Charmonium absorption cross section by nucleon

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The $J/\psi$ absorption cross section by nucleon is studied using a gauged SU(4) hadronic Lagrangian but with empirical particle masses, which has been used previously to study the $J/\psi$ absorption cross section by pion and rho meson. Including both two-body and three-body final states, we find that with a cutoff parameter of 1 GeV at interaction vertices involving charm hadrons, the $J/\psi - N$ absorption is at most 5 mb and is consistent with that extracted from $J/\psi$ production from both photo-nuclear and proton-nucleon reactions.

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I. INTRODUCTION

Two main mechanisms for $J/\psi$ suppression observed in relativistic heavy ion collisions are the dissociation by the quark-gluon plasma and the absorption by comoving hadrons, mainly pions and rho mesons. The cross sections of $J/\psi$ by hadrons are, unfortunately, not well determined. In the perturbative QCD approach, based on the dissociation of charmonium bound states by energetic gluons inside hadrons, the dissociation cross section increases monotonically with the kinetic energy of hadrons and has a value of only about 0.1 mb at 0.8 GeV. On the other hand, both the quark-interchange model and the pion-exchange model based on hadronic Lagrangians give $J/\psi$ absorption cross sections by pion and rho meson which are more than an order of magnitude larger, i.e., a few mb. A similar magnitude for the $J/\psi - \pi$ absorption cross section has also been obtained in the QCD sum rules.

Since the $J/\psi$ absorption cross sections by pion and rho meson cannot be directly measured, it is useful to find empirical information which can constrain their values. One such constraint is the $J/\psi$ absorption cross section by nucleon, as this process can be viewed as $J/\psi$ absorption by the virtual pion and rho meson cloud of the nucleon. From $J/\psi$ production in photo-nucleus reactions, the cross section of $J/\psi$ absorption by nucleon can be extracted, and its magnitude has been found to be about 4 mb. The $J/\psi - N$ absorption cross section has also been extracted from proton-nucleus collisions at proton energies from 200 to 800 GeV, and the empirical value is about 7 mb.

In the meson-exchange model of Refs. and , the interaction Lagrangians between pseudoscalar and vector mesons are obtained from the SU(4) invariant free Lagrangian for pseudoscalar mesons by treating vector mesons as gauge particles. This then leads to not only pseudoscalar-pseudoscalar-vector-meson couplings but also three-vector-meson and four-point couplings. Since the SU(4) symmetry is explicitly broken by hadron masses, empirical hadron masses are used in the Lagrangian. Furthermore, values for the coupling constants are taken either from empirical information if they are available or from theoretical models, such as the vector meson dominance model and the QCD sum rules. Otherwise, they are determined by using relations derived from the SU(4) symmetry. In this paper, we shall generalize this Lagrangian to study the $J/\psi$ absorption cross section by nucleon and to see if its magnitude is consistent with that extracted from $J/\psi$ production in photo-nucleus and proton-nucleon reactions.

This paper is organized as follows. In Section II, we first consider $J/\psi$ absorption by nucleon via pion and rho meson exchange. The process of $J/\psi$ absorption by nucleon via charm exchange is studied in Section III. The effect due to the anomalous parity interaction of $J/\psi$ with charm mesons is studied in Section IV. In Section V, the total $J/\psi$ absorption cross section by nucleon is given. Finally, conclusions and discussions are given in Section VI. An Appendix is included to derive the SU(4) relations for some of the coupling constants involving charm hadrons.

II. $J/\psi$ ABSORPTION BY NUCLEON VIA PION AND RHO MESON EXCHANGE

Possible processes for $J/\psi$ absorption by nucleon involving its virtual pion and rho meson cloud are $J/\psi N \rightarrow D^*\bar{D}N(D^*\bar{D}N)$, $J/\psi N \rightarrow D\bar{D}N$, and $J/\psi N \rightarrow D^*\bar{D}^*N$, as shown by the diagrams in Fig. 1. The cross sections for these processes can be evaluated using the Lagrangians introduced in and for $J/\psi$ absorption by real pion and rho meson and in Ref. for charm meson scattering by these hadrons.

The interaction Lagrangian densities that are relevant to the present study are given as follows:

\begin{align}
\mathcal{L}_{\pi NN} &= -ig_{\pi NN}\bar{N}\gamma_\mu\tau N\cdot\pi, \\
\mathcal{L}_{\rho NN} &= g_{\rho NN}\bar{N}(\gamma_\mu\tau\cdot\rho_\mu + \frac{\kappa_\rho}{2m_N})N, \\
\mathcal{L}_{\pi DD^*} &= ig_{\pi DD^*}D^{\mu*}\tau\cdot(D\bar{\partial}\tau\rho - \bar{D}\partial\tau\rho) + \text{H.c.}, \\
\mathcal{L}_{\rho DD^*} &= ig_{\rho DD^*}(D\bar{\partial}\rho D - \bar{D}\partial\rho D)\cdot\pi^\mu, \\
\mathcal{L}_{\rho D^*D} &= ig_{\rho D^*D^*}[[\partial_\mu D^{\nu\mu}\tau D^\nu_\rho - D^{\nu\mu}\partial_\mu D_\rho^\nu]\cdot\rho^\rho
+ (D^{\nu\rho}\partial_\mu D^{\nu\mu} - \partial_\mu D^{\nu\rho}\cdot D_\nu\rho)D^{\mu\nu}
+ D^{\nu\rho}\tau\partial_\mu D_\rho^\nu - \tau\cdot\partial_\mu D_\rho^\nu]].
\end{align}
\[ \mathcal{L}_{\psi DD} = ig_{\psi DD}\psi^\mu[D\partial_\mu \tilde{D}] - (\partial_\mu D)\tilde{D}, \]
\[ \mathcal{L}_{\psi D^* D^*} = ig_{\psi D^* D^*}\psi^\mu(\partial_\mu D^{*\mu}\tilde{D}^* - D^{*\mu}\partial_\mu \tilde{D}^*) + (\partial_\mu \psi^\mu D^{*\mu} - \psi^\mu \partial_\mu D^{*\mu})\tilde{D}^{*\mu} + D^{*\mu}(\psi^\mu \partial_\mu \tilde{D}^* - \partial_\mu \psi^\mu \tilde{D}^*), \]
\[ \mathcal{L}_{\pi\psi DD^*} = -g_{\pi\psi DD^*}\psi^\mu(D^{*\mu}\tilde{D} + D\tilde{D}^{*\mu}) \cdot \vec{\pi}, \]
\[ \mathcal{L}_{\rho\psi DD^*} = g_{\rho\psi D^* D^*}(\psi^\mu D^{*\mu}\tilde{D}^* + \psi^{*\mu} D^{*\mu}\tilde{D}^*) - 2g_{\rho\psi D^* D^*}(\psi^{*\mu} \tilde{D}^{*\mu} \cdot \vec{\rho}). \]

In the above, \( \vec{\pi} \) are Pauli spin matrices, and \( \pi \) and \( \rho \) denote the pion and rho meson isospin triplet, respectively, while \( D = (D^0, D^+) \) and \( D^* = (D^{*0}, D^{*+}) \) denote the pseudoscalar and vector charm meson doublets, respectively. The \( J/\psi \) is denoted by \( \psi \) while \( N \) represents the nucleon.

\[
\begin{align*}
\text{FIG. 1.} & \quad J/\Psi \text{ absorption by nucleon via pion and rho meson exchanges.} \\
\end{align*}
\]

For coupling constants, we use the empirical values \( g_{\pi NN} = 13.5 \) \([13]\), \( g_{\rho NN} = 3.25 \), and \( \kappa_\rho = 6.1 \) \([14]\), and \( g_{\pi DD^*} = 4.4 \) \([14]\). From the vector dominance model, we have \( g_{\rho DD} = g_{\rho D^* D^*} = 2.52 \) and \( g_{\psi DD} = g_{\psi D^* D^*} = 7.64 \) \([12]\). For the four-point coupling constants, we relate their values to the three-point coupling constants using the SU(4) relations \([15]\), i.e.,

\[ g_{\pi\psi DD^*} = g_{\pi DD}g_{\psi DD^*}, \quad g_{\rho\psi DD} = 2g_{\rho DD}g_{\psi DD}, \quad g_{\rho\psi D^* D^*} = g_{\rho D^* D^*}g_{\psi D^* D^*}. \]

The amplitudes for the first two processes in Fig. 1 are given by

\[ M_1 = -ig_{\pi NN}\vec{N}(p_3)\gamma_5 N(p_1)\left\{ \frac{1}{t - m_\pi^2} \right\}, \]

\[ M_2 = g_{\rho NN}\vec{N}(p_3) \left[ \gamma^\mu + i\frac{\kappa_\rho}{2m_\rho} \sigma^{\mu\nu}(p_1 - p_3)_\nu \right], \]

\[ M_3 = N(p_1) \left[ -g_{\mu} + \frac{(p_1 - p_3)_\mu(p_1 - p_3)_\nu}{m_\rho^2} \right] \frac{1}{t - m_\rho^2}(M_{2a}^* + M_{2b}^* + M_{2c}^*), \]

where \( p_1 \) and \( p_3 \) are the four-momenta of the initial and final nucleons, respectively. In the above, \( M_{1a}, M_{1b}, M_{1c} \) are the amplitudes for the subprocess \( \pi \psi \to D^* \tilde{D} \) in the top three diagrams of Fig. 1, while \( M_{2a}, M_{2b}, M_{2c} \) are the amplitudes for the subprocesses \( \rho \psi \to D^* \tilde{D} \) in the middle three diagrams. The amplitude for the third process has a similar expression as that for the second process with \( M_{2a}^*, M_{2b}^*, M_{2c}^* \) replaced by \( M_{3a}^*, M_{3b}^*, M_{3c}^* \), which are the amplitudes for the subprocess \( \rho \Psi \to D^* \tilde{D}^* \) in the bottom three diagrams. Expressions for these amplitudes can be found in Ref. 1.

The cross sections for these processes with three particles in the final state can be expressed in terms of the off-shell cross sections of the subprocesses described by the amplitudes \( M_1, M_2 \), and \( M_3 \). Following the method of Ref. 14 for the reaction \( NN \to NAK \), the spin and isospin averaged differential cross sections for the first two processes in Fig. 1 can be written as

\[
\frac{d\sigma_{\phi NN \to ND^* \tilde{D}}}{dtds_1} = \frac{g_{\phi NN}^2}{16\pi^2 s_1^{5/2}} k\sqrt{s_1}\left\{ -\frac{F_{2NN}(t)}{(t - m_2^2)^2} \right\} \times \sigma_{\pi\psi \to D^* \tilde{D}}(s_1, t),
\]

\[
\frac{d\sigma_{\phi NN \to ND^* \tilde{D}}}{dtds_1} = \frac{3g_{\rho NN}^2}{32\pi^2 s_1^{5/2}} k\sqrt{s_1}\left\{ -\frac{F_{2NN}(t)}{(t - m_2^2)^2} \right\} \times \left\{ -\frac{4(1 + \kappa_\rho)^2}{2m_2^2} + 4(1 + \kappa_\rho) \right\} \times \kappa_\rho(4m_2^2 - t) \sigma_{\rho\psi \to D^* \tilde{D}}(s_1, t),
\]

and the differential cross section for \( J/\psi \Psi \to D^* \tilde{D}^* N \) is similar to that for \( J/\psi N \to D^* \tilde{D}N \) with \( \sigma_{\rho\psi \to D^* \tilde{D}} \) replaced by \( \sigma_{\rho \psi N} \). In the above, \( p_1 \) is the center-of-mass momentum of \( J/\psi \) and \( N \), \( t \) is the squared four momentum transfer, and \( s_1 \) and \( k \) are, respectively, the squared invariant mass and center-of-mass momentum of \( \pi \) and \( J/\psi \) in the process \( J/\psi NN \to D^* \tilde{D} \) or \( \rho \) and \( J/\psi \) in the processes \( J/\psi \Psi \to D^* \tilde{D}N \) and \( J/\psi \Psi \to D^* \tilde{D}^* \). We have also introduced form factors \( F_{2NN} \) and \( F_{\rho NN} \) at the \( \pi NN \) and \( \rho NN \) vertices, respectively. As in Ref. 14, both are taken to have the monopole form, i.e.,

\[ F_1(t) = \frac{\Lambda^2 - m^2}{\Lambda^2 - t}, \]

where \( m \) is the mass of exchanged pion or rho meson, and \( \Lambda \) is a cutoff parameter. Following Refs. 13, 14, we take \( \Lambda_{\pi NN} = 1.3 \) GeV and \( \Lambda_{\rho NN} = 1.4 \) GeV.
The cross sections $\sigma_{\pi\psi \to D^* \bar{D}}(s_1, t)$, $\sigma_{\rho\psi \to D\bar{D}}(s_1, t)$, and $\sigma_{\rho\psi \to D^* \bar{D}^*}(s_1, t)$ are the spin and isospin averaged differential cross sections for the subprocesses $\pi\psi \to D^* \bar{D}$, $\rho\psi \to D\bar{D}$, and $\rho\psi \to D^* \bar{D}^*$ with off-shell pion or rho meson. Explicit expressions for these cross sections can be obtained from Ref. [3] by replacing the square of pion or rho meson masses by $t$. In evaluating these cross sections, we also introduce form factors at the interaction vertices. Following Ref. [3], the form factors at three-point $t$ channel and $u$ channel vertices, i.e., $\pi DD^*$, $\rho DD$, $\rho D^*D^*$, $\psi DD$, and $\psi D^*D^*$ that involve heavy virtual charm mesons, are taken to have the following form:

$$F_2(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2},$$

(17)

instead of the monopole form of Eq. (16). In the above, $q$ is the three momentum transfer in the center-of-mass of $\psi$ and pion or rho meson.

The form factor at four-point vertices, i.e., $\pi\psi DD^*$, $\rho\psi DD$, and $\rho\psi D^*D^*$, are taken to be

$$f_4 = \left(\frac{\Lambda_1^2}{\Lambda_1^2 + <q^2>}\right) \left(\frac{\Lambda_2^2}{\Lambda_2^2 + <q^2>}\right),$$

(18)

where $\Lambda_1$ and $\Lambda_2$ are the two different cutoff parameters at the three-point vertices present in processes with the same initial and final particles, and $<q^2>$ is the average value of the squared three momentum transfers in $t$ and $u$ channels.

FIG. 2. $J/\psi$ absorption cross sections by nucleon due to the virtual pion and rho meson cloud of the nucleon as functions of center-of-mass energy.

Using the same value of 1 GeV for cutoff parameters in the form factors involving charm mesons as in Refs. [8], we have evaluated the cross sections for $J/\psi$ absorption by nucleon, and they are shown in Fig. 2 as functions of total center-of-mass energy. It is seen that all cross sections are less than 2 mb. Furthermore, the cross section for $J/\psi N \to D^* \bar{D}N$ and $J/\psi N \to D^* \bar{D}N$ (solid curve) due to pion exchange is larger than those for $J/\psi N \to D \bar{D}N$ (dashed curve) and $J/\psi N \to D^* \bar{D}^*$ (dotted curve) that are due to rho meson exchange.

Our result for $\sigma_{J/\psi N \to D \bar{D}N}$ is order-of-magnitude smaller than that of Ref. [17], where this processes is viewed as the elastic scattering of a nucleon with one of the charm mesons from the decay of $J/\psi$. The latter cross section is then assumed to have a constant value of 20 mb. Compared to our approach, they have neglected both the energy dependence and the off-shell effect of the subprocess involved in $J/\psi - N$ absorption to three-body final state. Also contributing to this large difference in the cross section is the value of cutoff parameter, 3.1 GeV in Ref. [17] versus 1 GeV used here, and the different momentum dependence, four momentum transfer in Ref. [17], while three momentum transfer in the present study. We note that the more important processes $J/\psi \to D^* \bar{D}N(D^* \bar{D}N)$ and $J/\psi \to D^* \bar{D}N$ are not considered in Ref. [17].

III. $J/\psi$ ABSORPTION BY NUCLEON VIA CHARM EXCHANGE

Besides absorption by the virtual pion and rho meson cloud of a nucleon, $J/\psi$ can also be absorbed by the nucleon via charm exchange in the reaction $J/\psi N \to D \Lambda_c$ and $J/\psi N \to D^* \Lambda_c$ shown by the diagrams in Fig. 3. These processes involve the following interaction Lagrangians:

$$L_{D N \Lambda_c} = ig_{D N \Lambda_c} (\bar{N} \gamma_5 \Lambda_c \bar{D} + D \Lambda_c \gamma_5 N),$$

(19)

$$L_{D^* N \Lambda_c} = g_{D^* N \Lambda_c} (\bar{N} \gamma_\mu \Lambda_c \bar{D}^* \gamma^\mu + D^* \mu \Lambda_c \gamma_\mu N),$$

(20)

$$L_{\psi \Lambda_c \Lambda_c} = g_{\psi \Lambda_c \Lambda_c} (\bar{\Lambda}_c \gamma_\mu \psi \mu \Lambda_c),$$

(21)

where $\Lambda_c$ denotes the charm baryon.
The amplitudes for these processes are given by

\[ M_{4a} = M_{4a}^{\mu} \varepsilon_{2\mu}, \]
\[ M_{4b} = M_{4b}^{\mu} \varepsilon_{2\mu}, \]
\[ M_{5a} = M_{5a}^{\mu \nu} \varepsilon_{4\mu} \varepsilon_{4\nu}, \]
\[ M_{5b} = M_{5b}^{\mu \nu} \varepsilon_{4\mu} \varepsilon_{4\nu}. \]

with \( \varepsilon_{2\mu} \) and \( \varepsilon_{4\mu} \) being the polarization vectors of \( J/\psi \) and \( D^* \), respectively, and

\[ M_{4a}^{\mu} = 2g_{vDD}g_{DN5}N \left( \frac{1}{t-m_D^2} \right) \bar{D}c(p_3)\gamma_5 N(p_1), \]
\[ M_{4b}^{\mu} = ig_{DN5}g_{vLc} \bar{L}c(p_3)\gamma_5 \frac{\hat{t} + m_{Lc}}{u - m_{Lc}} \gamma_5 N(p_1), \]
\[ M_{5a}^{\mu \nu} = -g_{DN5}g_{vLc} \bar{L}c(p_3)\gamma_5 \frac{\hat{t} + m_{Lc}}{u - m_{Lc}} \gamma_5 N(p_1) \]
\[ \times \left[ g_{\alpha \beta} - \frac{(p_1 - p_3)_\alpha (p_1 - p_3)_\beta}{m_D^2} \right], \]
\[ \times \frac{1}{t - m_D^2} \left( p_2^\mu g^{\beta \mu} - (p_2 + p_4)^\beta g^{\mu \nu} + 2p_4^\mu g^{\beta \nu} \right), \]
\[ M_{5b}^{\mu \nu} = g_{DN5}g_{vLc} \bar{L}c(p_3)\gamma_5 \frac{\hat{t} + m_{Lc}}{u - m_{Lc}} \gamma_5 N(p_1). \]

In the above, \( q = p_1 - p_4 \), and \( s = (p_1 + p_2)^2 \) and \( t = (p_2 - p_3)^2 \) are the standard Mandelstam variables.

The spin and isospin averaged differential cross sections for these two-body processes are then

\[ \frac{d\sigma_{\psi N \rightarrow \bar{D}\Lambda_c}}{dt} = \left( \frac{1}{64\pi spt} \right) |M_{4a} + M_{4b}|^2, \]
\[ \frac{d\sigma_{\psi N \rightarrow D^*\Lambda_c}}{dt} = \left( \frac{1}{64\pi spt} \right) |M_{5a} + M_{5b}|^2, \]

where \(|M_{4a} + M_{4b}|^2\) and \(|M_{5a} + M_{5b}|^2\) can be evaluated using the software package FORM [18].

FIG. 4. \( J/\psi \) absorption cross sections by nucleon due to charm exchange as functions of center-of-mass energy.

The coupling constants \( g_{DN5}, g_{D^*N\Lambda_c}, \) and \( g_{vLc,\Lambda_c} \) can be related to known coupling constants \( g_{vNN} \) and \( g_{vNN} \) using the \( SU(4) \) symmetry as shown in the Appendix. Using \( g_{vNN} = 13.5 \) and \( g_{vNN} = 3.25 \), we then have \( g_{DN5} = 13.5, \ g_{D^*N\Lambda_c} = -5.6, \) and \( g_{vLc,\Lambda_c} = -1.4 \). We again introduce monopole form factors of Eq. (17) at the vertices with cutoff parameter \( \Lambda = 1 \) GeV. The resulting cross sections for \( \psi N \rightarrow \bar{D}\Lambda_c \) and \( \psi N \rightarrow D^*\Lambda_c \) are shown in Fig. 4 by the dashed and solid curves, respectively. Their values are seen to be less than 1 mb. Furthermore, \( \sigma_{\psi N \rightarrow \bar{D}\Lambda_c} \) is much larger than \( \sigma_{\psi N \rightarrow D^*\Lambda_c} \) due to the three vector mesons coupling, which has been shown to increase significantly the \( J/\psi - \pi \) absorption cross section as well [7].

In Ref. [7], only diagram (4a) in Fig. 3 has been studied, and the result there is about a factor of 4 larger than our cross section for \( J/\psi N \rightarrow \bar{D}\Lambda_c \), which includes also diagram (4b). The larger cross section in Ref. [7] is again due to both a larger cutoff parameter of 2 GeV versus 1 GeV used here and the use of four momentum instead of three momentum transfer in the form factors. Our total \( J/\psi - N \) absorption cross section due to charm exchange is, however, larger as we have also included the more important processes shown by diagrams (5a) and (5b).

IV. ANOMALOUS PARITY INTERACTIONS

There are also anomalous parity interactions of \( J/\psi \) with charm mesons [3], i.e.,

\[ L_{\psi D^*D} = g_{\psi D^*D} \varepsilon_{\alpha \beta \mu \nu} (\partial^\alpha \psi^\beta) ([\partial^\mu D^\nu]) D + \bar{D} (\partial^\mu D^\nu), \]

which not only introduces additional diagrams for the processes shown in Fig. 3 but also leads to the reactions \( J/\psi N \rightarrow \bar{D}\Lambda_c \) via \( D^* \) exchange and \( J/\psi N \rightarrow D^*\Lambda_c \) via \( D \) exchange shown by the diagrams in Fig. 3.

FIG. 5. \( J/\psi \) absorption cross section by nucleon via charm meson exchange through the anomalous parity interaction.
As shown in Ref. [3], the anomalous interaction is not important for $J/\psi - \rho$ absorption and increases the $J/\psi - \pi$ absorption cross section by only about 50%. Thus, inclusions of additional diagrams due to the anomalous parity interactions in processes involving three-body final states shown in Fig. 1 will probably increase the $J/\psi - N$ absorption cross section calculated here by less than 50%.

The amplitudes for the process $J/\psi N \to \bar{D}\Lambda_c$ and $J/\psi N \to D^*\Lambda_c$ are given by

$$M_6 = M_6^\mu \varepsilon_{2\mu},$$

$$M_7 = M_7^\mu \varepsilon_{2\mu} \varepsilon_{4\nu},$$

with $\varepsilon_{2\mu}$ and $\varepsilon_{4\nu}$ being the polarization vectors of $J/\psi$ and $D^*$, respectively, and

$$M_6^\mu = -g_{\psi D^* D} g^{D^* N \Lambda_c} \frac{1}{t - m_D^2} \varepsilon^{\mu\nu\alpha\beta} p_{2\alpha}(p_1 - p_3) \beta \times \Lambda_c(p_3)\gamma_\nu N(p_1),$$

$$M_7^\mu = ig_{\psi D^* D} g^{D^* N \Lambda_c} \frac{1}{t - m_D^2} \varepsilon^{\mu\nu\alpha\beta} p_{2\alpha}p_{4\beta} \times \Lambda_c(p_3)\gamma_\nu N(p_1).$$

Because of the anomalous parity in the $\Psi D^* D$ vertex, the process $J/\psi N \to \bar{D}\Lambda_c$ via $D^*$ exchange does not interfere with the similar process via $D$ exchange shown in Fig. 1. The differential cross sections for the two anomalous processes in Fig. 5 are given by similar expressions as Eqs. (23) and (20) with

$$|M_6|^2 = \frac{g_{\psi D^* D} g_{D^* N \Lambda_c}^2}{12m_\psi^2} \frac{1}{(t - m_D^2)^2} \left\{ \frac{4m_N^2}{(m_N + m_\Lambda_c - t)^2} \right\}$$

$$\times \left\{ [(m_\psi^2 + m_\Lambda_c^2 - u)^2 - 2(m_\Lambda_c^2 - m_\Lambda_c^2) - 2] \right\} \times \left\{ [(m_\psi^2 + m_\Lambda_c^2 - u)^2 - 2(m_\Lambda_c^2 - m_\Lambda_c^2) - 2] \right\},$$

and

$$|M_7|^2 = \frac{g_{\psi D^* D} g_{D^* N \Lambda_c}^2}{6m_\psi^2} \frac{1}{(t - m_D^2)^2} [(m_N - \Lambda_c)^2 - t]$$

$$\times [(m_\psi^2 + m_\Lambda_c^2 - t)^2 - m_\psi^2 m_D^2],$$

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

The coupling constant in the anomalous parity interaction has been determined to be $g_{\psi D^* D} = 8.61$ GeV$^{-1}$ from the radiative decay of $D^*$ to $D$ using the vector dominance model. With a monopole form factor similar to Eq. (17) at the $D^* N \Lambda_c$ vertex and a cutoff parameter of 1 GeV, the cross sections for the reactions $J/\psi N \to \bar{D}\Lambda_c$ due to $D^*$ exchange and $J/\psi N \to D^*\Lambda_c$ due to $D$ exchange are shown in Fig. 3. Their values are seen to be less than 0.15 mb, which is negligible compared to the contributions from the normal interactions studied in Sections II and III.

![Fig. 6. Contributions of the anomalous interaction to $J/\psi$ absorption cross sections by nucleon as functions of center-of-mass energy.](image)

We note that the two processes in Fig. 6 due to the anomalous interaction have also been studied in Ref. [17]. Their coupling constant is related to ours by $g_{\psi D^* D} = g_{\psi DD^*} = 7.64$ based on an incorrect quotation from Ref. [19], the strength of the anomalous coupling constant in their study is only 2.47 GeV$^{-1}$ and is about a factor of 3 smaller than that used here. However, they have used a much larger value for $g_{D^* N \Lambda_c} = -19$ than that given by the SU(4) relation. As a result, their cross section for diagram (7) in Fig. 6 should have a similar magnitude as ours while that of diagram (6) should be larger than our value. Because of the larger value of cutoff parameter of 2 GeV and the use of four momentum transfer in the form factor, the results in Ref. [17] from the anomalous interaction turn out to be order-of-magnitude larger than ours.

V. TOTAL $J/\psi$ ABSORPTION CROSS SECTION BY NUCLEON

The total $J/\psi$ absorption cross section by nucleon, obtained by adding the contributions shown in Figs. 2 and 3, is given in Fig. 3. At low center-of-mass energies, the cross section is dominated by the process $J/\psi N \to D^*\Lambda_c$ while at high center-of-mass energies, the processes $J/\psi N \to D^* D N$ and $J/\psi N \to D^* D N$ due to the virtual pion cloud of the nucleon are most important. The total $J/\psi$ absorption cross section is at most 5 mb.
and is consistent with that extracted from $J/\psi$ production in photo-nucleus and proton-nucleus reactions.

FIG. 7. Total $J/\psi$ absorption cross sections by nucleon as functions of center-of-mass energy.

VI. CONCLUSIONS AND DISCUSSIONS

We have used a meson-exchange model to study the $J/\psi$ absorption cross section by a nucleon. The interaction Lagrangians are based on the gauged SU(4) flavor symmetry, but with empirical masses. Using coupling constants taken either from the empirical information or via the SU(4) relations and form factors with cutoff parameter of 1 GeV, we obtain a $J/\psi$-nucleon absorption cross section of at most 5 mb, which is consistent with the empirical cross section extracted from $J/\psi$ production in photo-nucleus and proton-nucleus reactions. Since the dominant process can be viewed as $J/\psi$ absorption by the virtual pion cloud of a nucleon, our results thus indicate that the cross sections for $J/\psi$ absorption by pion and rho meson evaluated in previous studies using the meson-exchange model are not in contradiction with the empirical cross section for $J/\psi$ absorption by nucleon.

Our results are not much affected if we use the coupling constants $g_{D\Lambda N} \sim 6.7 - 7.9$ and $g_{D^*\Lambda N} \sim -7.5$ determined from the QCD sum rules [20] or from the SU(4) symmetry. With these values, $\sigma_{\psi N \to D\Lambda}$ will be even smaller while $\sigma_{\psi N \to D^*\Lambda}$ will be about a factor of two larger than those shown in Fig. 4. In this case, the $J/\psi - N$ absorption cross section is only increased by about 1 mb. On the other hand, if the cutoff parameter is taken to be $\Lambda = 2$ GeV at vertices involving charm hadrons as suggested by QCD sum rules [21], then the total $J/\psi - N$ absorption cross section increases to about 10 mb, which is about a factor of two larger than the empirical value from $J/\psi$ production in photo-nucleus and proton-nucleus reactions. With this cutoff parameter, the $J/\psi - \pi$ absorption cross section is also about 10 mb as shown in Ref. [2]. Since the meson-exchange model is based on effective hadronic Lagrangians, one can either fit the empirical $J/\psi - N$ absorption cross section by treating the cutoff parameter as a phenomenological parameter, or use the cutoff parameter from the QCD sum rules but with a different effective Lagrangian. In the former case, a cutoff parameter of 1 GeV is required at the interaction vertices involving charm hadrons in order to have the correct $J/\psi N$ absorption cross section. The meson-exchange model of Ref. [2] then gives a $J/\psi - \pi$ absorption cross section of about 3 mb, which is also consistent with that used in the comover model for $J/\psi$ suppression in heavy ion collisions [22]. In the latter case, one may follow the suggestion of Ref. [22] to drop the nongradient pion couplings in the effective Lagrangians, as they breaks the chiral $SU(2) \times SU(2)$ symmetry. As shown in Ref. [22], neglecting these terms reduces the $J/\psi - \pi$ absorption cross section by about a factor of two, leading again to a $J/\psi - \pi$ absorption cross section similar to that in the comover model. The $J/\psi - N$ absorption cross section obtained with such an effective Lagrangian is expected to be reduced as well.

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APPENDIX

In the SU(4) quark model, baryons belong to the 20-plet states. These states can be conveniently expressed by tensors $\phi_{\mu\nu\lambda}$ [23], where $\mu, \nu, \lambda$ run from 1 to 4, that satisfy the conditions

$$\phi_{\mu\nu\lambda} + \phi_{\nu\lambda\mu} + \phi_{\lambda\mu\nu} = 0, \quad \phi_{\mu\nu\lambda} = \phi_{\nu\mu\lambda}. \quad (38)$$

For baryons without charm quarks, i.e., belonging to SU(3) octet, they are given by

$$p = \phi_{112}, \quad n = \phi_{221}, \quad \Lambda = \sqrt{\frac{2}{3}} (\phi_{321} - \phi_{312}),$$

$$\Sigma^+ = \phi_{113}, \quad \Sigma^0 = \sqrt{2}\phi_{123}, \quad \Sigma^- = \phi_{223},$$

$$\Xi^0 = \phi_{331}, \quad \Xi^- = \phi_{332}. \quad (39)$$

For baryons with one charm quark, they are
\[ \Sigma_c^+ = \phi_{114}, \quad \Sigma_c^+ = \phi_{142}, \quad \Sigma_c^0 = \phi_{224}, \quad \Xi_c^- = \phi_{134}, \quad \Xi_c^- = \phi_{234}, \]
\[ \Xi_c^{0*} = \sqrt{\frac{2}{3}}(\phi_{431} - \phi_{431}), \quad \Xi_c^{0*} = \sqrt{\frac{2}{3}}(\phi_{432} - \phi_{432}), \]
\[ \Lambda_c^+ = \sqrt{\frac{2}{3}}(\phi_{421} - \phi_{421}), \quad \Omega_c^- = \phi_{334}. \tag{40} \]

For baryons with two charm quarks, they are
\[ \Xi_{cc}^{++} = \phi_{441}, \quad \Xi_{cc}^{++} = \phi_{442}, \quad \Omega_{cc}^+ = \phi_{443}. \tag{41} \]

Mesons in the SU(4) quark model belong to the 15-plet. In the tensor notations, pseudoscalar and vector mesons are expressed by \( P_\alpha^0 \) and \( V_\beta^\gamma \), respectively. For pseudoscalar mesons, we have
\[
\pi_c^+ = P_1^2, \quad \pi_c^- = P_2^1, \quad \pi_c^0 = \frac{1}{\sqrt{2}}(P_1^1 - P_2^2), \]
\[
K_c^+ = P_3^3, \quad K_c^0 = P_3^2, \quad K_c^- = P_3^1, \quad K_c^0 = P_3^2, \]
\[
D_c^+ = P_4^4, \quad D_c^0 = P_4^3, \quad D_c^- = P_4^2, \quad D_c^0 = P_4^3, \]
\[
\eta_c = \frac{1}{\sqrt{6}}(P_1^1 + P_2^2 - 2P_3^3), \]
\[
\eta_c = \frac{1}{\sqrt{12}}(P_1^1 + P_2^2 + P_3^3 - 3P_4^4). \tag{42} \]

Similarly, we have for vector mesons
\[
\rho_c^+ = V_1^2, \quad \rho_c^- = V_2^1, \quad \rho_c^0 = \frac{1}{\sqrt{2}}(V_1^1 - V_2^2), \]
\[
K_c^{*+} = V_3^3, \quad K_c^{*0} = V_3^2, \quad K_c^{*-} = V_3^1, \quad K_c^{*0} = V_3^2, \]
\[
D_c^{*+} = V_4^4, \quad D_c^{*0} = V_4^3, \quad D_c^{*-} = V_4^2, \quad D_c^{*0} = V_4^3, \]
\[
\omega_c = \frac{1}{\sqrt{6}}(V_1^1 + V_2^2 - 2V_3^3), \]
\[
J/\psi = \frac{1}{\sqrt{12}}(V_1^1 + V_2^2 + V_3^3 - 3V_4^4). \tag{43} \]

In tensor notations, the SU(4) invariant interaction Lagrangians between baryons and pseudoscalar mesons as well as between baryons and vector mesons can be written, respectively, as
\[
\mathcal{L}_{PBB} = g_p \left[ \frac{1}{\sqrt{2}}(a - \frac{5}{4}b)\bar{N}\gamma_5\pi^\nu \right] \cdot \bar{q} \gamma^\nu N \]
\[
\mathcal{L}_{VBB} = g_v \left[ \frac{1}{\sqrt{2}}(c - \frac{5}{4}d)\bar{N}\gamma_5\pi^\nu \right] \cdot \bar{q} \gamma^\nu N \]
\[
+ \frac{3\sqrt{6}}{8}(b - a)(\bar{N}\gamma_5 K A + \bar{N}\gamma_5 D A c) + \cdots, \tag{46} \]
\[
\mathcal{L}_{VBB} = g_v \left[ \frac{1}{\sqrt{2}}(c - \frac{5}{4}d)\bar{N}\gamma_5\pi^\nu \right] \cdot \bar{q} \gamma^\nu N \]
\[
+ \frac{3\sqrt{6}}{8}(d - c)(\bar{N}\gamma_5 K^* \gamma^\nu A + \bar{N}\gamma_5 D^* \gamma^\nu A c) + \cdots \tag{47} \]

The baryon-pseudoscalar-meson coupling in SU(3) is usually written as \( D^Tr[(BB + BB)M] + F^Tr[(BB - BB)M] \), where \( B \) and \( M \) are the baryon and pseudoscalar meson octet. In terms of the ratio \( \alpha_D = D/(D + F) \), which has an empirical value of about 0.64, we then have the following relation between \( g_{\pi NN} \) and \( g_{K N A} \) in the Lagrangians \( \mathcal{L}_{\pi NN} \) given by Eq. (39) and \( \mathcal{L}_{K N A} = i g_{K N A} \bar{N}\gamma_5 \Lambda K \):
\[
g_{K N A} = \frac{3 - 2\alpha_D}{\sqrt{3}} g_{\pi NN}. \tag{48} \]

Comparisons with the SU(4) relations in Eq. (46) then gives
\[
\frac{b}{a} = \frac{3 - 8\alpha_D}{6 - 10\alpha_D}. \tag{49} \]

The baryon-vector-meson coupling is usually introduced through minimal coupling by treating vector mesons as gauge particles. In SU(3), this leads to the following relation between \( g_{\rho NN} \) and \( g_{K^* NA} \) in the Lagrangians \( \mathcal{L}_{\rho NN} \) given by Eq. (38) and \( \mathcal{L}_{K^* NA} = g_{K^* NA} \bar{N}\gamma_\mu A K^* \):
\[
g_{K^* NA} = -\sqrt{3} g_{\rho NN}. \tag{50} \]

Comparing with the SU(4) relations in Eq. (46), we have
\[
\frac{d}{c} = \frac{1}{2}. \tag{51} \]

Using Eqs. (49) and (51) in Eqs. (46) and (47), we then have
\[
g_{DN A c} = \frac{3 - 2\alpha_D}{\sqrt{3}} g_{\pi NN}, \quad g_{\psi A c} = -\frac{g_{\rho NN}}{\sqrt{6}}, \quad g_{D^* N A c} = -\sqrt{3} g_{\rho NN}, \tag{52} \]

for the coupling constants in the Lagrangians given by Eqs. (39), (40), and (41).
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