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Charmonium coherent photoproduction and hadroproduction with effects of quark gluon plasma

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ABSTRACT

We study the charmonium coherent photoproduction and hadroproduction consistently with modifications from both cold and hot nuclear matters. The strong electromagnetic fields from fast moving nucleus interact with the other target nucleus, producing abundant charmonium in the extremely low transverse momentum region $p_T < 0.1$ GeV/c. This results in significative enhancement of J/ψ nuclear modification factor in semi-central and peripheral collisions. In the middle p_T region such as $p_T < 3 \sim 5$ GeV/c, J/ψ final yield is dominated by the combination process of single charm and anti-charm quarks moving in the deconfined matter, $c + \bar{c} \to J/\psi + g$. In the higher p_T region, J/ψ production are mainly from parton initial hard scatterings at the beginning of nucleus–nucleus collisions and decay of B hadrons. We include all of these production mechanisms and explain the experimental data well in different colliding centralities and transverse momentum regions.

With the nuclear collisions at the relativistic heavy ion collisions (RHIC) and the large hadron collider (LHC), there have been a lot of interesting topics about nuclear properties studied in experiments and theories. One of the main goals at RHIC and LHC is to find a deconfined state of nuclear matter, called "quark-gluon plasma" (QGP), which may be produced in the extremely high energy and/or baryon densities with a phase transition [1], and furthermore, extract the transport properties of this QGP [2]. There are also other projects referred to as "*non-QGP*" physics, concerning about cosmic ray physics and others [3]. As QGP can only be produced in the nucleon collisions in the overlap area of two nuclei, "*non-QGP*" topics are usually studied in Ultra-peripheral nuclear collisions (UPC) where QGP background is absent.

In order to study the existence of the extremely hot deconfined matter, produced in the early stage of heavy ion collisions, J/ψ abnormal suppression has been proposed as one of sensitive signals by Matsui and Satz in 1986 [4]. J/ψ suffers relatively weaker dissociation by the hadron gas compared with QGP, due to its large binding energy [5]. With strong color screening effect and parton inelastic scatterings of QGP, J/ψ production can be significantly suppressed in nucleus–nucleus collisions, which has been observed in many experiments at RHIC and LHC colliding energies in semi-central and central collisions (with impact parameter $b < 2R_A$, where R_A is the nuclear radius) [6–9]. From RHIC to LHC, J/ψ production is relatively enhanced in the transverse momentum region $p_T \le 3 \sim 5$ GeV/c compared with the scale of the pp collisions [8]. This phenomenon has been well explained with charmonium regeneration mechanism: At higher colliding energy, more charm quark pairs can be produced from hard process in hadronic collisions, which enhance the recombination probability of charm and anti-charm quarks inside QGP [10–14]. New J/ψs are continuously regenerated during the QGP evolutions. With sufficiently high initial temperature of QGP and abundant number of charm quarks, the primordially produced J/ψs are strongly suppressed and therefore regenerated J/ψs dominate the final total yields in Pb–Pb collisions at LHC energies [15,16].

Also, in the relativistic heavy ion collisions, the nuclei with charges move with nearly the speed of light, $v > 0.99c$ at RHIC and LHC. The strongest magnetic field on earth can be produced, with a magnitude of $eB \sim 5m_\pi^2$ at RHIC Au–Au and $70m_\pi^2$ at LHC Pb–Pb collisions [17,18]. Electromagnetic fields become strongly Lorentz contracted in the longitudinal direction (nuclear accelerating direction, defined as z-axis) [19]. In semi-central nuclear collisions, both strong electromagnetic fields and the QGP can be produced

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[17,20]. In the QGP, there will be interactions between magnetic fields and chiral light quarks at the limit of zero mass $m_q = 0$ in the deconfined matter. A lot of topics about the magnetic field induced QCD chirality are studied widely, such as chiral magnetic effect [21,22], chiral magnetic wave [23], chiral vortical effect [24], and chiral electric separation effect [25].

The electromagnetic fields can also interact with the other nucleus (γA or γN interactions) or with the electromagnetic fields of the other nucleus ($\gamma\gamma$ interactions), and produce hadronic final states [19,26–30]. Fermi first proposed that the transverse electromagnetic fields can be approximated as a swarm of equivalent photons, called "Equivalent Photon Approximation" (EPA) [31]. This idea was also extended by Weizsäcker [32] and Williams [33] independently and therefore also called "Weizsäcker–Williams-Method". This allows a simple and straightforward calculations of vector meson photoproduction between the target nucleus and electromagnetic fields [34]. With long range of electromagnetic interactions, a hard equivalent photon from one nucleus may penetrate into the other nucleus and interact with quarks or gluons. Therefore, one goal of this photoproduction is to study the parton densities of a bound nucleon inside the nucleus, such as shadowing effect. The interactions of γA (or γN) and $\gamma\gamma$ can produce heavy quark pairs $Q\bar{Q}$, dileptons $l\bar{l}$, and vector mesons $V = \phi, \rho^0, J/\psi, \psi(2S)$ [35–38]. In semi-central collisions with $b < 2R_A$, these heavy quarks or vector mesons will also go through hot medium and suffer dissociations [39]. With the strong electromagnetic fields, charmonium photoproduction may become larger than the hadroproduction in extremely low p_T region even in the semi-central collisions with the production of deconfined matter, which has already been observed by experiments at RHIC [40] and LHC [41].

In Pb–Pb semi-central collisions at $\sqrt{s_{NN}} = 2.76$, the initial temperature of QGP is around $(1.5 \sim 2)T_c$ where T_c is the critical temperature of deconfined phase transition [16]. With the realistic evolutions of QGP and all the sources of charmonium production including photoproduction and hadroproduction (consists of primordial production, regeneration and decay of B hadrons), we give the J/ψ nuclear modification factor as a function of number of participants $R_{AA}(N_p)$ and transverse momentum $R_{AA}(p_T)$. We find that primordial production, regeneration and photoproduction plays the important role in different p_T regions of charmonium production, showing different physics on heavy ion collisions.

With a large mass, charmonium evolutions in the hot medium can be described by a classical Boltzmann transport equation. It has described well hadroproduced charmonium $R_{AA}(N_p)$ at different colliding energies from SPS to LHC [15,42,43], mean transverse momentum square $\langle p_T^2\rangle(N_p)$ [44], and rapidity distribution $R_{AA}(y)$ [16]. The transport equation for hadroproduced charmonium with cold and hot nuclear matter effects is

$$\frac{\partial f_\Psi}{\partial \tau} + \mathbf{v}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi \quad (1)$$

where f_Ψ is the charmonium distribution in phase space. $\tau = \sqrt{t^2 - z^2}$ is the local proper time (here t is the time variable). The second term on the L.H.S. of Eq. (1) represents free streaming of Ψ with transverse velocity $\mathbf{v}_T = \mathbf{p}_T/\sqrt{m_\Psi^2 + p_T^2}$. On the R.H.S. of Eq. (1), the loss term α_Ψ represents charmonium decay rates in QGP due to color screening effect and parton inelastic scatterings, and is written as

$$\alpha_\Psi = \frac{1}{2E_T}\int \frac{d^3\mathbf{k}}{(2\pi)^3 2E_g}\sigma_{g\Psi}(\mathbf{p},\mathbf{k},T)4F_{g\Psi}(\mathbf{p},\mathbf{k})f_g(\mathbf{k},T) \quad (2)$$

where E_g and $E_T = \sqrt{m_\Psi^2 + p_T^2}$ are the gluon energy and charmonium transverse energy, respectively. $F_{g\Psi}$ is the flux factor. Charmonium decay rate in QGP is proportional to the gluon thermal density $f_g(\mathbf{k}, T)$ and also their inelastic cross sections $\sigma_{g\Psi}(T)$ [44]. The cross section for gluon dissociation in vacuum $\sigma_{g\Psi}(0)$ can be derived through the operator production expansion. It is extended to the finite temperature by geometry scale, $\sigma_{g\Psi}(T) = \sigma_{g\Psi}(0) \times \langle r_\Psi^2\rangle(T)/\langle r_\Psi^2\rangle(0)$, where $\langle r_\Psi^2\rangle(T)$ is the charmonium mean radius square at finite temperature, which can be obtained from potential model with the color screened heavy quark potential from Lattice calculations [45]. The divergence of charmonium radius at $T \to T_d^\Psi$ indicates the melting of the bound state Ψ. Charm and anti-charm quarks in the deconfined matter can also combine to generate a new bound state, represented by the gain term β_Ψ. It is connected with the loss term α_Ψ through detailed balance between the gluon dissociation process and its inverse process, $g + \Psi \leftrightarrow c + \bar{c}$.

With the loss and gain terms in Eq. (1), one can write the analytic solution for charmonium phase space distribution at the time τ to be

$$\begin{aligned} &f_\Psi(\mathbf{p}_T, \mathbf{x}_T, \tau|\mathbf{b}) \\ &= f_\Psi(\mathbf{p}_T, \mathbf{x}_T - \mathbf{v}_\Psi(\tau-\tau_0), \tau_0)e^{-\int_{\tau_0}^{\tau} d\tau'\alpha_\Psi(\mathbf{p}_T, \mathbf{x}_T - \mathbf{v}_\Psi(\tau-\tau'), \tau')} \\ &\quad + \int_{\tau_0}^{\tau} d\tau'\beta_\Psi(\mathbf{p}_T, \mathbf{x}_T - \mathbf{v}_\Psi(\tau-\tau'), \tau') \\ &\qquad \times e^{-\int_{\tau'}^{\tau} d\tau''\alpha_\Psi(\mathbf{p}_T, \mathbf{x}_T - \mathbf{v}_\Psi(\tau-\tau''), \tau'')} \end{aligned} \quad (3)$$

where $\tau_0 \sim 0.6 fm/c$ is the time scale of QGP reaching local equilibrium, fixed by light hadron spectra in hydrodynamic models. Charmonium initial distribution in nucleus–nucleus collisions $f_\Psi(\mathbf{p}_T, \mathbf{x}_T, \tau_0|\mathbf{b})$ is obtained by the geometry scale with pp collisions $\bar{f}_\Psi(\mathbf{p}_T, \mathbf{x}_T, \tau_0|\mathbf{b})$ in Eq. (4), with additional modifications from shadowing effect [46] and Cronin effect [16].

$$\begin{aligned} &\bar{f}_\Psi(\mathbf{p}_T, \mathbf{x}_T, \tau_0|\mathbf{b}) \\ &= \int dz_A dz_B \rho_A(\mathbf{x}_T + \frac{\mathbf{b}}{2}, z_A)\rho_B(\mathbf{x}_T - \frac{\mathbf{b}}{2}, z_B)\frac{d^2\sigma_{J/\psi}^{pp}}{dy 2\pi p_T dp_T} \end{aligned} \quad (4)$$

where $\rho_{A(B)}$ is the Woods-Saxon nuclear density. The differential cross section for charmonium hadroproduction in pp collisions is parametrized with [16,47],

$$\frac{d^2\sigma_{J/\psi}^{pp}}{dy 2\pi p_T dp_T} = \frac{2(n-1)}{2\pi(n-2)\langle p_T^2\rangle}[1 + \frac{p_T^2}{(n-2)\langle p_T^2\rangle}]^{-n}\frac{d\sigma_{J/\psi}^{pp}}{dy} \quad (5)$$

Here $y = 1/2\ln[(E+p_z)/(E-p_z)]$ and $\langle p_T^2\rangle$ are the rapidity and the mean transverse momentum square of J/ψ. At $\sqrt{s_{NN}} = 2.76$ TeV pp collisions, we fit the experimental data of J/ψ inclusive hadroproduction cross section at forward rapidity $2.5 < y < 4$ to obtain $n = 4.0$ and $\langle p_T^2\rangle = 7.8$ (GeV/c)^2 [48]. J/ψ rapidity differential cross section is $d\sigma_{J/\psi}^{pp}/dy = 2.3$ μb in the forward rapidity [49].

The regeneration rate β_Ψ is proportional to the densities of charm and anti-charm quarks which are produced through nuclear hard process. Charm quark initial densities in nucleus–nucleus collisions are obtained through

$$\rho_c(\mathbf{x}_T, \eta, \tau_0) = \frac{d\sigma_{c\bar{c}}^{pp}}{d\eta}\frac{T_A(\mathbf{x}_T + \mathbf{b}/2)T_B(\mathbf{x}_T - \mathbf{b}/2)\cosh(\eta)}{\tau_0} \quad (6)$$

where $T_{A(B)}(\mathbf{x}_T)$ is the thickness function of nucleus A(B) at the transverse coordinate $\mathbf{x}_T$, with the definition $T(\mathbf{x}_T) = \int dz\rho(\mathbf{x}_T, z)$. $\eta = 1/2\ln[(t+z)/(t-z)]$ is the spatial rapidity. Charm pair production cross section is taken to be $d\sigma_{c\bar{c}}^{pp}/d\eta = 0.38$ mb in the forward