Quarkonia suppression in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Abstract

We estimate the modification of quarkonia yields due to different processes in the medium produced in PbPb collisions at LHC energy. The quarkonia and heavy flavour cross sections calculated upto Next to Leading Order (NLO) are used in the study and shadowing corrections are obtained by EPS09 parametrization. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. Quarkonia dissociation cross section due to gluon collisions has been considered and the regeneration rate has been obtained using the principle of detailed balance. The modification in quarkonia yields due to collisions with hadronic comovers has been estimated assuming it to be caused by pions. The manifestations of these effects in different kinematic regions in the nuclear modification factors for both $J/\psi$ and $\Upsilon$ has been demonstrated for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in comparison with the measurements. Both the suppression and regeneration due to deconfined medium strongly affect low and intermediate $p_T$ range. The large observed suppression of $J/\psi$ at $p_T$ above 10 GeV/c exceeds the estimates of suppression by gluon dissociation.

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I. INTRODUCTION

Heavy ion collisions at relativistic energies are performed to create and characterize Quark Gluon plasma (QGP), a phase of strongly interacting matter at high energy density where quarks and gluons are no longer bound within hadrons. Quarkonia state ($J/\psi$ and $\Upsilon$) have been one of the most popular tools since their suppression was proposed as a signal of QGP formation \[1\]. The understanding of these probes has evolved substantially via measurements through three generations of experiments: SPS (at CERN), RHIC (at BNL) and the LHC (at CERN) and by voluminous theoretical activities [For recent reviews see Refs. \[2–4\]]. Quarkonia are produced early in the heavy ion collisions and if they evolve through deconfined medium their yields should be suppressed in comparison with those in $pp$ collisions. The first such measurement was the ‘anomalous’ $J/\psi$ suppression discovered at the SPS which was considered as a hint of QGP formation. The RHIC measurements showed almost the same suppression at a much higher energy contrary to the expectation \[4, 5\]. Such an observation was consistent with the scenarios that at higher collision energy the expected more suppression is compensated by regeneration of $J/\psi$ through recombination of two independently produced charm quarks \[6\]. After the LHC started PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, a wealth of results have become available on quarkonia production \[7, 8\]. The CMS experiment carries out $J/\psi$ measurement at high transverse momentum ($p_T > 6.5$ GeV/$c$). The nuclear modification factor $R_{AA}$ of these high $p_T$ prompt $J/\psi$ decreases with increasing centrality \[9, 10\] showing moderate suppression even in the most peripheral collisions. Moreover $R_{AA}$ is found to be nearly independent of $p_T$ (above 6.5 GeV/$c$) showing that $J/\psi$ remain suppressed even at very high $p_T$ upto $\sim 16$ GeV/$c$. On comparing with the STAR results \[11\] at RHIC it follows that the suppression of (high $p_T$) $J/\psi$ has increased with collision energy. The ALICE results \[12\] of $J/\psi$ covers low $p_T$ range which have little or no centrality dependence. The ALICE $J/\psi$ suppression decrease substantially with decreasing $p_T$. When compared with PHENIX forward rapidity measurement at RHIC \[5\], it suggests that low $p_T$ $J/\psi$ are less suppressed at LHC. These observations suggest regeneration of $J/\psi$ at low $p_T$ by recombination of independently produced charm pairs. At LHC energy $\Upsilon$ are produced with good statistics. The CMS measurements \[13, 14\] reveal that the higher $\Upsilon$ states are more suppressed relative to the ground state, a phenomenon known as sequential suppression. The ALICE measurements in forward rapidity ($2.5 \leq y^{\Upsilon} \leq 4.0$) are consistent
with CMS measurements in mid rapidity region ($|y^\Upsilon| \leq 2.4$).

Many theoretical frameworks have been developed in pre-LHC years for the modification of quarkonia due to different processes. The suppression of quarkonia in QGP are understood in terms of colour screening models e.g. Ref. [1, 15] and alternatively in terms of dissociation of quarkonia by gluon collision process [16, 17]. The statistical models [6, 18] offer estimates of the regeneration of quarkonia from charm quark pairs. The inverse of gluon dissociation process is also used to estimate regeneration [19]. The quarkonia yields in heavy ion collisions are also modified due to non-QGP effects such as shadowing, an effect due to the change of the parton distribution functions inside the nucleus, and dissociation due to hadronic or comover interaction [20]. There have been many recent calculations to explain the LHC results on quarkonia using a combination of above theoretical frameworks and models [21, 22].

In this paper, we calculate the quarkonia (both $J/\psi$ and $\Upsilon$) production and suppression in a kinetic model which includes dissociation due to thermal gluons, modification of yield due to change in parton distribution functions inside nucleus and due to collisions with comover hadrons. Regeneration by thermal heavy quark pairs is also taken into account. Our goal is obtain the nuclear modification factor of quarkonia as a function of transverse momentum and centrality of collision and compare it with experimental data from CMS and ALICE.

II. THE PRODUCTION RATES AND SHADOWING

The production cross sections for heavy quark pairs are calculated to NLO in pQCD using the CTEQ6M parton densities [23, 24]. The central EPS09 parameter set [25] is used to calculate the modifications of the parton densities in PbPb collisions. We use the same set of parameters as that of Ref. [26] with the NLO calculation of Ref. [27] to obtain the exclusive $q\bar{q}$ pair rates. The production cross sections for heavy flavor and quarkonia at $\sqrt{s_{NN}} = 2.76$ TeV [28] are given in Table I. The number of $q\bar{q}$ pairs in a minimum bias PbPb event is obtained from the per nucleon cross section, $\sigma_{\text{PbPb}}$, by

$$N_{q\bar{q}} = \frac{A^2 \sigma_{\text{PbPb}}}{\sigma_{\text{PbPb}}^{\text{tot}}}.$$  \hspace{1cm} (1)$$

At 2.76 TeV, the total PbPb cross section, $\sigma_{\text{PbPb}}^{\text{tot}}$, is 7.65 b [29].
TABLE I. Heavy quark and quarkonia production cross sections at $\sqrt{s_{NN}} = 2.76$ TeV. The cross sections are given per nucleon pair while $N_{\text{PbPb}}$ (including shadowing) gives the number of heavy quark pair/quarkonia per PbPb event.

|       | $\bar{c}c$ | $J/\psi$ | $b\bar{b}$ | $\Upsilon$ |
|-------|------------|-----------|------------|------------|
| $\sigma_{\text{PbPb}}$ | $1.76_{-1.25}^{+2.32}$ mb | 31.4 $\mu$b | $89.3_{-27.2}^{+42.7}$ mb | 0.38 $\mu$b |
| $N_{\text{PbPb}}$ | $9.95_{-7.30}^{+13.10}$ | 0.177 | $0.50_{-0.15}^{+0.25}$ | 0.01 |
| $N_{pp}$ | 0.190 | 0.0105 |

III. MODIFICATION OF QUARKONIA IN THE PRESENCE OF QGP

In the kinetic approach [19], the proper time ($\tau$) evolution of the quarkonia population $N_Q$ is given by the rate equation

$$\frac{dN_Q}{d\tau} = -\lambda_D \rho_g N_Q + \lambda_F \frac{N_{q\bar{q}}^2}{V(\tau)},$$

(2)

where $V(\tau)$ is the volume of the deconfined spatial region and $N_{q\bar{q}}$ is the number of initial heavy quark pairs produced per event depending on the centrality defined by the number of participants $N_{\text{part}}$. The $\lambda_D$ is the dissociation rate obtained by the dissociation cross-section averaged over the momentum distribution of gluons and $\lambda_F$ is the formation rate obtained by the formation cross-section averaged over the momentum distribution of heavy quark pair $q$ and $\bar{q}$. $\rho_g$ is the density of thermal gluons. The number of quarkonia at freeze-out time $\tau_f$ is given by the solution of Eq. (2) as

$$N_Q(p_T) = S(p_T) N_{\text{PbPb}}^Q(p_T) + N_{Q}^F(p_T).$$

(3)

Here $N_{\text{PbPb}}^Q(p_T)$ is the number of initially produced quarkonia (including shadowing factor) as a function of $p_T$ and $S(p_T)$ is their survival probability from gluon collisions at freeze-out time $\tau_f$ and is written as

$$S(\tau_f, p_T) = \exp \left( -\int_{\tau_0}^{\tau_f} f(\tau) \lambda_D(T, p_T) \rho_g(T) d\tau \right).$$

(4)

The temperature $T(\tau)$ and the QGP fraction $f(\tau)$ evolve from initial time $\tau_0$ to freeze-out time $\tau_f$ due to expansion of QGP. The initial temperature and the evolution is dependent on $N_{\text{part}}$. $N_{Q}^F(p_T)$ is the number of regenerated quarkonia per event and is given by

$$N_{Q}^F(p_T) = S(\tau_f, p_T) N_{q\bar{q}}^2 \int_{\tau_0}^{\tau_f} \frac{\lambda_F(T, p_T)}{V(\tau) S(\tau, p_T)} d\tau$$

(5)
The nuclear modification factor \( R_{AA} \) can be written as

\[
R_{AA}(p_T) = S(p_T)R(p_T) + \frac{N_Q^F(p_T)}{N_Q^{pp}(p_T)}.
\]

Here \( R(p_T) \) is the shadowing factor. \( R_{AA} \) as a function of collision centrality, including the regeneration will be

\[
R_{AA}(N_{\text{part}}) = \frac{\int_{p_T \text{ Cut}} N_{\text{pp}}^{pp}(p_T)S(p_T)R(p_T)dp_T}{\int_{p_T \text{ Cut}} N_Q^{pp}(p_T)dp_T} + \frac{\int_{p_T \text{ Cut}} N_Q^F(p_T)dp_T}{\int_{p_T \text{ Cut}} N_Q^{pp}(p_T)dp_T}.
\]

Here \( p_T \text{ Cut} \) defines the \( p_T \) range as per the experimental measurements. \( N_{\text{pp}}^{pp}(p_T) \) is the unmodified \( p_T \) distribution of quarkonia obtained by NLO calculations which is scaled to a particular centrality \( (N_{\text{part}}) \) of PbPb collisions.

The evolution of the system for each centrality of collision is governed by an isentropical cylindrical expansion with volume element

\[
V(\tau) = \tau \pi \left( R + \frac{1}{2} a \tau^2 \right)^2,
\]

where \( a_T = 0.1 \text{c}^2 \text{ fm}^{-1} \) is the transverse acceleration \[21\]. The initial transverse size, \( R \) as a function of centrality is obtained as

\[
R(N_{\text{part}}) = R_{0-5\%} \sqrt{\frac{N_{\text{part}}}{(N_{\text{part}})_{0-5\%}}},
\]

where \( R_{0-5\%} = 0.92 R_{\text{Pb}} \); \( R_{\text{Pb}} \) being the radius of the Pb nucleus.

The evolution of entropy density for each centrality is obtained by entropy conservation condition \( s(T) V(\tau) = s(T_0) V(\tau_0) \). The equation of state obtained by Lattice QCD along with hadronic resonance gas \[30\] is used to obtain the temperature as a function of proper time \( \tau \). The initial entropy density for each centrality is calculated using

\[
s(\tau_0) = s(\tau_0)_{0-5\%} \left( \frac{dN/d\eta}{N_{\text{part}}/2} \right) / \left( \frac{dN/d\eta}{N_{\text{part}}/2} \right)_{0-5\%}.
\]

Measured values of \( \left( \frac{dN/d\eta}{N_{\text{part}}/2} \right) \) as a function of \( N_{\text{part}} \) \[31\] are used in the calculations. The initial entropy density \( s(\tau_0)_{0-5\%} \) for 0-5\% centrality is obtained as

\[
s(\tau_0)_{0-5\%} = \frac{a_m}{V(\tau_0)_{0-5\%}} \left( \frac{dN}{d\eta} \right)_{0-5\%}.
\]

Here \( a_m \) is a constant which relates the total entropy with the multiplicity. It is obtained from hydrodynamic calculations \[32\].
FIG. 1. (Color online) (a) Temperature and (b) QGP fraction in the system as a function of proper time $\tau$ in case of the most central (0-5%) collisions for longitudinal and cylindrical expansions using first order and lattice equation of state.

Using $(dN/d\eta)_{0-5\%}=1.5\times1600$ obtained from the charge particle multiplicity measured in PbPb collisions at 2.76 TeV and with lattice equation of state we obtain the initial temperature for the most central collisions as 0.492 GeV at time $\tau_0 = 0.3$ fm/c.

The (proper) time evolution of temperature is shown in Fig. (a) and that of QGP fraction in Fig. (b), in case of most central (0-5%) collisions. Here we compare the evolutions obtained with longitudinal and cylindrical expansions using both first order and lattice Equation of state (EOS). For the first order EOS, $T_C = 0.170$ GeV and the QGP fraction goes from 1 to 0 at this temperature assuming a mixed phase of QGP and hadrons. The QGP fraction in case of lattice EOS governs number of degrees of freedom decided by entropy density. It is fixed to 1 above an entropy density corresponding to a 2-flavour QGP and fixed to zero below entropy density for a hot resonance gas. The freeze out temperature in all cases is $T_f = 0.140$ GeV.
A. Dissociation Rate

In colour dipole approximation, the gluon dissociation cross section as function of gluon energy $q^0$ in the quarkonium rest frame is given by [16]

$$
\sigma_D(q^0) = \frac{8\pi}{3} \frac{16^2}{3^2} \frac{a_0}{m_q} \frac{(q^0/\epsilon_0 - 1)^{3/2}}{q^0/\epsilon_0^3},
$$

where $\epsilon_0$ is the quarkonia binding energy and $m_q$ is the charm/bottom quark mass and $a_0 = 1/\sqrt{m_q \epsilon_0}$. The values of $\epsilon_0$ are taken as 0.64 and 1.10 GeV for ground states $J/\psi$ and $\Upsilon(1S)$, respectively [33]. For excited state of bottomonia ($\Upsilon(2S)$) we use dissociation cross section from Ref. [34].

Figure 2 shows the gluon dissociation cross section of $J/\psi$ and $\Upsilon(1S)$ as a function of gluon energy. The dissociation cross section is zero when gluon energy is less than the binding energy of the quarkonia. It increases with gluon energy and reaches maximum at 1.2 (1.5) GeV for $J/\psi$ ($\Upsilon$). At higher gluon energy, the interaction probability decreases. $q^0$ is related to the centre of mass energy square $s$, of quarkonium-gluon system as

$$
q^0 = \frac{s - M_Q^2}{2M_Q}.
$$

Using this relation, $\sigma_D(q^0(s))$ can be obtained which we write as $\sigma_D(s)$ where $s$ can be obtained as $s = M_Q^2 + 2p_g \sqrt{M_Q^2 + p^2} - 2p_g p \cos \theta$, where $M_Q$ and $p$ are mass and momentum of quarkonium and $\theta$ is angle between the quarkonium and the gluon.

We can calculate dissociation rate as a function of quarkonium momentum by integrating the dissociation cross-section on thermal gluon momentum distribution $f_g(p_g)$ as

$$
\lambda_D \rho_g = \langle \sigma v_{\text{rel}} \rangle \rho_g = \frac{g_g}{(2\pi)^3} \int d^3p_g f_g(p_g) \sigma_D(s) v_{\text{rel}}(s)
$$

$$
= \frac{g_g}{(2\pi)^3} \int 2\pi p_g^2 dp_g f_g(p_g) \int \sigma_D(s) v_{\text{rel}}(s) d(\cos \theta)
$$

The relative velocity $v_{\text{rel}}$ between the quarkonium and the gluon is given by

$$
v_{\text{rel}} = \frac{s - M_Q^2}{2p_g \sqrt{M_Q^2 + p^2}}.
$$

The gluon dissociation rates of $J/\psi$ as a function of temperature are shown in Fig. 3(a) and as a function of transverse momentum in Fig. 3(b). The dissociation rate increases with temperature due to increase in gluon density. The dissociation rate is maximum when quarkonium is at rest and decreases with its (transverse) momentum.
FIG. 2. Gluon dissociation cross-section of quarkonia as a function of gluon energy ($q^0$) in quarkonia rest frame.

FIG. 3. (Color online) Gluon dissociation rate of $J/\psi$ as a function of (a) temperature and (b) transverse momentum.
B. Formation Rate

We can calculate formation cross section from dissociation cross section using detailed balance relation [19, 35] as

$$\sigma_F = \frac{48}{36} \sigma_D (q^0) \frac{(s-M_Q^2)^2}{s(s-4m_q^2)}.$$  \hspace{1cm} (16)

The formation rate of quarkonium with momentum \( \mathbf{p} \) can be written as

$$\frac{d\lambda_F}{d\mathbf{p}} = \int \sigma_F(s) v_{\text{rel}}(s) f_q(p_1) f_{\bar{q}}(p_2) d^3p_1 d^3p_2 \delta(\mathbf{p} - (\mathbf{p}_1 + \mathbf{p}_2)) \hspace{1cm} (17)$$

Here \( f_q/\bar{q}(p) \) are taken as thermal distribution function of \( q/\bar{q} \) which are normalized to one as per \( \int f_q(p)d^3p = 1 \). \( v_{\text{rel}} \) is relative velocity between \( q\bar{q} \) quark pair and is given by

$$v_{\text{rel}} = \frac{\sqrt{(p_1.p_2)^2 - m_q^4}}{E_1 E_2}$$ \hspace{1cm} (18)

Here \( p_1 = (E_1, \mathbf{p}_1), p_2 = (E_2, \mathbf{p}_2) \) are the four momenta of heavy quark and anti-quarks, respectively.

Figure 4 (a) shows variation of formation rate of \( J/\psi \) as a function of medium temperature and Fig. 4 (b) shows as a function of transverse momentum of \( J/\psi \). The \( J/\psi \) generated from recombination of uncorrelated heavy quark pairs will have softer \( p_T \) distributions than that of \( J/\psi \) coming from initial hard scattering and thus effect of recombination will be important only at low \( p_T \).

IV. EFFECT OF HADRONIC COMOVERS

The suppression of quarkonia by comoving pions can be calculated by folding the quarkonium-pion dissociation cross section \( \sigma_I \) over thermal pion distributions [36]. It is expected that at LHC energies, the cross-section of comover suppression will be small [37]. We take 1 mb cross-section for both \( J/\psi \) and \( \Upsilon \) states. The dissociation rate \( \lambda_{D_n} \) can be written as

$$\lambda_{D_n} \rho_\pi = \frac{g_\pi}{(2\pi)^3} \int d^3p f_\pi(p) \sigma_I v_{\text{rel}} \hspace{1cm} (19)$$

$$= \frac{g_\pi}{(2\pi)^3} \int 2\pi p^2 dp f_\pi(p) \int \sigma_I v_{\text{rel}}(s) \Theta(s-4m_D^2) d(cos \theta)$$
FIG. 4. (Color online) Formation rate of $J/\psi$ as a function of (a) temperature and (b) transverse momentum.

FIG. 5. (Color online) Calculated nuclear modification factor ($R_{AA}$) as a function of $J/\psi$ transverse momentum compared with (a) ALICE and (b) CMS measurements.

where $f_\pi(p, T)$ is taken as the thermal pion distribution and the pion density $\rho_\pi$ is given by

$$ \rho_\pi = \frac{g_\pi}{(2\pi)^3} \int d^3p \, f_\pi(p) $$

(20)
FIG. 6. (Color online) Calculated nuclear modification factor ($R_{AA}$) compared with (a) ALICE and (b) CMS measurements at LHC. The regeneration for high $p_T$ CMS comparison is negligible. Similar cold nuclear matter effects are assumed for both ALICE and CMS rapidity ranges.

The survival probability from pion collisions at freeze-out time $\tau_f$ is written as

$$S_\pi(p_T) = \exp \left( - \int_{\tau_0}^{\tau_f} (1 - f(\tau)) \lambda_{D_\pi}(T, p_T) \rho_\pi(T) \, d\tau \right). \quad (21)$$

The hadronic fraction $(1-f(\tau))$ is zero in QGP phase. The probability $S_\pi(p_T)$ is used along with $S(p_T)$ term in Eq. (6).

V. RESULTS AND DISCUSSION

Figure 5(a) show different contributions in nuclear modification factor ($R_{AA}$) of $J/\psi$ as a function of transverse momentum compared with ALICE measurements [12] and the Fig. 5(b) shows the same along with high $p_T$ measurements of CMS experiment [10]. At low $p_T$, regeneration of $J/\psi$ is the dominant process and this seems to be the reason for the enhancement of $J/\psi$ in the ALICE low $p_T$ data. The gluon suppression is also substantial at low $p_T$ and reduces as we move to high $p_T$. Both of these processes (regeneration and dissociation) due to the presence of QGP are at play in low and intermediate $p_T$. The high $p_T$ suppression ($p_T > 10 \text{ GeV}/c$) of $J/\psi$ measured by CMS is far more to be originating due to the dissociation by gluons in QGP.
FIG. 7. (Color online) Calculated nuclear modification factor ($R_{AA}$) compared with CMS (a) $\Upsilon(1S)$ and (b) $\Upsilon(2S)$ measurements. The regeneration is assumed to be small.

We have also calculated $R_{AA}$ as a function of centrality of collisions (system size). Figure 6 (a) shows different contributions of $J/\psi$ nuclear modification factor as a function of system size along with the measurements by ALICE [12]. Figure 6 (b) shows the same for $p_T \geq 6.5 \text{ GeV/c}$, measured by CMS experiment [10]. Figure 6 (a) indicates that $J/\psi$’s are increasingly suppressed when system size grows. Since the number of regenerated $J/\psi$’s also grows, the nuclear modification factor remains flat for most of the centrality range. Our model calculations seems to overestimate the suppression in the most peripheral data. The centrality dependence of $R_{AA}$ of $J/\psi$ by CMS is well described by the model. Most of the contribution to CMS data comes from $J/\psi$ $p_T$ between 6.5 and 10 GeV/c where the suppression seems to be due to gluon dissociation process.

Figure 7 (a) demonstrates contribution of different processes in the centrality dependence of $\Upsilon(1S)$ nuclear modification factor along with the data measured in mid rapidity by CMS experiment [14] and in forward rapidity by ALICE experiment [38]. The calculations underestimate the suppression but reproduce the shape of centrality dependence. The may be due to the feed down effects from the excited states. Figure 7 (b) shows the same for $\Upsilon(2S)$ nuclear modification factor along with the measurements in mid rapidity by CMS experiment. The excited $\Upsilon(2S)$ states are highly suppressed. The effect of regeneration
(not shown here) is negligible for Υ states. We did not include feed down corrections as the dissociation cross sections for excited states specially for charmonia are not reliable. Also the feed down fractions in different states are not very well known.

VI. SUMMARY

We have carried out detailed calculations of $J/\psi$ and Υ modifications in PbPb collisions at LHC. The quarkonia and heavy flavour cross sections calculated upto NLO are used in the study and shadowing corrections are obtained by EPS09 parametrization. A kinetic model is employed which incorporates quarkonia suppression inside QGP, suppression due to hadronic comovers and regeneration from charm pairs. The dissociation and formation rates have been studied as a function of medium temperature and transverse momentum of particles.

The nuclear modification factor for $J/\psi$ and Υ as a function of centrality and transverse momentum have been compared to the measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. At low $p_T$, regeneration of $J/\psi$ is the dominant process and this seems to be the process for the enhancement of $J/\psi$ in the ALICE low $p_T$ data. The gluon suppression is also substantial at low $p_T$ and becomes small as we move to high $p_T$. Both of these processes (regeneration and dissociation) due to the presence of QGP are affecting the yields of quarkonia in low and intermediate $p_T$. The high $p_T$ suppression ($p_T > 10$ GeV/$c$) of $J/\psi$ measured by CMS is far more than expected due to the dissociation by gluons in QGP.

The centrality dependence of nuclear modification indicates that $J/\psi$’s are increasingly suppressed when system size grows. Since the number of regenerated $J/\psi$’s also grows, the nuclear modification factor in case of low $p_T$ measurements (ALICE case) remains flat for most of the centrality regions. The centrality dependence of $R_{AA}$ of high $p_T$ $J/\psi$ is also well described by the model. The centrality dependence of suppression of Υ states are reproduced by model calculations. Feed down corrections seems to important for Υ(1S).

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