Form-factor dependence of the $J/\psi$ dissociation cross sections in meson exchange model

Yongseok Oh,¹,† Taesoo Song,¹,† Su Houng Lee,¹,‡ and Cheuk-Yin Wong²,§

¹Institute of Physics and Applied Physics, Department of Physics, Yonsei University, Seoul 120-749, Korea
²Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

Abstract

The $J/\psi$ dissociation by $\pi$ and $\rho$ mesons is examined in meson exchange model and compared to the quark interchange model. We found that the main difference between the predictions of the two models could be resolved by the form factors and the contact interactions in meson exchange model calculations. By adopting covariant form factors and adjusting the four-point couplings, we found that the meson exchange model could give similar predictions with the quark interchange models not only for the magnitudes but also for the energy dependence of the low-energy dissociation cross sections of the $J/\psi$ by $\pi$ and $\rho$ mesons. Our finding suggests a way to understand one of the discrepancies among the existing model predictions on the $J/\psi$ dissociation cross sections by light hadrons.

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¹Electronic address: yoh@phya.yonsei.ac.kr
†Electronic address: tssong@phya.yonsei.ac.kr
‡Electronic address: suhoung@phya.yonsei.ac.kr
§Electronic address: wongc@ornl.gov
The $J/\psi$ suppression has attracted much attention as a possible signal of quark-gluon plasma (QGP) formation [1]. The recently observed anomalous $J/\psi$ suppression in Pb-Pb collisions by the NA50 Collaboration [2] was interpreted as a strong indication of the production of a deconfined quark-gluon phase in the collisions. However, $J/\psi$ suppression is already present in hadron-nucleus collisions and it is very important to disentangle the absorption of the $J/\psi$ by nucleons and comovers from the measured data before one makes a definitive conclusion on the formation of QGP [3]. At present, the observed $J/\psi$ suppression can be explained either by the suppression due to the formation of QGP [4, 5, 6] or by the suppression by comovers [7, 8, 9, 10] with a sufficiently large dissociation cross sections by hadrons. Therefore, it is necessary to understand the $J/\psi$ dissociation cross sections by hadrons, which are the basic inputs in the comovers approaches.

The dissociation process of the $J/\psi$ by hadrons has been considered in several approaches, but the predicted cross sections show very different energy dependence and magnitudes near threshold. Hence careful analyses of the existing model calculations are indispensable to understand their limitations and expected corrections.

Using the method of perturbative QCD, Peskin and Bhanot [11] and later Kharzeev and Satz [12] estimated the scattering cross sections of the $J/\psi$ with light hadrons, which was recently rederived using the QCD factorization combined with the Bethe-Salpeter amplitude [13]. The pQCD result was recently improved by including the finite target mass corrections [14, 15] and the relativistic correction to the phase space of the reactions [13]. The estimated dissociation cross sections of the $J/\psi$ by light hadrons depend on the gluon distribution function of the hadron. As for the dissociation cross section by the nucleon, it is in the order of $\mu b$ near threshold and saturates to a few mb at higher energy. However, the higher-twist effects are expected to be non-trivial and should be properly accounted for [13].

Martins et al. [16] estimated the $J/\psi$ dissociation cross sections using the quark interchange model of Barnes and Swanson [17]. The calculation has been improved by Wong and collaborators by employing a more realistic confining potential [18]. The estimated dissociation cross section of $\pi + J/\psi$ has a peak at around 1 mb and that of $\rho + J/\psi$ is in the order of several mb near threshold. The recent calculation using QCD sum rules [19] seems to favor the quark interchange model but shows different energy dependence.

Another approach to $J/\psi$ scattering with light hadrons is to use effective meson Lagrangian [20, 21, 22, 23, 24, 25, 26, 27, 28]. In this approach, one assumes SU(4) flavor symmetry to classify the possible interactions of the $J/\psi$ by light mesons and fixes the necessary couplings either by phenomenology or by model calculations. Matinyan and Müller considered $t$-channel $D$-meson exchanges only and found small values for the cross sections of the $J/\psi$ dissociation by $\pi$ and $\rho$. However the small mass difference between the $D$ and the $D^*$ implies that the $D^*$-meson exchange should also be important. Indeed, it was found by Haglin [21] and Lin and Ko [22] that such additions increase the cross sections to several mb. In Ref. [23], Oh et al. have improved this model by introducing anomalous parity interactions such as $D^*D^*\pi$ whose coupling is related to the $D^*D\pi$ interaction by heavy quark symmetry. This opens new channels and additional mechanisms for the $J/\psi$ dissociation processes and it was found to decrease the cross sections by up to about 50% near threshold.

However, the resulting cross sections are different from those of perturbative QCD and quark interchange models not only for the magnitudes but also for energy dependence. It should be also mentioned that the cross sections in the meson exchange model depend strongly on the employed form factors which could not be justified a priori. Therefore, proper choice for the form factors is very crucial to obtain more reliable model predictions.
since the range of heavy meson exchange is much smaller than the sizes of the initial hadrons. It is especially important in this case, because the kinematical point at which the couplings are fixed can be very different from the point at which the couplings are actually used in the calculation. One example is the \( g_{D^*D\pi} \) coupling and its contribution to the \( D^* \) exchange in the \( \pi + J/\psi \rightarrow D^* + \bar{D} \) process at high energy. The couplings are determined at the on-shell point of each particle, but in the exchange diagram at high energy the exchanged \( D^* \) becomes highly spacelike. This means that a proper covariant form factor has to be used to properly take the off-shell-ness of the exchanged particles into account. In this paper, we show that the main difference between the meson exchange model and the quark interchange model stems from the choice of the form factors for the vertices in meson exchange model calculations. In principle, the form factors and their cutoff parameters should be determined by fitting the experimental data. But because of the lack of any experimental data on \( J/\psi \) dissociation processes, we compare our results with those of the quark interchange model of Ref. [18]. By employing covariant form factors, we will show that meson exchange model can mostly reproduce the characteristic features of the quark interchange model predictions for the cross sections of \( \pi(\rho) + J/\psi \).

We use the effective Lagrangian and the conventions adopted by Ref. [23], which reads

\[
\mathcal{L}_{D^*D\pi} = ig_{D^*D\pi} \left( D^*_\mu \partial^\mu \pi \bar{D} - D \partial^\mu \pi \bar{D}^*_\mu \right), \\
\mathcal{L}_{\psi DD} = ig_{\psi DD} \psi \left( \partial^\mu DD - D \partial^\mu \bar{D} \right), \\
\mathcal{L}_{\psi D^*D^*} = -ig_{\psi D^*D^*} \left\{ \left( \partial^\mu \psi \right) \left( \bar{D}^*_\mu D^* \right) - \left( \partial^\nu \bar{D}^*_\nu D^* \right) \right\}, \\
\mathcal{L}_{\psi D^*D^*} = g_{\psi D^*D^*} \left( D_\mu \partial^\mu \bar{D} - \partial^\mu D \bar{D} \right), \\
\mathcal{L}_{D^*\rho D^*} = ig_{D^*\rho D^*} \left\{ \partial^\mu D^*_\rho \partial^\mu \bar{D}^* - \partial^\mu \rho \partial^\mu \bar{D}^* \right\}, \\
\mathcal{L}_{\psi D^*\rho D^*} = -g_{\psi D^*\rho D^*} \psi \left( \partial^\mu D^*_\rho \partial^\mu \bar{D}^* - \partial^\mu \rho \partial^\mu \bar{D}^* \right), \\
\mathcal{L}_{D^* D^*} = -g_{D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \partial^\mu \bar{D}_{\nu} \partial^\alpha \bar{D}_{\beta}, \\
\mathcal{L}_{\psi D^* D^*} = -g_{\psi D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \partial^\mu \psi \left( \bar{D}_\alpha D^*_\beta \right), \\
\mathcal{L}_{\psi DD\pi} = -ig_{\psi DD\pi} \varepsilon^{\mu \nu \alpha \beta} \partial^\mu \psi \partial^\nu \bar{D}_{\alpha} \partial^\alpha \bar{D}_{\beta}, \\
\mathcal{L}_{\psi D^* D^*} = -ig_{\psi D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \psi \left( \bar{D}_\nu D^*_\alpha \bar{D}_{\beta} \right) - ig_{\psi D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \bar{D}_\nu \partial^\nu \psi \left( \bar{D}_\alpha D^*_\beta \right), \\
\mathcal{L}_{D^* D^*} = -g_{D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \left( \partial^\mu \rho \partial^\nu \bar{D}_{\alpha} \partial^\alpha \bar{D}_{\beta} \right), \\
\mathcal{L}_{\psi D^* D^*} = ig_{\psi D^* D^*} \varepsilon^{\mu \nu \alpha \beta} \psi \left( \bar{D}_\nu D^*_\alpha \bar{D}_{\beta} + \partial^\nu \rho \partial^\nu \bar{D}_{\alpha} \right). 
\]
\[-i\hbar \psi_{D^*D\rho} \varepsilon^{\mu\nu\alpha\beta} \psi_{\mu} \left( D_{\rho\mu} \partial_{\nu} D^*_{\beta} - \partial_{\nu} D^*_{\alpha} \rho_{\beta} \bar{D} \right),\]

(1)

where \( \pi = \tau \cdot \pi, \rho = \tau \cdot \rho \) with \( \varepsilon_{0123} = +1 \). The charm meson iso-doublets are defined as \( \bar{D}^T = (D^0, D^-) \), \( D = (D^0, D^+) \), etc. The details on the derivation of the effective Lagrangian and the determination of the couplings are explained in Refs. \[21, 22, 23\] and will not be repeated here. The only difference with the couplings of Ref. \[23\] lies on the \( g_{D^*D\pi} \)-channel diagrams shown in Figs. 1 and 2 of Ref. \[23\], which are obtained by respecting the rules explained in Ref. \[23\]. Note that our convention for \( g \) is then used to determine the values for \( g_{D^*D^*} \) according to the rules explained in Ref. \[23\].

In Ref. \[23\], the QCD sum rule prediction \[24\] for the coupling, i.e., \( g_{D^*D\pi} = 8.8 \), was used since only the upper limit of the \( D^* \to D\pi \) decay width was known \[30\]. But the recent measurement of \( \Gamma(D^*) \) by the CLEO Collaboration \[31\] allows one to determine the coupling constant rather precisely,

\[ g_{D^*D\pi} = 12.6 \pm 1.4, \]

(2)

which is then used to determine the values for \( g_{D^*D^*} \), \( g_{\psi D^*D\pi} \), \( g_{\psi D D^*\pi} \), \( g_{D^*D^*\pi} \), and \( h_{D^*D^* \pi} \) according to the rules explained in Ref. \[23\]. Note that our convention for \( g_{D^*D\pi} \) is different from that of Refs. \[23, 31\] by \( 1/\sqrt{2} \).

Then the \( J/\psi \) dissociation processes by \( \pi \) and \( \rho \) mesons can be calculated from the \( t \)- and \( u \)-channel diagrams shown in Figs. 1 and 2 of Ref. \[23\], which are obtained by respecting the OZI rule.\(^1\) In Ref. \[23\], the form factors were chosen to be

\[ F_3(r) = \frac{\Lambda^2}{\Lambda^2 + r^2}, \quad F_4(r) = \frac{\Lambda^2}{\Lambda^2 + r^2} \frac{\Lambda^2}{\Lambda^2 + r^2} \]

(3)

following Ref. \[24\], where \( r^2 = (p_1 - p_3)^2 \) or \( (p_2 - p_3)^2 \) and \( \bar{r}^2 = [(p_1 - p_3)^2 + (p_2 - p_3)^2]/2 \). Here \( F_3(r) \) and \( F_4(r) \) are the form factors for the three-point and four-point vertices, respectively. \( p_1 \) and \( p_2 \) are the \( J/\psi \) and initial light meson (\( \pi \) or \( \rho \)) momentum, respectively, while \( p_3 \) and \( p_4 \) are the momenta of the final state mesons. The cutoff parameters may take different values for different vertices. However, because of the paucity of experimental information, we use the same cutoff parameters for all the vertices in this exploratory study in order to investigate the dependence of the cross sections on the cutoff parameters. The cross sections thus obtained are shown in Fig. 1, where the numerical errors committed in Ref. \[23\] are also corrected. This evidently shows that the predictions for the magnitudes and the energy dependence of the cross sections are quite different from those of the quark interchange model \[18\], which are shown as solid lines in Figs. 2 and 3.

However, the form factors in Eq. (3) are not Lorentz-invariant and do not fully take into account the off-shell-ness of the exchanged particle. For example, because it depends on the three-momentum squared, they are not normalized to be 1 even when the exchanged particles are on-mass shell. In the other extreme, it can be 1 even for particles far off-shell as long as they are at rest. This may be a good starting approximation for very low energy reactions, but we expect much corrections in \( J/\psi \) dissociation processes especially for large

\(^1\) One may have \( s \)-channel diagrams by including the OZI-violating interaction, \( \mathcal{L}_{\psi \rho \pi} = g_{\psi \rho \pi} \varepsilon^{\mu\nu\alpha\beta} \partial_{\mu} \psi_{\nu} \tilde{\epsilon}_{\alpha \beta} \), where \( |g_{\psi \rho \pi}| = 1.07 \times 10^{-3} \text{ GeV}^{-1} \) from the decay width of \( J/\psi \to \rho \pi \) \[8\]. It allows \( s \)-channel diagrams (\( \rho \) and \( \pi \) exchanges) for \( \pi + J/\psi \to D + \bar{D}, D^* + \bar{D}, D^* + D^* \) and \( \rho + J/\psi \to D^* + \bar{D}, D^* + D^* \). However, we found that such diagrams give the cross sections at the order of pb or fb and hence suppressed because of the small value of the coupling constant \( g_{\psi \rho \pi} \).
energies since the exchanged $D$ and $D^*$ mesons will be \textit{highly off-shell}. A similar conclusion was drawn by Friman \textit{et al.} \cite{32} by showing that the form factor (3) would overestimate the contribution of the $\Delta(1232)$ in the calculation for the vector meson spectral densities in nuclear matter. (See also Ref. \cite{33}.) Therefore, instead of the form factors in (3), we will employ the covariant form factor in (4) suggested by Pearce and Jennings \cite{34}, to study the dependence of the $J/\psi$ dissociation cross section on the form factor:

$$F(p^2) = \left( \frac{n\Lambda^4}{n\Lambda^4 + (p^2 - M_{ex}^2)^2} \right)^n. \quad (4)$$

Here, $p$ is the four-momentum of the exchanged particle of mass $M_{ex}$. (Other forms for the form factors are suggested in Refs. \cite{28,33}.) The function $F(p^2)$ is normalized to 1 when the particles are on-shell ($p^2 = M_{ex}^2$) and becomes smaller when they are off-shell. In the extreme limit $n \to \infty$, $F(p^2)$ approaches a Gaussian in $(p^2 - M_{ex}^2)$ with width $\Lambda^2$ \cite{34}. Here, we vary the cutoff $\Lambda$ and $n$ and compare the resulting cross sections to the quark interchange model.

As for the models for $J/\psi$ dissociation processes, we consider two cases. In model (I), we include the meson-exchange diagrams with three-point vertices only by discarding the four-point contact terms, since their couplings are not well-determined. The relevant diagrams can be identified from Figs. 1 and 2 of Ref. \cite{23}. Given in Fig. 2 are the results for $\pi + J/\psi$ (left panel) and $\rho + J/\psi$ (right panel). The form factor (4) is multiplied to each vertex with $\Lambda = 1.8$ GeV for $\pi + J/\psi$ and $\Lambda = 2.3$ GeV for $\rho + J/\psi$. The dotted, dashed, and dot-dashed lines are obtained with $n = 1, 5$, and 20, respectively. Our results show that the cross sections converge with increasing $n$. As can be seen in Fig. 2, we find that the meson exchange model with three-point vertices does not agree well with the quark interchange model, especially for the energy dependence of the cross sections. Although our form factor at large $n$ should be related to the Gaussian nature of the hadron wavefunctions in the quark model, our cross section for the process $\pi + J/\psi \to D^* + \bar{D}$ is different from that obtained in Ref. \cite{28}, which also employs exponential form factors, motivated from the hadron wavefunctions, but which are complicated functions of both $s$ and $t$ (or $u$). Also, the form factors used in Ref. \cite{28} still do not satisfy the on-shell condition.

In Fig. 3, we consider model (II), which includes the four-point contact diagrams in addition to the meson exchange diagrams. Since the four-point couplings are only poorly known, we treat the four-point couplings as free parameters and try to find a best fit to the quark interchange model results. For the form factors, we use

$$F(p^2) = \left( \frac{n\Lambda^4}{n\Lambda^4 + [(p_1 + p_2)^2 - (M_3 + M_4)^2]^2} \right)^n \quad (5)$$

for the contact terms assuming an internal structure of the couplings, where $M_3$ and $M_4$ are the final state meson masses. For the three-point vertices, the form factor (4) is used as in model (I). The results shown in Fig. 3 are obtained with $\Lambda = 1.2$ GeV for $\pi + J/\psi$ and $\Lambda = 1.0$ GeV for $\rho + J/\psi$. As in Fig. 2, the dotted, dashed, and dot-dashed lines are obtained with $n = 1, 5$, and 20, respectively and the solid lines are from the quark interchange model. In this model, we found that the meson exchange terms (three-point vertices) are overwhelmed by the contact terms (four-point vertices) such that their contributions are found to be suppressed. The coupling constants used in Fig. 3 are $g_{\psi D\bar{D} \pi} = 23$ (23), $g_{\psi D^* D \pi} = 34$ (49), $g_{\psi D^* D^* \pi} = h_{\psi D^* D^* \pi} = 7$ (55), $g_{\psi D \bar{D} \rho} = 39$ (39), $g_{\psi D^* D \rho} = h_{\psi D^* D \rho} = 17$.
(22), and \( g_{\psi D^* D^* \rho} = 27 \) (19), where the values in the parentheses are determined as in Ref. [23] with \( g_{D^* D \pi} \) of Eq. (2). The \( \pi + J/\psi \to D + \bar{D} \) and \( \rho + J/\psi \to D + \bar{D} \) processes are suppressed compared to the other processes and we do not vary the corresponding couplings. The resulting magnitudes of the cross sections are strongly dependent on the couplings and Fig. 3 shows that the quark interchange model would prefer model (II). The big difference of the couplings from those in the parentheses would imply the strong violation of the SU(4) symmetry relations used in previous meson exchange model calculations [23]. Therefore it is very important to estimate the four-point couplings and the corresponding form factors within the quark models.

In summary, we have reinvestigated the \( J/\psi \) dissociation cross sections by \( \pi \) and \( \rho \) in effective Lagrangian approach. We found that the quark interchange model predictions can be explained by model (II) of meson exchange model, where the contact terms are dominant. Although this does not prove the predictions of the quark interchange models on the \( J/\psi \) dissociation processes, our finding suggests that most of the discrepancies between the two models can be resolved by choosing appropriate form factors and strength for the contact terms, which should be closely related to the hadron wavefunctions and interquark forces in the quark model. In addition, for a more detailed comparison between the two models, it is necessary to include the contributions from the exchange of higher resonances, such as the axial vector \( D_1(2420) \), in the meson exchange model. This is so because the exchanged quark-antiquark pairs in quark interchange model implicitly contain all possible meson states.

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Figures
FIG. 1: Cross sections for $\pi + J/\psi$ and $\rho + J/\psi$ with the form factors in Eq. (3) with $\Lambda = 2$ GeV (left panel) and 1 GeV (right panel). The dotted lines are for $J/\psi + \pi(\rho) \rightarrow D + \bar{D}$, the dashed lines for $J/\psi + \pi(\rho) \rightarrow D + D^*$, $D^* + \bar{D}$, and the dot-dashed lines for $J/\psi + \pi(\rho) \rightarrow D^* + \bar{D}$. The solid lines are the sums.
FIG. 2: Cross sections for $\pi + J/\psi$ and $\rho + J/\psi$ in model (I). The form factor (4) is used with $\Lambda = 1.8$ GeV for $\pi + J/\psi$ and $\Lambda = 2.3$ GeV for $\rho + J/\psi$. The dotted, dashed, and dot-dashed lines are obtained with $n = 1, 5, \text{and } 20$, respectively. The solid line is the quark interchange model result of Ref. [18].
FIG. 3: Cross sections for $\pi + J/\psi$ and $\rho + J/\psi$ in model (II). The form factors (4) and (5) are used with $\Lambda = 1.2$ GeV for $\pi + J/\psi$ and $\Lambda = 1.0$ GeV for $\rho + J/\psi$. Notations are the same as in Fig. 2.