A Model for J/ψ - Kaon Cross Section

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We calculate the cross section for the dissociation of J/ψ by kaons within the framework of a meson exchange model. We find that, depending on the values of the coupling constants used, the cross section can vary from 5 mb to 30 mb at $\sqrt{s} \sim 5$ GeV.

In relativistic heavy ion collisions J/ψ suppression has been recognized as an important tool 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 [12-17]. 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 non-perturbative effects negligible [9-11,18].

The meson exchange approach was applied basically to $J/\psi-\pi$ 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 will evaluate the $J/\psi - K$ cross section using a meson-exchange model as in ref. [13], but we will treat the VVV and four-point couplings in the effective Lagrangians as in ref. [14].

As in refs. [13-16] we start with the SU(4) Lagrangian for the pseudo-scalar and vector mesons. The effective Lagrangians relevant for the study of the J/ψ absorption by kaons are:

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

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

$$\mathcal{L}_{\psi DD} = ig_{\psi DD}\,\psi^\mu\left(D\partial_\mu\overline{D} - (\partial_\mu D)\overline{D}\right)\,, \tag{3}$$

$$\mathcal{L}_{\psi D_sD_s} = ig_{\psi D_sD_s}\,\psi^\mu\left(D_s\partial_\mu\overline{D}_s - (\partial_\mu D_s)\overline{D}_s\right)\,, \tag{4}$$

$$\begin{aligned}\mathcal{L}_{\psi D^*D^*} &= ig_{\psi D^*D^*}\,\Big[\psi^\mu\left((\partial_\mu D^{*\nu})\overline{D_\nu^*} - D^{*\nu}\partial_\mu\overline{D_\nu^*}\right)\\ &+ \left((\partial_\mu\psi^\nu)D_\nu^* - \psi^\nu\partial_\mu D_\nu^*\right)\overline{D^{*\mu}}\\ &+ D^{*\mu}\left(\psi^\nu\partial_\mu\overline{D_\nu^*} - (\partial_\mu\psi^\nu)\overline{D_\nu^*}\right)\Big]\,,\end{aligned} \tag{5}$$

$$\begin{aligned}\mathcal{L}_{\psi D_s^*D_s^*} &= ig_{\psi D_s^*D_s^*}\,\Big[\psi^\mu\left((\partial_\mu D_s^{*\nu})\overline{D}_{s\nu}^* - D_s^{*\nu}\partial_\mu\overline{D}_{s\nu}^*\right)\\ &+ \left((\partial_\mu\psi^\nu)D_{s\nu}^* - \psi^\nu\partial_\mu D_{s\nu}^*\right)\overline{D}_s^{*\mu}\\ &+ D_s^{*\mu}\left(\psi^\nu\partial_\mu\overline{D}_{s\nu}^* - (\partial_\mu\psi^\nu)\overline{D}_{s\nu}^*\right)\Big]\,,\end{aligned} \tag{6}$$

$$\mathcal{L}_{K\psi D_sD^*} = -g_{K\psi D_sD^*}\,\psi^\mu\left(D_\mu^*K\overline{D}_s + D_s\overline{KD_\mu^*}\right)\,, \tag{7}$$

$$\mathcal{L}_{K\psi DD_s^*} = -g_{K\psi DD_s^*}\,\psi^\mu\left(\overline{D}_{s\mu}^*KD + \overline{DK}D_{s\mu}^*\right)\,, \tag{8}$$

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

The processes we want to study for the absorption of J/ψ by kaons are:

$$K J/\psi \to D_s \overline{D}^*, \qquad \overline{K} J/\psi \to D^* \overline{D}_s \tag{9}$$
$$K J/\psi \to D_s^* \overline{D}, \qquad \overline{K} J/\psi \to D \overline{D}_s^*. \tag{10}$$

The two processes in eqs.(9) and (10) have the same cross section. Therefore, in Fig. 1 we only show the diagrams for the first process in eqs. (9) and (10).

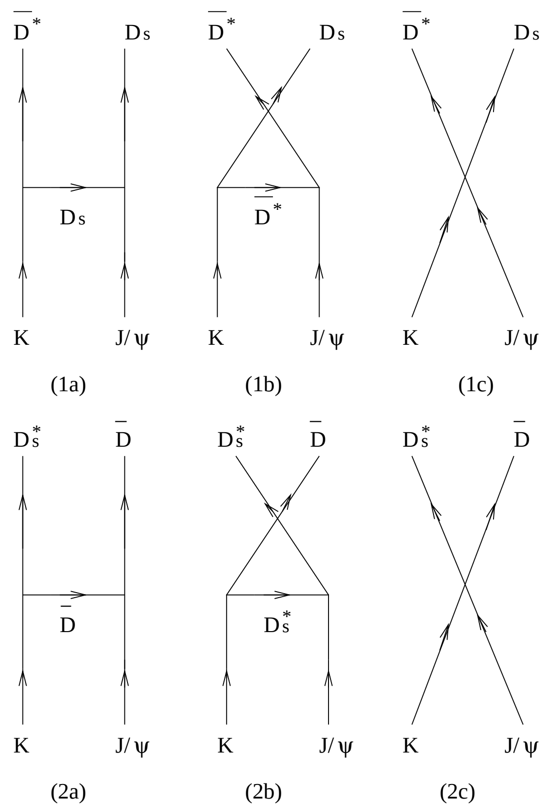

Figure 1. Diagrams for J/ψ absorption processes: 1) $K\psi \to D_s\overline{D}^*$; 2) $K\psi \to D_s^*\overline{D}$. Diagrams for the processes $\overline{K}\psi \to \overline{D}_s D^*$ and $\overline{K}\psi \to \overline{D}_s^* D$ are similar to (1a)-(1c) and (2a)-(2c) respectively, but with each particle replaced by its anti-particle.

Defining the four-momentum of the kaon, the J/ψ, the vector and pseudo-scalar final-state mesons respectively by p_1, p_2, p_3 and p_4, the full amplitude for the first process $K\psi \to D_s\overline{D}^*$, without isospin factors and before summing and averaging over external spins, is given by

$$\mathcal{M}_1 \equiv \mathcal{M}_1^{\nu\lambda}\,\epsilon_{2\nu}\epsilon_{3\lambda} = \left(\sum_{i=a,b,c}\mathcal{M}_{1i}^{\nu\lambda}\right)\epsilon_{2\nu}\epsilon_{3\lambda}, \tag{11}$$

with

$$\begin{aligned}
\mathcal{M}_{1a}^{\nu\lambda} &= -g_{KD_sD^*}g_{\psi D_sD_s}\,(-2p_1+p_3)^\lambda\left(\frac{1}{t-m_{D_s}^2}\right)\\
&\times(p_1-p_3+p_4)^\nu,\\
\mathcal{M}_{1b}^{\nu\lambda} &= g_{KD_sD^*}g_{\psi D^*D^*}\,(-p_1-p_4)^\alpha\left(\frac{1}{u-m_{D^*}^2}\right)\\
&\times\left[g_{\alpha\beta}-\frac{(p_1-p_4)_\alpha(p_1-p_4)_\beta}{m_{D^*}^2}\right]\left[(-p_2-p_3)^\beta g^{\nu\lambda}\right.\\
&\left.+(-p_1+p_2+p_4)^\lambda g^{\beta\nu}+(p_1+p_3-p_4)^\nu g^{\beta\lambda}\right],\\
\mathcal{M}_{1c}^{\nu\lambda} &= -g_{K\psi D_sD^*}\,g^{\nu\lambda},
\end{aligned}\tag{12}$$

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

Similarly, the full amplitude for the second process $K\psi \to D_s^*\overline{D}$ is given by

$$\mathcal{M}_2 \equiv \mathcal{M}_2^{\nu\lambda}\,\epsilon_{2\nu}\epsilon_{3\lambda} = \left(\sum_{i=a,b,c}\mathcal{M}_{2i}^{\nu\lambda}\right)\epsilon_{2\nu}\epsilon_{3\lambda}, \tag{13}$$

with

$$\begin{aligned}
\mathcal{M}_{2a}^{\nu\lambda} &= -g_{KDD_s^*}g_{\psi DD}\,(-2p_1+p_3)^\lambda\left(\frac{1}{t-m_D^2}\right)\\
&\times(p_1-p_3+p_4)^\nu,\\
\mathcal{M}_{2b}^{\nu\lambda} &= g_{KDD_s^*}g_{\psi D_s^*D_s^*}\,(-p_1-p_4)^\alpha\left(\frac{1}{u-m_{D_s^*}^2}\right)\\
&\times\left[g_{\alpha\beta}-\frac{(p_1-p_4)_\alpha(p_1-p_4)_\beta}{m_{D_s^*}^2}\right]\left[(-p_2-p_3)^\beta g^{\nu\lambda}\right.\\
&\left.+(-p_1+p_2+p_4)^\lambda g^{\beta\nu}+(p_1+p_3-p_4)^\nu g^{\beta\lambda}\right],\\
\mathcal{M}_{2c}^{\nu\lambda} &= -g_{K\psi DD_s^*}\,g^{\nu\lambda}.
\end{aligned}\tag{14}$$

We can see that the differences between these two processes are basically due to the meson exchanged. It can be shown [14] that the full amplitudes $\mathcal{M}_i^{\nu\lambda}$ (for $i=1,2$) given above satisfy current conservation: $\mathcal{M}_i^{\nu\lambda}p_{2\nu}=\mathcal{M}_i^{\nu\lambda}p_{3\lambda}=0$.

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

$$\begin{aligned}
\frac{d\sigma_i}{dt} &= \frac{1}{192\pi s p_{0,\mathrm{cm}}^2}\mathcal{M}_i^{\nu\lambda}\mathcal{M}_i^{*\nu'\lambda'}\left(g_{\nu\nu'}-\frac{p_{2\nu}p_{2\nu'}}{m_2^2}\right)\\
&\times\left(g_{\lambda\lambda'}-\frac{p_{3\lambda}p_{3\lambda'}}{m_3^2}\right),
\end{aligned}\tag{15}$$

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

$$p_{0,\mathrm{cm}}^2 = \frac{\left[s-(m_1+m_2)^2\right]\left[s-(m_1-m_2)^2\right]}{4s} \tag{16}$$

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

To estimate the cross sections we have first to determine the coupling constants of our effective Lagrangians. Exact

SU(4) symmetry would give the following relations among the coupling constants:

$$g_{KD_sD^*} = g_{KDD_s^*} = \frac{g}{2\sqrt{2}} ,$$
$$g_{\psi DD} = g_{\psi D_sD_s} = g_{\psi D^*D^*} = g_{\psi D_s^*D_s^*} = \frac{g}{\sqrt{6}} ,$$
$$g_{K\psi D_sD^*} = g_{K\psi DD_s^*} = \frac{g^2}{4\sqrt{3}} . \quad (17)$$

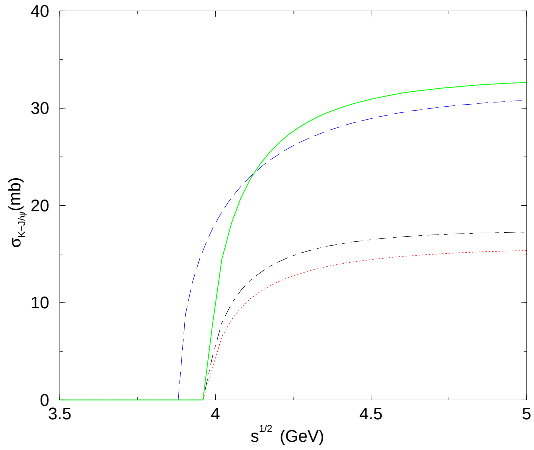

Figure 2. Total cross sections of the processes J/ψ kaons $\rightarrow \overline{D}^* D_s + D^* \overline{D}_s$ (dot-dashed line), $\overline{D} D_s^* + \overline{D}_s^* D$ (dotted line). The solid line gives the total J/ψ dissociation by kaons cross section. For comparison, the dashed line gives the $J/\psi\ \pi \rightarrow \overline{D} D^* + D \overline{D}^*$ cross section.

For ψDD, ψD_sD_s, ψD^*D^* and $\psi D_s^*D_s^*$ couplings we follow refs. [12, 14] and make use of the vector meson dominance model (VDM). We get

$$g_{\psi DD} = g_{\psi D_sD_s} = g_{\psi D^*D^*} = g_{\psi D_s^*D_s^*} = 7.64. \quad (18)$$

Using the above SU(4) relations we get for the other coupling constants:

$$g_{KD_sD^*} = g_{KDD_s^*} = 6.6 , \quad (19)$$

and $g_{K\psi D_sD^*} = g_{K\psi DD_s^*} = 50.55$.

The solid line in Fig. 2 shows the total cross section of J/ψ dissociation by kaons as a function of the initial energy $\sqrt{s}$. The dot-dashed line includes the contribution for both $KJ/\psi \rightarrow D_s\overline{D}^*$ and $\overline{K}J/\psi \rightarrow D^*\overline{D}_s$, while the dotted line includes the contribution for both $KJ/\psi \rightarrow D_s^*\overline{D}$ and $\overline{K}J/\psi \rightarrow D\overline{D}_s^*$. In Fig. 2 we also show, for comparison, the cross section for the process $\pi J/\psi \rightarrow D^*\overline{D} + \overline{D}^* D$ (dashed line) using the same coupling constants as in ref. [14]. We see that, considering all allowed process for the J/ψ dissociation by kaons, we get a cross section bigger than the pion-J/ψ dissociation cross section.

If instead of using the VDM to determine the couplings, we follow ref. [13] and use the experimental value of the $\rho\pi\pi$ coupling constant:

$$g_{\rho\pi\pi} = \frac{g}{2} = 6.06, \quad (20)$$

we get:

$$g_{\psi DD} = g_{\psi D_sD_s} = g_{\psi D^*D^*} = g_{\psi D_s^*D_s^*} = 4.95$$
$$g_{KD_sD^*} = g_{KDD_s^*} = 4.3 . \quad (21)$$

In this case we get a much smaller cross section, as can be seen by the solid line in Fig. 3, where we also show (dot-dashed line) the previous result.

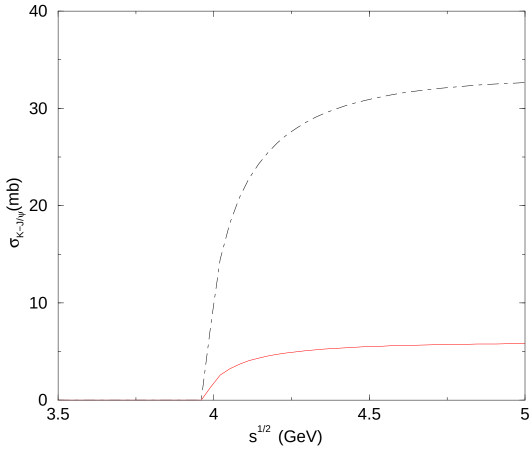

Figure 3. Total cross sections of J/ψ dissociation by kaons evaluated by using the values for the couplings given by Eqs. (18) and (19) (dot-dashed line) and by Eq. (21) (solid line).

As can be seen by Fig. 3, the result for the cross section can vary by almost one order of magnitude, even without considering form factors in the hadronic vertices [14, 16]. 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 [19], the $J/\psi - \pi$ and $J/\psi - \rho$ cross sections were evaluated by using form factors and coupling constants estimated using QCD sum rules [20, 21, 22, 23]. The results show that with the appropriate form factors, the total cross section can even fall for values of $\sqrt{s}$ bigger than 4.5 GeV. In a future work we will include from factors in the hadronic vertices as well as anomalous parity interactions [16].

In summary, we have studied the cross section of J/ψ dissociation by kaons in a meson-exchange model that includes pseudo-scalar-pseudo-scalar-vector-meson couplings, three-vector-meson couplings, and four-point couplings. We find that these cross sections are even bigger than the $J/\psi - \pi \rightarrow \overline{D}D^* + \overline{D}^* D$ dissociation cross section, and have a very strong dependence with the values of the coupling constants in the hadronic vertices. Resulting cross sections can vary between 5 mb and 30 mb for $\sqrt{s} \sim 5$ GeV, depending on the values of the couplings. Since these couplings are not known experimentally, it is very important to have better estimates for them.

Acknowledgments

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