affects mainly the high $p_t$ $J/\psi$'s, the mean values ($p_t$) < 1.2 GeV/c and $\langle p_t^2 \rangle$ < 2 (GeV/c)^2 for Pb - Pb collisions can not reflect the leakage effect sufficiently. In order to see the leakage effect more clearly, we calculate in this paper the $J/\psi$ $p_t$ distributions in different centrality bins, and compare them with the data of NA50. We will focus our attention on the region 1 < $p_t$ < 3 GeV/c for central collisions where the leakage effect and anomalous suppression are both important, and the error bars of the data are small.

$J/\psi$'s produced in a nucleus-nucleus collision experience first normal suppression via inelastic $J/\psi - N$ collisions and show normal broadening of $\langle p_t^2 \rangle$ above $\langle p_t^2 \rangle_{NN}$ via gluon rescattering [4]. A gluon from a projectile nucleon and a gluon from a target nucleon fuse to form a $J/\psi$ at a point with space coordinates $(\vec{s}, z_A)$ in the rest frame of the target A and $(\vec{b} - \vec{s}, z_B)$ in the rest frame of the projectile B, where $\vec{b}$ is the impact parameter for the BA collision. On its way out, the $J/\psi$ experiences the thickness $T_A(\vec{s}, z_A, \infty)$ and $T_B(\vec{b} - \vec{s}, -\infty, z_B)$ in the nuclei A and B, and is suppressed with an effective absorption cross section $\sigma_{abs}$, where the thickness function $T$ is defined as $T(\vec{s}, z_1, z_2) = \int_{z_1}^{z_2} dz \rho(\vec{s}, z)$ with $\rho_{A,B}$ being the density of nuclei A and B. Before the fusion, the two gluons traverse thicknesses $T_A(\vec{s}, -\infty, z_A)$ and $T_B(\vec{b} - \vec{s}, z_B, \infty)$ of nuclear matter in A and B, and obtain additional transverse momentum via $gN$ collisions. Neglecting effects of formation time [16], one has after the normal suppression the $J/\psi$ distribution function $f_N$ in the transverse phase space at given $\vec{b}$,

$$f_N(\vec{p}_t | \vec{b}, \vec{s}) = \int dz_A dz_B \rho_A(\vec{s}, z_A) \rho_B(\vec{b} - \vec{s}, z_B) \times e^{-\sigma_{abs}(T_A(\vec{s}, z_A, \infty) + T_B(\vec{b} - \vec{s}, -\infty, z_B))} \frac{1}{\langle p_t^2 \rangle_N} e^{-p_t^2/\langle p_t^2 \rangle_N}$$ (1)

with

$$\langle p_t^2 \rangle_N(\vec{b}, \vec{s}, z_A, z_B) = \langle p_t^2 \rangle_{NN} + a_g N \rho_0^{-1} \left( T_A(\vec{s}, -\infty, z_A) + T_B(\vec{b} - \vec{s}, z_B, \infty) \right)$$ (2)

where we have assumed a Gaussian $p_t$ dependence. The constants $\sigma_{abs}$ and $a_g N$ are usually adjusted to the data from pA collisions where $J/\psi$'s experience only normal suppression.

Anomalous suppression is attributed to the action on the $J/\psi$ by the mostly baryon free phase of partons and/or hadrons which is formed after the nuclear overlap. We define $t = 0$ as the time when the normal suppression
and normal generation of \( \langle p_t^2 \rangle \) have ceased, and describe the time evolution of the \( J/\psi \) density \( f(\vec{p}_t, t|\vec{b}, \vec{s}) \) in the transverse phase space by a transport equation \[ (7) \]

\[
\frac{\partial f}{\partial t} + \vec{v}_t \cdot \nabla_s f = -\alpha f
\]

with the initial condition

\[
f(\vec{p}_t, 0|\vec{b}, \vec{s}) = f_N(\vec{p}_t, \vec{b}, \vec{s}) .
\]

The second term on the left handside of the transport equation arises from the free streaming of the \( J/\psi \) with transverse velocity \( \vec{v}_t = \vec{p}_t / \sqrt{p_t^2 + m_{J/\psi}^2} \), and the loss term is due to anomalous suppression. The function \( \alpha(\vec{p}_t, t|\vec{b}, \vec{s}) \) contains all details about the mechanism of anomalous suppression.

The transport equation (3) can be solved analytically with the result \[ (7) \]

\[
f(\vec{p}_t, t|\vec{b}, \vec{s}) = e^{-\int_0^t dt' \alpha(\vec{p}_t, t' \mid \vec{b}, \vec{s} - \vec{v}_t(t-t'))} f_N(\vec{p}_t, \vec{b}, \vec{s} - \vec{v}_t t) .
\]

If the anomalous suppression ceases at time \( t_f \), \( \alpha(\vec{p}_t, t > t_f \mid \vec{b}, \vec{s}) = 0 \), the observed yield \( Y \) as a function of transverse momentum \( p_t \) and transverse energy \( E_t \) can be related to the phase space density \( f \) via

\[
Y(p_t, E_t) = \int d^2 \vec{b} \, d^2 \vec{s} \, \bar{p}_t \, P(E_t|\vec{b}) \, f(\vec{p}_t, t_f|\vec{b}, \vec{s}) \, \delta(p_t - \sqrt{p_t^2 + p_y^2}) .
\]

Here, \( P(E_t|\vec{b}) \) describes the distribution of transverse energy \( E_t \) in events with a given impact parameter \( \vec{b} \). It is chosen as a Gaussian distribution \[ (12) \]

\[
P(E_t|\vec{b}) = \frac{1}{\sqrt{2\pi q^2 a N_p(b)}} e^{-\frac{(E_t - \langle E_t|\vec{b} \rangle)^2}{2q^2 a N_p(b)}}
\]

with the number of participant nucleons defined as

\[
N_p(b) = \int d^2 \vec{s} \, n_p(\vec{b}, \vec{s}) ,
\]

\[
n_p(\vec{b}, \vec{s}) = T_A(\vec{s} - \infty, \infty) \left( 1 - e^{-\sigma_{NN} T_B(\vec{b} - \vec{s} - \infty, \infty)} \right) + T_B(\vec{b} - \vec{s}, -\infty, \infty) \left( 1 - e^{-\sigma_{NN} T_A(\vec{s} - \infty, \infty)} \right) ,
\]

\[
\langle E_t \rangle(b) = q N_p(b) ,
\]

and \( \alpha = 1.27, q = 0.274 \text{ GeV} \) and \( \sigma_{NN} = 32 \text{ mb} \) [12] for Pb-Pb collisions at SPS energy.

In order to see clearly the leakage effect which is important for the \( J/\psi \)'s with high transverse momenta produced in the events with high transverse energy, we consider the ratio between the \( J/\psi \) \( p_t \) distributions in the \( E_t \) bin \( i \) and in the \( E_t \) bin \( j \).

\[
R_{ij}(p_t) = \frac{\int \Delta E_t \, dE_t \, Y(p_t, E_t)/N_{DY}^E}{\int \Delta E_t \, dE_t \, Y(p_t, E_t)/N_{DY}^E} .
\]

To compare the ratio with the experimental data [5], we have normalized the distributions to the number of Drell-Yan pairs in the same \( E_t \) bins,

\[
N_{DY}^{E_t} = \int \Delta E_t \, dE_t \, \int d^2 \vec{b} d^2 \vec{s} dA dz B P(E_t|\vec{b}) \times \rho_A(\vec{s}, z_A) \rho_B(\vec{s} - \vec{s}, z_B) .
\]

Since the physical origin of anomalous suppression is not yet clear, we calculate the ratio \( R \) for two rather different scenarios: Instantaneous absorption involving a threshold in the energy density and continuous absorption by comovers.

We begin with the threshold model and use the approach by Blaizot et. al. [12] for simplicity. The suppression function in this approach can be recovered within the transport formalism (5) by setting

\[
\alpha(\vec{p}_t, t|\vec{b}, \vec{s}) = \alpha_0 \theta(n_p(\vec{b}, \vec{s}) - n_c) \delta(t)
\]

and taking the limit \( \alpha_0 \rightarrow \infty \). \( J/\psi \)'s are totally and instantaneously destroyed if the energy density which is directly proportional to the participant density \( n_p \) is larger than a critical density, and nothing happens elsewhere. While the threshold approach successfully describes the data in the full \( E_t \) range of the \( J/\psi \) suppression after the only one free parameter, \( n_c \), is adjusted, the predictions for \( \langle p_t^2 \rangle(E_t) \) are significantly below the data, especially in the high \( E_t \) region.

It is difficult to understand that the anomalous suppression happens instantaneously at time \( t = 0 \). The sudden suppression (11) was changed to a continuous suppression between times \( t_0 \) and \( t_1 \) [7],

\[
\alpha(\vec{p}_t, t|\vec{b}, \vec{s}) = \frac{\alpha_0}{t_1 - t_0} \theta(n_p(\vec{b}, \vec{s}) - n_c) \theta(t_1 - t) \theta(t - t_0) .
\]

From the comparison [7] of the yield \( Y(E_t) \) and mean transverse momentum \( \langle p_t^2 \rangle(E_t) \) with the data, the average anomalous suppression time \( t_A \) was found to be a function of \( E_t \). It increases from 0 to about 4 fm/c when \( E_t \) increases from 0 to the maximum (\( \sim 140 \text{ GeV} \)) for Pb-Pb collisions.

With the parameters \( \sigma_{abs} = 6.4 \text{ mb} \) and \( n_c = 3.75 \text{ fm}^{-2} \) [12] for the suppression and \( \langle p_t^2 \rangle_{NN} = 1.11 \text{ (GeV/c)^2} \) and \( a_{NN} = 0.081 \text{ (GeV/c)^2 fm}^{-1} \) [5] for the mean transverse momentum, we calculated the ratios \( R_{ij}(p_t) \). We also accounted for the transverse energy fluctuations [12] which have been shown to be significant for the explanation of the sharp drop of \( J/\psi \) suppression in the domain of very large \( E_t \) values, by replacing \( n_p \) by \( \frac{E_t}{\langle E_t \rangle} n_p \) where \( \langle E_t \rangle \) is the mean transverse
energy at given $b$. For the comparison with the data [5] of Pb - Pb collisions, we consider five $E_t$ bins with $\Delta E_t^i = [5, 34], [34, 60], [60, 80], [80, 100], [100, 140]$ GeV corresponding to $i = 1, 2, 3, 4, 5$, respectively. The theoretical results $R_{i/1}(p_t)$ with $i = 2, 3, 4, 5$ together with the data are shown in Fig. 1. The dashed lines indicate the results with normal suppression only. Since the nuclear absorption deviates from the data and becomes saturated above $E_t \sim 40$ GeV [3,4], the calculated ratios $R_{i/1}$ are always above the data for any values of $p_t$ and in any $E_t$ bin. The dotted lines are calculated with the original Blaizot approach (11) without considering leakage effect ($\bar{v}_i = 0$ in (5)), and the solid lines are obtained by taking the average anomalous suppression time $t_A = 0, 1, 2, 3, 4$ fm corresponding to the $E_t$ bins $i = 1, 2, 3, 4, 5$, respectively. It is clear that the leakage effect becomes more and more important when the anomalous suppression time increases and/or the transverse momentum $p_t$ increases. While the instantaneous threshold approach, namely the dotted lines, can describe the data in the region $p_t < 3$ GeV/c when $E_t$ is not high enough, the calculated ratio $R_{3/1}$ deviates from the data clearly. Due to the leakage effect reflected in the transport approach (5), high transverse momentum $J/\psi$'s may escape the anomalous suppression. This is the reason why the solid line is always above the dotted line in any $E_t$ bin. When the degree of centrality is low, the system is difficult to reach the critical density $n_c$, the anomalous suppression is not important, and then the leakage effect is weak. With increasing centrality, more anomalous suppression happens and more $J/\psi$'s leak out of the suppression region. For the $E_t$ bins 1 and 2, almost no leakage happens, the solid and dotted lines coincide for $R_{2/1}$. For $R_{3/1}$ the leakage is still not important. However, when the centrality increases further, the leakage effect leads to a remarkable difference between the solid and dotted lines. For $R_{4/1}$ and $R_{5/1}$ the leakage improves considerably the threshold approach. Due to the big error bars of the data above $p_t$ around 3 GeV/c, it is difficult to judge the leakage effect in the very high $p_t$ region from the comparison with the data.

We now turn to the comover model. The comoving partons and/or hadrons lead to a continuous $J/\psi$ absorption of long duration due to inelastic collisions with the comoving particles. As a representative model, we use the approaches by Capella et al. [14,15] and Kharzeev et. al. [17]. The absorption term $\alpha$ in the transport equation (3) takes the form [7]

$$\alpha(p_t, t|b, \slashed{s}) = \sigma_{co} \frac{n_c(b, \slashed{s})}{t} \left( \frac{n_c(b, \slashed{s})}{n_f} t_0 - t \right) \theta(t - t_0),$$

where $\sigma_{co}$ is the cross section of $J/\psi$-comover interaction, $n_c$ the comover density at initial time $t_0$. The absorption

![FIG. 1. The ratio between the $J/\psi$ $p_t$ distributions in the $E_t$ bin $i$ ($i = 2, 3, 4, 5$) and in the first $E_t$ bin ($i = 1$). The distributions are normalized to the Drell-Yan results in the same $E_t$ bins. The five $E_t$ bins correspond to the $E_t$ range $\Delta E_t = [5, 34], [34, 60], [60, 80], [80, 100], [100, 140]$ GeV. The data are from NA50. Dashed, dotted and solid lines are calculated within the threshold model. The dashed lines show the result of normal suppression alone, the dotted lines include the anomalous suppression but without leakage effect, and the solid lines include also the leakage effect with the average anomalous suppression time $t_A = 0, 1, 2, 3, 4$ fm/c corresponding to the $E_t$ bin $i = 1, 2, 3, 4, 5$, respectively.](image-url)
the same means that the calculated ratios are shown in Fig. 2. Again the result with only normal suppression deviates from the data. From the comparison with the threshold scenario, the result of the comover scenario looks more close to the experimental data.

FIG. 2. The ratio between the $J/\psi$ $p_t$ distributions in the $E_t$ bin $i$ ($i = 2, 3, 4, 5$) and in the first $E_t$ bin ($i = 1$). The distributions are normalized to the Drell-Yan number in the same $E_t$ bin. The five $E_t$ bins correspond to the $E_t$ range $\Delta E_t = [5, 34], [34, 60], [60, 80], [80, 100], [100, 140]$. The data are from NA50. Dashed lines (with only normal suppression), dotted lines (with anomalous suppression but without leakage effect) and solid lines (with anomalous suppression and leakage effect) are calculated within the comover model.

With the general transport equation proposed in ref. [7] which describes the time evolution of the $J/\psi$’s during anomalous suppression including leakage effect, we calculated within the threshold and comover models the ratio $R_{i/1}(p_t)$ between the $J/\psi$ $p_t$ distribution in the higher $E_t$ bin $i$ and the same distribution in the lowest $E_t$ bin. Our motivation is to study the leakage effect in high $p_t$ and high $E_t$ region where the anomalous suppression is most important. We found that in this region the leakage effect leads to a better agreement with the data for the two models. The results support the idea [7] that the anomalous suppression happens on average at $3 – 4$ fm/c after the normal suppression ends. From the comparison of the two very different models, our calculation with the mechanism of continuous comover action over a comparably long time can better describe the ratios for all $E_t$ bins.

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[1] T. Matsui, H. Satz, Phys. Lett. B 178 (1986) 416.
[2] M.C. Abreu et al., NA50 Collaboration, Nucl. Phys. A 610 (1996) 404c.
[3] R. Vogt, Phys. Rep. 310 (1999) 197.
[4] C. Gerschel, J. Hufner, Ann. Rev. Nucl. Part. Sci. 49 (1999) 255.
[5] M.C. Abreu et al., NA50 Collaboration, Phys. Lett. B 499 (2001) 85.
[6] J. Hufner, P. Zhuang, Phys. Lett. B 515 (2001) 115.
[7] J. Hufner, P. Zhuang, nucl-th/0208004, accepted by Phys. Lett. B.
[8] F. Karsch, R. Petronzio, Z. Phys. C 37 (1988) 627.
[9] J.P. Blaizot, J.Y. Ollitrault, Phys. Lett. B 199 (1987) 627.
[10] D. Kharzeev, M. Nardi, H. Satz, Phys. Lett. B 405 (1997) 14.
[11] E. Shuryak, D. Jeaney, Phys. Lett. B 430 (1998) 37.
[12] J.P. Blaizot, P.M. Dinh, J.Y. Ollitrault, Phys. Rev. Lett. 85 (2000) 4010.
[13] J.P. Blaizot, J.Y. Ollitrault, Phys. Rev. Lett. 77 (1996) 1703.
[14] A. Capella, E.G. Ferreiro and A.B. Kaidalov, Phys. Rev. Lett. 85 (2000) 2080.
[15] A. Capella, A.B. Kaidalov and D. Sousa, Phys. Rev. C65 (2002)054908.
[16] J. Hufner, B.Z. Kopeliovich, Phys. Rev. Lett. 76 (1996) 192.
[17] D. Kharzeev, C. Lourenço, M. Nardi, H. Satz, Z. Phys. C74 (1997) 307.