Suppression of bottomonia states in finite size quark gluon plasma in PbPb collisions at Large Hadron Collider

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The bottomonium states due to their varying binding energies dissolve at different temperatures and thus their nuclear modification factors and relative yields have potential to map the properties of Quark Gluon Plasma (QGP). We estimate the suppression of bottomonia states due to color screening in an expanding QGP of finite lifetime and size with the conditions relevant for PbPb collisions at LHC. The properties of Υ states and recent results on their dissociation temperatures have been used as ingredients in the study. The nuclear modification factors and the ratios of yields of Υ states are then obtained as a function of transverse momentum and centrality. We compare our theoretical calculations with the bottomonia yields measured with CMS in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). The model calculations explain the data very well.

Keywords: quark gluon plasma, Relativistic heavy-ion collisions

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1. 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). The recent results from Large Hadron Collider (LHC) experiments 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 both of the charmonium (\( J/\psi, \psi(2S), \chi_c, \) etc) and the bottomonium (\( \Upsilon(1S), \Upsilon(2S), \chi_b, \) 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 PbPb collisions with the higher energy and luminosity available at the LHC. The ATLAS measurements...
show suppression of inclusive $J/\psi$ 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 $J/\psi$ as a function of centrality with nuclear modification factor $R_{AA}$ remaining $<1$ even in the peripheral bin.

The melting temperature of the quarkonia states depends on their binding energy. The ground states, $J/\psi$ and $\Upsilon(1S)$ are expected to dissolve at significantly higher temperatures than the more loosely bound excited states. The difference in binding energies among different quarkonia indicate that they melt in a hot QGP at different temperatures and the quarkonium spectrum can serve as plasma thermometer. 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 PbPb run the CMS published results on sequential suppression of $\Upsilon(nS)$ states as a function of centrality with enlarged statistics over their first measurement where a suppression of the excited $\Upsilon$ states with respect to the ground state have been observed in PbPb collisions compared to pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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 interactions. Due to higher mass, the nuclear suppression is expected to be less for bottomonia over charmonia. 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. The effect of regeneration is expected to be less significant for bottomonia as compared to charmonia since bottom quarks are much smaller in number as compared to charm quarks. In addition, due to higher bottom mass the bound state properties obtained from potential models are more reliable. Thus recent years witness a shift in the interest to bottomonia. The ratios of the yields of excited states to the ground states is considered even more robust QGP probe as the cold nuclear matter effects if any cancel out and can be neglected in the ratios. The calculation of ratios of $\Upsilon$ states was also made in few works e.g. in past which showed that the $p_T$ dependence of such ratio would show large variations and this would be a direct probe of the QGP.

In this paper, we calculate the bottomonia suppression due to color screening in an expanding QGP using the model by Chu and Matsui which takes into account the finite QGP lifetime and spatial extent. We start by describing the properties of quarkonia obtained from potential models and then give a brief description of the model which is extended to get the survival probabilities of $\Upsilon$ states as a function of centrality of the collisions. Finally we compare the model calculations with the experimental data recently measured by the CMS experiment.
2. Properties of the Υ states from potential models

Interaction between the heavy quark and its antiquark inside the quarkonium at zero temperature can be described by Cornell potential.\textsuperscript{19–21} The solution of the Schrödinger equation for such potential gives mass, bound state radius and the formation time $\tau_F$, the time needed to form a bound state after the production of heavy quark pairs. All parameters obtained with zero temperature potential using the parameter values given in\textsuperscript{21, 22} are summarized in first three rows of Table I, which describe well the experimentally observed quarkonia spectroscopy.

The potential model can be extended to finite temperature with the main assumption that medium effects can be accounted for as a temperature-dependent potential. Instead of just looking at the individual bound states (at $T = 0$ where quarkonium is well defined), one could rather obtain a unified treatment of bound states, threshold and continuum by determining the spectral function. Using a class of screened potentials based on lattice calculations of the static quark-antiquark free energy, spectral functions at finite temperature are calculated in a work\textsuperscript{23, 24} and it was found that all quarkonium states, except the 1S bottomonium, dissolve in the deconfined phase at temperatures smaller than 1.5$T_C$. An upper limit on binding energy and the thermal width of different quarkonia states are then estimated using spectral functions in the quark-gluon plasma. Corresponding upper bounds on their dissociation temperatures $T_D$\textsuperscript{24} are given in second last row of Table I. We used slightly lower values of $T_D$ given in the last row to obtain a good match with measured $R_{AA}$.

| Bottomonium properties | Υ(1S) | χ_b(1P) | Υ(2S) | Υ(3S) | χ_b(2P) |
|------------------------|-------|---------|-------|-------|---------|
| Mass [GeV/c²]          | 9.46  | 9.99    | 10.02 | 10.36 | 10.26   |
| Radius [fm]            | 0.28  | 0.44    | 0.56  | 0.78  | 0.68    |
| $\tau_F$ [fm]        | 0.76  | 2.60    | 1.9   | 2.4   |
| $T_D$ [GeV] upper limit\textsuperscript{23} | 2 $T_C$ | 1.3 $T_C$ | 1.2 $T_C$ | 1 $T_C$ |
| $T_D$ [GeV] used in the present work | 1.8 $T_C$ | 1.15 $T_C$ | 1.1 $T_C$ | 1.0 $T_C$ |

3. Quarkonia suppression in finite size QGP

The bottomonia survival probabilities due to color screening in an expanding QGP are estimated using a dynamical model which takes into account the finite lifetime and spatial extent of the system.\textsuperscript{15} The competition between the resonance formation time $\tau_F$ and the plasma characteristics such as temperature, lifetime and spatial extent decide the $p_T$ dependence of the survival probabilities of Υ states. We describe the essential steps used to develop the model which is then extended to
get the survival probabilities as a function of centrality of the collision.

The model assumes that quark gluon plasma is formed at some initial entropy density $s_0$ corresponding to initial temperature $T_0$ at time $\tau_0$ which undergoes an isentropic expansion by Bjorken’s hydrodynamics. The plasma cools to an entropy density $s_D$ corresponding to the dissociation temperature $T_D$ in time $\tau_D$ which is given by

$$\tau_D = \tau_0 \left( \frac{s_0}{s_D} \right) = \tau_0 \left( \frac{T_0}{T_D} \right)^3,$$

As long as $\tau_D/\tau_F > 1$, quarkonium formation will be suppressed.

In the finite system produced in heavy ion collision, the suppression and entropy depend on the size of the system. The initial entropy density is assumed to be dependent on radius $R$ (decided by the centrality of the collision) of the QGP as

$$s_0(r) = s_0 \left( 1 - \left( \frac{r}{R} \right)^2 \right)^{1/4},$$

Using Eq. (1) and Eq. (2) one can obtain the $r$ dependence of $\tau_D$ as

$$\tau_D(r) = \tau_D(0) \left( 1 - \left( \frac{r}{R} \right)^2 \right)^{1/4},$$

where $\tau_D(0)$ is the value of $\tau_D$ for resonances produced in the center of the system.

Let a $Q\bar{Q}$ pair is created at the position $r$ in the transverse plane with a transverse momentum $p_T$ and transverse energy $E_T = \sqrt{M^2 + p_T^2}$. The $\Upsilon$ formation time is $\tau_F\gamma$ which on equating with the screening duration $\tau_D(r)$ given in Eq (3) one obtains the critical radius $r_D$, which is the boundary of the suppression region as

$$r_D = R \left( 1 - \left( \frac{\gamma \tau_F}{\tau_D(0)} \right)^4 \right)^{1/2},$$

where $\gamma = E_T/M$ is the Lorentz factor associated with the transverse motion of the pair. A bottom-quark pair can escape the screening region $r_D$ and form $\Upsilon$ if the position at which it is created satisfies

$$|r + \frac{\tau_F p_T}{M}| > r_D,$$

where the screening region $r < r_D$ is shrinking because of the cooling of the system. Defining $\phi$ to be the angle between $p_T$ and $r$, the Eq. (5) leads to a range of $\phi$ for which the bottom-quark pair can escape:

$$\cos \phi \geq z \quad \text{where} \quad z = \frac{r_D^2 - r^2 - (\tau_F p_T/M)^2}{2r (\tau_F p_T/M)},$$
With this we can then calculate probability for the pair created at \( r \) with transverse momentum \( p_T \) to survive as

\[
\phi(r, p_T) = \begin{cases} 
1 & z \leq -1 \\
\left( \frac{\cos^{-1}z}{\pi} \right) & |z| < 1 \\
0 & z \geq 1,
\end{cases}
\]

If the probability \( \rho(r) \) of a quark pair to be created at \( r \) which is symmetric in transverse plane is parameterized as

\[
\rho(r) = \left(1 - \left( \frac{r}{R} \right)^2 \right)^{1/2},
\]

the survival probability of quarkonia becomes

\[
S(p_T, R) = \frac{\int_0^R \! r \, \rho(r) \, \phi(r, p_T) \, dr}{\int_0^R \! r \, \rho(r) \, dr}.
\]

The survival probability as a function of centrality can be obtained by integrating over \( p_T \) as follows

\[
S(N_{\text{part}}) = \int S(p_T, R(N_{\text{part}})) \, Y(p_T) \, dp_T.
\]

Here \( Y(p_T) \) is \( p_T \) distribution (normalized to one) obtained from Pythia. The size \( R = R(N_{\text{part}}) \) as a function of centrality is obtained in terms of the radius of the Pb nucleus given by \( R_0 = r_0 \, A^{1/3} \, (r_0 = 1.2 \, \text{fm}) \) and the total number of participants \( N_{\text{part}0} = 2A \) in head-on collisions as

\[
R(N_{\text{part}}) = R_0 \, \sqrt{\frac{N_{\text{part}}}{N_{\text{part}0}}}.
\]

We assumed initial temperature \( T_0 \) is the temperature in 0-5% central collisions and calculated it for a given initial time \( \tau_0 \) by

\[
T_0^3 \, \tau_0 = \frac{3.6}{4a_q \pi R_0^2} \left( \frac{dN}{d\eta} \right)_{0-5\%},
\]

Here \( (dN/d\eta)_{0-5\%} = 1.5 \times 1600 \) obtained from the charge particle multiplicity measured in PbPb collisions at 2.76 TeV \(^{26}\) and \( a_q = 37\pi^2/90 \) is the degrees of freedom we take in quark gluon phase. Using Eq. (10) we can obtain the transverse size of the system for 0-5% centrality as \( R_{0-5\%} = 0.92 R_0 \). For \( \tau_0 = 0.1 \, \text{fm/c} \), we obtain \( T_0 \) as 0.65 GeV using Eq. (10). The critical temperature is taken as \( T_C = 0.170 \, \text{GeV} \). The initial temperature as a function of centrality is calculated by

\[
T(N_{\text{part}})^3 = T_0^3 \left( \frac{dN/d\eta}{N_{\text{part}}/2} \right)_{0-5\%} / \left( \frac{dN/d\eta}{N_{\text{part}}/2} \right)_{0-5\%},
\]

where \( (dN/d\eta) \) is the multiplicity as a function of number of participants measured by ALICE experiment.\(^{20}\) Both ALICE and CMS measurements on multiplicity...
Fig. 1. a) Measured \( \frac{dN/d\eta}{(N_{\text{part}}/2)^2} \) \(^{26}\) as a function of \( N_{\text{part}} \) along with the function \( \frac{dN/d\eta}{\pi R^2} \). (b) The initial temperature obtained from measured multiplicity using Eq. \( \text{(11)} \) agree well with each other. Equation \( \text{(11)} \) giving the variation of initial temperature as a function of centrality differs from the approach taken in the work of Ref.\(^{28}\) where it is taken to vary as a third root of number of participants.

The nuclear modification factor, \( R_{\text{AA}} \) is obtained from survival probability taking into account the feed-down corrections as follows,

\[
\begin{align*}
R_{\text{AA}}(3S) &= S(3S) \\
R_{\text{AA}}(2S) &= f_1 \, S(2S) + f_2 \, S(3S) \\
R_{\text{AA}}(1S) &= g_1 \, S(1S) + g_2 \, S(\chi_b(1P)) + g_3 \, S(2S) + g_4 \, S(3S)
\end{align*}
\]

The factors \( f \)'s and \( g \)'s are obtained from CDF measurement\(^{29}\). The values of \( g_1, g_2, g_3 \) and \( g_4 \) are 0.509, 0.27, 0.107 and 0.113 respectively. Here it is assumed that the survival probabilities of \( \Upsilon(3S) \) and \( \chi_b(2P) \) are same and \( g_4 \) is their combined fraction. The values of \( f_1 \) and \( f_2 \) are taken as 0.50 guided by the work from Ref.\(^{30}\).

4. Results and discussions

Figure 1 (a) shows measured \( \frac{dN/d\eta}{(N_{\text{part}}/2)^2} \) \(^{26}\) as a function of \( N_{\text{part}} \). The function \( \frac{dN/d\eta}{\pi R^2} \) gives the multiplicity divided by transverse area obtained using Eq.\( \text{(9)} \). Figure 1 (b) gives the initial temperature obtained from measured
Fig. 2. The screening radius $r_D$ (in fm) as a function of $p_T$ for $R = 6.8$ fm (corresponding to head-on collisions) and $R = 3.7$ fm (corresponding to minimum bias collisions) for (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$. The straight lines $|r + \tau_F/p_T|/M |$ mark the distance a bottom quark pair (created at $r = 0$) will travel before forming a bound state. The mesh region in both the figures marks the escape region for bottom quark pair in case of head-on collisions and total shaded (mesh+lines) region marks the escape region in case of minimum bias collisions.

Fig. 3. (a) The survival probability as a function of $p_T$ for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\chi_b(1P)$ for $R = 3.7$ fm (corresponding to average $N_{\text{part}} = 114$ for minimum bias collisions). (b) The nuclear modification factor for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ which is obtained from survival probabilities including feed down corrections. The solid squares are $\Upsilon(1S)$ $R_{AA}$ measured in the minimum bias PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by CMS experiment.

multiplicity using Eq. (11). Except in peripheral collisions, the initial temperature has weak dependence on centrality of collisions. Figure 2 demonstrates working of the model. It shows the screening radius $r_D$ (in fm) as a function of $p_T$ for $R = 6.8$ fm...
Fig. 4. The nuclear modification factor, $R_{AA}$ as a function of $N_{part}$ for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The solid squares and circles are measured $R_{AA}$ by CMS experiment in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $\Upsilon(1S)$ and $\Upsilon(2S)$ respectively and solid triangles are the minimum bias data points. The boxes at unity are the common systematic uncertainties in pp luminosity measurement and the pp yield. The lines(solid for $\Upsilon(1S)$ , dashed for $\Upsilon(2S)$ and dotted for $\Upsilon(3S)$) represent the present model calculations.

(corresponding to head-on collisions) and $R = 3.7$ fm (corresponding to minimum bias collisions) for (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$. The straight lines $|r + \frac{r_{cend} \Delta r}{M}|$ mark the distance a bottom quark pair (created at $r = 0$) will travel before forming a bound state. The mesh region in both the figures marks the escape region for bottom quark pair in case of head-on collisions and total shaded (mesh+lines) region marks the escape region in case of minimum bias collisions. If $r$ is non-zero, the region where a bottomonium can escape screening, enlarges.

Figure 3 (a) shows the survival probability as a function of $p_T$ for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\chi_b(1P)$ for $R = 3.7$ fm (corresponding to average $N_{part} = 114$ for minimum bias collisions). The survival probability $S(p_T)$ has a unique $p_T$ dependence decided by the $T_D$ and $\tau_F$ of each $\Upsilon$ state. In general, the survival probabilities of resonance states increase with increasing $p_T$ and become unity at different $p_T$ for different states corresponding to complete survival. Since $\Upsilon(1S)$ is expected to dissolve at a higher temperature it has more probability to survive the plasma region even at lower $p_T$ as compared to the cases of other bottomonia states. The model gives very similar survival probabilities for $\Upsilon(2S)$ and $\Upsilon(3S)$. This is due to the fact that $\Upsilon(3S)$ has large formation time even though its dissociation temperature is smaller in comparison to $\Upsilon(2S)$. Figure 3 (b) shows the nuclear modification...
factor for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ which is obtained from survival probabilities including feed down corrections. The solid squares are $\Upsilon(1S) R_{AA}$ measured in the minimum bias PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by CMS experiment. The model reproduces the trend of the $p_T$ dependence of low statistics measurements of $R_{AA}$ from 2010 PbPb collisions by CMS.

Figure 4 shows the nuclear modification factor, $R_{AA}$ as a function of $N_{part}$ for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. The solid squares and circles are measured $R_{AA}$ by CMS experiment in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $\Upsilon(1S)$ and $\Upsilon(2S)$ respectively and solid triangles are the minimum bias data points. The lines (solid for $\Upsilon(1S)$, dashed for $\Upsilon(2S)$ and dotted for $\Upsilon(3S)$) represent the present model calculations. The common systematic uncertainties in pp luminosity measurement and the pp yield are represented by the boxes at unity. The model correctly reproduces the measured nuclear modification factors of both $\Upsilon(1S)$ and $\Upsilon(2S)$ for all centralities using the parameters given in the Table I. The survival probabilities for $\Upsilon(2S)$ and $\Upsilon(3S)$ are very similar.

We also calculated the ratio of $R_{AA}$ of $\Upsilon(2S)$ to that of $\Upsilon(1S)$ which is equivalent to the so called double ratio $[\Upsilon(2S)/\Upsilon(1S)]_{PbPb}/[\Upsilon(2S)/\Upsilon(1S)]_{pp}$. The double ratio has the advantage that the effects such as initial-state nuclear effects and regeneration which we ignore in our calculations are supposedly canceled out. Figure 5 shows the double ratio measured by CMS experiment along with the present cal-

Fig. 5. Double ratio, $[\Upsilon(2S)/\Upsilon(1S)]_{PbPb}/[\Upsilon(2S)/\Upsilon(1S)]_{pp}$ as a function of $N_{part}$ measured by CMS experiment along with the present calculation (solid line). The box at unity is the common systematic uncertainty in the pp yield.
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culation. The calculations reproduce the measured double ratio even for the most peripheral data point.

The most important parameters in above study are formation time and dissociation temperatures of bottomonia states. There are reliable calculations of formation time obtained from zero temperature potential models which reproduce the bottomonia spectroscopy very well. Upper limits are available for dissociation temperatures which are obtained from potential models at finite temperature. We used slightly lower values of the dissociation temperature to get a good description of the measured nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$. The dynamics of the system is affected by the initial conditions which in the present calculations are fixed using measured charged particle multiplicity at LHC. There can be suppression due to initial nuclear effects which we assume to be much smaller than that due to colour screening and hence are ignored in the present work. The calculations of shadowing in PbPb show that it will effect the bottomoina yields by approximately 20% for most central collisions. Thus, the dissociation temperatures obtained by us are still considered to be the upper limits. Conversely there are other views which say that $\Upsilon$ ground state is not much affected by the color screening up to the temperatures of $\sim 3 - 4T_C$ and regeneration of the states are not negligible at the LHC. The bottom quark mass is 10 times higher than the temperature we are considering for the system and hence the regeneration effect can be safely ignored in calculating nuclear modification for bottomonia. The uncertainties in the measurements of feed-down fractions would introduce uncertainties in the calculated nuclear modification factor. Finally we mention that the uncertainties arising from the effects other than colour screening are small and supposedly will have little or no effect on the double ratio.

5. Conclusions

In summary, we calculate the survival probabilities of $\Upsilon$ states and obtain the nuclear modification factors due to colour screening in an expanding quark gluon plasma of finite lifetime and size produced during PbPb collisions $\sqrt{s_{NN}} = 2.76$ TeV. The formation time and dissociation temperatures of bottomonia states obtained from potential models are used as input parameters in the model. We used slightly lower values of the dissociation temperatures to get a good description of the measured nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$. The model reproduces the centrality dependence of measured nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$ and the double ratio very well at $\sqrt{s_{NN}} = 2.76$ TeV. The trend of $p_T$ dependence of low statistics measurements of nuclear modification factor from 2010 PbPb collisions of CMS is reproduced as well. The uncertainties arising from effects other than colour screening are assumed to be small and supposedly will have little or no effect on the double ratio calculations.
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