J/ψ-kaon cross section in meson exchange model

R. S. Azevedo and M. Nielsen

Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05389-970 São Paulo, São Paulo, Brazil

(Received 24 October 2003; published 2 March 2004)

We calculate the cross section for the dissociation of J/ψ by kaons within the framework of a meson-exchange model including anomalous parity interactions. Off-shell effects at the vertices were handled with QCD sum rule estimates for the running coupling constants. The total J/ψ-kaon cross section was found to be 1.0–1.6 mb for $4.1 \leqslant \sqrt{s} \leqslant 5$ GeV.

DOI: 10.1103/PhysRevC.69.035201 PACS number(s): 25.75.−q, 13.75.Lb, 14.40.Aq

I. INTRODUCTION

Suppression of J/ψ in relativistic heavy ion collisions is still considered as one of the important signatures to identify the possible phase transition to quark-gluon plasma (QGP) [1] (for a review of data and interpretations see Refs. [2,3]). Since there is no direct experimental information on J/ψ absorption cross sections by hadrons, several theoretical approaches have been proposed to estimate their values. In order to elaborate a theoretical description of the phenomenon, we have first to choose the relevant degrees of freedom. Some approaches were based on charm quark-antiquark dipoles interacting with the gluons of a larger (hadron target) dipole [4–6] or quark exchange between two (hadronic) bags [7,8], or QCD sum rules [9–11], whereas other works used the meson-exchange mechanism [12–18]. In this case it is not easy to decide in favor of quarks or hadrons because we are dealing with charm quark bound states, which are small and massive enough to make perturbation theory meaningful, but not small enough to make nonperturbative effects negligible [9–11,19].

The meson-exchange approach was applied basically to $J/\psi-N$, $J/\psi-\pi$, and $J/\psi-\rho$ cross sections, with the only exception of Ref. [13], where $J/\psi-K$ cross section was also estimated. However, as pointed out in Ref. [14], there are some inconsistencies in the Lagrangians defined in Ref. [13]. In this work we extend the analysis done in Ref. [20] and evaluate the $J/\psi-K$ cross section using a meson-exchange model, considering anomalous parity terms as in Ref. [17].

II. EFFECTIVE LAGRANGIANS

We follow Refs. [13,14,16,17] and start with the SU(4) Lagrangian for the pseudoscalar and vector mesons. The effective Lagrangians relevant for the study of the J/ψ absorption by kaons are

$$\mathcal{L}_{KDD_s^*} = ig_{KDD_s^*}D_s^{*\mu}[\bar{D}\partial_\mu\bar{K} - (\partial_\mu\bar{D})\bar{K}] + \text{H.c.}, \tag{1}$$

$$\mathcal{L}_{KD_sD^*} = ig_{KD_sD^*}D^{*\mu}[\bar{D}_s\partial_\mu K - (\partial_\mu\bar{D}_s)K] + \text{H.c.}, \tag{2}$$

$$\mathcal{L}_{\psi DD} = ig_{\psi DD}\psi^\mu[D\partial_\mu\bar{D} - (\partial_\mu D)\bar{D}], \tag{3}$$

$$\mathcal{L}_{\psi D_sD_s} = ig_{\psi D_sD_s}\psi^\mu[D_s\partial_\mu\bar{D}_s - (\partial_\mu D_s)\bar{D}_s], \tag{4}$$

$$\mathcal{L}_{\psi D^*D^*} = ig_{\psi D^*D^*}\{\psi^\mu[(\partial_\mu D^{*\nu})\bar{D}^*_\nu - D^{*\nu}\partial_\mu\bar{D}^*_\nu] + [(\partial_\mu\psi^\nu)D^*_\nu - \psi^\nu\partial_\mu D^*_\nu]\bar{D}^{*\mu} + D^{*\mu}[\psi^\nu\partial_\mu\bar{D}^*_\nu - (\partial_\mu\psi^\nu)\bar{D}^*_\nu]\}, \tag{5}$$

$$\mathcal{L}_{\psi D_s^*D_s^*} = ig_{\psi D_s^*D_s^*}\{\psi^\mu[(\partial_\mu D_s^{*\nu})\bar{D}^*_{s\nu} - D_s^{*\nu}\partial_\mu\bar{D}^*_{s\nu}] + [(\partial_\mu\psi^\nu)D^*_{s\nu} - \psi^\nu\partial_\mu D^*_{s\nu}]\bar{D}_s^{*\mu} + D_s^{*\mu}[\psi^\nu\partial_\mu\bar{D}^*_{s\nu} - (\partial_\mu\psi^\nu)\bar{D}^*_{s\nu}]\}, \tag{6}$$

$$\mathcal{L}_{\psi KD_sD^*} = -g_{\psi KD_sD^*}\psi^\mu(D^*_\mu K\bar{D}_s + D_s\overline{KD^*_\mu}), \tag{7}$$

$$\mathcal{L}_{\psi KDD_s^*} = -g_{\psi KDD_s^*}\psi^\mu(\bar{D}^*_{s\mu}KD + \overline{DK}D^*_{s\mu}), \tag{8}$$

where we have defined the charm meson and kaon isodoublets $D \equiv (D^0, D^+)$, $D^* \equiv (D^{*0}, D^{*+})$, and $K \equiv (K^0, K^+)$.

In addition to the normal terms given above, which were considered in Ref. [20], there are also anomalous parity terms introduced in Ref. [17] for the $J/\psi-\pi$ case. In the $J/\psi-K$ case they are

$$\mathcal{L}_{\psi D^*D} = g_{\psi D^*D}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\partial_\alpha\bar{D}^*_\beta D + \partial_\alpha D^*_\beta\bar{D}), \tag{9}$$

$$\mathcal{L}_{\psi D_s^*D_s} = g_{\psi D_s^*D_s}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\partial_\alpha\bar{D}^*_{s\beta}D_s + \partial_\alpha D^*_{s\beta}\bar{D}_s), \tag{10}$$

$$\mathcal{L}_{KD_s^*D^*} = -g_{KD_s^*D^*}\epsilon^{\mu\nu\alpha\beta}(\partial_\mu\bar{D}^*_\nu\partial_\alpha D^*_{s\beta}\bar{K} + \partial_\mu D^*_\nu\partial_\alpha\bar{D}^*_{s\beta}K), \tag{11}$$

$$\mathcal{L}_{\psi KD_sD} = -ig_{KD_sD\psi}\epsilon^{\mu\nu\alpha\beta}\psi_\mu(\partial_\nu\bar{D}\partial_\alpha\bar{K}\partial_\beta D_s - \partial_\nu D\partial_\alpha K\partial_\beta\bar{D}_s), \tag{12}$$

$$\begin{aligned}\mathcal{L}_{\psi KD_s^*D^*} = &-ig_{KD_s^*D^*\psi}\epsilon^{\mu\nu\alpha\beta}\psi_\mu(\bar{D}^*_\nu\partial_\alpha\overline{KD}^*_{s\beta} - D^*_\nu\partial_\alpha K\bar{D}^*_{s\beta})\\ &- ih_{\psi KD_s^*D^*}\epsilon^{\mu\nu\alpha\beta}(\partial_\mu D^*_\beta\psi_\nu\bar{D}^*_{s\alpha}K + \partial_\mu\bar{D}^*_{s\alpha}\psi_\nu D^*_\beta K\\ &+ 3\partial_\mu\psi_\nu\bar{D}^*_{s\alpha}D^*_\beta K - \partial_\mu\bar{D}^*_\beta\psi_\nu D^*_{s\alpha}\bar{K} - \partial_\mu D^*_{s\alpha}\psi_\nu\bar{D}^*_\beta\bar{K}\\ &- 3\partial_\mu\psi_\nu D^*_{s\alpha}\bar{D}^*_\beta\bar{K}).\end{aligned} \tag{13}$$

In Fig. 1 we show the processes we want to study for the absorption of J/ψ by kaons. They are

$$KJ/\psi \to D_s\bar{D}^*, \quad \bar{K}J/\psi \to D^*\bar{D}_s, \tag{14}$$

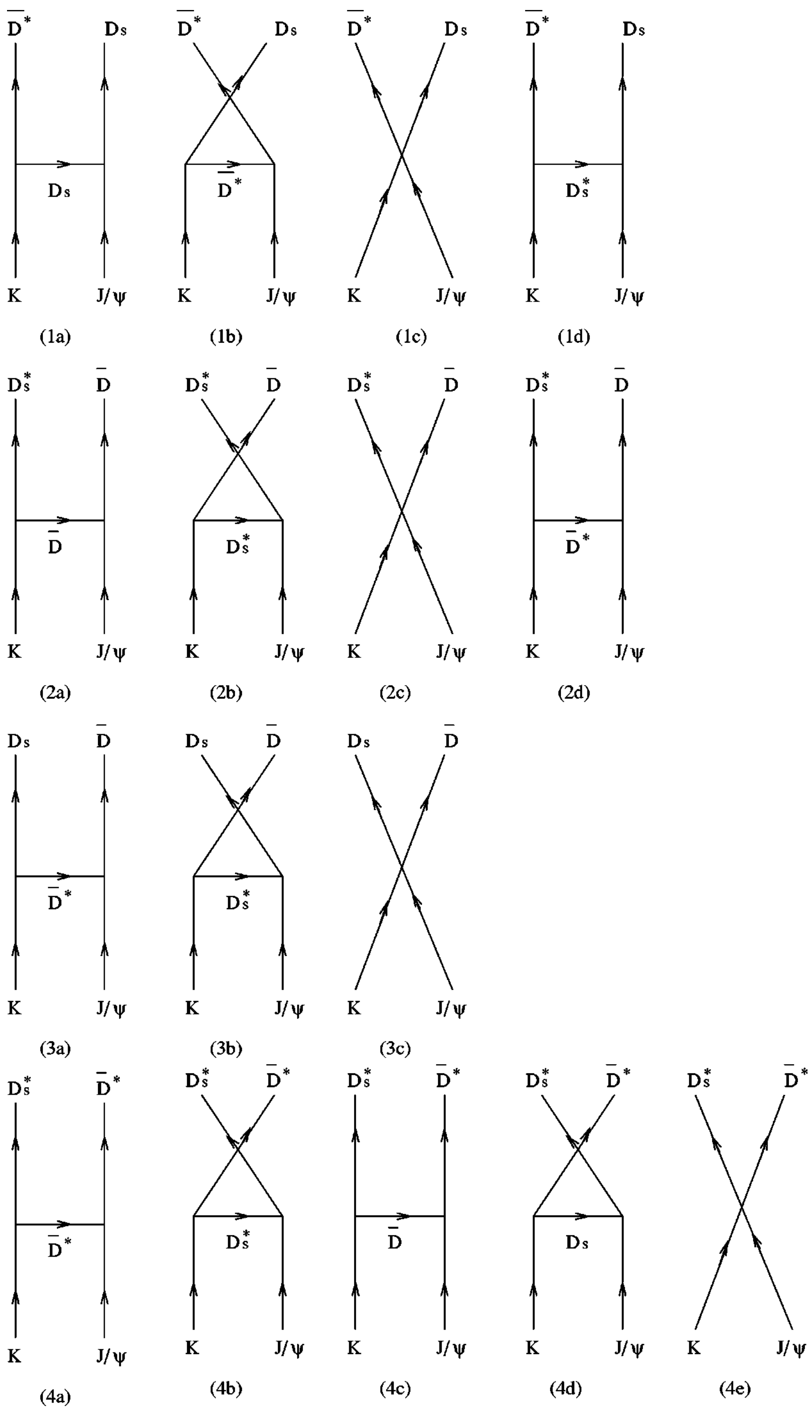

FIG. 1. Diagrams for J/ψ absorption processes: (1) $K\psi \to D_s\overline{D^*}$, (2) $K\psi \to D_s^*\overline{D}$, (3) $K\psi \to D_s\overline{D}$, (4) $K\psi \to D_s^*\overline{D^*}$. Diagrams for the processes $\overline{K}\psi \to \overline{D}_s D^*$, $\overline{K}\psi \to \overline{D}_s D^*$, $\overline{K}\psi \to \overline{D}_s D$, and $\overline{K}\psi \to \overline{D}_s^* D^*$ are similar to (1a)–(1d) through (4a)–(4d), respectively, but with each particle replaced by its antiparticle.

$$KJ/\psi \to D_s^*\overline{D}, \quad \overline{K}J/\psi \to D\overline{D_s^*}, \tag{15}$$

$$KJ/\psi \to D_s\overline{D}, \quad \overline{K}J/\psi \to D\overline{D_s}, \tag{16}$$

$$KJ/\psi \to D_s^*\overline{D^*}, \quad \overline{K}J/\psi \to D^*\overline{D_s^*}. \tag{17}$$

Since the two processes in Eqs. (14)–(17) have the same cross section, in Fig. 1 we only show the diagrams for the first process in Eqs. (14) through (17).

Defining the four-momentum of the kaon and the J/ψ by p_1, p_2, respectively, and the four-momentum of the vector and pseudoscalar final-state mesons, respectively, by p_3 and p_4, the full amplitude for the processes $K\psi \to D_s\overline{D}^*$ and $K\psi \to D_s^*\overline{D}$, shown in diagrams (1) and (2) of Fig. 1, without isospin factors and before summing and averaging over external spins, is given by

$$\mathcal{M}_i \equiv \mathcal{M}_i^{\nu\lambda}\epsilon_{2\nu}\epsilon_{3\lambda}^* = \left(\sum_{j=a,b,c,d}\mathcal{M}_{ij}^{\nu\lambda}\right)\epsilon_{2\nu}\epsilon_{3\lambda}^* \quad \text{for} \quad i=1,2, \tag{18}$$

with

$$\mathcal{M}_{1a}^{\nu\lambda} = -g_{KD_sD^*}g_{\psi D_sD_s}(-2p_1+p_3)^\lambda\left(\frac{1}{t-m_{D_s}^2}\right)(p_1-p_3+p_4)^\nu,$$

$$\mathcal{M}_{1b}^{\nu\lambda} = g_{KD_sD^*}g_{\psi D^*D^*}(-p_1-p_4)^\alpha\left(\frac{1}{u-m_{D^*}^2}\right)\times\left[g_{\alpha\beta}-\frac{(p_1-p_4)_\alpha(p_1-p_4)_\beta}{m_{D^*}^2}\right][(-p_2-p_3)^\beta g^{\nu\lambda}+(-p_1+p_2+p_4)^\lambda g^{\beta\nu}+(p_1+p_3-p_4)^\nu g^{\beta\lambda}],$$

$$\mathcal{M}_{1c}^{\nu\lambda} = -g_{\psi KD_sD^*}g^{\nu\lambda},$$

$$\mathcal{M}_{1d}^{\nu\lambda} = -\frac{g_{KD_s^*D^*}g_{\psi D_s^*D_s}}{t-m_{D_s^*}^2}\epsilon^{\lambda\rho\sigma\alpha}\epsilon^{\nu\gamma\delta\beta}\times\left[g_{\alpha\beta}-\frac{(p_1-p_3)_\alpha(p_1-p_3)_\beta}{m_{D_s^*}^2}\right]p_{1\sigma}p_{2\gamma}p_{3\rho}p_{4\delta}, \tag{19}$$

$$\mathcal{M}_{2a}^{\nu\lambda} = -g_{KDD_s^*}g_{\psi DD}(-2p_1+p_3)^\lambda\left(\frac{1}{t-m_D^2}\right)(p_1-p_3+p_4)^\nu,$$

$$\mathcal{M}_{2b}^{\nu\lambda} = g_{KDD_s^*}g_{\psi D_s^*D_s^*}(-p_1-p_4)^\alpha\left(\frac{1}{u-m_{D_s^*}^2}\right)\times\left[g_{\alpha\beta}-\frac{(p_1-p_4)_\alpha(p_1-p_4)_\beta}{m_{D_s^*}^2}\right][(-p_2-p_3)^\beta g^{\nu\lambda}+(-p_1+p_2+p_4)^\lambda g^{\beta\nu}+(p_1+p_3-p_4)^\nu g^{\beta\lambda}],$$

$$\mathcal{M}_{2c}^{\nu\lambda} = -g_{\psi KDD_s^*}g^{\nu\lambda},$$

$$\mathcal{M}_{2d}^{\nu\lambda} = -\frac{g_{KD_s^*D^*}g_{\psi D^*D}}{t-m_{D^*}^2}\epsilon^{\lambda\rho\sigma\alpha}\epsilon^{\nu\gamma\delta\beta}\times\left[g_{\alpha\beta}-\frac{(p_1-p_3)_\alpha(p_1-p_3)_\beta}{m_{D^*}^2}\right]p_{1\sigma}p_{2\gamma}p_{3\rho}p_{4\delta}, \tag{20}$$

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

We can see that the differences between these two processes are basically due to the meson exchanged. It can be shown [14,17] that the full amplitudes $\mathcal{M}_i^{\nu\lambda}$ (for $i=1,2$) given above satisfy current conservation: $\mathcal{M}_i^{\nu\lambda}p_{2\nu}=0$.

Calling the four-momentum of the two pseudoscalar final-state mesons, respectively, by p_3 and p_4, the full amplitude for the processes $K\psi\to D_s\bar{D}$ shown in diagram (3) of Fig. 1 is

$$\mathcal{M}_3 \equiv \mathcal{M}_3^\nu\epsilon_{2\nu} = \left(\sum_{i=a,b,c}\mathcal{M}_{3i}^\nu\right)\epsilon_{2\nu}, \tag{21}$$

with

$$\mathcal{M}_{3a}^\nu = \frac{g_{KD_sD^*}g_{\psi D^*D}}{t-m_{D^*}^2}\epsilon^{\nu\beta\gamma\delta}\left(g_{\alpha\beta}-\frac{(p_1-p_3)_\alpha(p_1-p_3)_\beta}{m_{D^*}^2}\right)\times(p_1+p_3)^\alpha p_{2\gamma}p_{4\delta},$$

$$\mathcal{M}_{3b}^\nu = -\frac{g_{KDD_s^*}g_{\psi D_s^*D_s}}{u-m_{D_s^*}^2}\epsilon^{\nu\beta\gamma\delta}\left(g_{\alpha\beta}-\frac{(p_3-p_2)_\alpha(p_3-p_2)_\beta}{m_{D_s^*}^2}\right)\times(p_1+p_4)^\alpha p_{2\gamma}p_{3\delta},$$

$$\mathcal{M}_{3c}^\nu = -g_{\psi KDD_s}\epsilon^{\nu\delta\lambda\gamma}p_{1\delta}p_{3\lambda}p_{4\gamma}. \tag{22}$$

For the diagram (4) in Fig. 1, representing the processes $K\psi\to D_s^*\bar{D^*}$, calling the four-momentum of the two vector final-state mesons, respectively, by p_3 and p_4, the full amplitude is given by

$$\mathcal{M}_4 \equiv \mathcal{M}_4^{\nu\lambda\mu}\epsilon_{2\nu}\epsilon_{3\lambda}^*\epsilon_{4\mu}^* = \left(\sum_{i=a,b,c,d,e}\mathcal{M}_{4i}^{\nu\lambda\mu}\right)\epsilon_{2\nu}\epsilon_{3\lambda}^*\varepsilon_{4\mu}^*, \tag{23}$$

with

$$\mathcal{M}_{4a}^{\nu\lambda\mu} = -g_{KD^*D_s^*}g_{\psi D^*D^*}\frac{1}{t-m_{D^*}^2}\times\left(g_{\alpha\beta}-\frac{(p_2-p_4)_\alpha(p_2-p_4)_\beta}{m_{D^*}^2}\right)\epsilon^{\lambda\sigma\rho\alpha}p_{3\sigma}p_{1\rho}\times[(2p_2-p_4)^\mu g^{\beta\nu}+(-p_2-p_4)^\beta g^{\mu\nu}+(-p_2+2p_4)^\nu g^{\beta\mu}],$$

$$\mathcal{M}_{4b}^{\nu\lambda\mu} = -g_{KD^*D_s^*}g_{\psi D_s^*D_s^*}\frac{1}{u-m_{D_s^*}^2}\times\left(g_{\alpha\beta}-\frac{(p_1-p_4)_\alpha(p_1-p_4)_\beta}{m_{D_s^*}^2}\right)\epsilon^{\mu\sigma\rho\alpha}p_{1\sigma}p_{4\rho}\times[(2p_3-p_2)^\nu g^{\beta\lambda}+(-p_2-p_3)^\beta g^{\nu\lambda}+(-p_3+2p_2)^\lambda g^{\beta\nu}],$$

$$\mathcal{M}_{4c}^{\nu\lambda\mu} = g_{KDD_s^*}g_{\psi D^*D}\frac{1}{t-m_D^2}\epsilon^{\nu\mu\gamma\delta}(2p_1-p_3)^\lambda p_{2\gamma}p_{4\delta},$$

$$\mathcal{M}_{4d}^{\nu\lambda\mu} = -g_{KD_sD^*}g_{\psi D_s^*D_s}\frac{1}{u-m_{D_s}^2}\epsilon^{\nu\lambda\gamma\sigma}(2p_1-p_4)^\mu p_{2\gamma}p_{3\sigma},$$

$$\mathcal{M}_{4e}^{\nu\lambda\mu} = -g_{\psi KD^*D_s^*}\epsilon^{\nu\lambda\mu\sigma}p_{1\sigma}+h_{\psi KD^*D_s^*}\varepsilon^{\nu\lambda\mu\sigma}(p_4+p_3-3p_2)_\sigma. \tag{24}$$

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

$$\frac{d\sigma_i}{dt} = \frac{1}{192\pi s p_{0,\mathrm{cm}}^2}\mathcal{M}_i^{\nu\lambda}\mathcal{M}_i^{*\nu'\lambda'}\left(g_{\nu\nu'} - \frac{p_{2\nu}p_{2\nu'}}{m_2^2}\right)\times\left(g_{\lambda\lambda'} - \frac{p_{3\lambda}p_{3\lambda'}}{m_3^2}\right) \quad \text{for } i=1,2, \tag{25}$$

$$\frac{d\sigma_3}{dt} = \frac{1}{192\pi s p_{0,\mathrm{cm}}^2}\mathcal{M}_3^{\nu}\mathcal{M}_3^{*\nu'}\left(g_{\nu\nu'} - \frac{p_{2\nu}p_{2\nu'}}{m_2^2}\right), \tag{26}$$

and

$$\frac{d\sigma_4}{dt} = \frac{1}{192\pi s p_{0,\mathrm{cm}}^2}\mathcal{M}_4^{\nu\lambda\mu}\mathcal{M}_4^{*\nu'\lambda'\mu'}\left(g_{\nu\nu'} - \frac{p_{2\nu}p_{2\nu'}}{m_2^2}\right)\times\left(g_{\lambda\lambda'} - \frac{p_{3\lambda}p_{3\lambda'}}{m_3^2}\right)\left(g_{\mu\mu'} - \frac{p_{4\mu}p_{4\mu'}}{m_4^2}\right), \tag{27}$$

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

$$p_{0,\mathrm{cm}}^2 = \frac{[s-(m_1+m_2)^2][s-(m_1-m_2)^2]}{4s} \tag{28}$$

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

III. NUMERICAL RESULTS

A. Coupling constants and form factors

To estimate the cross sections we have first to determine the coupling constants of the effective Lagrangians. Exact SU(4) symmetry would give the following relations among the coupling constants [14,17]:

$$g_{KD_sD^*} = g_{KDD_s^*} = \frac{g}{2\sqrt{2}},$$

$$g_{\psi DD} = g_{\psi D_sD_s} = g_{\psi D^*D^*} = g_{\psi D_s^*D_s^*} = \frac{g}{\sqrt{6}},$$

$$g_{\psi KD_sD^*} = g_{\psi KDD_s^*} = \frac{g^2}{4\sqrt{3}},$$

$$g_{\psi D^*D} = g_{\psi D_s^*D_s} = \frac{g_{KD_s^*D^*}}{\sqrt{3}} = \frac{\sqrt{2}g_a^2N_c}{64\sqrt{3}\pi^2F_\pi},$$

$$g_{\psi KDD_s} = \frac{g_aN_c}{96\sqrt{6}\pi^2F_\pi^3},$$

$$g_{\psi KD^*D_s^*} = 5h_{\psi KD^*D_s^*} = \frac{5g_a^3N_c}{2^8\sqrt{3}\pi^2F_\pi}, \tag{29}$$

where $N_c=3$ and $F_\pi=132$ MeV.

Since none of the above couplings are known experimentally, one has to use models to estimate them. In Ref. [20] we have calculated the cross section for the processes J/ψ kaons $\to \bar{D}^*D_s + D^*\bar{D}_s + \bar{D}D_s^* + \bar{D}_s^*D$ considering only the normal terms given by the Lagrangians in Eqs. (1) through (8), and using two different ways to estimate the coupling constants: vector meson dominance model estimate of $g_{\psi DD}$ plus SU(4) relations, and the experimental result for $g_{\rho\pi\pi}$ plus SU(4) relations. We showed that the results for the cross section can vary by almost one order of magnitude, depending on the values of the coupling constants used, even without considering form factors in the hadronic vertices [14,17]. This gives an idea of how important it is to have a good estimate of the value of the coupling constants. In a recent work [21], the $J/\psi-\pi$ and $J/\psi-\rho$ cross sections were evaluated by using form factors and coupling constants estimated using QCD sum rules [22–25]. The results in Ref. [21] 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 πD^*D, determined from QCD sum rules [23,26], and the above SU(4) relations to estimate the form factors and coupling constants in all vertices.

From Ref. [26] we get $g_{\psi DD^*}=4.0$ GeV^{-1} and $g_{\psi DD}=5.8$. Using these numbers in the SU(4) relations given in Eq. (29) we obtain

$$g_{\psi DD} = g_{\psi D_sD_s} = g_{\psi D^*D^*} = g_{\psi D_s^*D_s^*} = 5.8,$$
$$g_{KD_sD^*} = g_{KDD_s^*} = 5.0,$$

$$g_{\psi KD_sD^*} = g_{\psi KDD_s^*} = 28.8, \quad g_{\psi D^*D} = g_{\psi D_s^*D_s} = 4.0\ \mathrm{GeV}^{-1},$$
$$g_{KD_s^*D^*} = 7.0\ \mathrm{GeV}^{-1},$$

$$g_{\psi KDD_s} = 6.6\ \mathrm{GeV}^{-3}, \quad g_{\psi KD^*D_s^*} = 41.6\ \mathrm{GeV}^{-1},$$
$$h_{\psi KD^*D_s^*} = 8.3\ \mathrm{GeV}^{-1}. \tag{30}$$

The form factors given in Ref. [26] are

$$g_{\psi DD^*}^{(D^*)}(t) = g_{\psi DD^*}\left(5e^{-((27-t)/18.6)^2}\right) = g_{\psi DD^*}h_1(t), \tag{31}$$

$$g_{\psi DD^*}^{(D)}(t) = g_{\psi DD^*}\left(3.3e^{-((26-t)/21.2)^2}\right) = g_{\psi DD^*}h_2(t), \tag{32}$$

$$g_{\psi DD}^{(D)}(t) = g_{\psi DD}\left(2.6e^{-((20-t)/15.8)^2}\right) = g_{\psi DD}h_3(t), \tag{33}$$

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 KD_s^*D or KD^*D_s, we make the supposition that they are similar to the form factor at the vertex πD^*D. From Ref. [23] we get

$$g_{\pi D^* D}^{(D)}(t) = g_{\pi D^* D}\left(\frac{(3.5\ \text{GeV})^2 - m_D^2}{(3.5\ \text{GeV})^2 - t}\right) = g_{\pi D^* D} h_4(t, m_D^2). \tag{34}$$

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

$$\mathcal{M}_{ia} \to h_3(t) h_4(t, m_{ia}^2) \mathcal{M}_{ia}, \quad \mathcal{M}_{ib} \to h_3(u) h_4(u, m_{ib}^2) \mathcal{M}_{ib}, \tag{35}$$

for $i=1,2,$ and 4, with $m_{1a}=m_{D_s}, m_{1b}=m_{4a}=m_{D^*}, m_{2a}=m_D$, and $m_{2b}=m_{4b}=m_{D_s^*}$.

$$\mathcal{M}_{ic} \to \tfrac{1}{2}[h_3(t) h_4(t, m_{ia}^2) + h_3(u) h_4(u, m_{ib}^2)] \mathcal{M}_{ic},$$
$$\mathcal{M}_{id} \to h_1(t) h_4(t, m_{id}^2) \mathcal{M}_{id}, \tag{36}$$

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

$$\mathcal{M}_{3a} \to h_1(t) h_4(t, m_{D^*}^2) \mathcal{M}_{3a}, \quad \mathcal{M}_{3b} \to h_1(u) h_4(u, m_{D_s^*}^2) \mathcal{M}_{3b},$$

$$\mathcal{M}_{3c} \to \tfrac{1}{2}[h_1(t) h_4(t, m_{D^*}^2) + h_1(u) h_4(u, m_{D_s^*}^2)] \mathcal{M}_{3c}, \tag{37}$$

and

$$\mathcal{M}_{4c} \to h_2(t) h_4(t, m_D^2) \mathcal{M}_{4c}, \quad \mathcal{M}_{4d} \to h_2(u) h_4(u, m_{D_s}^2) \mathcal{M}_{4d},$$

$$\mathcal{M}_{4e} \to \tfrac{1}{4}[h_3(t) h_4(t, m_{D^*}^2) + h_3(u) h_4(u, m_{D_s^*}^2)$$
$$+ h_2(t) h_4(t, m_D^2) + h_2(u) h_4(u, m_{D_s}^2)] \mathcal{M}_{4e}. \tag{38}$$

One can argue that our prescription to introduce the form factors in Eqs. (35) through (38) might spoil the current conservation associated with the J/ψ 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: $\mathcal{M}_1^{\nu\lambda} = \Sigma_{j=a,b,c,d} \mathcal{M}_{1j}^{\nu\lambda}$. Keeping only terms that will contribute to the cross section, it can be written as

$$\mathcal{M}_1^{\nu\lambda} = \Lambda_1 p_1^\nu p_1^\lambda + \Lambda_2 p_3^\nu p_1^\lambda + \Lambda_3 p_1^\nu p_2^\lambda + \Lambda_4 g^{\nu\lambda} + \Lambda_5 p_3^\nu p_2^\lambda, \tag{39}$$

where, before introducing the form factors, we have

$$\Lambda_1 = 4\frac{g_{\psi D_s D_s} g_{K D_s D^*}}{t - m_{D_s}^2} - \frac{g_{\psi D^* D} g_{K D_s^* D^*}}{t - m_{D_s^*}^2} \frac{(m_\psi^2 + m_{D^*}^2 - u)}{2}, \tag{40}$$

$$\Lambda_2 = -4\left(\frac{g_{\psi D_s D_s} g_{K D_s D^*}}{t - m_{D_s}^2} + \frac{g_{\psi D^* D^*} g_{K D_s D^*}}{u - m_{D^*}^2}\right)$$
$$- \frac{g_{\psi D^* D} g_{K D_s^* D^*}}{t - m_{D_s^*}^2} \frac{(m_K^2 + m_\psi^2 - s)}{2}, \tag{41}$$

$$\Lambda_3 = 4\frac{g_{\psi D^* D^*} g_{K D_s D^*}}{u - m_{D^*}^2} - \frac{g_{\psi D^* D} g_{K D_s^* D^*}}{t - m_{D_s^*}^2} \frac{(m_{D^*}^2 - m_K^2 + t)}{2}, \tag{42}$$

$$\Lambda_4 = \frac{g_{\psi D^* D^*} g_{K D_s D^*}}{u - m_{D^*}^2}\left(s - t + \frac{(m_K^2 - m_{D_s}^2)(m_\psi^2 - m_{D^*}^2)}{m_{D^*}^2}\right)$$
$$- g_{K\psi D_s D^*} - \frac{g_{\psi D^* D} g_{K D_s^* D^*}}{4(t - m_{D_s^*}^2)}[m_{D^*}^2(m_\psi^2 - m_K^2 - m_{D_s}^2)$$
$$+ t(u - s) + m_K^2(m_{D^*}^2 - m_\psi^2 + m_{D_s}^2)], \tag{43}$$

$$\Lambda_5 = -\frac{g_{\psi D^* D} g_{K D_s^* D^*}}{t - m_{D_s^*}^2} \frac{(m_K^2 - m_{D^*}^2 + t)}{2}. \tag{44}$$

Without interfering in the final result for the cross section, the amplitude in Eq. (39) can be rewritten as

$$\mathcal{M}_1^{\nu\lambda} = \Lambda_1\left(p_1^\nu - \frac{p_1 \cdot p_2}{m_\psi^2} p_2^\nu\right) p_1^\lambda + \Lambda_2\left(p_3^\nu - \frac{p_3 \cdot p_2}{m_\psi^2} p_2^\nu\right) p_1^\lambda$$
$$+ \Lambda_3\left(p_1^\nu - \frac{p_1 \cdot p_2}{m_\psi^2} p_2^\nu\right) p_2^\lambda + \Lambda_4\left(g^{\nu\lambda} - \frac{p_2^\nu p_2^\lambda}{m_\psi^2}\right)$$
$$+ \Lambda_5\left(p_3^\nu - \frac{p_3 \cdot p_2}{m_\psi^2} p_2^\nu\right) p_2^\lambda, \tag{45}$$

which is explicitly gauge invariant independently of the values of the parameter Λ_i. Therefore, our prescription in keeping gauge invariance, when the form factors from Eqs. (35) to (38) are introduced, is to introduce new terms, proportional to p_2^ν, in the amplitude, as in Eq. (45). A different prescription can be found in Ref. [21].

B. Cross sections

We first give the cross sections for the J/ψ absorption by kaons without considering the form factors, i.e., we use the expressions for the amplitudes in Eqs. (19) through (24). We will be always including the contributions for both $J/\psi K$ and $J/\psi \bar{K}$.

In Fig. 2 we show the cross section of J/ψ dissociation by kaons 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/ψ kaons $\to \bar{D}^* D_s + D^* \bar{D}_s$, $\bar{D} D_s^* + \bar{D}_s^* D$, $\bar{D} D_s + D \bar{D}_s$, $\bar{D}^* D_s^* + D^* \bar{D}_s^*$, and total, respectively. We see that for $\sqrt{s} > 4.4$ GeV the process J/ψ kaons $\to \bar{D}^* D_s^* + D^* \bar{D}_s^*$ dominates. However, for smaller values of $\sqrt{s}$ the processes given by diagrams (1) and (2) in Fig. 1 are the most important ones. This is similar to what was found in Ref. [17] for the J/ψ dissociation by pions.

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. (35) through (38). The first important conclusion is that the use of appropriate form fac-

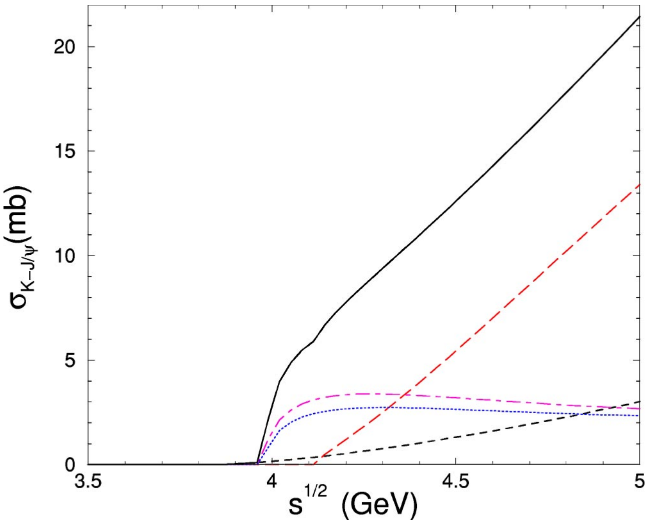

FIG. 2. Total cross sections, without form factors, for the processes J/ψ kaons $\to \bar{D}^* D_s + D^* \bar{D}_s$ (dot-dashed line), $\bar{D} D_s^* + \bar{D}_s^* D$ (dotted line), $\bar{D} D_s + D\, \bar{D}_s$ (dashed line), and $\bar{D}^*\, D_s^* + D^*\, \bar{D}_s^*$ (long-dashed line). The solid line gives the total J/ψ dissociation by kaons cross section.

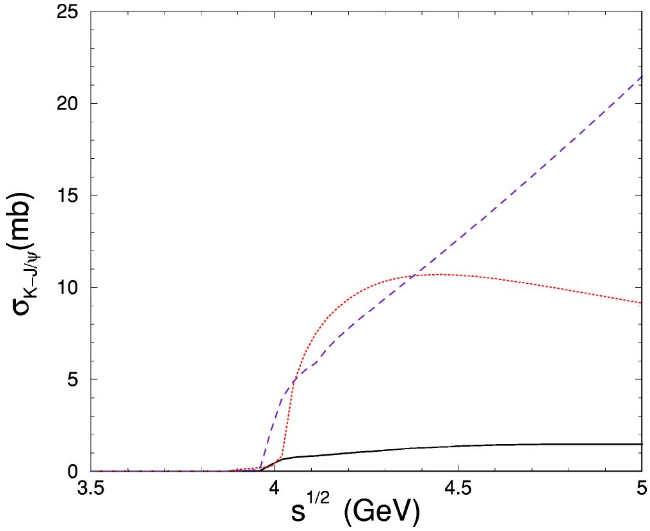

FIG. 4. Total J/ψ absorption cross section as a function of the initial energy. The solid and dashed lines give the results for J/ψ absorption by kaons with and without form factors, respectively. The dotted line gives the results for J/ψ absorption by pions with form factors.

tors do change the behavior of the cross section as a function of $\sqrt{s}$, as obtained in Ref. [21]. 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 no 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.

Other important result of our calculation is the fact that, using appropriate form factors with cut-offs of order of $\sim$4 GeV [see Eqs. (31) through (34)], 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 cutoffs of the order of $\sim$1 GeV, which are considered very small for charmed mesons.

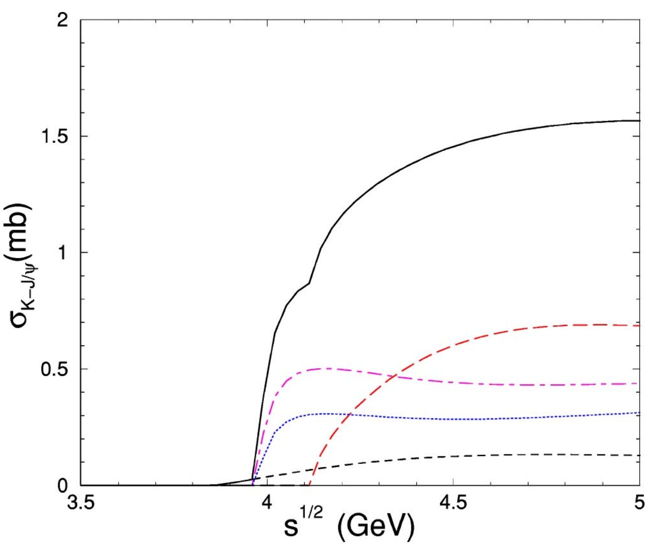

FIG. 3. Same as in Fig. 2 but with form factors.

In Fig. 4 we also show, for comparison, the total cross section for J/ψ absorption by pions (dotted line) using the same form factors and coupling constants given here, and the experimental value for the $D^* D\pi$ coupling constant: $g_{\pi D^* D} = 12.6$ [27]. It is important to mention that the smallness of the value of the total J/ψ-kaon absorption cross section, as compared with the J/ψ-pion absorption cross section, is due to the use of the experimental value for $g_{\pi D^* D}$, which is much bigger than what one would get by using SU(4) relations: $g_{\pi D^* D} = g/4 = 3.6$. In Ref. [20] we have showed that, using coupling constants related by SU(4) relations, the J/ψ-kaon absorption cross section is even bigger than the J/ψ-pion absorption cross section. Therefore, once more this shows how important it is to have good estimates for the couplings.

IV. CONCLUSIONS

We have studied the cross section of J/ψ dissociation by kaons in a meson-exchange model that includes pseudoscalar–pseudoscalar–vector-meson couplings, three-vector-meson couplings, pseudoscalar–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 (pseudoscalar–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, $\sqrt{s} > 4.4$ GeV.

As shown in Fig. 2 our results, without form factors, have the same energy dependence of J/ψ absorption by pions 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. [21] for J/ψ absorption by pions.

With QCD sum rules estimates for the coupling constants and form factors, the total J/ψ-kaon cross section was found to be 1.0–1.6 mb for $4.1 \leqslant \sqrt{s} \leqslant 5$ GeV. Using the same form factors and the experimental value for $g_{\pi D^* D}$ we get for the J/ψ-pion total dissociation cross section $9.0 \sim 10.0$ mb in the same energy range.

ACKNOWLEDGMENTS

This work was supported by CNPq and FAPESP.

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
[2] R. Vogt, Phys. Rep. **310**, 197 (1999).
[3] C. Gerschel and J. Huefner, Annu. Rev. Nucl. Part. Sci. **49**, 255 (1999).
[4] G. Bhanot and M. E. Peskin, Nucl. Phys. **B156**, 391 (1979); M. E. Peskin, *ibid.* **B156**, 365 (1979).
[5] D. Kharzeev and H. Satz, Phys. Lett. B **334**, 155 (1994).
[6] S. H. Lee and Y. Oh, J. Phys. G **28**, 1903 (2002); Y. Oh, S. Kim, and S. H. Lee, Phys. Rev. C **65**, 067901 (2002).
[7] C.-Y. Wong, E. S. Swanson, and T. Barnes, Phys. Rev. C **62**, 045201 (2000); **65**, 014903 (2001).
[8] K. Martins, D. Blaschke, and E. Quack, Phys. Rev. C **51**, 2723 (1995).
[9] F. S. Navarra, M. Nielsen, R. S. Marques de Carvalho, and G. Krein, Phys. Lett. B **529**, 87 (2002).
[10] F. O. Durães, S. H. Lee, F. S. Navarra, and M. Nielsen, Phys. Lett. B **564**, 97 (2003).
[11] F. O. Durães, H. Kim, S. H. Lee, F. S. Navarra, and M. Nielsen, Phys. Rev. C **68**, 035208 (2003).
[12] S. G. Matinyan and B. Müller, Phys. Rev. C **58**, 2994 (1998).
[13] K. L. Haglin, Phys. Rev. C **61**, 031902 (2000).
[14] Z. Lin and C. M. Ko, Phys. Rev. C **62**, 034903 (2000).
[15] A. Sibirtsev, K. Tsushima, and A. W. Thomas, Phys. Rev. C **63**, 044906 (2001).
[16] K. L. Haglin and C. Gale, Phys. Rev. C **63**, 065201 (2001).
[17] Y. Oh, T. Song, and S. H. Lee, Phys. Rev. C **63**, 034901 (2001); Y. Oh, T. Song, S. H. Lee, and C.-Y. Wong, J. Korean Phys. Soc. **43**, 1003 (2003).
[18] F. S. Navarra, M. Nielsen, and M. R. Robilotta, Phys. Rev. C **64**, 021901(R) (2001).
[19] H. G. Dosch, F. S. Navarra, M. Nielsen and M. Rueter, Phys. Lett. B **466**, 363 (1999).
[20] R. S. Azevedo and M. Nielsen, nucl-th/0310022.
[21] K. L. Haglin and C. Gale, J. Phys. G **30**, S375 (2004).
[22] F. S. Navarra, M. Nielsen, M. E. Bracco, M. Chiapparini, and C. L. Schat, Phys. Lett. B **489**, 319 (2000).
[23] F. S. Navarra, M. Nielsen, and M. E. Bracco, Phys. Rev. D **65**, 037502 (2002).
[24] R. D. Matheus, F. S. Navarra, M. Nielsen, and R. Rodrigues da Silva, Phys. Lett. B **541**, 265 (2002).
[25] M. E. Bracco, M. Chiapparini, A. Lozea, F. S. Navarra, and M. Nielsen, Phys. Lett. B **521**, 1 (2001).
[26] R. D. Matheus, F. S. Navarra, M. Nielsen, and R. Rodrigues da Silva, hep-ph/0310280.
[27] S. Ahmed *et al.*, CLEO Collaboration, Phys. Rev. Lett. **87**, 251801 (2001). Our convention for $g_{\pi D^* D}$ is different by $1/\sqrt{2}$.