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J/ψ absorption by nucleons in the meson-exchange model

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We reinvestigate the J/ψ dissociation processes induced by the reactions with nucleons, $J/\psi+N \to \bar{D}^{(*)}+\Lambda_c$, in the meson-exchange model. Main constraints used in this work are vector-meson dominance and charm vector-current conservation. We show that the cross section for $J/\psi + N \to \bar{D} + \Lambda_c$ can be larger than that for $J/\psi + N \to \bar{D}^* + \Lambda_c$ when these constraints are imposed. The dependence of the cross sections on the coupling constants is analyzed in detail, and the comparison with the recent quark-interchange model predictions is also made.

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I. INTRODUCTION

Since the suggestion of J/ψ suppression as a signal for the formation of the quark-gluon plasma in relativistic heavy-ion collisions [1], understanding the interactions of the J/ψ with other hadrons has been an important issue as J/ψ dissociation by hadrons could also cause the suppression of the produced J/ψ [2]. Because the J/ψ-hadron interactions cannot be directly accessed by present experiments, the J/ψ-hadron cross sections have been estimated through several assumptions and/or model calculations. Empirically, the J/ψ-nucleon cross sections have been estimated by using the data for J/ψ photoproduction from the nucleon [3], J/ψ photoproduction from nuclei, and J/ψ production from the nucleon-nucleus collisions [4]. Because those data are scattered over a wide range of energy and the estimation is model dependent, the estimated values for the J/ψ-nucleon cross sections range from ~ 1 to ~ 7 mb. (See also Ref. [5] for a recent study on this subject.)

Theoretically, these cross sections have been estimated in various ways including the perturbative quantum chromodynamics (QCD) [6], QCD sum-rule approach [7], meson-exchange models [8–12], Regge theory approach [13], quark models [14,15], lattice QCD [16], and other methods [17]. Despite the efforts to resolve the model dependence of the cross sections, the uncertainties in theoretical/model calculations for the J/ψ-hadron cross sections are not yet clarified and the predicted cross sections are model dependent not only in the magnitude but also in the energy dependence.

Recently, the J/ψ-nucleon dissociation cross sections have been calculated in a quark-interchange model by Hilbert *et al.* [15], and the results show a large difference from the meson-exchange model predictions of Ref. [12]. In particular, the two models predict very different values for the ratio of the cross sections,[1] $R_{D/D^*} = \sigma(J/\psi + N \to \bar{D} + \Lambda_c)/\sigma(J/\psi + N \to \bar{D}^* + \Lambda_c)$, namely $R_{D/D^*} > 50$ in Ref. [15], whereas $R_{D/D^*} < 0.5$ in the model of Ref. [12]. In this article, to understand this discrepancy, we re-examine and improve the meson-exchange model of Ref. [12] by using vector-meson dominance and charm vector-current conservation to constrain the coupling constants and form factors of this model. We will show that these constraints can lead to $R_{D/D^*} > 1$ in the meson-exchange model. We will also discuss the role driven by the tensor coupling terms of the interactions of vector mesons.

This article is organized as follows. In the next section, we discuss the coupling constants of the relevant effective Lagrangians for the J/ψ-nucleon absorption processes. The J/ψ coupling constants are discussed in connection with vector-meson dominance, which leads to the universality of the J/ψ coupling. The role of the conserved charm vector-current in determining coupling constants and in constraining form factors are also explained. Section III contains the numerical results, and the dependence of the cross sections on the coupling constants and form factors are explored. We summarize in Sec. IV.

II. THE MODEL

The diagrams which contribute to the J/ψ-nucleon dissociation reactions are shown in Fig. 1. To evaluate these diagrams, we use the following effective Lagrangians:

$$
\begin{aligned}
\mathcal{L}_{\psi DD} &= -i g_{\psi DD} \psi^\mu \left(D \partial_\mu \bar{D} - \partial_\mu D \bar{D} \right), \\
\mathcal{L}_{\psi D^* D^*} &= -i g_{\psi D^* D^*} [\psi^\mu (\partial_\mu D^{*\nu} \bar{D}^*_\nu - D^{*\nu} \partial_\mu \bar{D}^*_\nu) \\
&\quad + (\partial_\mu \psi_\nu D^{*\nu} - \psi_\nu \partial_\mu D^{*\nu}) \bar{D}^{*\mu} \\
&\quad + D^{*\mu} (\psi^\nu \partial_\mu \bar{D}^*_\nu - \partial_\mu \psi_\nu \bar{D}^{*\nu})], \\
\mathcal{L}_{\psi D^* D} &= -g_{\psi D^* D} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu \psi_\nu (\partial_\alpha D^*_\beta \bar{D} + D \partial_\alpha \bar{D}^*_\beta), \\
\mathcal{L}_{\psi \Lambda_c \Lambda_c} &= g_{\psi \Lambda_c \Lambda_c} \bar{\Lambda}_c \left(\gamma_\mu \psi^\mu - \frac{\kappa_{\psi \Lambda_c \Lambda_c}}{2M_N} \sigma_{\mu\nu} \partial^\nu \psi^\mu \right) \Lambda_c, \\
\mathcal{L}_{D N \Lambda_c} &= -i g_{D N \Lambda_c} \bar{N} \gamma_5 \bar{D} \Lambda_c + \text{H.c.}, \\
\mathcal{L}_{D^* N \Lambda_c} &= -g_{D^* N \Lambda_c} \left(\bar{N} \gamma_\mu \bar{D}^{*\mu} - \frac{\kappa_{D^* N \Lambda_c}}{2M_N} \sigma_{\mu\nu} \partial^\nu \bar{D}^{*\mu} \right) \Lambda_c \\
&\quad + \text{H.c.},
\end{aligned}
\tag{1}
$$

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[1] The ratio R_{D/D^*} depends on the energy. Here, we compare the peak values of the two cross sections.

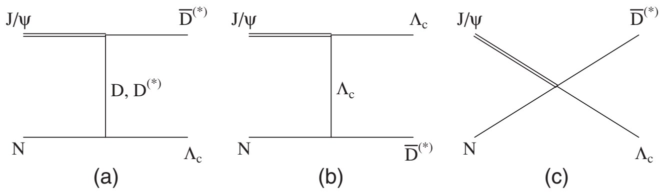

FIG. 1. Diagrams for the reaction of $J/\psi + N \to \bar{D}^{(*)} + \Lambda_c$.

where ψ_μ is the J/ψ vector-meson field and D is the isodoublet D meson field, $D = (D^0, D^+)$ and $\bar{D} = (\bar{D}^0, D^-)^T$. The isodoublet D^* vector-meson field is defined in the similar way. To determine the coupling constants, several methods have been suggested and these include quark models using the heavy quark effective theory approach [18], QCD sum rules [19–21], and the SU(4) symmetry. In this section, we discuss the coupling constants in the effective Lagrangians in some detail.

A. Vector-meson dominance and the J/ψ couplings

For the J/ψ couplings we use vector-meson dominance (VMD) as in Refs. [9–11]. In VMD, the photon couples to a hadron through intermediate vector mesons so that

$$\langle H|J^\mu_{\rm em}|H\rangle = \sum_V \frac{1}{M_V^2 - p^2}\langle 0|J^\mu_{\rm em}|V\rangle\langle H|V|H\rangle\bigg|_{p^2\to 0}, \quad (2)$$

where the sum runs over vector meson states V and the current-field identity gives $\langle 0|J^\mu_{\rm em}|V\rangle = -(M_V^2/f_V)\varepsilon^\mu_V$ with the vector meson polarization vector ε^μ_V. The parameter f_V can be obtained from $\Gamma(V \to e^+e^-) = 4\pi\alpha^2_{\rm em}M_V/(3f_V^2)$. The most recent compilation of the data gives $f_\rho = 4.95$, $f_\omega = 17.10$, $f_\phi = 13.39$, $f_\psi = 11.16$ so that $f_\rho : f_\omega : f_\phi : f_\psi = 1 : 3.45 : 2.70 : 2.25$, whereas the SU(4) symmetry gives $f_\rho : f_\omega : f_\phi : f_\psi = 1 : 3 : 3/\sqrt{2} : 3/2\sqrt{2} \approx 1 : 3 : 2.12 : 1.06$. This evidently shows the aspect of the badly broken flavor SU(4) symmetry. Application to the Υ meson makes the symmetry relation worse as we have $f_\Upsilon/f_\rho \approx 8$ from the data, whereas the SU(5) symmetry implies $f_\Upsilon/f_\rho = 3/\sqrt{2}$. For the intermediate state, we consider $V = \rho, \omega, \phi, J/\psi$ by expecting either that the higher vector meson contributions are suppressed or that there is a strong cancellation among them, especially in the charm sector [18]. Applying VMD to the D-meson isodoublet (D^0, D^+), we then have the following relations among the coupled equations [11]:

$$\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{g_{\rho DD}}{f_\rho}\begin{pmatrix} 1 \\ -1 \end{pmatrix} + \frac{g_{\omega DD}}{f_\omega}\begin{pmatrix} 1 \\ 1 \end{pmatrix} + \frac{g_{\psi DD}}{f_\psi}\begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad (3)$$

which can be solved by using the SU(2) symmetry relations, $g_{\omega DD} = g_{\rho DD}$ and $f_\omega = 3f_\rho$. Thus, we have

$$\frac{2}{3} = \frac{g_{\psi DD}}{f_\psi}. \quad (4)$$

This means that the photon sees the charm quark charge through the intermediate J/ψ vector-meson.[2] By applying to the D^* isodoublet, we get the relation, $g_{\psi DD} = g_{\psi D^* D^*}$. In the QCD sum-rule calculations of Refs. [19,21], this relation holds within 20 ∼ 30%.

For the $J/\psi D^* D$ coupling, we use the relation of the heavy quark mass limit [18],

$$g_{\psi D^* D} = g_{\psi DD}/\tilde{M}_D, \quad (5)$$

where $\tilde{M}_D$ is the (average) mass scale of the D/D^* mesons. This leads to the coupling constants

$$g_{\psi DD} = g_{\psi D^* D^*} = 7.44, \qquad g_{\psi D^* D} = 3.84\,\text{GeV}^{-1}. \quad (6)$$

The coupling constant $g_{\psi\Lambda_c\Lambda_c}$ can also be estimated through VMD. As we have seen before, the photon sees the charm quark charge through the J/ψ. If we apply this to Λ_c^+, then we have

$$g_{\psi\Lambda_c\Lambda_c} = g_{\psi DD} = g_{\psi D^* D^*}, \quad (7)$$

that is, the universality of the J/ψ coupling. This is also closely related to the charm vector-current conservation as will be shown below. In Ref. [12], $g_{\psi\Lambda_c\Lambda_c}$ was estimated from the SU(4) relation assuming that the J/ψ belongs to the **15**-multiplet, which gives $g_{\psi\Lambda_c\Lambda_c} = -1.4$. But, with this assumption, the J/ψ contains significant light quark components and, as a result, $g_{\psi\Lambda_c\Lambda_c}$ is underestimated by a factor of 5 compared with our estimate.

The tensor coupling constant $\kappa_{\psi\Lambda_c\Lambda_c}$ can also be estimated by using VMD with the anomalous magnetic moment of Λ_c. The magnetic moment of Λ_c has not been measured, but the quark model predicts $\mu(\Lambda_c) \approx 0.37$ [22], and this gives a predicted anomalous magnetic moment $\kappa_{\Lambda_c} = -0.63$ for Λ_c. Because the light u, d quarks form a spin-0 state in Λ_c, the Λ_c magnetic moment is solely determined by the charm quark. Therefore, VMD gives

$$\kappa_{\Lambda_c} = \frac{g_{\psi\Lambda_c\Lambda_c}\kappa_{\psi\Lambda_c\Lambda_c}}{f_\psi}, \quad (8)$$

which leads to $\kappa_{\psi\Lambda_c\Lambda_c} \approx -0.94$.

B. D and D^* meson couplings

In flavor SU(4), mesons are in a **15**-multiplet and baryons are in a **20**-multiplet, which correspond to the meson octet and baryon octet of SU(3), respectively. Because $\mathbf{15} \otimes \bar{\mathbf{20}} = \mathbf{140} \oplus \bar{\mathbf{60}} \oplus \bar{\mathbf{36}} \oplus \mathbf{20}' \oplus \mathbf{20} \oplus \mathbf{20} \oplus \bar{\mathbf{4}}$, there are two couplings for the meson-baryon-baryon interactions as in the case of SU(3), and they can be related to the SU(3) coupling constants D and F. This gives the SU(4) symmetry relations, $g_{DN\Lambda_c} = g_{KN\Lambda}$ and $g_{D^*N\Lambda_c} = g_{K^*N\Lambda}$, of Ref. [12]. The empirical values of

[2]If we apply VMD to the kaon isodoublet, we have $-1/3 = g_{\phi KK}/f_\phi$, which gives $g_{\phi KK} = -4.46$. This should be compared with $|g_{\phi KK}| = 4.49$ determined from the experimental data for $\Gamma(\phi \to K\bar{K})$.

Ref. [23] for strange hadrons then give

$$g_{DN\Lambda_c} = -13.2, \quad g_{D^*N\Lambda_c} = -4.3. \tag{9}$$

These values are quite different from the QCD sum-rule predictions of Ref. [24]

$$|g_{DN\Lambda_c}| = 7.9, \quad |g_{D^*N\Lambda_c}| = 7.5. \tag{10}$$

This difference can affect the value of the ratio R_{D/D^*} as will be discussed below.

For the tensor coupling constant $\kappa_{D^*N\Lambda_c}$, there is no theoretical prediction for its value. If we assume the SU(4) relation again, we have [24]

$$\kappa_{D^*N\Lambda_c} = 2.65. \tag{11}$$

However, it should be mentioned that the SU(4) symmetry breaking effects can significantly alter the values of the coupling constants given in Eqs. (9) and (11). Therefore, in this work, we investigate the role of the $DN\Lambda_c$ and $D^*N\Lambda_c$ interactions by varying their coupling constants.

The nonvanishing tensor coupling for the $D^*N\Lambda_c$ interaction also causes the four-point interaction that is shown in Fig. 1(c). This term can be obtained by gauging the tensor interaction and it reads

$$\mathcal{L}_{\psi D^* N\Lambda_c} = -i\frac{g_\psi}{2M_N} g_{D^*N\Lambda_c}\kappa_{D^*N\Lambda_c}\bar{N}\sigma_{\mu\nu}\bar{D}^{*\mu}\psi^\nu\Lambda_c + \text{H.c.}, \tag{12}$$

where g_ψ is the gauge coupling constant. As we shall see below, g_ψ can be related to the universal J/ψ coupling constant by charm vector-current conservation.

C. Production amplitudes and form factors

The production amplitudes can be written as

$$\begin{aligned} \mathcal{M}(J/\psi + N \to \bar{D} + \Lambda_c) &= \mathcal{M}_D^\mu \varepsilon_\mu(\psi), \\ \mathcal{M}(J/\psi + N \to \bar{D}^* + \Lambda_c) &= \varepsilon_\nu^*(D^*)\mathcal{M}_{D^*}^{\mu\nu}\varepsilon_\mu(\psi), \end{aligned} \tag{13}$$

with

$$\begin{aligned} \mathcal{M}_D^\mu &= \mathcal{M}_t^\mu + \mathcal{M}_u^\mu + \mathcal{M}_{\text{an}}^\mu, \\ \mathcal{M}_{D^*}^{\mu\nu} &= \mathcal{M}_t^{\mu\nu} + \mathcal{M}_u^{\mu\nu} + \mathcal{M}_{\text{an}}^{\mu\nu} + \mathcal{M}_c^{\mu\nu}, \end{aligned} \tag{14}$$

where $\mathcal{M}_t$ is the t-channel amplitude, $\mathcal{M}_u$ is the u-channel amplitude, $\mathcal{M}_{\text{an}}$ is the t-channel amplitude including the anomalous $J/\psi D^* D$ interaction, and $\mathcal{M}_c$ is from the contact term. The amplitudes can be obtained straightforwardly from the interaction Lagrangians, e.g., as in Ref. [12], and will not be given here.

Now we impose the conservation condition of the charm vector-current to the production amplitudes, i.e., $p_{\psi_\mu}\mathcal{M}_D^\mu = 0$ and $p_{\psi_\mu}\mathcal{M}_{D^*}^{\mu\nu} = 0$, where p_ψ is the four-momentum of the J/ψ. The anomalous terms and the $\kappa_{\psi\Lambda_c\Lambda_c}$ terms already satisfy this condition separately, and we have

$$\begin{aligned} p_{\psi_\mu}\mathcal{M}_D^\mu &= i g_{DN\Lambda_c}\left(g_{\psi DD} - g_{\psi\Lambda_c\Lambda_c}\right)\gamma_5, \\ p_{\psi_\mu}\mathcal{M}_{D^*}^{\mu\nu} &= g_{D^*N\Lambda_c}\left(g_{\psi\Lambda_c\Lambda_c} - g_{\psi D^*D^*}\right)\gamma^\nu \\ &\quad + \frac{g_{D^*N\Lambda_c}\kappa_{D^*N\Lambda_c}}{2M_N}\sigma^{\nu\lambda}[p_{D^*\lambda}(g_{\psi D^*D^*} - g_{\psi\Lambda_c\Lambda_c}) \\ &\quad + p_{\psi\lambda}(g_\psi - g_{\psi D^*D^*})], \end{aligned} \tag{15}$$

where p_{D^*} is the four-momentum of the produced D^* meson. Thus, vector-current conservation leads to

$$g_\psi = g_{\psi\Lambda_c\Lambda_c} = g_{\psi DD} = g_{\psi D^*D^*}. \tag{16}$$

Therefore, one can verify that the charm vector-current conservation leads to the VMD relation (7) for the coupling constants and fixes the gauge coupling constant g_ψ.

Because of the finite size of hadrons, it is required to include form factors in effective Lagrangian approaches, which are functions of the momentum of exchanged (or off-shell) particles. The form factors may be calculated from more microscopic theories [23,25], but here we employ a simple phenomenological form [26]

$$F\left(p_{\text{ex}}^2\right) = \left[\frac{n\Lambda^4}{n\Lambda^4 + \left(p_{\text{ex}}^2 - M_{\text{ex}}^2\right)^2}\right]^n, \tag{17}$$

where p_{ex} and M_{ex} are the four-momentum and mass of the exchanged particle, respectively. Therefore, when the exchanged particle is on its mass-shell, it has the correct normalization $F(p_{\text{ex}}^2 = M_{\text{ex}}^2) = 1$ and, as $n \to \infty$, $F(p^2)$ becomes a Gaussian of $(p^2 - M_{\text{ex}}^2)$ with a width of Λ^2. In this work, we take the limit $n \to \infty$.

However, employing such form factors violates the current conservation condition. There is no unique way to restore current conservation with form factors and in this work we follow the prescription of Ref. [27], namely current conservation is recovered by introducing the contact diagram of Fig. 1(c), which is, in practical calculation, equivalent to replace the form factors by a universal one in the form of

$$1 - [1 - F(s)][1 - F(u)]. \tag{18}$$

This form factor is also employed for $\bar{D}^*\Lambda_c$ production in the presence of the $D^*N\Lambda_c$ tensor interaction.

III. RESULTS

We first discuss our results without the tensor coupling terms, i.e., by setting $\kappa_{\psi\Lambda_c\Lambda_c} = \kappa_{D^*N\Lambda_c} = 0$ for a comparison with the results of Ref. [12]. Shown in Fig. 2 are our results on the total cross sections for $J/\psi + p \to \bar{D}^{(*)0} + \Lambda_c$ obtained with the couplings of Eq. (9). The results depend on the cutoff Λ, and $\Lambda = 1.8$ GeV is used for this calculation. The dependence of our results on Λ will be discussed later. The dashed, dotted, and dot-dashed lines are the contributions from the t-channel, u-channel, and anomalous terms, respectively, and the solid lines are their sums. There are several comments in comparing with the results of Ref. [12]. We first verify the

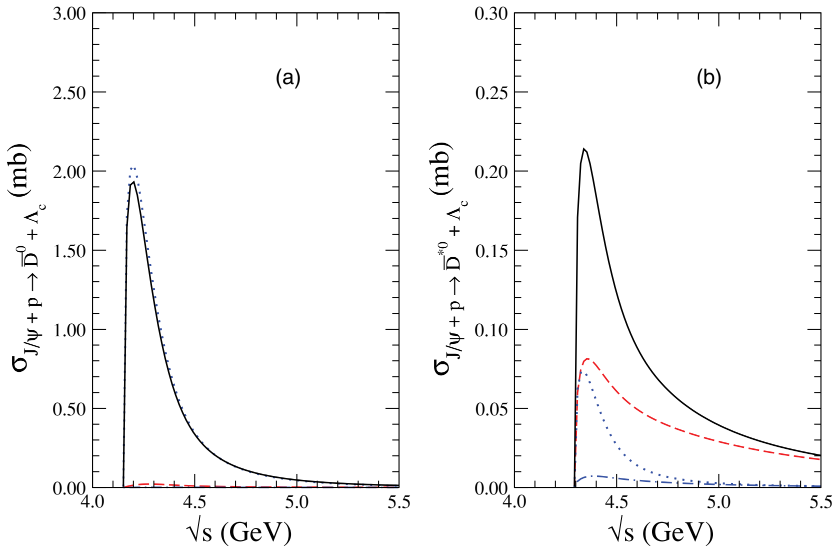

FIG. 2. (Color online) Total cross section for (a) $J/\psi + p \to \bar{D}^0 + \Lambda_c$ and (b) $J/\psi + p \to \bar{D}^{*0} + \Lambda_c$ when the tensor interactions are turned off, $\kappa_{\psi\Lambda_c\Lambda_c} = \kappa_{D^*N\Lambda_c} = 0$. The dashed, dotted, and dot-dashed lines are the contributions from the t-channel, u-channel, and anomalous terms, respectively, and the solid lines are their sums.

conclusion of Ref. [12] that the anomalous interaction terms give small contributions in both reactions. However, there are several crucial differences. Because the VMD and current conservation condition require much larger $g_{\psi\Lambda_c\Lambda_c}$ coupling constant, this enhances the contribution from the u-channel diagram in both reactions. As a result, the $J/\psi + p \to \bar{D}^0 + \Lambda_c$ reaction is dominated by the u-channel diagram, and the $J/\psi + p \to \bar{D}^{*0} + \Lambda_c$ has comparable contributions from both the t- and u-channel diagrams. Furthermore, this makes the cross section ratio R_{D/D^*} to be larger than 1, which is opposite to the result of Ref. [12]. In addition, our predictions on the energy dependence of the cross sections show more rapid decrease of the cross sections at larger energies than that of Ref. [12]. Although this is partly due to the Gaussian form factor adopted in this model, it is the current conserved form of the form factors (18) that is mainly responsible for this energy dependence of the cross sections. Taking into account all these effects, we found that $R_{D/D^*} \approx 10$ with our parameters, and the peak value of the cross sections for $\bar{D}^0\Lambda_c$ final state reaction is close to 2 mb.

We also found that the tensor interactions, $\kappa_{\psi\Lambda_c\Lambda_c}$ term and $\kappa_{D^*N\Lambda_c}$ term, can give nontrivial contributions to the cross sections but play a different role. To see the role of these terms, we first present the results with $\kappa_{\psi\Lambda_c\Lambda_c} = -0.94$ but with $\kappa_{D^*N\Lambda_c} = 0$ in Fig. 3, while keeping the other parameters as in the case of Fig. 2. In this case, the u-channel contributions are further enhanced. Furthermore, because of the large contributions from the $\kappa_{\psi\Lambda_c\Lambda_c}$ term, the t-channel and u-channel diagrams interfere constructively in $\bar{D}\Lambda_c$ production and destructively in $\bar{D}^*\Lambda_c$ production, which is opposite to the results of Fig. 2. Consequently, the $J/\psi + N \to \bar{D}\Lambda_c$ cross sections are enhanced, but the $J/\psi + N \to \bar{D}^*\Lambda_c$ cross sections are not changed so much. This leads to the increase of the cross section ratio and we have $R_{D/D^*} \approx 30$, which is close to the prediction of the quark-interchange model of Ref. [15].

To verify the role of the $\kappa_{D^*N\Lambda_c}$ tensor term, we use the value of Eq. (11) because there is no theoretical prediction for this coupling constant. Other parameters are the same as in the case of Fig. 3 and the results are given in Fig. 4. This shows that the effect of the $\kappa_{D^*N\Lambda_c}$ term in $J/\psi + N \to$

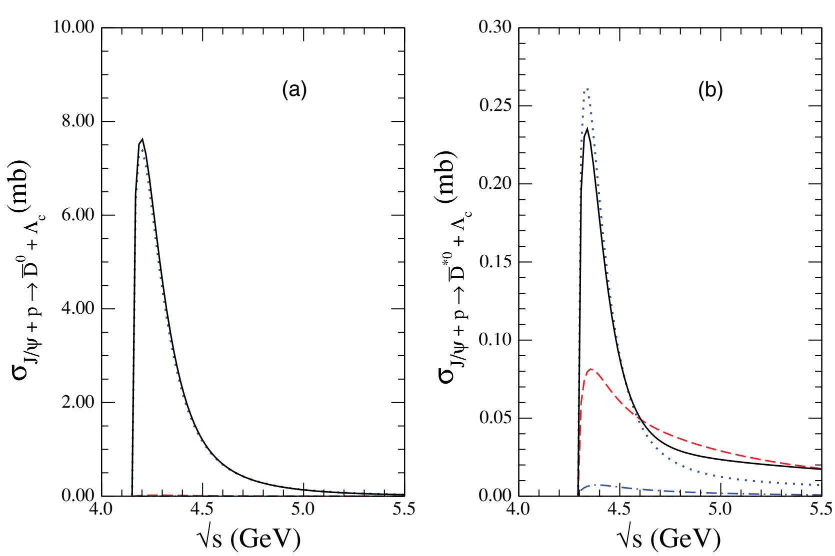

FIG. 3. (Color online) Total cross section for (a) $J/\psi + p \to \bar{D}^0 + \Lambda_c$ and (b) $J/\psi + p \to \bar{D}^{*0} + \Lambda_c$ with $\kappa_{\psi\Lambda_c\Lambda_c} = -0.94$ and $\kappa_{D^*N\Lambda_c} = 0$. Notations are the same as in Fig. 2.

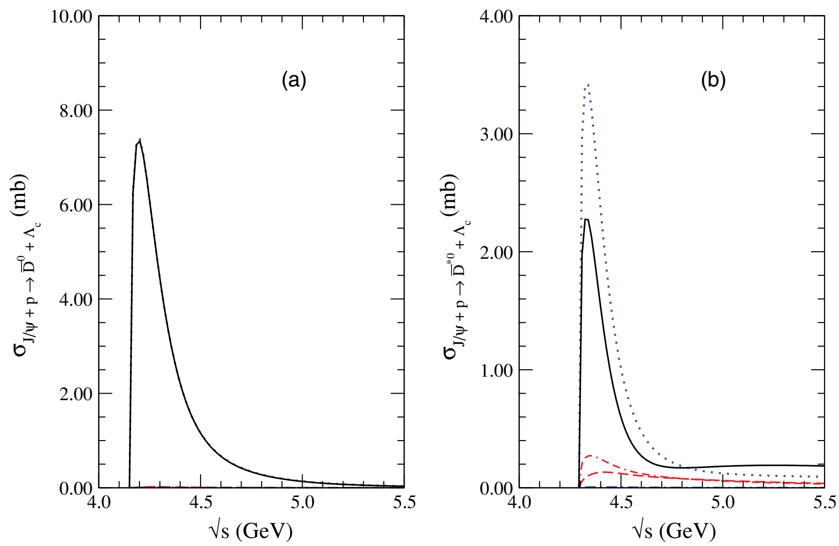

FIG. 4. (Color online) Total cross section for (a) $J/\psi + p \to \bar{D}^0 + \Lambda_c$ and (b) $J/\psi + p \to \bar{D}^{*0} + \Lambda_c$ with $\kappa_{\psi\Lambda_c\Lambda_c} = -0.94$ and $\kappa_{D^*N\Lambda_c} = 2.65$. In (a), the u-channel diagram dominates and the contributions from the other diagrams are suppressed and cannot be seen. In (b), the dot-dash-dashed line is the contribution from the contact term. Other notations are the same as in Fig. 2.

$\bar{D} + \Lambda_c$ is negligible, which is expected because it contributes to the suppressed t-channel anomalous term only. However, this tensor interaction can change noticeably the cross sections for the $J/\psi + N \to \bar{D}^* + \Lambda_c$ reaction. This is because the tensor term enters both in the t-channel and in the u-channel diagrams. Furthermore, this term requires the presence of the contact term. As a result, the $\kappa_{D^*N\Lambda_c}$ term enhances the $\bar{D}^*\Lambda_c$ production cross sections and leads to a smaller value of the ratio R_{D/D^*}, and $R_{D/D^*} \approx 3$ is observed in Fig. 4.

The cross sections and their ratio R_{D/D^*} depend on the coupling constants $g_{DN\Lambda_c}$ and $g_{D^*N\Lambda_c}$ that are not well understood yet. To see this dependence, we use the coupling constants (10) predicted by the QCD sum-rule calculation of Ref. [23]. This gives very different values of the cross section ratio, and instead of $R_{D/D^*} \sim 30$ and ~ 3 (Figs. 3 and 4), we have $R_{D/D^*} \sim 8$ and ~ 0.7, respectively. This also changes the corresponding maximum values of the $J/\psi + p \to \bar{D}^0 + \Lambda_c$ cross sections and they are ~1.6 and ~1.4 mb for the two cases, respectively, as shown in Table I.

As was mentioned before, the cross sections also depend on the cutoff parameter Λ, and we have used $\Lambda = 1.8$ GeV. To see the dependence of our results on the form factor, we repeat the calculation for three different values of the cutoff, i.e., $\Lambda = 1.5, 1.8,$ and 2.1 GeV. Shown in Table I are the peak values of the $J/\psi + N \to \bar{D} + \Lambda_c$ cross sections and the ratio R_{D/D^*}. We found that the cross sections for the $J/\psi + N \to \bar{D}^* + \Lambda_c$ reaction are more sensitive to the cutoff than those for the $J/\psi + N \to \bar{D} + \Lambda_c$ reaction. Thus the ratio R_{D/D^*} decreases as the cutoff parameter Λ increases. However, we found that the $\kappa_{D^*N\Lambda_c}$ term suppresses R_{D/D^*} regardless of the cutoff parameter value.

IV. CONCLUSION

In this work, we have reanalyzed and improved the meson-exchange model for J/ψ-nucleon reaction of Ref. [12]. We found that vector-meson dominance and charm vector-current conservation lead to the universality of the J/ψ meson couplings, which can drastically change the ratio R_{D/D^*} of the cross sections of $J/\psi + N \to \bar{D} + \Lambda_c$ and $J/\psi + N \to \bar{D}^* + \Lambda_c$. It is also found that this ratio is sensitive to the relative strengths of $g_{DN\Lambda_c}$ and $g_{D^*N\Lambda_c}$ as well as to the tensor coupling terms in the $J/\psi\Lambda_c\Lambda_c$ and $D^*N\Lambda_c$ interactions. We found that the VMD and vector-current conservation lead to a large value of R_{D/D^*}. This value can be further enhanced by the $J/\psi\Lambda_c\Lambda_c$ tensor interaction. But the $D^*N\Lambda_c$ tensor interaction has the opposite role by decreasing R_{D/D^*}.

TABLE I. The peak values of the cross section for $J/\psi + N \to \bar{D} + \Lambda_c$ and the ratio R_{D/D^*} for different choices of the D/D^* coupling constants and for three different values of the cutoff parameter Λ. (I) is for $\kappa_{D^*N\Lambda_c} = 0$ and (II) is for $\kappa_{D^*N\Lambda_c} = 2.65$. We use $\kappa_{\psi\Lambda_c\Lambda_c} = -0.94$ for the both cases.

Λ (GeV)		With the couplings in Eq. (9)		With the couplings in Eq. (10)	
		(I)	(II)	(I)	(II)
1.5	$\sigma(J/\psi + N \to \bar{D} + \Lambda_c)$	0.86 mb	0.86 mb	0.3 mb	0.3 mb
	R_{D/D^*}	~225	~30	~38	~3
1.8	$\sigma(J/\psi + N \to \bar{D} + \Lambda_c)$	7.5 mb	7.5 mb	1.6 mb	1.4 mb
	R_{D/D^*}	~30	~3	~8	~0.7
2.1	$\sigma(J/\psi + N \to \bar{D} + \Lambda_c)$	20.5 mb	19.5 mb	6.6 mb	6.1 mb
	R_{D/D^*}	~12	~1.2	~1.4	~0.12

To match the quark-interchange model predictions of Ref. [15] with those from our effective Lagrangian approach leads us to conclude that $g_{DN\Lambda_c}$ must be larger than $g_{D^*N\Lambda_c}$ and $\kappa_{D^*N\Lambda_c}$ must be small. The first condition contradicts with the QCD sum-rule predictions of Ref. [23] that prefers a similar strength for the two couplings. Instead, the SU(4) symmetry relations satisfy this condition. However, SU(4) symmetry gives a large value for $\kappa_{D^*N\Lambda_c}$ and thus does not fulfill the second condition. Because SU(4) symmetry must be broken by the heavy charm quark mass, it would be interesting to see how badly the SU(4) symmetry relations for $g_{DN\Lambda_c}$, $g_{D^*N\Lambda_c}$, and $\kappa_{D^*N\Lambda_c}$ are broken. Therefore, more rigorous studies on these couplings are required, which will eventually help to reconcile the predictions of the quark-interchange model and of the meson-exchange model. Nevertheless, the constraints used in this work, VMD and charm vector-current conservation, are found to have a nontrivial role to fill the gap between the quark-interchange model and meson-exchange model predictions to some extent.

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