Consequences of a modified charmed current

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We study the inclusive production of D^+ and diffractive production of D^{*+} in neutrino scattering using the $V+A$ form of the charm current. Cross sections for production of D^+ and D^{*+} are of the order of 10^{-35} cm^2/GeV^3 and 10^{-38} cm^2/GeV^3, respectively.

I. INTRODUCTION

The most probable interpretations of recently observed narrow resonances ψ at 3.105 (Ref. 1) and ψ' at 3.695 (Ref. 2) have come in the form of extending SU(3), the usual symmetry group of strong interactions, to (i) the $SU(3)\otimes SU(3)$ color scheme of Han and Nambu[3] and (ii) SU(4) charm.[4] In the SU(4) scheme, which we confine ourselves to in the present paper, the hypothesis is that ψ is essentially a pure $C\overline{C}$ (charm-anticharm) state and ψ' is its radial excitation. The narrow widths of ψ and ψ' can be understood qualitatively if they lie below the threshold for production of a pair of charmed particles. Recent discovery[5] of η_c, η_c', χ states in radiative decay of ψ' and ψ lend support to the charm hypothesis. This hypothesis also seems to provide the most promising explanations for production of anomalous leptons[6] and dimuons.[7]

A natural consequence of the SU(4) scheme for hadrons is to incorporate the charmed particles as members of various multiplets of this group. Since both strong and electromagnetic interactions conserve charm, particles with nonzero charm quantum number can only be produced in pairs in these interactions. Consequently, a simple threshold argument would tell us that the production cross section for charmed hadrons would be substantially reduced compared to those for ordinary hadrons. Weak current, instead, can accommodate charm-changing terms. Thus one expects copious production of charmed hadrons in high-energy neutrino scattering.[4]

In a recent work[8] we estimated the F^* production cross section using the powers of Regge-pole theory. We worked with the familiar $V-A$ weak current of Glashow, Iliopoulos, and Maiani (GIM).[9] Recently, however, De Rújula, Georgi, and Glashow[10] (DGG) have suggested a new form of weak current in order to provide a satisfactory explanation of the $\Delta I=\frac{1}{2}$ rule and the anomalous strength of nonleptonic decays of hadrons. The hadronic part of the modified charmed weak current is

$$J'_\mu=\overline{\mathcal{O}}\gamma_\mu(1+\gamma_5)(\mathfrak{N}\cos\theta+\lambda\sin\theta)+\overline{\mathcal{P}}'\gamma_\mu(1+\gamma_5)(\lambda\cos\theta-\mathfrak{N}\sin\theta)+\overline{\mathcal{P}}'\gamma_\mu(1-\gamma_5)\mathfrak{N}\,. \qquad (1)$$

The last term in Eq. (1) has $V+A$ structure. Some of the shortcomings of this model have been pointed out by Golowich and Holstein[11]; however, Branco and Mohapatra[12] have shown that some of the above objections could be avoided. Thus it seems that this question is still unsettled.

The purpose of this work is to present yet another implication of the modified charm current in production of charmed mesons. It is based on the observation that the absence of Cabibbo suppression in the $V+A$ term enhances cross section for production of certain charmed pseudoscalar and vector mesons. Specifically, we study the inclusive reaction $\nu+p\to\mu^-+D^++X$ and diffractive process $\nu+p\to\mu^-+D^{*+}+p$. The calculation is based upon the assumption of our previous work[8] that Regge phenomenology plays an important role in understanding the interaction of current with hadron at high energies.

II. KINEMATICS

Defining the kinematical variables for the process $\nu+p\to\mu^-+X$ as

p (p') = initial (final) momentum of lepton,

P = initial momentum of the hadron ($P^2=M^2$),

$q=p-p'$,

$\nu=q\cdot P=(E-E')M$,

θ = scattering angle of lepton in the laboratory,

$Q^2=-q^2=4EE'\sin^2(\frac{1}{2}\theta)$,

and a scale variable $\omega=2\nu/Q^2$. The cross section in the zero lepton mass limit is given by

$$\frac{d\sigma}{d\Omega' dE'} = \frac{G^2E'^2}{2\pi^2}\left[2W_1(q^2,\nu)\sin^2(\tfrac{1}{2}\theta) + W_2(q^2,\nu)\cos^2(\tfrac{1}{2}\theta) + \frac{E+E'}{M}W_3\sin^2(\tfrac{1}{2}\theta)\right]. \tag{2}$$

In the limit of our interest, q^2 fixed and $E\to$ large, i.e., θ small,

$$\frac{d\sigma}{d\Omega' dE'} = \frac{G^2E'^2}{2\pi^2}W_2. \tag{3}$$

Noting that the structure functions W_i are related to the total scattering cross section of the spin-averaged proton and the longitudinal (transverse) component of the current in the manner,

$$\sigma_S(q^2,\nu) = \left(1+\frac{\nu^2}{Q^2M^2}\right)W_2 - W_1, \tag{4a}$$

$$\sigma_R(q^2,\nu) = W_1 + \frac{1}{2M}\left(\frac{\nu^2}{M^2}-q^2\right)^{1/2}W_3, \tag{4b}$$

$$\sigma_L(q^2,\nu) = W_1 - \frac{1}{2M}\left(\frac{\nu^2}{M^2}-q^2\right)^{1/2}W_3, \tag{4c}$$

then

$$\frac{d\sigma}{d\Omega' dE'} = \frac{G^2E'^2}{2\pi^2}\frac{\sigma_S+\frac{1}{2}(\sigma_R+\sigma_L)}{1+\nu^2/Q^2M^2}. \tag{5}$$

Now the invariant cross sections for $\nu+p\to\mu^-+D^+ +X$ and $\nu+p\to\mu^-+D^{*+}+p$ are respectively given by

$$E_D\frac{d\sigma}{d\Omega' dE' d^3k} = \frac{d\sigma}{d\Omega' dE'}\frac{E_D}{\sigma}\frac{d\sigma}{d^3k} \tag{6}$$

and

$$\frac{d\sigma}{d\Omega' dE' dt} = \frac{d\sigma}{d\Omega' dE'}\frac{1}{\sigma}\frac{d\sigma}{dt}. \tag{7}$$

In the above relations $E_D(d\sigma/d^3k)$ is the inclusive cross section for $J^{+i}+p\to D^+ +X$, $d\sigma/dt$ is the differential cross section for $J^{+i}+p\to D^{*+}+p$, and σ is the total cross section for $J^{+i}+p$. Since $d\sigma/d\Omega' dE'$ is determined from deep-inelastic neutrino scattering via relation (5), we hereafter concentrate on $E_D(d\sigma/d^3k)$ and $(d\sigma/dt)$.

III. EVALUATION OF CROSS SECTIONS

(a) $\nu+p\to\mu^-+D^+ +X$. It follows from the quark structure of D^+ that π^0 is exchanged in the t channel of the process $J_\mu+p\to D^+ +X$. Hence one expects a narrow forward peak for small $|t|$ in the current fragmentation region. The kinematical variables are defined as [see Fig. 1(a)]

$$s=(P+q)^2,\quad t=(q-k)^2,\quad M_X{}^2=(P+q-k)^2. \tag{8}$$

Here q is the four-momentum of the current with $Q^2=-q^2$. The region of our interest is $s\to$ large, $M_X{}^2\to$ large, $|t|$ small, and q^2 fixed. We consider

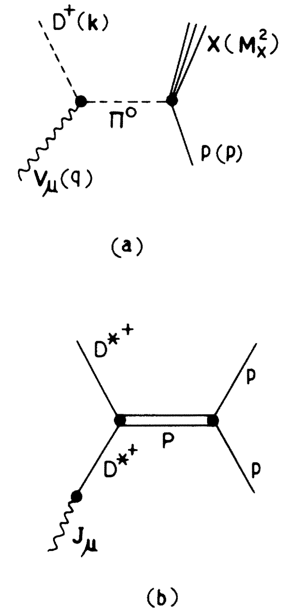

FIG. 1. (a) Diagram for $V_\mu+p\to D^+ +X$ through π^0 exchange. (b) Diffractive production of D^{*+} on proton target.

Reggeized pion exchange instead of elementary pion exchange. It follows that only vector current can couple to two pseudoscalars, i.e., D^+ and π^0. Thus the inclusive cross section is

$$s\frac{d\sigma}{dt\,dM_X{}^2} = \frac{1}{64\pi s}|\langle\pi^0D^+|V_\mu|0\rangle|^2\alpha'\Gamma^2(-\alpha_\pi(t)) \times\left(\frac{s}{M_X{}^2}\right)^{2\alpha_\pi(t)}|1+e^{i\pi\alpha_\pi(t)}|^2 \times\beta_{\alpha_\pi 0p}(M_X{}^2,t). \tag{9}$$

The matrix element $\langle\pi^0D^+|V_\mu|0\rangle$ is parametrized similarly to the K_{l3} form factor in the following form[13]:

$$\langle\pi^0D^+|V_\mu|0\rangle = q_\mu f_+(0)(1+\lambda_+q^2/m_\pi{}^2). \tag{10}$$

In writing Eq. (10) we have neglected the contribution of $f_-(q^2)$ which is known to be small[13] in the case of $K^+\to\pi^0\mu^+\nu$. It should be noted, however, that Eq. (10) corresponds to the assumption that the form factor is a smooth function of q^2 and can be extrapolated from the timelike to the spacelike region. Since SU(4) is a badly broken symmetry it might be a drastic assumption to replace the D_{l3} form factor by the K_{l3} form factor. However, in the absence of any estimation of D_{l3} form factors and symmetry-breaking effects therein we are forced to make the above assumption.[4] Therefore, our calculation will provide a qualitative estimation of the inclusive cross section. Now we proceed to evaluate Eq. (9).

In the kinematical region of our interest

$$\beta_{\alpha_\pi 0 p}(M_X^2, t) \xrightarrow[M_X^2 \to \text{large}]{} M_X^2 \sigma_{\alpha_\pi 0 p}(M_X^2, t) , \qquad (11)$$

where $\sigma_{\alpha_\pi 0 p}(M_X^2, t)$ is the proton-Reggeon total cross section. It is reasonable to assume that $\sigma_{\alpha_\pi 0 p}(M_X^2, t) = \sigma_{\pi 0 p}$ for small values of $|t|$. Furthermore, exact isospin invariance in the strong interaction implies, $\sigma_{\pi 0 p} = \frac{1}{2}(\sigma_{\pi^+ p} + \sigma_{\pi^- p})$. Therefore Eq. (9) reduces to

$$s\frac{d\sigma}{dt\, dM_X^2} = \frac{\alpha'}{64\pi} \Gamma^2(-\alpha_\pi(t)) |f_+(0)|^2 \times \left|1 + \frac{\lambda_+ q^2}{m_\pi^2}\right|^2 (1-\sin\theta)^2 \left(\frac{s}{M_X^2}\right)^{2\alpha_\pi(t)-1} \times |1 + e^{i\pi\alpha_\pi(t)}|^2 \tfrac{1}{2}(\sigma_{\pi^+ p} + \sigma_{\pi^- p}) . \qquad (12)$$

Equation (12) does not contain any free parameter if $f_+(0)$ and λ_+ are taken from K_{l3} decay processes. Now the expression for the inclusive cross section [Eq. (6)] could be written as

$$E_D \frac{d\sigma}{d\Omega' dE' d^3k} = \frac{d\sigma}{d\Omega' dE'} \frac{s}{\pi} \frac{d\sigma}{dt\, dM_X^2} . \qquad (13)$$

Thus if s and M_X^2 are chosen to be large enough such that $s/M_X^2 \to$ large and $\sigma_{\pi p}(M_X^2) \simeq$ constant, then the inclusive cross section (13) is determined completely. Indeed if charmed mesons exist, then observation of the above inclusive process will provide a test for the DGG weak current. We have used $\theta \simeq 15°$, $f_+ = 0.212/\sin\theta$, $\lambda_+ = 0.027$, $q^2 = 2$ GeV^2, $s = 80$, 100, and 120 GeV^2, $M_X^2 = 0.2s$, $E' = 20$ GeV, $\frac{1}{2}(\sigma_{\pi^+ p} + \sigma_{\pi^- p}) = 25$ mb, and $\alpha_\pi(t) = \alpha'(tm_\pi^2)$, with $\alpha' = 0.9$ GeV^{-2}. We find that the cross section (see Fig. 2) is of the order of 10^{-35} cm^2/GeV^3.

(b) $\nu + p \to \mu^{-1} + D^{*+} + p$. We consider the process $J_\mu^{i+} + p \to D^{*+} + p$, incorporating the SU(4) scheme. It has been argued by Inami[14] and also by Gaillard, Jackson and Nanopolos[15] that the hypothesis of vector-meson dominance for electromagnetic current can be generalized for the charged and neutral weak current as

$$\langle 0 | J_\mu^i | V_i \rangle = \epsilon_\mu (m_{V_i}^2 / g_{V_i}) . \qquad (14)$$

It follows from the generalized vector-meson dom dominance hypothesis[14,15] that

$$\frac{d\sigma}{dt}(J^i + p \to D^{*+} + p) = \frac{A_{V_i}}{g_{V_i}^2} \frac{d\sigma}{dt}(D^{*+}p \to D^{*+}p) , \qquad (15)$$

where $A_{V_i} = m_{V_i}^2/(m_{V_i}^2 + Q^2)$ is introduced to consider the effect of off-mass-shell current, carrying momentum q with $Q^2 = -q^2$. Following the prescription of Inami[14] to introduce effective SU(4)-breaking mechanisms for coupling of the Pomeranchukon we get

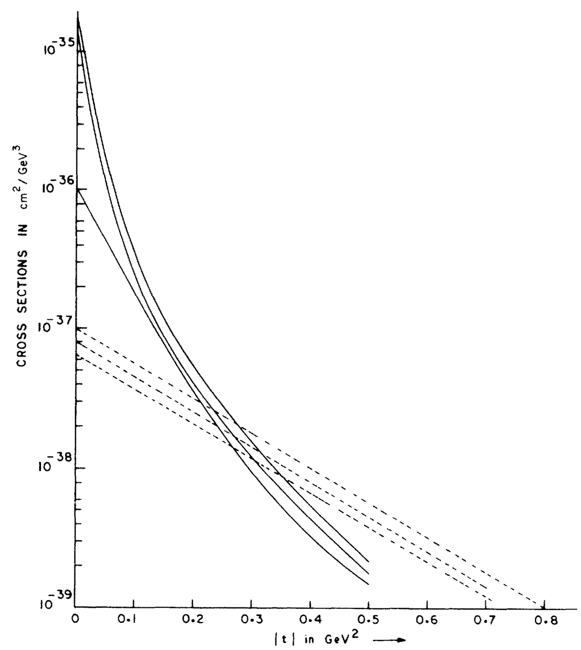

FIG. 2. Dashed lines are the inclusive cross section $E_D(d\sigma/d\Omega' dE' d^3k)$ for $\nu + p \to \mu^- + D^+ + X$, for $s = 80$, 100, and 120 GeV^2. Solid curves are for the diffractive process $\nu + p \to \mu^- + D^{*+} + p$ for above values of s.

$$\frac{d\sigma}{dt}(D^{*+}p \to D^{*+}p) = \frac{A_{D^{*+}}}{4A_{\rho^+}} (1 + \gamma_2(t))^2 \frac{m_\rho}{m_{D^*}} \times \left(\frac{1-\sin\theta}{\cos\theta}\right)^2 \frac{d\sigma}{dt}(\rho^+ p \to \rho^+ p) . \qquad (16)$$

Here $\gamma_2(t) = [1 - \alpha_f(t)][1 - \alpha_{f_c}(t)]^{-1}$ with $\alpha_f(t) = 0.5 + 0.9t$ and $\alpha_{f_c}(t) = -3.8 + 0.5t$. $d\sigma/dt(\rho p \to \rho p)$ is parametrized as

$$\frac{d\sigma}{dt}(\rho p \to \rho p) = \frac{\sigma_T^2(\rho p)}{16\pi} e^{bt} . \qquad (17)$$

Thus Eq. (16) takes the form

$$\frac{d\sigma}{dt}(D^{*+}p \to D^{*+}p) = \frac{\sigma_T^2(\rho p)}{64\pi} \frac{A_{D^{*+}}}{A_{\rho^+}} \frac{m_\rho}{m_{D^*}} [1 + \gamma_2(t)]^2 \times \left(\frac{1-\sin\theta}{\cos\theta}\right)^2 e^{bt} . \qquad (18)$$

Now we evaluate Eq. (7) using Eq. (18) with $Q^2 = 0.25$ GeV^2, $m_D = 2.2$ GeV, $\sigma_T(\rho p) = 26$ mb, and $b = 6$ GeV^{-2}. The cross section is shown in Fig. 2 for different values of s.

We mention here that pion exchange of the form $\langle D^*\pi | A_\mu | 0 \rangle$ can contribute to the cross section considered above. However, it should be noted that the Pomeranchukon contributes dominantly [Fig. 1(b)]. Thus pion exchange can be neglected.

Notice that in the case of the GIM charm current $(1-\sin\theta)^2$ will be replaced by $\sin^2\theta$ and thus the cross section will be reduced by an order of magnitude. We feel that this process provides another criterion to test the DGG model for weak current.

IV. CONCLUSION

We have used the Regge-pole model to study charm particle production in the DGG scheme. This technique will be particularly useful in the small-$|t|$ region. The cross section thus calculated could be measured in present high-energy neutrino experiments. We conclude this paper with the following remarks: (i) The inclusive process $V_\mu + p \to D^+ + X$ will show a sharp forward peak due to π^0 exchange. The magnitude of the cross section depends crucially on the form of the hadronic weak current. We emphasize that Eq. (13) contains no free parameter once the D_{l3} form factor is fixed. Observation of the D^+ inclusive cross section will provide a check for the present investigation. (ii) Similarly, diffractive production of D^{*+} will provide another test for the DGG model. In this case we have restricted ourselves to rather low-Q^2 values where vector-meson dominance is expected to give better results.

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