Neutral current and diffractive production of vector mesons in neutrino scattering

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We examine the consequences of the neutral-current phenomenology by supplementing the Glashow, Iliopoulos, and Maiani model with generalized vector-meson dominance and Regge-pole phenomenology. We feel that the diffractive production of the vector mesons in exclusive as well as inclusive reactions with high-energy neutrino beams would test the experimental validity of this model.

I. INTRODUCTION

Recent experiments on neutrino scattering have revealed some interesting information regarding the structure of the weak neutral current. The experiment on electron-neutrino scattering[1] provides the magnitude of the Weinberg angle, whereas the elastic scattering of neutrinos on nucleon targets indicates that the weak neutral-current interaction is likely to be of the $V-A$ form.[2] Furthermore, the recent discovery of charmed hadrons[3] lends support to the possibility of constructing a renormalizable and unified theory of weak and electromagnetic interactions.[4,5] One of the most attractive models in this direction is due to Glashow, Iliopoulos, and Maiani (GIM).[6] In this model the Weinberg angle relates the weak neutral current to the electromagnetic current. Therefore, it appears worthwhile to examine in detail the consequences of the above model on neutral-current interactions which can be put to experimental verifications in high-energy neutrino scattering experiments now being carried out at CERN and at Fermilab.

The purpose of this paper is to study the following reactions:

$$\nu+p\to\nu+V+p\ , \tag{1}$$

$$\nu+p\to\nu+V+\text{anything}\ , \tag{2}$$

in the inclusive as well as exclusive diffractive production of the vector mesons V (ρ, ω, ϕ, and ψ) due to neutral currents in high-energy neutrino scattering, making use of the GIM model. However, we add two more ingredients to this model: (i) the hypothesis of generalized vector-meson dominance (GVMD) and (ii) Regge-pole phenomenology. It is well known that GVMD is quite reliable in the low-q^2 region. On the other hand, the Regge-pole model has been found useful[7,8] in studying the current-hadron interactions. The diffractive production of charmed vector mesons had been studied by several authors.[9,10] The present investigation is intended to provide qualitative as well as quantitative estimates of different diffractive cross sections for the reactions mentioned above so that they can readily be subjected to experimental verifications. It would thus provide a test for the validity of our assumptions in describing the neutral-current phenomenology for processes (1) and (2).

The hadronic part of the neutral-current interactions in the GIM model can be given as follows:

$$J_\mu^{NC}=\tfrac{1}{2}[\bar{\mathcal{P}}\gamma_\mu(1+\gamma_5)\mathcal{P}-\bar{\mathcal{N}}\gamma_\mu(1+\gamma_5)\mathcal{N}+\bar{c}\gamma_\mu(1+\gamma_5)c-\bar{\lambda}\gamma_\mu(1+\gamma_5)\lambda]-2\sin^2\theta_W\, j_\mu^{em}\ . \tag{3}$$

Alternatively, we could present it as

$$J_\mu^{NC}=V_\mu{}^3-A_\mu{}^3-2\sin^2\theta_W\, J_\mu^{em}\ . \tag{4}$$

Here $\mathcal{P},\mathcal{N},\lambda,c$ are the four basic quarks and θ_W is the Weinberg angle. It is also well known that by studying the final states in neutrino interactions in the diffractive region we can explore the space-time structure of neutral currents and their quantum numbers. Thus we can use a standard tool like Regge-pole phenomenology in this region and make further applications of the GVMD hypothesis and the SU(4) scheme. Thus the coupling of the weak neutral currents to the vector mesons (Fig. 1) studied in the final state tests the GVMD hypothesis. We would like to mention here that reaction (1) alone has been discussed by Gaillard *et al.*[9] and Einhorn and Lee.[11] However, we use Regge-pole phenomenology to describe the hadronic interactions and make further application of broken SU(4) for the couplings of the Pomeron to vector mesons.[12] Thus in our calculation all the parameters are well determined by the conventional hadronic interactions.

The plan of the paper goes as follows. In Sec. II we define the kinematical variables and the method of our calculation for the diffractive exclusive vector-meson production. In Sec. III we propose to give the formulation for the inclusive vector-meson production cross sections. In Sec. IV we present our concluding remarks and criticism of our model.

II. EXCLUSIVE PRODUCTION OF VECTOR MESONS

The kinematical variables are defined as follows:

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

P = momentum of initial nucleon ($P^2 = M^2$ defines the metric) ,

$q = (p - p')$,

$\nu = q \cdot P$,

$Q^2 = -q^2$,

θ = scattering angle of lepton in laboratory,

k = momentum of vector meson ,

$s = (P+q)^2 = M^2 + q^2 + 2\nu$,

$t = (q-k)^2$.

The cross section for reaction (1) can be written as

$$\frac{d\sigma}{d\Omega' dE' dt} = \frac{d\sigma}{d\Omega' dE'} \frac{1}{\sigma} \frac{d\sigma}{dt} (V + p \to V + p) , \qquad (5)$$

where E' is the energy of the scattered neutrino and σ is the current nucleon total cross-section. In what follows we assume that the vector mesons are produced diffractively due to the coupling of the vector current to the vector mesons. Since the Pomeron contributes dominantly to the diffractive cross sections, the effect of the low-lying trajectories can be ignored. With these assumptions, we can safely neglect the effect of the axial-vector current.[9]

Therefore, the differential cross sections for process (1), as shown in Fig. 1(a), can be written as

$$\frac{d\sigma}{d\Omega' dE' dt} = \frac{G_F{}^2 E'^2}{(2\pi)^3} \frac{1}{1 + \nu^2/Q^2 M^2} \frac{d\sigma}{dt} (J_\mu^{\rm NC} p \to Vp) , \qquad (6)$$

with

$$\frac{d\sigma}{dt} (J_\mu^{\rm NC} p \to Vp) = \frac{x_V A_V}{g_V{}^2} \frac{d\sigma}{dt} (Vp \to Vp) , \qquad (7)$$

where G_F is the universal Fermi coupling constant and a form factor $A_V = m_V{}^2/(Q^2 + m_V{}^2)$ is introduced to account for the off-mass-shell effects of the currents, and

$$x_V = \tfrac{1}{2}(1 - 2\sin^2\theta_W)^2 \quad \text{for } \rho^0 ,$$
$$= (2\sin^2\theta_W)^2 \quad \text{for } \omega^0, \phi^0, \psi^0 . \qquad (8)$$

For $\rho^0 p$ elastic diffractive production, we parametrize the forward peak as follows:

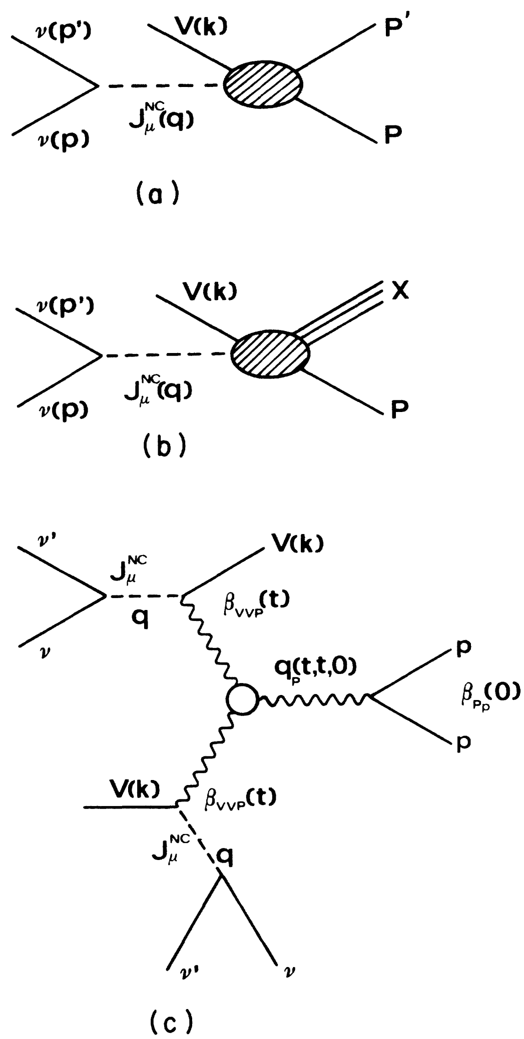

FIG. 1. (a) Exclusive vector-meson production in neutrino-proton scattering, (b) inclusive vector-meson production in neutrino-proton scattering, and (c) Mueller-Regge triple-Pomeron graph for inclusive process (2).

$$\frac{d\sigma}{dt} (\rho^0 p \to \rho^0 p) = \frac{\sigma_T{}^2}{16\pi} e^{bt} . \qquad (9)$$

In Eq. (9) the slope parameter[10] is taken from the experimental value as $b = 6$, $\sigma_T = 26$ mb, and the coupling constant $g_\rho{}^2/4\pi = 2.3$. In order to obtain the differential cross sections for $\omega p \to \omega p$, $\phi p \to \phi p$, and $\psi p \to \psi p$ in (7), we adopt the procedure invoked by Inami and Barger[12] to account for the SU(4)-breaking effects in Pomeron couplings. Thus the cross sections for ω, ϕ, and ψ production can be related to $(d\sigma/dt)(\rho p \to \rho p)$ as follows:

$$\frac{d\sigma}{dt} (\omega p \to \omega p) = \frac{d\sigma}{dt} (\rho p \to \rho p) , \qquad (10)$$

$$\frac{d\sigma}{dt}(\phi p \to \phi p) = \gamma_1{}^2(t)\frac{d\sigma}{dt}(\rho p \to \rho p)\,, \tag{11}$$

$$\frac{d\sigma}{dt}(\psi p \to \psi p) = \gamma_2{}^2(t)\frac{d\sigma}{dt}(\rho p \to \rho p)\,, \tag{12}$$

where

$$\gamma_1(t) = \frac{1-\alpha_f(t)}{1-\alpha_{f'}(t)}\,,$$

$$\gamma_2(t) = \frac{1-\alpha_f(t)}{1-\alpha_{f_c}(t)}\,,$$

with

$$\alpha_f(t) = 0.5 + 0.9t\,,$$

$$\alpha_{f'}(t) = 0.3 + 0.8t\,,$$

$$\alpha_{f_c}(t) = -3.5 + 0.5t\,.$$

Thus the cross sections for the production of ω, ϕ, and ψ can easily be obtained using Eq. (9) with Eqs. (10), (11), and (12), respectively.

III. INCLUSIVE PRODUCTION OF VECTOR MESONS

In this section we consider the formulation for process (2). The missing mass is defined as

$$M_X{}^2 = (P + q - k)^2\,. \tag{13}$$

The inclusive cross section is

$$E_V\frac{d\sigma}{d\Omega' dE' d^3k_V} = \frac{G_F{}^2E'^2}{(2\pi)^4(1+\nu^2/Q^2M^2)}\,s\,\frac{d\sigma}{dtdM_X{}^2}\,, \tag{14}$$

where $d\sigma/dtdM_X{}^2$ is the inclusive cross section for the process $J_\mu^{NC} + p \to V + X$ and the rest of the quantities have their usual meaning, as defined in Sec. II.

The kinematical region of our interest is $s \to$ large, $t \to$ fixed and small, $M_X{}^2 \to$ large, and $s/M_X{}^2 \to$ large. This corresponds to the triple-Regge region. Consequently, the cross section can be written[10] as

$$\frac{d\sigma}{dtdM_X{}^2} = \frac{x_V{}^2}{8\pi s^2}\frac{A_V{}^2}{g_V{}^2}\,|\beta_{VVP}(t)|^2 g_P(t,t,0)\beta_{pP}(0) \times (s/M_X{}^2)^{2\alpha_P(t)}(M_X{}^2)^{\alpha_P(0)}\,, \tag{15}$$

where $A_V{}^2/g_V{}^2$ appears as a consequence of the GVMD hypothesis, $\beta_{VVP}(t)$ is the V-V-P residue with P as the Pomeron, $g_P(t,t,0)$ is the triple-Pomeron coupling, and $\beta_{pP}(0)$ is the proton-proton-Pomeron residue. The various residue functions are normalized as follows:

$$\frac{d\sigma}{dt}(Vp \to Vp) = \frac{1}{8\pi}\,|\beta_{VVP}(t)|^2|\beta_{pP}(t)|^2 s^{2\alpha_P(t)-2} \tag{16}$$

and

$$\frac{d\sigma}{dt}(pp \to pp) = \frac{1}{8\pi}\,|\beta_{pP}(t)|^4 s^{2\alpha_P(t)-2}\,. \tag{17}$$

Thus Eq. (15) can be rewritten as

$$\frac{d\sigma}{dtdM_X{}^2} = \frac{A_V{}^2x_V{}^2}{g_V{}^2 s}\,G(t)\left(\frac{s}{M_X{}^2}\right)^{2\alpha_P(t)-1} \times\frac{(d\sigma/dt)(Vp\to Vp)}{(d\sigma/dt)(pp\to pp)}\,, \tag{18}$$

where

$$G(t) = \frac{1}{16\pi}\,|\beta_{pP}(t)|^2 g_P(t,t,0)\beta_{pP}(0)\,. \tag{19}$$

Here we parametrize $G(t)$ and $(d\sigma/dt)(pp\to pp)$ as follows:

$$G(t) = G_0 e^{Bt}\,, \tag{20}$$

$$\frac{d\sigma}{dt}(pp \to pp) = 40e^{10t}\,, \tag{21}$$

where we take $G_0 = 4$ mb GeV^{-2} and $B = 4.5$ GeV^{-2}. The slope of pp differential cross section is chosen to be 10 GeV^{-2} in the range 80 GeV$^2 \leq s \leq 120$ GeV^2, which fits the experimental data in this energy range. $(d\sigma/dt)(Vp\to Vp)$ is obtained from Eqs. (9)–

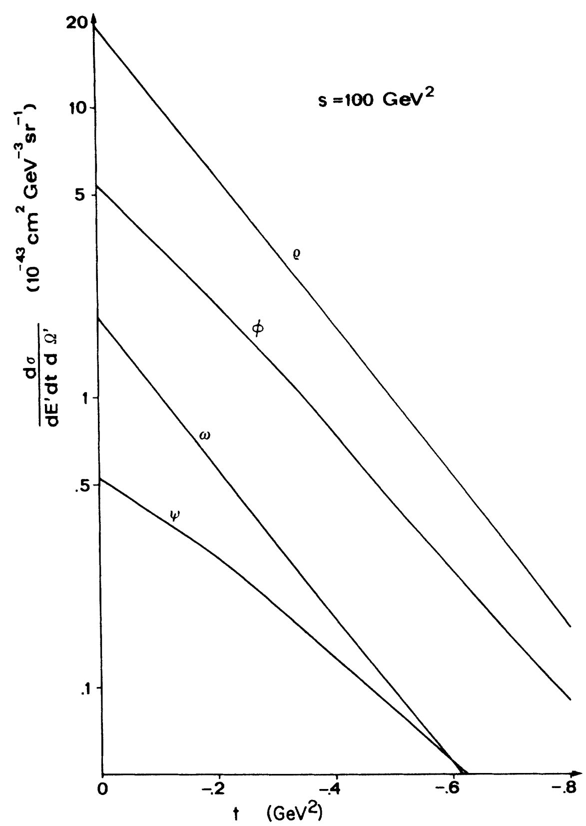

FIG. 2. The cross-section distributions for the process (1) are shown at $s = 100$ GeV^2.

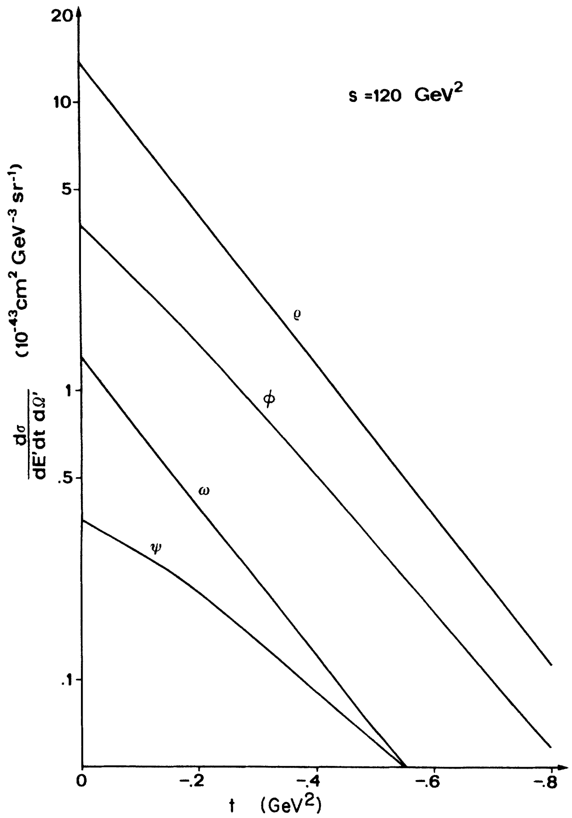

FIG. 3. The cross-section distributions as calculated for the process (1) are shown at $s = 120$ GeV^2.

(12) for the specific reactions. We thus find that when Eqs. (20) and (21) are substituted in (18), all parameters are fixed from available data on hadronic interactions. Thus the inclusive cross sections for production of vector mesons as given by Eq. (14) are purely governed by the hadronic processes.

IV. DISCUSSION

We have plotted the results of our calculations in Figs. 2–4. In doing so, we utilize the most recent value of the Weinberg angle ($\sin^2\theta_W = 0.3$) as determined by Reines *et al.*[1] In addition, we use the following values of the coupling constants[12]: $g_\rho^2/4\pi = 2.3$, $g_\omega^2/4\pi \simeq 18.4$, $g_\phi^2/4\pi = 14.4$, $g_\psi^2/4\pi \simeq 9.2$. Our theoretical curves depict the qualitative as well as the quantitative features which follow from our model. It would, therefore, be quite interesting to check the experimental validity of this simple model in describing the neutral-current phenomenology.

It is well known that the GVMD hypothesis together with the Regge-pole model provides a useful tool in describing the diffractive production of vector mesons. Thus we hope that a similar technique would continue to be useful for diffractive production of vector mesons by neutral currents. In our calculations we have also ignored the effects of low-lying trajectories. We hope that the diffractive production of vector mesons can be well described by the Pomeron exchange alone at high energies. Moreover, we have taken into account the SU(4)-breaking effects in evaluating the cross sections.

The theoretical distributions for the exclusive cross sections have been shown in Fig. 2 at $s = 100$ GeV^2 and in Fig. 3 at $s = 120$ GeV^2. The shape of the curves appears very diffractive for all the vector mesons. In contrast, we find that the inclusive cross sections which have been shown in Fig. 4 are very flat.[13] The distributions for ϕ and ψ inclusive productions give very interesting shapes, and they appear directly due to SU(4)-breaking effects incorporated in their residue functions. Thus we feel that the experimental checking for these distributions would directly reveal the validity of SU(4) breaking. For inclusive processes we have exploited the factorization hypothesis in the Mueller-Regge technique to obtain the

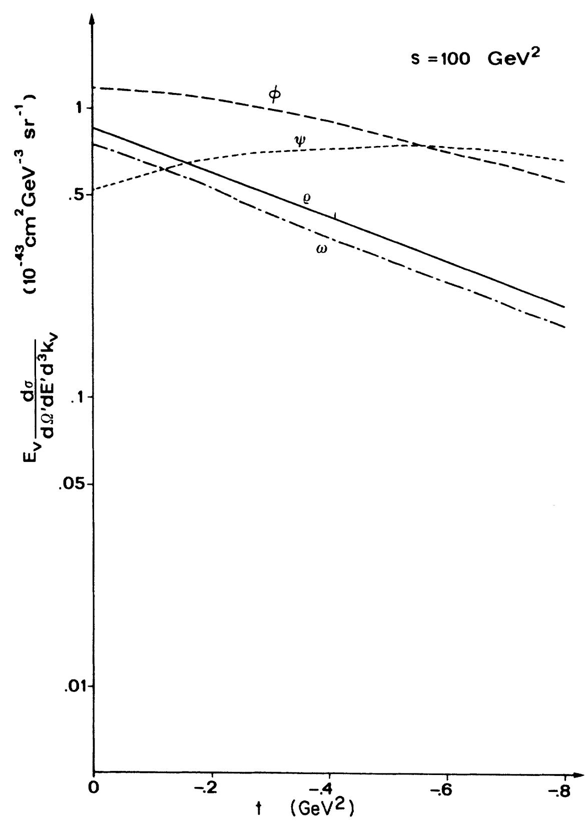

FIG. 4. The cross-section distributions for the process (2) are shown at $s = 100$ GeV^2.

residue functions. We hope that our calculations would provide a qualitative description of various processes. It may be added that if Regge cuts are found to play an important role in inclusive reactions, factorization may not be valid in that case and the distributions would change significantly.

It should be mentioned here that we have completely ignored the effect of axial-vector currents. We presume that the interference effect of axial-vector currents is not significant for the diffractive exclusive as well as inclusive productions of vector mesons in our model. However, the axial-vector currents will play a dominant role for the production of axial-vector mesons as has also been pointed out by Gaillard *et al.*[9]

High-energy neutrino beams are now available at Fermilab and CERN. Therefore, it will be possible experimentally to observe reactions (1) and (2) in near future. These experiments are feasible,[14] and they have been proposed[9] as a means of determining simply and unambiguously the isospin and space-time structure of the neutral current which is not so easily given by other proposed[15] experiments; for example, we can take the pion-production reaction in neutrino scattering. Here in reactions (1) and (2), production of ρ^0 gives the isovector vector current and ϕ^0, ω^0, and ψ^0 involve isoscalar vector currents. One of the most interesting features of the experiments which we propose would be the measurement of the relative magnitude of cross sections for productions of the above vector mesons in inclusive as well as exclusive neutrino reactions. However, an important ingredient of our calculation is the specific form of the weak neutral current given by the Weinberg-Salam model.[4,5] Thus the present investigation quantitatively explores another phenomenological aspect of unified theory of weak and electromagnetic interactions.

In conclusion, we find that the diffractive production of the vector mesons in the exclusive as well as inclusive processes induced by high-energy neutrino beams can be used to examine the phenomenology as well as the space-time structures of the neutral currents.

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