Acta Phys. Hung. A 24/1–4 (2005) 253–258

HEAVY ION PHYSICS

Hadronic Form Factors and J/ψ Dissociation

R.S. Azevedo, F.S. Navarra and M. Nielsen

Instituto de Física, Universidade de São Paulo
C.P. 66318, 05389-970 São Paulo, SP, Brazil

Received 8 July 2004

Abstract. A meson-exchange model, based on effective Lagrangians including anomalous parity interactions, is used to calculate the cross section for the dissociation of J/ψ by pions. Off-shell effects at the vertices are included with QCD sum rule estimates for the coupling constants and form factors. The total J/ψ–π cross section was found to be 10–11 mb for $4.2 \leq \sqrt{s} \leq 5$ GeV.

Keywords: QGP, J/ψ suppression
PACS: 25.75.-q, 13.75.Lb, 14.40.Aq

1. Introduction

The size of the cross section of J/ψ on light hadrons has attracted a lot of attention since the proposal, by Matsui and Satz [1], that suppression of J/ψ production in heavy ion collisions, could be used as a signature for formation of the quark–gluon plasma (QGP). This is because that, even if the QGP is not formed, the J/ψ can be dissociated by many other "comoving" light hadrons produced in such collisions. 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 [2–15].

In this work we focus on the meson-exchange approach based on effective Lagrangians for the J/ψ–π dissociation. The first meson exchange calculation, due to Matinyan and Müller [9], considered only the D exchange as the mechanism for the reactions $J/\psi + \pi \to D^*\bar{D} + \bar{D}^*D$. At $\sqrt{s} = 4.5$ GeV they got a very small result for the cross section: $\sigma_{\psi\pi} \sim 1.5$ mb. The next calculation was done almost simultaneously by Haglin [10] and Lin and Ko [11]. They have considered also the exchange of D^* mesons, and have introduced four-point couplings, which are fundamental to maintain gauge invariance. They find a much larger J/ψ–π cross section, as compared with Ref. [9]. At $\sqrt{s} = 4.5$ GeV they got $\sigma_{\psi\pi} \sim 20$ mb. A common feature of all these works is that they take $SU(4) \times SU(4)$ symmetry as the point of departure for describing mesonic interactions. As this symmetry is badly broken in nature, at

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some stage of the calculation one is forced to use the empirical values of the relevant masses. In Ref. [12] it was shown that this procedure, using the empirical values of the relevant masses, also breaks chiral symmetry when the exchange of D^* mesons are considered. By using a different Lagrangian, which respects chiral symmetry, the authors in Ref. [12] have shown that the J/ψ–π cross section can be reduced by a factor 2. At $\sqrt{s} = 4.5$ GeV they got $\sigma_{\psi\pi} \sim 10$ mb.

Next, Oh, Song and Lee [13] have considered anomalous parity interactions which have opened the channels $J/\psi + \pi \to D^*\bar{D}^*$ and $J/\psi + \pi \to D\bar{D}$. With these two new channels the total J/ψ–π cross section can reach huge values of order of 100 mb at $\sqrt{s} = 4.5$ GeV. These unrealistic large values for the cross section are a consequence of the assumption of point-like mesons in the effective Lagrangians. With monopole form factors, with cut-offs of the order of 1 GeV, these cross sections can be reduced by one order of magnitude [11, 13]. However, cut-offs of the order of 1 GeV, in vertices with charmed mesons, are very small to be trusted. Besides, Haglin and Gale [14] have also shown that the inclusion of form factors, just by replacing the coupling constants by form factors, can destroy the gauge invariance of the calculation. In Ref. [14] the authors have used form factors evaluated in the QCD sum rules approach [16–20], with cut-offs of the order of 3.5 GeV, and have expanded the four-point vertices over general Lorentz structures, to maintain gauge invariance. Without considering the anomalous parity interactions, they got at $\sqrt{s} = 4.5$ GeV $\sigma_{\psi\pi} \sim 6$ mb. In this work we extend the analysis done in Ref. [14] and evaluate the J/ψ–π cross section using a meson-exchange model, considering anomalous parity terms as in Ref. [13].

2. Numerical Results

We follow Refs. [9–11, 13] and start with the SU(4) Lagrangian for the pseudoscalar and vector mesons including also the anomalous parity terms.

$$\mathcal{L}_{D^*D\pi} = ig_{D^*D\pi}\left(D^*_\mu \partial^\mu \pi \bar{D} - D\partial^\mu \pi \bar{D}^*_\mu\right), \tag{1}$$

$$\mathcal{L}_{\psi DD} = ig_{\psi DD}\psi_\mu\left(\partial^\mu D\bar{D} - D\partial^\mu \bar{D}\right), \tag{2}$$

$$\begin{aligned}\mathcal{L}_{\psi D^*D^*} = -ig_{\psi D^*D^*}\Big\{&\psi^\mu\left(\partial_\mu D^{*\nu}\bar{D}^*_\nu - D^{*\nu}\partial_\mu \bar{D}^*_\nu\right) + \left(\partial_\mu \psi_\nu D^{*\nu} - \psi_\nu \partial_\mu D^{*\nu}\right)\bar{D}^{*\mu} \\ &+ D^{*\mu}\left(\psi^\nu \partial_\mu \bar{D}^*_\nu - \partial_\mu \psi_\nu \bar{D}^{*\nu}\right)\Big\},\end{aligned} \tag{3}$$

$$\mathcal{L}_{\psi D^*D\pi} = g_{\psi D^*D\pi}\psi^\mu\left(D\pi\bar{D}^*_\mu + D^*_\mu \pi\bar{D}\right), \tag{4}$$

$$\mathcal{L}_{D^*D^*\pi} = -g_{D^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu D^*_\nu \pi \partial_\alpha \bar{D}^*_\beta, \tag{5}$$

$$\mathcal{L}_{\psi D^*D} = -g_{\psi D^*D}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu \psi_\nu\left(\partial_\alpha D^*_\beta \bar{D} + D\partial_\alpha \bar{D}^*_\beta\right), \tag{6}$$

$$\mathcal{L}_{\psi DD\pi} = -ig_{\psi DD\pi}\varepsilon^{\mu\nu\alpha\beta}\psi_\mu \partial_\nu D\partial_\alpha \pi \partial_\beta \bar{D}, \tag{7}$$

$$\mathcal{L}_{\psi D^*D^*\pi} = -ig_{\psi D^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\psi_\mu D^*_\nu \partial_\alpha \pi \bar{D}^*_\beta - ih_{\psi D^*D^*\pi}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu \psi_\nu D^*_\alpha \pi \bar{D}^*_\beta, \tag{8}$$

where $\pi = \vec{\tau} \cdot \vec{\pi}$ and $\varepsilon^{0123} = +1$.

In Fig. 1 we show the processes we will consider for the J/ψ dissociation by pions.

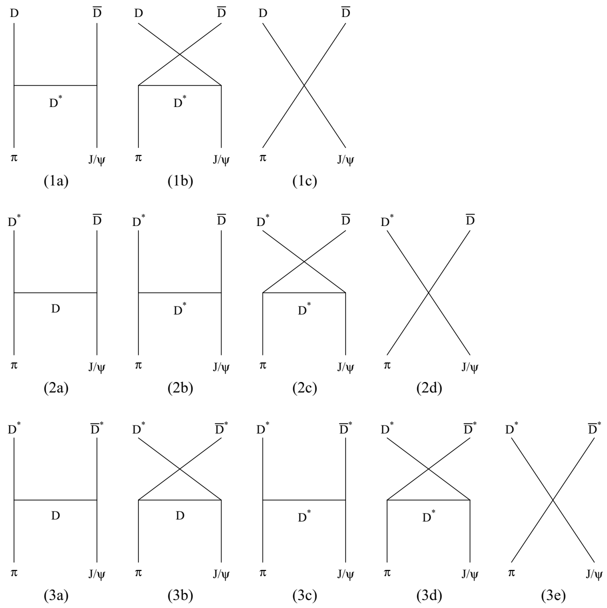

Fig. 1. Diagrams for J/ψ dissociation processes by pion: (1) J/$\psi + \pi \rightarrow$ D + $\bar{\text{D}}$, (2) J/$\psi + \pi \rightarrow$ D*+$\bar{\text{D}}$, and (3) J/$\psi + \pi \rightarrow$ D*+$\bar{\text{D}}^*$. The process J/$\psi + \pi \rightarrow$ D+$\bar{\text{D}}^*$ has the same cross section as (2)

To estimate the cross sections we have first to determine the coupling constants of the effective Lagrangians. A recent measurement of the decay D$^* \rightarrow$ Dπ [21] fixes the value of the coupling constant $g_{\text{D}^*\text{D}\pi} = 12.6$. The other couplings are not known experimentally and one has to use models to estimate them. Here we use the QCD sum rules estimates for the coupling constants and form factors. From Ref. [20] we get $g_{\psi\text{DD}^*} = 4.0$ GeV^{-1} and $g_{\psi\text{DD}} = 5.8$. The form factors are given by [17, 18, 20]:

$$g_{\psi\text{DD}^*}^{(\text{D}^*)}(t) = g_{\psi\text{DD}^*}\left(5\ \exp\left\{-\left(\frac{27-t}{18.6}\right)^2\right\}\right) = g_{\psi\text{DD}^*}\ h_1(t)\,, \tag{9}$$

$$g_{\psi\text{DD}^*}^{(\text{D})}(t) = g_{\psi\text{DD}^*}\left(3.3\ \exp\left\{-\left(\frac{26-t}{21.2}\right)^2\right\}\right) = g_{\psi\text{DD}^*}\ h_2(t)\,, \tag{10}$$

$$g_{\psi\text{DD}}^{(\text{D})}(t) = g_{\psi\text{DD}}\left(2.6\ \exp\left\{-\left(\frac{20-t}{15.8}\right)^2\right\}\right) = g_{\psi\text{DD}}\ h_3(t)\,, \tag{11}$$

$$g^{(\mathrm{D})}_{\mathrm{D}^*\mathrm{D}\pi}(t) = g_{\mathrm{D}^*\mathrm{D}\pi}\left(\frac{(3.5\,\mathrm{GeV})^2 - m_{\mathrm{D}}^2}{(3.5\,\mathrm{GeV})^2 - t}\right) = g_{\mathrm{D}^*\mathrm{D}\pi}\ h_4(t)\,, \tag{12}$$

where $g^{(1)}_{123}$ 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 factor at the vertex $\pi\mathrm{D}^*\mathrm{D}^*$, we make the supposition that it is similar to the form factor at the vertex πDD given in Eq. (11). For the 4-point couplings we depend on the SU(4) relations, which gives

$$\begin{aligned} g_{\psi\mathrm{D}^*\mathrm{D}\pi} &= \frac{1}{2} g_{\psi\mathrm{DD}} g_{\mathrm{D}^*\mathrm{D}\pi}\,, \\ g_{\psi\mathrm{D}^*\mathrm{D}^*\pi} &= h_{\psi\mathrm{D}^*\mathrm{D}^*\pi} = \frac{1}{2}\,\frac{g_a^3 N_c}{32\pi^2 F_\pi}\,, \\ g_{\psi\mathrm{DD}\pi} &= \left(\frac{\sqrt{3}}{6} - \frac{1}{4}\right)\frac{g_a N_c}{16\pi^2 F_\pi^3}\,, \end{aligned} \tag{13}$$

where $N_c = 3$, $F_\pi = 132$ GeV and $g_{\psi\mathrm{DD}^*} = (\sqrt{2}/4\sqrt{3})(g_a^2 N_c/16\pi^2 F_\pi)$. This completes the determination of our coupling constants.

With these form factors the full amplitude associated, for instance, with the processes represented by diagrams (2) in Fig. 1: $\mathcal{M}_2^{\nu\lambda} = \sum_{j=a,b,c,d}\mathcal{M}_{2j}^{\nu\lambda}$, where ν and λ are the vector indexes associated with the vector mesons J/ψ and D^*, respectively, can be written as

$$\mathcal{M}_2^{\nu\lambda} = \Lambda_1 p_\pi^\nu p_\pi^\lambda + \Lambda_2 p_{\mathrm{D}^*}^\nu p_\pi^\lambda + \Lambda_3 p_\pi^\nu p_\psi^\lambda + \Lambda_4 g^{\nu\lambda} + \Lambda_5 p_{\mathrm{D}^*}^\nu p_\psi^\lambda, \tag{14}$$

where the expressions for Λ_i in Eq. (14) are given in [15].

Without interfering in the final result for the cross section, the amplitude in Eq. (14) can be rewritten as

$$\begin{aligned} \mathcal{M}_1^{\nu\lambda} = {} & \Lambda_1\left(p_\pi^\nu - \frac{p_1\cdot p_\psi}{m_\psi^2} p_\psi^\nu\right) p_\pi^\lambda + \Lambda_2\left(p_{\mathrm{D}^*}^\nu - \frac{p_{\mathrm{D}^*}\cdot p_\psi}{m_\psi^2} p_\psi^\nu\right) p_\pi^\lambda + \Lambda_3\left(p_\pi^\nu \right. \\ & \left. - \frac{p_1\cdot p_\psi}{m_\psi^2} p_\psi^\nu\right) p_\psi^\lambda + \Lambda_4\left(g^{\nu\lambda} - \frac{p_\psi^\nu p_\psi^\lambda}{m_\psi^2}\right) + \Lambda_5\left(p_{\mathrm{D}^*}^\nu - \frac{p_{\mathrm{D}^*}\cdot p_\psi}{m_\psi^2} p_\psi^\nu\right) p_\psi^\lambda\,, \end{aligned} \tag{15}$$

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. (9) to (12) are introduced, is to introduce new terms, proportional to p_ψ^ν, in the amplitude, as in Eq. (15). A different prescription can be found in Ref. [14].

3. Conclusions

In Fig. 2 we show the cross section of J/ψ dissociation by pions as a function of the initial energy $\sqrt{s}$. The dotted, dashed, long-dashed and solid lines give the contributions for the processes J/$\psi\,\pi \rightarrow \bar{\mathrm{D}}^*\mathrm{D} + \mathrm{D}^*\bar{\mathrm{D}}$, $\bar{\mathrm{D}}\mathrm{D}$, $\bar{\mathrm{D}}^*\mathrm{D}^*$ and total, respectively. We see that the for $\sqrt{s} > 4.1$ GeV the process J/$\psi\,\pi \rightarrow \bar{\mathrm{D}}^*\mathrm{D}^*$ 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. [13].

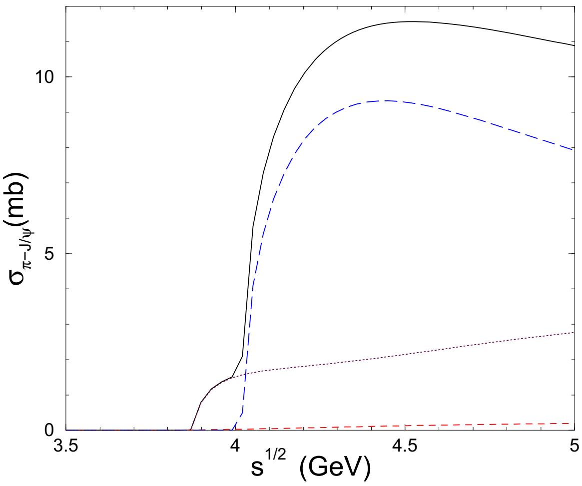

Fig. 2. Total cross sections for the processes J/$\psi\,\pi \rightarrow \bar{\mathrm{D}}^*\mathrm{D} + \mathrm{D}^*\bar{\mathrm{D}}$ (dotted line), $\bar{\mathrm{D}}\mathrm{D}$ (dashed line) and $\bar{\mathrm{D}}^*\mathrm{D}^*$ (long-dashed line). The solid line gives the total J/ψ dissociation by pions cross section

We have studied the cross section of J/ψ dissociation by pions 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, $\sqrt{s} > 4.1$ GeV.

As can be seen by Fig. 5 from Ref. [13], the inclusion of the form factors changes the energy dependence of the absorption cross section in a nontrivial way, as shown in Fig. 2. This modification in the energy dependence is similar to what was found in Ref. [14].

With QCD sum rules estimates for the coupling constants and form factors, the total J/ψ π dissociation cross section was found to be 10–11 mb for $4.2 \leq \sqrt{s} \leq 5$ GeV.

Other important result of our calculation is the fact that, using appropriate form factors with cut-offs of order of ∼4 GeV (see Eqs. (9) through (12)), the value of the cross section can be reduced by one order of magnitude. The same effect was obtained in Refs. [11, 13] using monopole form factors, but with cut-offs of order of ∼1 GeV, which are considered very small for charmed mesons.

Acknowledgments

This work was supported by CNPq and FAPESP.

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