Charmonium dissociation by mesons in heavy-ion collisions

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The charmonium dissociation by mesons in relativistic heavy-ion reactions is analyzed within the Regge approach. It is shown that the inclusion of the initial and final state interactions in the dissociation of $J/\Psi$ to $\bar{D}^*D^*$ close to threshold increases the cross section significantly and can not be neglected in comparison to the total dissociation rate. This is due to resonant $\bar{D}^*-D^*$ interactions in $\sqrt{s}$ close to the masses of the $\Psi(4.04)$ and $\Psi(4.16)$ mesons. We also investigate thermal effects of the $(c\bar{c})$ width for such processes in the medium. All these effects change both the magnitude and the shape of the cross section as a function of $\sqrt{s}$. The results obtained should be applied in the analysis of open and hidden charm production in heavy-ion collisions.

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In the last decade the search for a quark-gluon plasma (QGP) has been intensified in line with the development of new experimental facilities \cite{1}. For instance, the $J/\Psi$-meson plays a significant role in the context of a phase transition to the QGP \cite{2} where charmonium $(c\bar{c})$ states might no longer be formed due to color screening \cite{3,4}. However, the suppression of $J/\Psi$ and $\Psi'$ mesons in the high density (hadronic) phase of nucleus-nucleus collisions \cite{5,6} might also be attributed to inelastic comover scattering (cf. \cite{7,8} and references therein), provided that the corresponding $J/\Psi$-hadron cross sections are in the order of a few mb \cite{9,10}. Present theoretical estimates here differ by more than an order of magnitude \cite{11} especially with respect to $J/\Psi$-meson scattering such that the question of charmonium suppression is not yet settled. Moreover, the calculation of these cross sections within the chiral Lagrangian approach results in either a constant or a slowly increasing cross section with energy \cite{9,10,12,13} that contradicts the true Regge asymptotics predicting a decrease with energy. The inclusion of meson structure and the introduction of meson form factors in this Lagrangian model lead to a large uncertainty for the shape and the magnitude of the $J/\Psi$ dissociation cross sections by mesons.

The amplitude of the reactions have to satisfy the Regge asymptotics at large $s$. For the elastic and the total hadron-proton cross section the relation of their true Regge asymptotics to the hadron form factors has been discussed in \cite{14}. Here we will find a
similar relation for $\bar{D}D^*$ production in $\pi(\rho)J/\Psi$ collisions. In Refs. [15, 16] the cross section of the reaction $\pi N \rightarrow \bar{D}(D^*)\Lambda_c$ was estimated within the framework of the Quark-Gluon String Model (QGSM) developed in Ref. [17]. The QGSM is a nonperturbative approach based on a topological $1/N$ expansion in QCD and on Regge theory. This approach can be considered as a microscopic model describing Regge phenomenology in terms of quark degrees of freedom. It provides a possibility of establishing relations between many soft hadronic reactions as well as masses and partial widths of resonances with different quark contents (see e.g. [18]).

The QGSM has been applied in Refs.[15, 20] to analyze the $p\bar{p}$ and $\pi(\rho)J/\Psi$ binary reactions, respectively. It has been shown [20] that the dissociation cross section of $J/\Psi$ by pions has a maximum value of a few mb at energies close to threshold and is decreasing smoothly with energy furtheron. Approximately the same result has been obtained in Ref.[21] within the relativistic quark model. The main contribution to this process stems from $\pi + J/\Psi \rightarrow \bar{D}D^*$ and $\pi + J/\Psi \rightarrow \bar{D}D^0$ channels. The $J/\Psi$ dissociation by pions to a $\bar{D}^*D^*$ pair usually is neglected because its cross section is estimated to be small (cf. Ref. [22]). However, the $\bar{D}^*-D^*$ interaction has a resonance form at invariant energies corresponding to the masses of the $\Psi(4.04)$ and $\Psi(4.16)$ mesons (cf. Fig.1 (lhs)).

In this contribution we focus on the analysis of the $J/\Psi$ dissociation by pions to $\bar{D}^*D^*$ mesons to show that the resonance form of the $\bar{D}^*-D^*$ cross section increases the cross section of this channel by a large amount. We include both the initial (ISI) and the final state interactions (FSI).

The amplitude of a binary reaction $a + b \rightarrow c + d$ in the impact parameter space including the ISI and FSI within the quasieikonal approximation can be presented in the
\[ \mathcal{M}(s, b, z) = \mathcal{M}_R(s, b, z) \exp \left( -[\chi^\alpha(s, b, z) + \chi^\beta(s, b, z)] \right), \]

where

\[ \chi^\alpha(s, b, z) = \frac{\sigma_{ab}^{\text{tot}} C}{4\pi \Lambda_P} \exp(-\frac{b^2}{2\Lambda_P}) \frac{1}{2\sqrt{2\Lambda_P \pi}} \int_{-\infty}^z \exp(-\frac{y^2}{2\Lambda_P}) dy, \]

and

\[ \chi^\beta(s, b, z) = \frac{\sigma_{cd}^{\text{tot}} C}{4\pi \Lambda_P} \exp(-\frac{b^2}{2\Lambda_P}) \frac{1}{2\sqrt{2\Lambda_P \pi}} \int_{z}^{\infty} \exp(-\frac{y^2}{2\Lambda_P}) dy, \]

\[ \mathcal{M}_R(s, b, z) = \frac{1}{(2\pi)^{3/2}} \int d^2 q_d dq_z \mathcal{M}_R(s, q_d, q_z) e^{i q_d b} e^{i q_z z}, \]

\[ = \mathcal{M}_R(s, t = 0) \exp(\frac{q_0^2 \Lambda_R/2}{2}) \exp \left( -\frac{b^2 + z^2}{2\Lambda_R} \right), \]

where \( C \) is the so-called “enhancement factor” including possible inelastic diffractive rescattering (cf. Refs. [19, 20]), \( \sigma_{ab}^{\text{tot}} \) and \( \sigma_{cd}^{\text{tot}} \) are the total cross sections for \( \pi - J/\Psi \) and \( D^* - D^* \) interactions. Here (cf. Refs. [15, 16]),

\[ \mathcal{M}_{\pi(p, p)}(s, t) = C_I \frac{g_1^2}{f(t)} (s/s_0)^{\alpha_{\pi}(t)} \exp(\frac{q_0^2 \Lambda_R/2}{2}), \]

where the isotopic factor \( C_I = \sqrt{2} \) for \( \pi^\pm(p)^\pm J/\Psi \) and \( C_I = 1 \) for \( \pi^0(\rho^0)J/\Psi \) reactions, respectively [18]. \( g_1^2 = (M_{\pi/\rho}^2) g_0^2 \) is the universal coupling constant and \( g_0^2/4\pi = 2.7 \) is determined from the width of the \( \rho \)-meson [15]. \( \alpha_{\pi}(t) = \alpha_{D^*} = \alpha_{D^*}(t) \) is the \( D^* \)-Regge trajectory, \( s = 1 \). \( (GeV)^2 \) is a universal dimensional factor, \( s_0 = 4.9 \ (GeV)^2 \) is the flavor-dependent scale factor which is determined by the mean transverse mass and the average momentum fraction of quarks in colliding hadrons [15], while \( F(t) \) is a form factor describing the \( t \) dependence of the residue (cf. Refs. [15, 16]). We assume – as in Refs. [15, 16] – that the \( D^* \)-Regge trajectory is linear in \( t \) and therefore can be expanded in the transfer \( t \) as: \( \alpha_{D^*}(t) = \alpha_{D^*}(0) + \alpha'_{D^*}(0) t \). The intercept \( \alpha_{D^*}(0) = -0.86 \) and the slope \( \alpha'_{D^*}(0) = 0.5 \text{GeV}^{-2} \) are found from their relations to the same quantities for the \( J/\Psi \) and \( \rho \) trajectories which are known [15]. Finally the scattering amplitude is

\[ \mathcal{M}(s, t) = \frac{1}{(2\pi)^{3/2}} \exp(\frac{q_0^2 \Lambda_R/2}{2}) \int d^2 b dz \mathcal{M}(s, b, z) e^{-i q_d b} e^{-i q_z z}, \]

where \( t = q_0^2 - q_x^2 - q_y^2 \) is the square of the four-momentum transferred having the components \( q_0, q_x, q_y \), \( \Lambda_R = 2\alpha_{D^*}(0)\ln(\frac{s_0}{s}) \) and \( \Lambda_P = 2\alpha_{D^*}(0)\ln(\frac{s_0}{s_0}) \), where \( \alpha_{D^*}(0) = 0.2 \text{GeV}^{-2} \) is the slope of the Pomeron trajectory [17]. One can see that for \( \sigma_{ab}^{\text{tot}} = \sigma_{cd}^{\text{tot}} \) the amplitude \( \chi(s, b, z) \) becomes the conventional phase function \( \chi(s, b) \) (cf. Ref. [19]). The cross section \( \sigma_{\pi J/\Psi}^{\text{tot}} \) is estimated assuming that \( \sigma_{\pi J/\Psi}^{\text{tot}} / \sigma_{\pi p}^{\text{tot}} = < r^2_{J/\Psi} > / < r^2_p > \), where \( \sigma_{\pi p}^{\text{tot}} \) and the square of the proton radius are well known experimentally, whereas the square of the \( J/\Psi \) radius \( < r^2_{J/\Psi} > \) has been taken from the calculation in Ref. [14]. The following \( D^* - D^* \) cross section has been calculated as in Ref. [23] in Breit-Wigner resonance form
and is presented in Fig.1. Furthermore, the dissociation rate of the charmonium \( (c \bar{c}) \) in a medium depends on the temperature \( T \). Such thermal effects can be incorporated in an increasing \( (c \bar{c}) \) width which broadens the shape of the cross section \( \sigma_{D^*D^*} \) slightly as seen from the lhs of Fig.1.

The cross section of \( J/\Psi \) dissociation to \( \bar{D}^0D^{++} \) by \( \pi^+ \) as a function of \( \sqrt{s} \) is presented in the rhs of Fig.1 which shows that the inclusion of the ISI, FSI and the thermal effects for the charmonium in a medium (solid line) lead to an increase of the cross section by a factor of \( 4 - 5 \). Note that the calculated cross section neglecting all these effects (dotted curve in the rhs of Fig.1) is similar to the results presented in Ref.[22]. The inclusion of all isotopic channels for the reaction \( \pi + J/\Psi \rightarrow \bar{D}^*D^* \) will increase the cross section in Fig.1 (rhs) at least by another factor of \( 4 - 5 \). Therefore the discussed type of the \( J/\Psi \) dissociation by pions can be comparable to the conventional channel \( \pi + J/\Psi \rightarrow \bar{D} + D^* \). The same conclusion applies to the \( J/\Psi \) dissociation to \( \bar{D}^*D^* \) by \( \rho \)- and \( \omega \)-mesons. Therefore the inclusion of the discussed effects is very important for the analysis of hidden and open charm production in heavy-ion collisions.

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