Cross Sections for π- and ρ-induced Dissociation of J/ψ and ψ'

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Abstract

We evaluate the cross sections for the dissociation of J/ψ and ψ' by π and ρ at low collision energies, using the quark-interchange model of Barnes and Swanson. The dissociation cross section for J/ψ by π is found to be relatively small with a maximum of about 1 mb and a kinetic energy threshold of 0.65 GeV. The pion-induced ψ' dissociation cross section is found to be much larger, with a maximum of about 5 mb and a lower threshold. Dissociation cross sections for J/ψ and ψ' by ρ mesons are also evaluated and are found to be large near threshold.

The suggestion by Matsui and Satz [1] that J/ψ production might be suppressed in a quark-gluon plasma has led to many experimental and theoretical studies of J/ψ production in high-energy heavy-ion collisions. The experimental observation by NA50 [2,3] of anomalous J/ψ suppression in Pb+Pb collisions in particular has been studied by many authors [4–11].

The evolution of a J/ψ or ψ' produced in a heavy-ion collision depends sensitively on charmonium dissociation cross sections, which arise from processes such as low-energy inelastic scattering of the $c\bar{c}$ state on π or ρ into open-charm final states. Small J/ψ dissociation cross sections by π or ρ may favor an interpretation of the Pb+Pb data in terms of the production of a new phase of matter, possibly the quark-gluon plasma. In contrast, a large ρ+J/ψ dissociation cross section might imply that ρ+J/ψ inelastic scattering may be an important part of the Pb+Pb anomaly because the density of ρ mesons increases approximately quadratically as the density of pions increases. In view of the importance of these dissociation cross sections for the interpretation of heavy-ion collisions, they should be evaluated and incorporated in Monte Carlo simulations before any final conclusions are reached regarding the underlying physics.

The dissociation of J/ψ by light mesons has been considered previously by several groups [12–16]. Unfortunately, the numerical cross sections quoted in these references span a considerable range, due largely to different assumptions regarding the dominant scattering mechanism.

Kharzeev, Satz, and collaborators [12,13] used the parton model and perturbative QCD "short-distance" approach of of Bhanot and Peskin [17,18], and found remarkably small low-energy cross sections for J/ψ on light hadrons. For example, their J/ψ+N cross section at $\sqrt{s} = 5$ GeV is only about 0.25 μb [12]. A finite-mass correction increases this cross section by about a factor of two [13]. However, in high-energy heavy-ion reactions, the collisions between the produced π and ρ with J/ψ and ψ' occur at low energies (of the order of a few hundred MeV to about 1 GeV relative kinetic energies). The applicability of the parton model and pQCD for reactions at this low energy region is open to question.

Matinyan and Müller [14], Haglin [15,19], and Lin [20] recently reported results for these dissociation cross sections in meson exchange models. They use effective meson Lagrangians and assume t-channel D and D^* meson exchange, which leads to numerical results for $\pi+J/\psi$ and $\rho+J/\psi$ dissociation cross sections. Matinyan and Müller found that these cross sections are rather small; both are $\approx$ 0.2-0.3 mb at $\sqrt{s} = 4$ GeV. Including form factors (arbitrarily chosen to be Gaussian with a width set to 1.5 GeV) would reduce the cross section by an order of magnitude. Haglin obtained a very different result, with much larger cross sections, by treating the D^* and $\bar{D}^*$ mesons as non-Abelian gauge bosons in a minimally-coupled Yang-Mills meson Lagrangian. Form factors were introduced in later calculations and the mb-scale cross sections are sensitive to the choices of the form factors [20,19]. Of course the use of a Yang-Mills Lagrangian for charmed mesons has no *a priori* justification, so the crucial initial assumption made in these references would require independent confirmation. In any case, the assumption of t-channel exchange of a heavy meson such as a D or D^* between π and J/ψ with point-like couplings is difficult to justify because the range of these exchanges ($1/M \approx 0.1$ fm) is much smaller than the physical sizes of the initial π and J/ψ mesons.

Charmonium dissociation processes can presumably be described in terms of the fundamental quark and gluon interactions, but are of greatest phenomenological interest at energy scales in the resonance region. For this reason, we advocate the use of the known quark-gluon forces to specify the underlying scattering amplitude, which must then be convolved with explicit nonrelativistic quark model hadron wavefunctions for the initial and final mesons.

Martins, Blaschke, and Quack [16] previously reported dissociation cross section calculations using essentially the approach we describe. The short-distance interaction used by these authors in particular is quite similar to the form we employ. For the confining interaction, however, they used a simplified color-independent Gaussian potential between quark-antiquark pairs only, rather than the now well-established linear $\boldsymbol{\lambda}(i) \cdot \boldsymbol{\lambda}(j)$ form. They found a rather large $\pi+J/\psi$ dissociation cross section which reached a maximum of about 7 mb at the kinetic energy in the center-of-mass system E_{KE} of about 0.85 GeV.

Although our approach is very similar to that of Martins *et al.*, our final numerical results differ significantly, due mainly to the modeling of the confining interaction.

In this paper we use the approach discussed above to evaluate the dissociation cross sections of J/ψ by π and ρ, and compare our results to other theoretical cross sections reported in the literature [12–16]. We also calculate cross sections for the dissociation of ψ' by π and ρ, which have not been evaluated elsewhere.

We employ the Barnes-Swanson quark-interchange model [21,22] to determine these dissociation amplitudes. This approach uses the nonrelativistic quark potential model and its interquark Hamiltonian to describe hadron-hadron interactions and therefore implicitly incorporates the successes of the quark model in describing the hadron spectrum and many static properties of hadrons. The model parameters are fixed by fits to the meson spectrum, so there is little additional freedom in determining scattering amplitudes and cross sections. One proceeds by calculating the scattering amplitude for a given process at Born order in the interquark Hamiltonian. In the case of meson-meson scattering, this scattering amplitude is given by the sum of the four quark line diagrams shown in Fig. 1. These are evaluated as overlap integrals of quark model wavefunctions, using the "Feynman rules" given in App. C of Ref. [21]. This method has previously been applied successfully to the closely related no-annihilation scattering channels $I=2$ $\pi\pi$ [21], $I=3/2$ $K\pi$ [23], $I=0,1$ S-wave KN scattering [24] and the short-range repulsive NN interaction [25].

Following Ref. [22], the interaction between each pair of constituents i and j is taken to be

$$\begin{aligned} H_{ij} &= \frac{\boldsymbol{\lambda}(i)}{2}\cdot\frac{\boldsymbol{\lambda}(j)}{2}\left\{V_{\rm colorCoulomb}(r_{ij}) + V_{\rm linear}(r_{ij}) + V_{\rm spin-spin}(r_{ij}) + V_{\rm con}\right\} \\ &= \frac{\boldsymbol{\lambda}(i)}{2}\cdot\frac{\boldsymbol{\lambda}(j)}{2}\left\{\frac{\alpha_s}{r_{ij}} - \frac{3}{4}br_{ij} - \frac{8\pi\alpha_s}{3m_im_j}\boldsymbol{S}_i\cdot\boldsymbol{S}_j\left(\frac{\sigma^3}{\pi^{3/2}}\right)e^{-\sigma^2 r_{ij}^2} + V_{\rm con}\right\}. \end{aligned} \tag{1}$$

This Hamiltonian is derived in the Coulomb gauge, which is the most convenient gauge for bound states and low-energy phenomena. The model parameter α_s is the strong coupling constant, b is the string tension, m_i and m_j are the interacting quark or antiquark masses, and σ is a range parameter in the Gaussian-smeared spin-spin hyperfine interaction. A constant shift V_{con} is also included in the interaction. For antiquarks the generator $\boldsymbol{\lambda}/2$ is replaced by $-\boldsymbol{\lambda}^T/2$.

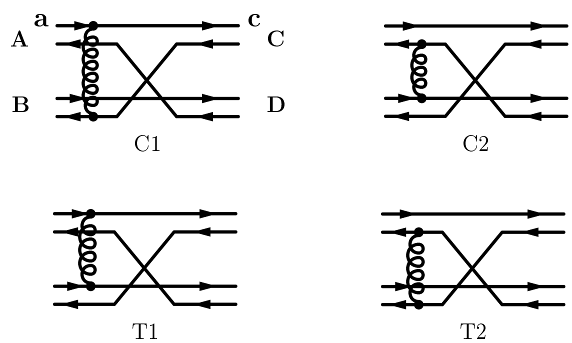

Fig. 1. Born-order quark line diagrams.
For example, a specific channel is $A = J/\psi$, $B = \pi^+$, $C = D^+$ and $D = \bar{D}^*$.

The model parameters we employed were $\alpha_s = 0.58$, $b = 0.18$ GeV^2, $\sigma = 0.897$ GeV, $m_u = m_d = 0.345$ GeV, $m_c = 1.931$ GeV and $V_{con} = -0.612$ GeV. This set of parameters gives masses within 0.08 GeV of experiment for the π, ρ, $D(1869)$, $D^*(2010)$, J/ψ, and ψ' mesons and also provides a very good description of the $I = 2$ S-wave $\pi\pi$ phase shift. An alternative set of parameters, found by fitting a large set of experimental masses, is $\alpha_s = 0.594$, $b = 0.162$ GeV^2, $\sigma = 0.897$ GeV, $m_u = m_d = 0.335$ GeV and $m_c = 1.6$ GeV. This second set, with a flavor-dependent V_{con}, was used to test the sensitivity of our results to parameter variations.

Before proceeding to our results, we note that the well-known "post-prior ambiguity" arises in calculations of bound state scattering amplitudes involving rearrangement collisions [26]. Since the Hamiltonian which describes the scattering process $AB \to CD$ can be separated into free and interaction parts in two ways, $H = H_A^{(0)} + H_B^{(0)} + V_{AB}$ or $H_C^{(0)} + H_D^{(0)} + V_{CD}$, there is an ambiguity in the choice of V_{AB} or V_{CD} as the interaction Hamiltonian. The first version is known as the "prior" form and leads to the scattering diagrams of Fig.

1, in which the interactions occur before quark interchange. The second choice is the "post" form, which leads to diagrams in which the interactions occur after quark interchange. One may show that the post and prior expressions for the scattering amplitude are equal, provided that exact eigenfunctions of the free Hamiltonians are used for the asymptotic states [26]. (The relevance of this to time reversal invariance is demonstrated numerically in Ref. [22].) In our calculations we employ numerically determined Hamiltonian eigenfunctions for each of the external meson states considered; in the nonrelativistic case this would suffice to eliminate the post-prior discrepancy. In the processes considered here we have used relativistic kinematics and phase space, but use Galilean boosts for the states, as appropriate for a nonrelativistic quark model calculation. In consequence we find that the post and prior scattering amplitudes differ slightly. (We note in passing that one could carry out a relativised version of this calculation, although the full relativistic boosts would induce small additional effects due to Wigner rotations and creation of quarks and gluons.) In this paper we use the mean of the post and prior results as our theoretical cross section, and the estimated errors due to the post-prior discrepancy and parameter variations are indicated by bands in the figures.

The cross sections we obtain for the dissociation of J/ψ and ψ' by π are shown in Fig. 2 as a function of the kinetic energy in the center of mass system, $E_{KE} = \sqrt{s} - M_A - M_B$, where M_A and M_B are the rest masses of the colliding particles in the initial channel. The lowest-lying allowed final states are $\bar{D}^*D$, $\bar{D}D^*$, and $\bar{D}^*D^*$, and the total dissociation cross section is taken to be the sum of these three channel cross sections; this is shown as a solid line in the figure. (The reactions $\pi{+}J/\psi \to \bar{D}D$ and $\pi{+}\psi' \to \bar{D}D$ are $\Delta S \neq 0$ transitions allowed in QCD but have zero transition matrix elements in our Hamiltonian (1). These transition amplitudes would be nonzero for example if we included spin-orbit terms in (1). The relatively weak process $\pi{+}J/\psi \to \bar{D}D$ has been considered in a Dyson-Schwinger formalism by Blaschke *et al.* [27], who find a maximum cross section of about 0.1 mb near threshold. Note that the S-wave to S-wave transition is absolutely forbidden, so although $\pi{+}\psi' \to \bar{D}D$ is actually exothermic, it does not lead to a divergent cross section at threshold.)

The π+J/ψ dissociation process is endothermic and requires an initial kinetic energy of 0.65 GeV. The cross section shows a rapid rise above threshold (as expected for an S-wave process) and has a broad maximum of about 1 mb not far above threshold (Fig. 2*a*). This is somewhat smaller than the ≈ 7 mb estimated by Martins *et al.*, which we discuss below.

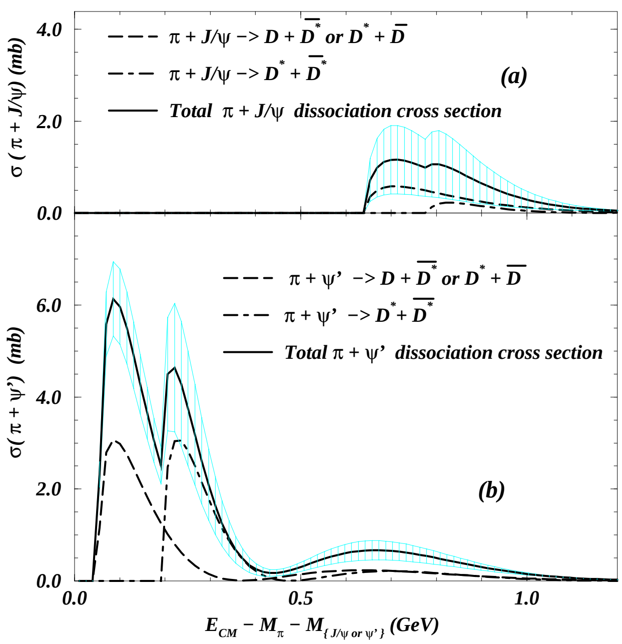

Fig. 2. Cross sections for pion-induced dissociation of J/ψ (Fig. 2*a*) and ψ' (Fig. 2*b*). The solid curves give the total dissociation cross section. Estimated systematic errors due to parameter uncertainties and the post-prior discrepancy are shown as bands.

The cross section for dissociation of the ψ' by π is rather larger in part because this reaction is only weakly endothermic; the initial π+ψ' kinetic energy in $\pi+\psi' \to \bar{D}D^*$ and $D\bar{D}^*$ is only about 0.05 GeV at threshold. The total cross section reaches a maximum of about 6.2(0.8) mb at the kinetic energy of about 0.1 GeV and has a secondary maximum of 4.6(1.8) mb at the kinetic energy of about 0.22 GeV due to the opening of the $D^*\bar{D}^*$ channel. Notice that the ratio of the peak values of the π+ψ' and π+J/ψ cross sections is roughly 6; this should be contrasted with the prediction of ~ 5000 given in Ref. [17]. The minimum in the cross section near the kinetic energy of 0.4 GeV is due to the complete destructive interference between transfer (T1 and T2) and capture (C1 and C2) diagrams.

We next calculate the ρ+J/ψ and ρ+ψ' dissociation cross sections. The allowed low-lying final states are $D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}$ ($S_{tot} = 0,1$), and $D^*\bar{D}^*$ ($S_{tot} = 0,1,2$). These cross sections are shown in Fig. 3. Since the reaction $\rho + J/\psi \to D\bar{D}$ is exothermic, this cross section diverges as $1/|\vec{v}_{\rho J/\psi}|$ near threshold. For other channels the thresholds occur at higher energies, so those subprocesses are endothermic. The total dissociation cross section is shown as a solid line in Fig. 3. It is numerically about 11(3) mb at a kinetic energy of 0.1 GeV, decreasing to 6(2) mb at a kinetic energy of 0.2 GeV.

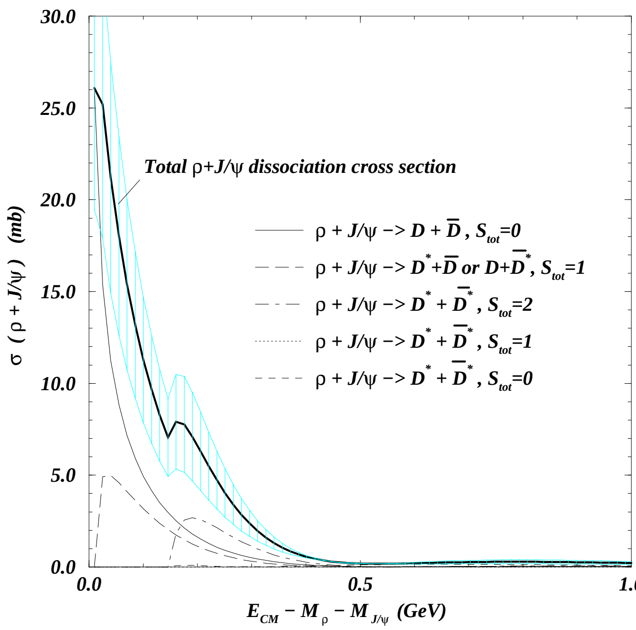

Fig. 3. Total and individual channel cross sections J/ψ dissociation by ρ.

In the case of ρ+ψ' dissociation, all the channels we consider are exothermic, so the low-energy divergence is quite pronounced. Our numerical results for these cross sections are shown in Fig. 4. The total cross section decreases from 15(2) mb to 6(2) mb as the kinetic energy increases from 0.1 to 0.2 GeV.

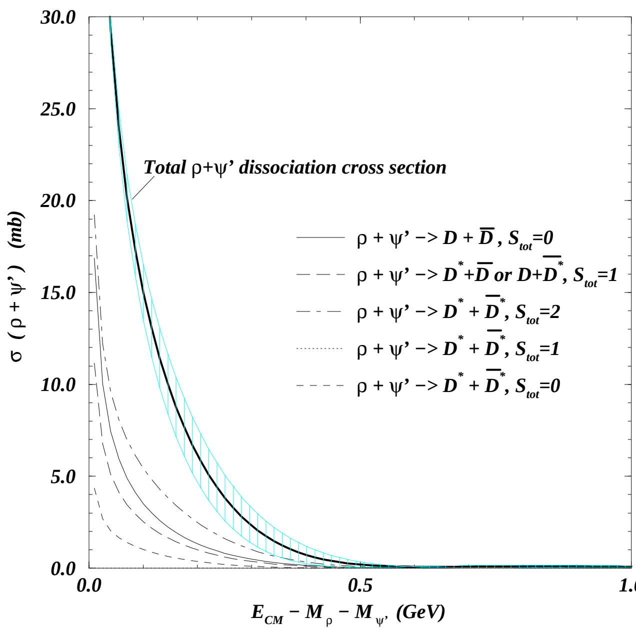

Fig. 4. Total and individual channel cross sections for ψ' dissociation by ρ.

We previously noted that our $\pi+J/\psi$ cross section is considerably smaller than the estimate of Ref. [16], although we use a similar approach. There are several differences between the two approaches which lead to this discrepancy. Martins *et al.* assumed that the confining interaction is an attractive Gaussian potential which acts only between quark-antiquark pairs. The neglect of the quark-quark and antiquark-antiquark confining interaction amounts to discarding the transfer diagrams (T1 and T2) for the confining potential. Since we find that the transfer and capture diagram confinement contributions are similar in magnitude but opposite in sign (due to color factors), Martins *et al.* did not include an important destructive interference. Their use of a Gaussian rather than a linear potential will obviously lead to quantitatively different cross sections. Furthermore, the cross section values are quite sensitive to the parameters used when T1 and T2 are not included. All these factors contribute to the differences between our results and those of Martin *et al*. for $\pi+J/\psi$ collisions.

The destructive interference between transfer and capture diagrams with spin-independent forces (color Coulomb and confinement) has been noted previously (see, for example, Refs. [21,22] and references cited in [25]). This interference explains the well-known spin-spin hyperfine dominance in light hadron scattering in channels such as $I = 2$ $\pi\pi$ and NN. In the presence of heavy quarks, however, most hyperfine interaction diagrams are suppressed by the large charm quark mass; this is the reason we included the color Coulomb and confining interactions in the present analysis. It is interesting in retrospect to examine the different channels and determine which of the various interactions dominates the amplitude. We find that the hyperfine interaction still dominates the $\pi+J/\psi$ dissociation amplitude, whereas the linear confining interaction dominates $\pi+\psi'$, $\rho+\psi$, and (for the kinetic energy less than 0.3 GeV) $\rho+\psi'$. Above 0.3 GeV, the color Coulomb interaction dominates $\rho+\psi'$ scattering. (We caution the reader that this decomposition depends on the choice of the post or prior form for the T-matrix; the results we quote are for the prior form, involving the diagrams of Fig. 1.)

There is no direct experimental measurement of these cross sections to which we can compare our results. We found a small $\pi+J/\psi$ cross section which starts at a high threshold and a large $\pi+\psi'$ cross section which starts at a low threshold. If these cross sections are folded with a distribution of pions with an average kinetic energy of about 200 MeV, we would obtain $\sigma_{\text{effective}}(\pi + J/\psi) << \sigma_{\text{effective}}(\pi + \psi')$, which is consistent with earlier observation in a model of J/ψ and ψ' suppression in O+A, and S+U collisions [4]. Hopefully, future Monte Carlo simulations of the dynamics of charmonium in heavy-ion collisions will lead to a more direct comparison. The large $\rho+J/\psi$ and $\rho+\psi'$ cross sections we have found imply that both the J/ψ and ψ' will be quickly dissociated if there is a significant ρ meson population in the medium. Since our results on the divergence of $\rho+J/\psi$ and $\rho+\psi'$ dissociation cross sections at threshold follow directly from simple kinematics, these results must be qualitatively correct. The normalization of these cross sections, however, required detailed calculation and should also be compared to experiment if possible. Since dissociations of J/ψ by π and ρ populate different states (for example $\pi+J/\psi$ doe not lead to $D\bar{D}$ but $\rho+J/\psi$ does), it may be possible to separate these processes and their associated cross sections by studying the relative production of $D\bar{D}$, $D^*\bar{D}+h.c.$ and $D^*\bar{D}^*$

if the expected open charm background can be subtracted.

In the future it may be useful to carry out detailed simulations of J/ψ absorption in heavy-ion collisions using the cross sections obtained here to test the accuracy of our results. If our cross sections do prove to be reasonably accurate, it will clearly be useful to incorporate them in simulations of J/ψ suppression in Pb+Pb collisions and in other processes that use charmonium as a signature of the quark-gluon plasma in order to subtract the effects of J/ψ suppression due to its interaction with hadron matter.

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