J/ψ production in PbPb collisions at $\sqrt{s}_{NN} = 2.76$ TeV

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Abstract

In this work we calculate the J/ψ suppression and regeneration in quark gluon plasma. The J/ψ suppression is estimated using gluon dissociation in medium. The rate of regeneration has been calculated using detailed balance.

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I. INTRODUCTION

The heavy ion collisions produce matter at extreme temperatures and densities where it is expected to be in the form of Quark Gluon Plasma (QGP), a phase in which the quarks and gluons can move far beyond the size of a nucleon making color degrees of freedom dominant in the medium. The experimental effort to produce such matter started with low energy CERN accelerator SPS and evolved through voluminous results from heavy ion collision at Relativistic Heavy Ion Collider (RHIC) [1]. The recent results from Large Hadron Collider (LHC) experiments [2] are pointing towards formation of high temperature system in many ways similar to the matter produced at RHIC. One of the most important signal of QGP is the suppression of quarkonium states [3], both of the charmonium (J/ψ, $\psi(2S)$, χ_c, etc) and the bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, χ_b, etc) families. This is thought to be a direct effect of deconfinement, when the binding potential between the constituents of a quarkonium state, a heavy quark and its antiquark, is screened by the colour charges of the surrounding light quarks and gluons. The ATLAS and CMS experiments have carried out detailed quarkonia measurements in Pb+Pb collisions with the higher energy and luminosity available at the LHC. The ATLAS measurements [4] show suppression of inclusive J/ψ with high transverse momenta p_T in central PbPb collisions compared to peripheral collisions at $\sqrt{s}_{NN} = 2.76$ TeV. Similarly, CMS measured a steady and smooth decrease of suppression of prompt J/ψ as a function of centrality with nuclear modification factor R_{AA} remaining < 1 even in the peripheral bin [5].

The melting temperature of the quarkonia states depend on their binding energy. The ground states, J/ψ and $\Upsilon(1S)$ are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. The $\Upsilon(2S)$ and $\Upsilon(3S)$ have smaller binding energies as compared to ground state $\Upsilon(1S)$ and hence are expected to dissolve at a lower temperature. With the 2011 Pb+Pb run the CMS published results on sequential suppression of $\Upsilon(nS)$ states as a function of centrality [6] with enlarged statistics over their first measurement [7], where a suppression of the excited Υ states with respect to the ground state have been observed in PbPb collisions compared to pp collisions at $\sqrt{s}_{NN} = 2.76$ TeV.[8]

The quarkonia yields in heavy ion collisions are also modified due to non-QGP effects such as shadowing, an effect due to change of the parton distribution functions inside the nucleus, and dissociation due to nuclear or comover interaction [9]. If large number of heavy quarks are produced in initial heavy ion collisions at LHC energy this could even lead to enhancement of quarkonia via statistical recombination [10, 11].

In this paper, we calculate the charmonia suppression due to thermal gluon activation in an expanding QGP. Another sources which can alter the yield of charmonium are considered e.g. nuclear shadowing and gluon saturation. Impact parameter dependence of parton distribution functions is also taken in account and at last we consider the effect of J/ψ regeneration using the statistical hadronization model. J/ψ yield is studied as a function of impact parameter or centerality of events. Calculations are compared with experimental data, where data is available.

II. CHARM PRODUCTION RATES

The large heavy quark mass allows their production to be calculated in perturbative QCD. We calculate the production cross sections for $c\bar{c}$ and $b\bar{b}$ pairs to NLO in pQCD using the CTEQ6M parton densities [12]. The central EPS09 parameter set [13] is used to calculate the modifications of the parton densities in Pb+Pb collisions.

We use the same set of parameters as that of Ref. [14] with the exclusive NLO calculation of Ref. [15] to obtain the exclusive $Q\overline{Q}$ pair rates as well as their decays to dileptons. We take $m_c = 1.5$ GeV/c^2, $\mu_F/m_T = \mu_R/m_T = 1$ and $m_b = 4.75$ GeV/c^2, $\mu_F/m_T = \mu_R/m_T = 1$ as the central values for charm and bottom production respectively. Here μ_F is the factorization scale, μ_R is the renormalization scale and $m_T = \sqrt{m^2 + p_T^2}$. The mass and scale variations are added in quadrature to obtain the uncertainty bands [14, 16].

The production cross sections for heavy flavor at $\sqrt{s_{_{NN}}} = 2.76$ TeV are shown in Table I. The number of $Q\overline{Q}$ pairs in a minimum bias Pb+Pb event is obtained from the per nucleon cross section, $\sigma_{\rm PbPb}$, by

$$N_{Q\overline{Q}} = \frac{A^2 \sigma^{Q\overline{Q}}_{\rm PbPb}}{\sigma^{\rm tot}_{\rm PbPb}} \ . \tag{1}$$

At 2.76 TeV, the total Pb+Pb cross section, $\sigma^{\rm tot}_{\rm PbPb}$, is 7.65 b [17].

TABLE I. Heavy flavor cross sections at $\sqrt{s_{NN}} = 2.76$ TeV. The cross sections are given per nucleon while $N_{Q\overline{Q}}$ and $N_{l^+l^-}$ are the number of $Q\overline{Q}$ and lepton pairs per Pb+Pb event.

	$c\overline{c}$	J/ψ
$\sigma_{\rm PbPb}$	$1.76^{+2.32}_{-1.29}$ mb	31.4 μb
$N_{Q\overline{Q}}$	$9.95^{+13.10}_{-7.30}$	0.177

III. MODIFICATION OF J/ψ IN PRESENCE OF QGP

In Kinetic approach [18] the proper time evolution of the J/ψ population is given by the rate equation

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F \frac{N_c N_{\bar{c}}}{V(\tau)} - \lambda_D N_{J/\psi} \rho_g. \tag{2}$$

with ρ_g the number density of gluons, τ the proper time and $V(\tau)$ the volume of the deconfined spatial region. The reactivities $\lambda_{F,D}$ are the reaction rates $\langle \sigma v_{\rm rel} \rangle$ averaged over the momentum distribution of the initial participants, i.e. c and $\bar{c}$ for λ_F and J/ψ and g for λ_D. The gluon density is determined by the equilibrium value in the QGP at each temperature. The solution of Eq. (2) is given by

$$N_{J/\psi}(\tau_f) = \epsilon(\tau_f)\, N_{J/\psi}(\tau_0) + \epsilon(\tau_f)\, N_{c\bar{c}}^2 \int_{\tau_0}^{\tau_f} \frac{\lambda_{\rm F}}{V(\tau)\, \epsilon(\tau)} d\tau \tag{3}$$

where τ_f is the hadronization time determined by the initial temperature (T_0) and final temperature (T_f). The function

$$\epsilon(\tau_f) = e^{-\int_{\tau_0}^{\tau_f} \lambda_{\rm D}\, \rho_g\, d\tau} \tag{4}$$

For a longitudinal isentropic [19] expansion the volume is given by

$$V(\tau) = V_o \frac{\tau}{\tau_o} = \pi\, R^2 \tau_0 \frac{\tau}{\tau_o} = \pi\, R^2 \tau, \tag{5}$$

which gives

$$N_{J/\psi}(\tau_f) = \epsilon(\tau_f) N_{J/\psi}(\tau_0) + \epsilon(\tau_f)\, \frac{N_{c\bar{c}}^2}{\pi R^2} \int_{\tau_0}^{\tau_f} \frac{\lambda_{\rm F}}{\tau\, \epsilon(\tau)} d\tau \tag{6}$$

The R_{AA} can be written as

$$R_{AA} = \epsilon(\tau_f) + \epsilon(\tau_f)\, \frac{N_{c\bar{c}}^2}{\pi R^2\, N_{J/\psi}(\tau_0)} \int_{\tau_0}^{\tau_f} \frac{\lambda_{\rm F}}{\tau\, \epsilon(\tau)} d\tau. \tag{7}$$

wher R is the spatial extension of quark gluon plasma given by

$$R(N_{\rm part}) = R_0 \sqrt{\frac{N_{\rm part}}{N_{\rm part0}}}. \tag{8}$$

The initial temperature as a function of centrality is calculated by

$$T(N_{\rm part})^3 = T_0^3 \left(\frac{dN/d\eta}{N_{\rm part}/2}\right) / \left(\frac{dN/d\eta}{N_{\rm part}/2}\right)_{0-5\%}, \tag{9}$$

where T_0 is the initial temperature assumed in 0-5% centrality and $(dN/d\eta)$ is the multiplicity as a function of number of participants measured by ALICE experiment [20]. Both ALICE and CMS [21] measurements on multiplicity agree well with each other. The initial temperature T_0 for 0-5% central collisions for a given initial time τ_0 is obtained by

$$T_0^3 \tau_0 = \frac{3.6}{4 a_q \pi R_{0-5\%}^2} \left(\frac{dN}{d\eta}\right)_{0-5\%}, \tag{10}$$

Here $(dN/d\eta)_{0-5\%} = 1.5{\times}1600$ obtained from the charge particle multiplicity measured in Pb+Pb collisions at 2.76 TeV [20] and $a_q = 37\pi^2/90$ is the degrees of freedom we take in in quark gluon phase. Using Eq. (8) we can obtain the transverse size of the system for 0-5% centrality as $R_{0-5\%} = 0.92 R_0$. For $\tau_0 = 0.1$ fm/c, we obtain T_0 as 0.62 GeV using Eq. (10). The critical temperature is taken as $T_C = 0.160$ GeV [2]. $\mathrm{N}_{J/\psi}(\tau_0)$ and $\mathrm{N}_{c\bar{c}}$ in Eq. (6) will also be a function of centrality. They will scale as number of collision in particular centrality class. Number of collisions and number of participants can be calculated from Glauber model calculations.

IV. DISSOCIATION RATE

The gluon-J/ψ dissociation cross section is given by [22]

$$\sigma(q^0) = \frac{2\pi}{3} \left(\frac{32}{3}\right)^2 \left(\frac{16\pi}{3 g_s^2}\right) \frac{1}{m_Q^2} \frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5}, \tag{11}$$

where g_s is the coupling constant of gluon and c quark, m_Q the c quark mass, and q^0 the gluon energy in the J/ψ rest frame; its value must be larger than the J/ψ binding energy ϵ_0. Since for the tightly bound ground state of quarkonium the binding force between the heavy quark and antiquark is well approximated by the one-gluon-exchange Coulomb potential, the $Q\bar{Q}$ bound state is hydrogen-like and the Coulomb relation holds,

$$\epsilon_0 = \left(\frac{3 g_s^2}{16\pi}\right)^2 m_Q . \tag{12}$$

The cross section thus can be rewritten as

$$\sigma(q^0) = \frac{2\pi}{3}\left(\frac{32}{3}\right)^2 \frac{1}{m_Q(\epsilon_0 m_Q)^{1/2}} \frac{(q^0/\epsilon_0 - 1)^{3/2}}{(q^0/\epsilon_0)^5} \, . \tag{13}$$

As shown in Monte Carlo simulations [23], the parton density in the early stage of high-energy heavy-ion collisions has an approximate Bjorken-type [19] scaling behavior. We will only consider J/ψ suppression in the central rapidity region ($y_{J/\psi} \simeq 0$). In this case, the J/ψ will move in the transverse direction with a four-velocity

$$u = (M_T, \vec{P}_T, 0)/M_{J/\psi}, \tag{14}$$

where $M_T = \sqrt{P_T^2 + M_{J/\psi}^2}$ is defined as the J/ψ's transverse mass. A gluon with a four-momentum $k = (k^0, \vec{k})$ in the rest frame of the parton gas has an energy $q^0 = k \cdot u$ in the rest frame of the J/ψ given by

$$\begin{aligned} q^0 &= \frac{k^0\, m_T + \vec{k} \cdot \vec{p_T}}{M_{J/\psi}} \\ &= \frac{s - M_{J/\psi}^2}{2\, M_J/\psi} \end{aligned} \tag{15}$$

The thermal gluon-J/ψ dissociation cross section is then defined as

$$\langle v_{\rm rel}\sigma(k \cdot u)\rangle_k = \frac{\int d^3k v_{\rm rel}\sigma(k \cdot u) f(k^0; T)}{\int d^3k f(k^0; T)}, \tag{16}$$

where the gluon distribution in the rest frame of the parton gas is

$$f(k^0; T) = \frac{\lambda_g}{e^{k^0/T} - 1} \tag{17}$$

The relative velocity $v_{\rm rel}$ between the J/ψ and a gluon is

$$\langle v_{\rm rel}\sigma(k \cdot u)\rangle_k = \frac{P_{J/\psi} \cdot k}{k^0 M_T} \tag{18}$$

$$= 1 - \frac{\vec{k} \cdot \vec{P}_T}{k^0 M_T} \tag{19}$$

$$= \frac{s - M_{J/\psi}}{2E_1 E_2} \tag{20}$$

$$\tag{21}$$

Changing the variable to the gluon momentum, $q = (q^0, \vec{q})$, in the rest frame of the J/ψ, the integral in the numerator of Eq. (16) can be rewritten as

$$\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k = \int d^3q \frac{M_{J/\psi}}{M_T}\sigma(q^0) f(k^0;T), \tag{22}$$

where

$$k^0 = (q^0 M_T + \vec{q}\cdot\vec{P}_T)/M_{J/\psi}\ . \tag{23}$$

putting the value of k^0 and solving

$$\begin{aligned}
\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k \ &=\ \frac{M_{J/\psi}}{M_T}\int d^3q\sigma(q^0)\frac{\lambda_g}{e^{\frac{q^0 m_T}{M_{J/\psi}T}}e^{\frac{\vec{q}\cdot\vec{p_T}}{M_{J/\psi}T}}-1} \\
&=\ \lambda_g\frac{M_{J/\psi}}{M_T}\int d^3q\sigma(q^0)\sum_{n=1}^{\infty} e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\, e^{\frac{-n\,\vec{q}\cdot\vec{p_T}}{M_{J/\psi}T}} \\
&=\ \lambda_g\frac{M_{J/\psi}}{M_T}\sum_{n=1}^{\infty}2\pi\int q^2dq\,\sigma(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\ \int_1^{-1} e^{\frac{-n\,q\,p_T cos\theta}{M_{J/\psi}T}}\ d(cos\theta) \\
&=\ \lambda_g\frac{M_{J/\psi}}{M_T}\sum_{n=1}^{\infty}2\pi\int q^2dq\,\sigma(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\,[e^{-\frac{nqp_T}{M_{J/\psi}T}}-e^{\frac{nqP_T}{M_{J/\psi}T}}]\,\frac{M_{J/\psi}T}{nqp_T} \\
&=\ \lambda_g\frac{M^2_{J/\psi}}{M_T}2\pi\sum_{n=1}^{\infty}\frac{T}{n}\int_{\epsilon_0}^{\infty} qdq\,\sigma(q^0)\,e^{\frac{-n\,q^0 m_T}{M_{J/\psi}T}}\,\frac{1}{p_T}\left[e^{\frac{nqp_T}{M_{J/\psi}T}}-e^{-\frac{nqP_T}{M_{J/\psi}T}}\right] \quad (24)
\end{aligned}$$
$$\tag{25}$$

$\sigma(q^0)$ can be written as

$$\sigma(q^0) = 4\pi\ \left(\frac{8}{3}\right)^3\ \frac{1}{m_Q^{3/2}}\,\epsilon_0^3\frac{(q^0-\epsilon_0)^{3/2}}{(q^0)^5} \tag{26}$$

One can carry out the integral in the denominator, $\int d^3kf(k^0;T) = 8\pi\zeta(3)\lambda_g T^3$, where $\zeta(3) = 1.202$.

The special case of Eq. (dissrate) for J/ψ $p_T = 0$ is

$$\frac{1}{p_T}\left[e^{\frac{nqp_T}{M_{J/\psi}T}}-e^{-\frac{nqP_T}{M_{J/\psi}T}}\right] = \frac{2nq}{M_{J/\psi}T}. \tag{27}$$

Using this we get

$$\langle v_{\rm rel}\sigma(k\cdot u)\rangle_k\ =\ \int 4\pi\,q^2\,dq\,\sigma(q^0)\frac{\lambda_g}{e^{\frac{q^0}{T}}-1}. \tag{28}$$

Raa_21June2_NColl_Tf_Pt65-eps-converted-to.pdf

FIG. 1. (Color online)R_{AA} from transport equation compared with CMS data.

V. FORMATION RATE

We can calculate formation rate from dissociation rate using detailed balance relation [24] the formation cross section is related to dissociatiob cross section by

$$\sigma_F = \frac{48}{30}\,\sigma_D(q^0)\,\frac{(s - M_{J/\psi})^2}{s(s-4m_c^2)}. \tag{29}$$

The formation rate can be written as

$$\lambda_F =< \sigma_F \; v_{\rm rel} > \tag{30}$$

$v_{\rm rel}$ is relative velocity between c $\bar{c}$ quark pair and is given by

$$\begin{aligned} v_{\rm rel} &= \frac{\sqrt{(p_1.p_2)^2 - m_Q^4}}{E_1\,E_2} \\ &= \frac{\sqrt{s(s-4m_Q^2)}}{2E_1E_2}. \end{aligned} \tag{31}$$

Here

$$\begin{aligned} s &= (E_1+E_2)^2 - (\vec{p_1}+\vec{p_2})^2 \\ &= m_Q^2 + m_Q^2 + 2E_1E_2 - 2|\vec{p_1}||\vec{p_2}|cos\theta \end{aligned} \tag{32}$$

where $\vec{p_1}$ and $\vec{p_2}$ are three momentum of quarks.

$$\vec{p} = (psin\theta cos\phi,\, psin\theta sin\phi,\, pcos\theta) \tag{33}$$

The dot product is given by

$$\vec{p_1}.\vec{p_2} \;=\; |\vec{p_1}||\vec{p_2}|sin\theta_1 sin\theta_2 cos(\phi_1 - \phi_2) + cos\theta_1 cos\theta_2. \tag{34}$$

Total expression for formation rate can be written as

$$\lambda_F \;=\; \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, d^3p_1\, d^3p_2}{\int\; f_c(p_1)\, d^3p_1 \;\; \int f_{\bar{c}}(p_2)\, d^3p_2} \tag{35}$$

$$\;=\; \frac{\int \sigma_F(s)\, v_{\rm rel}\, f_c(p_1)\, f_{\bar{c}}(p_2)\, 4\pi p_1^2 dp_1\, 2\pi p_2^2 dp_2 d(cos\theta)}{4\pi \int p_1^2 dp_1\, f_c(p_1)\;\, 4\pi \int p_2^2 dp_2\, f_{\bar{c}}(p_2)}. \tag{36}$$

Here σ_F is cross section of c$\bar{c}$ pair going to J/ψ particle. which is defined as

$$\sigma_F = \frac{\Theta(q^2)\,\Theta(4m_D^2 - 4m_c^2 - q^2)\,\sigma(J/\psi)}{N_{c\bar{c}}} \tag{37}$$

here Θ(x) is heaviside step function. We take σ_{pp} = 7 fm^2 and m$_D$ = 1.868 GeV. and $f_c(p)$ and $f_{\bar{c}}(p)$ are parton distribution function of c and $\bar{c}$ respectively.

$$f_c(p) = \frac{g_c(=6)}{1 + \exp[\frac{(p^2+m^2)^{1/2}}{T}]}. \tag{38}$$

VI. STATISTICAL HADRONIZATION MODEL

The heavy quark production at LHC is substantial which may lead to incoherent recombination of uncorrelated pairs of heavy quarks and anti quarks which result from multiple pair production. In statistical approach [25] the number of J/ψ produced is given by

$$N_{J/\psi} = 4\frac{n_{ch} n_{J/\psi}}{n_{\rm open}^2}\frac{N_{c\bar{c}}^2}{N_{ch}}. \tag{39}$$

where n_i's are the thermal densities and $N_{c\bar{c}}$ is the number of charm pairs produced and N_{ch} is the number of total charged particle produced.

The freeze out parameters are $T = 170$ MeV and $\mu_B = 0$. For $dN_{ch}/dy = 1600$ [20] and $dN_{c\bar{c}}/dy = 17.8$, we obtain $dN_{J/\psi}/dy$ =?. The densities can be calculated using thermal distributions of various particles.

$$n_{open} = \frac{4\pi \, g_D}{(2\pi)^3} \int_0^\infty f_D(p) p^2 dp \tag{40}$$

by the same method we can calculate the J/ψ number density as

$$n_{J/\psi} = \frac{4\pi \, g_{J/\psi}}{(2\pi)^3} \int_0^\infty f_{J/\psi}(p) p^2 dp \tag{41}$$

For total charge particle density we can use

$$n_{ch} = 2\, n_\pi + 2\, n_K + 2\, n_p, \tag{42}$$

where

$$n_\pi = \frac{4\pi \, g_\pi}{(2\pi)^3} \int_0^\infty f_\pi(p) p^2 dp. \tag{43}$$

VII. COLD MATTER EFFECTS

The J/ψ can be suppressed due to cold matter effects such as shadowing and due to nuclear matter and comover interaction.

VIII. SUMMARY

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