New charm resonances and $J/\psi$ interactions in a hadron gas

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In relativistic heavy ion collisions, after the quark gluon plasma (QGP) phase there is a hadron gas (HG) phase. In both phases $J/\psi$ may be formed and destroyed. In this note we study the $J/\psi$ interactions with other mesons in the hadron gas phase. Making use of effective field Lagrangians we obtain the cross sections for the production and absorption processes. With respect to the existing calculations, the improvements introduced here are the inclusion of $K$ and $K^*$’s in the effective Lagrangian approach (and the computation of the corresponding cross sections) and the inclusion of processes involving the new exotic charmonium states $Z_c(3900)$ and $Z_c(4025)$.

We conclude that the interactions between $J/\psi$ and all the considered mesons reduce the original $J/\psi$ abundance (determined at the end of the quark gluon plasma phase) by 20% and 24% in RHIC and LHC collisions respectively. Consequently, any really significant change in the $J/\psi$ abundance comes from dissociation and regeneration processes in the QGP phase.

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I. INTRODUCTION

Quark gluon plasma (QGP) is formed in relativistic heavy ion collisions. In the QGP phase $J/\psi$’s are destroyed and created in a complex and rich dynamical process, which involves many properties of the QGP which we wish to know better [1]. After cooling and hadronization there is a hadron gas (HG) phase, in which the $J/\psi$’s can be destroyed and created in interactions with other mesons. New charmonium states, the so-called X,Y and Z states [2], open new channels for the $J/\psi$-light meson reactions, as first noticed in Ref. [3]. In [4] the existing calculations of the $J/\psi$-strange meson dissociation cross sections were improved and also the cross sections of processes involving $Z_c(3900)$ and $Z_c(4025)$ intermediate states were calculated for the first time. Here we present a summary of [4] and briefly discuss some questions raised after its appearance.

II. $J/\psi$ - MESON INTERACTIONS

The $J/\psi$ production processes $D^{(*)} + \bar{D}^{(*)} \to J/\psi + \pi$, $D^{(*)} + \bar{D}^{(*)} \to J/\psi + \rho$, $D_s^{(*)} + \bar{D}^{(*)} \to J/\psi + K$, $D_s^{(*)} + \bar{D}^{(*)} \to J/\psi + K^*$ can be studied with mesonic effective Lagrangians [5]. In [4] these interactions were treated within the framework of an $SU(4)$ effective theory. The relevant Lagrangians are given by [1, 2]

$$
\mathcal{L}_{PPV} = -ig_{PPV} V_\mu [P, \partial_\mu P],
\mathcal{L}_{VVV} = ig_{VVV} (\partial_\mu V_\nu [V^\mu, V^\nu]),
\mathcal{L}_{PPVV} = g_{PPVV} \{P V^\mu [V_\mu, P]\},
\mathcal{L}_{VVVV} = g_{VVVV} (V^\mu V^\nu [V_\mu, V_\nu]),
$$

where the indices $PPV$ and $VVV$, $PPVV$ and $VVVV$ denote the type of vertex incorporating pseudoscalar and vector meson fields in the couplings and $g_{PPV}$, $g_{VVV}$, $g_{PPVV}$ and $g_{VVVV}$ are the respective coupling constants. The symbol (…) stands for the trace over $SU(4)$-matrices. The symbols $V_\mu$ and $P$ represent the corresponding $SU(4)$ 15-plets of vector and pseudoscalar fields respectively (see [4] and references therein for details). It is important to include the anomalous parity terms:

$$
\mathcal{L}_{PPV} = -g_{PPV} \epsilon^{\mu
u\alpha\beta} (\partial_\mu V_\nu \partial_\alpha V_\beta P),
\mathcal{L}_{PPVV} = -ig_{PPVV} \epsilon^{\mu
u\alpha\beta} (V_\mu (\partial_\nu P) (\partial_\alpha P) (\partial_\beta P)),
\mathcal{L}_{VVVV} = ig_{VVVV} \epsilon^{\mu
u\alpha\beta} \left( V_\mu V_\nu \partial_\alpha \partial_\beta P + \frac{1}{3} (V_\mu (\partial_\nu V_\alpha) V_\beta P) \right).
$$

The $g_{PPV}$, $g_{PPVV}$, $g_{VVVV}$ are the coupling constants of the $PVV$, $PPVV$ and $VVVV$ vertices. As usual, form factors are included in the vertices to account for higher order corrections and finite sizes effects. These form factors
can be calculated in different approaches (see, for example, [3]) but very often one uses simple parametrizations, which contain a cut-off parameter. In [4] we have used expressions of the type $F = \frac{\Lambda^2}{\Lambda^2 + q^2}$, where $q$ is the three-momentum flowing in the vertex and $\Lambda$ is a cut-off mass of the order of 2 GeV.

III. THE EFFECT OF THE NEW CHARMONIUM STATES

The state $Z_c(3900)$ opens a new s-channel for $J/\psi$ interactions: $J/\psi + \pi \rightarrow Z_c \rightarrow D + \bar{D}^*$. The amplitude for this process can be written as

$$M_Z = \frac{\alpha_{J/\psi \pi} \alpha_{D \bar{D}^*}}{s - M_Z^2 + i M_Z \Gamma_Z} \times \left(-g_{\mu\nu} + \frac{p^\mu k^\nu}{M_Z^2}\right) e^{\alpha}(k)e^{\alpha^*}(p'),$$

(3)

where $M_Z$ and $\Gamma_Z$ represent the mass and width of the $Z_c(3900)$ respectively. Also, $\alpha_{J/\psi \pi}$ and $\alpha_{D \bar{D}^*}$ are the couplings of the $Z_c$ to the $J/\psi \pi$ and to the $D \bar{D}^*$ states, respectively.

The state $Z_c(4025)$, which is assumed to be a $J^P(J^{PC}) = 1^+(2^{++})$ resonance, opens another s-channel for $J/\psi$ interactions: $J/\psi + \rho \rightarrow Z_c(4025) \rightarrow D^* + \bar{D}^*$. The amplitude of this process is given by:

$$M_{Z'} = \frac{\eta_{J/\psi \rho} \eta_{D^* \bar{D}^*}}{s - M_{Z'}^2 + i M_{Z'} \Gamma_{Z'}} \times P^{\mu\nu\alpha\beta}(q)\epsilon_\rho(k)\epsilon_\rho^*(p')\epsilon_\rho^*(k'),$$

(4)

where $M_{Z'}$ and $\Gamma_{Z'}$ are the mass and width of the $Z_c(4025)$ respectively. $\eta_{J/\psi \rho}$ and $\eta_{D^* \bar{D}^*}$ are the couplings of $Z_c(4025)$ to the channels $J/\psi \rho$ and $D^* \bar{D}^*$ and $P^{\mu\nu\alpha\beta}(q)$ is the spin 2 projector. The coupling constants $\eta_{J/\psi \rho}$ and $\eta_{D^* \bar{D}^*}$ were estimated in previous works.

In Fig. 1 we show the cross sections of the processes $J/\psi + \pi \rightarrow (Z_c(3900)) \rightarrow D + \bar{D}^*$ (top left), $D + \bar{D}^* \rightarrow (Z_c(3900)) \rightarrow J/\psi + \pi$ (top right), $J/\psi + \rho \rightarrow (Z_c(4025)) \rightarrow D^* + \bar{D}^*$ (bottom left) and $D^* + \bar{D}^* \rightarrow (Z_c(4025)) \rightarrow J/\psi + \rho$ (bottom right). The solid lines show the results obtained without the new resonances and the dashed lines show the effect of including the $Z_c(3900)$ and $Z_c(4025)$. As can be seen the effect of the new resonances is small.

IV. TIME EVOLUTION OF THE $J/\psi$ ABUNDANCE

For each cross section mentioned above we can compute the thermally averaged cross section, which for a given process $ab \rightarrow cd$ is given by

$$\Sigma_{ab \rightarrow cd} = \frac{\int d^3 p_a d^3 p_b f_a(p_a) f_b(p_b) \sigma_{ab \rightarrow cd} v_{ab}}{\int d^3 p_a d^3 p_b f_a(p_a) f_b(p_b)}$$

(5)

where $v_{ab}$ represents the relative velocity of initial two interacting particles $a$ and $b$ and the function $f_i(p_i)$ is the Bose-Einstein distribution (of particles of species $i$), which depends on the temperature $T$. With the help of (5) we can study the time evolution of the $J/\psi$ abundance in a hot hadronic medium. The momentum-integrated evolution equation has the form:

$$\frac{dN_{J/\psi}}{d\tau} = \sum_{a,b} \sum_\phi \Sigma_{ab \rightarrow \phi J/\psi} n_a N_b - \Sigma_{\phi \rightarrow J/\psi ab} n_\phi N_{J/\psi}$$

(6)

where $n_a(\tau)$ are $N_c(\tau)$ denote the density and the abundances of $\pi, \rho, K, K^*$, charmed mesons and their antiparticles in hadronic matter at proper time $\tau$. $a$ and $b$ are $D, D^*, D_s$ and $D_s^*$ mesons and their antiparticles.

We assume that $\pi, \rho, K, K^*$, $D$ and $D^*$ are in equilibrium. Therefore the density $n_i(\tau)$ can be written as

$$n_i(\tau) \approx \frac{1}{2\pi^2 \gamma_i g_i m_i^2 T(\tau)} K_2 \left(\frac{m_i}{T(\tau)}\right),$$

(7)

where $\gamma_i$ and $g_i$ are respectively the fugacity factor and the degeneracy factor of the relevant particle. The abundance $N_i(\tau)$ is obtained by multiplying the density $n_i(\tau)$ by the volume $V(\tau)$. The time dependence is introduced through the temperature $T(\tau)$ and volume $V(\tau)$ profiles appropriate to model the dynamics of relativistic heavy ion collisions after the end of the quark-gluon plasma phase. The hydrodynamical expansion and cooling of the hadron gas is modeled by the boost invariant Bjorken flow with an accelerated transverse expansion:

$$T(\tau) = T_C - (T_H - T_F) \left(\frac{\tau - \tau_H}{\tau_F - \tau_H}\right)^{\frac{2}{3}} \quad V(\tau) = \pi \left[R_C + v_C (\tau - \tau_C) + \frac{a_C}{2} (\tau - \tau_C)^2\right]^2 \tau_C.$$
FIG. 1: $J/\Psi$ absorption (top left) and production (top right) cross sections by $\pi$'s. The solid lines represent the cross sections obtained without including the $Z_c$ (3900) exchange in the s-channel. The dashed lines show the results with the exchange of $Z_c$ (3900) in the s-channel included. Bottom panels show the $J/\Psi$ absorption (bottom left) and production (bottom right) cross sections by $\rho$'s. The solid lines in these panels show the cross sections obtained without including the $Z_c$ (4025) exchange in the s-channel. The dashed lines show the results obtained by including the $Z_c$ (4025) exchange in the s-channel.

In the equation above, $R_C$ and $\tau_C$ denote the final transverse and longitudinal sizes of the quark-gluon plasma, while $v_C$ and $a_C$ are its transverse flow velocity and transverse acceleration at this time. $T_C = 175$ MeV is the critical temperature for the quark-gluon plasma to hadronic matter transition; $T_H = T_C = 175$ MeV is the temperature of the hadronic matter at the end of the mixed phase, occurring at the time $\tau_H$. The freeze-out temperature $T_F = 125$ MeV then leads to a freeze-out time $\tau_F$. We show results for the $J/\psi$ evolution in the hadron gas formed in two types of collisions: central $Au - Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC and central $Pb - Pb$ collisions at $\sqrt{s_{NN}} = 5$ TeV at the LHC. The parameters which we need as input are taken from the phenomenological studies of the EXHIC Collaboration [7].

In Fig. 2, we present the time evolution of the $J/\psi$ abundance as a function of the proper time for the two types of collisions discussed above: at RHIC (on the left panel) and at the LHC (on the right panel). The different curves represent the interactions: only $J/\psi\pi$ (solid lines); adding $J/\psi\rho$ (dashed lines); adding $J/\psi K$ (dotted lines) and adding also $J/\psi K^*$ (dash-dotted lines).

While the cross sections alone would lead to an enhancement of the $J/\psi$ yield, the relative multiplicities favor its reduction, since in the hadron gas there are much more pions and kaons (which hit and destroy the charmonium states) than $D$’s, $\bar{D}$’s, $D_s$’s and $\bar{D}_s$’s (which can collide and create them). The result of this competition is a decrease
FIG. 2: Left: Time evolution of $J/\psi$ abundance as a function of the proper time in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Solid, dashed, dotted, dot-dashed lines represent the situations with only $\pi - J/\psi$ interactions and also adding the $\rho - J/\psi$, $K - J/\psi$ and $K^* - J/\psi$ contributions, respectively. Right: the same as on the left for LHC conditions.

of the $J/\psi$ yield of approximately 20 % at RHIC and 24 % at the LHC.

V. SUMMARY

In this note we have described how to improve the study of $J/\psi$ interactions in a hadron gas (in the effective Lagrangian approach) in two aspects: the inclusion of processes with $K$ and $K^*$ in the initial and final states and the inclusion of processes with $Z_c(3900)$ and $Z_c(4025)$ in the intermediate states. We conclude that the interactions between $J/\psi$ and all the considered mesons reduce the original $J/\psi$ abundance (determined at the end of the quark gluon plasma phase) by 20 % and 24 % in RHIC and LHC collisions respectively. Consequently, any really significant change in the $J/\psi$ abundance comes from dissociation and regeneration processes in the QGP phase. More details can be found in [4].

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