Quarkonia production in relativistic heavy ion collisions

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Abstract. Using the two-component model that includes both initial production from
nucleon-nucleon hard scattering and regeneration from produced quark-gluon plasma (QGP), we
have studied the effect of medium modifications of the binding energies and radii of quarkonia on
their production in heavy-ion collisions. We find that the inclusion of medium effects is helpful
for understanding the observed suppression of quarkonia production in experiments carried out
at SPS, RHIC, and LHC.

Since the suggestion by Matsui and Satz [1] that the production of $J/\psi$ would be suppressed
in relativistic heavy-ion collisions as a result of the screening of color charges in QGP and
thus could be used as a signature for the produced QGP in these collisions, there have been
extensive experimental and theoretical studies on this very interesting phenomenon. Although
experiments from SPS, RHIC, and LHC have indeed shown a suppressed production of $J/\psi$ as
well as the $\Upsilon$, a satisfactory explanation involves the interplay of many effects from both the
initial cold nuclear matter and the final hot partonic and hadronic matters. Including these
effects in a two-component model that takes into account both initial production from nucleon-
nucleon hard scattering and regeneration from produced QGP [2], we have recently carried out
a series of studies of quarkonia production in relativistic heavy ion collisions [3, 4, 5].

In our studies, the numbers of initially produced quarkonia are obtained from the binary
collisions among nucleons in the two colliding nuclei by using the empirical production cross
sections and after including the shadowing effect via the EPS09 package [6] by assuming that
it is proportional to the path length of a parton in a nucleus. The absorption effect in the
cold nuclear matter is included for $J/\psi$ by using a $J/\psi$-nucleon absorption cross section of 4.18
mb [7] and 2.8 mb [8] for SPS and RHIC, respectively, and 0 or 2.8 mb for LHC, but is neglected
for $\Upsilon$ because of its large binding and small size. The local temperature of initially produced
matter, which is needed for determining if quarkonia from nucleon-nucleon hard scattering can
be formed, is estimated from the local entropy density $ds/d\eta = C[(1 - \alpha)n_{\text{part}}/2 + \alpha n_{\text{coll}}]$ in
terms of the number densities $n_{\text{part}}$ and $n_{\text{coll}}$ of participants and binary collisions, respectively.
The parameters $C$ and $\alpha$ are determined to be 14.6 and 0 for Pb+Pb collisions at 158A GeV
at SPS, 18.7 and 0.11 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC, and 27.0 and 0.15
for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at LHC from fitting measured multiplicity of final

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charged particles after hydrodynamic evolution. The latter is based on a schematic viscous hydrodynamics [9] using an equation of state given by the quasiparticle model of three flavors for the QGP and the resonance gas model for the hadron gas (HG) [10], together with the specific shear viscosity $\eta/s$ taken to be 0.16 for the QGP at SPS and RHIC and 0.2 for that at LHC. The hydrodynamic equations are solved using an initial thermalization time $\tau_0 = 1.0, 0.9$, and 1.05 fm/c for central collisions at SPS, RHIC, and LHC [12], respectively, with corresponding initial maximum temperatures of 224, 324 and 390 MeV and mean temperatures of 218, 269 and 311 MeV. We note that the longer initial thermalization time at LHC is to compensate for the larger viscosity, which would otherwise lead to too large a radial flow [12].

The in-medium properties of quarkonia in the QGP are determined by using the screened Cornell potential [13] between heavy quark and antiquark, i.e., a radial flow [12].

The in-medium properties of quarkonia in the QGP are determined by using the screened Cornell potential [13] between heavy quark and antiquark, i.e., $V(r,T) = (\sigma/\mu(T))[1 - e^{-\mu(T)r}] - (\alpha_s/r)e^{-\mu(T)r}$, with $\sigma = 0.192$ GeV$^2$, $\alpha_s = 0.471$, and the screening mass $\mu(T) = \sqrt{N_c/3 + N_f/6} g T$ in terms of the color number $N_c$, the light quark flavor number $N_f$, and the QCD coupling constant $g$. Compared to results from the lattice QCD calculations for a heavy quark and antiquark pair in the QGP [14], this potential is closer to their internal energy at high temperature but to their free energy at low temperature, thus interpolating smoothly the expected temperature-dependent potential between heavy quark and antiquark [15]. Taking the heavy quark masses $m_c = 1.32$ GeV and $m_b = 4.746$ GeV [13] and $g = 1.87$, we solve the resulting Schrödinger equation for the heavy quark and antiquark pair to obtain the binding energies and radii of quarkonia in the QGP. The resulting dissociation temperatures are 1.76 $T_c$ for $J/\psi$, 1.0 $T_c$ for $\psi'$ and $\chi_{c}$, and 4.0, 1.67, 1.12, 1.51 and 1.09 $T_c$ for $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \chi_{b}(1P)$ and $\chi_{b}(2P)$, respectively, where the critical temperature is taken to be $T_c = 170$ MeV.

For quarkonia that have survived in the QGP from initial dissociations, their number $N_i$ of type $i$ evolves in time according to the rate equation $dN_i/d\tau = -\Gamma_i(N_i - N_i^{eq})$, where $\tau$ is the longitudinal proper time and $\Gamma_i$ is the thermal decay width of quarkonia. The number of equilibrated quarkonia of type $i$ is given by $N_i^{eq} = \gamma^2 R n_i f V \theta(T_i - T)$, where $n_i$ is the number density in grandcanonical ensemble; $f$ is the fraction of QGP in the mixed phase; and $\theta(T_i - T)$ is the step function with $T_i$ being the dissociation temperature of quarkonia of type $i$. The effect of chemical and kinetic off-equilibrium of heavy quarks in the QGP is included through their fugacity $\gamma$ and relaxation factor $R$, with the former obtained from the conservation of heavy quark flavor [4] and the latter defined as $R(\tau) = 1 - \exp[-(\tau - \tau_0)/\tau_{eq}]$ where $\tau_{eq}$ is the relaxation time of heavy quarks [5]. With $\tau_{eq} \sim m_Q$ [16], the relaxation time is about 4 fm/c for charm quarks [4, 17] and about 14 fm/c for bottom quarks. The thermal decay widths of quarkonia in QGP are calculated using the quarkonium dissociation cross sections $\sigma_i^{\text{dis}}$ evaluated up to the next-to-leading order (NLO) in perturbative QCD [18], including thus dissociation by absorbing not only a thermal gluon but also the gluon emitted from a thermal quark or gluon. For the thermal width in the mixed phase, it is taken to be a linear combination of those in the QGP and the HG with the latter evaluated by using the quarkonia dissociation cross sections that are obtained from the factorization formula for the ground-state [18] and the assumption that those of excited states are proportional to their squared radii. The thermal decay widths of quarkonia obtained with their in-medium binding energies and radii are found to increase with temperature and are significantly larger than those in free space.

In the left and middle windows of Fig. 1, we show by solid lines the calculated nuclear modification factor $R_{AA}$ of $J/\psi$ as a function of the participant number in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV at SPS, Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC, and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at LHC (for transverse momentum larger than 6.5 GeV/c). They agree very well with the experimental data [7, 19, 20], which show a decreasing $R_{AA}$ with increasing number of participants. Also shown are results from the primordial (dashed lines) and the regenerated $J/\psi$ in the QGP (dotted lines), and they are seen to decrease and increase,
Figure 1. (Color online) Left window: Nuclear modification factor $R_{AA}$ of $J/\psi$ (solid lines) as a function of the participant number $N_{\text{part}}$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV at SPS (upper panel) and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC (lower panel). Middle window: Same for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at LHC without (upper panel) and with (lower panel) the shadowing effect. Dashed and dotted lines represent, respectively, the contributions from primordial hard nucleon-nucleon scattering and regeneration in the QGP. Upper solid lines and dot-dashed lines in the right window are the $R_{AA}$ of $J/\psi$ at LHC for the nuclear absorption cross sections of $\sigma_{\text{abs}} = 0$ and the contribution from decay of bottom hadrons, respectively. Right window: Same for the sum of $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S) at RHIC (upper panel) and that of $\Upsilon$(1S) at LHC (lower panel). Solid and dashed lines are, respectively, results with and without medium effects on bottomonia. Dotted lines are results including also the shadowing or anti-shadowing effect. Experimental data are from Refs. [7, 19, 20, 23].

respectively, with increasing collision energy. For LHC, we have shown the results for both with (lower panel of middle window) and without (upper panel of middle window) the shadowing effect. The shadowing effect suppresses the production of charm pairs and consequently the regeneration of $J/\psi$. We have also included the contribution to $J/\psi$ production from the decay of bottom hadrons at LHC [21, 22] by assuming that the $R_{AA}$ of $J/\psi$ from the decay of bottom hadrons is independent of the centrality [20]. As shown by the dash-dotted line in the middle window of Fig. 1, this contribution is comparable to that from the regenerated $J/\psi$ (dotted lines) in peripheral collisions and more important than the primordial ones (dashed lines) in more central collisions. The lower solid lines in the middle window for LHC are the final $R_{AA}$ of $J/\psi$ obtained with a non-zero nuclear absorption cross section of 2.8 mb, and it differs from that without the nuclear absorption mainly in collisions of small number of participants as the primordial $J/\psi$ are mostly dissolved in central and semi-central collisions.

In the upper panel of the right window of Fig. 1, the calculated $R_{AA}$ of the sum of $\Upsilon$(1S), $\Upsilon$(2S) and $\Upsilon$(3S) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC as a function of the participant number is shown and compared with the experimental data from the STAR Collaboration [23]. The solid and dotted lines are results obtained without and with the anti-shadowing effect in cold nuclear matter, and the latter is larger than the former. Because of the large experimental errors, both can describe the data from RHIC for all centralities. For Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at LHC, only the $R_{AA}$ of $\Upsilon$(1S) has been measured by the CMS Collaboration [20]. Our results without (solid line) and with (dotted line) the cold nuclear matter effect, shown in the lower panel, both agree with the data for peripheral (20-100%).
and most central (0-10%) collisions. For midcentral (10-20%) collisions, our model significantly underestimates the measured $R_{AA}$. We note that the suppression of $\Upsilon(1S)$ is largely due to the reduced feed-down contribution from its suppressed excited states. Also, the contribution from regeneration to the $R_{AA}$ of bottomonia is less than 1% at both RHIC and LHC and for all centralities as a result of the small number of bottom quarks and the much longer bottom quark relaxation time than the lifetime of produced QGP. For comparison, results for the $R_{AA}$ of bottomonia without medium effects are shown by dashed lines in the right window of Fig. 1, and they are larger than those with medium effects as expected and is thus large compared to the experimental data from RHIC, particularly for more central collisions. This is also the case for heavy ion collisions at the LHC except for midcentral collisions where the result obtained without medium effects can better describe the experimental data.

We have further studied the effects of initial state fluctuations on the $R_{AA}$ of bottomonia at LHC by using the 2+1 dimension ideal hydrodynamics [5]. We find that while initial fluctuations hardly affect the yield of the 1S ground state bottomonium, their effect on that of excited bottomonium states is not small. Compared to the case with smooth initial conditions, the survival probabilities of excited bottomonium states are reduced at low transverse momentum in the case of large initial fluctuations while they are increased in the case of small initial fluctuations as a result of the smearing effect introduced in solving the hydrodynamic equations. The observed suppression of the excited bottomonia relative to the ground state bottomonium of an average transverse momentum of 6.57 GeV/c by CMS Collaborations can, however, be described at present with both smooth and fluctuating initial conditions.

In summary, using the two-component model that includes both initial production from nucleon-nucleon hard scattering and regeneration from produced quark-gluon plasma, we have studied quarkonia production in heavy-ion collisions at SPS, RHIC, and LHC by including the medium effects on the thermal properties of quarkonia and their dissociation cross sections. Our study shows that the inclusion of medium effects on quarkonia is helpful for describing the experimental observations.

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