DIFFRACTIVE ELASTIC NEUTRINO-PRODUCTION
OF VECTOR MESONS

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A B S T R A C T

The diffractive elastic neutrino production of vector mesons has been studied in detail. The results of this analysis encourage experimental effort which may provide useful information concerning the nature of neutral currents and of the recently discovered new particles.

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1. - INTRODUCTION

With the advent of machines such as the SPS at CERN II and the Fermilab accelerator, highly energetic (~ 100 GeV) beams of neutrinos and antineutrinos are becoming available. These beams may be used to study the production mechanisms involved in several types of reactions, among them diffractive production of vector mesons from heavy nuclei. This report will be concerned with the diffractive production of vector mesons in neutrino interactions. This is especially interesting in the light of the recent discovery ^{1),2)} of two new, heavy, narrow width vector particles at Brookhaven, SLAC, DESY and Frascati.

Indeed, by studying final states in neutrino interactions in the diffractive region (this will be defined presently), we are studying the space-time structure of neutral and charged currents and their quantum numbers ³⁾. Within the context of certain model assumptions we can examine what new vector mesons might be produced, i.e., axial and/or charged analogues of the new vector mesons. In this report we make use of the following models or concepts : the Salam-Weinberg unified gauge model ⁴⁾ of weak and electromagnetic interactions, with charm ⁵⁾ included (this gives us our space-time structure of the neutral and charged currents) and vector meson dominance, generalized to weakly coupled currents. We assume that the diffractive behaviour of vector meson nucleus cross-sections is as suggested in electro- and photoproduction experiments ⁶⁾.

Let us now review each of these ideas in turn.

Let us consider the diffractive processes of Fig. 1 in neutrino reactions involving charged and neutral currents.

In the diffractive region, q^2 (the leptonic momentum transfer) is $\sim$ a few GeV^2 and t (the hadronic momentum transfer) is small (see Fig. 1). Then we expect vacuum (or Pomeron) exchange to be the dominant exchange in the t channel. It is then easy to see that studying the quantum numbers of the final state vector mesons tells us about the space-time properties and quantum numbers of the weak currents. The amplitudes for processes of types a and b each involve a matrix element of the weak current (see Fig. 1) between the vacuum and the observed vector meson state, $\langle 0 | J | V \rangle$. This implies that the current J has a component with quantum numbers identical to those of the vector meson, V . Therefore, we learn about the isotopic

spin nature of the current and its V, A content, i.e., the ratio g_A/g_V . In a general theory S, P and T couplings are allowed for the neutral current ; however, preliminary data on x and y distributions suggest that its couplings are V and A ⁷⁾.

Now, we believe we understand the structure of charged currents, namely V-A (pure ρ^+ production would imply a pure V charged current, pure A_1^+ production a pure A charged current, etc.). For neutral currents, pure ρ^0 , A_1^0 and ω, ϕ production would imply pure V, I=1, pure A I=1 and pure V, I=0 neutral currents, respectively. In a model such as the Salam-Weinberg model, there is a mixing of vector and axial vector couplings in the weak current such that the relative production of vector and axial vector mesons is a measure of the Weinberg angle θ_W , e.g., the ratio of the cross-section for $\nu Z \rightarrow \nu Z \rho^0$ relative to that of $\nu Z \rightarrow \mu^- Z \rho^+$ is proportional to $(1-2 \sin^2 \theta_W)/\sqrt{2}$.

There are three other aspects of diffractive meson production which may be studied.

- i) Diffraction mechanisms : is there an exponential fall off in momentum transfer, i.e., does there exist a diffractive peak, e^{At} , representing coherent scattering off the nucleus ? We assume these features for the diffractive differential cross-section to be checked a posteriori by comparison with the data.
- ii) Pomeron properties : couplings to vector mesons, especially the new particles, t dependence.
- iii) Vector meson dominance (VMD) and charm : the coupling of the weak currents to the vector mesons (Fig. 1) studied in the final state tests the VMD hypothesis and the SU(4) scheme emerging from introducing a "charmed" quark into the Salam-Weinberg model to eliminate strangeness changing neutral currents, à la Glashow-Iliopoulos-Maiani ⁵⁾. In this model the hadronic part of the neutral current has the well-known form :

$$\begin{aligned}
 j_\mu^2 &= \frac{1}{2} \left[\bar{p} \gamma_\mu (1-\gamma_5) p - \bar{n} \gamma_\mu (1-\gamma_5) n + \bar{c} \gamma_\mu (1-\gamma_5) c - \bar{\lambda} \gamma_\mu (1-\gamma_5) \lambda \right] \\
 &\quad - 2 \sin^2 \theta_W j_\mu^{e.m.} \\
 &= V_\mu^3 - A_\mu^3 - 2 \sin^2 \theta_W j_\mu^{e.m.} .
 \end{aligned}
 \tag{1}$$

Let us briefly review vector meson dominance and diffractive production.

1.1. - Vector meson dominance

Vector meson dominance allows us to relate the cross-section for $V+N \rightarrow V+N$ to that for $\gamma+N \rightarrow V+N$, i.e., it relates the cross-section for the scattering of a vector meson off a nucleon (or nucleus) to the photo-production of the vector meson. Consider the diagram of Fig. 2 for $\gamma+N \rightarrow V+N$. Using vector meson dominance we get for $t=0$,

$$\begin{aligned} \left. \frac{d\sigma(\gamma N)}{dt} \right|_{t=0} &= A \frac{e^2}{g_v^2} \left. \frac{d\sigma(VN)}{dt} \right|_{t=0} \\ &= A \frac{e^2}{g_v^2} \frac{1}{16\pi} \sigma_T^2(VN) \end{aligned} \quad (2)$$

where the last step follows from the optical theorem, and assuming, as usual, a purely imaginary diffractive amplitude. The factor A involves the vector meson propagator and depends on the mass q^2 of the photon. For real photons, $A=1$. More generally ^{*)}

$$A = \frac{m_v^2}{m_v^2 + q^2} \quad (3)$$

For electroproduction (Fig. 3), $q^2 > 0$ and $A < 1$.

In complete analogy ⁸⁾ to the virtual photon in electroproduction, one can produce a virtual vector boson as in Fig. 4, where ℓ can be a neutrino or some other lepton. Then we generalize the vector meson dominance concept from vector mesons coupled to photons to neutrino interactions by the replacements :

$$\begin{aligned} (e^- \rightarrow e^-) &\rightarrow (\nu \rightarrow \ell) \\ \gamma &\rightarrow W^\pm, Z^\pm \\ \rho^0, \omega, \varphi &\rightarrow \rho^\pm, \Lambda_1^\pm, \rho^0, \Lambda_1, \omega, \varphi, \dots \end{aligned}$$

^{*)} Here we have neglected the longitudinal part of the vector meson propagator. Under contraction with the leptonic coupling, its contribution vanishes identically for vector (electromagnetic) couplings and gives a term proportional to the lepton mass for V-A (weak couplings).

The standard vector meson dominance procedure follows, but where now the weak current vector meson couplings take account of the structure of weak current. Let us discuss this briefly. Consider a particle V with a certain quark content :

$$V = \frac{1}{N} [a_1 \bar{q}_1 q_1 + a_2 \bar{q}_2 q_2 + \dots] , \quad (4)$$

where $N = [a_1^2 + a_2^2 + \dots + a_n^2]^{\frac{1}{2}}$. Then the coupling f_V of the particle V to a photon is given by

$$f_V = \frac{1}{N} [a_1 Q_1 + a_2 Q_2 + \dots] . \quad (5)$$

where the Q_i are quark charges (for coupling to the electromagnetic current ; for coupling to other currents, the Q_i are the coupling constants of the quarks to the current in question). For example, consider

$$\rho^0 = \frac{\bar{p}p - \bar{n}n}{\sqrt{2}} ;$$

then

$$f_{\rho^0} = \frac{1}{\sqrt{2}} \left[\frac{2}{3} - (-\frac{1}{3}) \right] = \frac{1}{\sqrt{2}} . \quad (6)$$

This is known as quark model universality and can be applied to relate the couplings for the ground state mesons (as usual $Q_p = Q_c = \frac{2}{3}$, $Q_n = Q_s = -\frac{1}{3}$ and $\varphi_c \equiv c\bar{c}$). The ratio of $f_{\varphi_c}^2$ to $f_{\varphi_c'}^2$ is experimentally determined if we identify φ_c and φ_c' with the new resonances observed at 3.1 GeV and 3.7 GeV, respectively, and consider the observed ratio of their widths for the decay $V \rightarrow e^+e^-$.

Then we obtain :

$$\begin{aligned} f_{\rho^0}^2 : f_{\omega}^2 : f_{\phi}^2 : f_{\phi_c}^2 : f_{\phi_c'}^2 = \\ \frac{1}{2} : \frac{1}{18} : \frac{1}{9} : \frac{4}{9} : \frac{2}{9} = 9 : 1 : 2 : 8 : 4 : 2 \end{aligned} \quad (7)$$

In practice, the ratios (7) will be modified by symmetry breaking effects ; there is a long-standing controversy as to whether to apply these ratios to the f 's or to the dimensionless constants, $1/g^2$. The relative strength of the leptonic coupling to the ρ and the ϕ is not very sensitive to the choice, but if we identify the observed resonance at 3.1 GeV with the ϕ_c , the difference is very important. We may use these new data to settle the controversy, if really $J = c\bar{c}$. Empirically, one finds ⁹⁾ that to a very good degree of accuracy the leptonic widths

$$\Gamma(V \rightarrow e^+e^-) = \frac{4\pi}{3} \alpha^2 \frac{m_V}{q_V^2} \quad (8)$$

are in the ratios

$$\Gamma(\rho) : \Gamma(\omega) : \Gamma(\phi) : \Gamma(\phi_c) \approx 9 : 1 : 2 : 8. \quad (9)$$

We extend this empirical rule to estimate the corresponding f 's for particles where the couplings are not directly measured. This means that the quantities m_V/g_V^2 satisfy (7).

We apply similar considerations to vector meson production in neutrino interactions using the Weinberg-Salam model. This allows us to compute the f_V 's for all vector mesons, e.g. :

$$f_\mu^2 = V_\mu^3 - A_\mu^3 - 2 \sin^2 \Theta_w j_\mu^{e.m.}$$

[see Eq. (1)], and

$$f_{\rho^0} = \frac{1 - 2 \sin^2 \Theta_w}{\sqrt{2}} \quad (10)$$

since the ρ meson couples only to the vector, V_3 , part of the current.

1.2. - Diffraction mechanisms

Experiment suggests ⁶⁾ that ρ^0 and φ photoproduction look very much like diffractive scattering, the main feature for our purposes being the exponential fall-off of the momentum transfer distribution. If we accept this as our hypothesis, we can parametrize our differential vector meson cross-sections with exponential forms in t .

According to the vector meson dominance ansatz, the virtual vector meson which is scattered by the nucleon has the same polarization as the photon. For real photons ($Q^2 = 0$) there is no longitudinal polarization, so that what one has is σ_T , the transverse cross-section. For virtual photons (or for our virtual vector mesons), there is a longitudinal σ_L , and a transverse part σ_T of the cross-section. This is embodied in a factor ϵ discussed in Section 2.2. However, for a neutral vector meson which has charged partners, we take the ratio of the cross-section for the neutral to the charged vector meson, the dependence on σ_L drops out.

2. - KINEMATICS

2.1. - Preliminaries

We are concerned with the process :

$$\{\nu, \bar{\nu}\} + Z \rightarrow \left\{ \begin{matrix} \mu^- \\ \nu \end{matrix}, \begin{matrix} \mu^+ \\ \bar{\nu} \end{matrix} \right\} + V + Z, \quad (11)$$

where Z represents the nucleus from which the neutrinos are being scattered and V the vector meson produced. The basic dynamics of this process are given in Fig. 5, where $\ell = \{\nu, \bar{\nu}, \mu^\mp\}$. The diffractive production of V is illustrated in Fig. 6, with :

$$\begin{aligned} q^2 &= -Q^2 < 0, \\ q'^2 &= m_V^2, \\ p_1^2 &= p_2^2 = M^2, \\ k^2 &= t < 0. \end{aligned} \quad (12)$$

The diffractive region is identified by restricting the hadronic momentum transfer to be less than the inverse pion Compton wavelength of the nucleus,

$$\sqrt{-t} < 1/r \quad (13)$$

where $r = r_0 A^{\frac{1}{3}} \approx A^{\frac{1}{3}}/m_\pi$. Kinematics tell us :

$$\begin{aligned} \text{i)} \quad q_0 &\geq \frac{m_\nu^2 + Q^2}{2\sqrt{-t}} \\ \text{ii)} \quad E_\nu &\geq m_\nu^2/2\sqrt{-t} \\ \text{iii)} \quad Q^2/E_\nu^2 &\leq -t/m_\nu^2 \\ \text{iv)} \quad \sin^2 \Theta_{q'} &\rightarrow 0 \end{aligned} \quad (14)$$

($\Theta_{q'}$ = angle between $\vec{q}$ and $\vec{q}'$).

We define x, y, v by the following

$$\begin{aligned} Q^2 = -q^2 &= 2E_\nu E_L (1 - \cos \Theta_L) = \nu x, \\ \nu &= 2(E_\nu - E_L) = 2E_\nu M y. \end{aligned} \quad (15)$$

Leptonic phase space is then given by

$$\begin{aligned} E_L dE_L d\cos\Theta_0 &= dQ^2 d\nu / 4E_\nu M = \\ &= \frac{1}{2} dQ^2 dy = E_\nu M y dy dx \end{aligned} \quad (16)$$

2.2. - The cross-section

Taking account of the leptonic tensor and the longitudinal and transverse polarization of the virtual vector meson, we have for the differential cross-section, per nucleon, for the process pictured in Fig. 5 :

$$\begin{aligned} \frac{d\sigma}{dt} &= \frac{|\vec{q}|}{E_\nu} \frac{G_F^2}{2} \left[\frac{m_\nu^2}{q_\nu} \frac{1}{m_\nu^2 + Q^2} \right]^2 \times \int \text{phase space} \\ &\times 8Q^2 \left[\frac{d\sigma^T}{dt} + \frac{1}{|\vec{q}|^2} (2q_0 q'_0 - \frac{Q^2}{2}) \left(\frac{d\sigma^T}{dt} + \frac{d\sigma^L}{dt} \right) \right] = \end{aligned} \quad (17)$$

$$= \int \text{phase space} \times \frac{|\vec{q}'|}{E_\nu} \frac{G_F^2}{2} \left[\frac{m_V^2}{q_V} \frac{1}{m_V^2 + Q^2} \right]^2 \\ \times 8 Q^2 (1 + \alpha) \left[\frac{d\sigma^T}{dt} + \varepsilon \frac{d\sigma^L}{dt} \right],$$

where $d\sigma^T/dt$ and $d\sigma^L/dt$ are the transverse and longitudinal differential cross-sections, respectively, and

$$\alpha = \frac{2q_0 q_0' - Q^2}{|\vec{q}'|^2}, \quad \varepsilon = \frac{\alpha}{\alpha + 1}. \quad (18)$$

Now, vector meson dominance and the optical theorem tell us that

$$\frac{d\sigma}{dt}(WN \rightarrow VN) = \frac{1}{q_V^2} \frac{d\sigma}{dt}(VN) = \frac{1}{q_V^2} \frac{1}{16\pi} \sigma_{\text{tot}}^2(VN) e^{bt}. \quad (19)$$

We define

$$C_V = \frac{G_F^2}{(2\pi)^3} \frac{1}{16} \frac{\sigma_{\text{tot}}^T(VN)}{q_V^2}$$

and

$$\frac{C_V}{C_P} = \left[\frac{\sigma_{\text{tot}}^T(VN)}{\sigma_{\text{tot}}^T(PN)} \right]^2 \frac{q_P^2}{q_V^2}. \quad (20)$$

Following the empirical rule of Eq. (9), we define the quark counting factor

$$A_V \text{ by: } q_P^2/q_V^2 = A_V \cdot m_P/m_V, \quad (21)$$

so

$$\frac{C_V}{C_P} = \left[\frac{\sigma_{\text{tot}}^T(VN)}{\sigma_{\text{tot}}^T(PN)} \right]^2 \frac{m_P}{m_V} \cdot A_V^2, \quad (22)$$

Finally, we obtain :

$$\frac{d\sigma}{dt} = \left(1 + \frac{\theta^2}{m_V^2}\right)^{-2} Q^2 dQ^2 y dy \left(1 + \varepsilon \frac{\sigma_{tot}^L}{\sigma_{tot}^T}\right) e^{bt} \times \frac{C_V}{C_\rho} C_\rho (1+\alpha). \quad (23)$$

where

$$C_\rho = \frac{1}{g_r^2} (1.25 \times 10^{-10}) \frac{mb}{GeV^2}. \quad (24)$$

Equation (23) is the basic equation from which all our results below emerge. For the ratio C_V/C_ρ we use measured values of σ_{tot}^T for ρ , K , π , then we use the additive quark model to calculate the rest. For the φ_c (assuming that φ_c is the 3.1 GeV resonance) the data ¹⁰⁾ on γ nucleus $\rightarrow \varphi_c N$, plus vector dominance, yields $\sigma(\varphi_c N) \sim 1$ mb. This implicitly assumes that one can extrapolate from $Q^2 = (3.1)^2 \text{ GeV}^2$ to $Q^2 = 0$. This is "justified" by appealing to the case of ρ photoproduction where the resulting $\sigma(\rho N) \sim 20$ mb is in accord with direct measurement. However, in the latter case the extrapolation is only from $Q^2 \sim 0.5 \text{ GeV}^2$ whereas for φ_c it is $Q^2 \sim 9.6 \text{ GeV}^2$. It is by no means clear ^{*)} that such extrapolations are warranted. Indeed as noted in Ref. 11), neglecting this extrapolation can lead to possible inconsistencies with data on $J' \rightarrow \eta \gamma$ decay among others. This suggests that Q^2 extrapolations may be important and if so suggests in turn that $\sigma(\varphi_c N) > 1$ mb, as noted also in Ref. 12). If so, then our subsequent estimates based on $\sigma(\varphi_c N) = 1$ mb will be under-estimates. Our results for C_V/C_ρ and A_V for the vector mesons are presented in the Table. In computing these values we use $\sin^2 \theta_w \simeq 0.36$ and $\sigma_\rho \simeq 26$ mb, $\sigma_\omega \simeq 26$ mb, $\sigma_\varphi \simeq 10$ mb, $\sigma_{\varphi_c} \simeq 1$ mb, $\sigma_{K^*} \simeq 20$ mb, $\sigma_{F^*} \simeq 5$ mb, $\sigma_D \simeq 13$ mb, etc.

*) We are indebted to Frank Close for calling our attention to this fact.

V	$F^{*\pm}$	$K^{*\pm}$	$D^{*\pm}$	$F_A^\pm$	$A_1^\pm$	$K_A^\pm$	$D_A^\pm$
A_V	1	1	1	1	1	1	1
c_V/c_ρ	0.017	0.02	4.2×10^{-3}	0.016	0.71	0.012	3.9×10^{-3}
V	ρ_0	ω	φ	φ_c	A_1^0	φ_A	φ_{c_A}
A_V	$\frac{1}{\sqrt{2}}(1-2\sin^2\theta_w)$	$-\frac{\sqrt{2}}{3}\sin^2\theta_w$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_w$	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_w$	$\frac{1}{\sqrt{2}}$	$-\frac{1}{2}$	$\frac{1}{2}$
c_V/c_ρ	0.04	0.03	8×10^{-3}	2×10^{-8}	0.35	0.03	10^{-4}

- TABLE -

All other A_V 's are zero in the Weinberg-Salam model.

We are only explicitly taking account of elastic nucleon-vector meson and nucleus-vector meson scattering. Our coherent cross-sections are obtained from the incoherent by the replacement $b \rightarrow A^{2/3}b$ in our exponential dependence on t . The case of inelastic diffractive scattering has been analyzed extensively in the literature ¹³⁾, which should be consulted parallel to our work.

We now discuss the total diffractive cross-section and the x, y and Q^2 distributions. Our starting point will always be Eq. (23) for $d\sigma/dt$.

2.2.1. - Total diffractive cross-section

We use Eq. (23) for the diffractive differential cross-section :

$$\frac{d\sigma}{dt} = \int \left(1 + \frac{Q^2}{m_V^2}\right)^{-2} Q^2 dQ^2 y dy \left(1 + \varepsilon \frac{\sigma_{tot}^L{}^2}{\sigma_{tot}^T{}^2}\right) ebt$$

$$\times (1+\alpha) \frac{c_V}{c_\rho} \cdot c_\rho \cdot$$

(25)

When we perform the phase space integrations, we obtain for the diffractive differential cross-sections, separated into transverse and longitudinal pieces :

$$\frac{d\sigma^T}{dt} = \left(\frac{m_V}{\text{GeV}}\right)^4 \frac{C_V}{C_P} e^{bt} F^T(y_0) \frac{3.1 \times 10^{-11}}{q_p^2} \frac{\text{mb}}{\text{GeV}^2}, \quad (26a)$$

and

$$\frac{d\sigma^L}{dt} = \left(\frac{m_V}{\text{GeV}}\right)^4 \frac{C_V}{C_P} e^{bt} F^L(y_0) \frac{3.1 \times 10^{-11}}{q_p^2} \frac{\text{mb}}{\text{GeV}^2}, \quad (26b)$$

where

$$F^T(y_0) = F(y_0) - \Delta F(y_0) \left(\frac{2m_V^2}{E}\right) + F'(y_0), \quad (27a)$$

and

$$F^L(y_0) = F'(y_0). \quad (27b)$$

y_0 is the lower limit of the y integration $= m_V^2/2E_V\sqrt{-t}$ from Eq. (14).
We have

$$\begin{aligned} F(y_0) &= 1 - 4y_0 + 3y_0^2 - 2\ln y_0, \\ \Delta F(y_0) &= \ln y_0 + 1/y_0, \\ F'(y_0) &= 4\ln^2 y_0 + 8y_0 \ln y_0 + 16\ln y_0 + 24(1-y_0). \end{aligned} \quad (28)$$

The first two terms, $F, \Delta F$ come from the piece of expression (25) which does not involve the factor α , the term F' has the α factor. The correction term ΔF is a consequence of the difference in $Q_{\max}^2$ for the phase space integral obtained from the hadronic vertex in Fig. 5 and the leptonic vertex. From the hadronic vertex we have $Q_{\max}^2 = (-t E_V^2)/(m_V^2)$ [Eq. (14)]. The maximum on Q^2 from the leptonic vertex comes from the condition $\sin^2 \theta > 0$, where θ is the scattering angle between the leptons in Fig. 5. This contribution is important for $y \sim 1$ (since the hadronic vertex constraint assumes $y < 1$) and yields $Q_{\max}^2 = 4E^2(1-y)$. This is a correction to the phase space integral, ΔF . Since $d\sigma^L/dt$ only involves α , it is completely given by F' (this has no leptonic vertex correction since the α term is important only for $y \ll 1$).

Now the total diffractive transverse and longitudinal cross-sections both involve an integral of the form

$$\int_{t_1}^{t_2} F(y_0) e^{bt} dt \quad (29)$$

where $t_1 = -\omega$ and $t_2 = -(m_V^2/2E_V)^2$ [see Eq. (14)]. Defining variables $\omega = -bt$ and $y_0 = m_V^2/(2E_V\sqrt{-t}) = 1/(2\sqrt{\omega}z)$ so that $E_V = m_V^2/\sqrt{bz}$, the integral in (29) becomes

$$I = \frac{1}{b} \int_{1/4z^2}^{\infty} d\omega F\left(\frac{1}{2\sqrt{\omega}z}\right) e^{-\omega} = \frac{B(z)}{b} \quad (30)$$

Now, since $\sigma_{\text{tot}} = 0.7 \times 10^{-38} \times E_V \text{ cm}^2$ for charged currents and $\sigma_{\text{tot}} \approx 0.18 \times 10^{-38} \times E_V \text{ cm}^2$ for neutral currents, we find that

$$\frac{\sigma_{\text{Diff}}}{\sigma_{\text{tot}}} = A \frac{C_V}{C_C} (0.3) \frac{m_V^2}{b^{3/2}} \frac{B(z)}{z} \quad (31)$$

where $B \rightarrow B - \Delta B(2m_V^2/E) + B'$ for σ^T and $B = B'$ for σ^L . This illustrates a point we wish to emphasize, namely the scaling of the ratio of the diffractive total cross-section to the total cross-section in the variable z . This means that all of the relative cross-sections for the production of vector mesons at a given b value should have the same shape. We have checked that with this formalism we get agreement for the electro- and photoproduction ⁶⁾ of ρ^0 .

2.2.2. - The y , Q^2 and x distributions

To obtain $d\sigma/dy$ we again use Eq. (23) and perform the Q^2 and t integrations using the limits on the integrals given above [see Eq. (14)]. For $d\sigma/dQ^2$ we integrate over y , t using previous limits.

To obtain $d\sigma/dx$ we do the t integration to yield $d\sigma/dQ^2 dy$, then from $Q^2 = xy \ 2ME_\nu$ [Eq. (15)], we have

$$\frac{d\sigma}{dx dy} = 2y ME_\nu \frac{d\sigma(Q^2, y)}{dQ^2 dy} . \quad (32)$$

We then perform the y integration after writing Q^2 in $d\sigma/dQ^2 dy$ in terms of x and y ; the y limits are as before.

3. - RESULTS AND CONCLUSIONS

3.1. - Total diffractive cross-section

In Figs. 7-10, we have plotted the incoherent and coherent relative cross-sections as a function of energy for the neutral and charged vector mesons ^{*}). For comparison purposes, in Fig. 11, we have plotted for ρ^+ the coherent and incoherent transverse and longitudinal relative cross-sections as a function of energy.

Note the scaling behaviour discussed in the previous section, i.e., the similarity of shape for the relative cross-sections for vector mesons produced at like b values as a function of energy (recall $E = m_V^2 \sqrt{bz}$). The detailed form of $B(z)$ (which determines the shape) depends on what dynamical assumptions are made about the diffractive mechanism. This means that one is free to "pick" a form for $B(z)$ and get the same scaling behaviour for all the relative cross-sections. Thus we have a type of universality of relative diffractive cross-sections for vector meson production in the

^{*}) For the slope parameters we have taken $b = 6 \text{ GeV}^{-2}$ and 4 GeV^{-2} for ρ and φ_c , respectively, and intermediate values for intermediate masses. Actually, experiment favours $b \simeq 8 \text{ GeV}^{-2}$ for ρ ⁶⁾ and $b \simeq 3 \text{ GeV}^{-2}$ for φ_c ¹⁰⁾.

scaling parameter $z = E_\nu / m_V^2 \sqrt{b}$, and predictions for any values of m_V , b and the over-all coupling C_V may be obtained from our curves by a simple vertical/horizontal shift.

3.2. - The y distribution

The curves for $d\sigma/dy$ are plotted in Fig. 12 for the incoherent and coherent cross-sections. Since y is the fraction of the lepton energy carried away by the virtual vector meson, there is a constraint on y , namely that the energy carried away by the virtual vector meson should be as high as possible for a diffractive process. This implies that high y values are more important than low y values at the y distribution. This is reflected in the curves shown. [The fall-off at $y=1$ for the ρ distributions is a reflection of the kinematical constraint at the lepton vertex as discussed in Section 2.2.1. This effect becomes negligible for high mass (cf. φ_c) or high energy.]

3.3. - The Q^2 distribution

Since $\langle Q^2 \rangle \approx m_V^2$, we expect to see an enhancement in the Q^2 distribution at the mass of the produced vector meson, which broadens as the mass of the vector meson increases. This appears to be so in the curves of Fig. 13.

3.4. - The x distribution

In the x distribution (Fig. 14) for the ρ , we see a coherent peak at small x , which is a reflection of an expected small t coherent peak, as kinematics constrains x by $x < \sqrt{|t|}/M_{\text{nucleus}}$. In the incoherent distribution the peak is broad and centred at $x \sim 0.1$. In the coherent distribution the peak is much more dramatic, everything is squeezed down to very small x .

To measure t we need to know the momenta and energies of all final state hadrons. To measure x , we only need to know E_ν and the final state lepton energy or E_ν and the total final state hadron energy. So it may be simpler to measure x distributions to study coherent peaks, etc., than to measure t distributions.

We believe that most of our results will remain qualitatively unchanged, if we use different models. But experiments can help a lot in checking quantitatively the assumptions used in our analysis.

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REFERENCES

- 1) J.J. Aubert et al. - Phys.Rev.Letters 33, 1404 (1974) ; Nuclear Phys. B89, 1 (1975) ;
J.E. Augustin et al. - Phys.Rev.Letters 33, 1406 (1975).
- 2) G.S. Abrams et al. - Phys.Rev.Letters 33, 1453 (1974) ;
W. Braunschweig et al. - Phys.Letters 53B, 393 (1974) ;
L. Criegee et al. - Phys.Letters 53B, 489 (1975) ;
C. Bacci et al. - Phys.Rev.Letters 33, 1408 (1975).
- 3) P. Musset - "Note on Diffractive Neutrino Interactions" CERN Report TC-L/int 74-6 (1974).
- 4) S. Weinberg - Phys.Rev.Letters 19, 1264 (1967) ;
A. Salam - Proceedings 8th Nobel Symposium, Stockholm (1968), Amqvist and Wiksell, Stockholm, 1968, p. 367.
- 5) S.L. Glashow, J. Iliopoulos and L. Maiani - Phys.Rev. D2, 1285 (1970).
See also :
M.K. Gaillard, B.W. Lee and J.L. Rosner - Revs.Modern Phys. 47, 277 (1975).
- 6) E.g. :
K. Berkelman - Proceedings of the 1971 International Symposium on Electron and Photon Interactions at High Energies, Cornell University, Ithaca, Ed. N.B. Mistry, p. 263.
- 7) B.C. Barish et al. - Proceedings "La Physique du Neutrino à Haute Energie", p. 291, Paris (1975). Presented by F. Merrit.
- 8) C.A. Piketty, and L. Stodolsky - Nuclear Phys. B15, 571 (1970). More recently some calculations along these lines have been made by T. Inami - Phys.Letters 56B, 291 (1975).
- 9) D.R. Yennie - Phys.Rev.Letters 34, 239 (1975).
- 10) B. Knapp et al. - Phys.Rev.Letters 34, 1040 (1975) ;
V. Camerini et al. - "Photoproduction of the ψ Particles" SLAC-PUB-1591, Wisconsin-461 (June 1975).
- 11) F.E. Close - Talk presented to the Palermo Conference (June 23-28, 1975).
- 12) V. Barger and R.J.N. Phillips - "Properties of ψ N Scattering" Wisconsin Preprint C00-462 (1972).
- 13) M.K. Gaillard et al. - Ref. 5) ;
B.A. Arbuzov, S.S. Gershtein and V.N. Folomeshkin - Preprint IHEP 75-11, Serpukhov (1975) ;
B.A. Arbuzov, S.S. Gershtein, V.V. Lapin and V.N. Folomeshkin - Preprint IHEP 75-25, Serpukhov (1975).

M.B. Einhorn and B.W. Lee (unpublished) have done detailed calculations of F^* production. See also: J. Pumplin and W. Repko, Michigan State University Preprint (1975);

V. Barger, T. Weiler and R.J.N. Phillips, Wisconsin Preprint C00-456 (1975).

FIGURE CAPTIONS

- Figure 1a Neutrino (antineutrino) elastic diffractive production of charged vector mesons.
- Figure 1b Neutrino (antineutrino) elastic diffractive production of neutral vector mesons.
- Figure 2a Photoproduction of vector meson.
- Figure 2b Photon vector meson vertex.
- Figure 3 Vertex for electroproduction of vector meson.
- Figure 4 Vertex for production of virtual vector boson.
- Figure 5 Neutrino (antineutrino) elastic production of vector mesons.
- Figure 6 Diffractive production of vector meson by virtual vector boson.
- Figure 7 Transverse contribution to incoherent vector meson cross-sections for neutral currents.
- Figure 8 Transverse contribution to coherent vector meson cross-sections for neutral currents ($b_{coh} = A^{2/3} b_{inc}$).
- Figure 9 Transverse contribution to incoherent vector meson cross-sections for charged currents.
- Figure 10 Transverse contribution to coherent vector meson cross-sections for charged currents ($b_{coh} = A^{2/3} b_{inc}$).
- Figure 11 Coherent and incoherent transverse and longitudinal cross-sections for ρ^+ .
- Figure 12 The y distributions, incoherent and coherent, for ρ^+ and φ_c , with $b = 6$ and 4 , respectively (i.e., $E_\nu = 3$ GeV and 40 GeV, respectively).

Figure 13 Transverse contribution to the Q^2 distributions, incoherent and coherent for ρ^+ , π^+ and A_1^+ .

Figure 14 The incoherent x distributions for the transverse and longitudinal parts of the cross-section for ρ^+ .

(a)

(b)

FIG. 1

(a)

$$\gamma \rightarrow V = \frac{m_V^2}{g_V} e = f_V$$

(b)

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

FIG. 13

FIG. 14