The $J/\psi - K^\ast$ dissociation cross section in a meson exchange model

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Abstract

In this work we study the energy dependence of the $J/\psi - K^\ast$ dissociation cross section, using a meson exchange model based on effective hadronic Lagrangian that includes couplings between pseudoscalar and vector mesons. We also consider anomalous parity terms. Off-shell effects at the vertices were handled with QCD sum rule estimates for the running coupling constants, and we compare the results with and without form factors. We also study the $J/\psi - \rho$ cross section with form factors. The total $J/\psi - K^\ast$ cross section was found to be $1.6 \sim 1.9 \text{ mb}$ for $4.2 \leq \sqrt{s} \leq 5 \text{ GeV}$. 
I. INTRODUCTION

In relativistic heavy ion collisions $J/\psi$ suppression has been recognized as an important tool to identify the possible phase transition to quark-gluon plasma (QGP) \cite{1, 2, 3}. However, even if the QGP is not formed, the $J/\psi$ can be dissociated by many other “comoving” light hadrons which are produced in such collisions. Therefore, the evaluation of the size of the $J/\psi$ cross section by light mesons is important to distinguish whether the QGP is formed or the $J/\psi$ is dissociated by other “comoving” hadrons.

Since the cross section of $J/\psi$ dissociation by hadrons can not be directly measured, several theoretical approaches have been proposed to estimate their values. Some approaches were based on charm quark-antiquark dipoles interacting with the gluons of a larger (hadron target) dipole \cite{4, 5, 6} or quark exchange between two (hadronic) bags \cite{7, 8}, or QCD sum rules \cite{9, 10, 11}, whereas other works used the meson exchange mechanism \cite{12, 13, 14, 15, 16, 17, 18, 19, 20}.

The meson exchange approach was applied to $J/\psi - N$, $J/\psi - \pi$, $J/\psi - \rho$, and $J/\psi - K$ cross sections \cite{12, 13, 14, 15, 16, 17, 18, 19, 20}. In ref. \cite{20}, analyzing the $J/\psi - K$ cross section, we have shown that the inclusion of off-shell effects at the vertices, through the introduction of QCD sum rule estimates for the form factors, can change the energy dependence of the absorption cross section in a nontrivial way. A similar result was obtained in \cite{19} for the $J/\psi - \pi$ dissociation cross section. In this work we extend the analysis done in ref. \cite{20} and evaluate the $J/\psi - K^*$ cross section using a meson-exchange model, considering anomalous parity terms as in ref. \cite{17, 20} and QCD sum rule estimates for the form factors. We also study the changes in the $J/\psi - \rho$ cross section caused by the inclusion of the appropriate form factors.

II. EFFECTIVE LAGRANGIANS

Following refs. \cite{13, 14, 16, 17, 20}, we assume that SU(4) symmetry is exact in order to obtain the SU(4) Lagrangian for the pseudo-scalar and vector mesons. The effective Lagrangians relevant to study the dissociation of $J/\psi$ by $K^*$ are:

$$\mathcal{L}_{\psi DD} = ig_{\psi DD} \psi^\mu \left( D\partial_\mu \bar{D} - (\partial_\mu D)\bar{D} \right),$$

(1)
\( \mathcal{L}_{\psi D^*D^*} = ig_{\psi D^*D^*} \left[ \psi^\mu \left( (\partial_\mu D^{\ast \nu}) \bar{D}^\ast_\nu - D^\ast_\mu \partial_\nu \bar{D}^\ast_\nu \right) + \left( (\partial_\mu \psi^\nu) D^\ast_\nu \right) \right] \),

(2)

\( -\psi^\nu \partial_\nu D^\ast_\nu + D^{\ast \mu} \left( \psi^\nu \partial_\mu \bar{D}^\ast_\nu - (\partial_\mu \psi^\nu) \bar{D}^\ast_\nu \right) \),

(3)

\( \mathcal{L}_{\psi D_\lambda D_s} = ig_{\psi D_\lambda D_s} \psi^s \left( D_\lambda \partial_\mu \bar{D}_s - \partial_\mu D_s \bar{D}_s \right) \),

(4)

where we have defined the charm meson and \( K^* \) iso-doublets \( D \equiv (D^0, D^+) \), \( D^* \equiv (D^{*0}, D^{*+}) \) and \( K^* \equiv (K^{*0}, K^{*+}) \).

The anomalous parity terms, introduced in ref. [17] for the \( J/\psi - \pi \) and \( J/\psi - \rho \) cases, important for the \( J/\psi - K^* \) case are:

\( \mathcal{L}_{\psi DD} = g_{\psi DD} \epsilon^{\mu\alpha\beta\gamma} \partial_\mu \psi_\nu \left( \partial_\alpha \bar{D}_\beta D + \partial_\alpha D_\beta \bar{D} \right) \),

(9)

\( \mathcal{L}_{\psi D_s^* D_s} = g_{\psi D_s^* D_s} \epsilon^{\mu\alpha\beta\gamma} \partial_\mu \psi_\nu \left( \partial_\alpha \bar{D}_s^* D_s + \partial_\alpha D_s^* \bar{D}_s \right) \),

(10)

\( \mathcal{L}_{K^* D_s D_s^*} = -g_{K^* D_s D_s^*} \epsilon^{\mu\alpha\beta\gamma} \left( \partial_\mu \bar{K}_\beta \partial_\alpha \bar{D}_s^* D_s + \partial_\mu \bar{K}_\beta \partial_\alpha D_s^* \bar{D}_s \right) \),

(11)

\( \mathcal{L}_{K^* D_s D_s} = -g_{K^* D_s D_s} \epsilon^{\mu\alpha\beta\gamma} \left( \partial_\mu \bar{K}_\alpha \partial_\beta \bar{D}_s D_s + \partial_\mu \bar{K}_\alpha \partial_\beta D_s \bar{D}_s \right) \),

(12)

\( \mathcal{L}_{K^* D_s D_s^*} = i g_{K^* D_s D_s^*} \epsilon^{\mu\alpha\beta\gamma} \psi_\mu \left( -\partial_3 \bar{D}_s K^*_\alpha D^*_\beta + \partial_3 D_s \bar{K}^*_\alpha \bar{D}^*_\beta \right) 

+ i h_{K^* D_s D_s^*} \epsilon^{\mu\alpha\beta\gamma} \psi_\mu \left[ \psi_\mu \left( (\partial_\nu \bar{K}^*_\alpha \bar{D}_s^* D_s - (\partial_\nu \bar{K}^*_\alpha) D^*_\beta \bar{D}_s + 3(\partial_\nu \bar{D}^*_\alpha \bar{K}^*_\beta \bar{D}_s - 3(\partial_\nu \bar{D}^*_\alpha \bar{K}^*_\beta \bar{D}_s) \right) 

- \partial_\nu \psi_\mu \left( \bar{K}^*_\alpha \bar{D}_s^* D_s - K^*_\alpha D^*_\beta \bar{D}_s \right) \right] \),

(13)

The processes we are interested in studying for the dissociation of \( J/\psi \) by \( K^* \) are repre-
FIG. 1: Diagrams for $J/\psi$ absorption processes: 1) $K^*\psi \rightarrow D_s\bar{D}$; 2) $K^*\psi \rightarrow D_s^*\bar{D}^*$; 3) $K^*\psi \rightarrow D_s\bar{D}^*$; 4) $K^*\psi \rightarrow D_s^*\bar{D}$. Diagrams for the processes $\bar{K}^*\psi \rightarrow \bar{D}_sD$, $\bar{K}^*\psi \rightarrow \bar{D}_s^*D$, $\bar{K}^*\psi \rightarrow \bar{D}_sD^*$, and $\bar{K}^*\psi \rightarrow \bar{D}_s^*D$ are similar to (1a)-(1e) through (4a)-(4e) respectively, but with each particle replaced by its anti-particle.

Sent by Fig. 1. They are:

\begin{align*}
K^*J/\psi & \rightarrow D_s\bar{D}, \quad \bar{K}^*J/\psi \rightarrow D\bar{D}_s, \quad (15) \\
K^*J/\psi & \rightarrow D_s^*\bar{D}^*, \quad \bar{K}^*J/\psi \rightarrow D^*\bar{D}_s^*, \quad (16) \\
K^*J/\psi & \rightarrow D_s\bar{D}^*, \quad \bar{K}^*J/\psi \rightarrow D^*\bar{D}_s, \quad (17) \\
K^*J/\psi & \rightarrow D_s^*\bar{D}, \quad \bar{K}^*J/\psi \rightarrow D\bar{D}_s^*, \quad (18)
\end{align*}
Since the two processes in eqs. (15), (16), (17) and (18) have the same cross section, in Fig. 1 we only show the diagrams for the first process in eqs. (15) through (18).

Defining the four-momentum of the $K^*$ and the $J/\psi$ by $p_1$, $p_2$ respectively, and the four-momentum of the final-state mesons by $p_3$ and $p_4$, the full amplitude for the processes $K^* \psi \rightarrow D_s \bar{D}$, shown in diagrams (1) of Fig. 1, without isospin factors and before summing and averaging over external spins, is given by

$$M_1 \equiv M_1^{\mu \nu} \epsilon_{1 \mu} \epsilon_{2 \nu}^* = \left( \sum_{j=a,b,c,d,e} M_{1j}^{\mu \nu} \right) \epsilon_{1 \mu} \epsilon_{2 \nu}, \quad (19)$$

with

$$M_{1a}^{\mu \nu} = -g_{\psi DD} g_{K^* D_s D} (p_1 - 2p_3)^\mu \left( \frac{1}{t - m_{D_s}^2} \right) (p_4 - p_3 + p_1)^\nu,$$

$$M_{1b}^{\mu \nu} = -g_{K^* D_s D} g_{\psi D_s D_s} (-p_1 + 2p_4)^\mu \left( \frac{1}{u - m_{D_s}^2} \right) (-p_1 - p_3 + p_4)^\nu,$$

$$M_{1c}^{\mu \nu} = g_{K^* D_s D} g^{\mu \nu},$$

$$M_{1d}^{\mu \nu} = -\frac{g_{K^* D_s D} g_{D_s D_s} g_{D_s D_s} D_s}{t - m_{D_s}^2} (p_1 - 3p_3 + p_1)^\mu \left( \frac{1}{t - m_{D_s}^2} \right) (p_4 - p_3 + p_1)^\nu,$$

$$M_{1e}^{\mu \nu} = -\frac{g_{K^* D_s D} g_{D_s D_s} g_{D_s D_s} D_s}{u - m_{D_s}^2} (p_1 - 3p_3 + p_1)^\mu \left( \frac{1}{u - m_{D_s}^2} \right) (p_4 - p_3 + p_1)^\nu, \quad (20)$$

where $t = (p_1 - p_3)^2$ and $u = (p_1 - p_4)^2$.

Similarly, the full amplitude for the processes $K^* \psi \rightarrow D_s^* \bar{D}^*$, shown in diagrams (2) of Fig. 1, without isospin factors and before summing and averaging over external spins, is given by

$$M_2 \equiv M_2^{\mu \nu \lambda \gamma} \epsilon_{1 \mu} \epsilon_{2 \nu}^* \epsilon_{3 \lambda} \epsilon_{4 \gamma}^* = \left( \sum_{j=a,b,c,d,e} M_{2j}^{\mu \nu \lambda \gamma} \right) \epsilon_{1 \mu} \epsilon_{2 \nu}^* \epsilon_{3 \lambda} \epsilon_{4 \gamma}^*, \quad (21)$$

where

$$M_{2a}^{\mu \nu \lambda \gamma} = g_{\psi D_s^* D^*} g_{K^* D_s^* D_s^*} \left[ 2p_3^\mu g_{\alpha \lambda} + (-p_1 - p_3)^\alpha g_{\mu \lambda} + 2p_1^\lambda g_{\mu \alpha} \right] \left( \frac{1}{t - m_{D_s}^2} \right) \left( g_{\alpha \beta} - \frac{(p_1 - p_3)\alpha(p_1 - p_3)\beta}{m_{D_s}^2} \right) \left[ -2p_2^\gamma g_{\beta \nu} + (p_2 + p_4)^\beta g_{\nu \gamma} - 2p_4^\nu g_{\beta \gamma} \right],$$

$$M_{2b}^{\mu \nu \lambda \gamma} = g_{K^* D_s D_s^*} g_{D_s^* D_s^*} \left[ 2p_3^\mu g_{\alpha \lambda} + (p_1 + p_4)^\alpha g_{\mu \lambda} + 2p_4^\lambda g_{\mu \alpha} \right] \left( \frac{1}{u - m_{D_s}^2} \right) \left( g_{\alpha \beta} - \frac{(p_1 - p_4)\alpha(p_1 - p_4)\beta}{m_{D_s}^2} \right) \left[ 2p_2^\gamma g_{\beta \nu} - (p_2 + p_3)^\beta g_{\nu \lambda} + 2p_3^\nu g_{\beta \lambda} \right].$$
\[ M_{2e}^{\mu \nu \lambda \gamma} = g_{K^* \psi D^* D} \left( g^{\mu \lambda} g^{\nu \gamma} + g^{\nu \gamma} g^{\mu \lambda} - 2g^{\nu \mu} g^{\gamma \lambda} \right), \]
\[ M_{2d}^{\mu \nu \lambda \gamma} = - \frac{g_{K^* D^* D} g_{\psi D^* D}}{t - m_{D^*}^2} \epsilon^{\mu \lambda \rho \sigma} \epsilon_{\nu \gamma \delta x} p_{1\sigma} p_{2\delta} p_{3\rho} p_{4\chi}, \]
\[ M_{2e}^{\mu \nu \lambda \gamma} = - \frac{g_{K^* D^* D} g_{\psi D^* D}}{u - m_{D^*}^2} \epsilon^{\mu \lambda \sigma \rho} \epsilon_{\nu \gamma \delta x} p_{1\sigma} p_{2\delta} p_{3\chi} p_{4\rho}. \] (22)

Calling the four-momentum of the pseudo-scalar and the vector final-state mesons by \( p_3 \) and \( p_4 \) respectively, the full amplitude for the processes \( K^* \psi \to D_s D^* \) shown in diagram (3) of Fig. 1 is
\[
\mathcal{M}_3 \equiv \mathcal{M}_3^{\mu \nu} \epsilon_{1\mu} \epsilon_{2\nu} \epsilon_{4\gamma}^* = \left( \sum_{i=a,b,c,d,e} \mathcal{M}_3^{\mu \nu \gamma} \right) \epsilon_{1\mu} \epsilon_{2\nu} \epsilon_{4\gamma}^*, \] (23)
with
\[
M_3^{\mu \nu \gamma} = - \frac{g_{K^* D^* D} g_{\psi D^* D}}{t - m_{D^*}^2} \epsilon_{\mu \nu \sigma \rho} \epsilon_{\gamma \delta } \left( g_{\alpha \beta} - \frac{(p_1 - p_3)_{\alpha} (p_1 - p_3)_{\beta}}{m_{D^*}^2} \right) p_{1\sigma} p_{2\delta} p_{3\rho} p_{4\chi}, \]
\[ 2p_1^\gamma g^{\alpha \mu} + (-p_1 - p_4)_{\gamma} g^{\mu \lambda} + 2p_4^\alpha g_{\lambda \gamma}, \]
\[ M_3^{\mu \nu \gamma} = g_{K^* D^* D} g_{\psi D^* D} \epsilon^{\mu \nu \gamma \delta} p_{3\delta} + h_{K^* D^* D} \epsilon^{\mu \nu \gamma \delta} (p_1 + 3p_4 - p_2)_{\delta}, \]
\[ M_3^{\mu \nu \gamma} = -2 \frac{g_{K^* D^* D} g_{\psi D^* D}}{t - m_{D^*}^2} \epsilon^{\nu \gamma \delta \chi} p_{2\delta} p_{4\chi} p_{3\mu}, \]
\[ M_3^{\mu \nu \gamma} = -2 \frac{g_{K^* D^* D} g_{\psi D^* D}}{u - m_{D^*}^2} \epsilon^{\mu \nu \rho \sigma} p_{1\sigma} p_{4\rho} p_{3\chi} p_{4\gamma}. \] (24)

For the diagram (4) in Fig. 1, representing the processes \( K^* \psi \to D_s D \), calling the four-momentum of the vector and pseudoscalar final-state mesons respectively by \( p_3 \) and \( p_4 \), the full amplitude is given by
\[
\mathcal{M}_4 \equiv \mathcal{M}_4^{\mu \lambda \nu \epsilon_{1\mu} \epsilon_{2\nu} \epsilon_{3\lambda}^* = \left( \sum_{i=a,b,c,d,e} \mathcal{M}_4^{\mu \nu \lambda \gamma} \right) \epsilon_{1\mu} \epsilon_{2\nu} \epsilon_{3\lambda}^*, \] (25)
with
\[
M_4^{\mu \nu \lambda \gamma} = - \frac{g_{K^* D^* D} g_{\psi D^* D}}{t - m_{D^*}^2} \epsilon^{\mu \lambda \rho \sigma} \epsilon_{\nu \chi \delta \chi} \left( g_{\alpha \beta} - \frac{(p_1 - p_3)_{\alpha} (p_1 - p_3)_{\beta}}{m_{D^*}^2} \right) p_{2\delta} p_{4\chi}, \]
\[ 2p_1^\gamma g^{\alpha \mu} + (-p_1 - p_3)_{\gamma} g^{\mu \lambda} + 2p_3^\alpha g_{\lambda \gamma}, \]
\[ M_4^{\mu \nu \lambda \gamma} = g_{K^* D^* D} g_{\psi D^* D} \epsilon^{\mu \nu \lambda \delta} p_{3\delta} + h_{K^* D^* D} \epsilon^{\mu \nu \lambda \delta} (p_1 + 3p_3 - p_2)_{\delta}, \]
\[ M_4^{\mu \nu \lambda \gamma} = -2 \frac{g_{K^* D^* D} g_{\psi D^* D}}{t - m_{D^*}^2} \epsilon^{\nu \lambda \rho \sigma} p_{1\sigma} p_{4\rho} p_{3\chi} p_{4\gamma}, \]
\[ M_4^{\mu \nu \lambda \gamma} = -2 \frac{g_{K^* D^* D} g_{\psi D^* D}}{u - m_{D^*}^2} \epsilon^{\mu \lambda \rho \sigma} p_{1\sigma} p_{4\rho} p_{3\chi} p_{4\gamma}. \]
\[ M_{4d}^{\mu \nu \lambda} = -2 \frac{g_{K^*D_sD} g_{\psi DD}}{t - m_D^2} \epsilon^{\mu \lambda \sigma \rho} p_1 \sigma p_4 \rho p_4, \]
\[ M_{4e}^{\mu \nu \lambda} = -2 \frac{g_{K^*D_sD} g_{\psi D_sD}}{u - m_{D_s}^2} \epsilon^{\nu \lambda \delta \sigma} p_2 \delta p_3 \lambda p_4. \] (26)

After averaging (summing) over initial (final) spins and including isospin factors, the cross sections for these four processes are given by

\[ \frac{d\sigma_1}{dt} = \frac{1}{576 \pi s p_{1,\text{cm}}^2} M_1^{\mu \nu} M_1^{\mu' \nu'} \left( g_{\mu \nu} - \frac{p_1 \mu p_1 \nu}{m_1^2} \right) \left( g_{\nu \nu'} - \frac{p_2 \nu p_2 \nu'}{m_2^2} \right), \] (27)
\[ \frac{d\sigma_2}{dt} = \frac{1}{576 \pi s p_{1,\text{cm}}^2} M_2^{\mu \nu \lambda \gamma} M_2^{\mu' \nu' \lambda' \gamma'} \left( g_{\mu \mu'} - \frac{p_1 \mu p_1 \mu'}{m_1^2} \right) \left( g_{\nu \nu'} - \frac{p_2 \nu p_2 \nu'}{m_2^2} \right) \times \left( g_{\lambda \lambda'} - \frac{p_3 \lambda p_3 \lambda'}{m_3^2} \right) \left( g_{\gamma \gamma'} - \frac{p_4 \gamma p_4 \gamma'}{m_4^2} \right), \] (28)
\[ \frac{d\sigma_3}{dt} = \frac{1}{576 \pi s p_{1,\text{cm}}^2} M_3^{\mu \nu \lambda \gamma} M_3^{\mu' \nu' \lambda' \gamma'} \left( g_{\mu \mu'} - \frac{p_1 \mu p_1 \mu'}{m_1^2} \right) \left( g_{\nu \nu'} - \frac{p_2 \nu p_2 \nu'}{m_2^2} \right) \times \left( g_{\gamma \gamma'} - \frac{p_4 \gamma p_4 \gamma'}{m_4^2} \right), \] (29)

and

\[ \frac{d\sigma_4}{dt} = \frac{1}{576 \pi s p_{1,\text{cm}}^2} M_4^{\mu \nu \lambda} M_4^{\mu' \nu' \lambda'} \left( g_{\mu \mu'} - \frac{p_1 \mu p_1 \mu'}{m_1^2} \right) \left( g_{\nu \nu'} - \frac{p_2 \nu p_2 \nu'}{m_2^2} \right) \times \left( g_{\lambda \lambda'} - \frac{p_3 \lambda p_3 \lambda'}{m_3^2} \right), \] (30)

with \( s = (p_1 + p_2)^2 \), and

\[ p_{0,\text{cm}}^2 = \frac{[s - (m_1 + m_2)^2][s - (m_1 - m_2)^2]}{4s} \] (31)

being the three-momentum squared of initial-state mesons in the center-of-momentum (c.m.) frame.

### III. RESULTS

Exact SU(4) symmetry would give the following relations among the coupling constants \[14, 17, 20\]:

\[ g_{K^*D_sD} = g_{K^*D_sD} = \frac{g}{2\sqrt{2}}, \]
\[ g_{\psi DD} = g_{\psi D_sD} = g_{\psi D_sD} = g_{\psi D_sD} = \frac{g}{\sqrt{6}}, \]
\[ g_{\psi K^* D_s D} = \frac{g^2}{2\sqrt{3}}, \]
\[ g_{\psi K^* D_s D^*} = \frac{g^2}{4\sqrt{3}}, \]
\[ g_{\psi D^* D} = g_{\psi D_s D^*} = \frac{\sqrt{2}g^2 N_c}{64\sqrt{3} \pi^2 F_\pi}, \]
\[ g_{K^* D_s D} = g_{K^* D_s D^*} = \frac{\sqrt{2}g^2 N_c}{64\pi^2 F_\pi}, \]
\[ g_{\psi K^* D_s D^*} = 3 h_{\psi K^* D_s D} = 3 h_{\psi K^* D_s D^*} = \frac{\sqrt{3}g^2 N_c}{256\pi^2 F_\pi}, \] (32)

where \( N_c = 3 \) and \( F_\pi = 132 \text{ MeV} \).

None of the above couplings are known experimentally, and one has to use models to estimate them. In refs. [19, 20], the \( J/\psi - \pi \), \( J/\psi - \rho \) and \( J/\psi - k \) cross sections were evaluated by using form factors and coupling constants estimated using QCD sum rules [21, 22, 23, 24]. The results in ref. [19, 20] show that, with appropriate form factors, even the behavior of the cross section as a function of \( \sqrt{s} \) can change. In this work we use the form factors in the vertices \( J/\psi DD \), \( J/\psi D^* D \) and \( \rho DD \), determined from QCD sum rules [22, 25], and the above SU(4) relations to estimate the form factors and coupling constants in all vertices.

From ref. [25] we get \( g_{\psi DD^*} = 4.0 \text{ GeV}^{-1} \) and \( g_{\psi DD} = 5.8 \). Using these numbers in the SU(4) relations given in Eqs. (32) we obtain

\[ g_{\psi DD} = g_{\psi D_s D} = g_{\psi D^* D^*} = g_{\psi D_s D^*} = 5.8, \quad g_{K^* D_s D} = g_{K^* D^* D^*} = 5.0, \]
\[ g_{\psi K^* D_s D} = 58.2, \quad g_{\psi K^* D_s D^*} = 29.0, \quad g_{\psi D^* D} = g_{\psi D_s D^*} = 4.0 \text{ GeV}^{-1}, \]
\[ g_{K^* D_s D^*} = g_{K^* D^* D^*} = 6.9 \text{ GeV}^{-1}, \]
\[ g_{\psi K^* D^* D^*} = g_{\psi K^* DD^*} = 24.8 \text{ GeV}^{-1}, \]
\[ h_{\psi K^* D^* D^*} = h_{\psi K^* DD^*} = 8.3 \text{ GeV}^{-1}. \] (33)

The form factors given in ref. [25] are

\[ g_{\psi DD^*}^{(D^* D^*)}(t) = g_{\psi DD^*} \left( 5 e^{-\left(\frac{27}{18.6}\right)^2} \right) = g_{\psi DD^*} h_1(t), \] (34)
\[ g_{\psi DD^*}^{(D D^*)}(t) = g_{\psi DD^*} \left( 3.3 e^{-\left(\frac{26}{44.8}\right)^2} \right) = g_{\psi DD^*} h_2(t), \] (35)
\[ g_{\psi DD}^{(D D)}(t) = g_{\psi DD} \left( 2.6 e^{-\left(\frac{24}{44.8}\right)^2} \right) = g_{\psi DD} h_3(t), \] (36)
where $g_{123}^{(1)}$ means the form factor at the vertex involving the mesons 123 with the meson 1 off-shell. In the above equations the numbers in the exponentials are in units of GeV$^2$. Since there is no QCD sum rule calculation for the form factors at the vertices $K^* D, D$, we make the supposition that they are similar to the form factor at the vertex $\rho DD$. From ref. [24] we get

$$g_{\rho DD}^{(D)}(t) = g_{\rho DD} \left( \frac{(3.5 \text{ GeV})^2 - m_D^2}{(3.5 \text{ GeV})^2 - t} \right) = g_{\rho DD} h_4(t, m_D^2).$$  \hspace{1cm} (37)

With these form factors the amplitudes will be modified in the following way:

$$\mathcal{M}_{ia} \rightarrow h_3(t)h_4(t, m_{ia}^2)\mathcal{M}_{ia}, \quad \mathcal{M}_{ib} \rightarrow h_3(u)h_4(u, m_{ib}^2)\mathcal{M}_{ib},$$   \hspace{1cm} (38)

for $i = 1, 2$, with $m_{1a} = m_D$, $m_{1b} = m_{D*}$, $m_{2a} = m_D^*$, and $m_{2b} = m_{D*}$.

$$M_{ic} \rightarrow \frac{1}{2} \left( h_3(t)h_4(t, m_{ia}^2) + h_3(u)h_4(u, m_{ib}^2) \right) M_{ic}, \quad M_{1d} \rightarrow h_1(t)h_4(t, m_{1d}^2)M_{1d},$$

$$M_{ic} \rightarrow h_1(u)h_4(u, m_{ie}^2)M_{ie}, \quad M_{2d} \rightarrow h_2(t)h_4(t, m_{2e}^2)M_{2d},$$

$$M_{2e} \rightarrow h_2(u)h_4(u, m_{2e}^2)M_{2e}.$$   \hspace{1cm} (39)

for $i = 1, 2$ with $m_{1d} = m_{D*}$, $m_{1e} = m_{D*}$, $m_{2d} = m_D$ and $m_{2e} = m_{D*}$.

$$M_{3a} \rightarrow h_3(t)h_4(t, m_{2a}^2)M_{3a}, \quad M_{3b} \rightarrow h_1(u)h_4(u, m_{2b}^2)M_{3b}$$

$$M_{3c} \rightarrow \frac{1}{4} \left( h_3(t)h_4(t, m_{2c}^2) + h_1(u)h_4(u, m_{2c}^2) + h_2(t)h_4(t, m_{2c}^2) + h_3(u)h_4(u, m_{2c}^2) \right),$$

$$M_{3d} \rightarrow h_2(t)h_4(t, m_{2d}^2)M_{3d}, \quad M_{3e} \rightarrow h_3(u)h_4(u, m_{2e}^2)M_{3e}$$   \hspace{1cm} (40)

and

$$M_{4a} \rightarrow h_1(t)h_4(t, m_{2a}^2)M_{4a}, \quad M_{4b} \rightarrow h_3(u)h_4(u, m_{2b}^2)M_{4b},$$

$$M_{4c} \rightarrow \frac{1}{4} \left( h_1(t)h_4(t, m_{2c}^2) + h_3(u)h_4(u, m_{2c}^2) + h_3(t)h_4(t, m_{2c}^2) + h_1(u)h_4(u, m_{2c}^2) \right) M_{4c}$$

$$M_{4d} \rightarrow h_3(t)h_4(t, m_{2d}^2)M_{4d}, \quad M_{4e} \rightarrow h_1(u)h_4(u, m_{2e}^2)M_{4e}.$$   \hspace{1cm} (41)

One can argue that our prescription to introduce the form factors in Eqs. (38) through (41) might spoil the current conservation associated with the $J/\psi$ current. However, this is not the case. Let us consider, for instance, the full amplitude associated with the processes represented by diagrams (1) in Fig. 1: $\mathcal{M}_{ij}^{uu} = \sum_{j=a,b,c,d,e} \mathcal{M}_{ij}^{uu}$. Keeping only terms that
will contribute to the cross section, it can be written as

$$
\mathcal{M}_1^{\mu\nu} = \Lambda_1 p_1^\nu p_1^\mu + \Lambda_2 p_2^\nu p_2^\mu + \Lambda_3 p_3^\nu p_3^\mu + \Lambda_4 p_4^\nu p_4^\mu + \Lambda_5 p_5^\nu p_5^\mu + \Lambda_6 p_6^\nu p_6^\mu + \Lambda_7 p_7^\nu p_7^\mu + \Lambda_8 g^{\mu\nu},
$$

(42)

where, before introducing the form factors, these $\Lambda$’s depend only on the coupling constants and masses.

Without interfering in the final result for the cross section, the amplitude in Eq. (42) can be rewritten as

$$
\mathcal{M}_1^{\mu\nu} = \Lambda_1 \left( p_1^\nu - \frac{p_2^\nu p_1^\mu}{m_{J/\psi}^2} p_2^\mu \right) p_2^\mu + \Lambda_2 \left( p_3^\nu - \frac{p_2^\nu p_3^\mu}{m_{J/\psi}^2} p_3^\mu \right) p_3^\mu + \Lambda_3 \left( p_1^\nu - \frac{p_2^\nu p_1^\mu}{m_{J/\psi}^2} p_2^\mu \right) p_3^\mu + \Lambda_4 \left( p_3^\nu - \frac{p_2^\nu p_3^\mu}{m_{J/\psi}^2} p_3^\mu \right) p_4^\mu + \Lambda_5 \left( p_4^\nu - \frac{p_2^\nu p_4^\mu}{m_{J/\psi}^2} p_4^\mu \right) p_4^\mu + \Lambda_6 \left( p_1^\nu - \frac{p_2^\nu p_1^\mu}{m_{J/\psi}^2} p_2^\mu \right) p_3^\mu + \Lambda_7 \left( p_4^\nu - \frac{p_2^\nu p_4^\mu}{m_{J/\psi}^2} p_4^\mu \right) p_2^\mu + \Lambda_8 \left( g^{\mu\nu} - \frac{p_2^\mu p_2^\nu}{m_{J/\psi}^2} \right),
$$

(43)

which is explicitly gauge invariant independently of the values of the parameter $\Lambda_1$. Therefore, our prescription in keeping gauge invariance when the form factors from Eqs (38) to (41) are introduced, is to introduce new terms, proporcional to $p_{2\nu}$, in the amplitude, as in Eq. (43). A different prescription can be found in ref. [19].

We first analyze the $J/\psi$ dissociation cross sections by $K^*$ without considering the form factors, i.e., we use the expressions for the amplitudes in Eqs. (20) through (26). We will be always including the contributions for both $J/\psi K^*$ and $J/\psi K^*$. In Fig. 2 we show the cross section of $J/\psi$ dissociation by $K^*$ as a function of the initial energy $\sqrt{s}$. The dot-dashed, dotted, dashed, long-dashed and solid lines give the contributions for the processes $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s + D \bar{D}_s$, $D^* D_s^* + \bar{D}^* D_s^*$ $D^*$, $\bar{D} D_s^* + D \bar{D}_s^*$, $\bar{D}^* D_s + D^* \bar{D}_s$ and total respectively. From this figure we can see that the process $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s + D \bar{D}_s$ has a different dependence with the energy near the threshold as compared with the processes $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s^* + D \bar{D}_s^*$, $D^* D_s + D^* \bar{D}_s$ and $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D}^* D_s^* + \bar{D}_s^* D^*$. This difference in the behaviour of the cross section can be understood by noticing that while for the process $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s + \bar{D}_s D$, $m_{D} + m_{D_s}$ is positive, for the other processes the mass difference between the initial and final states is negative. This means
FIG. 2: Total cross sections, without form factors, for the processes $J/\psi K^* + J/\psi \bar{K}^* \rightarrow D D_s + D \bar{D}_s$ (dot-dashed line), $\bar{D}^* D_s^* + \bar{D}_s^* D^*$ (dotted line), $D D_s^* + \bar{D} D_s^*$ (dashed line) and $\bar{D}^* D_s + D^* \bar{D}_s$ (long-dashed line). The solid line gives the total $J/\psi$ dissociation by $K^*$ cross section.

that the process $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s + D \bar{D}_s$ is exotermic and can happen even with $K^*$ and $J/\psi$ at rest. The other processes are endotermic, i.e., the reaction only occurs if either $J/\psi$ or $K^*$ have some initial energy.

We see also that until $\sqrt{s} \sim 4.6$ GeV the process $J/\psi K^* + J/\psi \bar{K}^* \rightarrow \bar{D} D_s + D \bar{D}_s$ dominates. However, for higher values of $\sqrt{s}$ the processes given by diagrams (3) and (4) in Fig. 1 are the most important ones. This is similar to what was found in ref. [17] for the $J/\psi$ dissociation by $\rho$ mesons.

FIG. 3: Same as in Fig. 2 but with form factors.
In Fig. 3 we show the same processes considered in Fig. 2, but with form factors. This means that we are now using the amplitudes given by Eqs. (38) through (41). The first important conclusion is that the use of appropriate form factors do change the behavior of the cross section as a function of $\sqrt{s}$, as obtained in refs. [19, 20]. The processes more affected by this change are the ones represented by diagrams (3) and (4) in Fig. 1. While the total cross section obtained without form factors show a very strong grown with $\sqrt{s}$, this is not more the case when the total cross section is obtained with form factors, as can be seen in Fig. 4, where we show the total cross section evaluated with and without form factors.

![Graph](image)

**FIG. 4:** Total $J/\psi$ dissociation cross section as a function of the initial energy. The solid and dashed lines give the results for $J/\psi$ absorption by $K^*$ with and without form factors respectively. The dotted line gives the results for $J/\psi$ absorption by $\rho$ with form factors.

One important result of our calculation is the fact that, using appropriate form factors with cut-offs of order of $\sim 3.5$ GeV (see Eqs. (34) through (37)), the value of the cross section can be reduced by one order of magnitude. The same effect was obtained in refs. [14, 17] using monopole form factors, but with cut-offs of order of $\sim 1$ GeV, which are considered very small for charmed mesons.

In Fig. 4 we also show, for comparison, the total cross section for $J/\psi$ absorption by $\rho$'s (dotted line) using the same form factors and coupling constants given here, and the value 4.3 for the $\rho DD$ coupling constant obtained using QCD sum rule [24].

Other important result that we can see by this figure is that, even with form factors, the
$J/\psi\,\rho$ dissociation cross section still increases with $\sqrt{s}$, differently to what happens with the $J/\psi\,K^*$ dissociation cross section. The reason for that is the fact that, without form factors the $J/\psi\,\rho$ dissociation cross section increases, with $\sqrt{s}$, in a much stronger way than the $J/\psi\,K^*$ dissociation cross section, as can be seen by Fig. 5.

![Graph showing comparison between $J/\psi\,K^*$ and $J/\psi\,\rho$ dissociation cross sections.](image)

**FIG. 5:** Comparison between the $J/\psi\,K^*$ dissociation cross section (solid line) and $J/\psi\,\rho$ dissociation cross section (dotted line) without form factors.

**IV. CONCLUSIONS**

We have studied the cross section of $J/\psi$ dissociation by $K^*$ in a meson-exchange model that includes pseudo-scalar-pseudo-scalar-vector-meson couplings, three-vector-meson couplings, pseudo-scalar-vector-vector-meson couplings and four-point couplings. Off-shell effects at the vertices were handled with QCD sum rule estimates for the form factors. The inclusion of anomalous parity interactions (pseudo-scalar-vector-vector-meson couplings) has opened additional channels to the absorption mechanism. Their contribution are very important especially for large values of the initial energy, $\sqrt{s} > 4.7$ GeV.

As shown in Fig. 2 our results, without form factors, have the same energy dependence of $J/\psi$ absorption by $\rho$ from ref. [17]. The inclusion of the form factors changes the energy dependence of the absorption cross section in a nontrivial way, as shown in Fig. 3. This modification in the energy dependence is similar to what was found in ref. [19] for $J/\psi$ absorption by $\rho$. 
With QCD sum rules estimates for the coupling constants and form factors, the total 
$J/\psi - K^*$ cross section was found to be $1.6 \sim 1.9$ mb for $4.2 \leq \sqrt{s} \leq 5$ GeV. Using the 
same form factors and QCD sum rules to estimate the value for $g_{\rho DD}$ we get for the $J/\psi - \rho$
total absorption cross section $3.0 \sim 10.0$ mb, in the same energy range.

Acknowledgments

This work was supported by CNPq and FAPESP.

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