CROSS SECTIONS FOR THE DISSOCIATION OF $J/\psi$ AND $\psi'$ BY $\pi$ AND $\rho$ AT LOW ENERGIES

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Abstract

Using the quark-interchange model of Barnes and Swanson, we evaluate the dissociation cross sections for $J/\psi$ and $\psi'$ by $\pi$ and $\rho$ at low collision energies. In collisions with $\pi$ mesons near threshold the $\pi+J/\psi$ dissociation cross section is predicted to be small, but the $\pi+\psi'$ cross section is found to be quite large, in qualitative agreement with experimental data on $J/\psi$ and $\psi'$ production in high-energy heavy-ion collisions. The $\rho+J/\psi$ and $\rho+\psi'$ dissociation cross sections are both predicted to be large numerically and are divergent near threshold. These $\rho+J/\psi$ and $\rho+\psi'$ cross sections show considerable sensitivity to the mass of the $\rho$ meson if it is off energy shell.

1 Introduction

In a high-energy heavy-ion collision, the fate of a $J/\psi$ or $\psi'$ produced in the collision depends sensitively on its dissociation cross sections with ordinary light hadrons. If we are to use $J/\psi$ production as an indicator of the formation of a quark-gluon plasma in a high-energy heavy-ion collision, as suggested by Matsui and Satz [1], we should concurrently evaluate the competing process of $J/\psi$ absorption by hadrons that are produced during the collision [2-10].

The dissociation of a $J/\psi$ by light mesons has been examined previously, but the cross sections from various analyses unfortunately differ considerably, due largely to different assumptions regarding the dominant scattering mechanism [11-18]. A description of the present calculations is found in Ref. [16].

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 the explicit non-relativistic quark model hadron wavefunctions of the initial and final mesons to obtain the dissociation cross section.

2 The model

The model of Barnes and Swanson, which we shall use to describe these processes, is a quark interchange model, with a quark-quark interaction taken from quark potential models [19]. In this model the meson-meson scattering amplitude is given by the sum of four quark line diagrams, which are shown in Fig. 1. These are evaluated as overlap integrals of quark model wavefunctions, using the “Feynman rules” given in App. C of Ref. [19]. This method has previously been applied successfully to the closely related no-annihilation scattering channels \( I = 2 \pi \pi \) [19], \( I = 3/2 K \pi \) [20], \( I = 0,1 \) S-wave \( KN \) scattering [21], and the short-range repulsive NN interaction [22].

![Fig. 1. Quark-exchange diagrams included in the calculation.](image)

The diagrams of Fig. 1 are the ‘prior’ forms; there are also ‘post’ forms, in which the interaction takes place after the interchange of the quarks. In the non-relativistic formulation one can show that these two forms are equivalent [23, 24], although we find small differences between them when we use relativistic kinematics for the initial and final mesons.

We take the interaction \( H_{ij}(r_{ij}) \) between quarks \( i \) and \( j \), represented by the curly line in Fig. 1, to be the conventional Coulomb plus linear plus spin-spin hyperfine interaction,

\[
H_{ij}(r_{ij}) = \frac{\lambda(i)}{2} \cdot \frac{\lambda(j)}{2} \left\{ \frac{\alpha_s}{r_{ij}} - \frac{3b}{4} r_{ij} - \frac{8\pi \alpha_s}{3m_i m_j} S_i \cdot S_j \frac{\sigma^3}{\pi^{3/2}} e^{-\sigma^2 r_{ij}^2} + V_{con} \right\}, \tag{1}
\]

where \( \alpha_s \) is the strong coupling constant, \( b \) is the string tension, \( m_i \) and \( m_j \) are the masses of the interacting constituents, and \( \sigma \) is the range parameter in the
Gaussian-regularized contact hyperfine term. (For antiquarks, the generator $\lambda/2$ is, as usual, replaced by $-\lambda T/2$.) We used the parameter set

$$\alpha_s = 0.58, \quad b = 0.18 \text{ GeV}^2, \quad \sigma = 0.897 \text{ GeV},$$

$$m_u = m_d = 0.345 \text{ GeV}, \quad m_c = 1.931 \text{ GeV}, \quad V_{con} = -0.612 \text{ GeV}, \quad (2)$$

which gives a reasonably accurate description of the $q\bar{q}$ meson spectrum and, when applied to scattering, also gives an $I = 2 \pi\pi$ phase shift, which is in good agreement with experiment. This Hamiltonian was used in the nonrelativistic Schrödinger equation to generate $q\bar{q}$ wavefunctions, which were in turn used with the same Hamiltonian in the diagrams of Fig. 1 to evaluate the scattering amplitudes and cross sections. We also used a second set of parameters, $\alpha_s = 0.594, \ b = 0.162 \text{ GeV}^2, \ \sigma = 0.897 \text{ GeV}, \ m_u = m_d = 0.335 \text{ GeV}, \ m_c = 1.6 \text{ GeV}$ and a flavor-dependent $V_{con}$, found by fitting a large set of experimental masses, to test the sensitivity of our results to parameter variations.

3 Cross section for the dissociation of $J/\psi$ and $\psi'$ by $\pi$

The dissociation of $J/\psi$ and $\psi'$ by pions of sufficient energy can lead to many different open-charm channels. In $\pi + J/\psi$ and $\pi + \psi'$ collisions the channels with the lowest thresholds are $D\bar{D}^*$, $D^*\bar{D}$, and $D^*\bar{D}^*$.

![Graphs showing cross sections](image)

Fig. 2. Total and partial $\pi + J/\psi$ (Fig. 2a) and $\pi + \psi'$ (Fig. 2b) dissociation cross sections.
In Fig. 2 we show the cross sections for the dissociation of $J/\psi$ and $\psi'$ by $\pi$ as a function of the initial kinetic energy in the center-of-mass system, $E_{KE} = \sqrt{s} - m_A - m_B$, where $A$ and $B$ are the colliding particles. The total cross sections are shown as thick solid curves and are the means of the ‘prior’ and ‘post’ results. The estimated errors due to the post-prior discrepancy and parameter variations are indicated by bands in the figures. The total cross section for the dissociation of $J/\psi$ by $\pi$ has an initial kinetic energy threshold of 0.65 GeV, and is about 1 mb just above threshold (Fig. 2a). This $\pi + J/\psi$ cross section is rather smaller than the 7 mb obtained by Martins et al. [15], who used the same formalism but made different assumptions about the confining interaction.

The threshold for $\pi + \psi' \rightarrow \{D\bar{D}^*, D^*\bar{D}\}$ is only 0.05 GeV. The total cross section for the dissociation of $\psi'$ by $\pi$ has local maxima at $E_{KE} \sim 0.1$ GeV and $\sim 0.22$ GeV, where the cross section is predicted to be, respectively, 6.2(0.8) mb and 4.6(1.8) mb (Fig. 2b). Thus, we find that the low energy $\pi + J/\psi$ dissociation cross section should be rather small, but in contrast we predict the $\pi + \psi'$ cross section to be quite large. This is in qualitative agreement with earlier analyses of $J/\psi$ and $\psi'$ suppression in pA, O-A, and S-U collisions [4, 5].

4 Cross section for the dissociation of $J/\psi$ and $\psi'$ by $\rho$

We next calculate the dissociation cross sections for $J/\psi$ and $\psi'$ in their collisions with $\rho$ mesons. A $\rho$ meson is a spin-1 particle, so the total spin of $\rho + \{J/\psi \text{ or } \psi'\}$ is $S_{tot} = 0, 1, \text{ and } 2$. The lowest mass final reaction products can be $(D, \bar{D})$ with $(S_3, S_4) = (0, 0)$ and $S_{tot} = 0$, $(D, \bar{D}^*)$ with $(S_3, S_4) = (0, 1)$ or $(D^*, \bar{D})$ with $(S_3, S_4) = (1, 0)$ for $S_{tot} = 1$, and $(D^*, \bar{D}^*)$ with $(S_3, S_4) = (1, 1)$, for which $S_{tot}$ can be 0, 1 or 2.

Note that since the reaction $\rho + J/\psi \rightarrow D\bar{D}$ is exothermic, this cross section diverges as $1/|\vec{v}_{\rho-(J/\psi)}|$ near threshold, independent of the detailed assumptions regarding the scattering mechanism. For the other channels the thresholds lie above $m_\rho + m_{J/\psi}$, so those subprocesses are endothermic and have zero cross section at threshold. The total dissociation cross section we find is shown as a solid line in Fig. 3. Numerically it is quite large, about 11(3) mb for an initial-state kinetic energy of 0.1 GeV, decreasing to 6(2) mb at a kinetic energy of 0.2 GeV.
5 Dependence of the dissociation cross sections on the ρ mass

The collision of two pions leads to isospin \( I = 0, 1 \) and 2 states. The \( I = 1 \) cross section at low energies is dominated by the \( ρ(770) \), which has a width of 0.150 GeV. Because of this large width, \( ρ \) mesons can be formed significantly far off the energy shell in \( ππ \) collisions.

A \( J/ψ \) interacting with off-shell \( ρ \) mesons will have a range of different effective thresholds, so it is useful to calculate these dissociation cross sections as a function of the \( ρ \) meson mass. For this calculation we assume that the off-shell \( ρ \) has the same spatial wavefunction as on-shell, and that only the kinematics of the reaction change. The results are shown in Fig. 4 for the \( J/ψ \) dissociation cross section as a function of the center-of-mass kinetic energy above the lowest threshold, \( E'_{KE} \). Here, \( E'_{KE} = \sqrt{s} - m_ρ - m_{J/ψ} - E_{th}(0) \), where \( E_{th}(0) \) is the lowest threshold, and is given by \( (m_D + m_{\bar{D}} - m_{J/ψ} - m_ρ)\Theta(m_D + m_{\bar{D}} - m_{J/ψ} - m_ρ) \).

Figure 4 shows that the cross section increases from about 1 mb to 3 mb as \( m_ρ \) increases from 0.45 GeV to 0.55 GeV. At \( m_ρ = 0.65 \) GeV, the reac-
tion $\rho + J/\psi$ becomes exothermic, and the cross section completely changes character; it diverges as $1/\sqrt{E'_{KE}}$ near $E'_{KE} = 0$.

The results in Fig. 4 show that the dissociation cross section for $\rho + J/\psi$ is quite sensitive to the $\rho$ mass; higher mass $\rho$ mesons have much larger cross sections near threshold.

![Graph showing dissociation cross section for different $m_\rho$.](image)

**Fig. 4.** The total $\rho + J/\psi$ dissociation cross section for different values of $m_\rho$.

We have carried out the corresponding calculations for the $\rho + \psi'$ dissociation cross sections as a function of the $\rho$ meson mass; the results are shown in Fig. 5 as a function of $E'_{KE} = \sqrt{s} - m_\rho - m_{\psi'} - E_{th}(0)$, where the lowest threshold is $E_{th}(0) = (m_D + m_{\bar{D}} - m_{\psi'} - m_\rho)\Theta(m_D + m_{\bar{D}} - m_{\psi'} - m_\rho)$. The cross section diverges as $1/\sqrt{E'_{KE}}$ near $E'_{KE} = 0$ for the $\rho$ masses considered in Fig. 5. There are additional contributions from the $D^* \bar{D}$ and $D^* \bar{D}^*$ channels. For a given $E'_{KE}$ and $m_\rho$, the $\psi'$ dissociation cross section is larger than the $J/\psi$ cross section, with the exception of $m_\rho = 770$ MeV and $E'_{KE} > 0.2$ GeV, at which the two cross sections are nearly equal.

The results of Fig. 5 show that the dissociation cross section for $\psi'$ by an
off energy shell $\rho$ is quite sensitive to $m_\rho$.

Fig. 5. The total dissociation cross sections for $\psi'$ by $\rho$ for different $m_\rho$.

6 Conclusions and future applications

The quark-interchange scattering model of Barnes and Swanson has been supported by extensive comparisons with experimental data in channels such as $I = 2 \pi\pi$ scattering, $I = 3/2 K\pi$ scattering, $I = 0, 1 S$-wave $KN$ scattering, the small $\pi + J/\psi$ and large $\pi + \psi'$ dissociation cross sections, and indirectly through its incorporation of a quark model Hamiltonian that gives a good description of the experimental meson spectrum. The results for $\rho + J/\psi$ and $\rho + \psi'$ dissociation cross sections we have found using this model are presumably qualitatively correct, since they depend mainly on the endothermic or exothermic nature of these processes. The more detailed numerical predictions certainly need to confront experimental data through a detailed study of $J/\psi$ and $\psi'$ production and evolution in high-energy heavy-ion collisions.

It may also be possible to infer the $\rho$ dissociation cross sections from studies of heavy-ion collisions. $\rho$ mesons are produced in $\pi\pi$ collisions and they also decay inversely into two pions. The production and the decay of $\rho$ mesons can readily reach an equilibrium and the the law of mass action applies. As
a consequence, the density of $\rho$ mesons should vary as the square of the pion density. In a heavy-ion collision the density of pions produced varies approximately as the path length $L$ of the colliding nuclei \cite{4}. Thus, the density of $\rho$ mesons depends approximately quadratically on the path length $L$. Charmonium absorption by these $\rho$ mesons thus leads to a term $c \times \sigma(\rho + J/\psi) \times L^2$ in the exponential absorption index. This quadratic dependence will be more evident if the cross section $\sigma(\rho+J/\psi)$ for $\rho + J/\psi$ dissociation is large, as we have found here. This term will also be enhanced as we increase the radii of the colliding nuclei, for example in going from S+U to Pb+Pb collisions. The degree to which the observed anomalous suppression in Pb+Pb collisions is due to $\rho + J/\psi$ dissociation will require a careful quantitative study, taking into account the variation of the dissociation cross section on the off energy shell $\rho$ mass. In any case, the possible importance of such a nonlinear suppression term should be considered in the attempt to identify the creation of a quark-gluon plasma through suppression of $J/\psi$ production.

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